School of Electrical and Computer Engineering

Active and Reactive Power-Sharing Method for Micro Grids With Multiple Grid Connections

Syed Muhammad Rizvi

0000-0002-0958-7288

This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

November 2024

DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:…………………………………………….

Date: …12/11/2024……………………...

TABLE OF CONTENTS

ABSTRACT

This thesis presents a mechanism for active and reactive power-sharing among multiple dispatchable and distributed generation units within a micro grid having multiple interconnections with the main grid. The proposed method is equally good for micro grids with single grid connection. Ideally, a micro grid should act either as a constant load or a constant source when connected to the main grid. However, to achieve ideal operation, natural load variations and the intermittency of renewable energy sources within the micro grid need to be adequately and timely compensated by the dispatchable power sources.

Various approaches for active power sharing, managing and controlling for different types and configurations of micro grids have been published in the literature. In these publications, several types of power – frequency (P-f) droop controller-based approaches are presented. They can be classified as having or not having communication to the central dispatch controllers. Active power-sharing approaches are examined for a micro grid with several dispatchable distributed generation units (DDGU) operating in grid-interconnected and independent/isolated modes. Renewable energy sources without battery energy storage are generally not included in active power sharing strategies within micro grids. This is because they lack the ability to provide a consistent and stable active power supply. In fact, their generation intermittency can be considered as load variation.

The layout of the micro grid, internal organisation / connectivity of the distributed generation units (DGUs) and loads and the number of grid interconnections, all have an impact on the performance of the active and reactive power-sharing approach. In this thesis multiple grid connections at different points of the micro grid are investigated, and recommended approaches are appraised. This enquiry gives a succinct comparison to allow an acceptable decision in the real utility setting. Certain claimed methods are found to have some performance

or design restrictions. It has also been noted that in micro grids with higher levels of renewable penetration, the amount of active power reserve in the dispatchable units is higher than in micro grids with lower levels of renewable penetration. Higher penetration levels, on the other hand, might result in bigger and more frequent load changes. Renewable sources within a micro grid provide an intermittent or non-dispatchable active power output, however with recent advancements in inverter technologies, they are now capable of contributing reactive power more reliably. As an example, solar inverters are now capable of providing reactive power during night time, using “night mode” operation of the inverters.

While several control algorithms have been reported in the literature to achieve ideal micro grid operation, majority of the proposed methods considered a micro grid with single interconnection with the main grid. While in the real-world, micro grids may have to maintain multiple live links with the main grid for several technical and operational reasons such as reliability, power dispatch restriction, voltage control, operational limitations, and other operational or network stability requirements. Therefore, initially a new and basic method of only active power-sharing is proposed in this thesis, which is equally effective for micro grids with single or multiple grid connections. The initial controller is then further enhanced to include an exclusive feature of frequency response balancing, within active power control logic, and an independent reactive power flow control logic. This enhanced controller can be tuned to manage the overall active power response based on the two fundamental motivators, namely interconnection active power flow and frequency response based on system frequency excursions, while micro grid is in grid connected mode of operations. This frequency response balancing feature in the active power control provides a complementary mechanism between the flow controller section and the frequency response section of the controller to maintain a constant active power flow even when frequency of the main grid varies within certain designed or physical limits. An integrated and independent reactive power flow control (IRFC) mechanism is introduced, further refining the controller's capabilities. This addition extends the controller's capability to ensure a constant reactive power flow from (or towards) the grid is maintained over the interconnection lines. This will enable the controller to manage reactive power flows at the interconnection lines with greater precision and efficiency, thus optimizing the overall performance and reliability of the micro grid when faced with the real-world operational challenges.

The robustness of the proposed method is validated under different micro grid operating conditions. Results validated the flexibility of the proposed method to adapt under various real-world operating conditions.

This thesis provides a new and a robust approach for active and reactive power-sharing among several DDGUs within a micro grid comprising multiple (or a single) interconnections with the main grid(s). The proposed active and reactive power-sharing method is an effort to establish a true power-sharing technique that can be categorised as applicable for all, or most, types of interconnected micro grids. The suggested method's resilience is tested under various micro grid operation situations. The results demonstrate the adaptability of the suggested technique under a variety of real-world operational scenarios.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS & PARAMETERS

AC	Alternating Current
AEMO	Australian Energy Market Operator
AEMC	Australian Energy Market Commission
BESS	Battery Energy Storage System
CAGR	Compound Annual Growth Rate
DC	Direct Current
DDGU	Dispatchable Distributed Generation Unit
DGU	Distributed Generation Unit
FACTS	Flexible AC Transmission System
FFC	Feeder Flow Control
HV	High Voltage
IBRG	Inverter-Based Renewable Generation
IEEE	Institute of Electrical and Electronics Engineers
IFC	Interconnection Flow Control
IRFC	Interconnection Reactive Power Flow Control
Km	Kilometres
MPPT	Maximum Power Point Tracking
MVA	Mega Volt Ampere
MVAr	Mega Volt Ampere reactive
MW	Mega Watt
NDDGU	Non-Dispatchable Distributed Generation Unit
NEM	National Electricity Market
PV	Photovoltaic
P-f	Power – Frequency
TWh	Tera Watt hour
UPC	Unit Power Control
VSG	Virtual Synchronous Generator
VSM	Virtual Synchronous Machine
WA	Western Australia

Parameters:

cosn	power factor
f	Grid frequency in Hz

f’	Final value of frequency
f0	Initial value of frequency
FL’	Final value of active power flow
FL0	Initial value of active power flow
FLREF	Active power flow reference
FLref	Active power flow reference
Fmeas	Measured frequency
Fref	Reference frequency
id	d-axis stator current
iq	q-axis stator current
J	Rotor’s moment of inertia
KF	FFC droop constant
KI	Frequency droop (UPC mode)
Kif	Integral gain for frequency response
KiFL	Integral gain for flow control
KiQFL	Integral gain for reactive power flow control
Kpf	Proportional gain for frequency response
KpFL	Proportional gain for flow control
KpQFL	Proportional gain for reactive power flow control
KU	UPC droop constant
N	Rotor speed in revolutions per minute (RPM)
P	Number of poles in the machine
P’	Final value of active power
P0	Initial value of active power
P1	Measured active power on interconnection Line 1
P2	Measured active power on interconnection Line 2
PDGa	Active power output from distributed generator ‘a’
Pgen	Generated active power from DDGU
Pmax	Max active power rating of the DDGU
pt	Turbine power or active power
Ptmax	Max active power rating of the DDGU
Ptmin	Minimum active power rating of the DDGU
Qline 1	Reactive power flow over interconnection line 1
Qline 2	Reactive power flow over interconnection line 2

Te	Electrical torque (in newton-meters),
Tm	Mechanical torque
ve	Signal to the DDGU's exciter
ω	Rotational speed of the rotor in radians per second.
ψd	d-axis flux linkage
ψq	q-axis flux linkage
δ	rotor angle (or power angle)

LIST OF PUBLICATIONS

1. Rizvi, S., and Abu-Siada, A. (2022). “Active Power Sharing in a Micro-Grid with Multiple Grid Connections.” *Designs*, 6(2), 24.
2. S. M. Rizvi, A. Abu-Siada, N. Das, M. F. Ishraque and S. A. Shezan, "Active Power Sharing Method for Microgrids with Multiple Dispatchable Generation Units using Modified FFC and IFC Mode Controller," in *IEEE Access*, doi: 10.1109/ACCESS.2023.3274674.
3. Rizvi S, Abu-Siada A. A Review on Active-Power-Sharing Techniques for Microgrids. Energies. 2023; 16(13):5175. https://doi.org/10.3390/en16135175.
4. S. M. Rizvi, A. Abu-Siada, S.M. Muyeen, M. F. Ishraque and S. A. Shezan, "Active and Reactive Power Sharing Method for Micro grids with Multiple Grid Interconnections using enhanced Interconnection Flow Controller." in IET Smart Grids, submitted for review and publication.

STATEMENT OF CONTRIBUTION TO PUBLICATIONS

This thesis incorporates material from the above listed published (and draft) papers.

The candidate made significant contributions to the above four journal papers, primarily focusing on the conception and design, simulations, comparing results, interpretation and discussion. Moreover, the candidate contributed to manuscript preparation and effectively incorporated valuable feedback from reviewers.

The co-authors significantly contributed to all four journal papers by reviewing results, validating the main author's contributions and the novelty of the findings, engaging in discussions, conducting comprehensive reviews of the manuscripts, and evaluating reviewers' comments.

Name	Author: Syed M. Rizvi	Supervisor: Ahmed Abu-Siada
Signature		

1. INTRODUCTION

Micro grids with high renewable penetration, once an idea, have now very much turned into a real-world reality. With the vast proliferation of distributed power generation sources, the concept of micro grid has evolved as one of the most practical and flexible options for disintegrating large power systems into smaller and more manageable operational units: micro grids. The increased energy efficiency of distributed conventional and renewable power generation sources, along with the widespread adoption of renewable sources in homes and businesses, was a major catalyst for developing this idea.

Micro grids are becoming an increasingly popular solution for managing power systems with high renewable penetration. They offer a flexible and decentralised approach to energy management, allowing communities and organizations to generate, store, and distribute their own electricity. This approach can increase energy efficiency, reduce costs, and improve the resilience of the overall power system.

In a micro grid, power generation sources can include a combination of conventional and renewable sources, such as solar panels, wind turbines, and biomass generators. The system may also include energy storage devices, such as batteries or flywheels, which can store excess energy for later use. In addition, advanced control systems can help manage the flow of electricity within the micro grid, optimising energy use and reducing waste.

The widespread adoption of micro grids has been driven by a number of factors, including the increasing cost-effectiveness of renewable energy sources, the desire for greater energy independence and resilience, and the need to reduce carbon emissions to combat climate change. As technology continues to advance and the benefits of micro grids become more widely recognised, it is likely that we will see even greater adoption of this approach to energy management in the years to come.

Traditionally, electric power is generated in bulk and at a centralised location suitable for such facility, usually at a fair distance from the consumers. The generated energy is delivered to the consumers over transmission and passive distribution networks. This model has been in use for many decades and has been effective in meeting the energy needs of large populations.

However, this model has some drawbacks. For one, it is often expensive to build and maintain large power plants and transmission networks. In addition, transmission losses can occur during long-distance transmission, reducing the efficiency of the system. There can also be reliability issues, such as power outages, that affect large areas.

The development of distributed power generation, such as micro grids, has the potential to address some of these drawbacks by bringing power generation closer to the point of use. By generating power locally, either through renewable sources or through smaller, more efficient conventional sources, it may be possible to reduce transmission losses and improve the overall efficiency of the system. It can also increase the resilience of the system by reducing the impact of power outages on large areas.

Another challenge with the traditional centralised model is that it is vulnerable to disruptions, such as natural disasters or cyberattacks, which can cause widespread power outages. Micro grids and distributed energy resources are seen as a way to increase the resilience and reliability of the power system by creating smaller, more flexible units that can operate independently.

Overall, while the traditional model of centralised power generation and distribution has served us well in the past, it is clear that new models and technologies are needed to meet the evolving needs of our modern energy system.

Large AC interconnected power systems were developed all over the world, connecting distant power generation units to the consumers. These grids consist of a network of high-voltage transmission lines, substations, and distribution lines that enable the efficient and reliable delivery of electricity over long distances.

The development of AC interconnected power systems began in the early 20th century and was driven by the need to connect remote power generation sources, such as hydroelectric power plants, to urban centres and industrial areas. These systems have since expanded to cover vast geographical areas and are capable of delivering large amounts of electricity to millions of consumers.

One of the key advantages of interconnected power systems is that they allow for the efficient sharing of power resources across a wide area. This means that when one area experiences a shortage of power, electricity can be quickly and easily transmitted from another area with excess power. Interconnected power systems also enable the integration of a variety of power generation sources, including renewable energy sources such as wind and solar power.

Despite their advantages, however, interconnected power systems are also vulnerable to disruptions, such as severe weather events or cyberattacks, which can cause widespread power outages. As a result, there is growing interest in the development of more localised, distributed power systems such as micro grids, which can operate independently or in parallel with the main grid, increasing resilience and reliability.

In Australia on the east coast we have one of the largest AC interconnected power systems [117], interconnecting 5 states, namely, South Australia, Tasmania, Victoria, New South Wales and Queensland. It spreads from Port Douglas in Queensland to Port Lincoln in South Australia, which is around 5000 km. The National Electricity Market (NEM) operates using this power network. Figure 1.1 shows the overall spread of the network. It has around

200 large generators and 13 major distribution networks, delivering around 200 TWh of electricity annually.

Conventionally, islanded operation of a segment of a network, even with sufficient distributed power generation sources, was once not considered to be one the best practices or recommended mode of operation for various utilities [11]. It was only recommended under certain extraordinary operational circumstances. Control and protection systems were also not designed to cater for such operation. However nowadays, to take the full benefit of the increased penetration levels, proliferation of high efficiency and low-cost distributed power sources and to reduce the cost of having a reliable and redundant grid infrastructure, micro grids are considered to be a smart, viable and sustainable option for the grid operators [11]. Due to the obvious economic and environmental benefits the model of having operational micro grids has now been studied in detail. Numerous studies are conducted and reported for evaluating the possibility of independent, isolated operation of a micro grid under varying operational conditions. This specific area of research has attracted a lot of interest and attention of the researchers.

Australia, being at the forefront of this grid evolution, is not only witnessing this transformation but embracing it to ensure their power systems also evolve according to the modern-day requirements of having an environmentally friendly green and sustainable energy infrastructure; an infrastructure that can facilitate higher levels of renewables penetration without compromising system reliability and security. Australia, with one of the largest interconnected power systems on the eastern coast, has 4 operational micro grids on the western side (WA) to serve remote industries or communities [118]. The four micro grids in WA are:

1) Perenjori
2) Bremer Bay
3) Kalbarri
4) Ravensthorpe

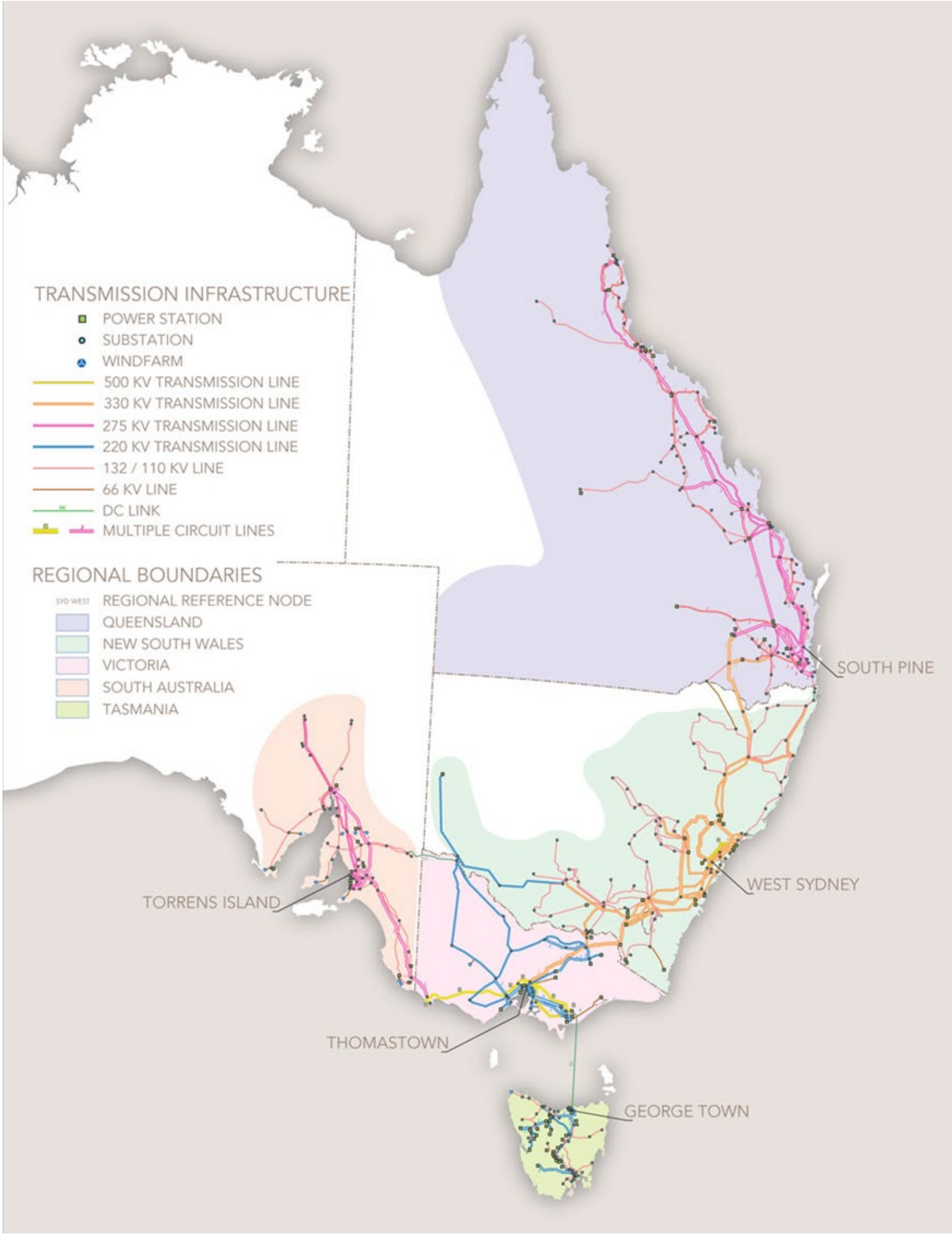

Figure 1.1. Australia interconnected system [117] (source: AEMO through AEMC).

Figure 1.2 shows all four micro grids operating in the South-West Interconnected System (SWIS). The first micro grid, Ravensthorpe was formed almost a decade ago in 2013, while the other 3 were formed in last 6 years; Bremer Bay in 2017, Perenjori in 2018 and finally Kalbarri in 2021.

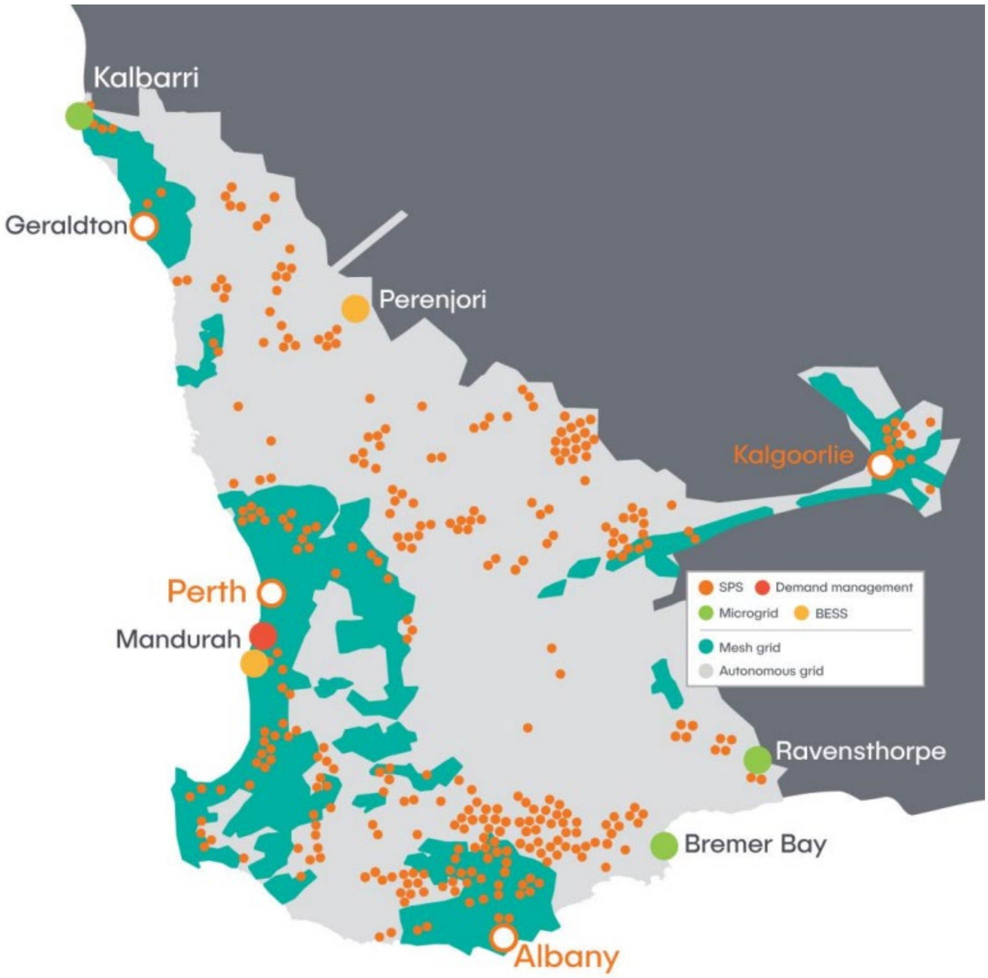

Figure 1.2. Micro grids and interconnected network map of WA [121].

Kalbarri being the largest micro grid of Australia operating only on renewable sources, connecting 1.6 MW of wind generation, 1 MW of roof top solar and 2 MWh of battery storage. The Kalbarri micro grid is connected with the main grid. The grid will provide the additional demand especially during the tourist season, however the micro grid itself can operate on its own in case grid interconnection is lost due to any network event [119]. The geographic view of the Kalbarri micro grid is depicted in Figure 1.3.

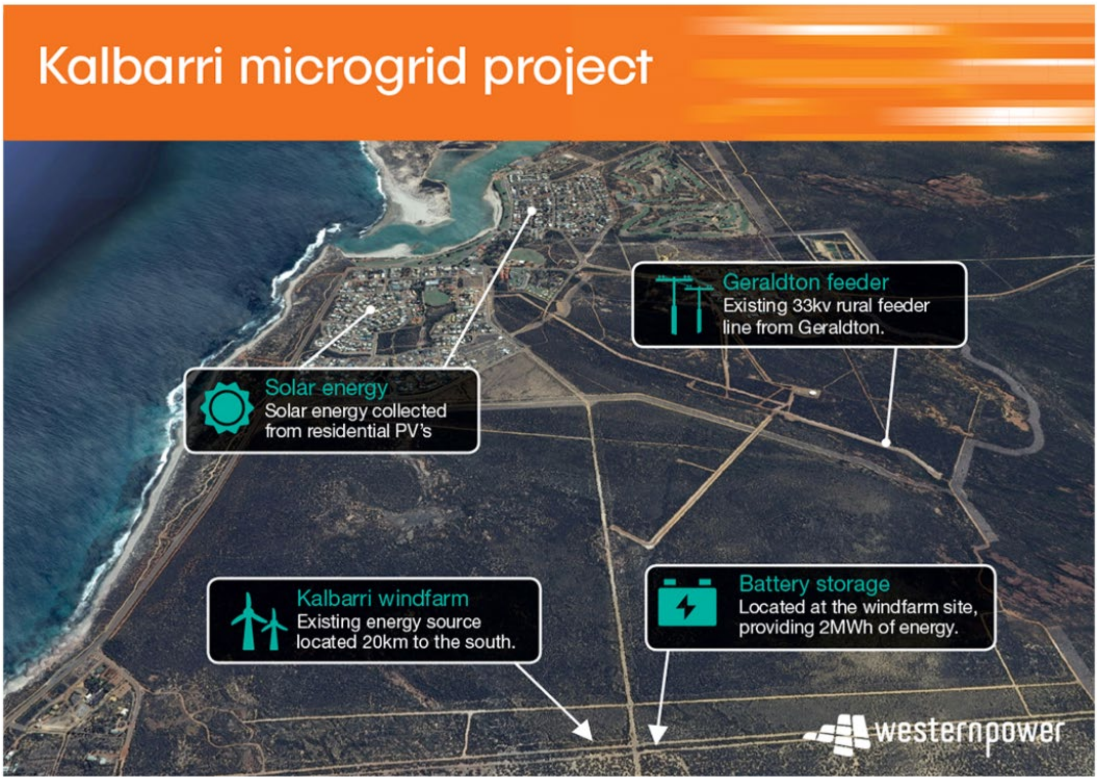

Figure 1.3. Geographic view of Kalbarri micro grid [122].

Apart from Western Power of Western Australia, several other power utilities throughout the world now also operate and maintain numerous micro grids. Studies related to stable and efficient design and operation of micro grids have lately attracted a lot of interest in academia and research [5]. It is expected that the global market for micro grids will grow to US25.04 b. in 2026 from US9.63 b. in 2022 at a CAGR of 20.4% [181].

In US, there are 160 micro grids in operation, mostly concentrated in seven states, namely, Alaska, California, Georgia, Maryland, New York, Oklahoma and Texas. These provide almost 0.2% of US electricity [182].

Micro grids with multiple grid interconnections to either a single main grid or multiple grids are a unique case, which has not been explored. Multiple connections to the grid or grids can be required for several operational reasons, primarily reliability. Several sensitive installations, such as relate to defence or process-critical industry might have additional reliability requirements. With recent advancements and the benefits of operating a dis-integrated power system, we might, in near future, see that the state level systems are operated as large micro grids. If we apply this hypothetical scenario to the Australia NEM network, then we might see that all or one interconnected state(s) might be operated as large micro grids. If we consider Queensland (QLD), at the north end of the interconnected NEM network, is being operated as a large micro grid then it already has multiple interconnections with New South Wales (NSW). This can be regarded as an example of a future micro grid with multiple interconnections. The two interconnections are not only at different nodes but are also quite different, as one is an AC interconnection while the other is a DC link. The DC link is called as Directlink, which is 110 kV DC link with flow limits provided in Table 1-1[183].

Table 1-1. Directlink active power flow limits.

From	To	Nominal Capacity
NSW	QLD	107 MW
QLD	NSW	210 MW

The other interconnector is called QNI – Queensland to New South Wales interconnector. This interconnector consists of following transmission lines:

- A new double-circuit 330 kV line between Armidale, Dumaresq, Bulli Creek and Braemar substations.
- A new double-circuit 275 kV line between Braemar and Tarong substations.
- Two 330/275 kV transformers at Braemar substation.

The overall active power flow limit on QNI is given in the Table 1-2. These overall flow limits in the existing interconnection, with several lines, demonstrates that a flow control which is based on the sum of active power flows on multiple lines is a real example.

Table 1-2. QNI active power flow limits.

From	To	Nominal Capacity
NSW	QLD	300-600 MW
QLD	NSW	1078 MW

A number of technical and commercial challenges related to micro grid operations have been noted and reported, and numerous solutions have been proposed in the literature [22][80]. One of the main technical issues relating to the ideal operation of a micro grid is an active power-sharing mechanism between dispatchable distributed generation units (DDGUs) within the micro grid. If a micro grid has only one large dispatchable generation unit (normally a synchronous machine or a dispatchable energy storage system) along with other small non-dispatchable distributed generation units (NDDGUs) (mainly renewable energy sources without any form of energy storage), then the only DDGU will have to compensate for any variations in the demand or generation from NDDGUs. However, if the micro grid has multiple DDGUs, they all must act in a coordinated manner in response to the changes in the demand, generation, and network configurations.

Changes in network configurations, load distribution or load concentration either caused by the emergence of new load centre or a generation station within a micro grid can result into a completely different active power flow within a micro grid. In evolving modern-day power systems such changes are highly probable. If the performance of the power-sharing method within a micro grid is dependent on network configuration, then for any and every such modification in the network, the whole algorithm of active power-sharing will have to be revisited or retuned according to the new operating conditions. Mostly, this aspect of the performance criterion is found to be missing for the methods which are presented in the research. In this research a method is suggested and this aspect is also evaluated to test the effectiveness of the suggested method.

As for the active power flow, managing and controlling flow of reactive power on the interconnection lines between the main grid(s) and the micro grid is also critical for the voltage stability of the grid as well as of micro grid. Maintaining a constant reactive power flow from or towards the main grid makes ensures that the micro grid operates ideally even with reference to its reactive power demand.

1.1 Definition of a Micro Grid

IEEE defines a micro grid as *"A micro grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid."* [120]

1.2 Types of Micro Grids

Micro grids are roughly classed into two types, based on their connections to the main grid: isolated micro grids and interconnected micro grids [25][60][78]. Isolated micro grids, as the name suggests, have no linkage with a larger grid or a power system, but interconnected micro grids may have single or multiple links to one or more larger grids or power systems. An interconnected micro grid, on the other hand, may or may not remain connected to the main grid/s. It may operate in three different modes:

1) linked to the main grid/s (Grid Connected Mode)
2) isolated
3) transition [35][90][110].

The detachment from the main power grid might be either intentional or unintentional. In any operational scenario, the micro grid must be able to remain stable in any mode of operation at any given moment [85]. Figure 1.4 depicts the types and the components of the micro grids.

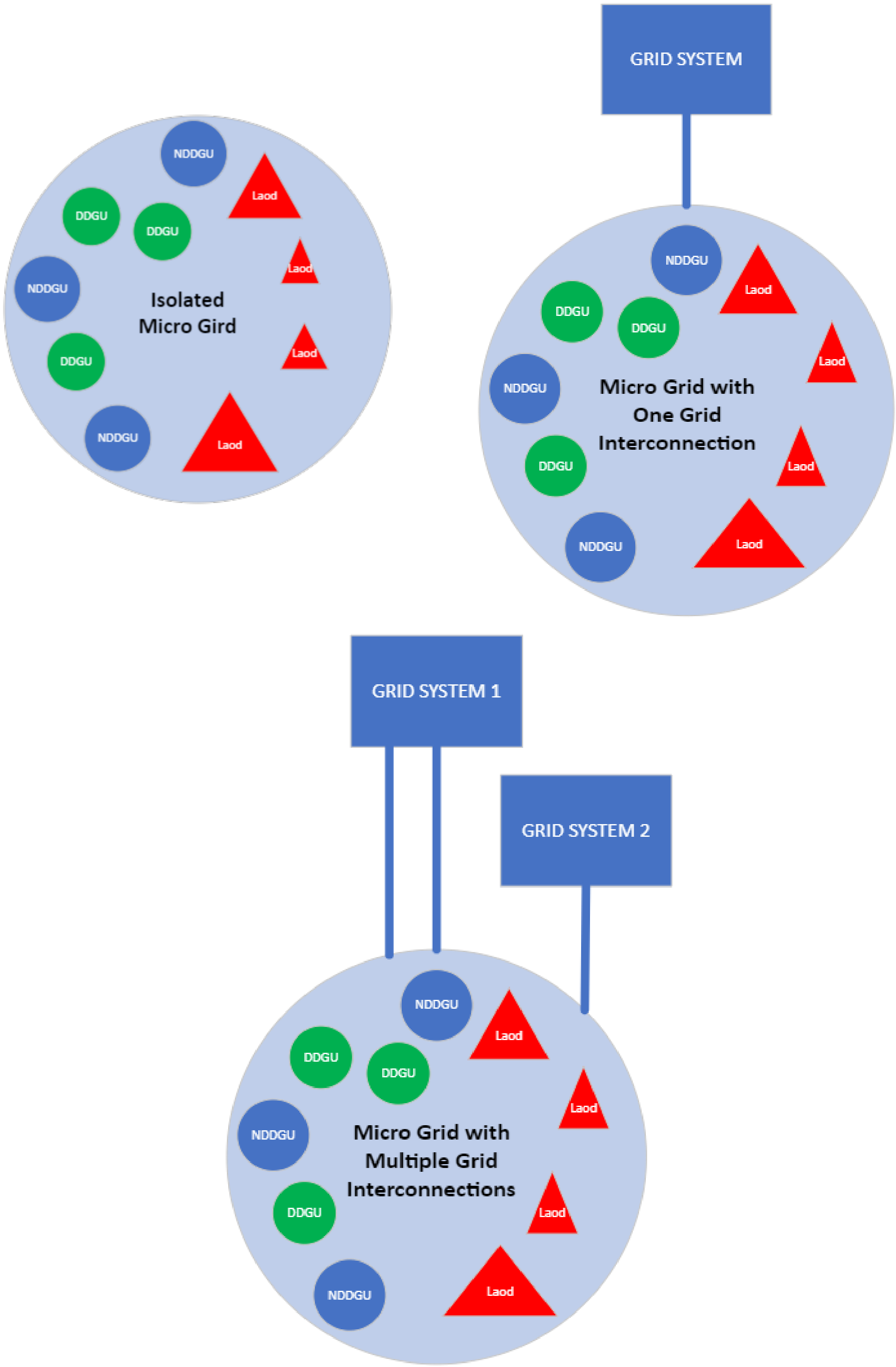

Figure 1.4. Types of micro grids.

Apart from the basis of grid interconnection, micro grids can also be classified based on type of load they serve, for example, residential, commercial or industrial.

The fundamental operational difference between a micro grid with a single grid interconnection and one with multiple grid(s) interconnections is the way in which interconnection flows are managed or controlled. Micro grid with multiple interconnections from one grid system at same voltage level and at same interconnecting node is operationally almost similar to a micro grid with single grid interconnection, apart from increased reliability. However, micro grid with multiple interconnections to a single grid system but at different connecting nodes or at different voltage levels is quite different in terms of controlling or managing active power flow from or to the connected grid system. Controlling active power flow over the interconnector lines is significantly more challenging in such networks.

The operational characteristics of a micro grid are significantly influenced by the nature of its grid interconnections. There is a fundamental operational difference between a micro grid with a single grid interconnection and one with multiple grid interconnections. The key distinction lies in how interconnection flows are managed and controlled within the micro grid.

1) Micro grid with a Single Grid Interconnection:
    - In a micro grid with a single grid interconnection, the management of active power flow is relatively straightforward. There is one primary connection to an external grid system, and the control of power flow, both into and out of the micro grid, is centred around this single point.
    - The operation of such a micro grid is simpler in terms of active power flow control, as there is only one interconnection point to manage.
2) Micro grid with Multiple Interconnections from One Grid System at the Same Voltage Level and Interconnecting Node:

- When a micro grid has multiple interconnections from a single grid system at the same voltage level and interconnecting node, its operational characteristics are similar to those of a micro grid with a single grid interconnection.
- The primary advantage of this configuration is increased reliability. If one interconnection experiences issues, the micro grid can still rely on the others for power supply or export.

3) Micro grid with Multiple Interconnections to a Single Grid System but at Different Connecting Nodes or at Different Voltage Levels:
    - In contrast, a micro grid with multiple interconnections to a single grid system, but at different connecting nodes or at different voltage levels, presents unique challenges in terms of controlling and managing active power flow.
    - The key complexity arises from the fact that these interconnections may be at different locations and voltage levels. Managing power flow in such a network necessitates coordination between various interconnections.
    - Ensuring that power is exchanged appropriately, maintaining grid stability, and managing power quality in a multi-node or multi-voltage-level configuration requires sophisticated control mechanisms.
4) Challenges in Managing Active Power Flow:
    - Controlling active power flow over the interconnector lines in micro grids with multiple, diverse interconnections is significantly more challenging due to the need for coordination between these connections.
    - Various factors, including voltage differences, synchronization requirements, and power flow distribution, must be carefully managed to ensure the reliable operation of the micro grid and the connected grid system.
5) Challenges in Managing Reactive Power Flow:

Managing reactive power flow in a micro grid presents several challenges that are critical for maintaining voltage stability, improving power quality, and ensuring the overall reliability of the system.

- Reactive power directly affects voltage levels in the micro grid. Inadequate or poorly managed reactive power can lead to voltage instability, causing voltage fluctuations, sags, or swells. This is particularly problematic in micro grids with high penetration of renewable energy sources, such as solar or wind, which can introduce variability and unpredictability in both active and reactive power flows.
- When a micro grid operates in grid-connected mode, it must coordinate reactive power flow with the main grid. The micro grid needs to manage its reactive power contribution to avoid overloading the local distribution network or causing undesirable voltage changes. This requires sophisticated control systems to ensure that reactive power exchange with the main grid is beneficial and does not compromise grid stability.

- Reactive power demand can vary significantly depending on the types of loads connected to the micro grid. For example, inductive loads such as motors and transformers require a substantial amount of reactive power, while capacitive loads might inject reactive power back into the system. Managing these varying demands requires continuous monitoring and adjustment of reactive power sources, which can be technically challenging, especially in real-time.

Micro grids often incorporate renewable energy sources like solar and wind, which are inherently intermittent and can cause fluctuations in both active and reactive power. The variability of these sources complicates the control of reactive power, as the micro grid must constantly adjust to changing generation levels to maintain voltage stability. In summary, the number and configuration of grid interconnections have a substantial impact on the operational characteristics of a micro grid. While micro grids with single or similar interconnections offer operational simplicity and reliability, those with multiple, diverse interconnections require more intricate control mechanisms to ensure the coordinated and effective management of active power flow. Addressing these challenges is essential for maintaining grid stability and reliable operation in complex multi-interconnection micro grid setups.

1.3 Micro Grid Operation

Interconnected micro grids should ideally function as a constant load or source for the main grid while interconnected [11][90]. In this research we extended this definition and included overall reactive power flow towards or from the micro grid in evaluating the ideal operation of the micro grid. This ideal operating condition is only attainable if the local (to micro grid) DDGUs are capable of correcting for the fluctuations in the load or generation within the micro grid. DDGUs must respond favourably to any load or generation fluctuation either caused by the intermittency of the renewable DDGUs or due to the loss of any power producing facility [111][95][98]. Achieving ideal operation of micro grids with higher renewable penetration levels and with varying loads/demand will be more challenging than the one with lower renewable penetration and with non-varying type load characteristics. Variations in reactive power demand or consumption can be caused by several factors, including changes in load types (such as inductive or capacitive loads), voltage fluctuations, the operation of large motors or industrial equipment, switching of capacitor banks, operation of transformer taps and grid disturbances. These variations impact the voltage stability of the system, as reactive power is essential for maintaining appropriate voltage levels across the network. Additionally, the integration of renewable energy sources, such as wind and solar, which produce intermittent power, can also lead to fluctuations in reactive power demand. Advances in power electronics-based or inverter-based renewable generation (IBRG) technologies, as well as flexible AC transmission system (FACTS) technologies, permitted the conversion of NDDGUs to partially dispatchable sources by incorporating battery energy storage systems (BESS). Furthermore, advances in power electronics-based generation have led to the development of grid-forming inverters with sophisticated grid-supporting capabilities such as virtual synchronous machine (VSM) control, fast frequency response, and dynamic voltage control. These breakthroughs have demonstrated that a micro grid can rely entirely on renewable energy sources to serve its demand [30][83].

The main challenges of existing micro grids can be summarised in the bullet points below:

- Operating an interconnected micro grid in an ideal manner, that is, either as a constant load or as a constant source for the main grid with reference to active and reactive power both.
- Having a coordinated response to internal load or generation variations.
- Ensuring a stable operation during and after grid isolation.
- Maintaining certain levels of active power flows at the interconnections when micro grid has multiple grid interconnections.

Apart from the challenges listed above, micro grids face a number of other challenges that must also be addressed in order to ensure their successful implementation and operation. Addressing these challenges will require a coordinated effort from stakeholders including industry, government, and academic institutions. With the right investments in technology, policy, and infrastructure, micro grids have the potential to revolutionise the way we generate, distribute, and consume energy. Some of the secondary challenges of micro grids include:

1) Cybersecurity. Micro grids are vulnerable to cyberattacks, which can disrupt their operation and potentially cause damage to equipment. This requires robust cybersecurity measures to protect against threats such as hacking and malware.
2) Financing and Economics. Micro grids can be expensive to implement, particularly in remote or rural areas. The economics of micro grids must be carefully considered to ensure that they are financially sustainable over the long term.
3) Regulatory and Policy Frameworks. Micro grids may face regulatory and policy barriers that make it difficult to implement them in certain regions. Clear and supportive regulatory and policy frameworks are needed to encourage the development of micro grids and ensure their integration with the larger power grid.
4) Technical Standards and Interoperability. Micro grids rely on a variety of equipment and technologies and ensuring that they are interoperable and compliant with technical standards is critical to their successful operation.

1.4 Motivation of Research

The main purpose of this research is to design an active and reactive power-sharing mechanism for the DDGUs within an interconnected micro grid, with single or multiple grid interconnections, to ensure ideal operation with reference to the main grid. The controller should be able to ensure ideal operation under all possible (and probable) operating scenarios, in regard to both, active and reactive power flow at interconnection lines. It was noticed as a research gap in our conducted literature review that a universal interconnection power (active and reactive) flow controller, purely designed to manage flows at multiple (or single) grid interconnections, is something which is not yet been developed and discussed in the referenced research papers. Such controller has the potential to be extremely useful for ensuring ideal operation of the micro grids having multiple grid interconnections. We intended to develop an active and reactive power interconnection flow controller which can remain effective and stable under varying load, intermittent generation (renewable), varying network operating conditions, such as modified network configuration, or load or generation location/profile.

When discussing reactive power control in the context of maintaining constant interconnection flow in a micro grid, the focus shifts from traditional voltage management to managing the reactive power exchanged between the micro grid and the main grid or across multiple interconnection points. In this context, the goal is set to ensure that the sum of the reactive power flowing across interconnection lines remains close to a reference value, thereby supporting balanced power exchange without causing fluctuations in the overall system.

This type of control is critical when a micro grid operates in parallel with the main grid or other networks and is responsible for maintaining a steady reactive power flow. For instance, if the reactive power demand in the micro grid fluctuates due to changes in load conditions, the interconnection flow control system should be able to change the reactive power outputs of dispatchable distributed generation units (DDGUs). These units respond dynamically to compensate for any deviations from the reference reactive power flow setpoint, ensuring the interconnection lines do not experience significant deviations.

Maintaining constant reactive power flow at the interconnection points is particularly important for optimizing the performance and efficiency of the grid. If reactive power fluctuates excessively, it can lead to inefficient power exchanges and imbalance between the micro grid and the main grid.

1.5 Main Objectives of Research

This research is intended to solve a key challenge faced by grid interconnected and isolated micro grids. The challenge of effectively sharing of the active power between the distributed and dispatchable power generation units of the micro grids for ensuring that the micro grids are operated in an ideal manner under all varying operating conditions. The need of time is to develop an active power sharing method for micro grids which is smart, resilient, stable, stand alone, self-adjustable, independent of network design/configuration, fit for all purposes and efficient.

The main objective of this research is to design/propose an active and reactive power-sharing mechanism which serves the purpose and has following operational features:

a. Should be able to ensure operation as a constant load or generation for the whole micro grid with reference to active and reactive power.

b. Should be applicable to micro grids with one or multiple grid interconnections.

c. Should allow stable independent (grid-isolated) operation of the micro grid.

d. Should have capability to control the active and reactive power flow on all or some of the identified (participating) interconnection lines from the main grid.

e. Should be able to adapt to changes in network configurations.

f. Should be self-resilient in manner that in case micro grid changes modes (grid interconnected to isolated or vice-versa) the DDGUs should be able to adapt accordingly.

g. Should be able to maintain the ideal operation of the micro grid to the extent possible, even during the transient frequency events.

i. Should be able to control or manage active and reactive power independently.

This thesis presents an active and reactive power-sharing method which provides all the features listed above. The proposed active and reactive power sharing method is designed to have these listed features which are considered to be “must have” for fulfilling the operational needs of today’s and future micro grids.

1.6 Research Questions

This research is intended to provide answer to the following questions:

a. How active and reactive power should be shared within the dispatchable and distributed power generating units within a micro grid which has multiple interconnections with the main grid(s) for ideal operation?

b. How the active and reactive power flow control over the interconnection lines be adhered using that active and reactive power sharing technique?

c. What would be the resiliency parameters/impacts of the suggested active and reactive power flow control methodology?

d. How micro grid should maintain an ideal operation during the frequency excursion of the main grid?

1.7 Research Process and Contribution

The proposed active and reactive power sharing method is unique in the sense that it will be equally effective for the micro grids with single or multiple interconnections with the main grid(s). Additionally, the proposed technique can ensure ideal operation of the micro grid even after any network configuration change has been implemented within the micro grid. As compared to other proposed techniques, this method has no operational or network configuration or design related limitations or conditions. It utilises the overall dispatchable power generation capacity in far efficient, smarter and global manner as compared to other techniques which, due to their design limitations, could not demonstrate. The proposed method can accommodate multiple grid interconnections with single or even multiple grids and that too at different network locations which can even be at different voltage levels. The flow control limitations can be applied to all participating interconnections without impacting flow on non-participating interconnections. All of these features are unique to the proposed technique which will prove to be extremely useful and effective for the micro grids of today and of future.

A conventional step type research process was adopted to complete this research. Figure 1.5 depicts the overall adopted process. The robust process ensured that the final design of the solution not only achieves the set objectives but also is tested vigorously, compared appropriately, discussed thoroughly, and reported clearly for the benefit of the research fraternity.

In this research project, a comprehensive and systematic approach was undertaken to address specific objectives and research gaps within the chosen domain of study. The following steps highlight the methodology and process employed in this research:

1) Literature Review:
    - The research commenced with an extensive literature review, involving a thorough examination of a wide range of related and recent research papers within the research domain. This step provided a foundational understanding of the existing body of work and helped identify gaps and opportunities for further research.
2) Identify Research Gaps
    - The available research was approached with a very critical angle. Assumptions were considered and challenged. Adopted methodology was also reviewed with reference to the real world requirements to create alternative options and to identify gaps.
3) Setting Research Objectives:

- After conducting the literature review, the research objectives were carefully formulated. These objectives were designed to address the identified gaps in the current body of research, aiming to contribute new insights and solutions to the field.

4) Initial Design Proposal
   - An initial design was proposed and evaluated. This design had several iterations of reviews to ensure that it aligns with the desired objectives and provide a unique and more appropriate solution to the identified problem/gap.
   - Theoretical comparative analysis was conducted before initiating the developing the control system.
5) Initial Model Development:
   - An initial test model was created based on the test/simulation models used in reference research papers. This initial model served as a starting point for the research and was employed to reproduce the results achieved in previous studies. It helped establish a baseline for the research.
6) Model Validation:
   - The initial model underwent validation to ensure its accuracy and reliability. This validation process involved comparing the model's results with those from prior research papers. Once the model was validated, it provided a sound basis for further development.
7) Model and Design Finalization:
   - Modifications were designed and implemented to enhance the initial model. These modifications were aimed at transforming the model into a flexible and adaptable test bed capable of demonstrating the research objectives. Careful

consideration was given to the model's ability to simulate various operational scenarios that micro grids may encounter.

8) Iterative Discussions:
    - Multiple iterations of discussions and consultations took place throughout the research. These discussions involved researchers and experts collaborating to refine the model, ensuring that it effectively represented the complexities of micro grid operations and the specific research objectives.

9) Evaluation of the Model:
    - The model was rigorously evaluated to guarantee its ability to simulate all possible operational scenarios encountered by micro grids. This evaluation process was critical in preparing the model for the study cases and testing of the proposed methodology.

10) Study Cases Simulation:
    - Identified study cases, which were essential for testing the features of the proposed method, were simulated using the model. The results obtained from these simulations were evaluated against the predefined research objectives.

11) Result Analysis and Comparison:
    - The achieved results were analysed thoroughly and compared with those from other available works. This comparative analysis helped establish the benefits and contributions of the proposed research work.

12) Thesis Drafting:
    - The research findings and the entire process were meticulously documented and presented in the form of a thesis. This document serves as a comprehensive exposition of the research methodology, objectives, model development,

simulations, and the results achieved. It offers a clear explanation of the research contributions and their significance within the chosen research domain.

In summary, this research followed a systematic approach, encompassing a literature review, model development, validation, enhancement, discussions, evaluations, simulations, and comparative analysis to achieve its research objectives and address identified gaps in the field of micro grids. Figure 1.5 describes the adopted process in a flow chart representation up to the first thesis submission. After receiving some advice from the thesis examiners, the design of the controller is further enhanced. The design enhancements and subsequent simulation test results, to test the performance of the enhancements, are outlined in this updated thesis. The resulting thesis encapsulates the research journey and findings, offering valuable insights and contributions to the domain.

It is important to emphasize that the proposed approach marks a significant and original contribution to the field of micro grid research. Although micro grids with multiple grid connections are highly relevant in the context of modern energy systems, this specific area has not been extensively studied or thoroughly addressed in the existing body of literature, at least within the scope of our review. This research introduces a new perspective and direction, offering valuable insights and potential solutions to the unique challenges and opportunities associated with micro grids that incorporate multiple grid connections. By addressing an existing gap, it enhances the growing knowledge base in the areas of micro grid control and operation, advancing understanding and paving the way for future developments in this crucial field.

The significance of maintaining an effective and robust method for maintaining a particular value of active and reactive power flow at the desired or selected interconnections, even when network configurations change, is paramount for micro grid operators. In the dynamic and evolving energy landscape, network configurations are frequently subject to modifications, whether due to grid expansions, new connections, or changes in load and generation patterns. As a result, having a control strategy that can seamlessly adapt to these changes without compromising performance is of immense value.

The proposed approach directly addresses this critical need by offering a solution capable of preserving the stability and reliability of power flow management by ensuring micro grid's idea operation under most probable and real-world operational scenarios. Specifically, it ensures that the overall active and reactive power exchange between the micro grid and the main grid remains consistent and stable, even if the network configurations are modified. This is particularly vital for maintaining grid stability, voltage control, and overall system reliability. The design is further enhanced to incorporate both reactive power flow control and balancing active power control in order to address the dual objectives of maintaining grid stability and optimizing power quality. Reactive power flow control ensures constant reactive flow between the grid and the micro grid by monitoring the sum of the reactive power flows on the interconnection lines, while balancing active power control helps in overwriting the frequency response to ensure constant active power exchange between the main grid and the micro grid even during the frequency excursion events.

The proposed, enhanced interconnection flow controller, is equipped with an independent reactive power flow control, the system can ensure that the reactive power flows remain within acceptable limits, allowing for smoother operation of both the micro grid and the larger grid system. Thus, in a micro grid with constant interconnection flow as a primary objective, reactive power control acts as a crucial mechanism to maintain equilibrium across multiple interconnections, without directly affecting voltage, but rather ensuring that the micro grid's power exchange remains stable and predictable under varying operating conditions.

These enhancements are crucial in systems where active power, frequency and reactive power must be simultaneously regulated. In traditional control systems, the focus was often on active power and frequency regulation, with less attention given to reactive power. In scenarios where the micro grid experiences fluctuations due to load changes or renewable energy variability, it is important to have a mechanism that not only manages active power (to meet demand) but also adjusts reactive power to ensure the interconnection flows remain within safe operational limits.

Overwriting frequency response using balancing active power control during frequency excursion events offers several key advantages in ensuring stable and efficient operation of a micro grid interconnected with a main grid. Here are the main advantages:

Ensuring stability during frequency excursions: Frequency excursions in the main grid can lead to deviations in active power flow between the micro grid and the main grid. If active power control can override the frequency response (within design and physical limits), it ensures that the active power exchange between the two grids remains constant, preventing sudden variations in power flow that could destabilize the micro grid or strain the interconnection.

Improved power reliability: By maintaining a constant active power exchange, this control ensures that the micro grid receives or supplies the necessary power without fluctuations that might otherwise occur due to frequency changes. This is particularly important when the micro grid relies on or provides critical loads, as uninterrupted power is necessary for smooth operation.

Prevents undesired reactions to frequency changes: When frequency excursions occur, traditional systems would respond by adjusting active power output to compensate for the frequency deviation. By overwriting the frequency response to the extent possible, the balancing active power control allows the micro grid to maintain a steady active power output, ensuring that frequency disturbances do not propagate through the micro grid and cause instability.

Efficient power sharing: During frequency deviations, active power-sharing mechanisms between DDGUs can remain uninterrupted. This enables all DDGUs to respond according to local demands rather than global frequency issues, which can be managed separately.

Enhanced resilience during grid disturbances: By focusing on active power control rather than frequency response within certain limits, the micro grid can remain more autonomous and resilient during minor grid disturbances. This allows the micro grid to continue operating smoothly even when the main grid experiences minor or frequent frequency variations, enhancing overall system resilience.

More effective load balancing: Active power control allows the micro grid to continue managing its internal loads more effectively during frequency excursions. This means that power generation and consumption within the micro grid can remain balanced without being influenced by the broader frequency variation in the main grid.

Efficient utilization of generation resources: By maintaining active power flow constant, energy storage systems, renewable generation, and other dispatchable units can operate at their optimal capacity, ensuring efficient energy utilization without frequent changes due to external frequency shifts.

Avoids overcompensation by frequency response: If active power is allowed to respond directly to frequency deviations, it may lead to overcompensation, where the micro grid adjusts too aggressively to frequency changes. By allowing flow control to overwrite this response within limits, the system avoids overcompensating, ensuring smoother and more controlled power delivery.

When tested under various simulated operating scenarios, the proposed method has demonstrated its success in maintaining the required sum of active and reactive power flow, whether the micro grid is operating as a power producer or consumer. This adaptability guarantees that, despite changes in the network's structure, the micro grid remains a predictable and reliable contributor to the overall power system. The proposed strategy not only enhances operational flexibility but also minimizes the risk of instability, ensuring smooth transitions during network reconfigurations and reducing the need for manual adjustments or system redesigns.

Ultimately, this capability is essential in modern energy systems, where micro grids must operate autonomously and flexibly, adjusting to evolving grid conditions without sacrificing performance. It represents a step forward in micro grid control, offering both operational resilience and efficiency in an increasingly complex energy environment.

This innovation not only advances theoretical knowledge but also holds practical implications for the design, control, and operation of future energy systems, where multiple interconnections and dynamic reactive power management will play an increasingly important role.

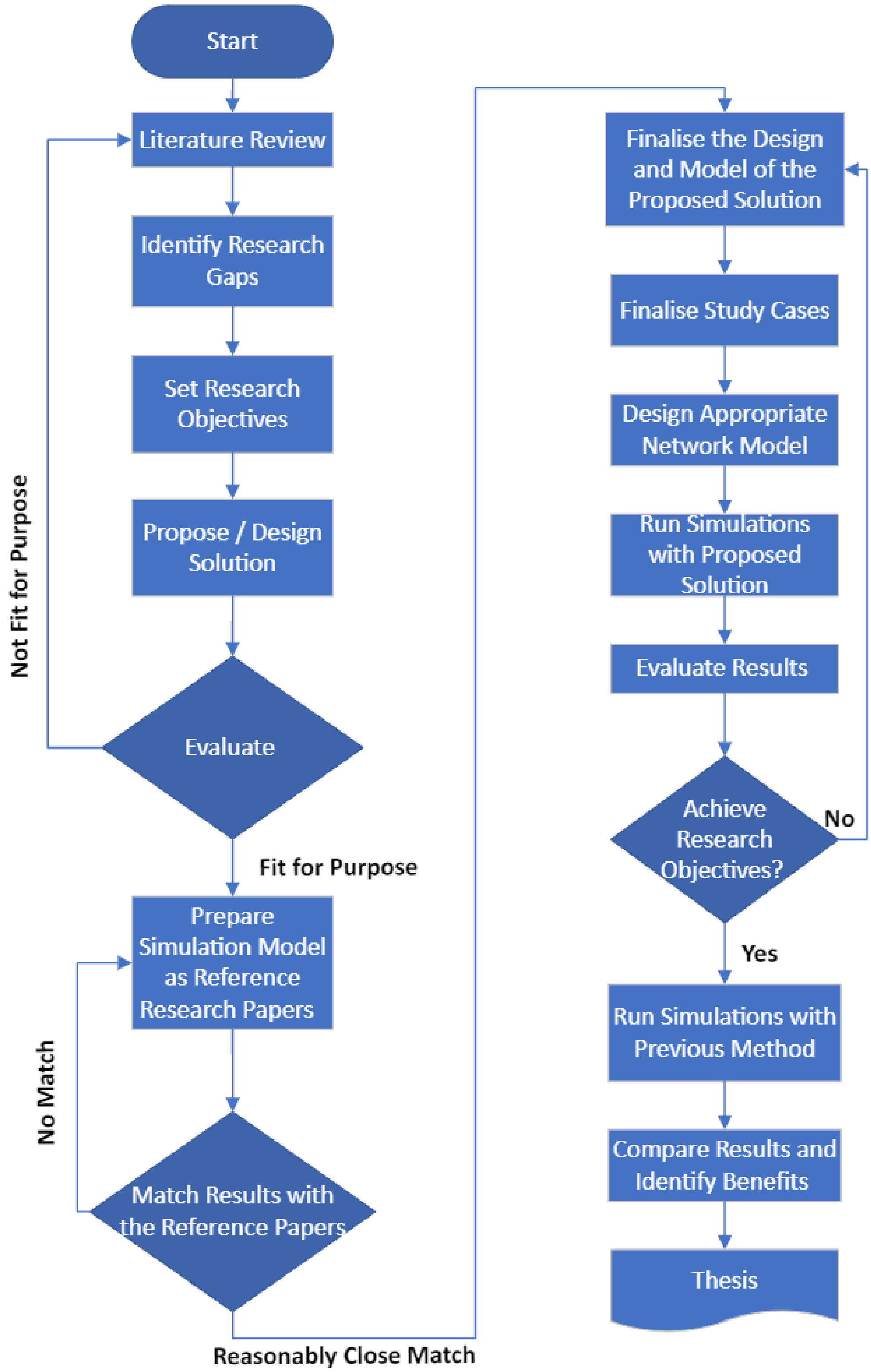

Figure 1.5. Process followed for this research.

1.8 Organisation of the Thesis

The literature review is presented in the next chapter (Chapter 2), while the methodology and details about the design of the proposed method is presented in Chapter 3. Results of the simulations and related discussion are presented in Chapter 4. Enhancements in the design are explained in Chapter 5 along with the results and discussion about the additional simulated cases to test the enhanced features. Conclusions of the work are outlined in Chapter 6, while referenced papers and resources are listed in Chapter 7.

2. LITERATURE REVIEW

In the literature, a number of ideas have been put up for effective active power-sharing within the DDGUs of a micro grid. For proper power-sharing across DDGUs, power versus frequency (P-f) droop control has been widely used in a variety of methods [7].

Conventionally, frequency-based droop controllers proved to be a very robust, simple and reliable mechanism to manage a DDGU's response to the varying load or generation in a micro grid system. Several studies used (P –f) droop control to ensure that the system's varying demand is met dynamically by the units [8]. In the context of power distribution control within a micro grid, the implementation of a common frequency signal provided to all generating units simplifies their ability to respond to any changes or fluctuations in the system without requiring additional signals. Each generating unit operates with a pre-established and unchanging droop constant, which is determined in advance.

Nonetheless, alternative techniques have been proposed in the literature that suggest periodic adjustments to the droop settings based on the unit's operating conditions and the overall system performance, as referenced in sources [9-11]. These methods fall under the category of "adjustable droop," as they allow for flexibility in modifying the droop control parameters as needed. In contrast, the conventional methods, which rely on fixed and predetermined droop constants for each unit, can be termed "fixed" or "constant" droop methods. The adjustable droop methods offer a more adaptable and fine-tuned approach to power-sharing control by dynamically modifying the droop parameters, which can enhance the overall performance and efficiency of the micro grid under varying operating conditions.

In [10], a droop controller is applied to the local DDGUs which continuously changes the droop settings according to the DDGUs current reserve, instead of their capacity. Traditionally, operators of DDGUs do not prefer to have adjustable droop controllers for their units, as this can cause units to not only change their power output level periodically but also at a varying rate. This can cause increased wear and tear on the mechanical devices such as valves and pumps.

Constant droop-based methods have demonstrated their suitability and robustness for micro grid applications. These approaches rely on fixed and predetermined droop constants for each generating unit, ensuring stable and predictable power distribution within the micro grid. This stability is advantageous, as it simplifies the control process and minimizes the need for frequent adjustments.

However, the concept of "constant" droop can become somewhat flexible when the droop constant values are still contingent on the network configuration (whether it's a series, radial, or parallel setup) and the number of machines operating in the system at any given time. In such cases, these methods can be considered somewhere in between adjustable and constant droop systems. This is because the droop constants are not completely fixed, and they may vary based on the network topology and the total number of machines interconnected.

The drawback of this semi-constant approach is that in scenarios where a central controller is unavailable for some time, the responsibility falls on the operators to manually calculate and adjust the new droop constants for each machine. This can be a labor-intensive and time-consuming process, potentially leading to inefficiencies and delays in the micro grid's operation. Therefore, while constant droop-based methods offer robustness and stability, their effectiveness can be compromised when the network configuration or the number of machines fluctuates, requiring manual intervention to maintain proper power-sharing.

A micro grid with strong connection(s) to a larger and stronger grid might not experience any change in the frequency because of any internal load or generation variation. The grid can dictate the frequency by maintaining it to a constant value and consequently challenge the effectiveness of the frequency-based active power-sharing mechanism.

In [66], a different approach is suggested that divides the micro grid into smaller sections with an emphasis on the economic dispatch of the units. In [12], a technique for centralized control of power-sharing is presented that makes use of a low bandwidth web-based communication system.

One study presented in [179] provided two adaptive and intelligent control techniques for controlling the micro grid voltage and frequency in islanded mode and allowing seamless transition between islanded and grid-connected modes. The two suggested controllers were based on H-infinity and model predictive control (MPC) approaches for increasing the performance of the droop control method. The suggested H-based control strategy is used to regulate the micro grid in its islanded mode and to provide a smooth transition between the micro grid's two operational modes.

The frequency and voltage of the micro grid are more tightly regulated using an addition to droop control, which is based on the same harmony search-based H-infinity control. Inside a solitary micro grid, the suggested control technique enhanced power quality performance. For modern inverters with complex features like virtual inertia or those who could function in the virtual synchronous machine (VSM) mode, a control strategy is advised [48][65]. The pitch adjustable rate (PAR) value is near to zero in the latter rounds, which disadvantages the harmony search-based H-infinity control algorithm and might cause algorithm convergence performance to plateau [16].

Based on a fuzzy control with MPC, another suggested technique altered the inertia constant *H* and damping coefficient *D* of the swing equation.

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \qquad [2.1]$$

$$M = \frac{GH}{\pi f} \qquad [2.2]$$

$$\frac{2GH}{\omega}\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \qquad [2.3]$$

Where:

M = Angular Momentum

D = Damping Coefficient

H = Inertia Constant

G = MVA Capacity

ω = Angular velocity

Pm = Mechanical Power

Pe = Electrical Power

This technique was shown to give improved frequency response for substantial load changes inside an islanded micro grid. A further-refined and hierarchical control scheme with three levels of control is provided for tighter frequency and voltage regulation and optimisation inside an isolated micro grid [88].

A distributed consensus-based voltage and frequency controller has been introduced to enhance the responsiveness of both frequency and voltage parameters in micro grids that are operating in isolation, meaning they are not connected to a larger grid system [57][37][112]. This control technique is specifically designed for use in islanded or grid-isolated micro grids, where maintaining the stability of voltage and frequency is essential.

One limitation associated with fuzzy logic control systems is their reliance on human knowledge and expertise. Fuzzy logic control systems operate based on predefined rules and linguistic variables that need to be crafted by human experts. These rules are often based on empirical or domain-specific knowledge. However, the drawback here is that these rules need to be updated and adjusted periodically to ensure that the system remains effective and responsive to changing conditions. This is a labor-intensive process, as it requires ongoing human intervention and expertise.

Furthermore, fuzzy logic control systems are not inherently capable of recognizing or adapting to machine learning or neural networks. These modern computational approaches, such as machine learning and neural networks, have the potential to autonomously learn and adapt to new data and patterns, which can make them more flexible and capable of handling complex and dynamic control tasks. Fuzzy logic, on the other hand, relies on explicitly defined rules and does not possess the self-learning capabilities of machine learning or neural networks.

In summary, the distributed consensus-based voltage and frequency controller is a promising solution for enhancing micro grid performance in isolated conditions. However, it's essential to be aware of the limitations of fuzzy logic control systems, which rely on human-crafted rules that must be periodically updated and cannot leverage the adaptability of machine learning or neural networks. These systems are unable to recognize neural networks or machine learning [17]. Several MPC models can only handle steady, open-loop processes. To explain a response, MPC frequently requires several model coefficients. Some MPC models are designed for output disturbances and may struggle with input disturbances. Even if the model is correct, control performance will be poor if the prediction horizon is incorrectly stated [18].

Traditional non-dispatchable energy sources like wind and solar PV rely on Maximum Power Point Tracking (MPPT) control for regular functioning. As a result, especially in the context of micro grids, these can significantly disturb system dispatch. In order to efficiently meet the dispatch command or market timetable, a novel cascading power-sharing control (PSC) technique is provided in [19] to coordinate wind and solar PV power production in micro grids while decreasing the loss of renewable energy production involved. The difference between dispatch instruction (market timetable) and actual renewable generation is first addressed by managing wind power output by temperately storing or releasing turbine rotor kinetic energy while taking into account the varied characteristics of wind and solar PV power producing systems. This method doesn't look at overall active power-sharing between all dispatchable generating units. Additionally, cascade control has three drawbacks. For one thing, it requires an extra measurement (typically flow rate) to function. Two, an extra controller must be calibrated. Third, the control technique is more difficult – for both engineers and operators [20].

The adoption of renewable energy sources in off-grid systems faces limitations due to the inherent unpredictability associated with the power output of renewable sources like solar and wind. These sources can be intermittent and are often not readily dispatchable to meet energy demand on demand. To overcome this challenge and make more efficient use of non-dispatchable renewable sources, advanced control techniques have been developed.

One such advanced control technique is described in reference [81], which presents a two-layer predictive management strategy for an off-grid hybrid micro grid. This micro grid comprises both controllable and non-controllable generating units, along with an energy storage system. The two-layer approach is designed to address the challenges associated with managing such a complex system.

In the upper layer of this control strategy, the focus is on unit commitment. Unit commitment involves deciding which generating units should be active at any given time to meet the energy demand while optimizing system performance. This upper layer aims to make strategic decisions about which sources to utilize based on the expected energy demand and the availability of renewable sources.

The second layer of this control strategy deals with real-time operation. It focuses on ensuring the smooth and stable operation of the micro grid, especially given the intermittent and variable nature of renewable sources. One important tool used in this layer is a response filter, which serves to smooth out the fluctuations in load generated by the gensets (internal combustion generators). By reducing load volatility, the micro grid can maintain a consistent and stable power supply, even when the non-controllable renewable sources fluctuate.

The two-layer predictive management technique described in [81] is designed to enhance the efficiency and reliability of off-grid hybrid micro grids by effectively managing both controllable and non-controllable generating units, as well as incorporating energy storage. This approach addresses the unpredictability of renewable energy sources by making informed decisions in the upper layer and maintaining system stability through real-time operation in the second layer, which includes load smoothing techniques. This can lead to improved energy management and a more reliable power supply in off-grid systems using renewable energy sources.

The concept of Virtual Synchronous Generator (VSG) control for inverters in micro grids has garnered significant attention from researchers, particularly in addressing the challenges related to low inertia in micro grids with a high penetration of renewable energy sources. In such systems, the traditional synchronous generators that provide inertia and stabilize the grid are often lacking, making the control of the grid more complex.

One of the key issues that researchers have identified in VSG control management is the difficulty in ensuring proportional reactive power-sharing among Distributed Generation (DG) units when there are uneven transmission line impedances [71]. While VSG control can effectively manage proportional active power-sharing among DG units, it struggles to maintain proportional reactive power-sharing in the presence of uneven impedances. To address this challenge, a novel approach is proposed in the referenced research. This approach is known as an adaptive virtual impedance-based VSG control strategy, which is applicable to both grid-connected and islanded micro grids. The primary objective of this strategy is to reduce the impedance differences at the inverter terminals and, as a result, achieve more equitable and proportional reactive power-sharing among DGs.

The adaptive virtual impedance consists of two components: an adaptive virtual resistance and a fixed virtual inductance. The key feature of this strategy is the adaptability of the virtual resistance. This resistance value is adjusted based on the micro grid's operating conditions, ensuring that it responds to the specific needs of the system. By dynamically changing the virtual resistance, the control system can effectively mitigate the differences in impedance across the micro grid, thereby enabling improved reactive power-sharing.

The research on adaptive virtual impedance-based VSG control addresses a critical issue in micro grids with high renewable energy penetration—uneven reactive power-sharing. By using a combination of adaptive virtual resistance and fixed virtual inductance, this control strategy offers a solution to enhance the proportional sharing of reactive power among DG units. It provides a more stable and efficient operation of micro grids, particularly in situations where uneven transmission line impedances pose a challenge to traditional VSG control.

Concerns regarding the ability of future grids to recover from such natural disasters are growing as frequent and severe weather events disrupt the power supply. Also taken into consideration as a potential source of resilience are micro grids. This research [33] focuses on micro grid design to fortify the network against significant breakdowns, in contrast to most prior studies, which have mostly concentrated on how to benefit from existing micro grids through operational methods. In order to determine the best nodes for tying up micro grids and the capacity of the dispatchable producing units positioned within micro grids, three potential methodologies are offered in this regard.

In [40], a distributed technique is put forward to address the challenges associated with managing the combined active and reactive power dispatch in isolated micro grids. These micro grids operate independently, not connected to a larger grid, and face unique control and optimization challenges. The proposed technique aims to optimize the allocation of both active (real) and reactive power generation within such micro grids.

The core concept of this approach involves the exchange of information among local controllers in the micro grid. These local controllers collaborate to achieve the optimal power dispatch in a secondary layer, which acts as a reference for the primary controllers in each generator. In other words, the local controllers work together to calculate the ideal distribution of active and reactive power within the micro grid, and this information is then shared with the main controllers of individual generators to implement the desired power dispatch.

The key advantage of this technique is its use of population dynamics-based strategy. This strategy simplifies the deployment of the algorithm, especially in micro grids with a high penetration of distributed generation resources (such as solar panels or wind turbines) and a basic or limited communication network. The population dynamics-based strategy allows for robust and efficient decision-making by considering the collective behaviour of local controllers without the need for extensive communication infrastructure.

To validate the proposed hierarchical method, the researchers have conducted tests using a co-simulation platform. This platform allows them to simulate real-world scenarios and study the performance of the distributed optimization technique in practical settings. The case study involves a specific micro grid with a management control scheme developed using the distributed optimization technique, providing insights into how this approach can be applied in actual micro grid operations.

The technique presented in [40] offers a distributed solution to address the combined active and reactive power dispatch challenges in isolated micro grids only. It relies on information exchange among local controllers, employing a population dynamics-based strategy for efficient and effective power allocation. The approach is especially valuable for micro grids with a significant presence of dispersed generation resources and limited communication infrastructure, and its performance is assessed through simulation in a real-world case study.

In [61], a novel approach for active power-sharing and frequency control in an islanded micro grid is introduced. This technique employs an event-triggered control scheme, which is designed to enhance the efficiency and effectiveness of power-sharing and frequency regulation within the micro grid.

The approach centres around a distributed secondary control scheme that relies on a sampled-data-based event-triggered communication mechanism. This mechanism operates in a manner where neighbouring units within the micro grid exchange data only when specific predefined triggering conditions are met. These conditions might be related to deviations in frequency or power-sharing imbalances. By using event-triggered communication, the system ensures that information exchange occurs precisely, when necessary, rather than at fixed intervals, allowing for a more responsive and efficient control strategy.

One key advantage of the proposed event-triggered communication mechanism is its ability to reduce the number of communications between neighbouring units. Traditional periodic communication methods often require data exchange at regular intervals, which can lead to unnecessary data transfer and overhead. The event-triggered approach optimizes communication by only transmitting data when it is required to maintain the necessary performance levels for micro grid operation.

The control strategy's effectiveness and impact on micro grid stability are assessed using the Lyapunov-Kravovskii functional technique. This technique is used to construct criteria that help characterize how control gains, system characteristics, and the sampling time influence the stability of the micro grid. By analysing these factors, the researchers can fine-tune the control strategy to ensure the micro grid remains stable and reliable under various operating conditions.

The strategy outlined in [61] emphasizes event-triggered mechanisms for active power-sharing and frequency control within isolated micro grids. This approach introduces a distributed secondary control system with event-triggered communication, which streamlines data exchange among micro grid units by only engaging when specific predefined conditions are met. This method offers distinct benefits compared to the traditional periodic communication approaches and is evaluated for its impact on enhancing micro grid stability using the Lyapunov-Kravovskii functional technique, ultimately resulting in improved operational performance and reliability for micro grids.

The Industrial Internet of Things (IIoT) is an architectural framework that builds upon the concepts of the Internet of Things (IoT) and cloud computing to enhance the control and management of existing industrial systems, including technologies like AC smart micro grids [19]. The research presented in reference [19] introduces a novel approach that focuses on ensuring the safe and efficient energy policy and load-sharing strategy in renewable micro grids designed for off-grid, independent usage. This strategy is implemented with power electronic jointing (PEJ) technologies integrated within the IIoT framework.

The approach assumes a two-layer system, with the upper layer responsible for system dispatch computations, and the lower layer dedicated to generating correct control procedures for the power electronic jointing (PEJ) devices. Communication plays a crucial role in facilitating this distributed control system, and it employs a decentralized multi-agent system (MAS) to manage the upper layer of intelligent control. This multi-agent system enables autonomous, yet coordinated, decision-making among various components within the micro grid.

Despite the benefits of the IIoT and its potential to enhance micro grid operations, it's important to acknowledge some of its limitations. One notable drawback is the high investment cost associated with adopting IIoT for micro grid operations. The cost of implementing IIoT technologies, including the necessary hardware and infrastructure, can be a significant barrier for many organizations.

Additionally, the challenge of secure data storage and management is another concern in the context of industrial IoT. IoT devices generate a vast amount of data, and ensuring the security and proper management of this data is essential. Furthermore, IoT devices may experience frequent connectivity outages, which can disrupt data transfer and system operations [45].

In the context of AC autonomous micro grids, the generating units are often distributed throughout the grid. To manage these dispersed units effectively, distributed control mechanisms are commonly employed. However, it's worth noting that these mechanisms rely on a supplemental communication network for transmitting information among the surrounding generators. Various interruptions or delays in this communication network can potentially impact the management of active power deviations in the micro grid.

In summary, the integration of IIoT in micro grid operations holds promise for improving energy policy and load sharing in renewable micro grids. Still, there are challenges to address, including the high implementation costs, data security concerns, and potential disruptions in communication networks that can affect the performance of distributed control mechanisms in AC autonomous micro grids.

A dispatchable droop control system for many dispersed generators is presented in research article [72] and may be applied in solitary AC micro grids. By using first-order inertia components to generate pseudo-hierarchical control, the proposed technique enables the generators to autonomously distribute the load on a smaller time scale while complying with the dispatch order on a larger time scale. The recommended method combines frequency restoration control and active power regulation. It features either a voltage control or a reactive power regulation control for various conditions. The suggested strategy is still useful even if the specified power control references are impossible. A MATLAB/Simulink simulation is used to show how effective the recommended technique is.

Achieving precise power-sharing in islanded micro grids presents a considerable challenge, primarily due to factors like mismatched feeder impedance. In the context of addressing this issue, the article [75] introduced an approach based on distributed event-triggered power-sharing control mechanism. This innovative control strategy is designed to overcome the impedance-related challenges and enable more accurate power-sharing in micro grid systems.

The proposed approach takes a dynamic and adaptive approach to managing virtual impedances, both at fundamental positive/negative sequence and harmonic frequencies. This adaptability allows the distributed generating units within the micro grid to effectively exchange reactive power, manage unbalanced conditions, and address the challenges posed by harmonic power fluctuations. By doing so, the micro grid can ensure that power-sharing is both accurate and equitable among the various generating units.

One notable advantage of this solution is its independence from precise knowledge of the feeder impedance. Traditional approaches often require detailed knowledge of the network's impedance characteristics, which can be challenging to obtain and maintain in real-world scenarios. The proposed approach eliminates this requirement, simplifying the design and deployment of power-sharing control mechanisms in micro grids.

Another key feature of this approach is the use of event-triggered communication. Instead of continuously transmitting data between units, communication only occurs when predefined triggering conditions are met. This approach minimizes the communication overhead, reducing the need for constant data exchange while still maintaining the necessary performance levels within the micro grid. Event-triggered communication can be especially beneficial in resource-constrained environments and helps enhance the efficiency of the control system.

The control mechanism introduced in article [75] addresses the challenges associated with accurate power-sharing in islanded micro grids, particularly due to impedance mismatches. By adaptively managing virtual impedances at different frequencies, this approach enables precise power exchange and control without requiring detailed knowledge of feeder impedance. Event-triggered communication further reduces communication overhead while ensuring the micro grid's performance remains at the desired level. This innovative approach offers a practical solution for enhancing power-sharing in micro grid systems.

This paper [114] addresses power-sharing and power quality improvement challenges in islanded single-/three-phase micro grids (S/T-MGs) with unbalanced sources and loads. A hierarchical distributed control approach is proposed, consisting of 1) a phase-independent virtual synchronous generator (P-VSG) control for primary control of distributed generators, 2) a distributed secondary power flow regulator for power-sharing control among distribute generators and between phases, and 3) a distributed secondary voltage regulator for voltage restoration and power quality improvement.

In [13], two different approaches are presented by utilising two modes of DDGU operation, namely unit power control (UPC) mode and feeder flow control (FFC) mode, which were previously proposed in [8, 15]. A problem was identified in [13] when multiple DDGUs are connected on the same radial feeder and operate in FFC mode.

In [14], a different approach to dealing with the issue of genuine power-sharing among the DDGUs of a micro grid is proposed. The biggest DDGU in a micro grid should preferably be linked near to the point of common coupling (PCC) or grid interconnection, according to this suggestion. While the other DDGUs run in UPC mode initially, that DDGU shall operate in FFC mode. The following unit shall enter FFC mode after the FFC unit is completely loaded as a result of the load increase. When the DDGU in front of it in the queue reaches its maximum actual power output, the process continues, and the DDGUs are then switched to FFC mode. The overall algorithm of selecting an operating mode within a DDGU is given in Figure 2.1.

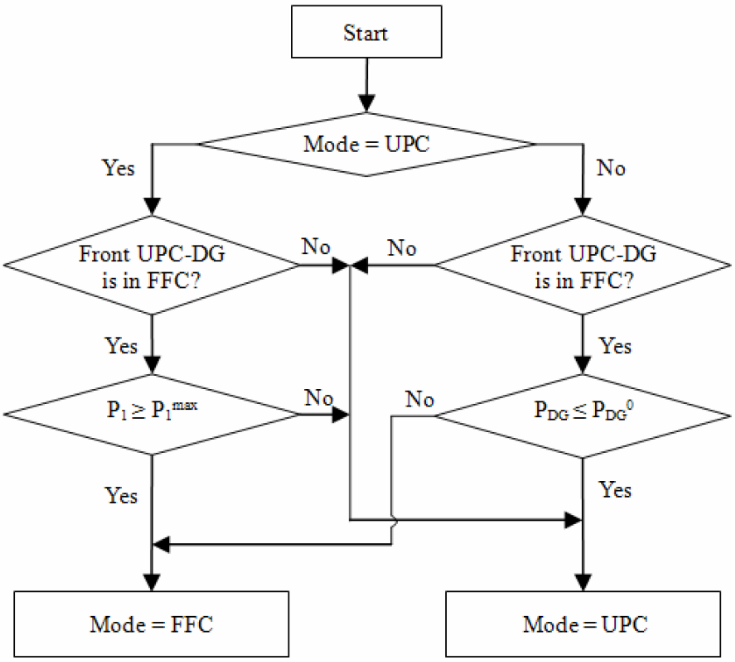

Figure 2.1. Algorithm for changing the control mode of DDGU [14].

One or more DDGUs must be operated in FFC mode since the basic goal of all power-sharing techniques is to make the micro grid a continuous power-consuming or supplying entity. The flow from the grid must be kept as high as feasible in order to have adequate reserve in the DDGUs (in FFC mode) to compensate for any load/generation change inside the micro grid. However, on the other hand, if the flow from (or to) the grid is high, then at the time of isolation (during transition mode) larger frequency deviation will result [14]. A critical balance needs to be maintained so that an unplanned isolation event can be sustained by the micro grid.

In order to maintain a steady flow of power on each internal feeder inside a micro grid by operating it in FFC mode, the proposed approach in [16] envisaged having one DDGU at the start of each internal feeder. Each internal feeder must maintain a constant flow in order for the total flow to or from the micro grid to be constant. However, it is simultaneously both utopian and constrictive to assume that there will be one DDGU at the beginning of each internal feeder of the micro grid. Idealistic in that having so many DDGUs within a micro grid can be seen as a costly luxury and constrictive because the DDGU will only be configured to account for variations within the feeder even though it has the ability to contribute for variations in other feeders within the micro grid.

For active and reactive (P&Q) power control and management within a micro grid several techniques are presented in the literature. All recent contributions in this area are mainly focused towards either the internal voltage control of a micro grid or economic dispatch of the DDGUs. In all the recent [184 – 200] referenced publications micro grid with one connection to the main grid was considered.

The research presented in [184] proposed a novel bi-level optimization model for Combined Cooling, Heating, and Power (CCHP)-dominated Integrated Community Energy Systems (ICESs) in the day-ahead distribution electricity market (DEM). The model introduced a new trading mechanism between ICES operators (ICESOs) and the Distribution System Operator (DSO) to optimize both active and reactive power scheduling. The proposed model enhances the operational efficiency of ICESs by enabling optimized power scheduling and effective integration of distributed energy resources.

In [185] an enhanced control strategy for micro grids integrating renewable energy sources is proposed. It utilizes a Finite Control Set-Model Predictive Control (FCS-MPC) approach, which is designed for both islanded and grid-connected operational modes. The proposed control strategy includes voltage control, power-sharing, and negative-sequence current control loops to ensure system stability and efficiency in both modes. By reducing computational demand and minimizing inverter switching, the control method enhances system performance in terms of voltage regulation, power quality, and harmonic reduction. A similar

MPC based method for dynamic control and optimization of distributed energy sources within a micro grid is presented in [186].

A predictive control-based algorithm is proposed in [187] for achieving optimal energy management (OEM) in renewable-based hybrid micro grids (HMGs). This method consisted of a modified model predictive control based improved Firefly1to3 algorithm (MMPC-IFA1to3). Using this method, active and reactive power references were generated resulting in simpler switching operations in voltage source converters. This research focused mainly on active and reactive power management through objective function minimization. The proposed IFA1to3 was demonstrated to minimize costs, ensure power availability, and mitigate voltage deviations in renewable-based HMGs.

Parallel operation of voltage source converters and synchronous generators within a micro grid is studied in [188] and a droop-based frequency control is recommended. The research proposed a supervisory centre controller to ensure stable system frequency.

A comprehensive comparison and review of reactive power sharing methods within micro grids operating in islanded mode is provided in [189 and 190]. The paper presented a review of the recommended communication-less reactive power sharing approaches recommended in referenced literature. The comparative analysis concluded that the new methods are all improvements to the traditional Q/V droop method and are greatly sensitive to the network configuration and other network parameters.

An improved VSG control algorithm based on fuzzy logic algorithm is proposed in [191]. This integrated control algorithm of power distribution is recommended for islanded micro grids.

In [192] a centralised reactive power sharing method is discussed for isolated micro grids. The proposed method is shown to be resilient to the communication link failures, which is the main cause of the reactive power sharing error and subsequent voltage instability of the micro grid. An adaptive virtual impedance control was used in a centralised manner under normal operating conditions, while in case of communication link failure, a centralised/decentralised control method is recommended.

A method for optimizing power flow in distribution networks that integrate multiple micro grids is presented in [193]. The research introduced a Multi-Actor-Attention-Critic (MAAC) deep reinforcement learning approach, designed to solve the challenges of dimensionality explosion in high-dimensional optimization problems. The proposed method focuses on balancing active and reactive power within large-scale non-convex environments, ensuring system stability, reducing network losses, and improving computational efficiency. Additionally, the paper incorporates transfer learning to enhance the adaptability of the optimization algorithm in dynamic operational scenarios, such as grid topology changes or device switches. The paper focused on optimizing power flow within a single grid environment that integrates multiple micro grids with one grid interconnection.

As another example of a dynamic droop controller, [194] proposed an advanced control strategy for managing the power flow between AC and DC subgrids in hybrid micro grids. The traditional normalized droop control, while useful for bidirectional power coordination, often leads to issues such as power transmission inaccuracies and voltage deviations from rated values, especially under varying load conditions. To address these challenges, the research introduced an adaptive droop control method that dynamically adjusts the droop coefficient based on real-time system conditions. Similar to all others mentioned above, this research also considered a micro grid with single grid connection.

The paper [195] proposed a data-driven strategy for coordinated Volt/Var control (VVC) in active distribution networks (ADNs) with multiple micro grids. This strategy aimed to ensure secure and efficient operation despite the presence of false data injection attacks (FDIAs). The approach utilized convolutional neural networks (CNNs) to emulate the behaviour of micro grid central controllers (MGCC. A voltage sensitivity-based reactive power adjustment method is also proposed to streamline the iterative optimization process. To protect data integrity and security, the paper integrated encryption algorithms (GGH and RSA) into the communication process between micro grids and distribution system operators (DSOs). This technique is based on the communication-based controller considering micro grids with single interconnections.

A control and power management system (CAPMS) for hybrid PV-battery micro grids that operates in both grid-connected and islanded modes is presented in [196]. This study emphasized on the real-time control of both AC and DC bus voltages and ensured a smooth transition between operational modes. By integrating maximum power point tracking (MPPT) and dynamic battery management, the system maintains power balance and stability even during fluctuations in solar irradiance or load demand. Additionally, CAPMS enabled flexible power flows and voltage regulation across various operating scenarios. The research provided a method to control power delivery within a hybrid inverter either in islanded or grid connected mode. Similar technique is proposed in [197] but only for isolated micro grids. The paper presented a decentralized power management and load sharing method for a photovoltaic-based islanded micro grid consisting of various photovoltaic (PV) units, battery units, and hybrid PV/battery units. The proposed method considered available PV power and battery conditions of the units to share the load among them.

A voltage control strategy for an integrated medium and low voltage distribution network based on active-reactive power coordination optimization is proposed in [198]. It established an integrated control model for the medium and low voltage distribution network, taking voltage offset and network loss as the optimization objectives. The method utilized reactive power compensation devices and active power control of energy storage systems (ESS) as control variables. The proposed strategy claimed to effectively solve the problem of voltage overrun in the distribution network by coordinating the active and reactive power of the medium and low voltage systems.

A comprehensive comparison of the proposed active and reactive power strategies is presented in [199], while [200] detailed various control mechanisms, including droop control, model predictive control (MPC), and multi-agent systems (MAS). The research addressed the increasing integration of renewable energy sources into micro grids and the associated control challenges. It reviewed state-of-the-art control strategies and trends, classifying micro grid control into three hierarchical levels: primary, secondary, and tertiary. These levels manage micro grid operations, from internal controls to coordination with the larger power grid. It is noted that none of the strategies reported in these technology reviews ([199, 200]) were focused on the interconnection flow, as almost all of the quoted research papers were focused on micro grids with single grid connection.

Table 2-1. Comparison of proposed control strategies in the literature [199].

Control Strategy	Benefits	Limitations
Sliding Mode Control	Strong power-sharing. Fast dynamic response. Small steady-state error. Ability to maintain DC link.	The amount of load charge, filter capacity, and the capacity of DG units should be considered in the design domain of the controller.
PQ Droop	Simple implementation.	Inadequate V-F regulation.

	Greater flexibility and expandability	Poor dynamic response and harmonics. Effect of physical parameters on performance.
V-P Droop and F-Q Boost Scheme	Simple implementation. Applicable to high-resistance TL.	Poor V-F regulation. Dependence on physical variables
Complex Line Impedance Droop Control	Better voltage regulation.	A pre-knowledge of line impedance is required.
Angle Droop	Better frequency regulation.	Requires smart information. communication based on GPS. Inadequate power-sharing.
Constant Power Band Based Droop	Within the permissible voltage limits. In line with the parameters of a micro-resource. MPPT based efficient Energy usage.	Affects the overall efficiency due to the requirement of a separate controller at each stage.
YID Control	Independent of physical parameters. Better system stability	Voltage regulation is not assured.
Optimized Virtual Impedance.	Non-linear load's power-sharing. Reduction in point of common coupling's harmonic voltage.	A pre-knowledge of physical parameters is required. Low-bandwidth communication.
VFT Method	Decoupled PQ Control.	No guarantee that all DGs have the same transformation angle. A pre-knowledge of physical parameters is required.
Adaptive Voltage Droop Control	Better stability and power-sharing.	A pre-knowledge of physical parameters is required.
Synchronized Reactive Power Compensation	Better power-sharing. Independent of physical parameters.	Low bandwidth communication is needed.

Coordinated operations based on Droop Control	No communication delay. Independent of physical parameters. Better power-sharing.	Low bandwidth communication is needed.
Q-V Dot Control	As simple as conventional droop control.	Prone to de-stabilization. The steady-state solution is critical to calculate. Depends upon the initial conditions.
Single Variable Control	Independent of physical parameters. Perfect for both linear and non-linear loads.	Voltage harmonics. Challenges in voltage measurements.
Virtual Generator Mode (VGM) Primary Control	Guarantees fast V/ F dynamics in an autonomous mode of operation. Gives rapid control actions during the grid-tied mode, too, enabling V-F support (GSM-FV). Provides power control by reference signals from the secondary level control (GSM-PQ).	Stability issues while transitions between the two operating modes.
Proportional Resonant	Better performance due to current controller. Zero steady-state error.	Poor harmonic profile. Complex system.
Hysteresis Current Control	Simple implementation. Fast-transient response.	Resonance issues. Power imbalance. Harmonics and poor voltage regulation.
Fuzzy Logic Control	Simple implementation. Independent of parameter variation. Beneficial for non-linear systems.	Slow controlling response.
Adaptive Droop	Simple implementation. Better voltage regulation and power-sharing.	System parameters are affected.
Multi-Agent System (MAS)	Robust control action. Better performance under uncertain disturbances.	Communication delay. Poor performance without communication links.

H-Infinity Controller	Applicable to both linear and non-linear systems. Robust control action.	Complicated mathematical model. Slow dynamics.

2.1 Reference Modes of Operation for Active Power Control

Two different modes of DDGU operation, namely UPC and FFC are explained in this section.

2.1.1 Unit Power Control (UPC) Mode

While micro grid is connected to the main grid, this mode is designed to keep the generating unit at a constant output power level regardless of the load or generation variation. The frequency of the system is maintained by the main grid and if all units within the micro grid operate in UPC mode, load variation will also be compensated by the main grid.

While a micro grid is isolated, the generating units operating in UPC mode within the micro grid react to the varying demand. Conventional power versus frequency (P–f) droop controller is adopted and power is shared among the units according to the droop controller constant KU. The same mode is explained and utilised in [16-18]. The term P-f refers to the relationship between real power output (P) and the frequency of the micro grid (f). The droop parameter is used to control the rate at which the generator changes its power output in response to changes in grid frequency.

P-f droop is commonly used in decentralised power systems with multiple generators, such as micro grids or islanded power systems. By using P-f droop control, the generators in the system can share the load and maintain stable grid frequency without the need for centralized control.

Overall, P-f droop is a simple and effective way to control the power output of generators in a grid and maintain stable grid frequency. It is widely used in decentralized power systems and is a key component of many modern power system control strategies.

The mathematical representation of the P–f droop controller is:

$$f' = f^0 - K^U (P' - P^0) \qquad [2.4]$$

where, K^U is the UPC droop constant while f^0, P^0, f' and P' are the initial and final values of frequency and power, respectively. Figure 2.2 below shows the conventional P-f droop curve.

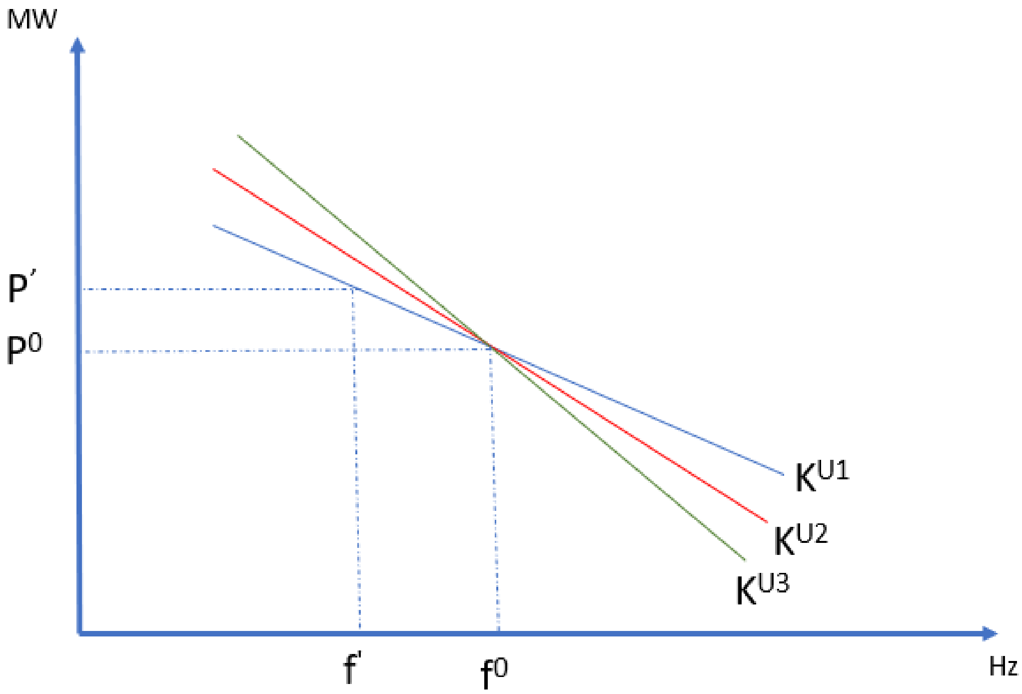

Figure 2.2. P-f Droop Curve for UPC mode of operation.

All units operating in the UPC mode can have same or different value of K^U. This value dictates their contribution to the change of the operating conditions. Value of Pref also depends on the rating of the unit. 3. Figure 2.3 depicts the operation of a unit in UPC mode in a micro grid. Once the micro grid is isolated, any load variation will result in change in the system frequency. The magnitude of the change in the frequency depends on the overall system wide effective value of K^u.

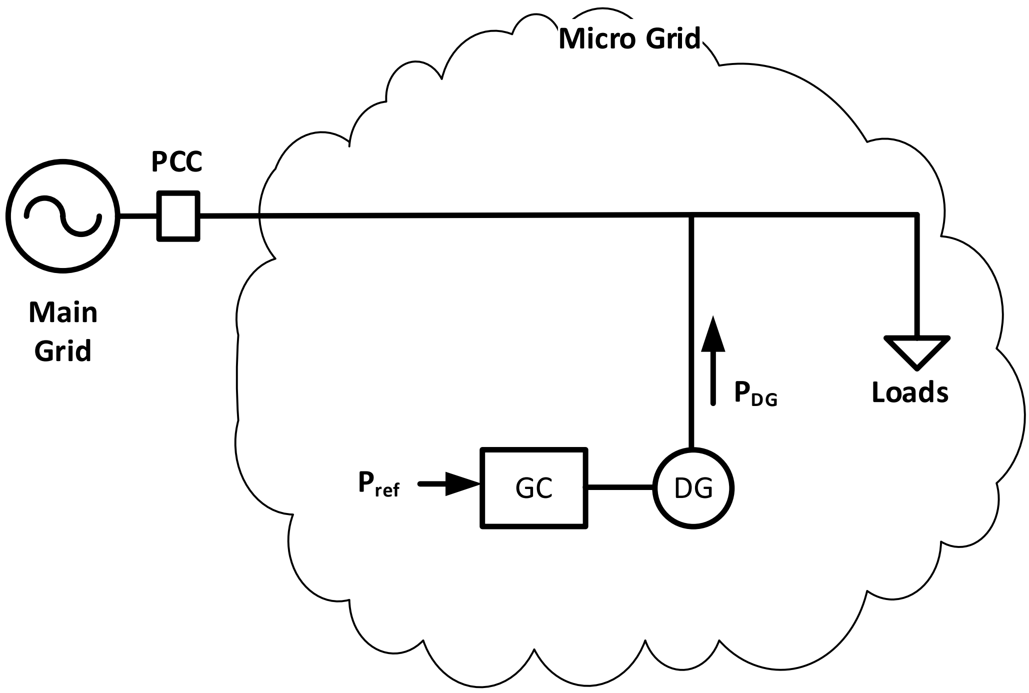

Figure 2.3. UPC mode of operation.

2.1.2 Feeder Flow Control (FFC) Mode

While a micro grid is connected to the main grid, the units in FFC mode, as depicted in Figure 2.4, will maintain the power flow at designated location within the micro grid at a desired value, termed as FL_{REF}. For all units operating in FFC mode in an internal feeder, FL_{REF} is set to a value of FL_{FEEDER} ($FL_{REF\ 1} = FL_{FEEDER\ 1}$ and $FL_{REF\ 2} = FL_{FEEDER\ 2}$). If the load demand increases (or generation decreases) in the micro grid, the generation units in FFC mode increase their real power output to maintain the power flow at FL_{REF} value, which is the flow at a designated location in the micro grid.

While micro grid is isolated, a feeder flow versus frequency (FL-f) droop controller is employed, instead of generated power versus frequency (P–f) droop, to maintain the flow at the designated location.

FFC mode can be represented mathematically as:

$$f' = f^0 - K^F (FL' - FL^0) \quad [2.5]$$

where, K^F is the FFC droop constant while f^0, FL^0, f' and FL' are the initial and final values of frequency and power flow, respectively.

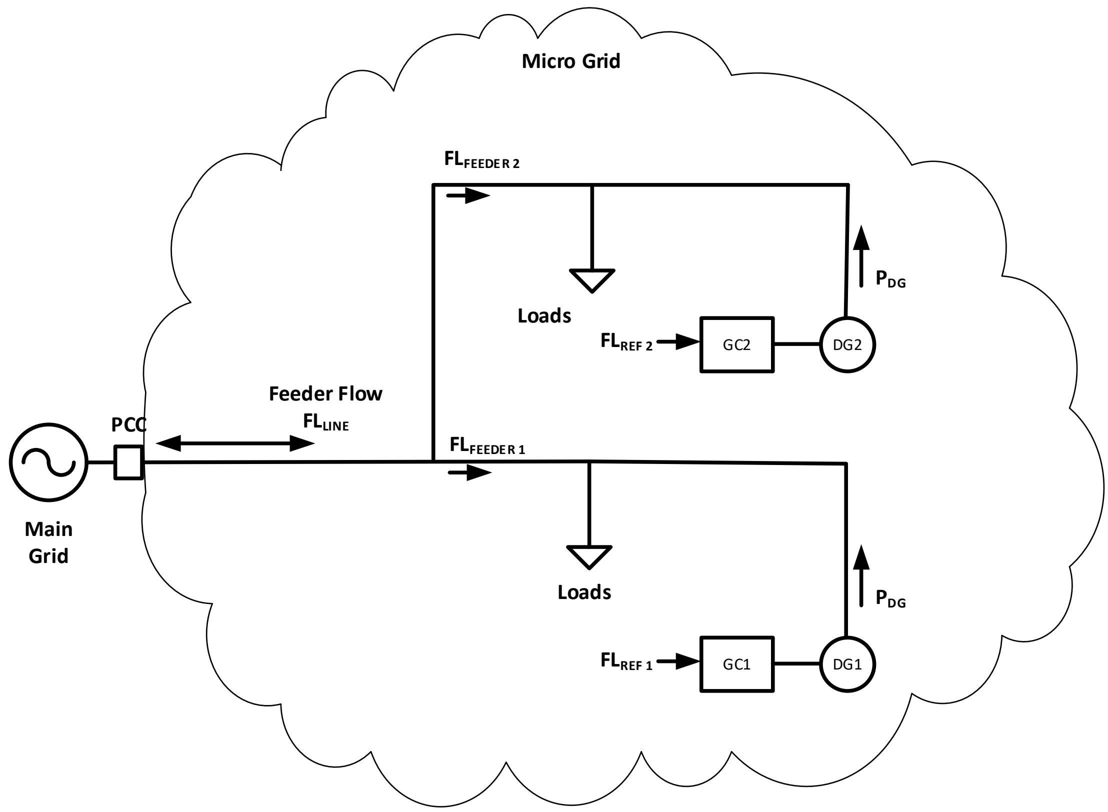

Figure 2.4. FFC mode of operation.

2.2 Summary

The active power-sharing control mechanisms described above are primarily intended for micro grids with one active grid link or for isolated micro grid operation. Little to no attention has been paid to creating suitable power-sharing plans for micro grids with several active grid links. The offered methods have a number of drawbacks and are only proven to work under one or a small number of operational situations.

A wide variety of proposed active power-sharing methods are based on droop control, which has several drawbacks that limit their applicability for a modern power system, and especially for a grid-connected micro gird or during grid-connected mode of micro grid operation. Various issues have been reported in texts related to such systems, including poor transient performance, ignoring of load dynamics and inability to impose a fixed system frequency. However, P–f droop-based active power-sharing methods are found to be well suited for island mode of micro grid operations.

Methods based on a central master controller which controls the load sharing among the DDGUs, have additional reliability requirements for the communication and control infrastructure/framework. Table 2-2 provides a comparative summary of the proposed active power sharing methods, their major drawback(s) and the corresponding feature of the proposed method in this thesis.

This thesis presents a new and universal power-sharing method that can be employed by micro grids with single or multiple active grid interconnections – an active power-sharing technique which can prove to be equally effective for isolated and grid-connected micro grids, with single or multiple grid interconnections.

Table 2-2. Comparison of proposed active power sharing methods in the literature and the method proposed in this thesis.

Methods Proposed in Literature	Major Drawback / Shortcoming	Proposed Method in this Thesis
Droop-based (Constant or Variable Droop)	Poor frequency regulation	Constant frequency while grid-connected
	Non-ideal operation in case frequency is constant due to grid system	Ideal operation while connected to grid(s)
	For variable ones, droop setting has to be changed manually or according to operating conditions	Constant droop value for the DDGU
Methods based on central controller	Require reliable communication network. Can't operate if communication link is lost	No such dependency
Methods for Islanded micro grids	No control feature for connected mode of operation	Equally effective for interconnected or isolated mode of operation
Methods for micro grids with single grid interconnection	Not designed for controlling or managing flow on multiple interconnecting lines	Can control various overall flow conditions on multiple interconnection lines
	Mostly dependent on network configuration	Designed for all network configurations
	Mostly tested for only one configuration	Tested for 3 most extreme configurations

3. METHODOLOGY

A micro grid which can import/export (active and reactive) power over multiple active grid interconnections will be more reliable as compared to micro grids with just one active grid interconnection. Multiple grid interconnections on one hand provide more flexibility and reliability in operations while on the other hand introduce some complexity in automatic active power-sharing mechanisms adopted by DDGUs. Micro grids can have multiple interconnections with one grid system or can also have single interconnection with multiple grid systems. Grid interconnections can be at different connection points or even at different voltage levels.

Indeed, the reliability and performance of a micro grid can be significantly enhanced when it has the capability to import or export power over multiple active grid interconnections compared to micro grids with just a single active grid interconnection. The presence of multiple grid interconnections offers several advantages but also introduces some complexities, particularly in the automatic active power-sharing mechanisms adopted by Distributed Dispatchable Generation Units (DDGUs).

The benefits of multiple active grid interconnections include:

1. Redundancy and Reliability: Having multiple interconnections increases the redundancy in the power supply. If one interconnection experiences a fault or goes offline for maintenance, the micro grid can rely on the others, ensuring a continuous and reliable power supply. This redundancy minimizes the risk of prolonged outages and improves the resilience of the micro grid.
2. Load Balancing: Multiple interconnections provide flexibility in load balancing. The micro grid can distribute power efficiently among the different interconnections, reducing the chances of overloading a single connection and preventing grid instability.

3. Improved Energy Management: With access to multiple grid systems, a micro grid can optimize its energy management by selecting the most cost-effective or sustainable power source at any given time. It can import power when it's more economical or use its own generation when it's favourable, enhancing cost savings and environmental sustainability.

However, the presence of multiple interconnections does introduce some complexities, especially in managing active power sharing among DDGUs:

1. Control and Coordination: Coordinating the operation of multiple interconnections requires a sophisticated control system. This system must ensure that the power-sharing mechanisms among DDGUs are well-coordinated to prevent imbalances and maintain grid stability.
2. Synchronization and Control Strategies: Different grid systems or voltage levels may have varying synchronization requirements and control strategies. Ensuring compatibility and synchronization among these systems can be challenging.
3. Communication and Information Exchange: Effective communication and data exchange among the interconnections are crucial for seamless power sharing and coordination. This requires reliable communication infrastructure and protocols.

In addition to the above, micro grids can choose to have multiple interconnections with one grid system or establish a single interconnection with multiple grid systems. The choice depends on various factors, including the micro grid's specific requirements, the availability of grid connections, and the desired level of autonomy.

Furthermore, grid interconnections can occur at different connection points within the micro grid, such as at various substations or distributed energy resources, and at different voltage levels, ranging from low-voltage to medium-voltage or even high-voltage connections. Each configuration offers specific advantages and challenges, making the design and management of multi-interconnection micro grids a complex yet rewarding Endeavor. Ultimately, the decision to adopt multiple active grid interconnections should align with the micro grid's goals, reliability requirements, and operational complexities it can accommodate.

To fulfill the overarching goal of managing a micro grid as either a constant source or load, it's essential to maintain a degree of control over the power flow within the system. There are a couple of approaches to achieve this, depending on the specific requirements and operational constraints of the micro grid.

One possible strategy is to maintain a constant power flow on all interconnections within the micro grid. In other words, the active and reactive powers exchanged between the micro grid and external grids or other micro grids remains fixed at a predetermined value. This approach ensures that the micro grid functions as a stable and predictable power source or load, which can be particularly valuable for maintaining grid stability and power quality.

However, in practice, a more realistic scenario often involves managing the sum of active and reactive power flows across interconnections rather than individual flows on each connection. This means that the total active and reactive power transfer over all the interconnection lines is controlled to remain constant, irrespective of the specific power exchanges on each line. This approach allows for flexibility in managing the micro grid's power balance and can accommodate varying conditions and generation patterns.

The thesis introduced a controller called "Interconnection Flow Control (IFC)" initially, which is then enhanced to “enhanced IFC” (refer to chapter 5 for details about enhanced IFC), which provides a mechanism for active and reactive power sharing in situations where the sum of active and reactive power flows over the interconnection lines must be maintained at a constant value. This controller is particularly useful when the DDGUs within the micro grid have limitations in their power output capacity.

All DDGUs within the micro grid are recommended to operate with this newly designed controller. This controller ensures that power sharing is actively managed, and the micro grid can operate as a constant source or load, as required. By regulating the total power flow over the interconnections, the micro grid can adapt to varying conditions, generation availability, and load demands while maintaining the desired level of stability and performance.

The enhanced IFC manages the active and reactive power-sharing among DDGUs within a micro grid when the total power flow over interconnections needs to remain constant. This strategy offers flexibility and adaptability to the micro grid's operation while ensuring power balance and stability in various operating conditions.

3.1 Interconnection Flow Control (IFC) Mode

When a micro grid is connected to the main grid through multiple interconnection lines as shown in the Figure 3.1, the interconnection flow control looks at the active power flow from all the interconnections and sums them within its controller and compares it with a reference value. If the sum of the active power flow is different from the reference value, then each DDGU will react according to its KI (gain of the PI controller) value. A dead band can also be introduced in the model to allow the sum of active power flow to remain within a specific range. Any load variations within the micro grid will also be compensated by the local DDGUs. If any of the DDGU trips, the others will respond accordingly to ensure that the sum of real power flow over interconnections remains constant. This is a huge advantage over FFC mode of operation, where every DDGU is only responding to the changes on their own feeder flow.

When a micro grid is connected to the main grid, the Interconnection Flow Control (IFC) system plays a crucial role in actively managing the active power flow over all the interconnections. Here's how it works:

1. Summation and Comparison: The IFC controller continuously monitors and sums the active power flows from all the interconnections within the micro grid. This summation

process is integral to the control mechanism. The sum of these active power flows is then compared to a reference value, which represents the desired total active power flow. This reference value can be set according to the micro grid's operational requirements and objectives.

2. Control Response: If the sum of the active power flow over the interconnections differs from the reference value, the IFC system triggers control responses. Each Distributed Distributed Generation Unit (DDGU) within the micro grid is equipped with a PI (Proportional-Integral) controller that has its own gain value (KI). These controllers come into play when a discrepancy between the actual sum and the reference value is detected.
3. Adaptive Control: The PI controllers of the DDGUs respond to the deviation by adjusting their active power output. Depending on their individual KI values, the DDGUs increase or decrease their power generation to collectively correct the power flow imbalance and bring the sum back to the desired reference value.
4. Introducing Dead Band: To introduce an element of flexibility and tolerance in the control system, a dead band can be incorporated into the model. The dead band sets a specific range within which the sum of active power flow can fluctuate without triggering immediate control actions. This helps prevent unnecessary adjustments and allows for minor deviations without overreacting.
5. Load Variations Compensation: Within the micro grid, any load variations are also addressed by the local DDGUs. If the local load within the micro grid changes, the DDGUs collectively adapt to ensure that the power supply remains stable and balanced, contributing to the overall load-following capabilities of the micro grid.
6. Fault Tolerance: In cases where one of the DDGUs experiences a trip or failure, the other DDGUs respond accordingly. They adjust their power output to compensate for

the loss, ensuring that the sum of real power flow over the interconnections remains constant. This fault tolerance is a significant advantage, as it maintains system stability even in the face of component failures.

This approach offers a significant advantage over the Feeder Flow Control (FFC) mode of operation, where each DDGU independently responds to changes in their own feeder flow without considering the overall system balance. The IFC mode, in contrast, ensures a coordinated response that collectively manages the power balance within the entire micro grid, promoting stable and reliable power supply in interconnected micro grid environments.

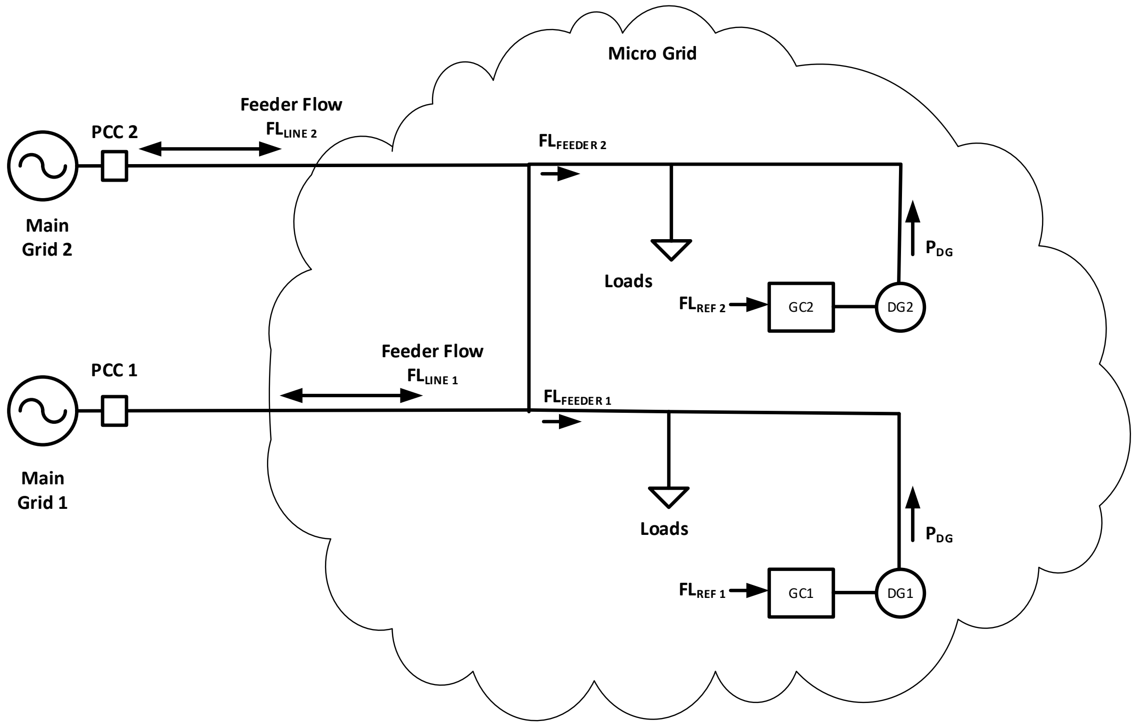

Figure 3.1. Micro Grid with Multiple Active Grid Interconnections.

While a micro grid is isolated, it replicates UPC mode of operation. Conventional power versus frequency (P–f) droop controller is adopted, and power is shared among the units according to the droop controller constant, as defined above. With reference to Figure 2.3. , IFC mode can be explained using [3.1] and [3.2]:

$$FL_{REF} = FL_{REF1} = FL_{REF2} = FL_{LINE1} + FL_{LINE2} \qquad [3.1]$$

$$(F\text{meas} - F_{\text{ref}})/K_{\text{I}} + (FL_{ref} - FL^{0}) = \text{to PI controller} \qquad [3.2]$$

where FL_{REF} is the reference value of the overall MW flow from the grid system while FL_0 is the real overall MW flow from the grid system over all the monitored interconnection lines.

When micro grid is isolated and there is no flow from (or towards) the main grid, then the only input to the PI controller will be from the frequency droop portion of the controller, hence will operate as a conventional P-f droop controller or UPC mode.

Controller design of IFC mode is shown in Figure 3.2. With multiple grid interconnections, active power flow to or from the main grid can have certain flow control limitations. The most common and probable one is to maintain an overall constant flow to or from the main grid. The operating condition to be fulfilled are given in equations below.

$$\sum_{i=1}^{n} FL_{LINEi} = CONSTANT = IF\ (Interconnector\ Flow) \qquad [3.3]$$

$$\sum_{a=1}^{n} P_{DGa} = Overall\ demand\ of\ the\ micro\ grid - IF\ (Interconnector\ Flow) \qquad [3.4]$$

$$Overall\ demand\ of\ the\ micro\ grid:$$

$$= \sum Active\ power\ demand\ of\ all\ loads - \sum Active\ power\ from\ all\ NDDGUs \qquad [3.5]$$

The equations show that the active power output from any DDGU will vary according to the overall demand of the micro grid. The overall demand, as defined in equation [3.5], is not just the load but the unserved load from the NDDGUs. This definition ensures that the intermittency of the NDDGUs is also compensated by the DDGUs within the micro grid.

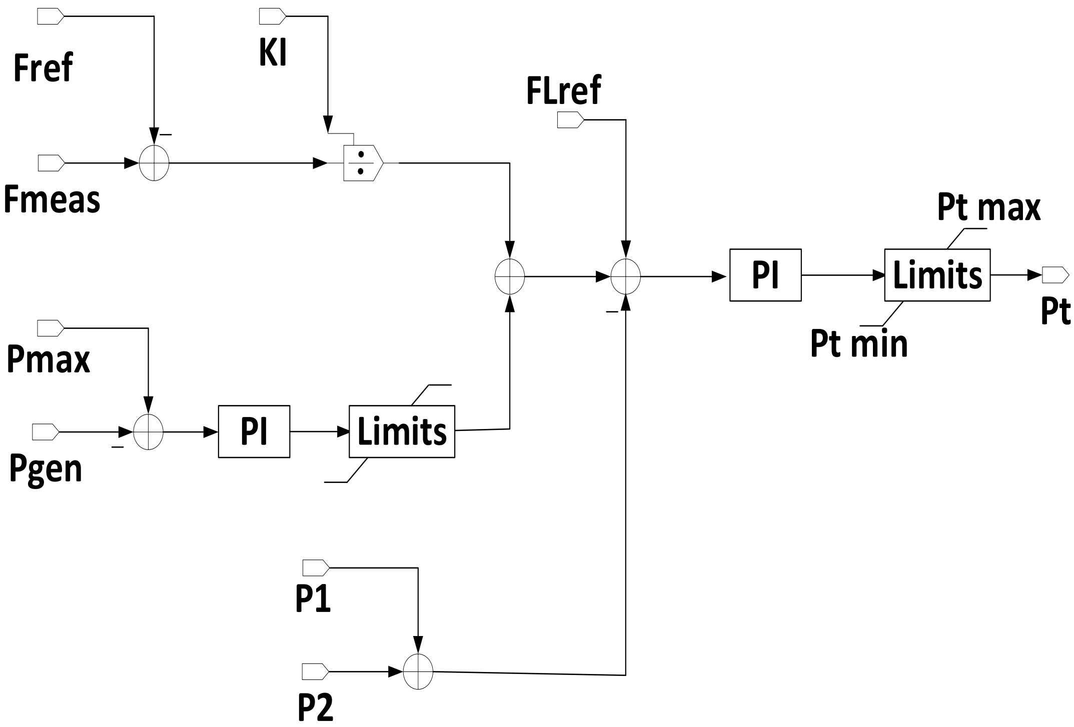

Figure 3.2. IFC Mode Controller.

Where:

Fref	is the reference frequency
Fmeas	is the measured frequency
KI	is the frequency droop (UPC mode)
FLref	is the active power flow reference
Pmax	is the max active power rating of the DDGU
Pgen	is the generated active power from DDGU
P1	is the measured active power on interconnection Line 1
P2	is the measured active power on interconnection Line 2
Ptmax	is the max active power rating of the DDGU
Ptmin	is the minimum active power rating of the DDGU

Table 3-1 provides a summary of various features and capabilities of different active power control and sharing methods, namely UPC, FFC and IFC.

Table 3-1. Comparison between active power control/sharing methods.

Feature	UPC	FFC	IFC
Compensate internal generation and demand variations while connected to grid	No	Limited to connected feeder level	Yes
Ensure ideal operation of the micro grid in grid-connected mode	No	Needs as many DDGUs as the number of internal feeders	Yes
Compensate for the loss of DDGU within the interconnected micro grid	No	No	Yes
Respond to change in the system frequency	Yes	Yes	Yes
Dependence on network configuration	No	Yes	No

3.2 Simulation Results and Discussions

The power system model that is used to test and demonstrate the performance of the IFC mode is shown in the Figure 3.3. This is the most simplified and most representative network of a micro grid mimicking a micro grid which is serving a large residential/commercial area or a small industrial system. The two interconnection lines are connected at two different nodes within the micro grid. Having interconnection lines connecting at two different nodes within the micro grid allows different values of active power to flow on the lines according to the physical laws of the load flow. In contrast, having two interconnection lines at the same node or connection point within a micro grid can only provide increased reliability, but the active power flow will always be symmetrical (equal) on each line. This modelling method is applied to simulate a challenging operating scenario for testing the performance of the designed IFC controller. This will also help in demonstrating that the designed controller is sensitive to the overall flow of active power and allows flexible active power flow on individual interconnections. The individual interconnection lines can have active power flow which is best suited for the most optimal power flow solution without having any undue operational restriction.

This model is intentionally simplified yet highly representative of a micro grid configuration, emulating scenarios where a micro grid serves a significant residential/commercial area or a smaller industrial system.

In this model, there are two interconnection lines that link the micro grid to external grid systems. What sets this configuration apart is that these two interconnection lines are connected at two distinct nodes within the micro grid. This structural choice has significant implications:

1) Diverse Active Power Flows: The presence of interconnection lines connected to different nodes within the micro grid allows for the realization of different values of active power flow on each line, conforming to the physical laws governing load flow. In essence, it simulates the real-world complexities of micro grid operations where power flows may vary based on network topology, distribution, and demand.
2) Asymmetrical Active Power Flows: This modelling approach deviates from the conventional setup where two interconnection lines meet at the same node or connection point within the micro grid. In such a symmetrical configuration, while it enhances reliability, it inherently leads to symmetric (equal) active power flows on each line. This constraint does not reflect the diversity and variability of real-world micro grid operations.
3) Challenging Operating Scenario: The model is specifically designed to simulate a challenging operating scenario. It serves as a rigorous test bed to evaluate the performance of the designed IFC controller. By doing so, it demonstrates that the IFC

controller is highly responsive to the change in overall active power flow within the micro grid, which is a crucial attribute in managing power balance and grid stability.

4) Flexible Active Power Flow: An essential feature of this model is its ability to allow for flexible active power flow on individual interconnection lines. This flexibility enables the micro grid to optimize power flow distribution for the most efficient solution without imposing undue operational restrictions.

In summary, the power system model presented in Figure 3.3 is a strategically designed representation of a micro grid configuration serving residential/commercial areas or small industrial systems. Its distinguishing feature is the use of two interconnection lines connected at different nodes, which enables the simulation of diverse and asymmetrical active power flows. This model serves as a challenging and realistic test environment for assessing the performance of the IFC controller, ensuring that it can adapt to various operating conditions and facilitate optimal power flow management within the micro grid.

Modelled DDGUs represent all types of dispatchable generating systems, either renewable dispatchable generating systems like hydro, batteries etc. or conventional fossil fuel-based like gas turbines or diesel engines etc. The intermittencies of the solar PV and wind type renewable generating systems are modelled or captured in as the variation in the load/demand. As the change in the amount of generation can be equalised by the change in the load/demand. As mentioned above, equation 3.5 defines the overall demand of the micro grid as the leftover demand from the NDDGUs. Therefore, the contribution and the intermittency from the NDDGUs are all factored in the simulations.

General P and Q type loads are modelled and varied at a specified rate to replicate either the intermittency of the renewable generation or a natural change in the demand. An overall load of 6.8 MW is modelled, which represent a considerable size of the micro grid. The initial overall import from the grid on both lines is set at 1.4 MW, divided unequally between two interconnection lines (0.9 MW and 0.5 MW). The internal line flows are naturally spread according to the load and generation distribution within the micro grid. Loads are also distributed unequally within the micro grid.

All three DDGUs are of different capacities, this is to represent a real or close to real scenario. Having multiple DDGUs within a micro grid with the same capacity can only be considered under ideal operating scenarios. The modelling information is provided in following tables.

The system is comprised of two interconnections with the main grid, marked as Line1 and Line2. Two interconnections are considered from one main grid. The three DDGUs in the system are modelled as synchronous generators (SGs). All three DDGUs are set to operate in IFC mode with the same value of KI. The following cases are studied to evaluate the performance of the proposed governor controller or mode of DDGU operation:

1. Case Study 1. In Case study1, internal load variations are simulated to test the ability of the control mode to compensate for the internal load or generation variations while connected with the main grid(s). IFC and FFC modes are compared for the same load variations.
2. Case Study 2. Internal load variations along with the step-wise disconnection of the two grid interconnections are studied in Case 2. This is to test the controller performance during transition and then the isolated mode of micro grid operations.
3. Case Study 3. Internal load variations along with one interconnection line loss and a DDGU tripping is studied in Case 3. This case tests the capability of the IFC controller with severe variations in the operating conditions.

4. Case Study 4. IFC mode performance is tested if the network configuration is changed within a micro grid. The loads are moved to different busses within the micro grid and then varied. IFC and FFC modes are compared for the same load variations.
5. Case Study 5. Another interconnection with another grid system is added to the micro grid. The third interconnection line, Line3, is connected to another bus within the micro grid. This case is to test the capability mode of the IFC to keep the sum of active power from the two previous interconnection lines constant under varying operating conditions.

These case studies collectively provide a comprehensive evaluation of the IFC mode's performance and sensitivity under different conditions, including load variations, grid disconnections, challenging scenarios, and network configuration changes. By comparing the IFC mode to the FFC mode and testing its adaptability to varying network structures, the research aims to offer valuable insights into the controller's capabilities and benefits in micro grid operations.

Detailed modelling parameters used in the model are provided in Appendix A. Parameters for the transmission lines are listed in Table 8-1 while modelling details of the transformers are listed in Table 8-2. Parameters used to model loads and generators are listed in Table 8-3 and Table 8-4 respectively.

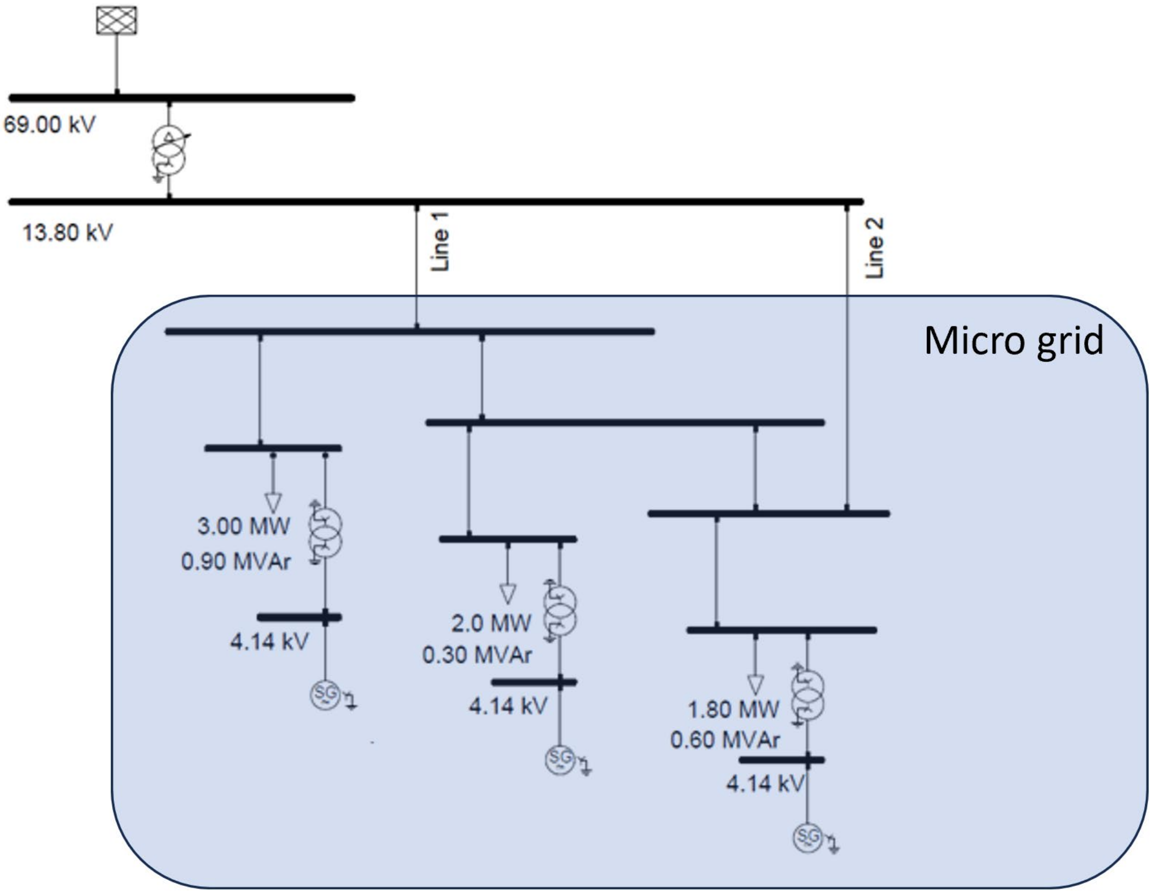

Figure 3.3. Basic network model of the studied micro grid (Configuration 1).

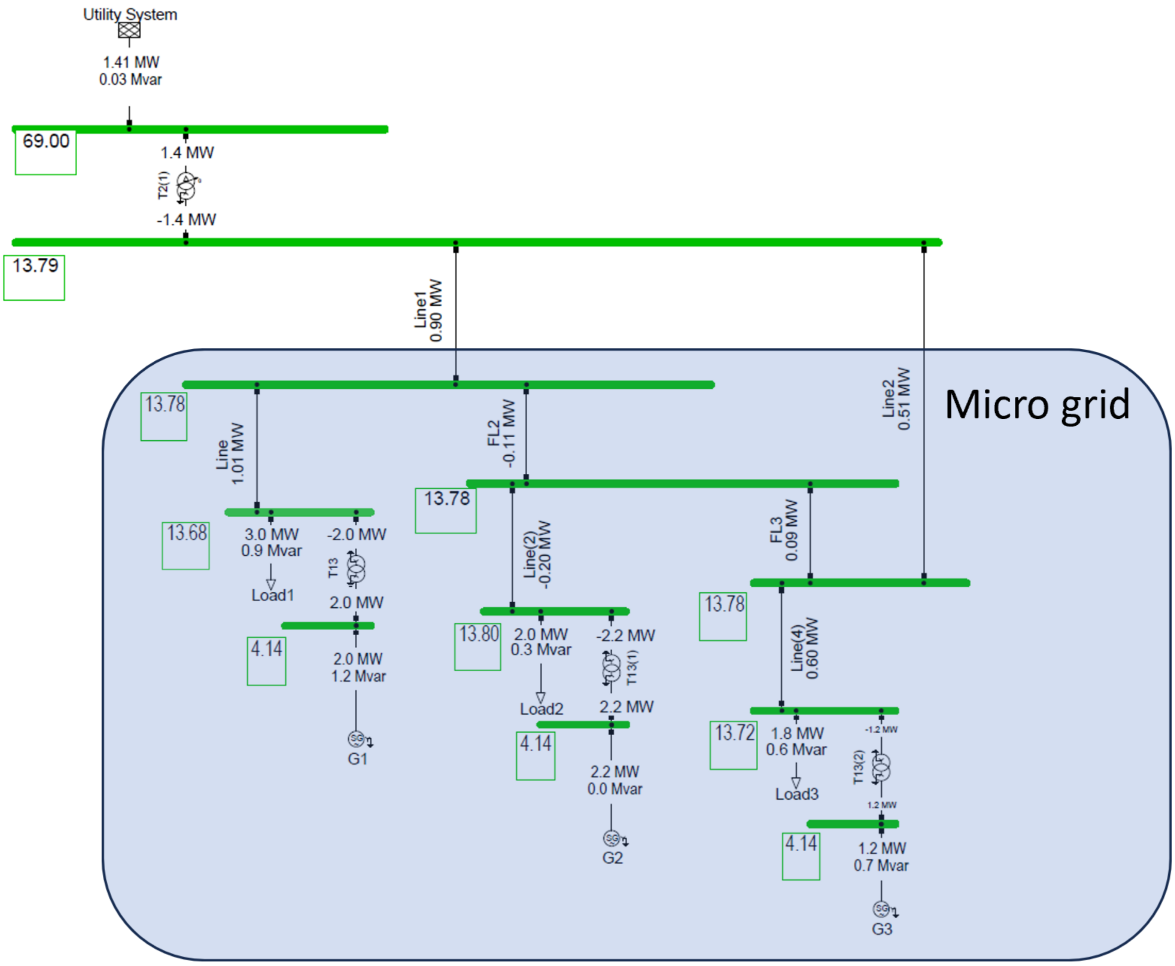

Figure 3.4. Load flow result of Configuration 1.

4. RESULTS AND DISCUSSION

4.1 Case Study 1: Load Variations.

In this case study, the below events are simulated:

1. At t = 1.2 s, Load1 (close to G1) was ramped down 20% in 0.2 s.
2. At t = 6 s, Load3 (close to G3) was ramped up 33% in 0.2 s.

This is the simplest test for the controller to demonstrate that all the DDGUs contribute to the load variation. The two loads are varied at different times and at different network locations, but the change in load (MW) remained the same at both instances. This is to test the accuracy of the DDGUs active power responses.

These simulated load variations represent either natural demand variance or intermittency in the generation of NNDGUs. Both will result in the same outcome, i.e. DDGUs will see the change in the overall demand of the micro grid.

As shown in the Figure 4.3, all the load variations are compensated by the local generators even when the micro grid is connected to the main grid, keeping the sum of real power flow from the main grid at a constant value. It can be seen that the power flow on the two interconnection lines is varied marginally, but the sum of flow from the main grid remains constant. Main grid maintains the frequency at a constant level and therefore P–f droop portion of the governor controller remains ineffective for all the variations of the load and subsequent dispatch variations.

It is evident from the results that for a reduction of 0.6 MW (Load1) at t = 0.2 s, all the DDGUs reduce their real power output in proportion to their capacities. If DDGUs would have operated in FFC mode instead of the proposed IFC, then only G1 would have adjusted its real power output as shown in 4.1. For the first load variation (-0.6 MW), Figure 4.1 shows the comparison between the generation contributions from the DDGUs when operated using FFC and IFC mode of operation. A proportional response from all the three DDGUs was evident in case when DDGUs were operated in IFC mode, while for FFC mode, a very localised response from only one DDGU was observed. This is a fundamental difference between the two controllers.

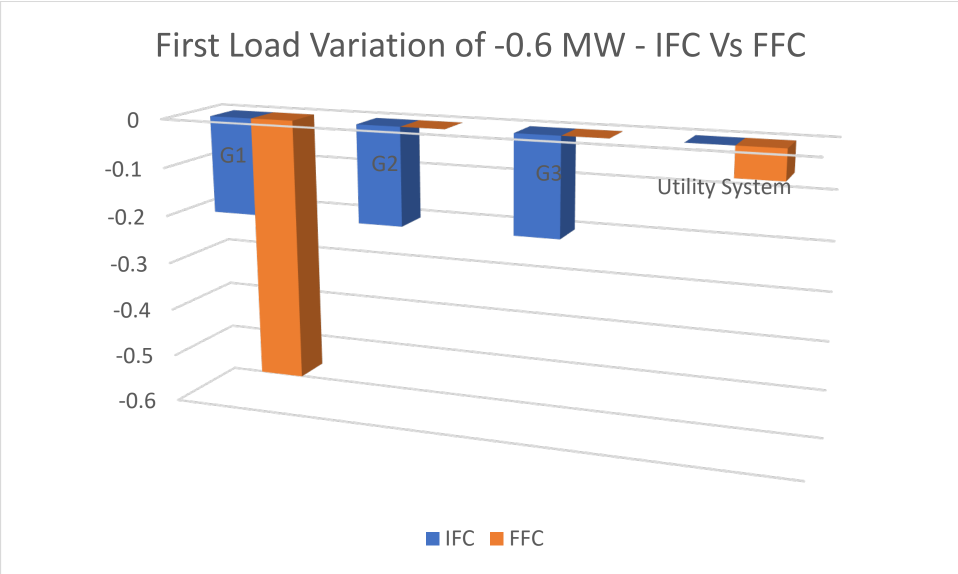

Figure 4.1. Active Power contribution from G1, G2, G3 and utility system for first load variation (-0.6 MW).

The results demonstrate that only G1's active power dispatch is varied for the variation of Load1, as Load1 is within the feeder of G1 or within the monitored area of G1. Monitoring points of each DDGU are highlighted in the Figure 4.9 when operated in FFC mode. None of the other DDGUs contribute to the variation of Load1. Slight change in the active power flow of Line1 is observed. This is because of the electrical proximity of the line to the varying load.

Similarly, when the same amount of load (0.6 MW) is increased at a different location (Load 3) within the micro grid, at t = 6 s, all DDGUs return to their initial values of real power output when operated in IFC mode. This adjustment in generation takes place without causing any limitation to the flow of any internal line and also while maintaining the sum of real power flow over the interconnection lines at a constant value.

If DDGUs are operated using FFC mode, when Load 3 is increased from 1.8 MW to 2.4 MW, G3 compensated for all the load variations within its feeder, as Load 3 is within G3 feeder. The real power output of G3 was raised to the maximum (100 %), leaving no room for any more positive load variations within its feeder, as shown in Figure 4.6 and Figure 4.2. However, with the IFC mode, G3 being the smallest unit, contributes only around 17 % of the overall load variation and is finally loaded to only up to 50 % of its capacity. This provides ample room for compensating any other positive load variations within the entire micro grid. This flexibility in IFC mode of operation provides more room for load/generation variations as compared to FFC mode of operation.

For the simulated variation of Load 3, FFC mode is not able to maintain a constant flow of active power from the utility system. Initially, the active power flow on Line2 is 0.5 MW, while after load variation the flow on Line2 is raised to 0.6 MW. Active power flow on Line1 is also observed to have a slight variation at the time when Load1 is varied. This is because of the proximity of these lines to the corresponding loads.

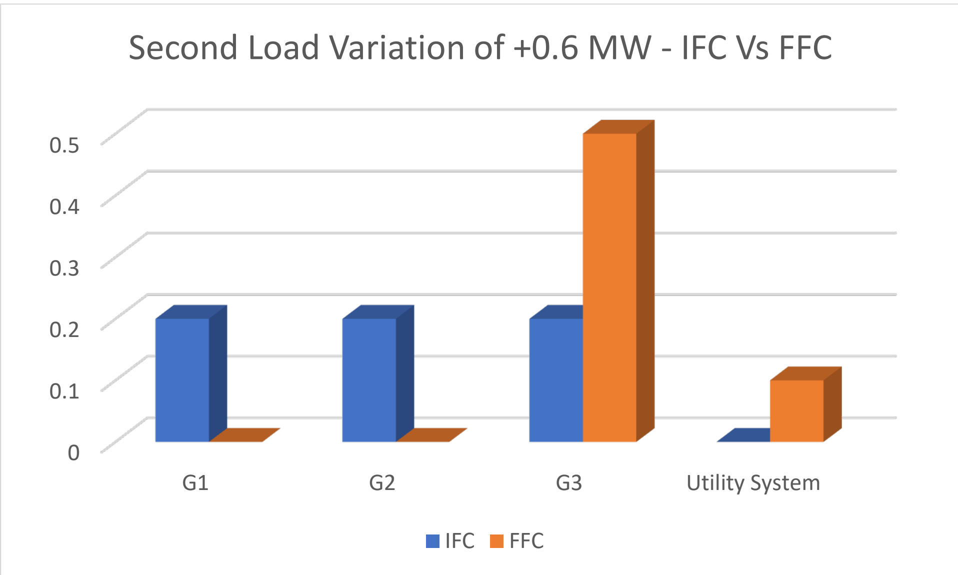

Figure 4.2. Active Power contribution from G1, G2, G3 and utility system for second load variation (+0.6 MW).

Simulation results are provided in following figures.

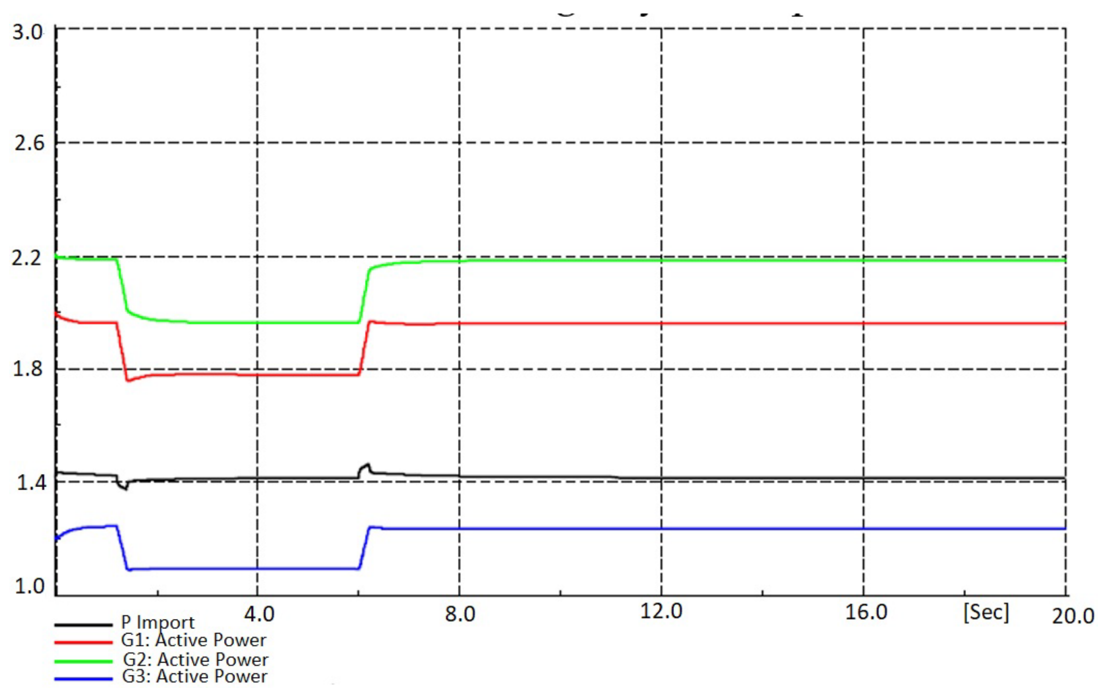

Figure 4.3. Active Power of G1, G2, G3 and utility system.

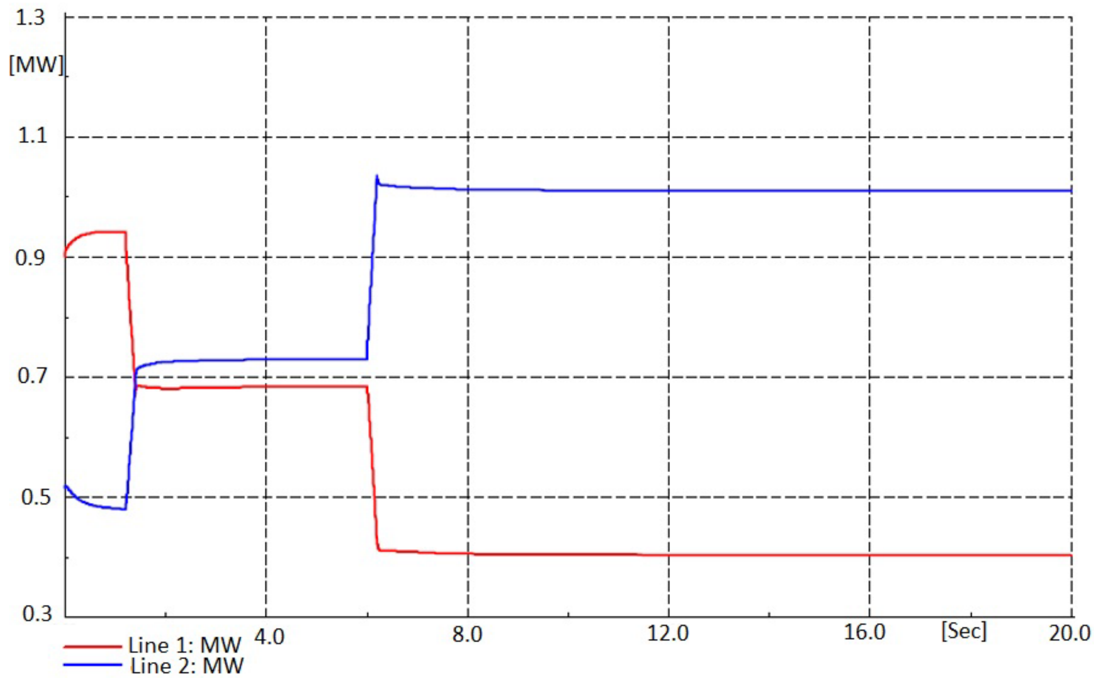

Figure 4.4. Active Power Flow on Line1 and Line2.

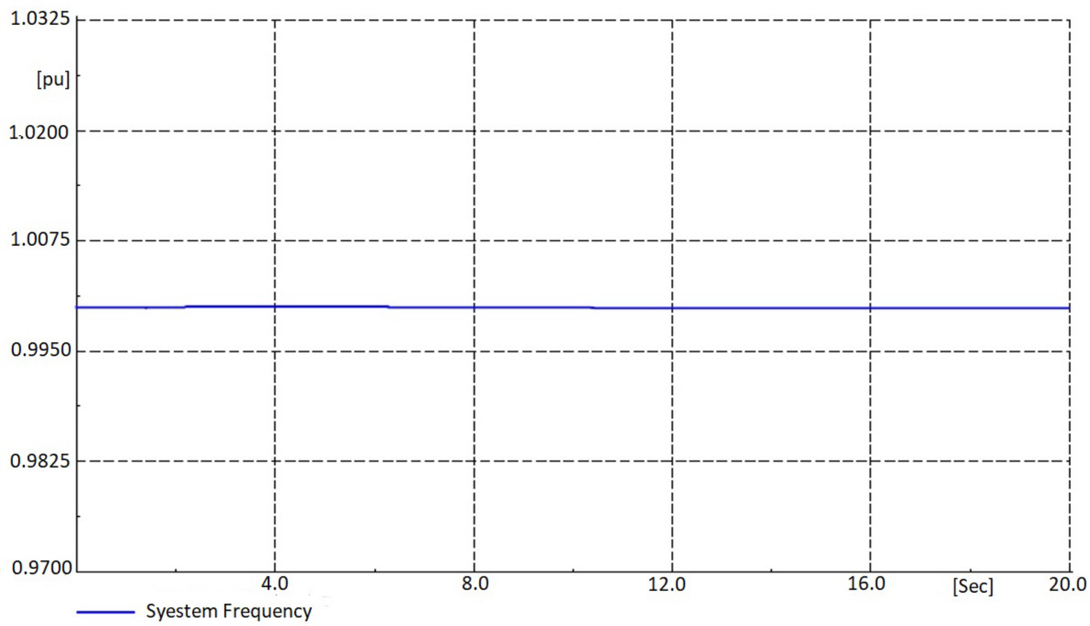

Figure 4.5. Frequency of the Micro Grid.

The final values of the real power flow over the two interconnection lines are different from their initial values, while the DDGUs return to their initial values of real power generation. This change in flow is attributed to the change in load distribution within the micro grid. After two load variation events, the overall load or demand of the micro grid returns to the initial value but since these variations are simulated at different locations, they cause the real power flow over the interconnection lines to take different final values.

Using IFC mode of operation makes DDGUs, within a micro grid, insensitive to the location of the load variations, as they all contribute to compensate for any load/generation variations anywhere within the micro grid. This is identified as one of the restrictions for the FFC mode, as it always needs at least one DDGU in every feeder of the micro grid. That feeder level DDGU only responds to the active power load variations within that particular feeder.

In the case where DDGUs are operated in FFC mode instead of the proposed IFC mode, for the same network configuration and for the same load variations, then the contributions from the DDGUs are shown in figures below.

Since all the load variations are studied when the micro grid remained connected with the main grid, therefore frequency of the system remained constant for both IFC and FFC mode studies.

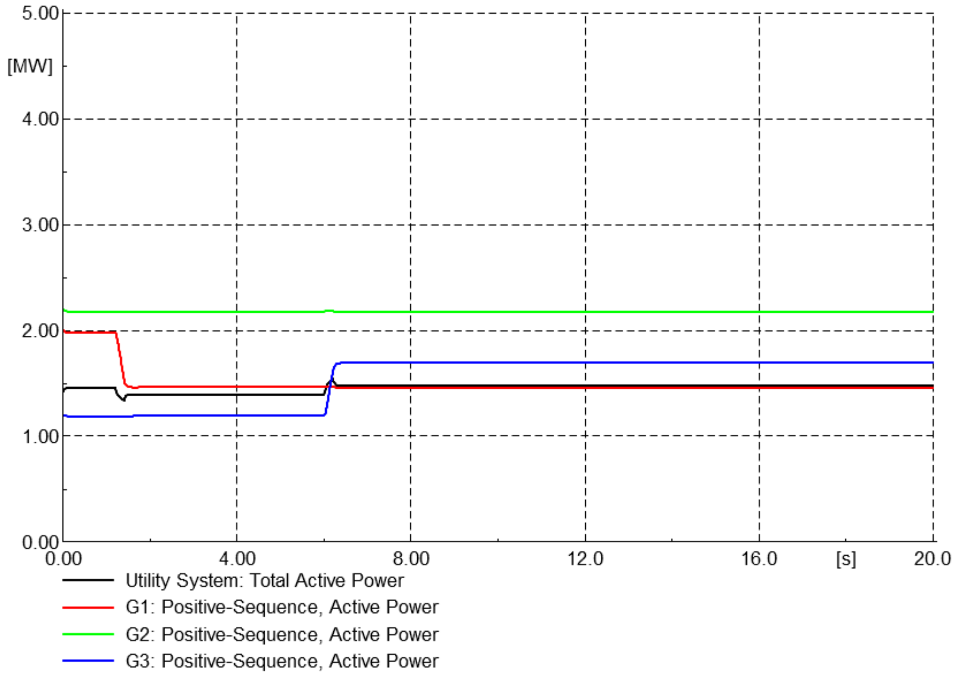

Figure 4.6. Active Power of G1, G2, G3 and utility system.

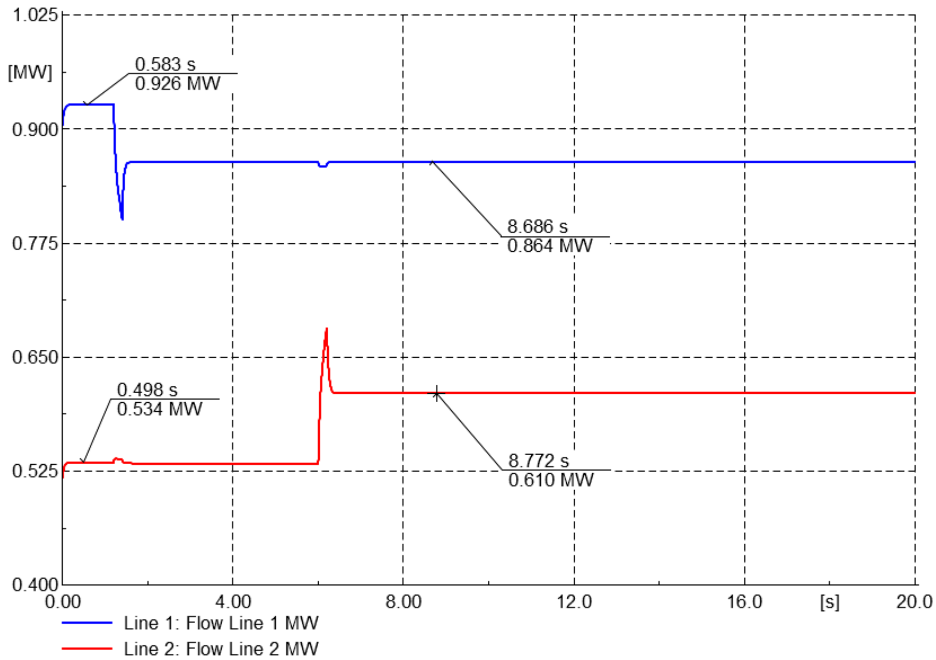

Figure 4.7. Active Power Flow on Line1 and Line2.

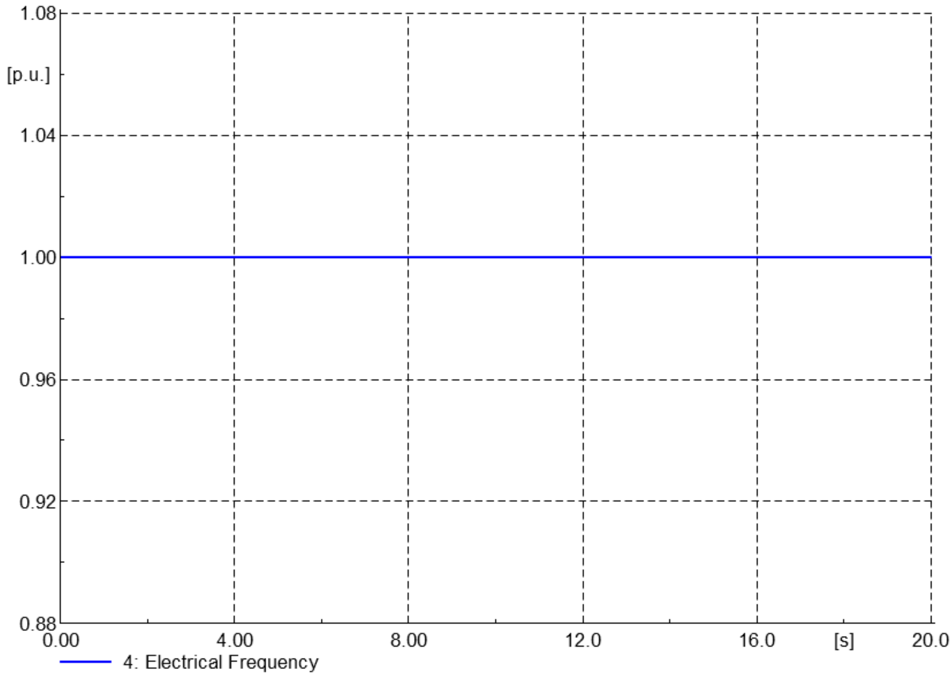

Figure 4.8. Frequency of the Micro Grid.

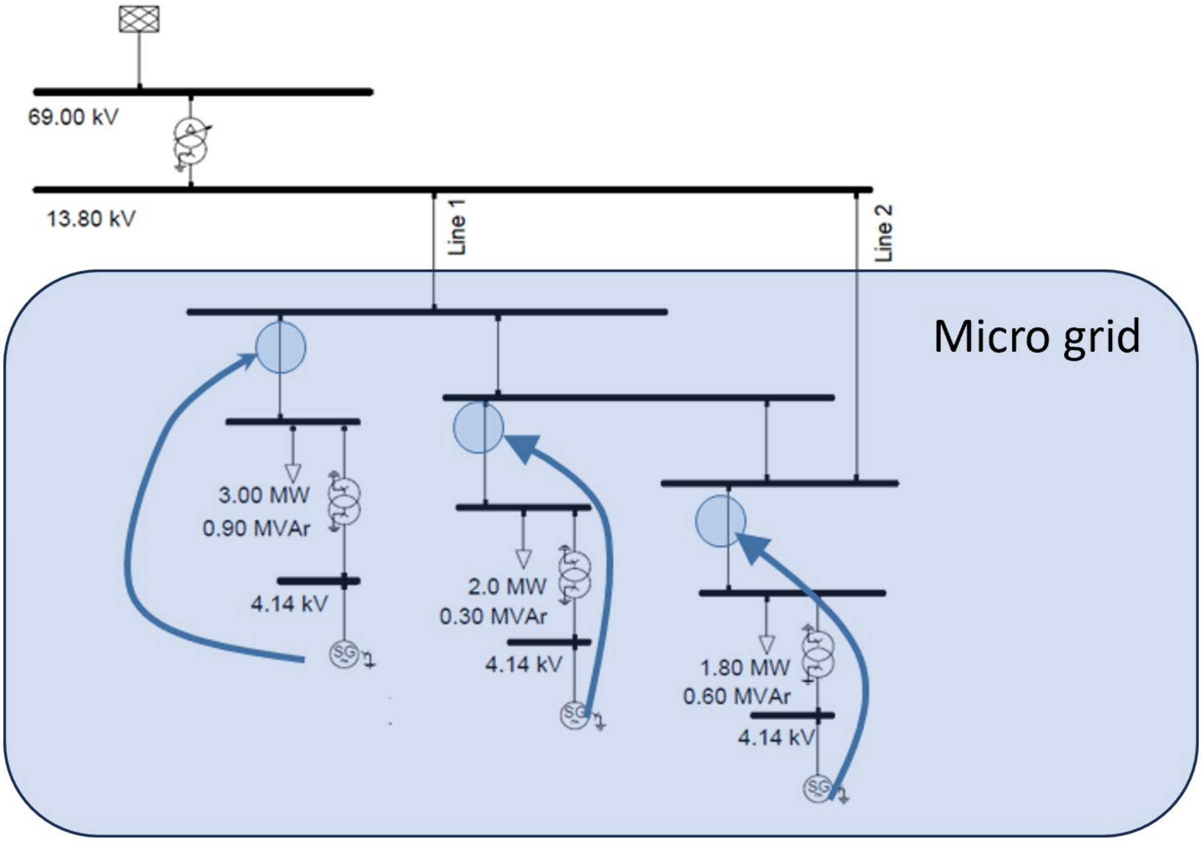

Figure 4.9 Active power measuring points for DDGUs in FFC mode.

The conclusion of Case Study 1 is that IFC mode is tested to prove its capability to operate at a global micro grid level, utilizing the overall capacity withing DDGUs in response to the any load variations within the micro grid. The results of Study Case 1 demonstrated that IFC mode satisfies following listed research objectives:

a. Ensuring operation as a constant load or generation for the whole micro grid.

b. Applicability to micro grids with one or multiple grid interconnections.

c. Demonstrated the capability to control the active power flow on all or some of the identified (participating) interconnection lines from the main grid.

d. Adaptability to changes in network configurations.

4.2 Case Study 2: Load Variations With Grid Disconnection.

In this case study, these events are simulated:

1. At t = 1.2 s, Load1 (close to G1) is ramped down 20% in 0.2 s.
2. At t = 4 s, Line1 is taken out of service.
3. At t = 6 s, Load3 (close to G3) is ramped up 33% in 0.2 s.
4. At t = 8 s, Line2 is taken out of service and the micro grid is isolated from the main grid.

Starting from the same initial conditions as for Case Study 1, Case Study 2 tests the performance of the proposed IFC mode of operation under step-wise isolation from the main grid during the load variations. These steps are designed to test the designed controller under all three possible operating conditions, namely grid connected, isolated and in transition. Although IFC mode is setup to monitor two interconnection lines in the model, however losing one line should not cause it to cease the operations. Similarly, if IFC mode is set up to monitor the sum of active power flow over any number of interconnecting lines, losing any line or any number of lines should not affect the performance of the controller. The flow from the grid will be maintained at a certain MW level if the remaining lines can take up the reference active power value.

Flow on each interconnection line depends on the load distribution within the modelled micro grid. The impact of each interconnection line tripping is different as they are not only carrying different active power values before tripping but are also connected at different network locations within the micro grid.

As shown in Figure 4.10, the first event replicates the negative load variation as in Case 1. For this initial load variation, as before, active power flow on individual interconnection lines do vary, while keeping the overall MW flow to a constant value for 1.4 MW.

When Line1 is tripped at t = 4 s, the overall real power flow from the main grid remains at a constant value (1.4 MW) as the flow on the other line (Line2) increases. Line2 takes up the whole active power flow to ensure micro grid continue to operate like either a constant load or generation for the main grid. DDGUs return to their previous real power output values after a transient spike. It can be observed that G1 and G3 experience opposite spikes. G1, being close to the Load1, initially increased its real power output at the tripping of Line1. At the time of tripping, Line1 carries around 0.7 MW. Positive spike in the generated power profile of G1, causes a negative spike in the real power flow from the main grid, however the flow from the main grid instantly returns to the initial value due to the negative spike in the real power generation of G3, which is instantly compensated by the positive spike of G1. At t = 6 s, when Load 3 is increased, introducing a positive load variation of the same value as in the first event, the real power flow (import) from the main grid remains at the same value, even with only one active interconnection (Line2) from the main grid. All three DDGUs contribute to the compensation for any load variations anywhere within the micro grid. This is a key advantage of the IFC mode of operation as compared to FFC. This also depicts the effectiveness of the IFC mode of operation for the micro grids with several number of interconnections with the main grid.

When the micro grid is completely isolated from the main grid at t = 8 s, frequency decreased to increase the power generation from the DDGUs as the real flow from the main grid drops to zero. As explained earlier, while completely isolated from the main grid, the IFC mode of operation acts like the UPC mode of operation. The change in the frequency can be calculated as below:

$$(f' - f^{\circ}) = K_I(FL_{REF} - FL^0) \qquad [4.1]$$

$$(f' - f^{\circ}) = 0.006 \text{ pu}$$

where: $K_I = -0.4$, $FL_{REF} = 0.01414$ (per unit on 100 MVA base) and $FL^0 = 0$ (as MG is isolated). For compensating the loss of the main grid, which was providing 1.4 MW to the micro grid, the overall drop in the frequency is 0.006 pu (0.3 Hz). Since all units are modelled with the same P-f droop value, therefore all the three generators contributed proportionally.

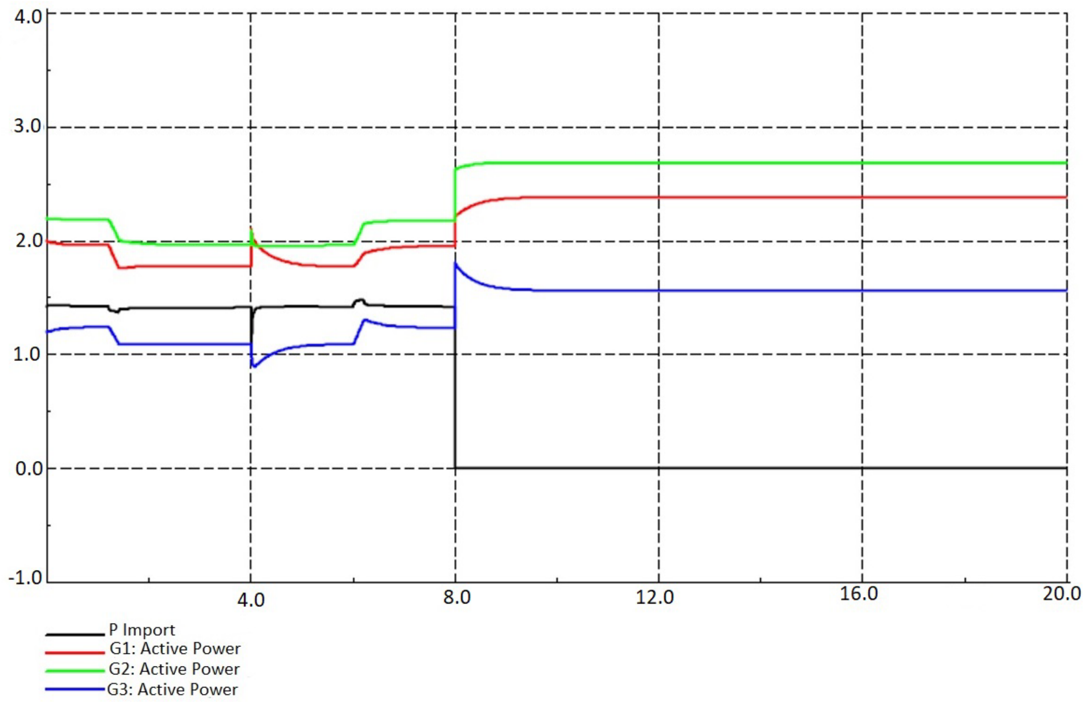

Figure 4.10. Active Power of G1, G2, G3 and utility system.

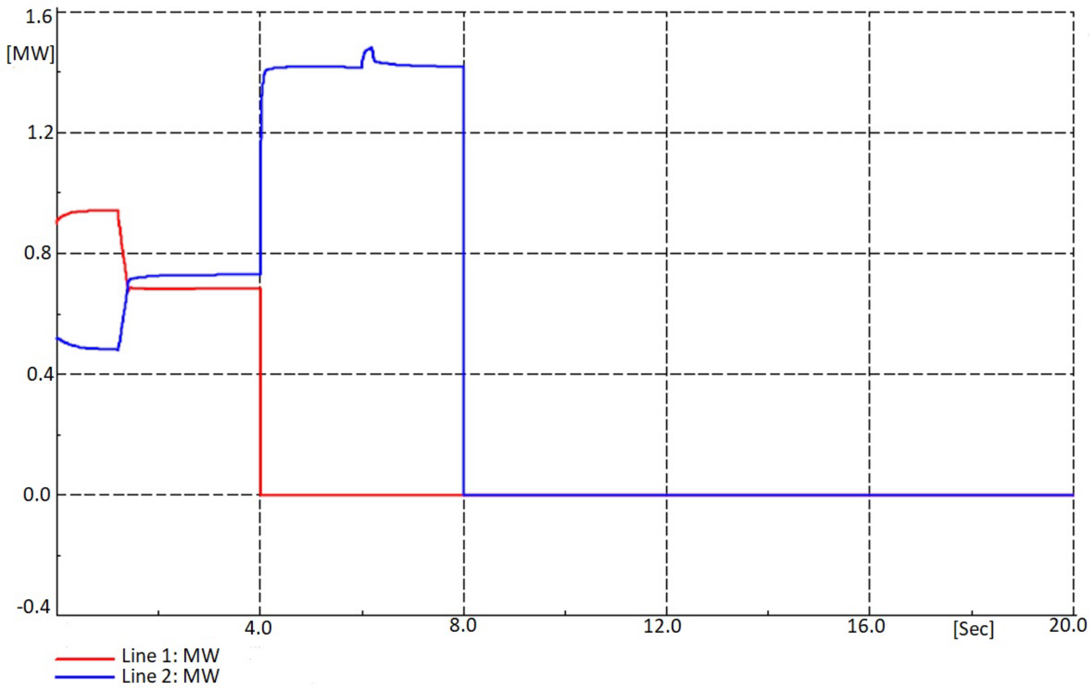

Figure 4.11. Active Power Flow on Line1 and Line2.

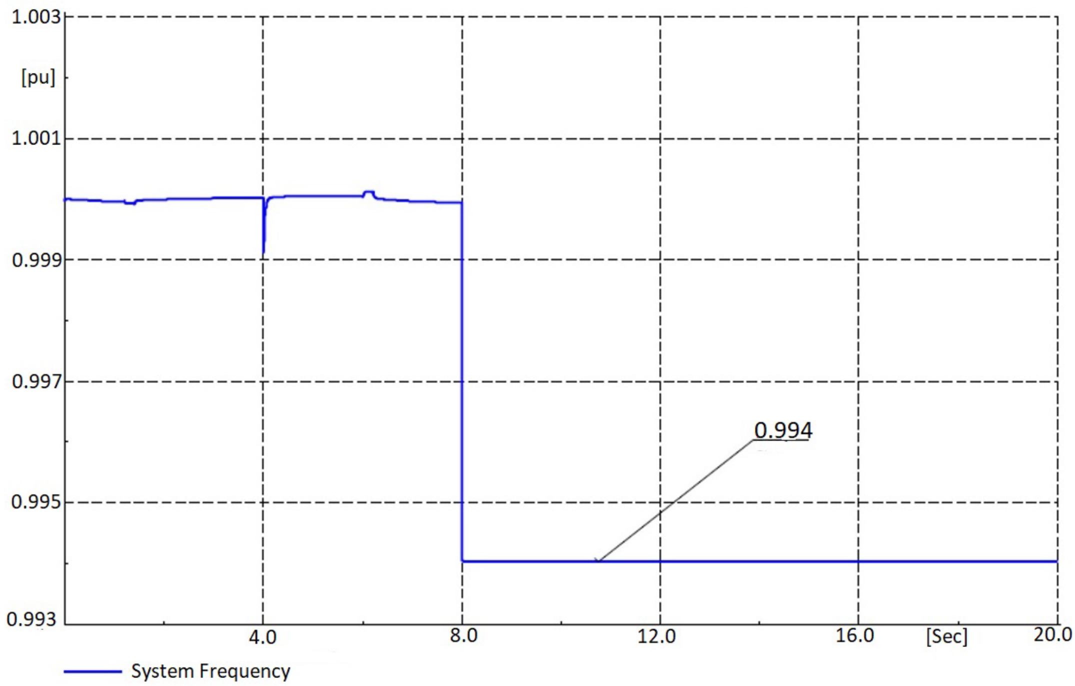

Figure 4.12. Frequency of the Micro Grid.

The conclusion of Case Study 2 is that IFC mode is tested to prove its capability to operate at a global micro grid level, utilizing the overall capacity within DDGUs in response to the any load variations within the micro grid and remains stable during and after the grid isolation.

The results of Study Case 2 demonstrated that IFC mode satisfies following listed research objectives:

a. Ensuring operation as a constant load or generation for the whole micro grid.

b. Applicability to micro grids with one or multiple grid interconnections.

c. Demonstrated the capability to control the active power flow on all or some of the identified (participating) interconnection lines from the main grid.

d. Adaptability to changes in network configurations.

e. Allowed stable independent (grid-isolated) operation of the micro grid.

f. Self-resilience in manner that in case micro grid changes modes (grid interconnected to isolated or vice-versa) the DDGUs adapted accordingly.

4.3 Case Study 3: Load Variations With DDGU Tripping

The following events are simulated for this case study:

1. At t = 1.2 s, Load1 (close to G1) is ramped down 20% in 0.2 s.
2. At t = 4 s, Line1 is taken out of service.
3. At t = 6 s, Load 3 (close to G3) is ramped up 33% in 0.2 s.
4. At t = 8 second, G3 is tripped.

This case study examines the capability of the proposed IFC mode of operation to cope with the loss of one DDGU within the micro grid. First three simulated events are same as Case Study 2 while the fourth simulated event at t = 8 s simulates tripping event of one DDGU, G3. Since for a micro grid operating it's DDGUs in IFC mode doesn't need to have one DDGU for every feeder, therefore the micro grid is tested with the loss of a DDGU within the micro grid. As demonstrated in previous cases, every generator operating in IFC mode contributes to the load variation proportionally, therefore tripping any DDGU should not cause any change in the active power flow from the main grid as long as other DDGUs have available capacity to compensate for the loss of the DDGU.

As shown in Figure 4.13, remaining two DDGUs are able to keep the real power flow from the main grid at a constant value even after losing one interconnection line (Line1) and one DDGU (G3). Since the micro grid is not completely isolated from the main grid, therefore the main grid is able to maintain the frequency at a constant value. Before the time of tripping ($t = 8$ s), G3 was generating around 1.2 MW, close to 18% of the overall demand of the micro grid. Loss of G3 causes a transient spike on the real power flow on the only active interconnection line (Line2) from the main grid, however subsequent and timely response from G1 and G2 brings the flow from the main grid back to its initial value.

Since the IFC mode of operation enables all active DDGUs to respond to load/generation variations within the micro grid as a single large virtual unit, therefore it is able to maintain the flow from the main grid at a constant value. This could not be achieved with the FFC mode of operation, as it restricts DDGUs to respond to only load/generation variations within their feeders.

Results attest that with the proposed IFC mode of operation, a micro grid can sustain two severe contingencies without losing its ideal operation – that is to act either a constant load or source for the main grid.

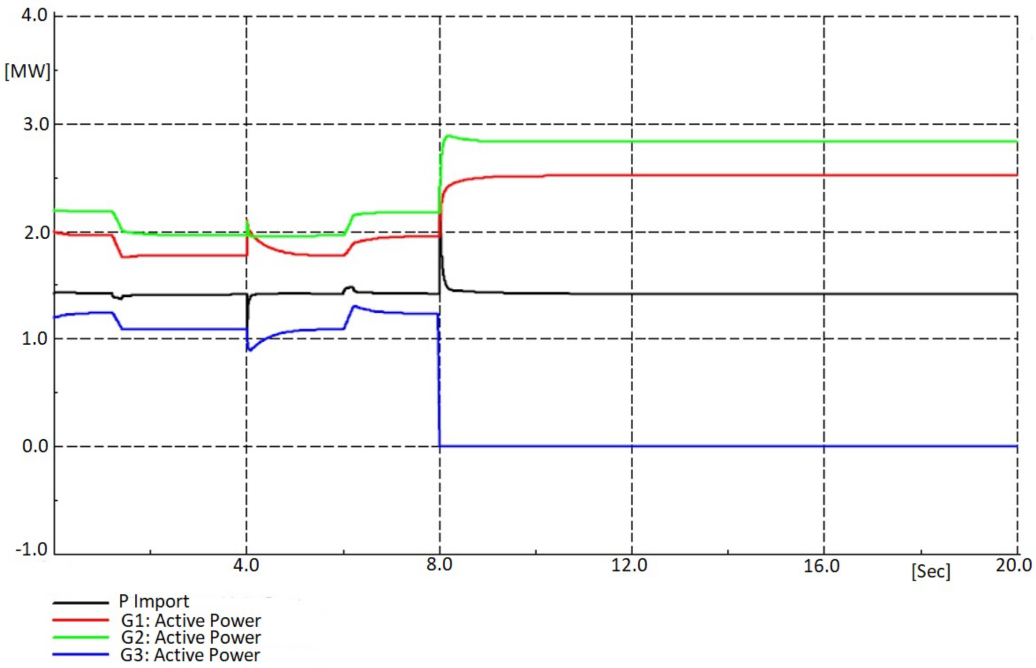

Figure 4.13. Active Power of G1, G2, G3 and utility system.

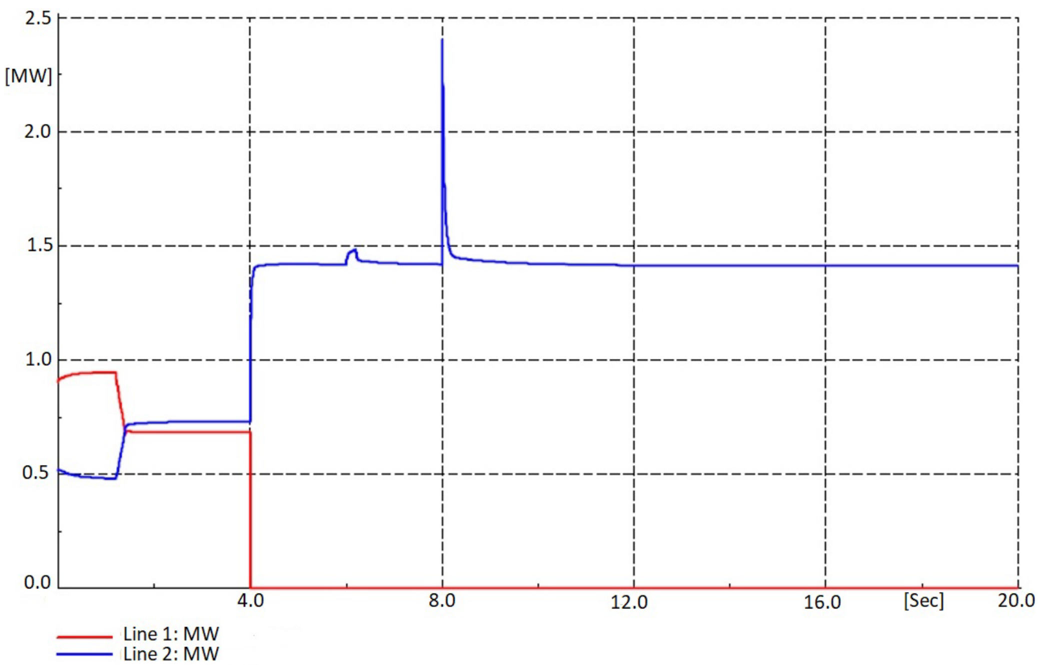

Figure 4.14. Active Power Flow on Line1 and Line2.

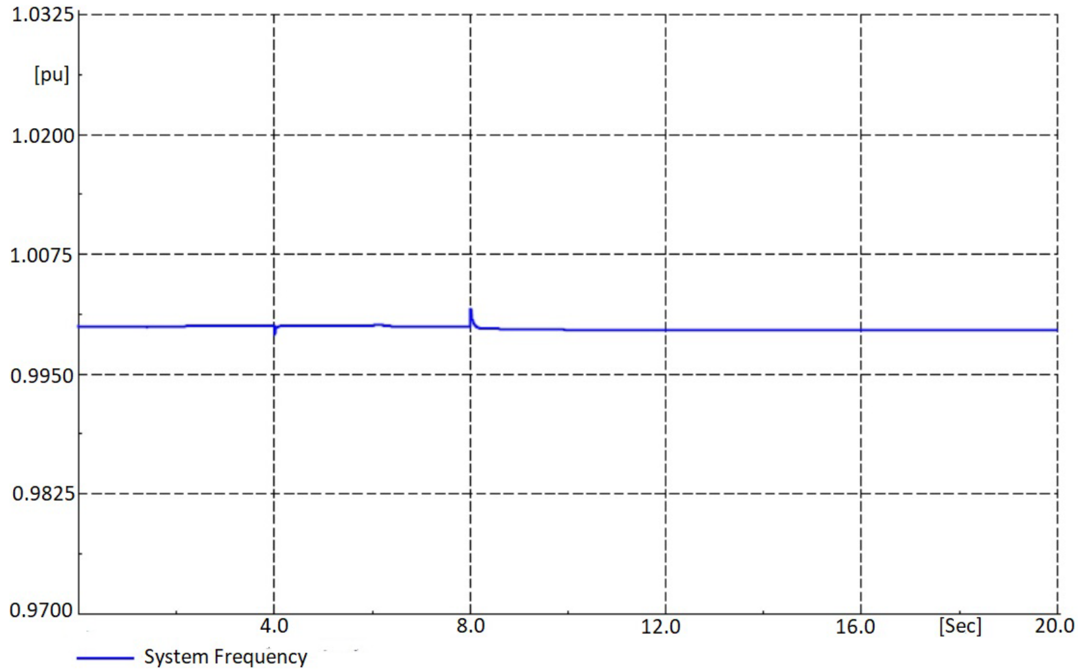

Figure 4.15. Frequency of the Micro Grid.

The conclusion of Case Study 3 is that IFC mode is tested to prove its capability to operate at the micro grid level, utilizing the overall capacity within DDGUs in response to the any load variations within the micro grid and remains stable during and after the loss of one internal DDGU.

The results of Study Case 3 demonstrated that IFC mode satisfies following listed research objectives:

a. Ensuring operation as a constant load or generation for the whole micro grid.

b. Applicability to micro grids with one or multiple grid interconnections.

c. Demonstrated the capability to control the active power flow on all or some of the identified (participating) interconnection lines from the main grid.

d. Adaptability to changes in network configurations.

4.4 Case study 4: Change in Network Configuration

In this case study, the below events are simulated:

1. At t = 1.2 s, Load1 (close to G1) is ramped down 20% in 0.2 s.
2. At t = 6 s, Load 3 (close to G3) is ramped up 33% in 0.2 s.

The network configuration is modified, as shown in the Figure 4.16 below, to test the flexibility and performance of the IFC mode under varying network conditions. Load1, Load2 and Load3 are moved within the micro grid and placed on different busses, as highlighted in Figure 4.17. This modified network configuration is referred as Configuration 2 in the discussion.

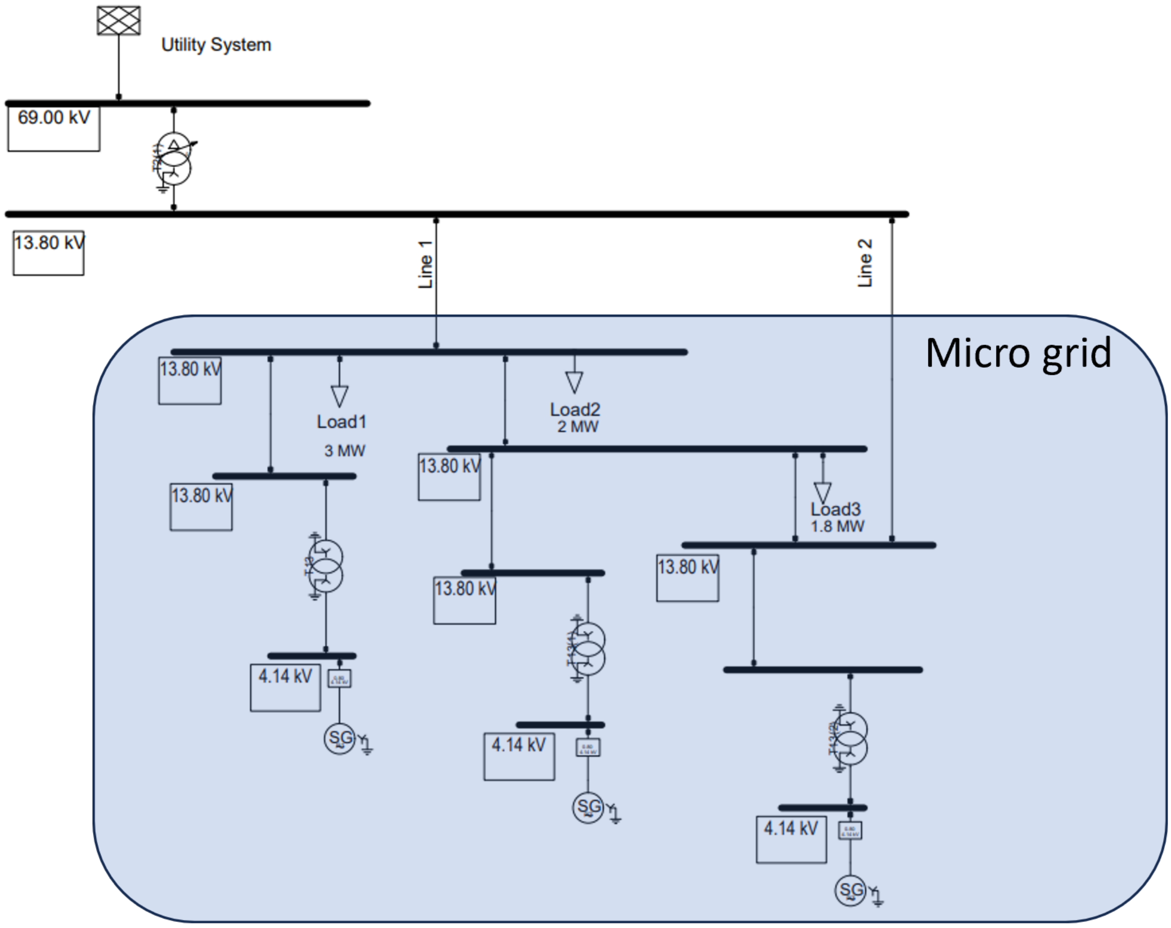

Figure 4.16. Modified network configuration (Configuration 2).

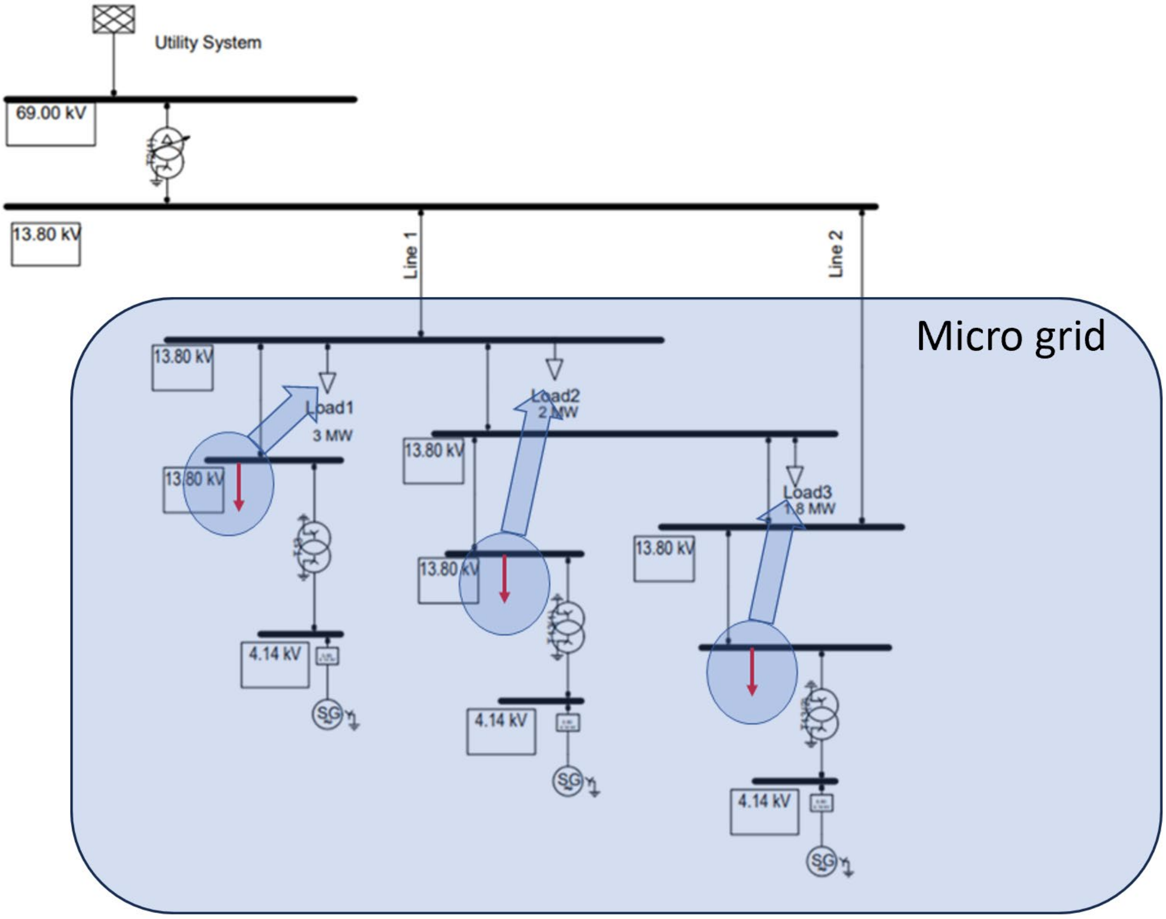

Figure 4.17 Configuration 2 with load transfer highlighted. Red arrows show the previous location of the loads.

This change in load distribution within the micro grid induces a consequential change in the overall active power flow within the micro grid. Since the values of loads and generation from DDGUs are kept almost the same, therefore no change in the sum of active power flow from the utility system is observed (1.4 MW in both cases).

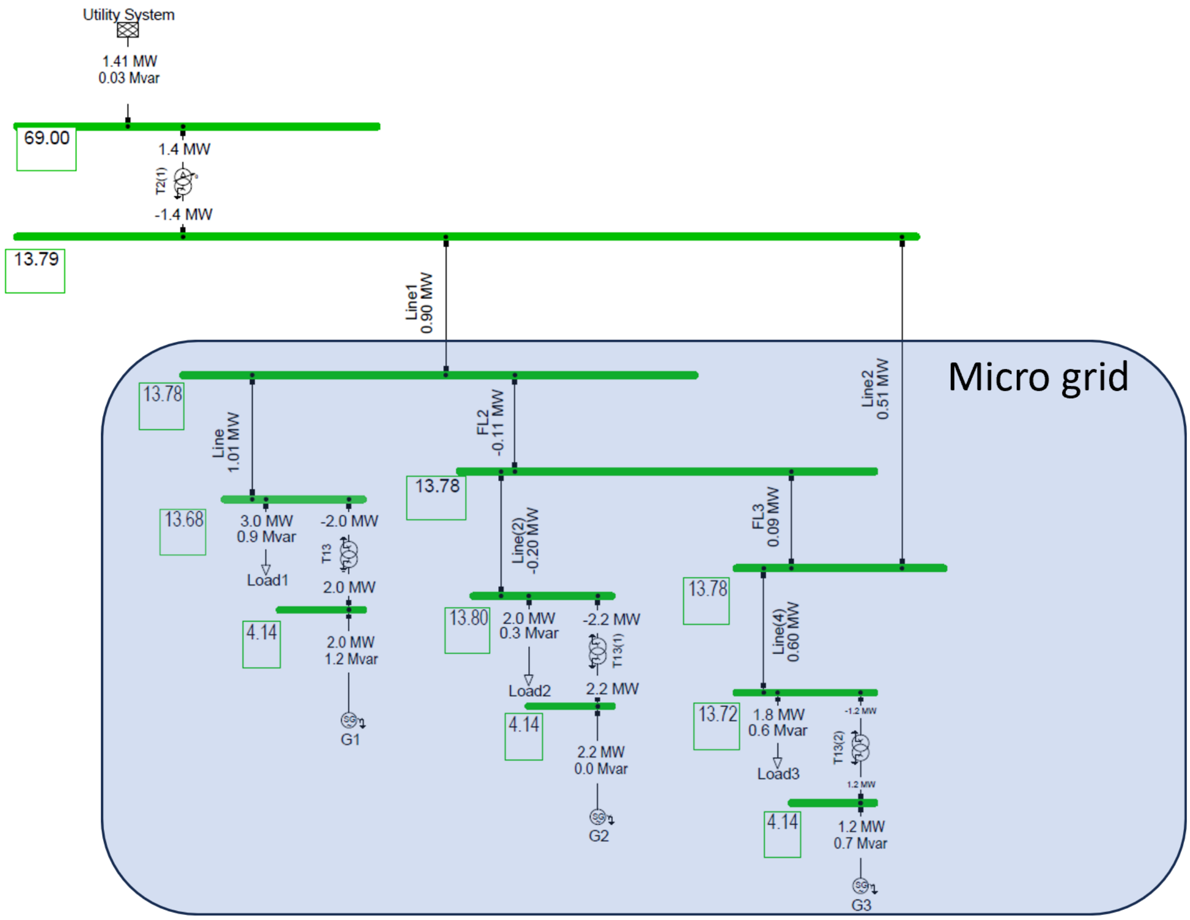

Figure 4.18. Load flow result of Configuration 1 used for Case Study 1.

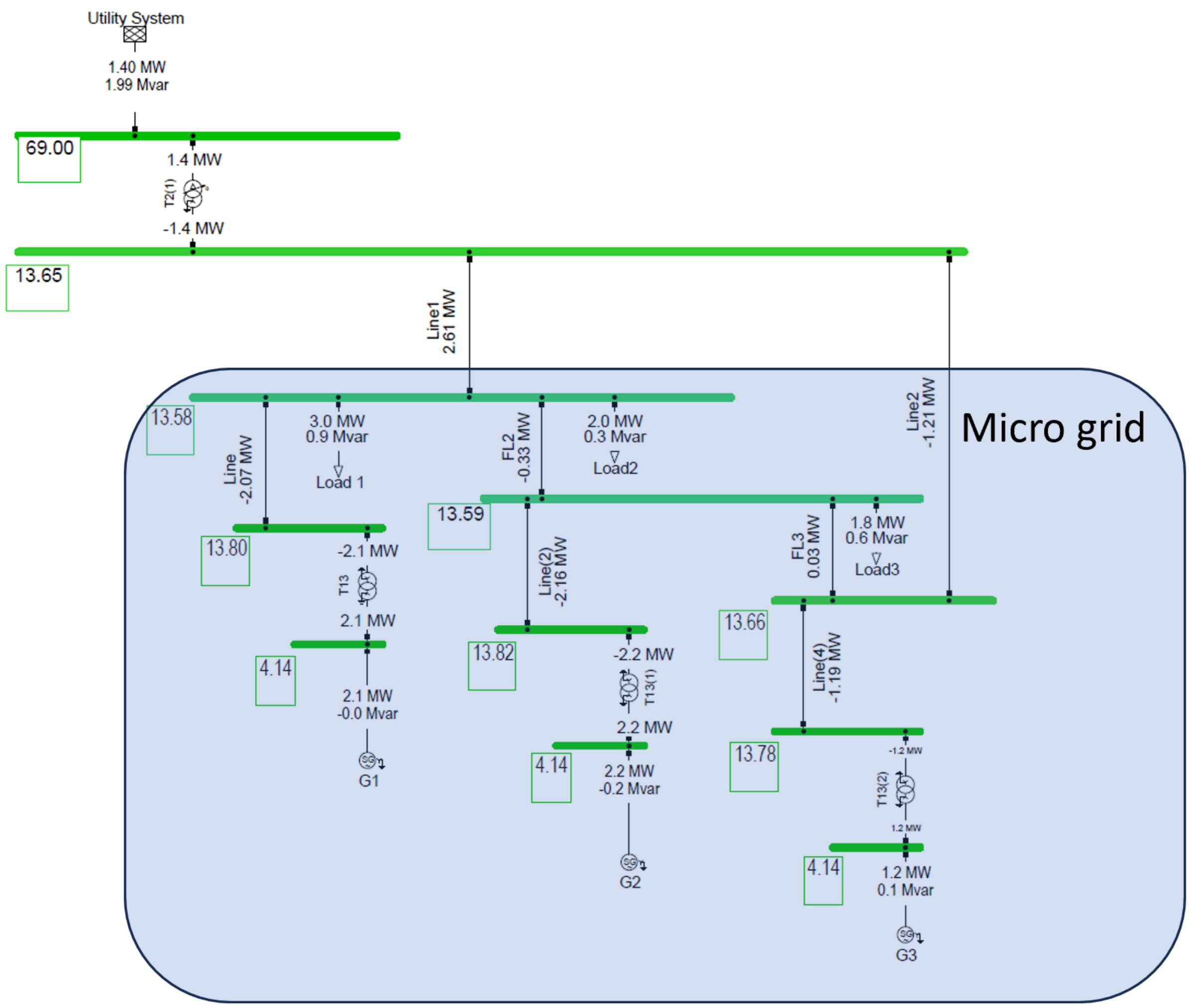

Figure 4.19. Load flow result of the Configuration 2 (Case Study 4).

The major differences between the two cases, with reference to the active power flow on the network branches, is summarised in the Table 4-1. The loading on branches changes significantly just by moving the loads to the different busses within the micro grid. In the modified network configuration, the loads are more concentrated on the first 13.8 kV bus of the micro grid, while in the initial network configuration they are distributed on downstream busses. This concentrated load on first 13.8 kV bus, attracts more active power to flow on the first interconnection line (Line1) from the utility system, while second interconnection line (Line2) is used to export active power from micro grid to ensure that the sum of active power on two lines remains at the desired level of 1.4 MW. Since IFC mode ensures the sum on the interconnection lines remains constant, it allows this flexibility of active power exchange for achieving most optimum power flow within the network. The network is so designed that the impedances of the lines or branches are not the same. The impedance of the lines labelled as FL2 and FL3 in Figure 4.19 is taken as 4.44 ohms, while impedance of Line1 and Line2 is 0.33 ohms. Therefore, to serve an overall concentrated load of 5 MW at the first 13.8 kV bus, 2.6 MW is allowed to be imported from the utility system from Line1, while all the generation from G3 (1.2 MW) is exported to utility system to balance the additional active power import. The generation remains equally distributed in both cases.

Table 4-1. Active power flow comparison.

Network Component	Identifier	Configuration 1	Configuration 2	% Change
Interconnection 1 to utility system	Line1	0.90	2.61	290.00
Interconnection 2 to utility system	Line2	0.51	-1.21	-237.25
13.8 kV line on G1 feeder	Line	1.01	-2.07	-204.95
13.8 kV Line1 on G2 feeder	FL2	-0.11	-0.33	300.00
13.8 kV Line2 on G2 feeder	Line (2)	-0.20	-2.16	1080.00
13.8 kV Line1 on G3 feeder	FL3	0.09	0.03	33.33
13.8 kV line2 on G3 feeder	Line (4)	0.60	-1.19	-198.33

As shown in the Figure 4.20, all the load variations are compensated by the local DDGUs similarly to the results shown in section 4.1. DDGUs within the micro grid are able to keep the sum of active power flow from the main grid at a constant value. The power flow on the two interconnection lines is varied, but the sum of flow from the main grid remains constant. This phenomenon is an important aspect of IFC mode of active power-sharing as it allows having varying values of active power import or export on individual interconnection lines (Line1 or Line2), as required by the load while maintaining the sum of the overall active power import or export at a constant level. The individual flow on the interconnection lines can be positive or negative. Main grid (utility system) maintain the frequency at a constant level and therefore the P–f droop portion of the governor controller remains ineffective for all the variations of the load.

It is evident from the results that for a reduction of 0.6 MW (Load1) at t = 1.2 s, all the DDGUs reduce their real power output in proportion to their capacities. Similarly, when the same amount of load (0.6 MW) is increased at a different location (Load 3) within the micro grid, at t = 6 s, all DDGUs return to their initial values of real power output, as is the case for Configuration 1. This adjustment of active power dispatch took place while maintaining the sum of real power flows over the interconnection lines at a constant value.

It is to be noted that similar load variations in Configuration 1 and 2 result in the similar active power contributions from the DDGUs. The similarity of active power contributions from DDGUs in two network configurations cases is evident in Figure 4.3 and Figure 4.20. The similar curves demonstrate that the changes in network configurations don't affect the performance of the IFC mode.

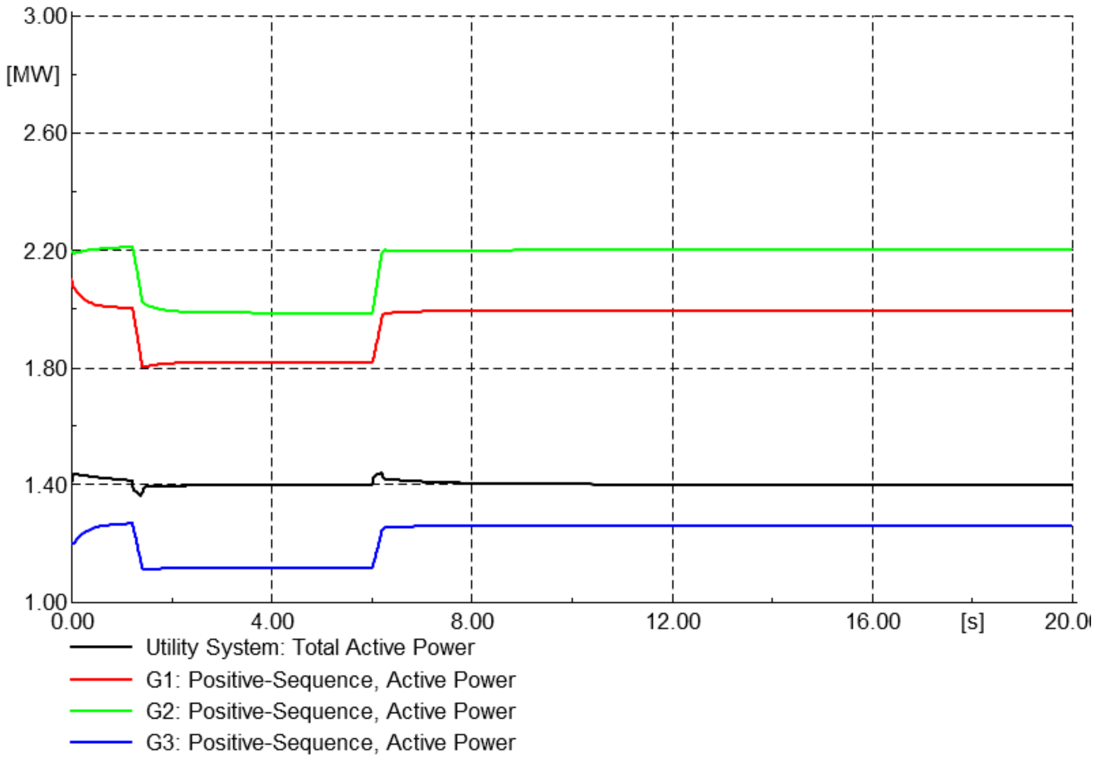

Figure 4.20. Active Power of G1, G2, G3 and utility system.

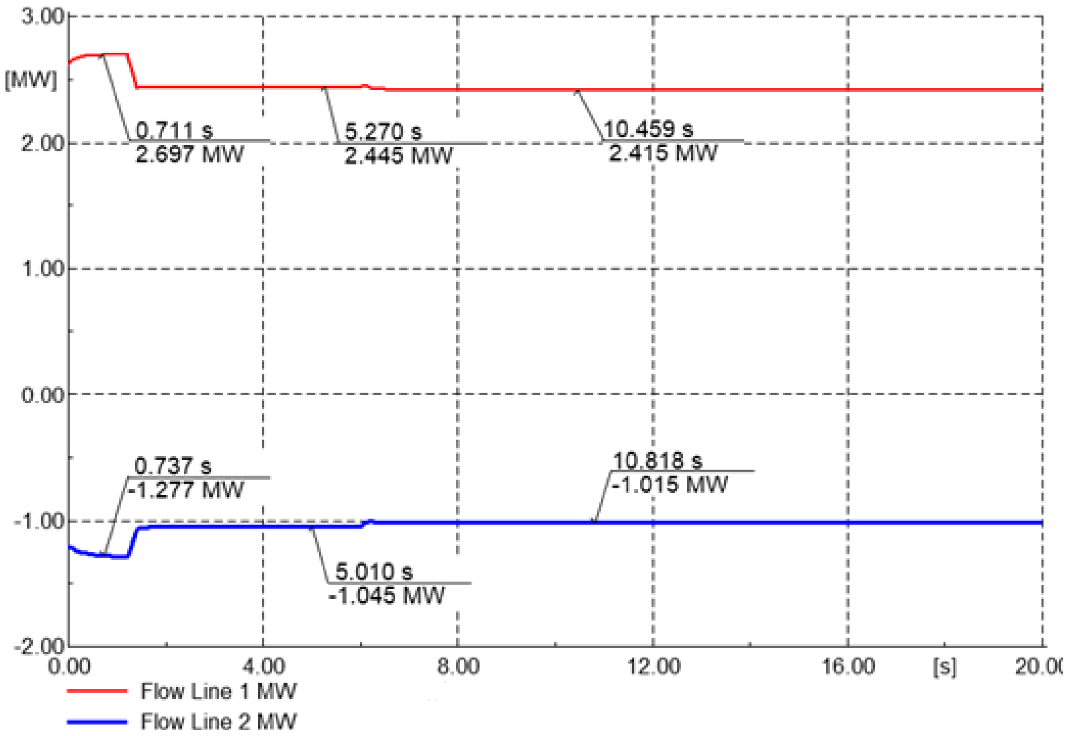

Figure 4.21. Active Power Flow on Line1 and Line2.

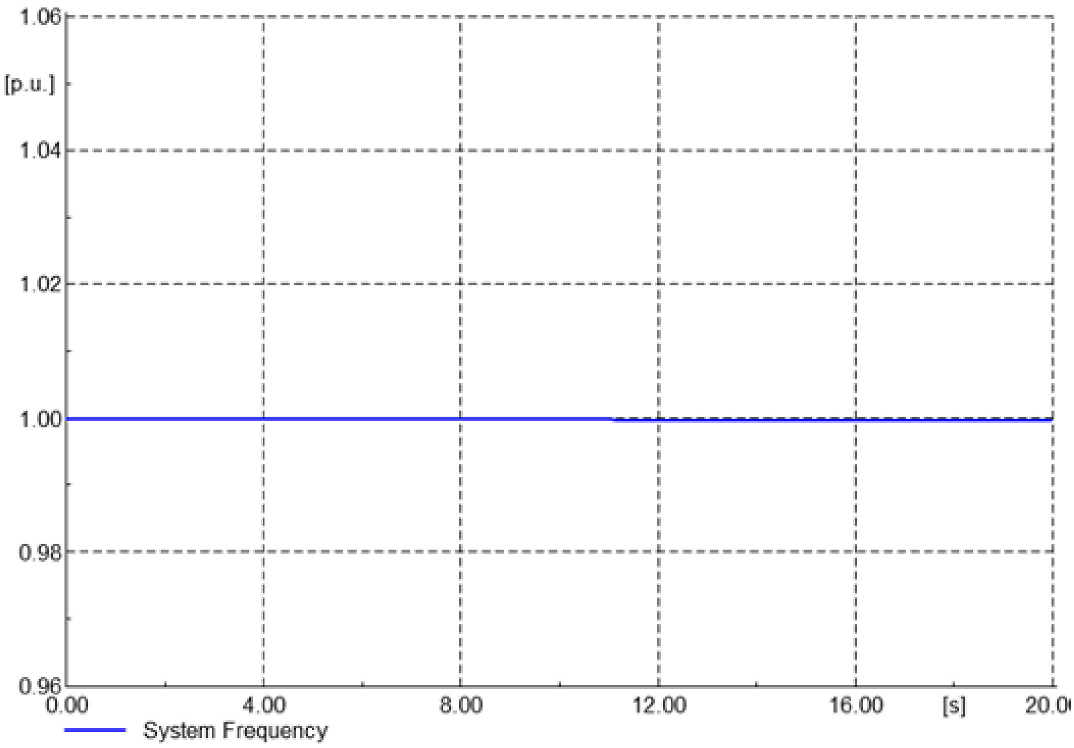

Figure 4.22. Frequency of the Micro Grid.

The final values of the real power flow over the two interconnection lines are different from their initial values, while the DDGUs return to their initial values of real power generation. This change in flow is attributed to the change in load distribution within the micro grid. After two load variation events, the overall load or demand of the micro grid returns to the initial value but since these variations are simulated at different locations, therefore causing the real power flow over the interconnection lines to take different final values. Using IFC mode of operation makes DDGUs, within a micro grid, insensitive to the location of variations, as they all contribute to compensate for any load/generation variations anywhere within the micro grid.

In case DDGUs are operated in FFC mode, instead of the proposed IFC mode, for the modified network configuration and for the same load variations, then the contributions from the DDGUs are shown in figures below.

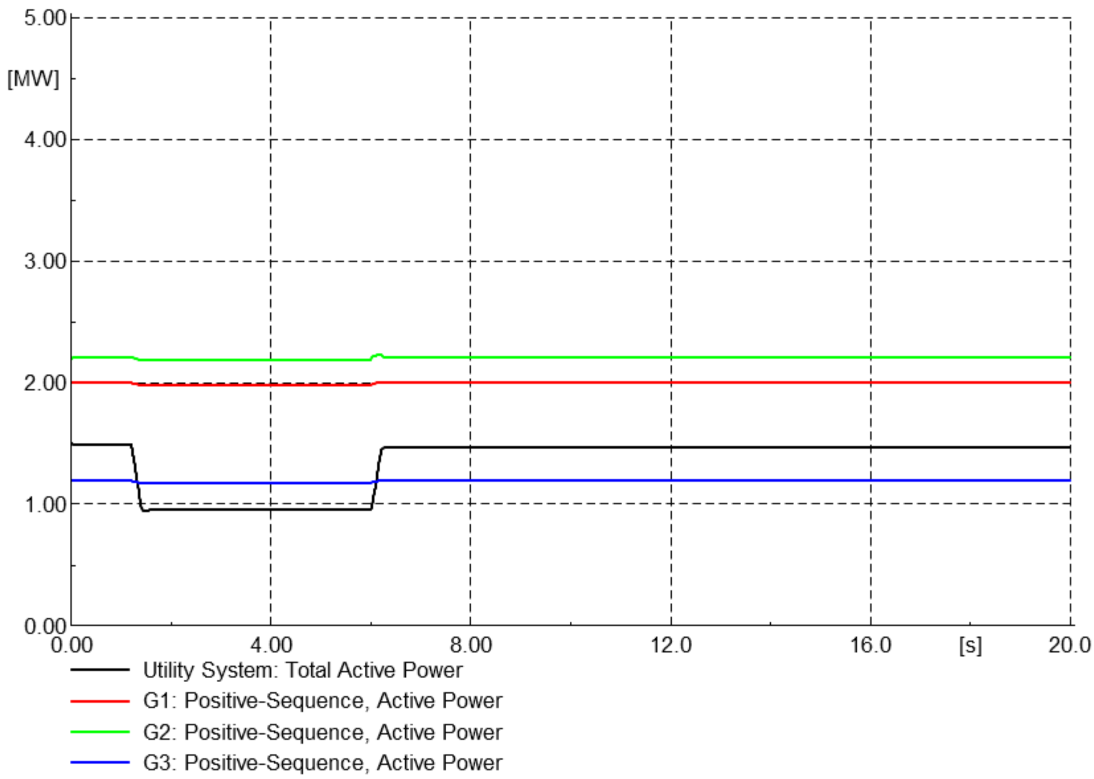

Figure 4.23. Active Power of G1, G2, G3 and utility system.

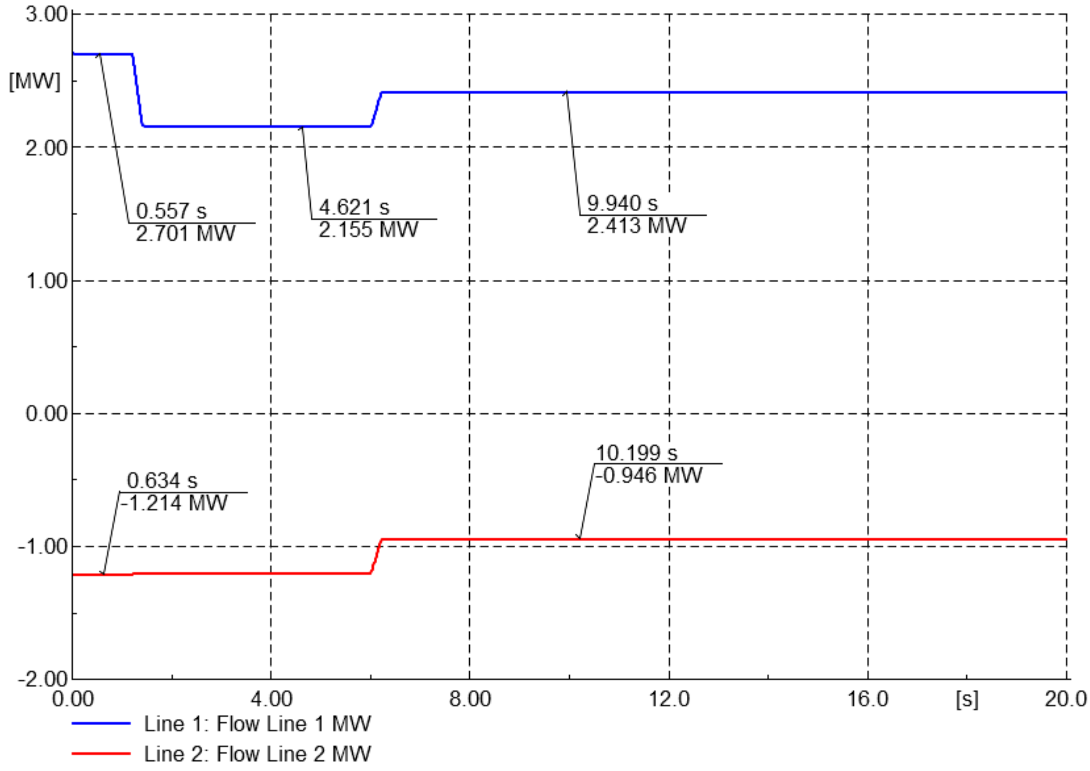

Figure 4.24. Active Power Flow on Line1 and Line2.

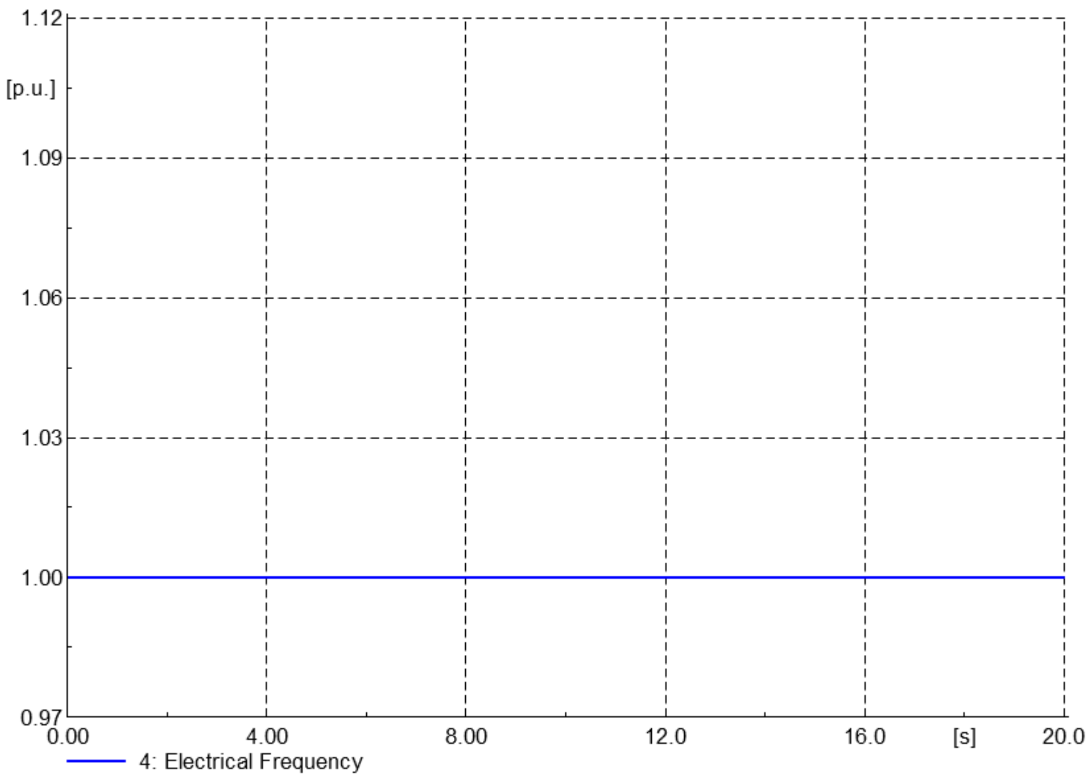

Figure 4.25. Frequency of the Micro Grid.

It is evident from the results that none of the DDGUs contribute during the load variations. All the required variation in active power, to compensate for the load variations, is provided by the utility system (or main grid). This is because of the modified network configuration; all the loads are moved to busses – which are not monitored by the DDGUs in FFC mode. In FFC mode, DDGUs only monitor flows on their feeder. The monitored points for each of the DDGU in FFC are highlighted in the following figure.

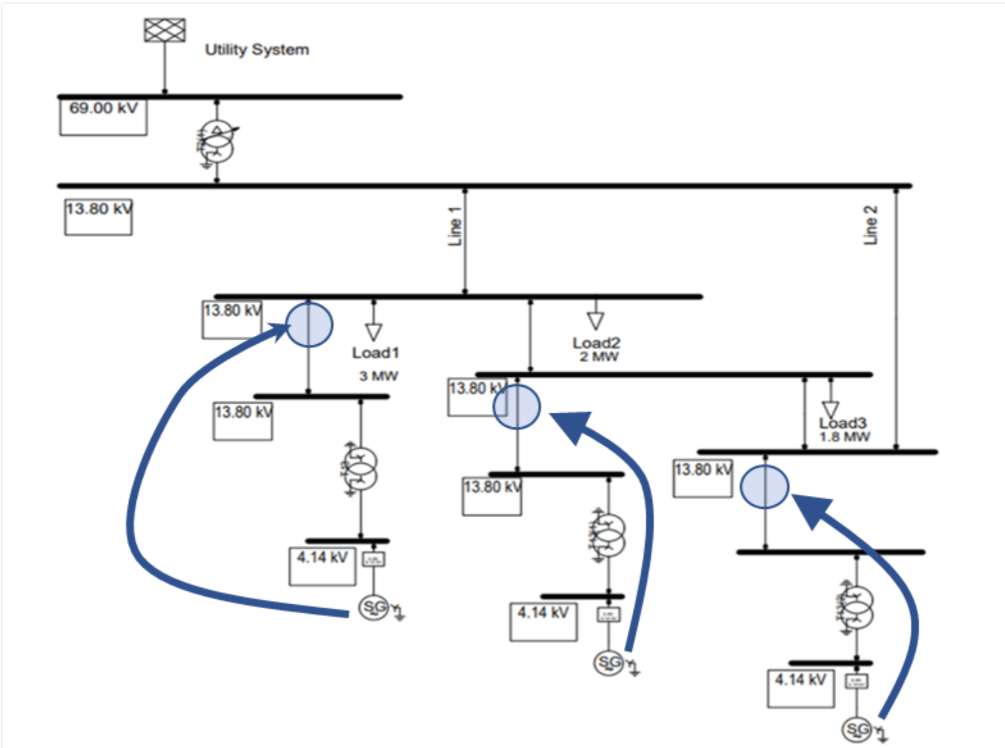

Figure 4.26. Active power measuring points for DDGUs in FFC mode.

The conclusion of Case Study 4 is that IFC mode is tested to prove its capability to stably operate at micro grid level, utilizing the overall capacity withing DDGUs in response to the any load variations within the micro grid.

The results of Study Case 4 demonstrated that IFC mode satisfies following specific research objectives:

a. Ensuring operation as a constant load or generation for the whole micro grid.

b. Applicability to micro grids with one or multiple grid interconnections.

c. Demonstrated the capability to control the active power flow on all or some of the identified (participating) interconnection lines from the main grid.

d. Adaptability to changes in network configurations.

4.5 Case Study 5: Connection With Two Utility Systems

In this case study, these events are simulated:

1. At t = 6 s, Load1 (close to G1) is ramped down 20% in 0.2 s.
2. At t = 12 s, G3 is tripped.
3. At t = 15 s, Load3 (close to G3) is ramped up by 33% in 0.2 s.

The network configuration is been further modified from Configuration 2, by adding another interconnection line (Line3) with another utility system (Utility System #2), as shown in the Figure 4.27 below. This network configuration is designed to model a micro grid with multiple interconnections with several grid systems. IFC mode of operation is used in a manner that it works to maintain the sum of the active power flow from Utility System #1 over two interconnection lines (Line1 and Line2), while allowing a natural flow of active power on the other interconnection line (Line3 from Utility System #2). Another load of 1.2 MW is added at the bus connected to the Utility System #2. Modifications to test network configuration are highlighted in the Figure 4.27. This network configuration is referred as Configuration 3 in the discussion.

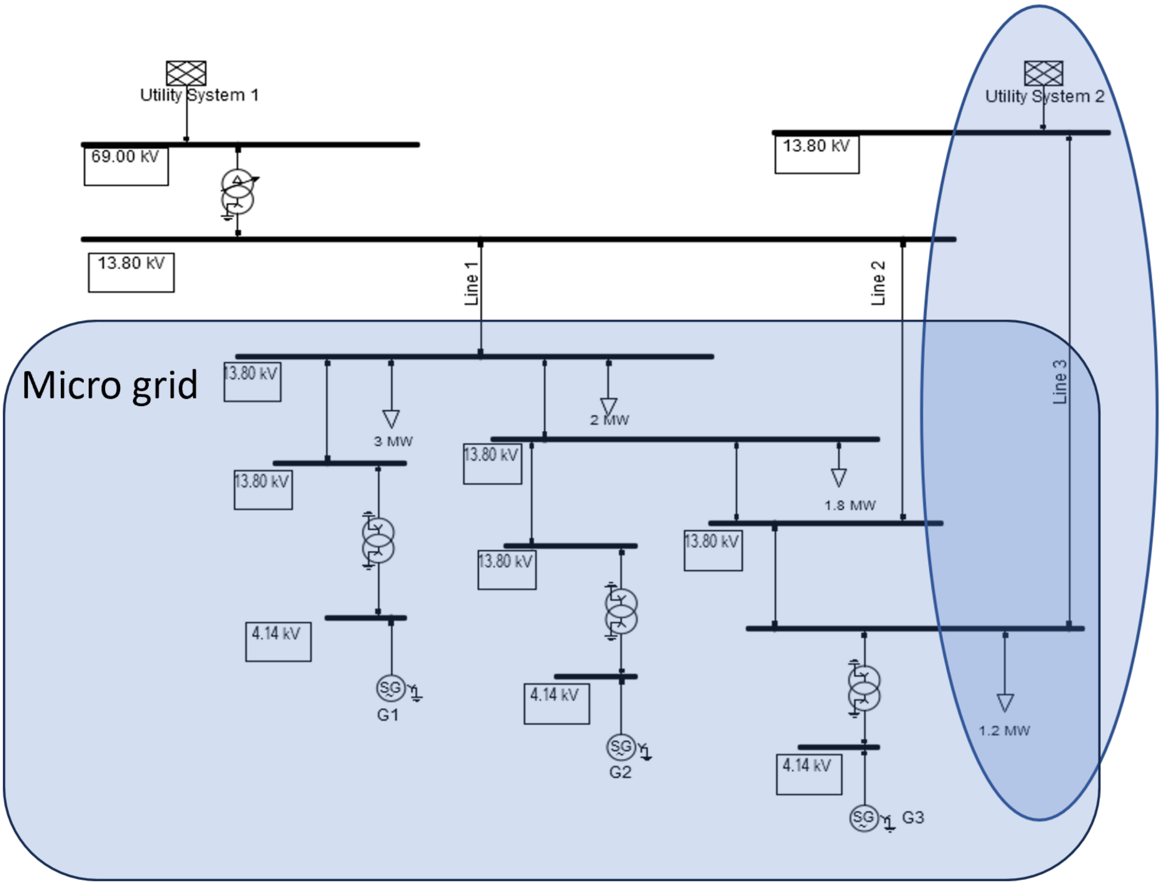

Figure 4.27. Network configuration with 3 interconnection lines (Network Configuration 3).

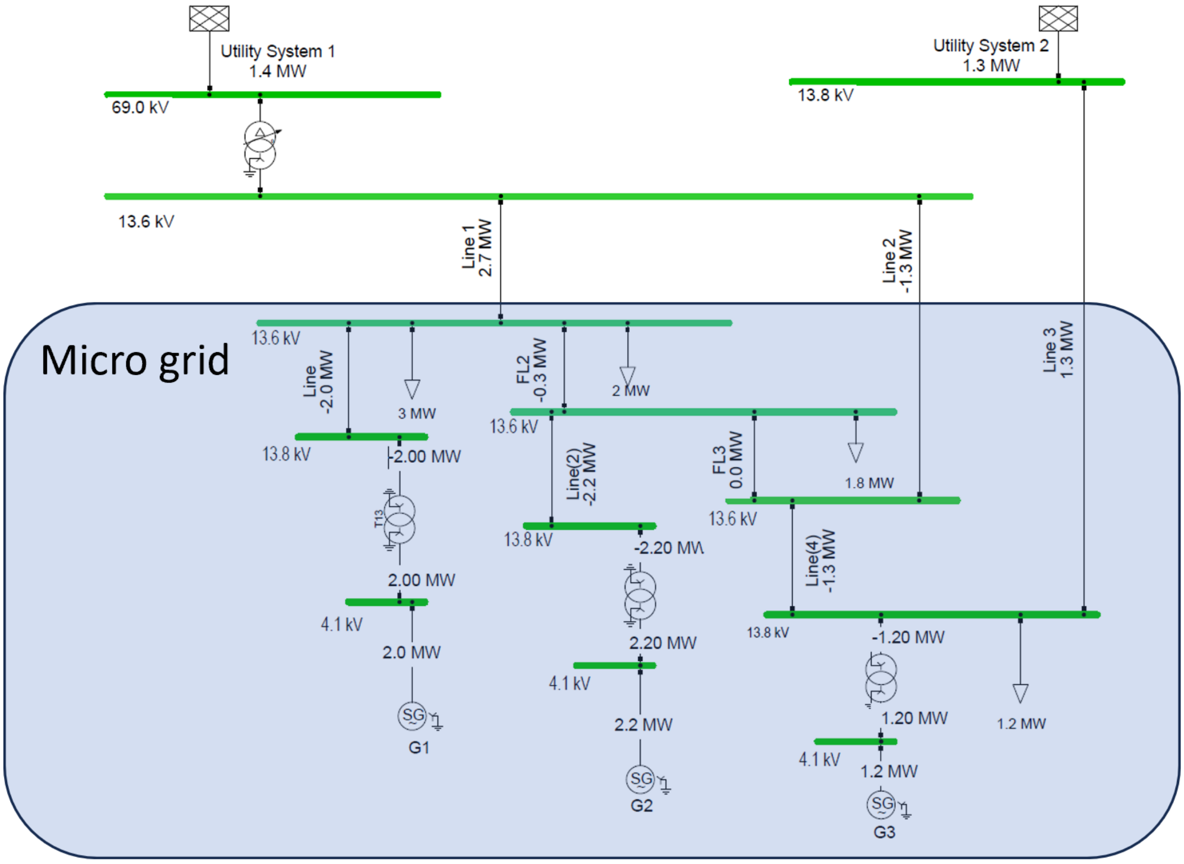

Figure 4.28. Network configuration with 3 interconnection lines (Network Configuration 3, Load flow result).

Configuration 3 is also designed to test the flexibility and performance of the IFC mode under varying network conditions. Following figures provide the results of the simulated events for Configuration 3.

For the first load variation all DDGUs and Utility System2 contribute to the load change, while the sum of flow from the two interconnection lines from Utility System1 remains constant at 1.4 MW as designed. When G3 wis tripped at 12 s, remaining DDGUs (G1 and G2) and Utility System #2 compensate for the loss of generation of G3. Sum of imports from Utility System #1 still remain constant. Finally, when Load 3 is increased at 15 s, the increased demand is also provided by G1, G2 and Utility System #2. The results demonstrated that the IFC mode is successfully able to maintain the sum of active power flow from one utility system even when the micro grid is interconnected with another equally strong grid system.

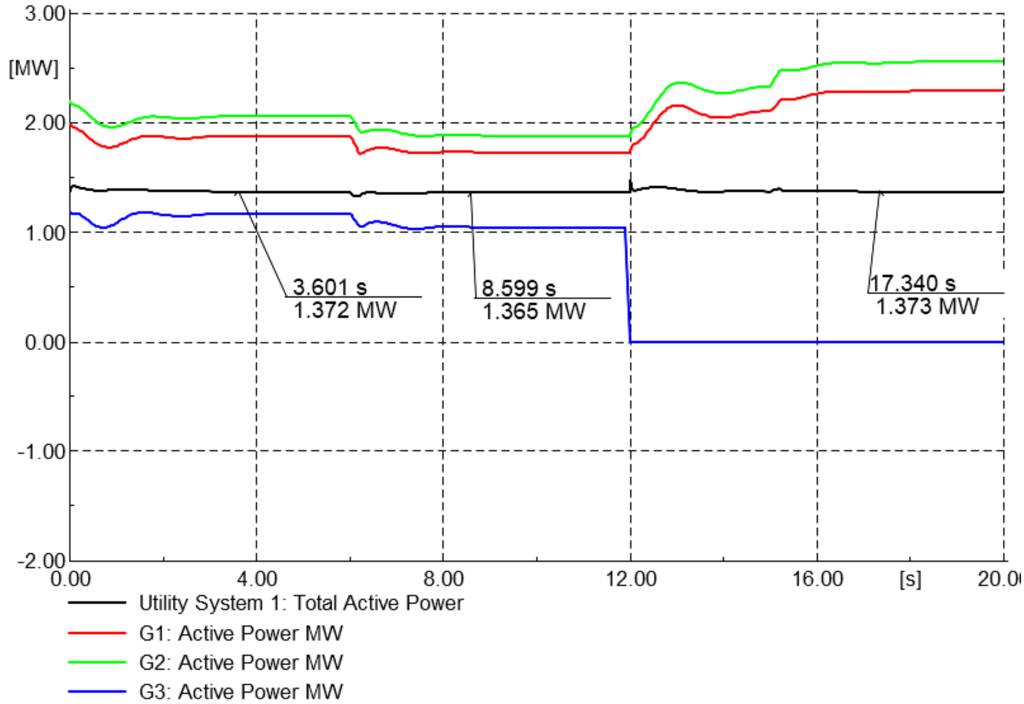

Figure 4.29. Active Power of G1, G2, G3 and Utility System #1.

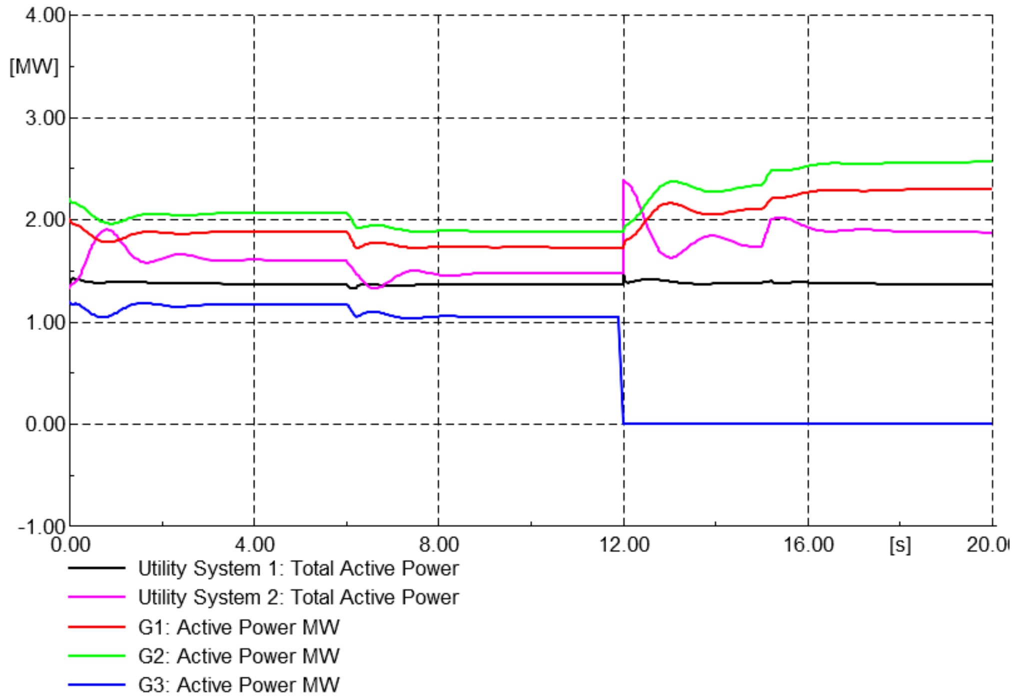

Figure 4.30. Active Power of G1, G2, G3 and Utility System #1 and Utility System #2.

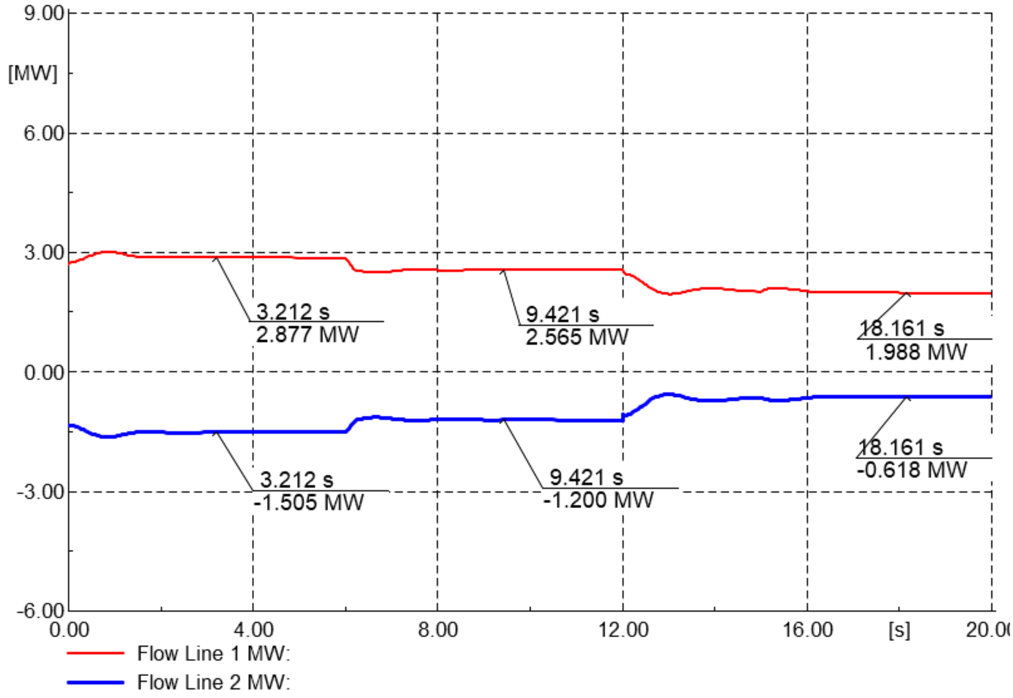

Figure 4.31. Active Power Flow on Line1 and Line2.

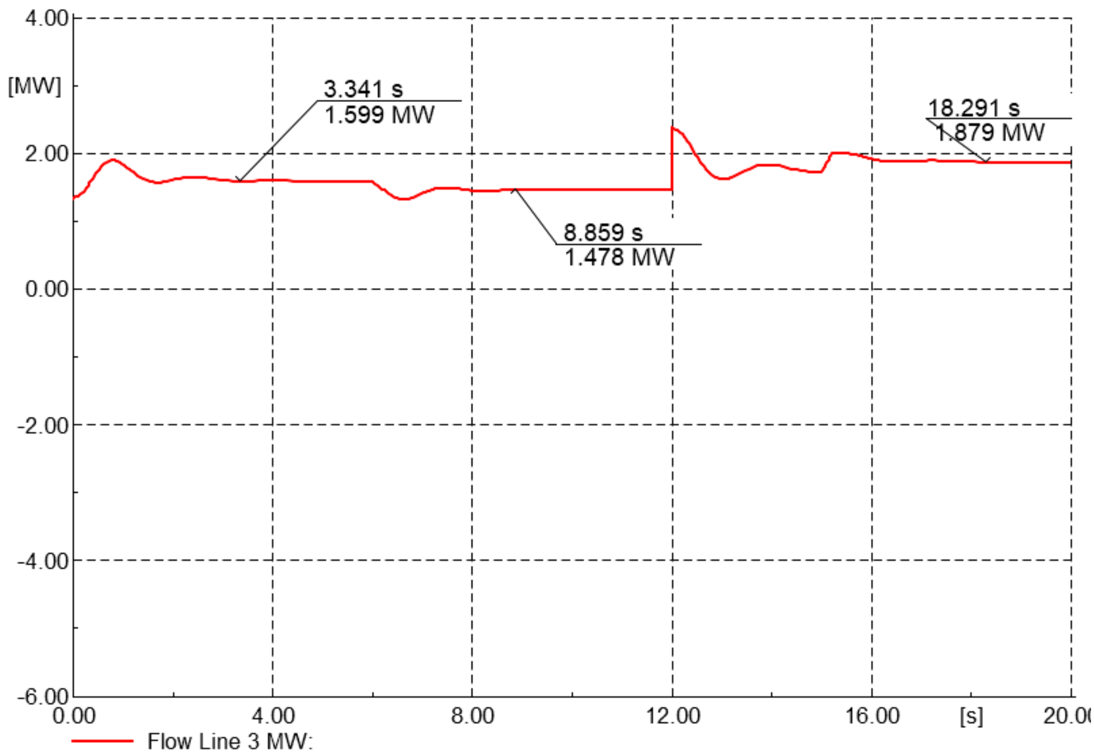

Figure 4.32. Active Power Flow on Line3.

The conclusion of Case Study 5 is that IFC mode is tested to prove its capability to stably operate with multiple grid interconnections with multiple grids. Two interconnections with Utility system1 were participating interconnections, that means they are participating in the flow control, while the third interconnection had no flow control.

The results of Study Case 5 demonstrated that IFC mode satisfies following specific research objectives:

a. Ensuring operation as a constant load or generation for the whole micro grid.

b. Applicability to micro grids with one or multiple grid interconnections.

c. Demonstrated the capability to control the active power flow on all or some of the identified (participating) interconnection lines from the main grid.

d. Adaptability to changes in network configurations.

5. Design Enhancements

Following two enhancements are made in the basic design of the controller:

1) Balancing of active power flow and frequency response
2) Interconnection Reactive Power Flow controller (IRFC)

5.1 Balancing of active power flow and frequency response

This modification in the design allows the controller to maintain constant active power flow from or towards the micro grid even when the frequency of the main grid varies from the normal.

IFC initial equation [3.2] (given below for easy reference) is been modified to [5.1].

$$(F\text{meas} - F_{\text{ref}})/K_{\text{u}} + (\text{FL}_{\text{ref}} - \text{FL}^0) = \text{to PI controller} \qquad [3.2]$$

$$(Kpf + Kif/s)\left((F\text{meas} - F\text{ref})/K\text{u}\right) + (KpFL + KiFL/s)(\text{FL}_{\text{ref}} - \text{FL}^0) = \text{pt} \qquad [5.1]$$

Where:

Fref is the reference frequency

Fmeas is the measured frequency

pt is turbine power or active power

Kpf is the proportional gain for frequency response

Kif is the integral gain for frequency response

KpFL is the proportional gain for flow control

KiFL is the integral gain for flow control

To demonstrate the balancing of frequency and flow response, equation 5.1 can be simplified as:

$$(\text{K}_\text{p}\text{f} + \text{Kif}/\text{s})(\text{Fmeas} - \text{Fref})/\ \text{Ku} = -(\text{FL}_{\text{ref}} - \text{FL}^0)(\text{K}_\text{P}\text{FL} + \text{KiFL}/\text{s}) \qquad [5.2]$$

Or:

$$\frac{(K_p f+Kif/s)}{K_u\cdot(K_p FL+KiFL/s)} = \frac{FL^0-FL_{ref}}{Fmeas-Fref} \quad [5.3]$$

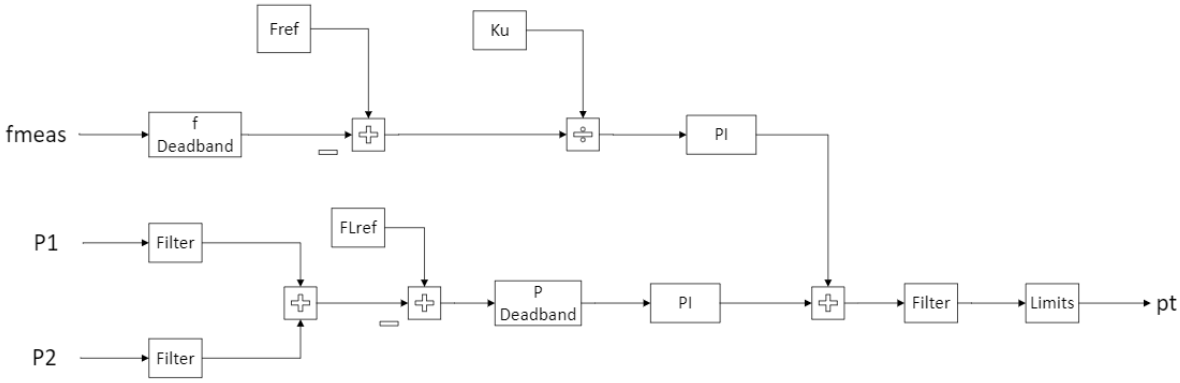

Figure 5.1. Balancing active power flow and frequency response controller.

The control block diagram of the enhanced IFC with frequency response balancing is shown in Figure 5.1. The parameters used in the simulations are given in Table 5-1.

Table 5-1. Used controller parameters.

Parameter	Value	Unit
f deadband	0.0015	pu
Fref	1	pu
Ku	-0.4	
Kpf	-10	
Kif	0	
P deadband	0.0001	pu
KpFL	-100	
KiFL	-50	
FLref	0.0141	pu

Frequency response control in a grid interconnected micro grid is designed to maintain system stability by adjusting the active power output from Distributed Generation Units (DDGUs) when the grid's frequency deviates from its nominal value.

When grid frequency increases: If the frequency of the main grid rises above the set deadband (the allowable range of frequency deviation before corrective action is taken), it indicates an over-supply of power. The frequency response control reduces the active power output from DDGUs to help balance the overall power supply.

Impact on power flow: As the active power output from the DDGUs decreases, the micro grid becomes more dependent on the power imported from the main grid via the interconnection lines. The active power flow control system monitors this increase in power flow from the main grid.

Flow deadband: If the power imported from the main grid exceeds the predefined flow deadband (the allowable deviation in power flow from reference), the flow controller reacts. It will increase the active power output from the DDGUs again to reduce the import from the main grid. This mechanism keeps the power flow within acceptable limits, maintaining the ideal operation of the micro grid, ensuring that micro grid always act either as a constant load or generator for the main grid.

When grid frequency decreases: A drop in the main grid frequency below the deadband signifies a power deficit in the system. The frequency response control will tend to increase the active power output from the DDGUs to counteract the shortage and stabilize the grid.

Impact on power flow: As the DDGUs produce more active power, the micro grid needs less power from the main grid, resulting in a reduction in power flow from the interconnection lines.

Flow deadband: If the reduction in power imported from the main grid exceeds the set flow deadband, the flow controller detects this change and decrease the active power output from the DDGUs. This action brings the power flow from the main grid back to within the allowable range, ensuring a balance between local generation and grid import/export.

Frequency Deadband: This is the range within which frequency fluctuations are tolerated without triggering a control response. The recently introduced frequency deadband allows for slight variations in frequency without immediately adjusting the power output of the DDGUs, providing more stability and reducing unnecessary actions.

Flow Deadband: Similarly, the flow deadband defines the acceptable range of deviation in the power flow from the main grid. If the flow of power from the grid deviates beyond this range, the flow control mechanism steps in to adjust the DDGUs' output.

Kpf (Frequency Proportional Gain): This parameter determines how strongly the frequency response control adjusts the active power output from the DDGUs in response to frequency deviations. A higher Kpf means that the DDGUs will respond more aggressively to frequency changes, either increasing or decreasing their power output quickly. Tuning this parameter allows operators to set the desired sensitivity of the micro grid's frequency response.

KpFL (Flow Proportional Gain): This parameter dictates how the flow controller reacts to deviations in the power flow through the interconnection lines. A higher KpFL will cause the system to respond more strongly to changes in power flow, adjusting the DDGUs' power output accordingly. Tuning KpFL helps maintain a stable power exchange with the main grid.

Balancing Action:

As described above, the system works to balance the active power flow in two main scenarios:

When grid frequency increases, the system temporarily reduces DDGU output, leading to more reliance on the main grid. If this causes too much power to flow from the grid (exceeding the flow deadband), the flow controller boosts the DDGUs' output again to limit the grid's contribution.

When grid frequency decreases, the system increases DDGU output to compensate for the shortfall. If this results in too little power flow from the main grid (below the flow deadband), the controller reduces the DDGUs' output to bring the grid flow back within limits.

This delicate balancing of power between the micro grid and the main grid ensures that the interconnection flow remains almost constant, even when subjected to minor frequency fluctuations. By setting the frequency and flow deadbands as well as the proportional gain parameters (Kpf and KpFL), system operators have the flexibility to fine-tune the micro grid's responsiveness and ensure smooth power sharing between local generation and the main grid.

5.2 Simulation Results and Discussions

To test the above mentioned balancing enhanced IFC controller, following simulations were conducted:

1. Case Study 6. In Case study 6, frequency of the main grid is reduced to 59.8 Hz (from 60 Hz nominal). IFC and Enhanced IFC modes are compared for the same frequency variation.
2. Case Study 7. In Case study 7, frequency of the main grid is increased to 60.2 Hz (from 60 Hz nominal). IFC and Enhanced IFC modes are compared for the same frequency variation.
3. Case Study 8. Step wise grid isolation test is conducted in case 8. The performance of simple IFC and Enhanced IFC is compared.

5.2.1 Case Study 6: Reduction in frequency of the main grid

In this case study, the below events are simulated:

1. At t = 5 s, frequency of the main grid is reduced to 59.8 Hz.
2. At t = 20 s, frequency of the main grid brought back to the nominal 60 Hz value.

In this case study, the described test simulates frequency disturbances in the main grid and examines how the enhanced IFC controller responds to these events over time.

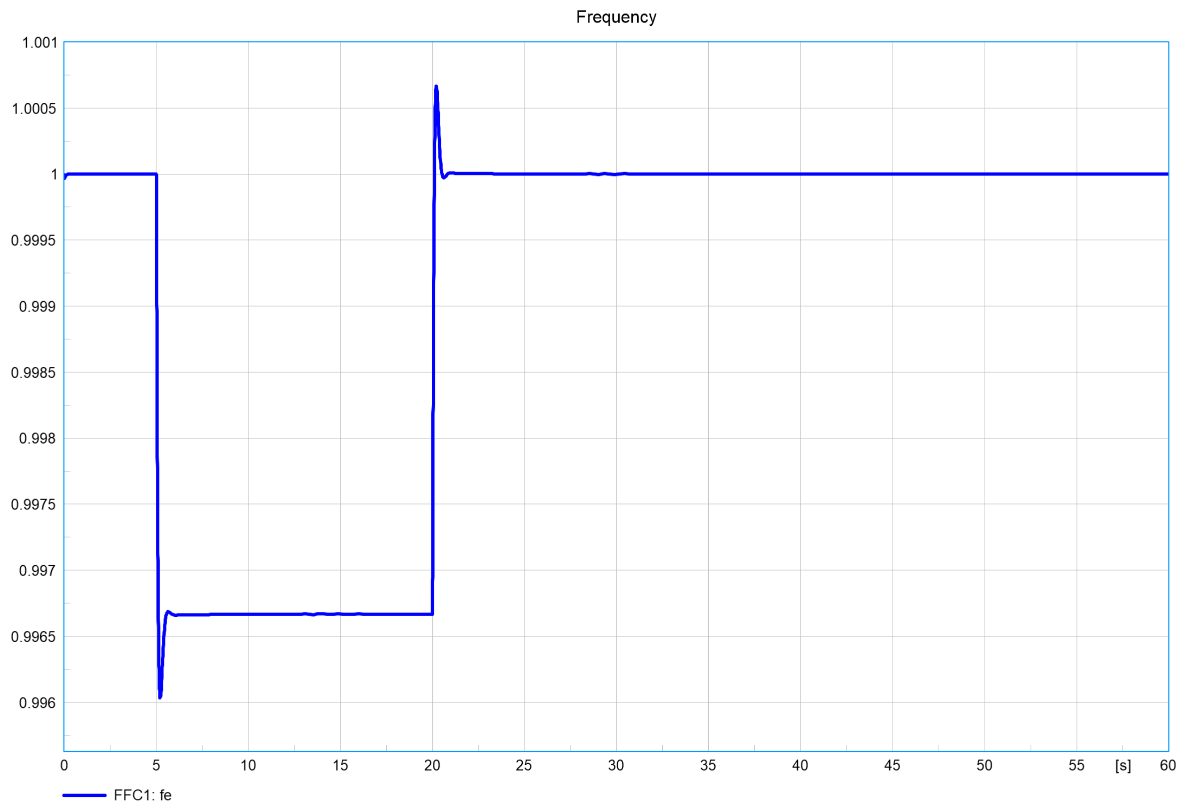

Figure 5.2. Frequency Variation.

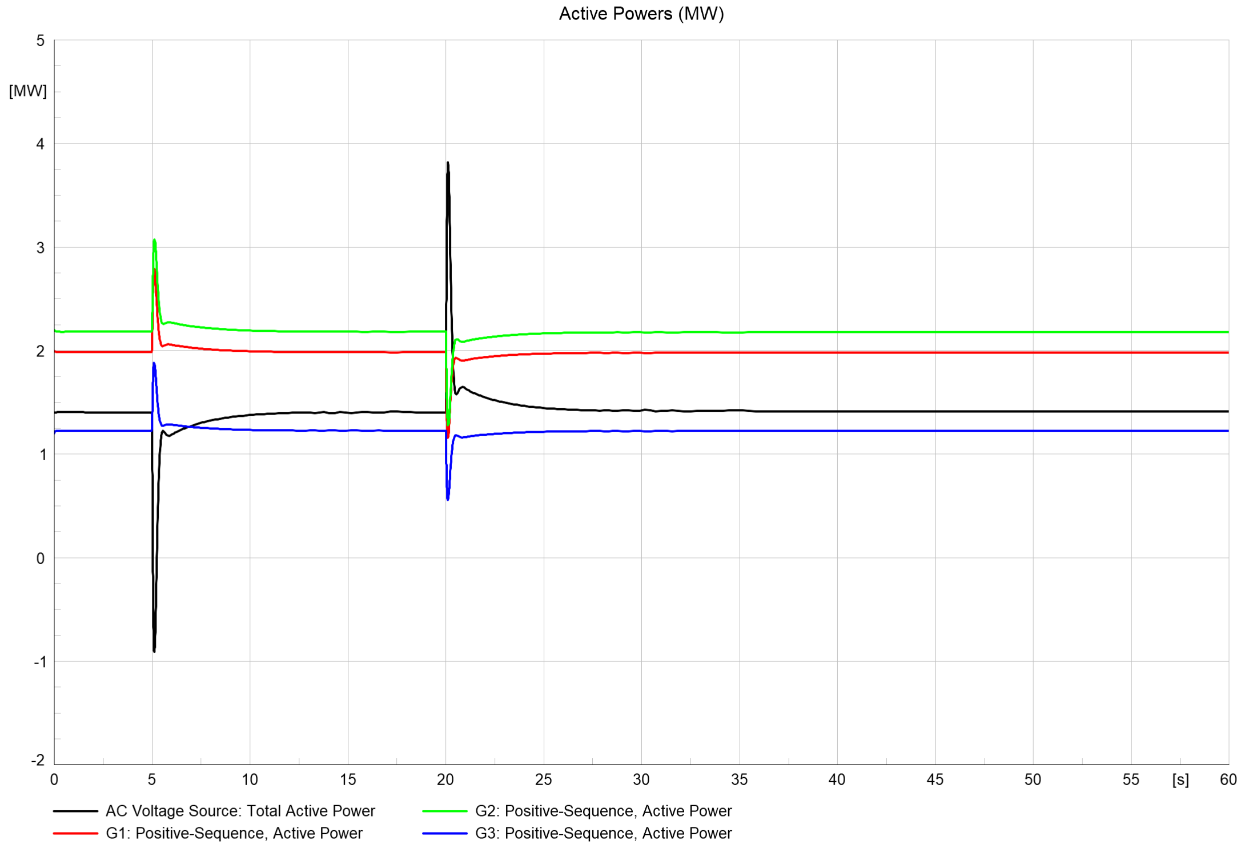

Figure 5.3. Active power from DDGUs and from the main grid.

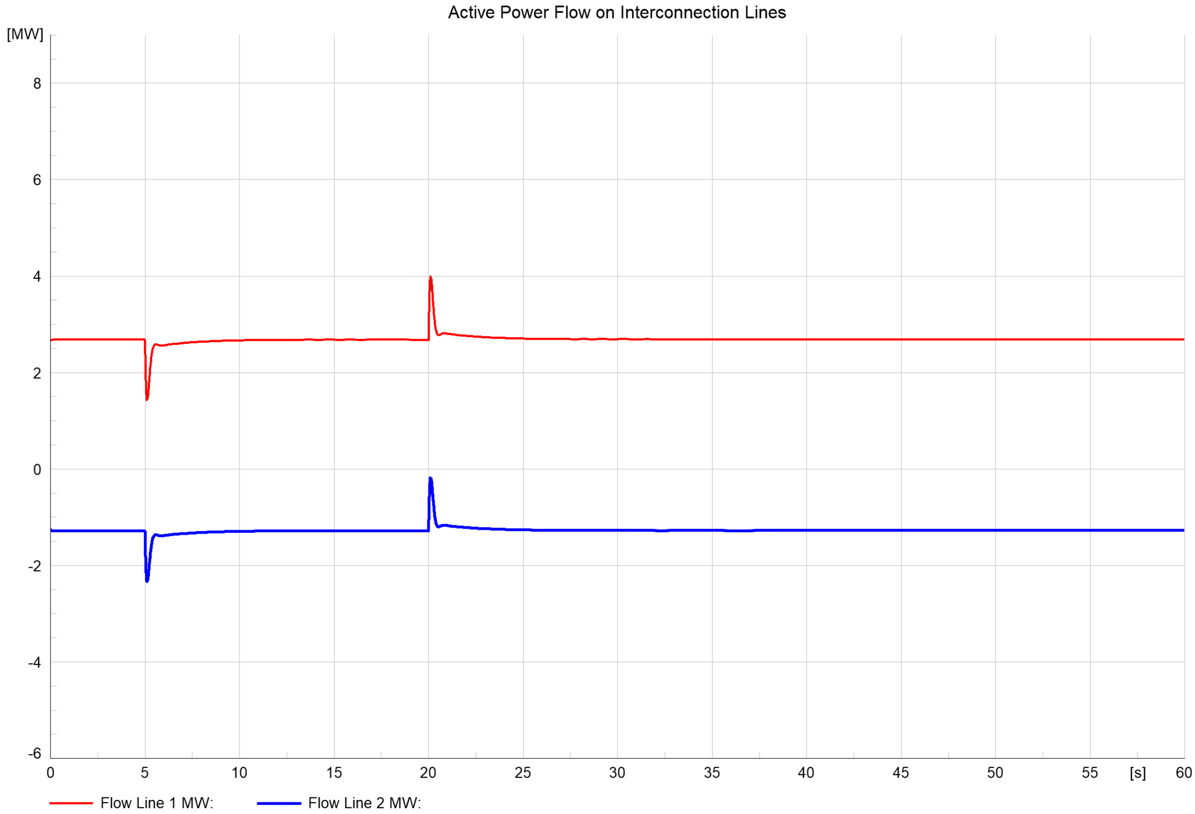

Figure 5.4. Active power flow over the interconnection lines.

Simulation Setup: At 5 seconds into the simulation, the frequency of the main grid is reduced from its nominal value of 60 Hz to 59.8 Hz. This represents a situation where the main grid experiences a power deficit or other disturbance, causing a frequency drop below the expected level. Figure 5.2 shows the change in the frequency of the main grid.

Micro grid Response:

Frequency Response Control Activation: The reduction in grid frequency triggers the micro grid's frequency response control within enhanced IFC controller. Since the main grid frequency has fallen below the frequency deadband, the enhanced IFC controller reacts by initially increasing the active power output from the Distributed Generation Units (DDGUs), as shown in Figure 5.3.

Active Power Flow Control: As the DDGUs increase their power output, the micro grid becomes less reliant on power from the main grid. This results in a reduction in the power flow through the interconnection lines between the micro grid and the main grid.

Flow Deadband Monitoring: Once the decrease in power flow from the grid exceeds the flow deadband, the flow control mechanism within enhanced IFC controller attempts to decrease the DDGUs' output to prevent over-adjustment and bring the active power flow closer to the desired reference range. Figure 5.4 shows the active power flows on both monitored interconnection lines.

Event 2: Frequency Restoration (at t = 20 s)

Simulation Setup: At 20 seconds into the simulation, the main grid's frequency is restored to the nominal value of 60 Hz. This simulates the recovery of grid stability, where the frequency is returned to normal operating conditions.

Micro grid Response:

Frequency Response Control Deactivation: Once the grid frequency is brought back to 60 Hz, the frequency response controller within the enhanced IFC controller no longer detects an abnormal condition. As a result, it tends to reduce the active power output from the DDGUs.

Active Power Flow Control: As the DDGUs' output decreases, the micro grid needs more power from the main grid to meet its demand. This leads to an increase in the active power flow through the interconnection lines.

Flow Deadband Monitoring: If the power flow from the grid increases beyond the flow deadband, the flow control will adjust by slightly increasing the DDGUs' output to reduce grid dependency and ensure that the power flow remains within allowable limits.

Objectives of the Test

Evaluate Frequency Response: The test is designed to assess how effectively the enhanced IFC’s frequency response control reacts to deviations in the main grid’s frequency. The system should respond promptly to stabilize both the micro grid and the grid's frequency.

Test Power Flow Control: The test also examines how well the active power flow control manages the power exchanged between the micro grid and the main grid, ensuring that the flow remains within predefined limits (deadbands) to ensure ideal operation of the micro grid.

Verify Control System Coordination: The balancing actions of both the frequency response control and the active power flow control are validated in this scenario. These systems must work in tandem to maintain grid stability, adjusting the power output of the DDGUs based on real-time grid conditions.

Power Flow Stability: Monitoring the power flow through the interconnection lines ensures that the flow remains within the allowable deadband, indicating that the micro grid's controllers are successfully balancing local generation with grid imports.

This test demonstrates the capability of the enhanced IFC controller to dynamically adjust its power output in response to grid disturbances, ensuring stability, and maintaining reliable operation through a combination of frequency and active power flow control.

If the same operating conditions are tested for simple IFC controller, then we get following results:

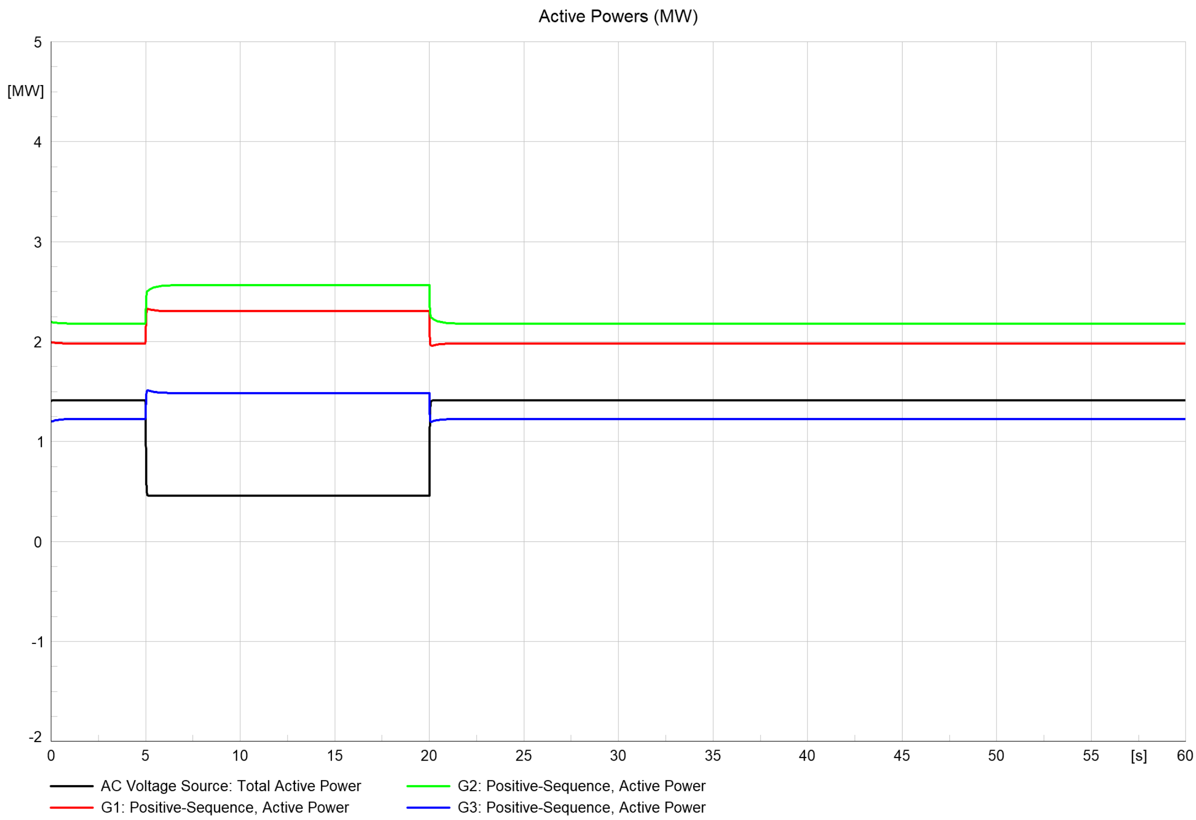

Figure 5.5. Active power from main grid and DDGUs using simple IFC controller.

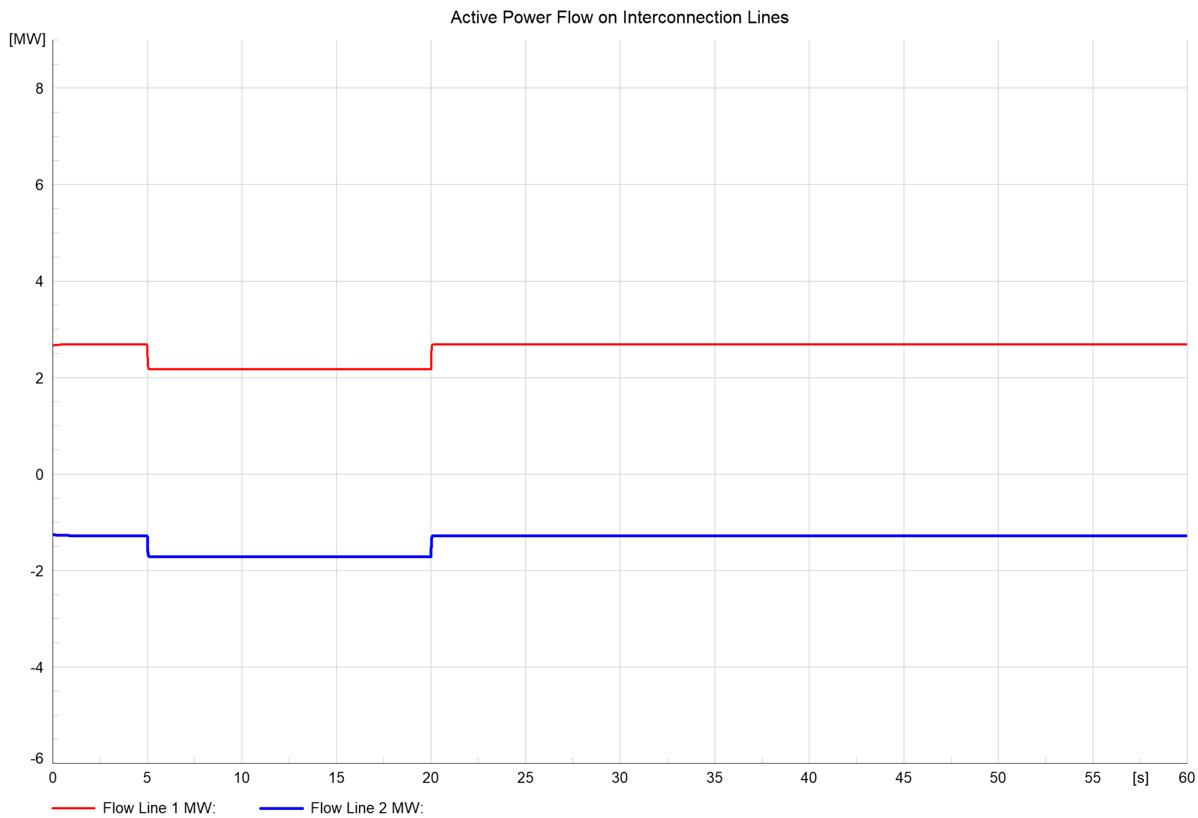

Figure 5.6. Active power flow over the interconnection lines using simple IFC controller.

It is evident from Figure 5.5 and Figure 5.6, that simple IFC controller was not able to maintain the active power flow over the interconnection lines. Frequency controller was able to dominate during the frequency event while flow controller was not able to maintain the sum of the active power flow over the interconnection lines while the frequency was depressed.

Performance of the Simple IFC Controller

Inability to maintain Active Power Flow: The simple Interconnection Flow Controller (IFC) failed to regulate the sum of the active power flow over the identified interconnection lines between the micro grid and the main grid effectively during the frequency disturbance. This issue arises because simple IFC was not sophisticated enough to handle the dynamic nature of the power flow, especially during events where there is a change in the frequency of the main grid.

Impact on Interconnection Lines: The active power flow over the interconnection lines fluctuated outside the expected or desired range, meaning that the micro grid's control system did not effectively balance the power exchange with the main grid.

Frequency Control Dominance During the Event: During the frequency event (when the grid frequency was depressed), the frequency controller took priority in managing the micro grid’s response. The frequency controller is designed to react to deviations from the nominal grid frequency (such as when the frequency drops below 60 Hz), increasing or decreasing the active power output of the Distributed Generation Units (DDGUs) to stabilize the frequency.

Flow Controller Inability to React: The flow controller could not maintain proper control over the active power flow through the interconnection lines. This indicates that the frequency controller’s actions, while effective in addressing the frequency issue, overwhelmed the flow controller, preventing it from regulating the power exchange.

Frequency Depression and Power Flow Imbalance: When the grid frequency is depressed (drops below nominal levels), the micro grid's frequency response control increases the active power output from its DDGUs to compensate for the grid's power shortfall. While this action may help in stabilizing the frequency, it can lead to unintended consequences in terms of power flow. The increased output from the micro grid reduces the power drawn from the main grid, causing the power flow across the interconnection lines to decrease.

Flow Controller's Role: The flow controller in enhanced IFC controller was able counterbalance this by adjusting the DDGUs' output to bring the power flow within allowable limits (as defined by the flow deadband). However, in this case, the flow controller was ineffective during the frequency event. It could not adjust the active power output to keep the power flow through the interconnection lines within acceptable levels, resulting in non-ideal behaviour of the micro grid as it could not act either as a constant load or generator for the main grid.

Controller Redesign: The observed inability of the IFC to maintain active power flow while the frequency was depressed suggested the need for a more advanced and smarter system design. Based on this, enhanced IFC was designed and provided desired results.

5.2.2 Case Study 7: Increase in frequency of the main grid

In this case study, the below events are simulated:

1. At t = 5 s, frequency of the main grid is increased to 60.2 Hz.
2. At t = 20 s, frequency of the main grid brought back to the nominal 60 Hz value.

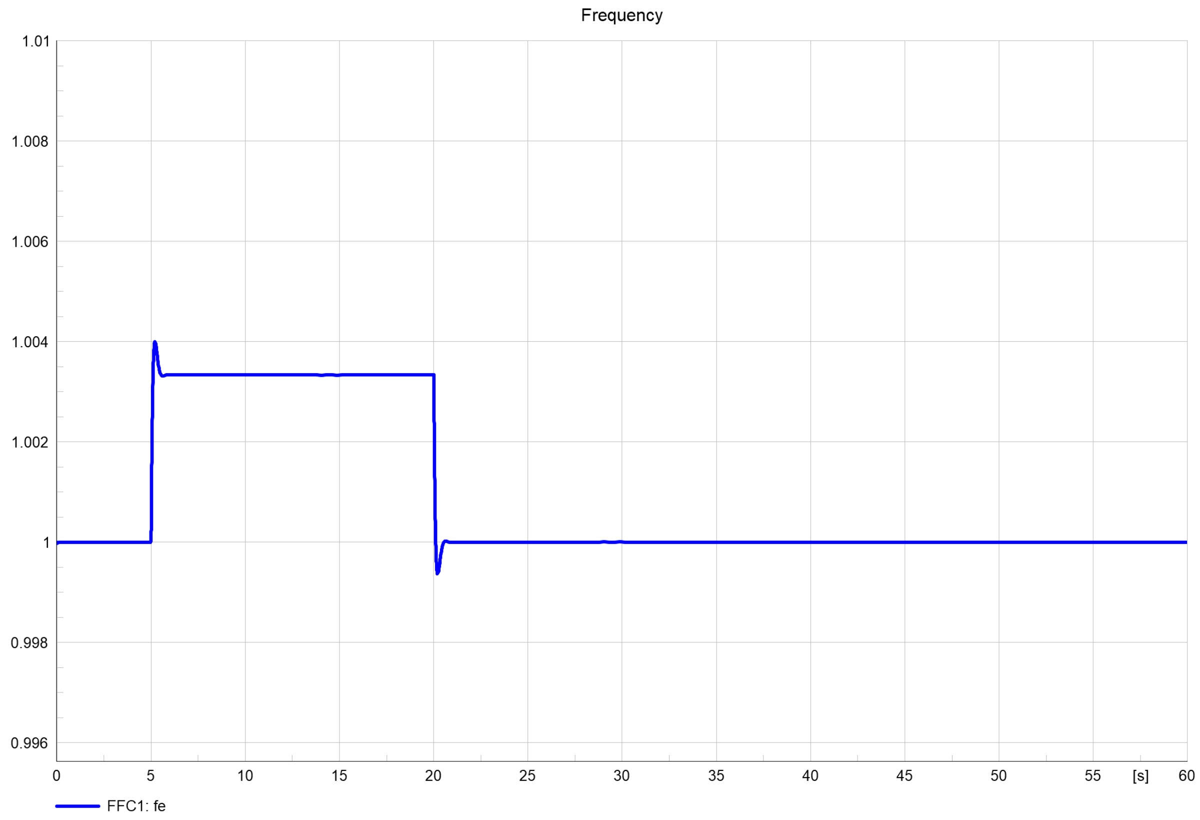

Figure 5.7. Frequency of the main grid.

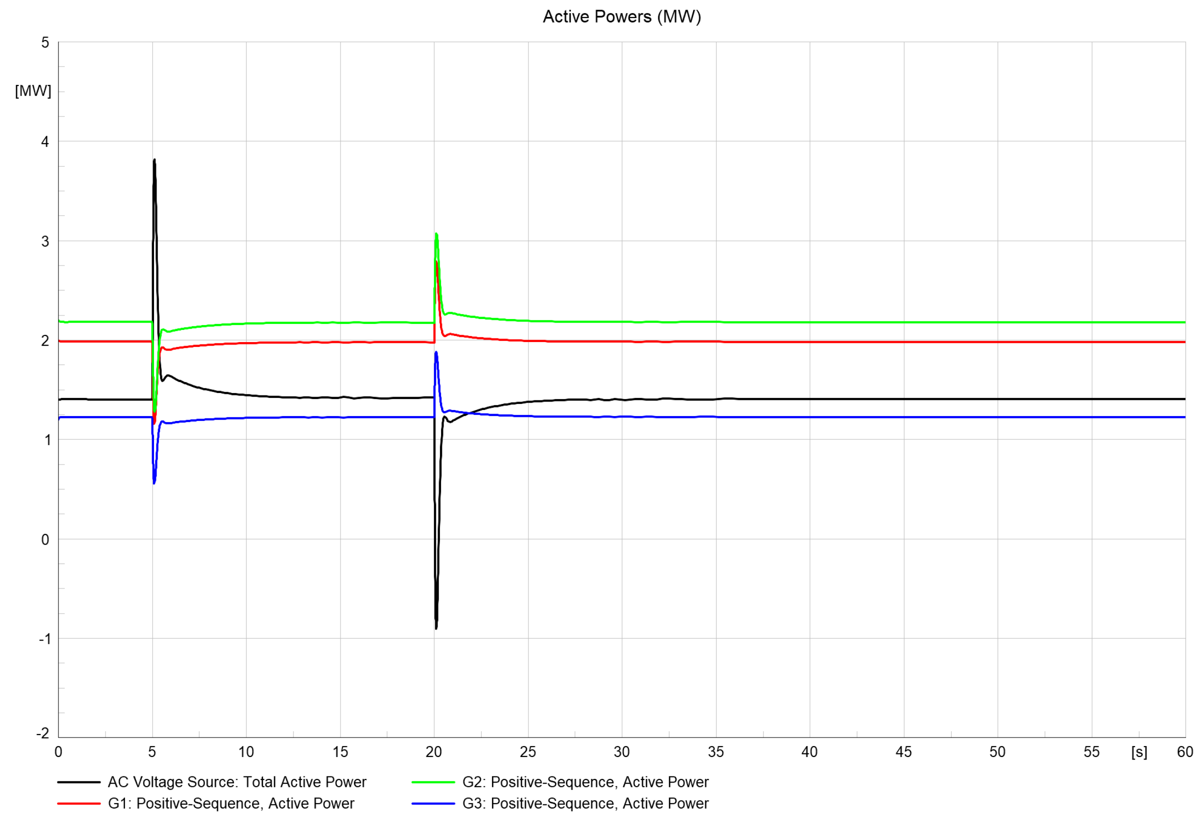

Figure 5.8. Active power from the main Grid and DDGUs using enhanced IFC.

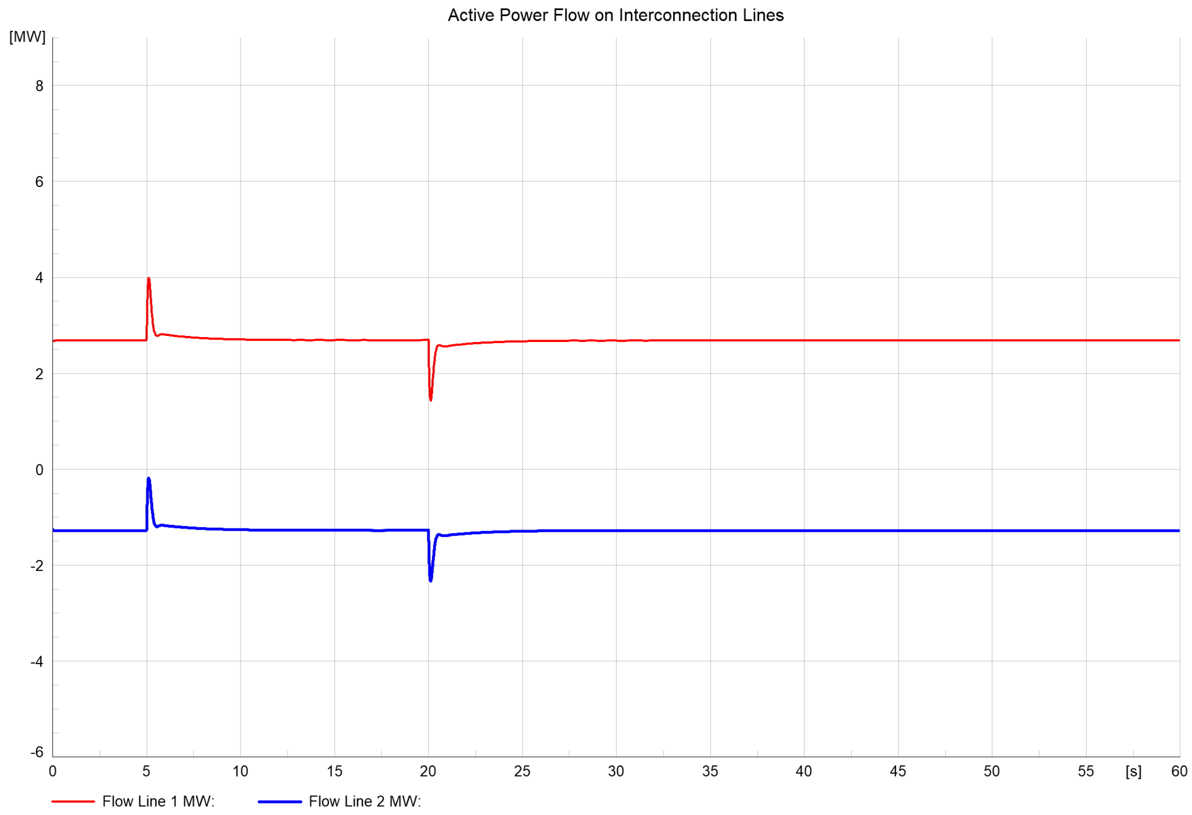

Figure 5.9. Active power flow over the interconnection lines (DDGUs with enhanced IFC).

Opposite to Case Study 6, when the frequency of the main grid is increased, the enhanced IFC controller was still able to maintain the sum of the active power flow over the two interconnection lines close the flow reference.

Frequency Increase vs. Frequency Decrease: Unlike Case Study 6, where a frequency decrease in the main grid was simulated, this scenario deals with an increase in the main grid's frequency. When the grid frequency increases, it indicates an oversupply of power, leading to the need for the micro grid to reduce its active power generation to help balance the system. Figure 5.7 captures the frequency of the main grid.

Enhanced IFC Controller Response: The enhanced IFC controller, as opposed to the basic version, was designed to respond more effectively to changes in both frequency and active power flow. In this case, even when the frequency of the main grid rose, the controller was able to maintain the sum of the active power flow over the two interconnection lines close to the desired flow reference, ensuring ideal operation of the micro grid.

Enhanced IFC Controller Functionality

Frequency Response: The enhanced IFC controller includes coordination between the frequency controller and the flow controller. When the frequency of the main grid increases, the frequency controller in the micro grid reduces the output from Distributed Generation Units (DDGUs). Figure 5.8 shows that the active power output from the DDGUs comes back to the initial value after a small transient caused by the change in the system's frequency. It also demonstrates the active power flow from the main grid remains within the allowable range of the of reference (1.4 MW).

Flow Control Coordination: Simultaneously, the flow controller monitors the active power flow through the interconnection lines. As the DDGU output is reduced, power from the main grid naturally increases to meet the demand of the micro grid. However, the enhanced IFC controller ensures that the sum of the power flow over the interconnection lines stays close to the flow reference (i.e., the desired power exchange level).

Effective Use of Flow Reference:

Flow Reference Maintenance: The flow reference represents the ideal amount of active power flow that should pass through the interconnection lines between the micro grid and the main grid. In this case, despite the frequency increase in the main grid, the enhanced IFC controller maintained the power flow near this reference point. This was achieved by balancing the DDGUs' output and the power imported from the grid, ensuring that the sum of active power over both interconnection lines remained stable.

Implications for Micro grid Stability

Maintaining Stability During Frequency Increase: The ability of the enhanced IFC controller to maintain power flow close to the flow reference, even during a frequency increase, is a crucial improvement. In practical terms, this means that the micro grid can operate more smoothly without causing imbalances in the power exchange with the main grid.

The results of the same simulated steps but with simple IFC controller is given below.

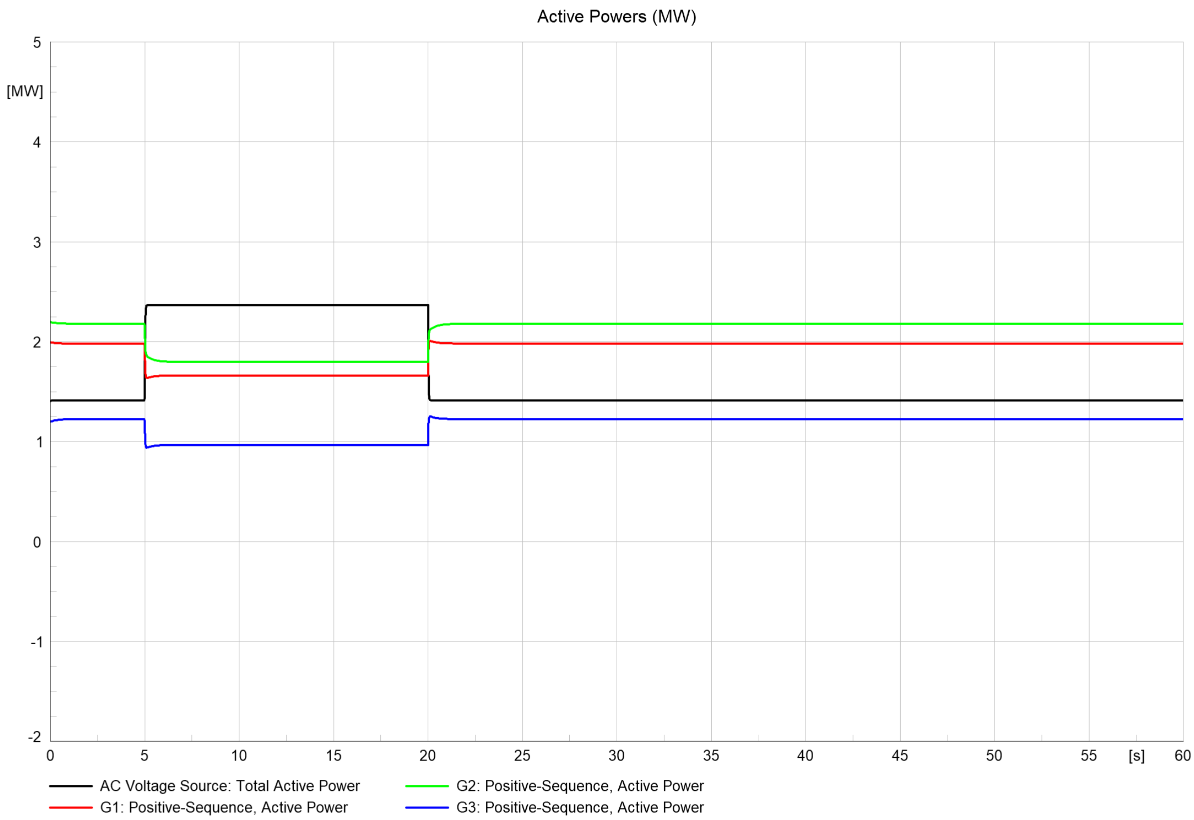

Figure 5.10. Active power from the main Grid and DDGUs using simple IFC.

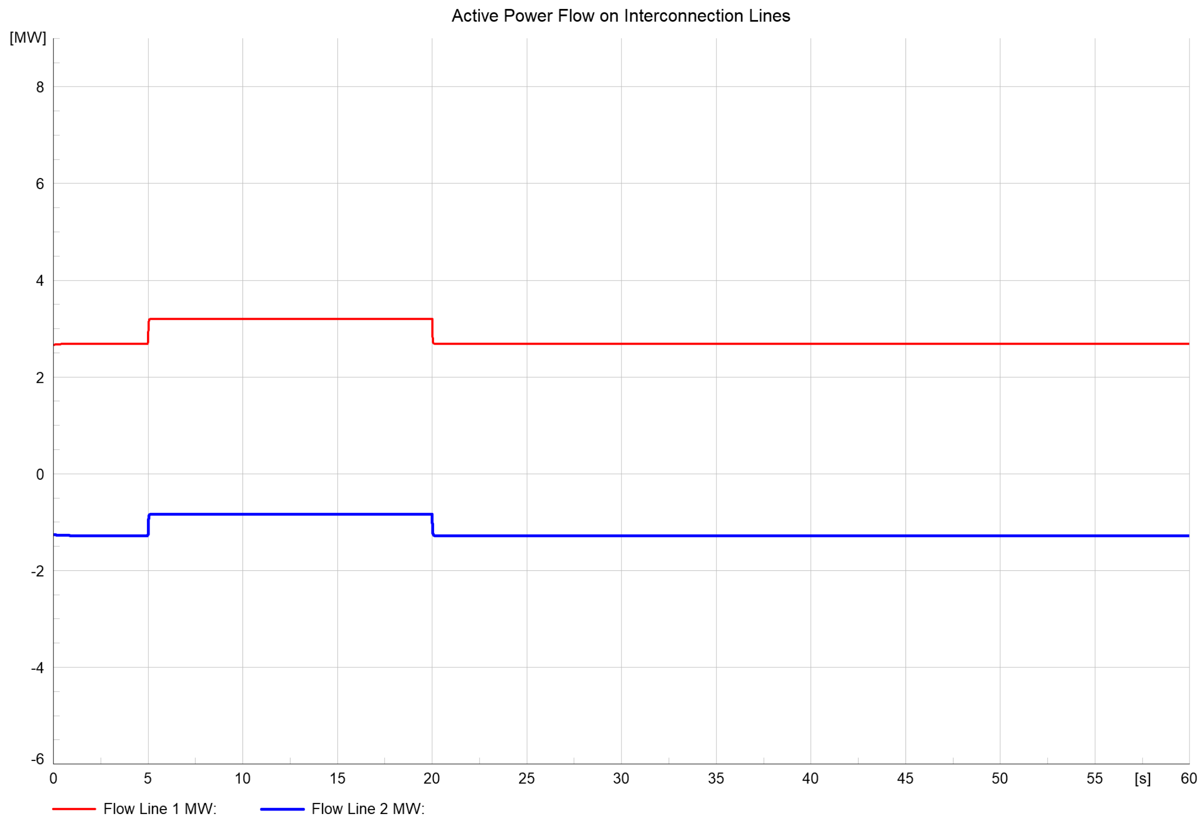

Figure 5.11. Active power flow over the interconnection lines (DDGUs with simple IFC).

Figure 5.10 and Figure 5.11 demonstrate that the simple IFC, as expected, is again failed to maintain the sum of the active power flow over the interconnection lines during the time when the main grid's frequency was over the normal value.

Increased Grid Frequency: When the grid frequency rose above its nominal value (e.g., due to an oversupply of power. The simple IFC failed to maintain active power flow during a frequency excursion, the enhanced IFC managed the flow successfully during a frequency rise. The enhanced IFC demonstrated better coordination between the frequency and flow controllers, preventing one system from dominating at the expense of overall power flow stability. This integrated control system ensured that both frequency deviations and power flow were handled effectively.

5.2.3 Case Study 8: Stepwise grid isolation

In this case study, the below events are simulated:

1. At t = 6 s, Line 1 is tripped.
2. At t = 20 s, Line 2 is tripped. Micro grid operated in grid isolation mode after 20 sec.

The stepwise grid isolation test for a micro grid involves simulating a transition from grid-connected operation to grid isolation mode by sequentially tripping interconnection lines between the micro grid and the main grid. This test is critical for evaluating the micro grid's or active power sharing controller’s resilience and ability to operate independently, ensuring a smooth transition without significant disturbances to local loads. Below is an elaboration of the test with each event and the expected response from the micro grid.

Stepwise Events Simulated

Event 1: Line 1 Trip at t = 6 s

At 6 seconds into the simulation, Line 1, which is one of the interconnection lines between the micro grid and the main grid, is tripped. This causes the micro grid to lose one of its primary paths for power exchange with the main grid. The overall active power flow is to be maintained at the flow reference level by the enhanced IFC controller.

Power Flow Redistribution: With Line 1 tripped, the micro grid can no longer export or import power through this line. As a result, the remaining Line 2 will need to handle the entire power exchange between the micro grid and the main grid.

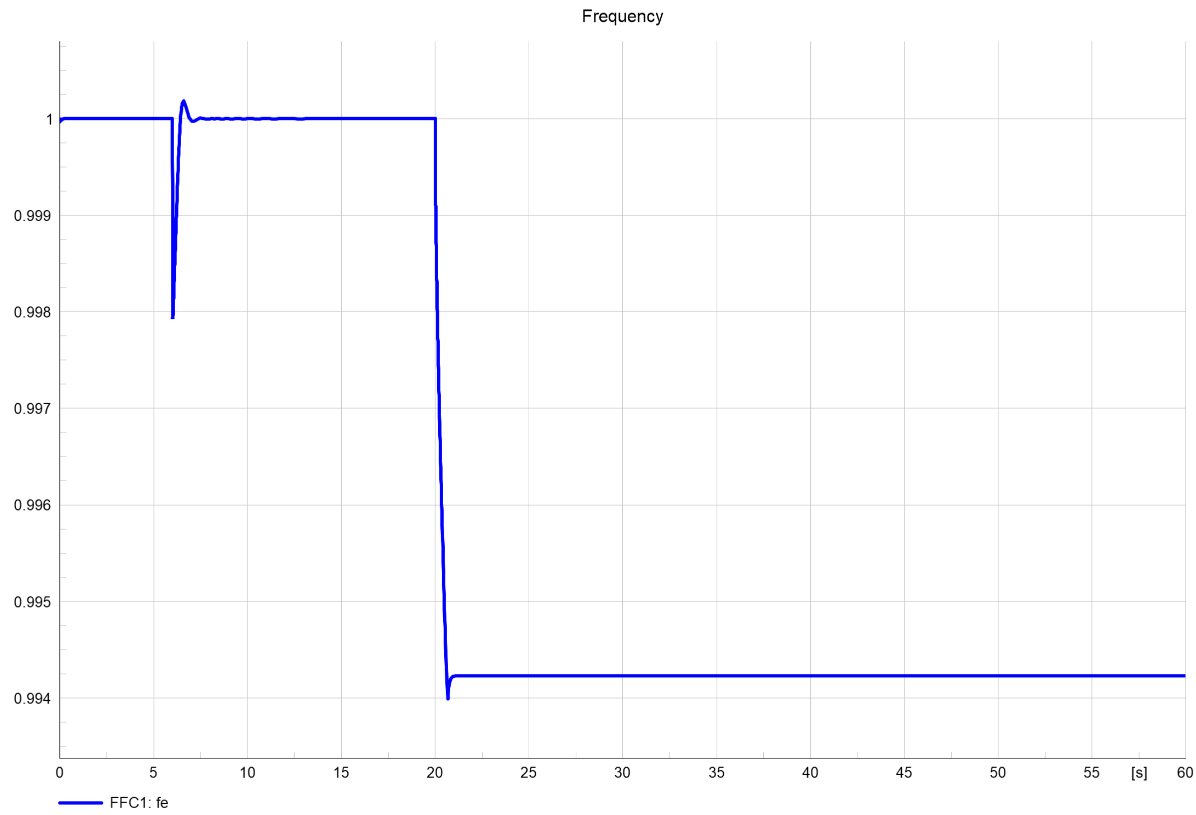

Figure 5.12. Frequency of the micro grid.

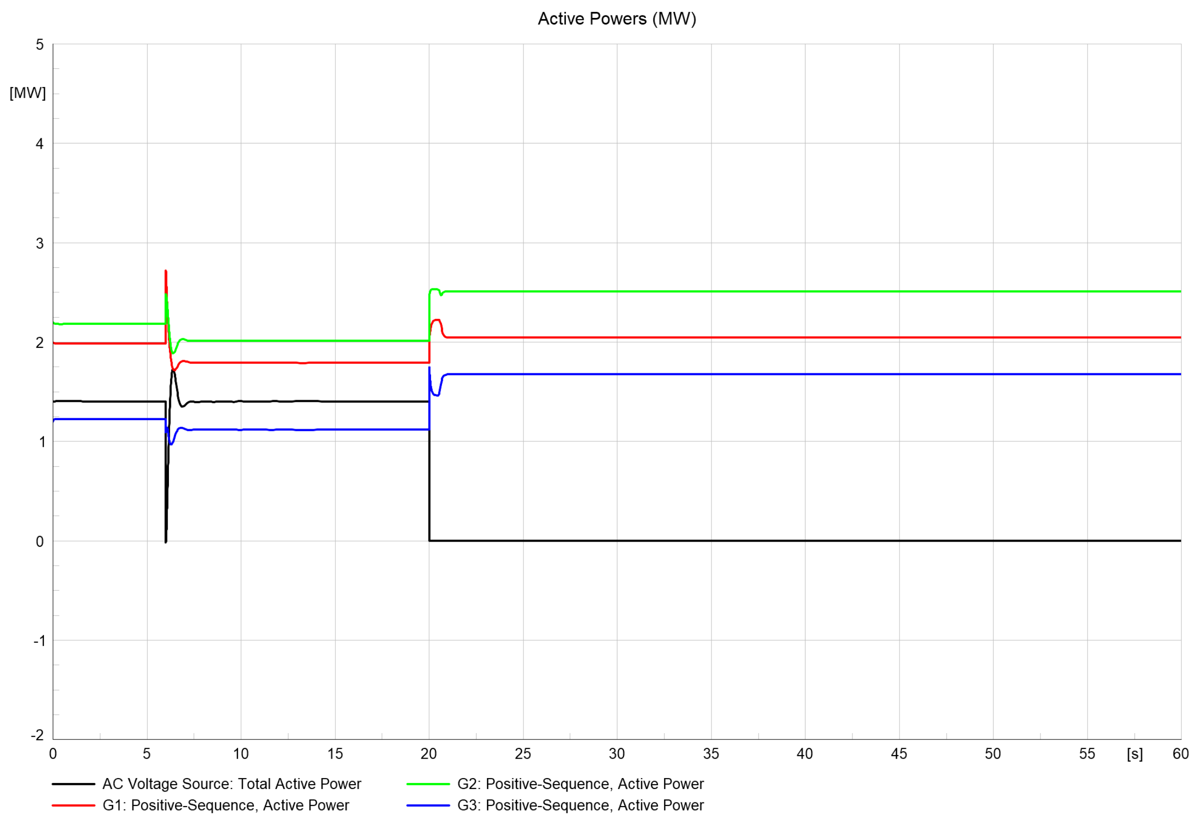

Figure 5.13. Active power from the main Grid and DDGUs using enhanced IFC.

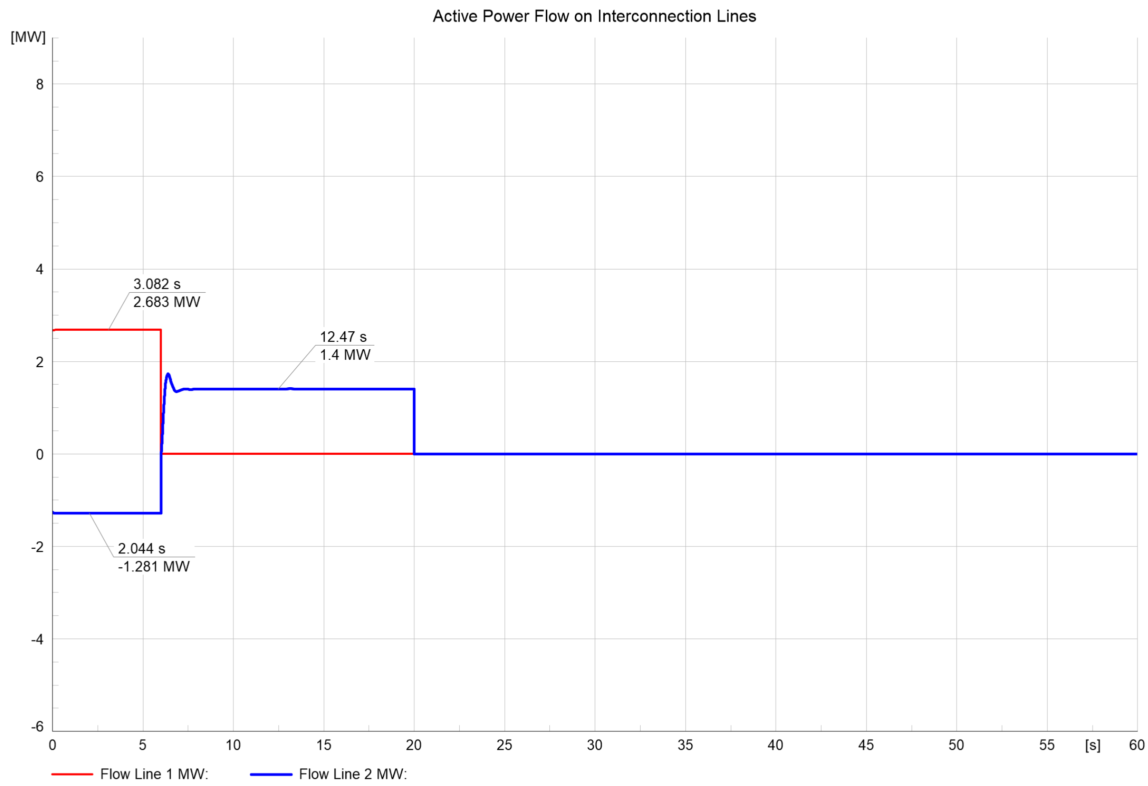

Figure 5.14. Active power flow over the interconnection lines (DDGUs with enhanced IFC).

Frequency Stability: During the transition, the micro grid was able to maintain its frequency, as shown in Figure 5.12.

Active Power Flow Controller Adjustment: Active powers from the DDGUs, shown in Figure 5.13, adjusts to ensure interconnection flow remains within allowable limits. The active power flow controller, enhanced IFC detected the change in power distribution caused by the loss of Line 1 and adjust the active power flow through Line 2 to ensure ideal operation of the micro grid by maintain the same overall (sum of active power flows over Line 1 and 2) active power flow (equal to flow reference) over only one interconnection line, Line 2. Figure 5.14 shows that the enhanced IFC was able to achieve an active power flow from main grid equal to the sum of initial line flows. The controller worked to maintain the flow close to the flow reference ensuring the ideal operation of the micro grid under N-1 operating conditions.

Event 2: Line 2 Trip at t = 20 s

At 20 seconds into the simulation, Line 2 is also tripped, disconnecting the micro grid entirely from the main grid. After this point, the micro grid operated in islanded mode or grid isolation mode, relying solely on its internal power generation to meet local demand.

Transition to Islanded Mode: The micro grid now enters isolation mode, meaning that it must supply its own power without any external support from the main grid. The DDGUs will become the sole source of power for the micro grid, and their control systems must quickly adapt to the new operating conditions.

Frequency Control in Isolation Mode: In grid isolation mode, the only method to vary the active power output from the DDGUs is by varying the frequency. The frequency controller will closely monitor any deviations from the nominal frequency and adjust the output of the DDGUs accordingly. As shown in Figure 5.12, the frequency of the micro grid was to be reduced to compensate for the loss of 1.4 MW import from the main grid. Since in enhanced IFC controller the flow control works in opposite direction, therefore the decrease in frequency is expected to be slightly higher than in case of simple IFC mode.

The results of the same test conducted with simple IFC mode is given below.

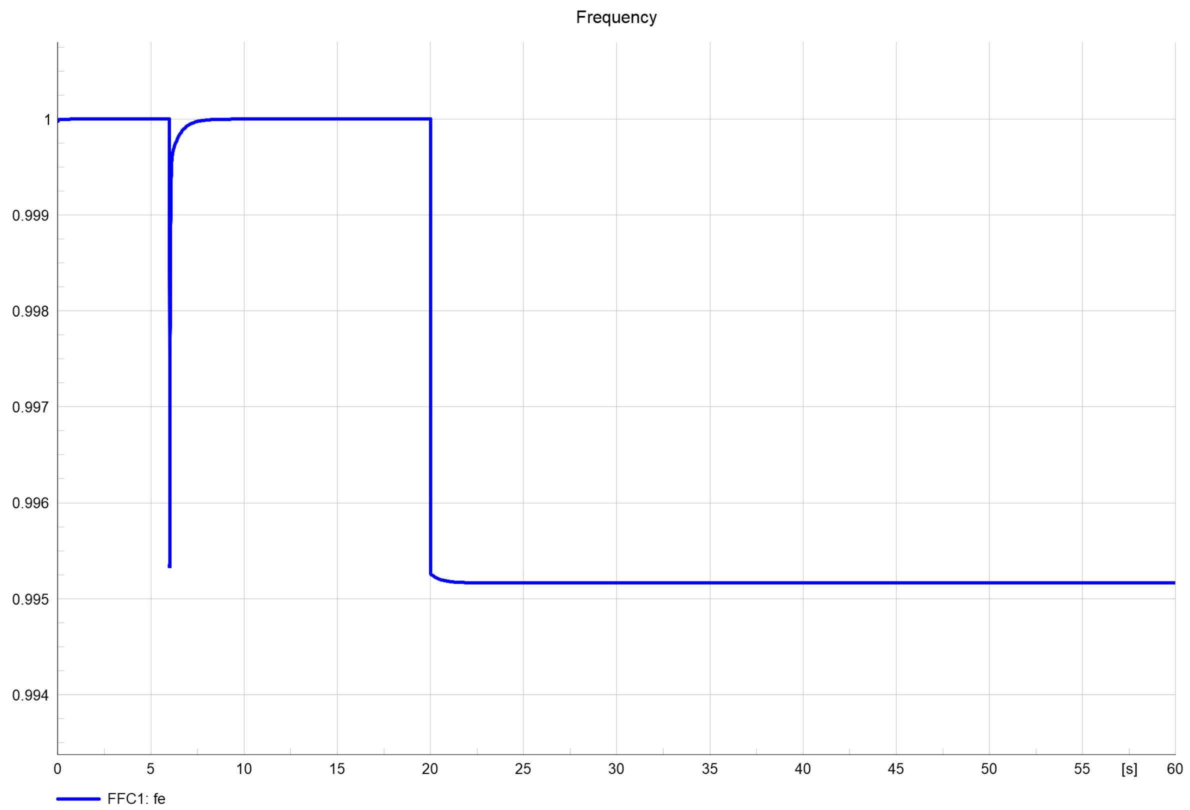

Figure 5.15. Frequency of the micro grid.

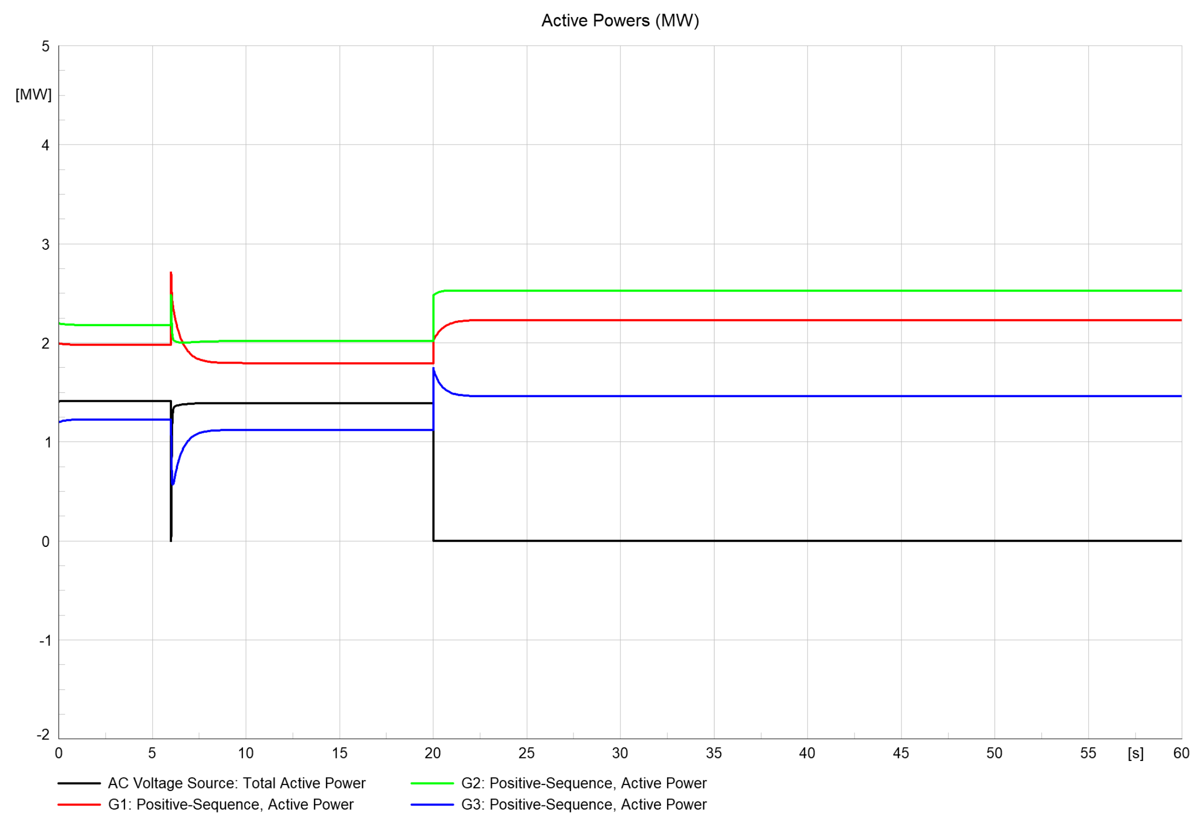

Figure 5.16. Active power from the main Grid and DDGUs using simple IFC.

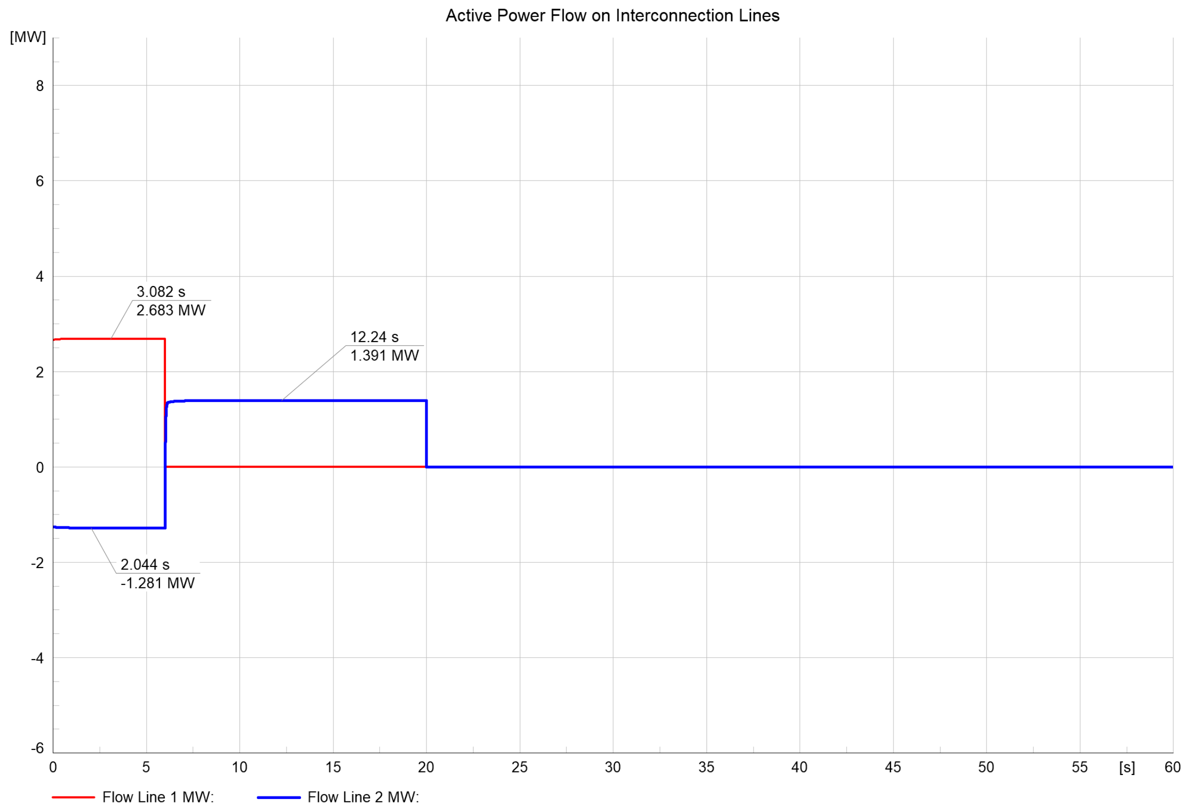

Figure 5.17. Active power flow over the interconnection lines (DDGUs with simple IFC).

Comparing Figure 5.12 and Figure 5.15 confirms that the change in frequency in case of enhanced IFC (0.994 pu) is slightly greater than simple IFC (0.995 pu). Results shown in Figure 5.13 and Figure 5.16, demonstrates that both IFC and enhanced IFC were able to adjust the DDGUs active power output, after the loss of first interconnection line, in a manner that the flow of active power at the remaining interconnection line remains within the allowable limits or close to the flow reference. The active power flow on interconnection lines are shown in Figure 5.14 and Figure 5.17.

5.3 Flow and frequency balancing action in Synchronous Generators

In a synchronous machine, the balance between mechanical and electrical torque is essential for stable operation, with frequency playing a key role due to its direct relation to the rotor's rotational speed. This balance is explained through the swing equation and becomes especially critical during dynamic conditions, such as changes in load or disturbances in the grid. The impact of change in frequency on mechanical and electrical torques in the context of synchronous generator operation is explained below.

5.3.1 Mechanical Torque (T_m)

Mechanical torque is generated by the prime mover or the turbine, such as a steam turbine, gas turbine, or water turbine, and is responsible for driving the rotor at the synchronous speed.

In synchronous machines, the rotor speed

$$N = \frac{120f}{P} \qquad [5.4]$$

Where:

N is the rotor speed in revolutions per minute (RPM),

f is the grid frequency in Hz,

P is the number of poles in the machine.

Any changes in grid frequency directly affect the rotor speed. As the mechanical torque is applied to maintain this speed, variations in frequency will require adjustments in mechanical torque to keep the rotor synchronized.

The mechanical torque for generator is calculated by the relation:

$$t_m = \frac{pt}{n} \qquad [5.5]$$

where:

pt is the Turbine Power input signal in (pu) n is the speed in (pu)

5.3.2 Electrical Torque (T_e)

Electrical torque is generated by the interaction between the rotating magnetic field of the stator and the rotor's magnetic field. This torque is a function of the power angle δ, which represents the angular displacement between the magnetic fields of the rotor and stator.

Electrical torque is sensitive to changes in the power angle δ, which is influenced by rotor speed and grid frequency. When the grid frequency changes, it affects the relative speed of the rotor, altering the power angle and thus the electrical torque. A drop in frequency increases the power angle, causing the machine to generate more electrical torque to compensate for the drop in speed. Conversely, an increase in frequency reduces the power angle, lowering the electrical torque.

The electrical torque T_e in a synchronous machine is generated by the interaction between the rotor's magnetic field and the stator's rotating magnetic field. The torque is related to the active power P being produced by the generator, and this relationship is governed by the following equation:

$$P = T_e \omega \qquad [5.6]$$

Where:

P is the active power (in watts),

T_e is the electrical torque (in newton-meters),

ω is the rotational speed of the rotor in radians per second.

The PowerFactory synchronous machine model for time domain simulations uses the rotor fluxes and the speed n. The electrical torque (T_e) is calculated using the stator currents (i_d and i_q) and stator fluxes (ψd and ψq) and the rated power factor cosn.

$$T_e = \frac{i_q \cdot \psi_d - i_d \cdot \psi_q}{\mathrm{cosn}} \qquad [5.7]$$

5.3.3 The Swing Equation and Torque Balance

The swing equation models the dynamic relationship between mechanical and electrical torque in terms of rotor acceleration or deceleration:

$$\frac{J\,d^2\delta}{dt^2} = T_m - T_e \qquad [5.8]$$

Where:

J is the rotor's moment of inertia,

δ is the rotor angle (or power angle),

T_m is the mechanical torque,

T_e is the electrical torque.

The swing equation shows that any imbalance between mechanical and electrical torque results in changes in rotor acceleration, which alters the rotor speed and, consequently, the frequency. During frequency deviations, this equation governs the machine's response to restore the torque balance.

The difference between mechanical and electrical torque in a synchronous machine is related to the power angle (δ), which is the angular difference between the rotor's magnetic field and the stator's magnetic field. As the mechanical torque increases, the power angle increases, resulting in a proportional increase in the electrical torque to balance the forces. The system aims to maintain a small, stable δ to keep the machine in synchronism.

During transient conditions, such as when there is a sudden change in load or mechanical input, there may be an imbalance between mechanical and electrical torque, causing the rotor to oscillate around its synchronous position. These oscillations are damped by the machine's inertia and damping systems, allowing the machine to return to a stable state.

The machine must ensure that any temporary imbalances are quickly corrected to avoid large deviations in speed or loss of synchronism.

The balance between mechanical and electrical torque is crucial for the stable and efficient operation of synchronous machines. This balance is constantly maintained to ensure the rotor speed matches the grid frequency, and any imbalance can result in oscillations or instability in the machine's operation.

5.3.4 Frequency Excursions and Torque Dynamics

In case of over frequency (f > nominal frequency) event, the rotor speed increases due to the direct relationship between rotor speed and frequency. In this case, the machine’s electrical torque decreases as the power angle δ reduces. Reduction in angle δ means reduction in active power output from the machine. To balance the system, the mechanical torque must be reduced to prevent the rotor from accelerating further. If not corrected, the machine could lose synchronism with the grid.

In case the frequency drops, the rotor slows down, causing an increase in the power angle δ. This leads to an increase in electrical torque, which works to slow down the rotor’s deceleration and maintain synchronization. The prime mover must increase the mechanical torque to bring the rotor speed back to synchronous speed and stabilize the system.

Overall, a synchronous machine or DDGU with IFC will have two levels of frequency responses, one the natural response based on the Equation 5.4 to 5.8 which is supported by the integrated UPC or droop based frequency response, as explained in Equation 2.4. However, in case of enhanced IFC, where flow control balances the droop based response the extent to which the natural response (based on Equation 5.4 to 5.8) can be balanced will depend upon the inertia constant, damping torque, change and duration of frequency excursion etc. In case enhanced IFC is used in DDGUs other than synchronous machines, such as Battery Energy Storage Systems (BESS) with grid following inverters, then the only response, the droop based response, can be completely compensated.

In a stable synchronous machine, the balance between mechanical and electrical torque is maintained even during minor frequency fluctuations. However, significant deviations in frequency can cause instability if the machine's control systems, such as governors for mechanical torque and automatic voltage regulators (AVRs) for electrical torque, are unable to respond fast enough to restore balance.

The machine's inertia J plays a critical role in dampening the effects of frequency deviations. A higher inertia slows the rate of change in rotor speed, giving the system more time to correct torque imbalances before the rotor slips out of synchronism. Machines with lower inertia are more sensitive to frequency deviations and require faster response times from control systems.

5.3.5 Deadband versus Balancing

Since active power balancing mechanism blocks the frequency response from the controller, therefore, one can think of widening the deadband (to block the frequency response) instead of using the balancing feature. Although apparently both options results in the same outcome, however there are some significant operational differences between the two methods. The first impact and disadvantage of having a wider frequency deadband will be evident when the micro grid goes into island mode of operation. At the time of disconnection from the main grid, controller with wider frequency deadband will experience larger frequency variation. Secondly, using this balancing feature, operators would be able to decide the degree of balancing they want to achieve by tuning the corresponding gain values (Kpf and KpFL).

5.4 Interconnection Reactive Power Flow Controller (IRFC)

For a micro grid with multiple interconnections with the main grid(s), the interconnection reactive power flow control (IRFC) is designed to control the flow of the reactive power between the micro grid and the main grid to a particular predefined reference value. Similar to

IFC, this controller is also designed to monitor the sum of the reactive power flow on the designated interconnection lines and will work to ensure that the overall flow towards or from the micro grid remains constant. This will ensure that the micro grid acts a constant load or a generator to the main grid even with reference to the reactive power flow.

Reactive power is critical in maintaining voltage levels, ensuring that both the micro grid and the main grid operate efficiently without voltage instability or fluctuations.

Overview of Reactive Power Flow Control in a Micro grid

Reactive power flow control in a micro grid interconnected with the main grid ensures that voltage stability is maintained across the system. Reactive power flow is influenced by the demand from local loads and the overall voltage profile of the micro grid and the interconnection with the main grid.

When the micro grid operates in grid-connected mode, the Interconnection Reactive Flow Controller (IRFC) continuously monitors the sum of reactive power flows across all designated (Line 1 and Line 2 in our case) interconnection lines between the micro grid and the main grid. The controller ensures that the reactive power flow stays within a specific reference range to ensure ideal operation of the micro grid.

Similar to active power control (IFC), the IRFC monitors the total reactive power flow over all (or designated) interconnection lines between the micro grid and the main grid. The sum of reactive power flows through the interconnections is calculated and compared to a reference value. This reference value corresponds to the optimal amount of reactive power exchange needed to maintain voltage stability across the micro grid.

If the sum of reactive power flowing through the interconnection lines deviates from the reference, the IRFC takes corrective actions by instructing the local Distributed Generation Units (DDGUs) to adjust their reactive power output. The overall control block diagram of the enhanced IFC with integrated IRFC is given in Figure 5.18. The parameters used in the simulations are given in Table 5-2.

Table 5-2. Used controller parameters.

Parameter	Value	Unit
f deadband	0.0015	pu
Fref	1	pu
Ku	-0.4	
Kpf	-10	
Kif	0	
P deadband	0.001	pu
KpFL	-100	
KiFL	-50	
FLref	0.0141	pu
KpQFL	-40	
KiQFL	-20	
QFLref	0.0195	pu
Q deadband	0.0001	pu

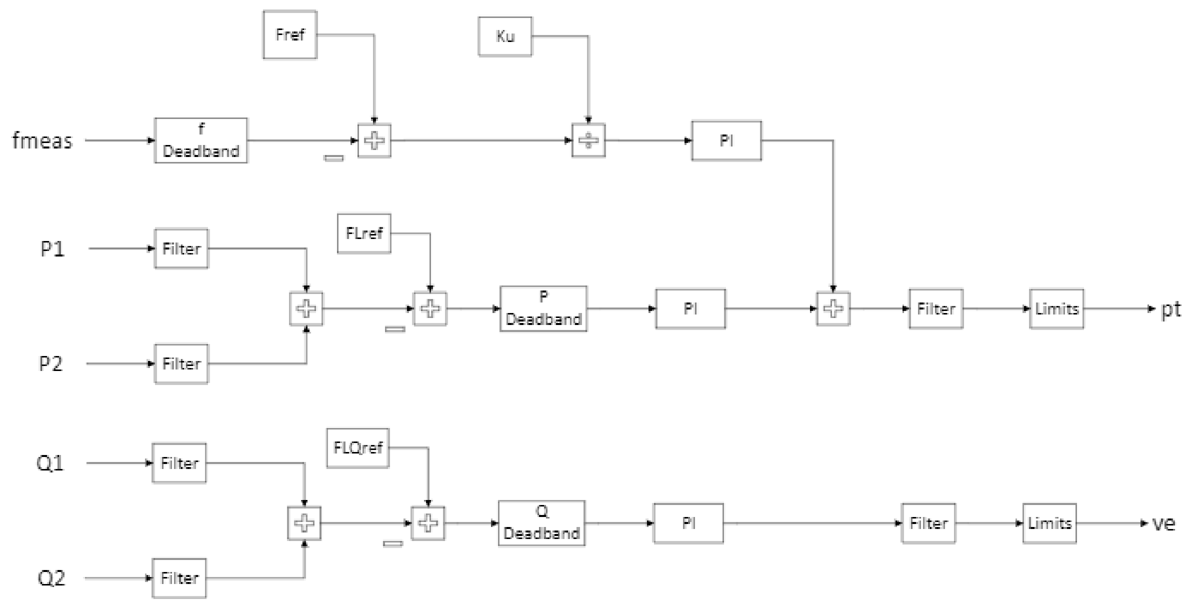

Figure 5.18. Enhanced IFC (inclusive of IRFC)

Reactive Power Compensation by DDGUs:

Each DDGU in the micro grid is capable of producing and absorbing reactive power, allowing it to compensate for any mismatches between reactive power supply and demand.

If the sum of reactive power flow through the interconnections falls outside the acceptable range (beyond the deadband), the DDGUs will adjust their reactive power output to bring the total reactive power flow closer to the reference value.

Proportional-Integral (PI) Control: The reactive power adjustment by the DDGUs is based on the PI controller. Each DDGU has a gain factor (KpQFL and KiQFL) that determines how strongly it reacts to changes in the overall reactive power flow. These gains ensures that the DDGUs responds in proportion to the size of the reactive power imbalance.

Introduction of a Deadband:

To avoid unnecessary and frequent reactive power adjustments for small fluctuations, a deadband is introduced in the controller. The deadband allows the sum of the reactive power flow to vary slightly around the reference value without triggering reactive power corrections.

This deadband reduces the wear and tear on equipment caused by constant adjustments and ensures that the reactive power flow stays within an acceptable range, promoting system stability.

Load Variation and Reactive Power Compensation:

When the load within the micro grid varies, there may be an accompanying change in the local demand for reactive power. Increased loads often lead to increased reactive power requirements to maintain voltage stability.

In this scenario, the local DDGUs will automatically compensate for these load variations by adjusting their reactive power output. For instance, if the micro grid experiences a high reactive power demand due to inductive loads (e.g., motors), the DDGUs will produce more reactive power to stabilize the voltage and for ensuring reactive flow on interconnection lines remains almost constant.

Response to DDGU Trips:

If one or more DDGUs within the micro grid trip or go offline, the remaining DDGUs will need to adjust their reactive power output to maintain voltage stability. This ensures that the overall reactive power flow across the interconnections stays balanced and that the system voltage does not drop or rise uncontrollably.

System-Wide Reactive Power Compensation:

One of the key strengths of interconnection reactive flow control is the ability to balance reactive power across multiple interconnections. If one DDGU is unable to meet the reactive power demand due to a fault or trip, the remaining DDGUs will increase their reactive power output to ensure that the sum of reactive power flow remains constant.

In contrast, any reactive power controller designed at feeder level, like FFC for active power, may lead to isolated pockets of voltage instability if one feeder experiences high reactive power demand that the local DDGU cannot compensate for, as other DDGUs in the system may not respond. By controlling the reactive power flow centrally, the IRFC ensures that the voltage levels across the micro grid are more stable and less prone to fluctuations, even during load variations or system disturbances.

Load Variations and Reactive Power Balancing:

The ability of DDGUs to compensate for local load variations in interconnection reactive flow control ensures that the micro grid can maintain stable operation even during periods of high reactive power demand.

In summary, the IRFC (being part of the enhanced IFC) manages the sum of reactive power flow across designated or all interconnections between the micro grid and the main grid, comparing it to a reference value and making necessary adjustments.

This comprehensive control system ensures that both active and reactive power flows are effectively managed by a micro grid connected to the main grid, supporting overall system stability and reliability and fulfilling the requirements of an ideal micro grid.

Mathematically, IRFC is represented by following equations

$$\{KpQFL + KiQFL/s\}\{QFLREF - (Qline\,1 + Qline\,2)\} = ve \qquad [5.2]$$

Where:

ve is the signal to the DDGU's exciter

KpQFL is the proportional gain for reactive power flow control

KiQFL is the integral gain for reactive power flow control

Qline 1 is the reactive power flow over interconnection line 1

Qline 2 is the reactive power flow over interconnection line 2

5.5 Simulation Results and Discussions

To test the IRFC controller, following simulations were conducted:

1. Case Study 9. Reactive power demand variation.

Using Configuration 2, as shown in Figure 4.16, reactive demand of Load 1 (0.9 MVAr) was ramped down to 0 MVAr at t = 6 sec in 0.2 sec. The reactive demand was then ramped back to 0.9 MVAr at t = 15 sec in 0.2 sec.

2. Case Study 10. Active and reactive power demand variation

   Using Configuration 2, as shown in Figure 4.16, reactive demand of Load 1 (0.9 MVAr) was ramped down in 0.2 sec to 0 MVAr and active power demand of Load 2 is ramped down to 1 MW (from 2 MW in 0.2 sec) at t = 6 sec. The reactive demand of Load 1 was then ramped back up to 0.9 MVAr and active demand of Load 2 was also restored back to 2 MW at t = 15 sec.

3. Case Study 11. Active power, reactive power and frequency all varied simultaneously.

   All three parameters (Frequency of the grid, Reactive demand of Load 1 and Active demand of Load 2) varied at t = 6 sec.

   Load 1 - 100% reactive power ramped down to 0 MVAr in 0.2 sec (from 0.9 MVAr) at t = 6 sec, and then ramped back up to previous value in the same time (0.9 MVAr in 0.2 sec) at t = 15 sec.

   Load 2 – 50% Active power ramped down to 1 MW at t = 6 sec, and then ramped back up to previous value (2MW in 0.2 sec) at t = 15 sec.

   Frequency of the grid was dropped instantly to 59.8 Hz at t = 6 sec and returned back to normal value (60 Hz) at t = 15 sec.

5.5.1 Case Study 9: Reactive power demand variation

To test the performance of the IRFC section of the enhanced IFC, reactive power demand of one of the simulated loads (Load 1) within the micro grid was reduced to 0 MVAr from 0.9 MVAr. This internal variation in the reactive power demand will induce a change in the overall reactive power flow, especially flow from the interconnection lines. In “Configuration 2”, as shown in Figure 5.19, Load1 is connected to the bus where one of the interconnection lines (Line 1) is connected, therefore any change in Load1's reactive demand should have a direct impact on the sum of reactive power flowing over the interconnection lines.

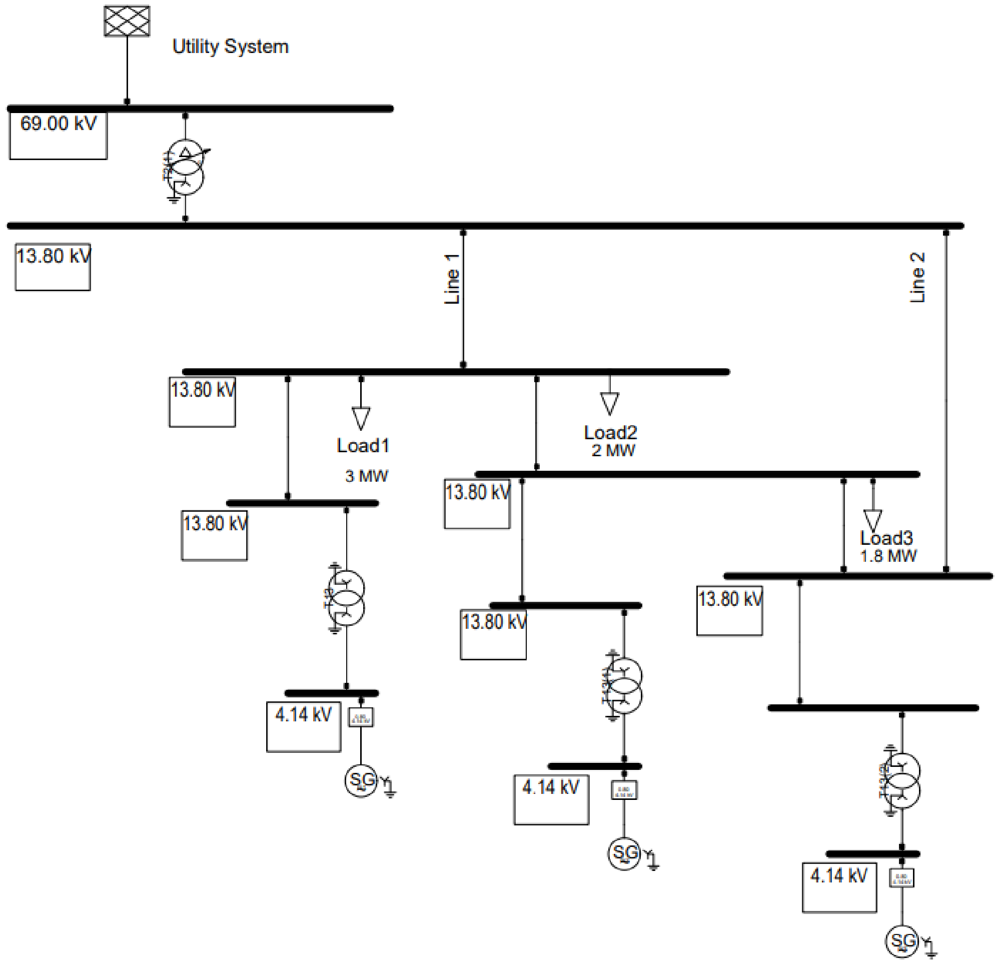

Figure 5.19. Configuration 2.

Impact on Interconnection Reactive Power Flow:

The reduction in Load1's reactive power demand caused a decrease in the reactive power flow over Line 1. The sum of reactive power flows across both interconnection lines (Line 1 and Line 2) was also reduced initially, as the overall reactive power demand of the micro grid was decreased.

The enhanced IFC, specifically the IRFC section, detected this change and worked to maintain reactive power flow over the interconnection lines by adjusting the output of the DDGUs.

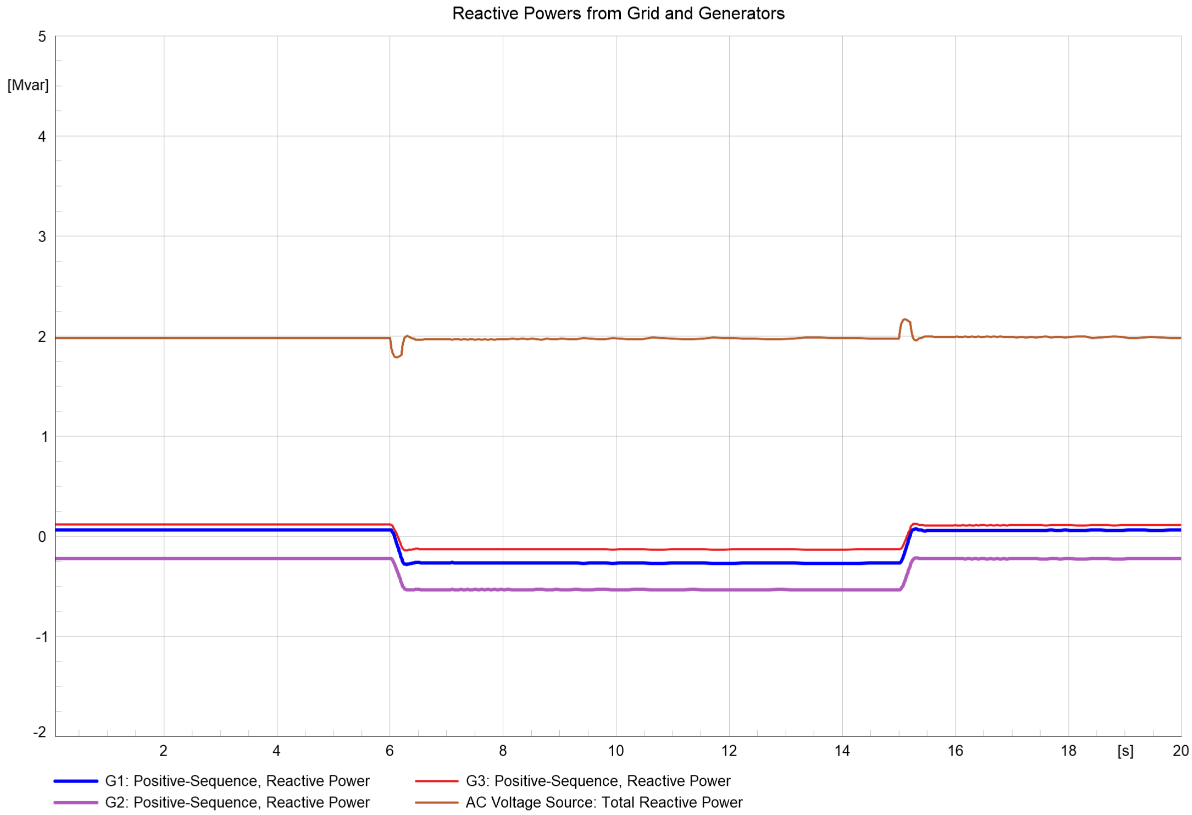

Figure 5.20. Reactive powers from the main grid and the DDGUs with enhanced IFC (IRFC).

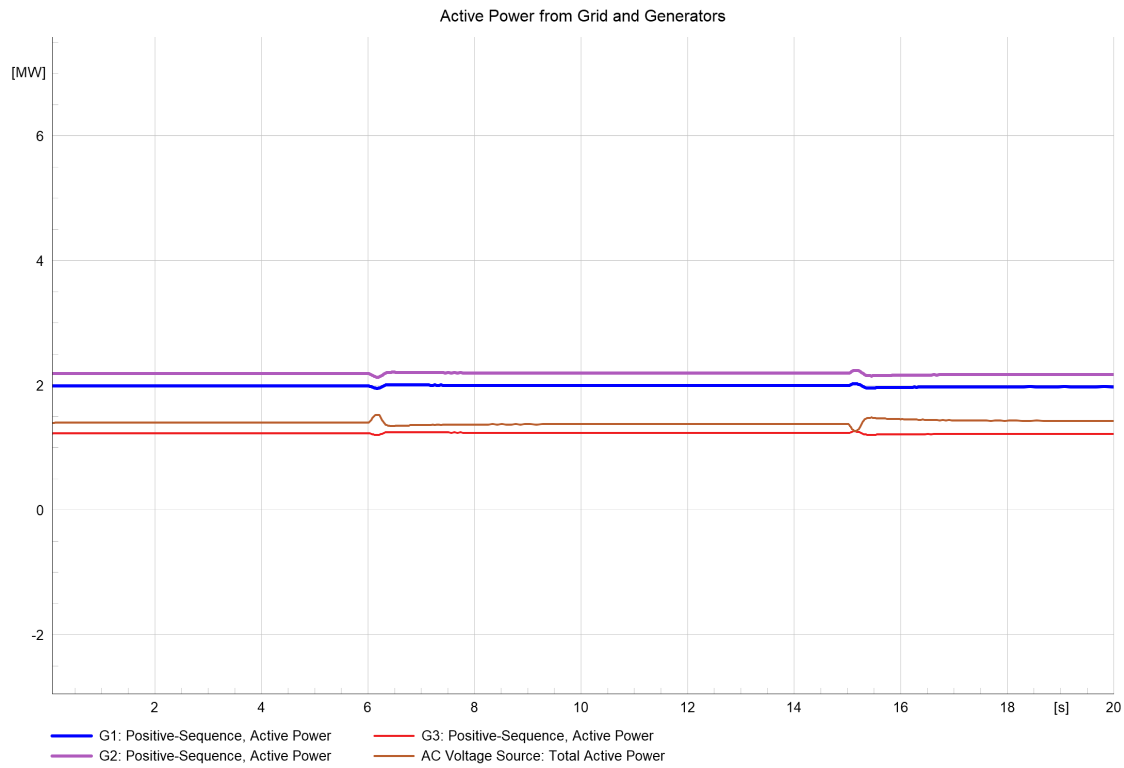

Figure 5.21. Active powers from the main grid and the DDGUs with enhanced IFC (IRFC).

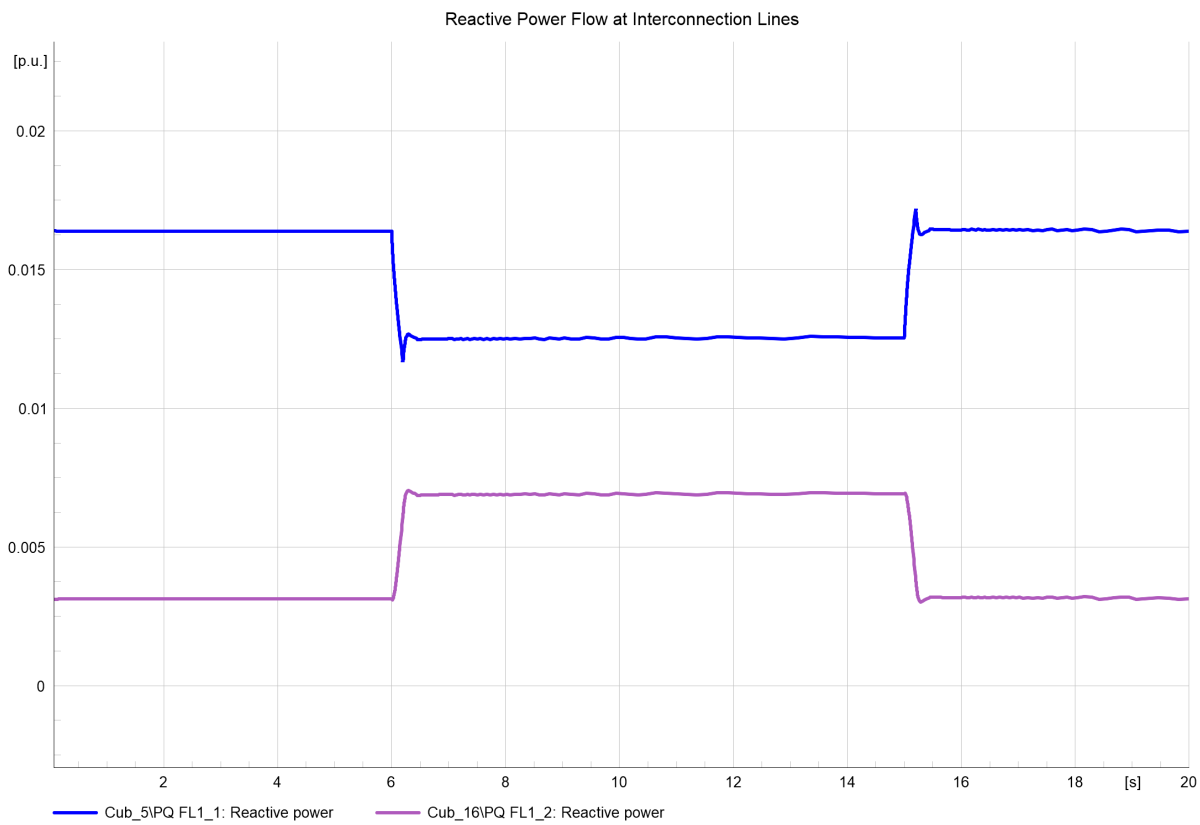

Figure 5.22. Reactive power flow over the interconnection lines (Line 1 and 2).

Results shown in Figure 5.20 to Figure 5.22 demonstrate the performance of the enhanced IFC with IRFC, as it was able to maintain a constant active and reactive power flow over the interconnection lines, Line 1 and Line 2. The internal reactive demand variation was compensated by the DDGUs by varying their reactive power outputs.

Only one load (Load1) was selected to simulate the reactive demand variation, however all three DDGUs contributed to compensate for the internal variation.

Reactive Power Flow Stabilization:

The enhanced IFC, with the integrated IRFC, was able to maintain a steady and controlled reactive power flow across both Line 1 and Line 2, which connect the micro grid to the main grid.

This is a critical achievement, as reactive power flow management directly impacts voltage stability in the micro grid. Any significant variations in reactive power can cause voltage fluctuations, leading to potential instability.

Despite the simulated reduction in reactive power demand from Load1 (from 0.9 MVAr to 0 MVAr), the system responded quickly to stabilize the reactive power flow and avoid voltage instability across the micro grid and its interconnections with the main grid.

Compensation by Distributed Generation Units (DDGUs):

A noteworthy aspect of the test is the cooperative behaviour of the DDGUs. While only Load1 was selected to undergo a change in reactive power demand, all three DDGUs contributed to compensating for this internal variation.

The enhanced IFC, through its Proportional-Integral (PI) control, ensured that each DDGU adjusted its reactive power output in proportion to the deviation in the overall reactive power flow. As shown in the Figure 5.20.

Importance of IRFC in Reactive Power Management:

The Interconnection Reactive Flow Controller (IRFC) is a key component of the enhanced IFC, specifically designed to handle reactive power flow challenges in a grid-connected micro grid. The PI controller used in the IRFC allows for fine-tuned adjustments to the reactive power outputs of the DDGUs based on system-wide feedback.

This outcome highlights the robustness of the IRFC in managing the reactive power flow over the interconnection lines, as IFC demonstrated that for active power flow. The ability of the IRFC to respond quickly to changes in reactive power demand enhances the overall resilience of the micro grid, ensuring stable operation even during dynamic load variations.

5.5.2 Case Study 9A: Reactive power demand variation with SEXS Automatic Voltage Regulator (AVR) at DDGUs

To highlight and benchmark the performance of IRFC, the same reactive power variation test is conducted while using a simple and standard Simplified Excitation System (SEXS) model of Automatic Voltage Regulator (AVR) at DDGUs. Its main function is to regulate the output voltage of a synchronous generator by controlling the excitation current supplied to the generator's field windings. The SEXS model is part of the IEEE standard models for excitation systems and is used extensively in power system studies due to its simplicity and ability to represent basic dynamic behaviours of excitation systems. The SEXS model uses a transfer function to represent the voltage regulator's dynamics and the generator's response.

In simplified terms, the SEXS model can be represented by a block diagram (Figure 5.23) that includes:

- A voltage error signal (difference between reference voltage and actual terminal voltage),
- An amplifier with a gain,

- A time delay representing the response of the exciter,
- Saturation limits to prevent over-excitation or under-excitation.

IFC was used as the active power controller during this test.

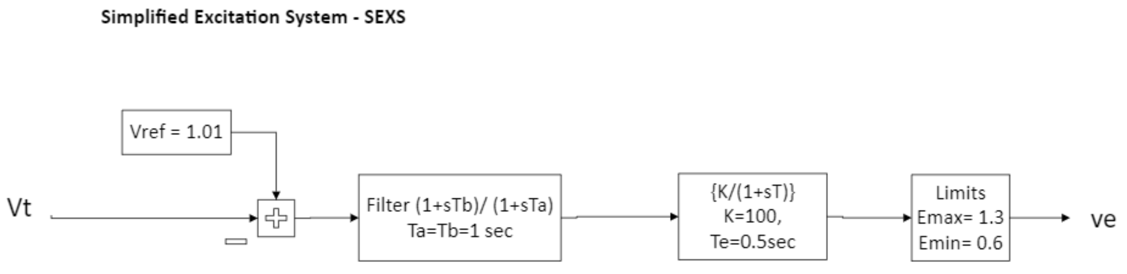

Figure 5.23. Simplified AVR SEXS controller model used in DDGUs.

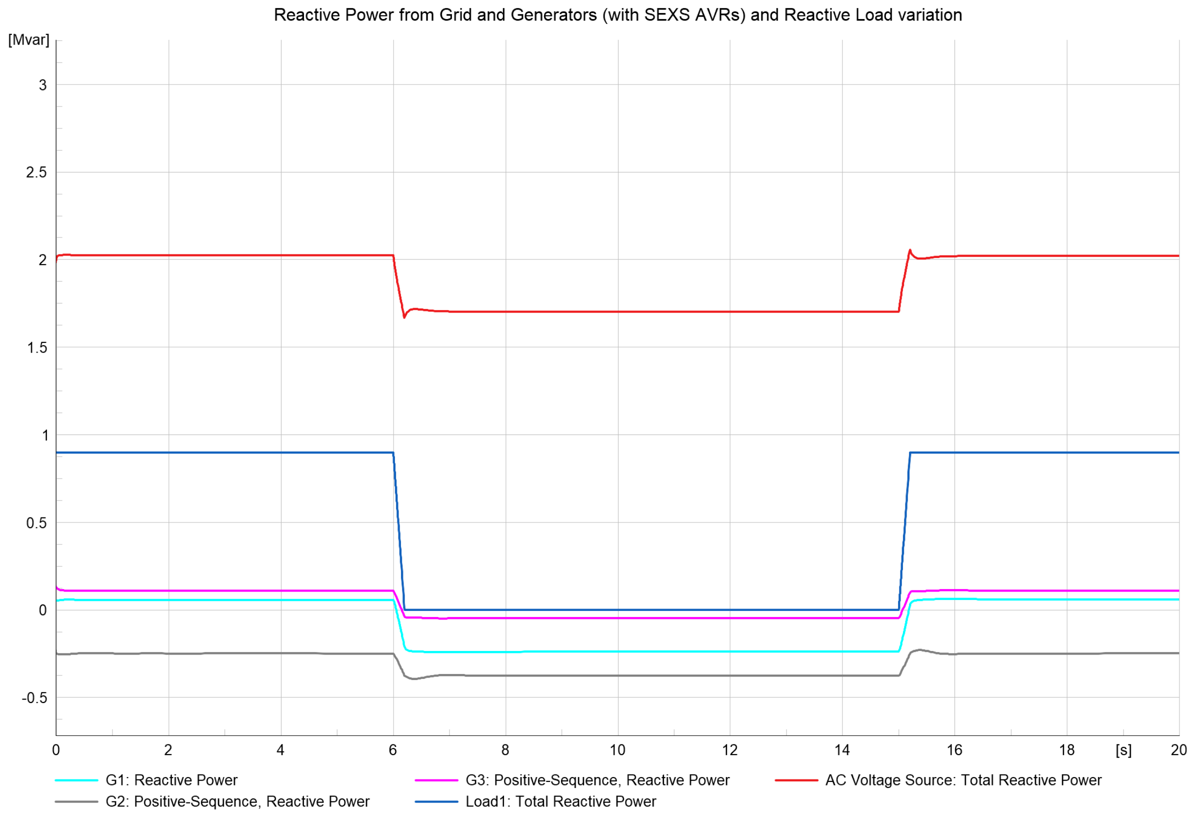

Figure 5.24. Reactive power from main grid and DDGUs along with Load 1 reactive demand.

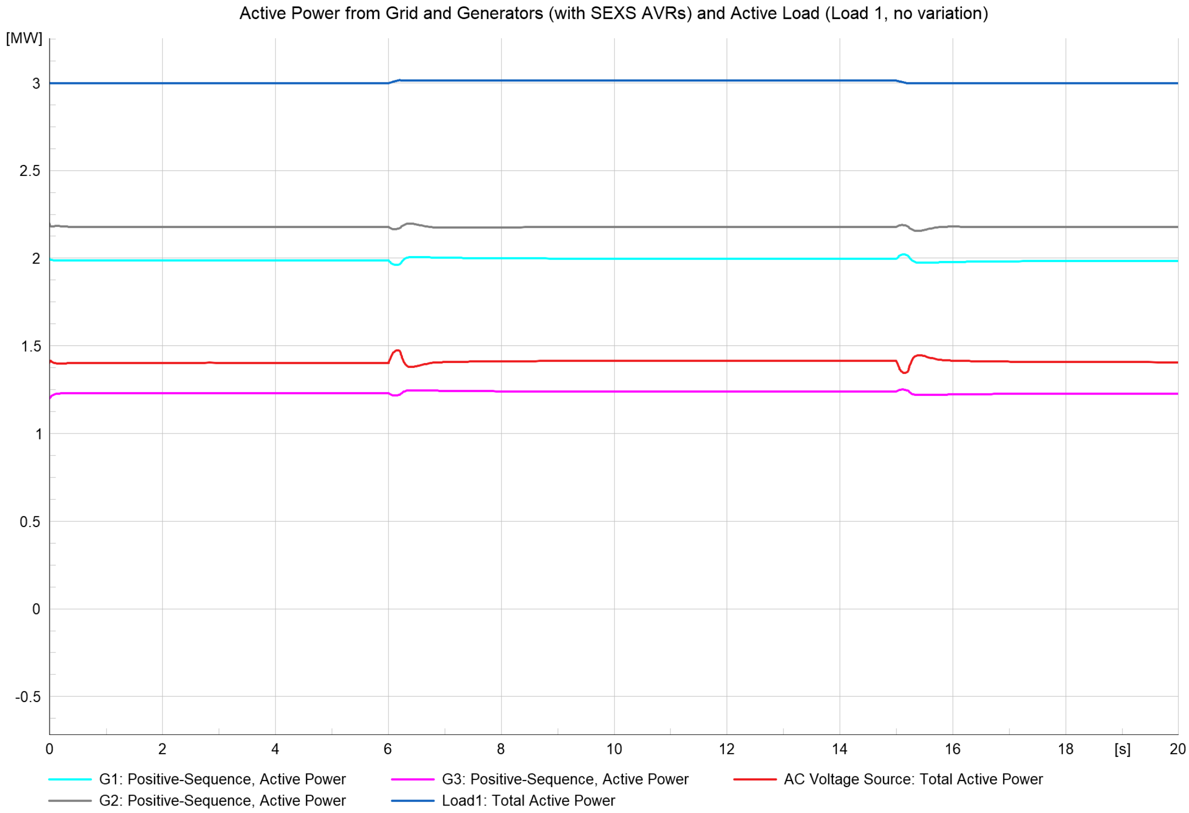

Figure 5.25. Active power from main grid and DDGUs.

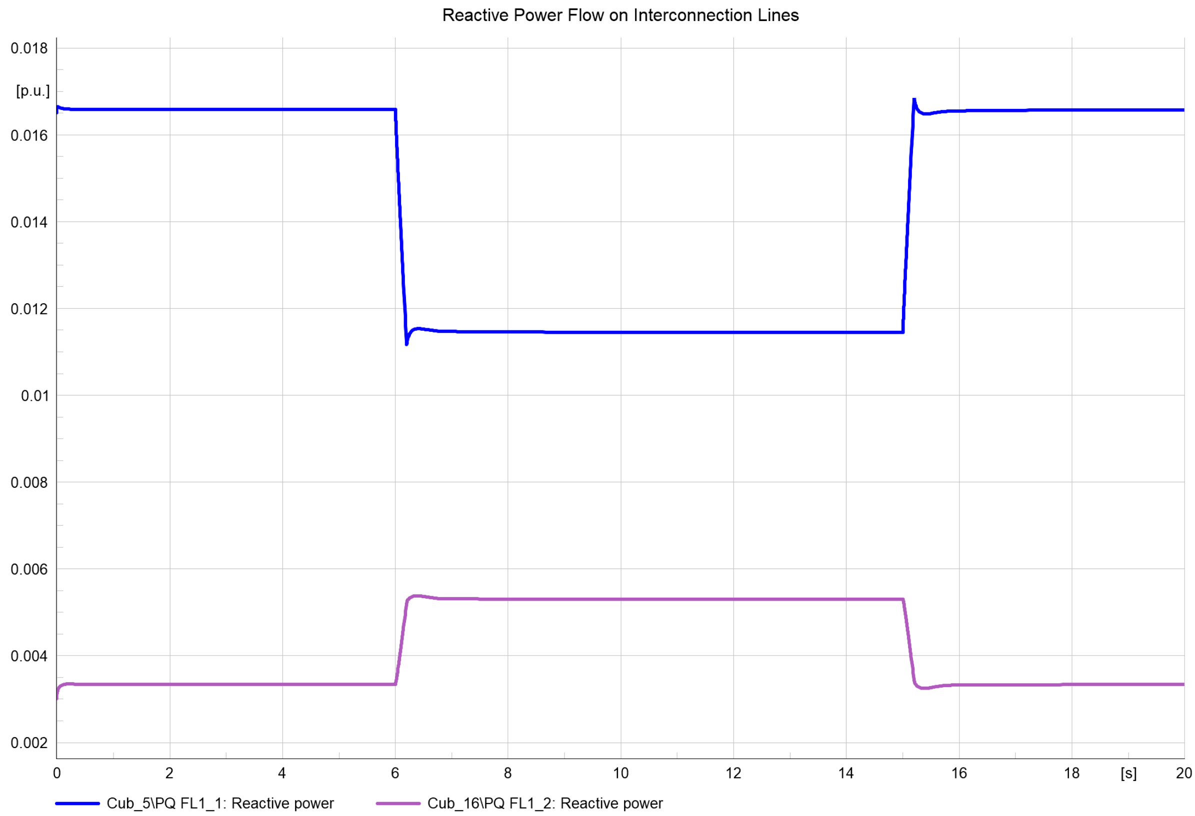

Figure 5.26. Reactive power flow on interconnection lines (Line 1 and Line 2).

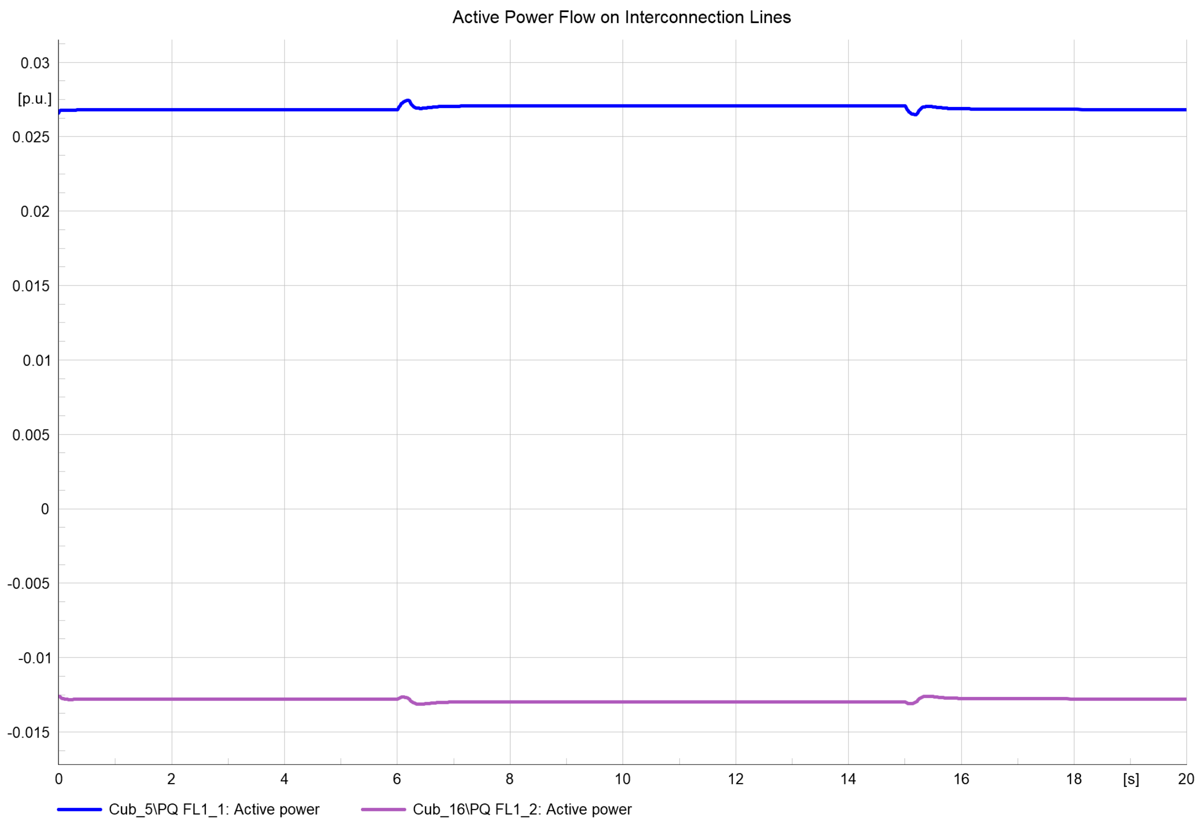

Figure 5.27. Active power flow on interconnection lines (Line 1 and Line 2).

Results depicted in Figure 5.24 to Figure 5.27 clearly demonstrate that SEXS exciter or AVR was not able to control the reactive power flow on the interconnection lines. This was the expected result from the SEXS controller.

5.5.3 Case Study 10: Active and Reactive power demand variation

Again, for Configuration 2, as shown in Figure 5.19, reactive demand of Load1 (0.9 MVAr) was ramped down in 0.2 sec to 0 MVAr and active power demand of Load2 is ramped down to 1 MW (from 2 MW in 0.2 sec) at t = 6 sec. The reactive demand of Load1 was then ramped back up to 0.9 MVAr and active demand of Load2 was also restored back to 2 MW at t = 15 sec.

This test was designed to test both sections (active and reactive power flow control) of the enhanced IFC. Ramping down active and reactive power simultaneously will allow us to evaluate the robustness of the controller under dynamic conditions, as both active and reactive power flows will have to be maintained at desired and corresponding reference levels.

By simultaneously manipulating both active and reactive power levels, the test evaluates the ability of the enhanced IFC to coordinate the two types of power flows, which are inherently interrelated but controlled separately. This will provide insights into how well the IRFC and Active Power Flow Control sections of the enhanced IFC perform together.

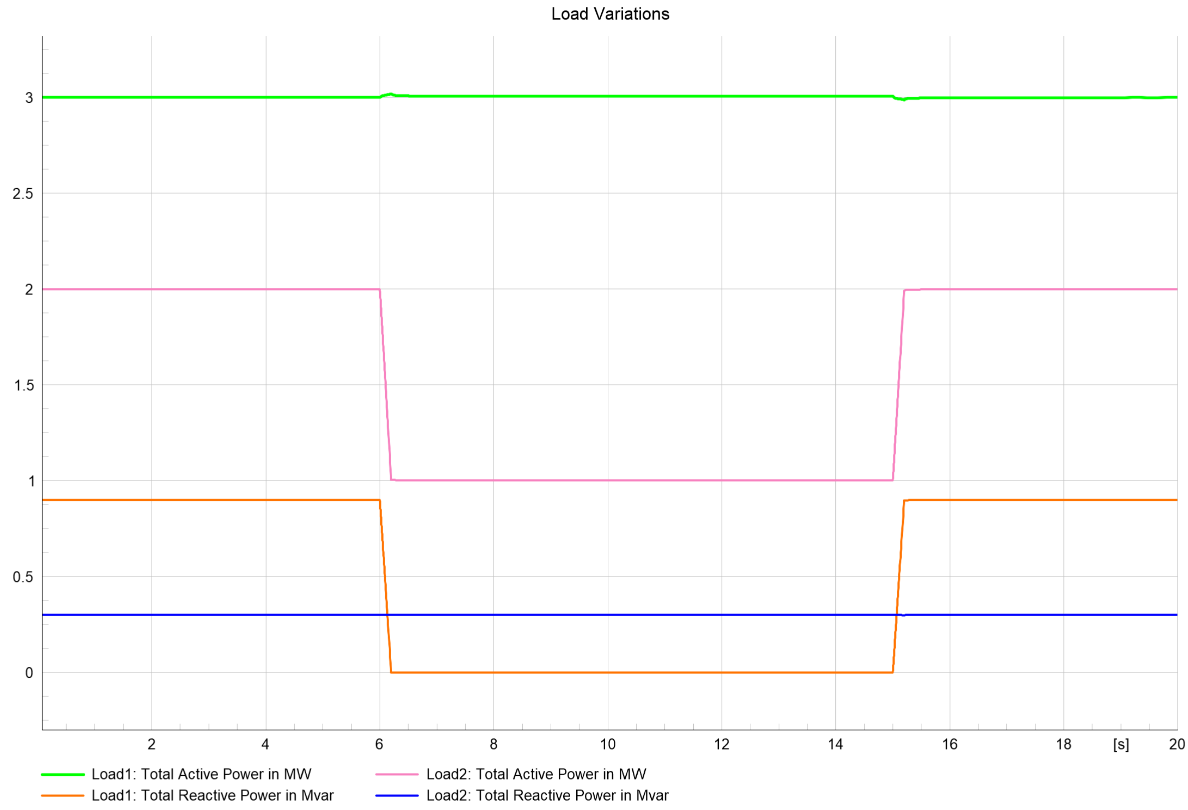

Figure 5.28. Load 1 and Load 2 Active and Reactive powers.

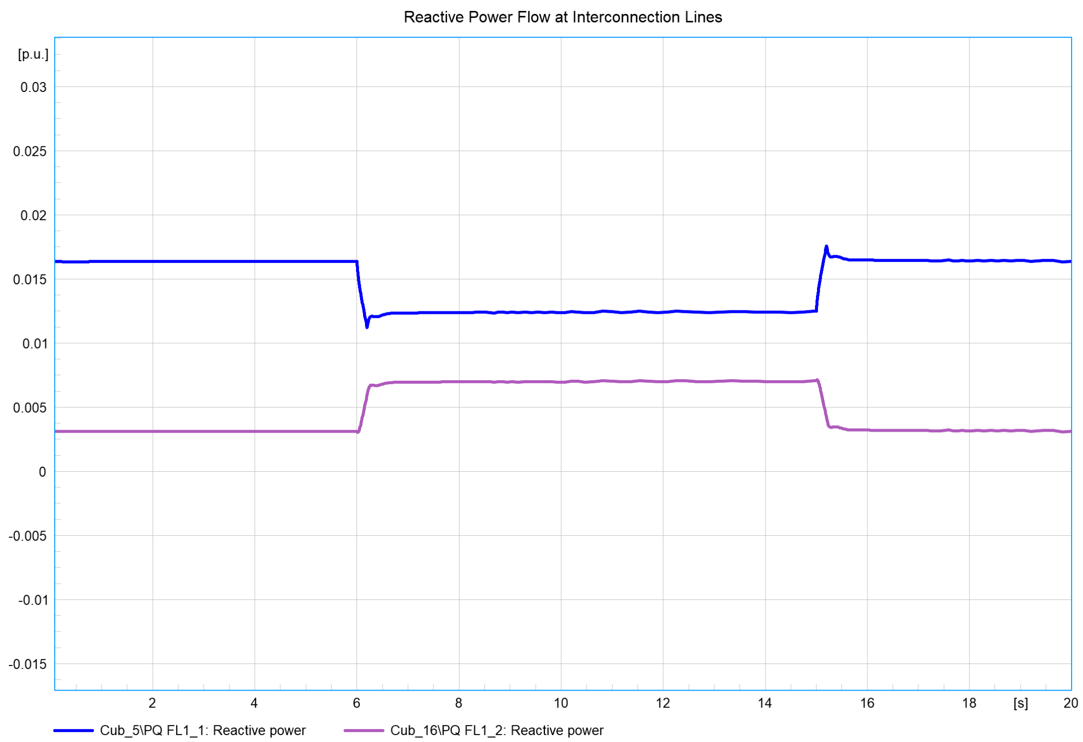

Figure 5.29. Reactive power flows over interconnection lines (Line 1 and Line 2).

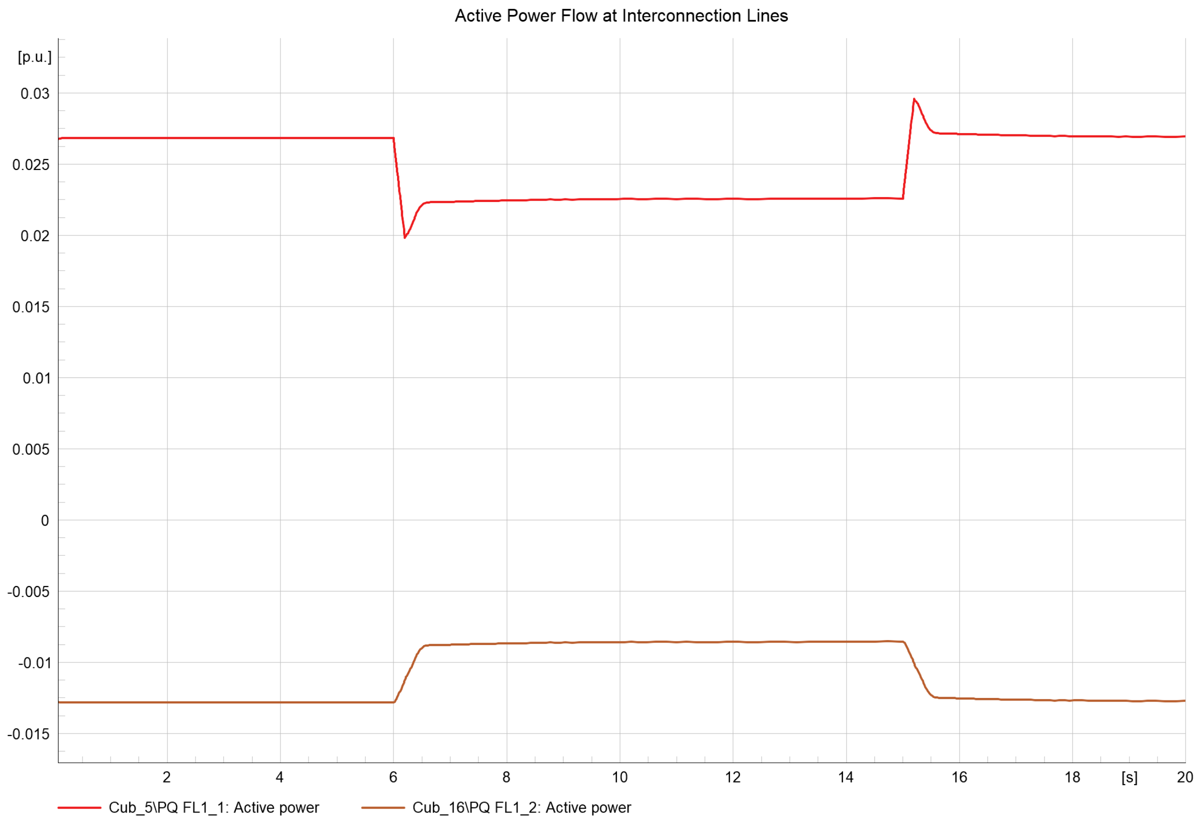

Figure 5.30. Active power flows over interconnection lines (Line 1 and Line 2).

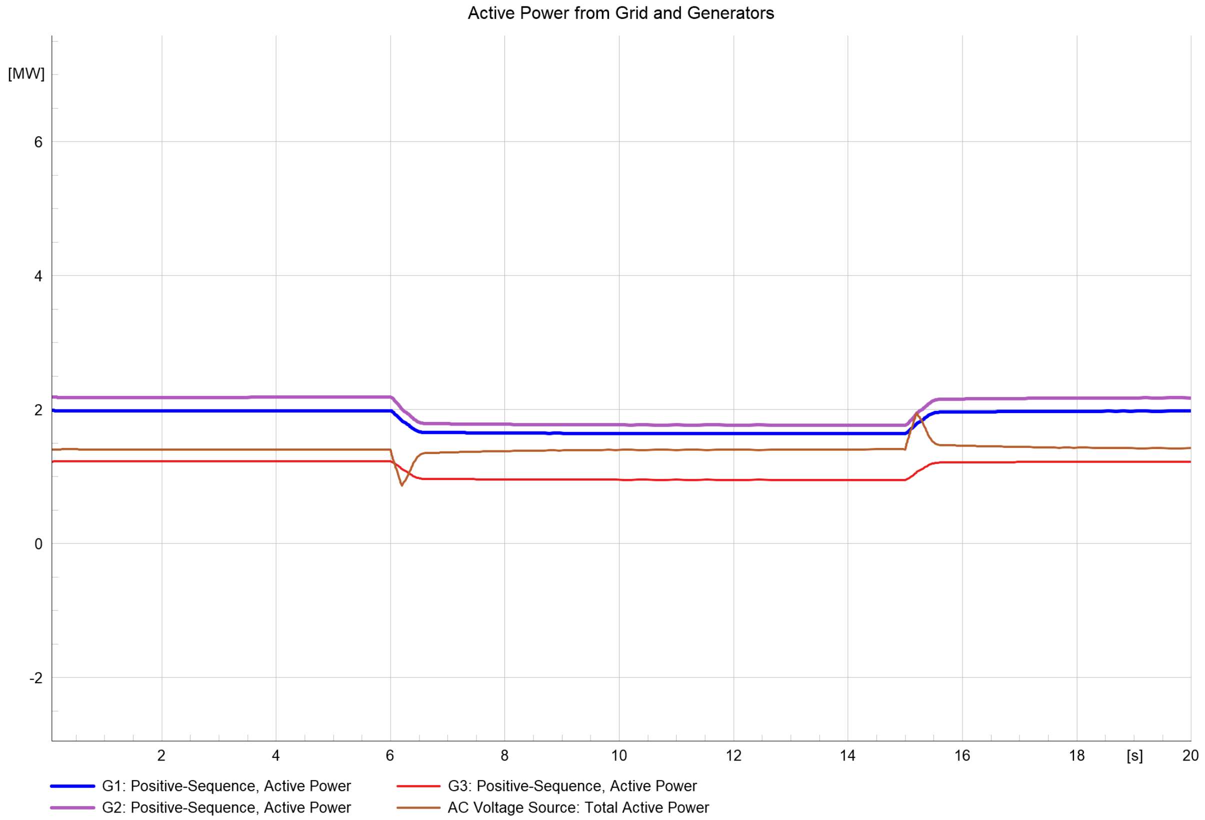

Figure 5.31. Active power from main grid and DDGUs.

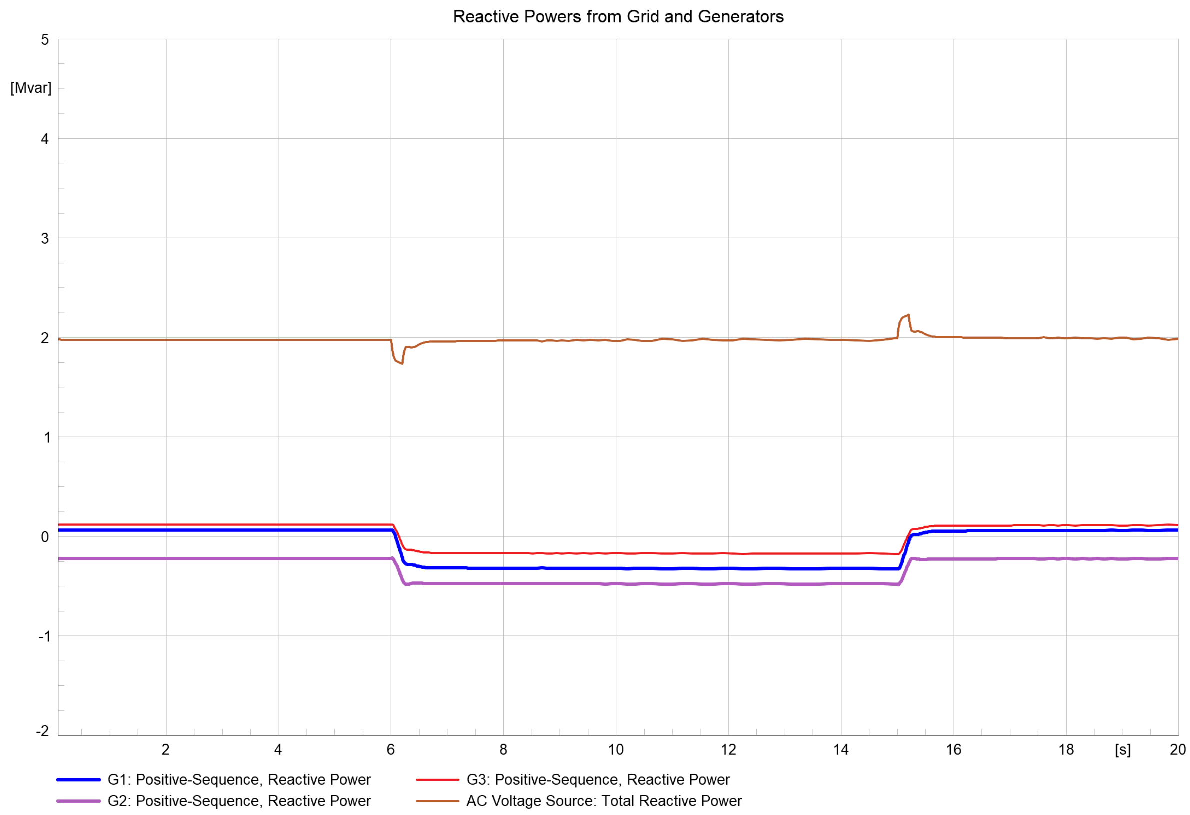

Figure 5.32. Reactive power from main grid and DDGUs.

Figure 5.28 shows the simulated active and reactive load variations. Figure 5.29 to Figure 5.32 demonstrate the action of the active and reactive power flow control simultaneously. Balanced active power flow control and IRFC worked together to ensure sum of both active and reactive power flows over the interconnection lines remains close to the corresponding flow reference values (as shown in Figure 5.29 and Figure 5.30). DDGUs were able to compensate active and reactive power variances diligently (active powers from DDGUs and main grid is shown in Figure 5.31, while the reactive powers are captured in Figure 5.32).

These results provide a detailed visualization of how the enhanced Interconnection Flow Controller (e-IFC), incorporating both active power flow control and the IRFC, operates by simultaneously managing active and reactive power flows at the interconnection lines. The balanced control strategy ensures that changes in either active or reactive power demand are compensated quickly and efficiently by the DDGUs within the micro grid.

The reactive power contribution from the DDGUs adjusts to compensate for any variation in reactive power demand, maintaining the ideal operation of the micro grid. Figure 5.32 particularly emphasizes that the reactive power flow stabilization achieved by the e-IFC, highlighting the controller's ability to prevent significant deviations from the reactive power flow reference.

A key feature demonstrated in these figures is the coordination between the active power flow control and IRFC.

Stable operation across interconnection lines: By maintaining both power flows close to their reference values, the e-IFC prevents disturbances from propagating across the micro grid. If active or reactive power flows deviate significantly from the references, it could lead to frequency or voltage instabilities, negatively impacting the micro grid's interaction with the main grid.

The use of deadbands within the control logic ensures that small fluctuations are tolerated without overcorrecting, which could otherwise destabilize the system.

The results highlight how the DDGUs smoothly transition to compensate for changes in power demand, whether active or reactive. This compensation is crucial to maintain balanced power flow over the interconnections, ensuring that neither active nor reactive power flows deviate significantly from the reference values.

5.5.4 Case Study 11: Frequency, Active and Reactive power demand variation

This test intends to test all three features (balancing active power control, frequency response control and IRFC) of enhanced IFC at the same time. All three parameters are varied at the same time instant to evaluate the stability and ability of the enhanced IFC controller.

Simultaneous Control of Multiple Parameters:

By varying active power, frequency, and reactive power at the same time, the test challenges the e-IFC's ability to handle multivariable control. The three control mechanisms must work in tandem to prevent disturbances in one parameter from affecting the others.

All three parameters (Frequency of the grid, Reactive demand of Load1 and Active demand of Load2) varied at t = 6 sec. Load1 - 100% reactive power ramped down to 0 MVAr in 0.2 sec (from 0.9 MVAr) at t = 6 sec, and then ramped back up to previous value in the same time (0.9 MVAr in 0.2 sec) at t = 15 sec. Load2 – 50% Active power ramped down to 1 MW at t = 6 sec, and then ramped back up to previous value (2MW in 0.2 sec) at t = 15 sec. Frequency of the grid was dropped instantly to 59.8 Hz at t = 6 sec and returned back to normal value (60 Hz) at t = 15 sec.

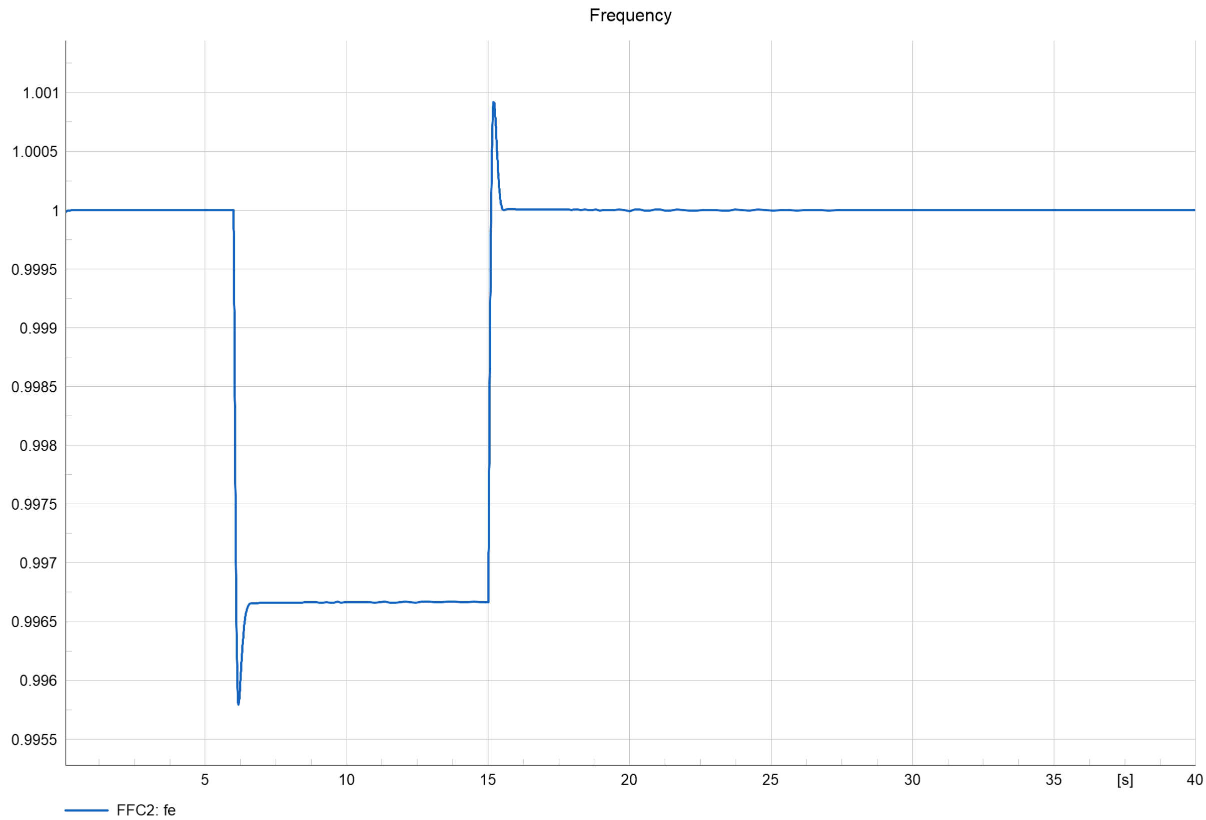

Figure 5.33. Frequency of the overall system.

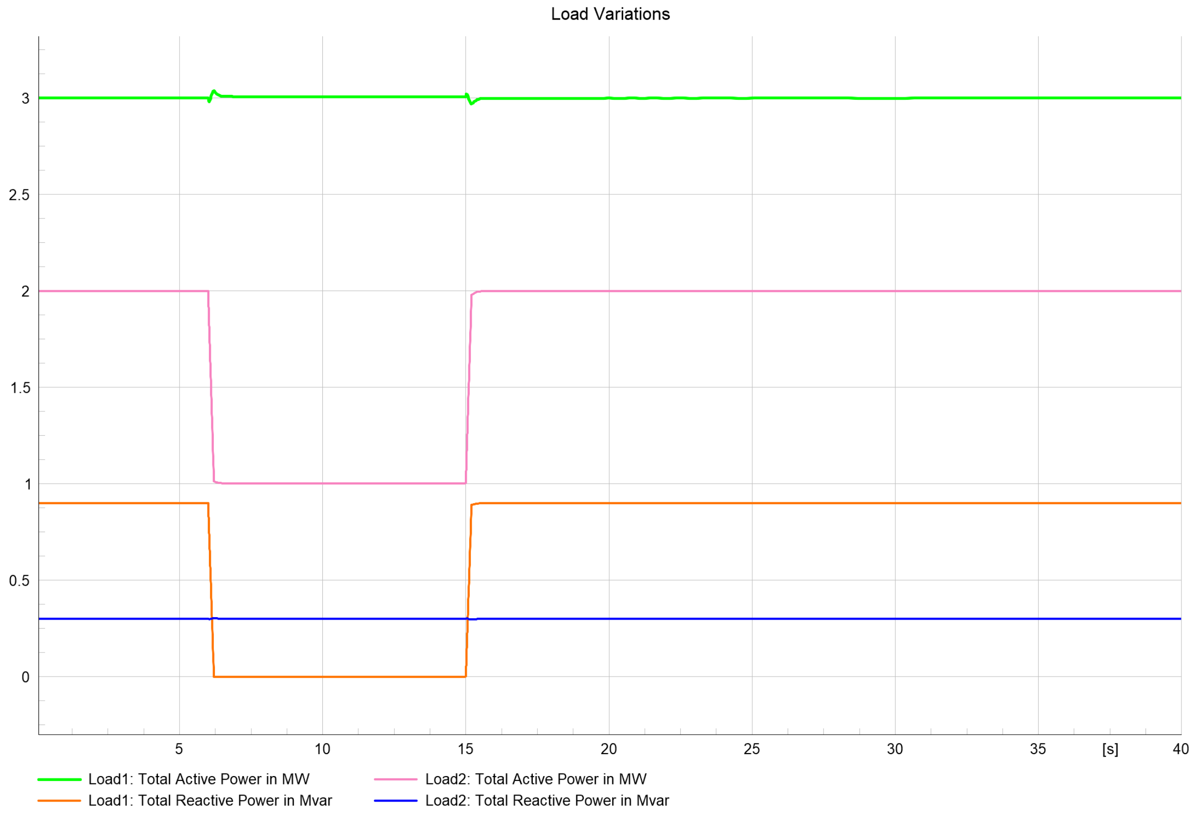

Figure 5.34. Load 1 and Load 2 Active and Reactive powers.

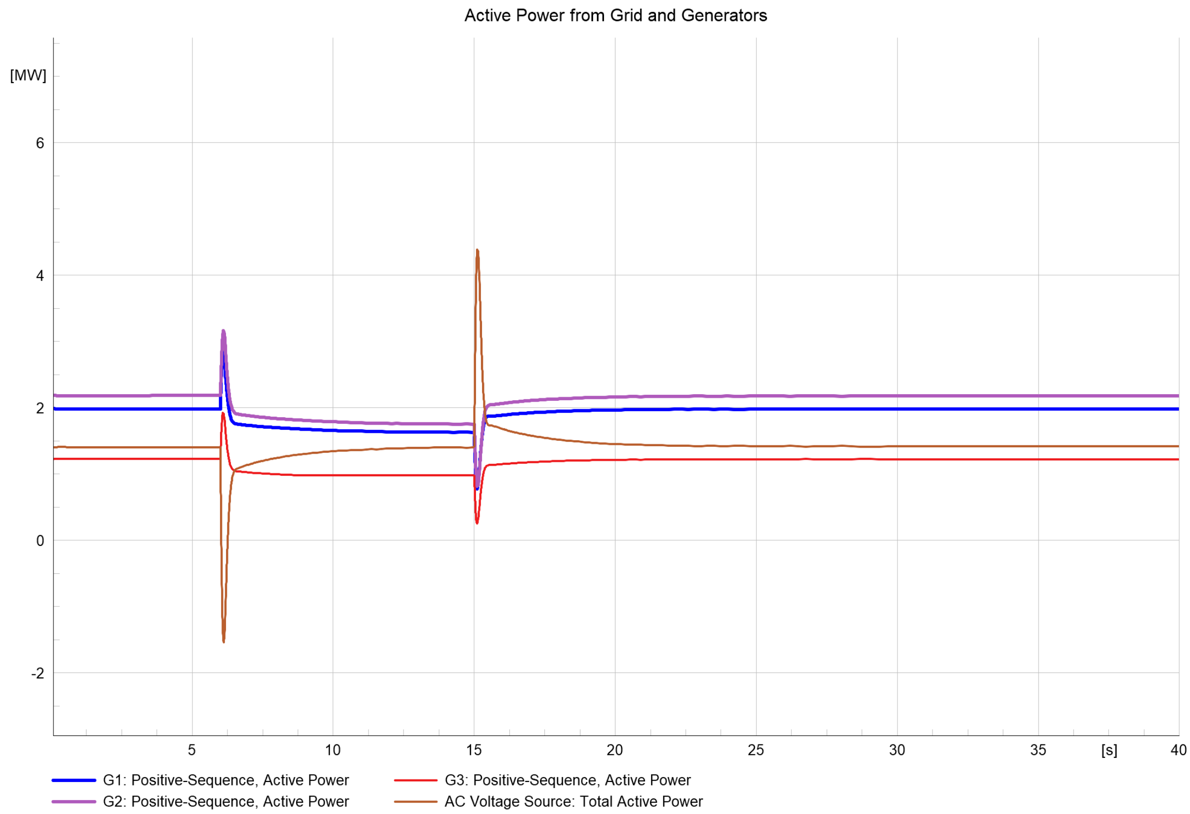

Figure 5.35. Active power from main grid and DDGUs.

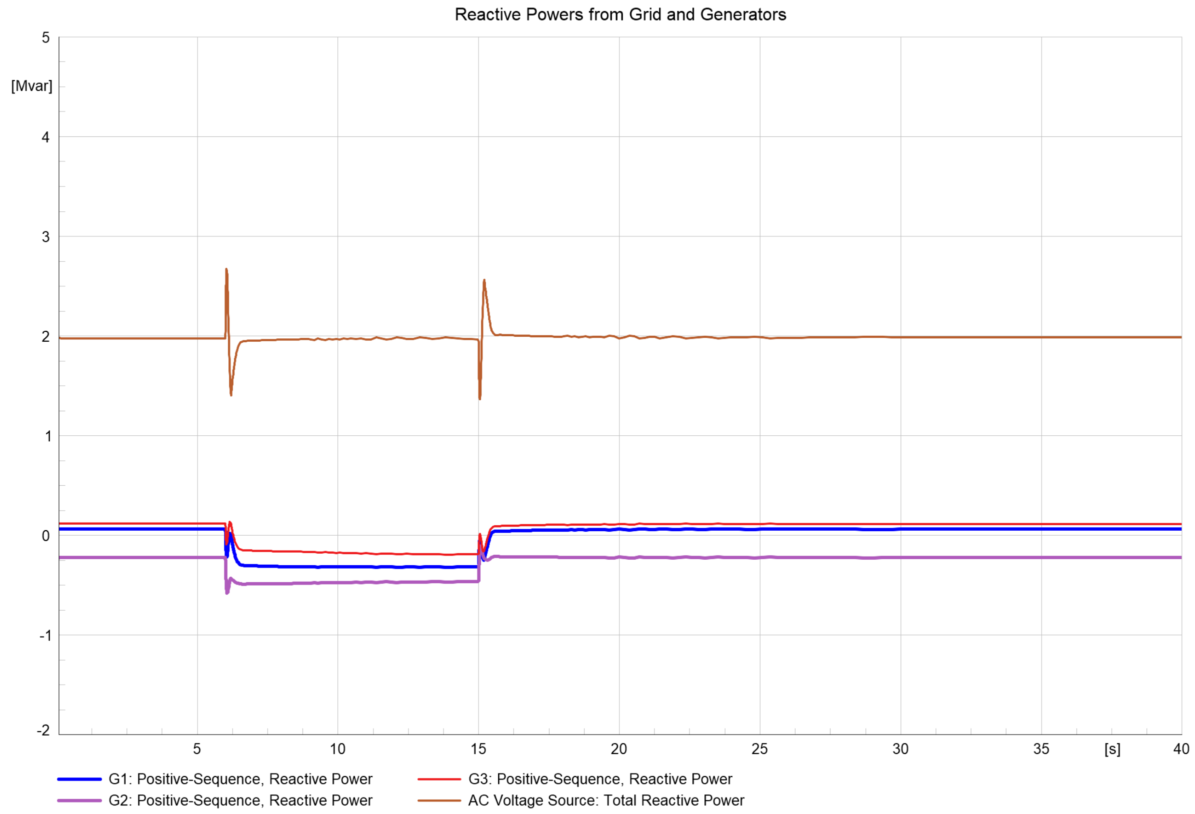

Figure 5.36. Reactive power from main grid and DDGUs.

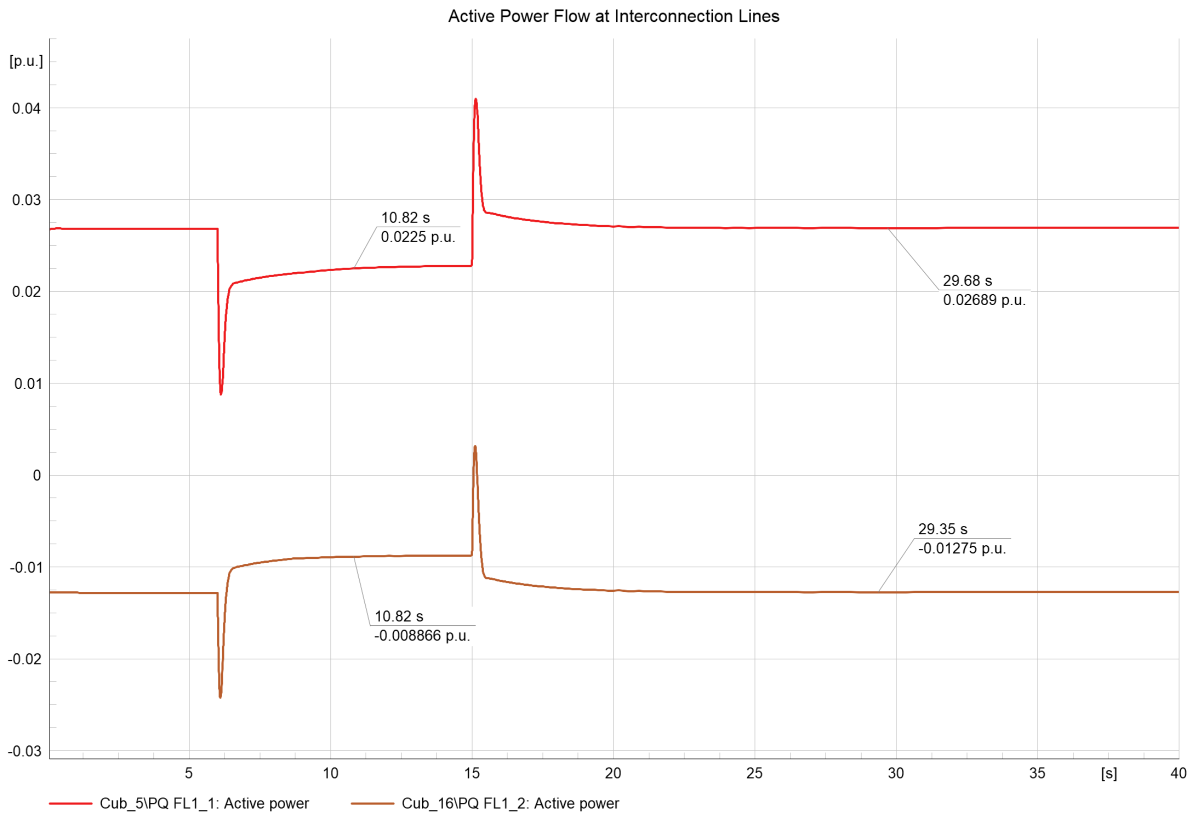

Figure 5.37. Active power flow over interconnection lines (Line 1 and Line 2).

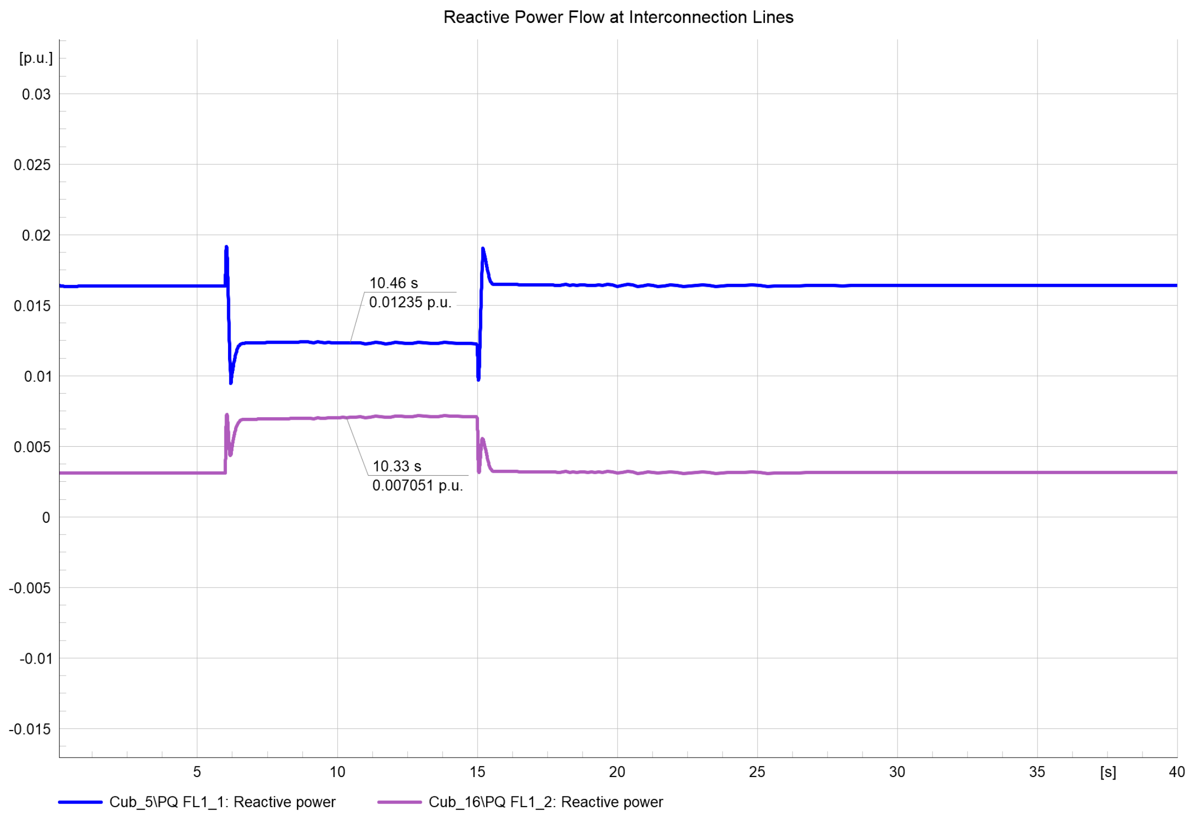

Figure 5.38. Reactive power flow over interconnection lines (Line 1 and Line 2)..

Figure 5.33 shows the induced change in the system frequency. Figure 5.34 captures the active and reactive power variations simulated for Load1 and Load2 (within the micro grid). All of these variations are set to occur at the same time. Figure 5.35 to Figure 5.38 demonstrate that the e-IFC was able to respond successfully for all three simulated variations. It was able to independently control and manage active and reactive power flows on the two interconnection lines to ensure micro grid's ideal operation even during dynamic operating conditions.

The key point in this test was both sections of the e-IFC controller related to balancing active power were tested at the same time, as the active demand of the micro grid was varied along with the frequency. The controller was able to only compensate the varied active demand and was able to balance the impact of the frequency response. The balancing active power control mechanism worked in tandem with the frequency response control, ensuring that the micro grid's internal active demand was met, while also addressing the frequency deviations from the main grid. This demonstrates the robustness and coordination between the different sections of the e-IFC, especially under dynamic operating conditions.

To demonstrate the independence of the active and reactive power controllers (IRFC) within e-IFC, the controller was tested by also varying the micro grid's internal reactive demand at the same instant. Figure 5.36 clearly demonstrate that the reactive power from the grid remained at a constant value during these variations. Although, reactive power flow on two interconnection lines did vary, as shown in Figure 5.38. However, the sum of the reactive power flow remained close to the flow reference value.

This test focused on the ability of the enhanced IFC to independently control active and reactive power flows on the two interconnection lines. Results demonstrate that the active and reactive power flow on both interconnection lines was effectively managed. The e-IFC was able to detect the changes in the active power demand and respond accordingly by adjusting the DDGUs active and reactive power outputs.

Key Takeaways

The test highlights several important points regarding the e-IFC's performance:

Effective Independent Control: The ability of the e-IFC to independently control active and reactive power flows is crucial for maintaining micro grid's stability, especially under dynamic and uncertain operating conditions. The system was not only able to manage changes in power demand but also ensures that these changes do not negatively impact other control processes.

Coordination Between Controls: The test results demonstrate the coordination between the balancing active power control, frequency response control, and IRFC mechanisms within the e-IFC. These controls work together seamlessly, ensuring that variations in one area (such as frequency) do not disrupt the stability of the overall system.

Stable Power Flow Over Interconnection Lines: Despite variations in the micro grid's internal demand and external grid conditions, the e-IFC successfully maintained the sum of both active and reactive power flows over the interconnection lines close to their respective flow reference values. This is essential for the ideal operation of the micro grid, particularly in scenarios where it relies on interconnection with a larger grid.

5.6 Independent Active and Reactive Power Control

In modern power systems, particularly in micro grids with distributed generation and high renewable penetration, the ability to independently control active (real) and reactive power is essential for ensuring system stability, power quality, and efficient / ideal operation. While active power (measured in watts) is directly responsible for doing useful work (running electrical devices, lighting, etc.), reactive power (measured in volt-amperes reactive, or VARs) is essential for maintaining voltage levels across the power grid, which is necessary for the transmission of active power.

In a complex power system, interactions between active and reactive power flows can introduce operational challenges. Without independent control, disturbances or changes in one type of power flow could inadvertently affect the other. This coupling between active and reactive power would lead to instability and inefficiency in system operations.

For example:

- If the system were to experience a change in reactive power demand (e.g., from inductive loads), and the active power control was not decoupled, this could result in frequency deviations or power imbalances.
- Conversely, variations in active power due to load changes or generation output fluctuations could induce undesirable voltage variations if reactive power is not independently controlled.

The decoupling of active and reactive power control ensures that disturbances or adjustments in one do not propagate or negatively affect the other. Independent control mechanisms provide the ability to manage these types of variations locally and effectively.

Modern power systems, particularly micro grids, often rely heavily on distributed generation (DG) sources such as wind turbines, solar PV systems, and energy storage. These systems face more complex and variable operational environments than traditional grids, due to fluctuating renewable energy output.

- Renewable generation introduces variability: Renewable energy sources, especially solar and wind, exhibit intermittency in power output. Independent active power control allows the system to manage variations in active power output from these sources without compromising the voltage stability provided by reactive power control.

- Power electronics in DG units: Many DG sources, like solar inverters, rely on power electronics that allow independent control of active and reactive power. This is critical for voltage regulation in the distribution network while also ensuring that the micro grid can maintain frequency stability.

The ability to manage active and reactive power independently is therefore critical to the successful operation of micro grids and renewable energy systems, where dynamic changes in power generation and consumption can have rapid and significant effects on both voltage and frequency. In systems where micro grids are interconnected with a larger grid, it is essential to independently control the flow of active and reactive power to maintain stability and avoid causing disturbances in the main grid.

In all of the simulated tests presented above, the e-IFC successfully demonstrated its capability to independently control both active and reactive power flows over the interconnection lines. This achievement highlights the robustness of the controller's design and its ability to manage power dynamics in real-time. With the enhancements made to the IFC, transforming it from a simple active power controller into a comprehensive PQ controller (Active-Reactive power controller), the independent management of active and reactive power is a key and critical feature.

6. CONCLUSION AND FUTURE WORK

6.1 Brief Summary

With several recommended ways for active and reactive power-sharing of DDGUs in a micro grid, utilities or micro grid operators should choose the method that is best suited to their individual micro grid architecture, configuration and load concentration. The active and reactive power-sharing approaches mentioned in the literature were primarily designed for the micro grids with one interconnection to the main grid system.

This thesis initially introduced an improved active power-sharing control for micro grids, namely IFC. which not only overcomes the constraints of previously proposed (in the literature) controller the FFC (for active power flow control) but has also been demonstrated to be effective for micro grids which have several interconnections with one or several main grids. Operating DDGUs with the proposed IFC allows them to compensate in a unified way for any load/generation changes anywhere inside the micro grid, i.e. as one huge virtual generating unit, rather than restricting their reaction to a specific area within the micro grid. When compared to FFC, the IFC mode of operation can more efficiently use the available actual power generating capacity inside the micro grid. The capacity of the DDGUs to adapt to global load/generation changes allows the micro grid to operate optimally even after severe contingencies, including the loss of DDGUs or interconnectors. This is the primary benefit of the IFC over the FFC.

The controller then further enhanced to a more versatile active and reactive power (P&Q) flow controller with the addition of frequency response balancing and interconnection reactive power flow controller (IRFC). These additional features make it a complete flow controller which can ensure ideal operation of the micro grid not only with reference to the active power demand/supply but also with reference to the reactive power exchange between the main grid(s) and the micro grid. With frequency response balancing, e-IFC demonstrated to maintain the ideal operation even during the transient frequency excursion events in the main grid. Such events are very common in the real-world power systems and therefore enhanced IFC can help interconnected micro grids to be more stable, predictable and controllable for the main grids, without losing its capability to manage isolated micro grids.

Frequency Response Balancing, allows the controller to over-write the active power response from DDGUs in response to minor frequency excursions in the main grid. This is a crucial advancement as it helps micro grids maintain stability and synchronism during frequency fluctuations in the larger grid, which are common in real-world power systems. During frequency deviations (such as over frequency or under frequency events), enhanced IFC acts by maintaining active power flow, ensuring the micro grid continues to operate ideally.

IRFC is another vital enhancement that specifically targets the management of reactive power flow between the micro grid and the main grid. Reactive power is critical for maintaining voltage levels and ensuring efficient operation of power systems, especially in interconnected grids. The IRFC allows for the independent management of reactive power, ensuring that the reactive power exchange remains stable, even when there are fluctuations in demand or generation within the micro grid.

Unlike traditional controllers that manage active and reactive power together (often prioritizing one over the other), the e-IFC independently manages these flows. This independence means that even during disturbances like load changes or grid frequency events, both active and reactive power remain balanced and within allowable limits.

How e-IFC Differs from Conventional Controllers:

Unlike many traditional power flow controllers that manage active and reactive power together or prioritize one over the other, the enhanced IFC offers independent control of both. This means the micro grid can react to active power demand variations without affecting reactive power management and vice versa. This independent control is crucial for maintaining both the stability of power flows and efficient operation of the grid.

Standard flow controllers are often designed to handle either active power flow or reactive power flow, not both simultaneously or independently. The e-IFC integrates both through its PQ control framework, offering comprehensive management of both power flows. This makes the e-IFC uniquely versatile, enabling it to handle a broader range of operating conditions, including dynamic load changes and renewable energy integration, without compromising stability or efficiency.

Enhanced IFC has demonstrated that it can ensure more predictable and controllable operation of the micro grids, even during dynamic conditions, makes it an excellent choice for modern power systems that intend to integrate significant naturally varying renewable energy sources and variable loads.

In conclusion, the e-IFC represents a significant advancement over traditional active and reactive flow controllers. Its ability to manage active and reactive power flows independently, balance power during frequency excursions, and offer robust control under various grid conditions makes it an essential tool for ensuring stable, efficient, and reliable micro grid operation in interconnected systems.

6.2 Key Contributions and Innovations

E-IFC is fundamentally designed to act as a universal active and reactive power-sharing controller which has no limitations with respect to micro grid's design, configuration, interconnections, placement and number of generation resources etc. The importance of maintaining an active and reactive power-sharing method that remains effective and robust even when network configurations are modified cannot be overstated for micro grid operators.

Network configurations are subject to change, especially in evolving energy landscapes, and having a control strategy that can seamlessly adapt to these changes is highly valuable.

The proposed approach offers a solution that addresses this critical need. It demonstrated its success in preserving the overall sum of active and reactive power flow to or from the main grid when tested across various simulated operating scenarios. This capability ensures that the micro grid remains a reliable and predictable source or consumer of active and reactive power, regardless of how the network configuration evolves over time.

One of the notable features of this proposed technique is its ability to accommodate diverse values of active and reactive power flows at different interconnections within the micro grid while maintaining a constant total active and reactive power flow to or from the micro grid. This flexibility allows the micro grid to adapt to varying power generation and consumption patterns, supporting operational efficiency and grid stability.

Furthermore, the suggested control approach is versatile and can be applied to micro grids with one or more active grid linkages. This adaptability is crucial, as micro grids come in various configurations and sizes, and the control strategy should be compatible with a broad range of micro grid setups.

The e-IFC provides several advanced capabilities that differentiate it from traditional active and reactive power controllers. Following are some key benefits of e-IFC.

1. Real-Time Dynamic Performance:

One of the major strengths of the enhanced IFC is its ability to react in real-time to the dynamic conditions of the grid. Traditional controllers often struggle with maintaining ideal operation during transient events, but the enhanced IFC is equipped to handle rapid fluctuations in both active and reactive power demands. By integrating frequency response balancing and reactive power flow control (IRFC), it ensures that the power flows are continuously adjusted in response to grid conditions. This real-time capability is critical for maintaining grid stability, especially in micro grids where sudden changes in load or generation are common, such as with the integration of intermittent renewable energy sources.

2. Decoupling of Active and Reactive Power Control:

The decoupling of active and reactive power control is a significant feature that is required in the modern day power systems. In traditional systems, controlling both parameters together can lead to conflicts, especially when both are required to change in response to grid variations. In contrast, the enhanced IFC ensures that active power can be adjusted in response to frequency deviations or demand/flow variations, while reactive power can be controlled independently to manage interconnection power flows. This decoupling ensures that both active and reactive power flows are kept within acceptable limits without one interfering with the other, providing more predictable behaviour in interconnected power systems.

3. Robustness During Grid Events:

In real-world operations, minor frequency excursion events—where grid frequency temporarily deviates from the nominal value—are common. These events can cause instability, particularly in systems with renewable energy sources, which may not be as flexible in adjusting output as conventional generators. The enhanced IFC's frequency response balancing allows the micro grid to respond effectively to such events.

4. Seamless Transition Between Grid-Connected and Islanded Modes:

Micro grids must often switch between being grid-connected and operating in islanded mode. The enhanced IFC facilitates a seamless transition between these modes by managing both active and reactive power flows independently. In grid-connected mode, it ensures that power exchange with the main grid remains stable. When transitioning to islanded mode, it takes control of the frequency regulation within the micro grid, providing a stable local environment without relying on external grid support. This flexibility is vital for micro grids, especially in situations where the main grid may experience outages or instability.

5. Improved Integration of Distributed Energy Resources (DERs):

The e-IFC is designed to work efficiently in environments that include a variety of Distributed Energy Resources (DERs) such as solar, wind, and battery storage. These resources are inherently variable and can introduce complexity into the management of power flows. Traditional controllers may struggle to manage these fluctuations effectively. However, the enhanced IFC can absorb the variability in both active and reactive power generation from DERs and adjust its control strategy accordingly. By doing so, it ensures smooth integration of renewable energy, making the micro grid more resilient and capable of accommodating higher levels of renewable penetration.

6. Operational Flexibility with Deadband Control:

One of the useful features that enhances the flexibility of the enhanced IFC is the ability to introduce deadbands in the control algorithms. A deadband is a range within which small fluctuations in power flows do not trigger corrective actions from the controller. This feature helps to reduce unnecessary switching and adjustments, which can improve the overall efficiency and reduce wear and tear on equipment. For example, in active power control, the enhanced IFC can allow small frequency deviations to exist without adjusting power flows, which can help avoid overreaction to minor events while still maintaining overall system stability.

7. Enhanced Predictability for Grid Operators:

From a grid operator's perspective, one of the key advantages of the enhanced IFC is its ability to ensure that the micro grid operates in a predictable and controllable manner. The independent control of active and reactive power flows, combined with frequency balancing, means that the micro grid can be relied upon to provide a stable output to the main grid even during disturbances. This predictability is critical in interconnected power systems, where disturbances in one part of the system can propagate and cause disruptions in other areas. By keeping the power exchange with the main grid stable, the enhanced IFC helps to maintain the overall integrity of the grid.

8. Customizability of Control Settings:

The e-IFC is highly customizable, allowing system operators to adjust parameters such as gain settings, deadbands, and frequency response characteristics. This customization ensures that the controller can be tailored to the specific needs of a micro grid, whether it is focused on renewable energy integration, load balancing, or grid support. This flexibility makes it an ideal solution for a wide range of applications, from small isolated micro grids to large interconnected systems.

The e-IFC demonstrated the potential to stand out as a powerful tool in modern micro grid management, ensuring the reliable, stable, and efficient operation of both active and reactive power flows.

It's also important to highlight that the proposed method represents a novel contribution to the field of micro grid research. While the topic of micro grids with multiple grid connections is highly relevant in modern energy systems, it has not been thoroughly explored or detailed in existing research papers, to the extent of our scope of search. This research opens up a new dimension and direction in the field, providing insights and solutions to the specific challenges and opportunities posed by micro grids with multiple grid connections. It contributes to the growing body of knowledge in micro grid control and operation, addressing a gap that has not been adequately covered in existing literature.

.

6.3 Future Work

This work has initiated a discussion which will need further elaborations on the following related operational aspects of micro grids with multiple grid connections:

1. Coordination of different interconnected micro grids.
2. Ancillary services from the micro grid to the main grid(s).
3. AI based predictive and economic Dispatch of DDGUs.
4. Implementing dynamic transient and voltage stability limits on active and reactive power flow at different interconnectors etc.

Future power systems may involve the coordination of multiple micro grids operating in parallel with the main grid. Such a setup offers potential for increased flexibility and reliability but requires sophisticated control strategies to avoid conflicts. A coordination protocol can be established using distributed control architectures where multiple micro grids interact with each other and the main grid to maintain overall system balance. Investigate peer-to-peer energy trading between micro grids for enhanced resilience and efficiency.

Micro grids can contribute to ancillary services (e.g., system restart or black start, system strength, frequency regulation, spinning reserve) for the larger grid. However, their participation in these markets is still limited due to technical and economic constraints. Future research should explore market frameworks that enable micro grids to provide ancillary services, either independently or as a group, effectively while maintaining their own individual (internal and external) operational goals. With the availability of the grid forming inverters, micro grids can provide black start ancillary service for the main grids using battery energy storage systems (BESS) to establish the initial voltage reference.

In future, AI-based predictive and economic dispatch controllers of DDGUs can revolutionize micro grid management by enhancing efficiency and resilience. Advanced AI algorithms will use real-time data from distributed energy sources and market conditions to predict demand and optimize both active and reactive power flows. These systems can enable precise economic dispatch while simultaneously ensuring grid stability, even during rapid fluctuations in renewable energy generation. Predictive maintenance powered by AI will further reduce downtime and operational costs.

With enhanced IFC, we used static flow references for active and reactive power flow control. In the future, we could further enhance the functionality of the Interconnection Flow Controller (IFC) by dynamically calculating active and reactive power flow references based on real-time stability limits. Instead of relying on static flow references, dynamic references would adjust in response to varying grid conditions, demand fluctuations, and transient events. These dynamically calculated flow references would ensure that the power exchange between the micro grid and the main grid operates within safe stability margins, optimizing system performance and resilience.

7. REFERENCES

[1] Setiawan, M., Abu-Siada, A., Shahnia, F. April 2018. “A New Technique for Simultaneous Load Current Sharing and Voltage Regulation in DC Microgrids.” *IEEE Transactions on Industrial Informatics*: Vol. 14, Issue 4: 1403-1414.

[2] Mubashwar, Md, Abu-Siada, A. S., Islam, and Dahidah, M. July 2018. "A New Cascaded Multilevel Inverter Topology with Galvanic Isolation." *IEEE Transactions on Industry Applications.* Vol. 54, Issue 4: 3463-3472.

[3] Aghanoori, N., et al. September 2020. “Enhancement of Microgrid Operation by Considering the Cascaded Impact of Communication Delay on System Stability and Power Management.” *International Journal of Electrical Power and Energy Systems*. Vol. 120: 105964.

[4] Ahn. Seon-Ju. 2020. “Power-sharing Method of Multiple Distributed Generators Considering Control Modes and Configurations of a Microgrid.” *IEEE Trans. Power Delivery*. Vol 25, 10.1109/TPWRD.~~2010~~: 2047736.

[5] Nguyen, Khanh-Loc. 2012. ‘Power Sharing Method for a Grid connected Microgrid with Multiple Distributed Generators.” *IEEE J. Elect. Eng. & Tech*. Vol 7: 459-467.

[6] Aghanoori, N. et al. 2019. “Improving Voltage of Remote Connection Using Wind-Solar Farms Equipped with New Voltage Control Strategy Using Virtual Impedance Monitoring Enabled by IEC61850 Communication.” *IET Generation, Transmission & Distribution.* Vol. 13, no. 11: 2199-2207.

[7] Jiayi, H. 2008A. "Review on distributed energy resources and microgrid.” *Renew. Sustain. Energy Rev.* Volume 12: 2472-2483.

[8] Bevrani, Hassan. 2013. “An Intelligent Droop Control for Simultaneous Voltage and Frequency Regulation in Islanded Microgrids.” *IEEE Trans. Smart Grid*. Vol 4: 1505-1513. 10.1109/TSG.2013.2258947.

[9] Ahn, Seon-Ju. 2013. "Power Scheduling of Distributed Generators for Economic and Stable Operation of a Microgrid." *IEEE Trans. Smart Grid.* Vol 4, 10.1109/TSG.2012.2233773.

[10] Katiraei, F. 2006. "Power Management Strategies for a Microgrid With Multiple Distributed Generation Units. IEEE Trans." *Power Systems*. Vol 21, 10.1109/TPWRS.2006.879260.

[11] Katiraei, F. 2005. "Micro-Grid Autonomous Operation During and Subsequent to Islanding Process." *IEEE Trans. Power Delivery.* Vol 20, 10.1109/TPWRD.2004.835051.

[12] Pecas Lopes, J. A. 2006. "Defining control strategies for microgrids islanded operation." *IEEE Trans. Power Syst*. Vol 21: 916-924.

[13] Khani, Davood. 2012. "Impacts of distributed generations on power system transient and voltage stability." *Electrical Power and Energy Systems*. Vol 43: 488-500.

[14] Minh Bui, Duong. 2012. "Investigate dynamic and transient characteristics of microgrid operation and develop a fast-scalable-adaptable algorithm for fault protection system." *Electrical Power Systems Research*. Vol 120: 214-233.

[15] Ai, Qian. 2014. "The impact of large-scale distributed generation on power grid and microgrids." *Renewable Energy*. Vol 62: 417-423.

[16] Ahn, S. J. 2009. *A new power sharing method for distributed generations in the next-generation grid*. Ph.D. dissertation: Seoul National Univ. Seoul, Korea.

[17] Laaksonen, Hannu, and Kauhaniemi, Kimmo. 2007. *Sensitivity analysis of frequency and voltage stability in islanded microgrid*. Proceedings of 19th Inter. Conf. on Elec. Distribution, paper 0371: Vienna, Austria, May 21-24, 2007.

[18] Wang, Peng. 2012. "Operational Adequacy Studies of Power Systems with Wind Farms and Energy Storages." *IEEE Trans. Power Systems*. Vol 27, 10.1109/TPWRS.2012.2201181.

[19] Abdulmohsen, A. M. and Omran, W. A. 2022. "Active/reactive power management in islanded micro grids via multi-agent systems. *International Journal of Electrical Power & Energy Systems*, 135, 107551.

[20] Golla, M.S., Thangavel, S., Simon, S. P. and Padhy, N. P. 2022. "An Enhancement of Power Quality With Efficient Active Power Transfer Capability in a PV–BSS-Fed UAPF for Micro grid Realization." *IEEE Systems Journal*.

[21] Barik, M. A., Pota, H. and Ravishankar, J. 2013. "A decentralized coordinated controller for load sharing in a micro grid with renewable generation. 2013." Conference report, *IEEE Power & Energy Society General Meeting.*

[22] Akbari, R., Tajalli, S. Z., Kavousi-Fardand, A. and Izadian. A. 2022. "Economic Operation of Utility-Connected Micro grids in a Fast and Flexible Framework Considering Non-Dispatchable Energy Sources." *Energies,* 15(8), 2894.

[23] Ali, S., Zheng, Z., Aillerie, M., Sawicki, J-P., Pera, M-C and Hissel, D. 2021. "A review of DC Micro grid energy management systems dedicated to residential applications." *Energies*, 14(14), 4308.

[24] Alizadeh, E., Birjandi, A. M. and Hamzeh, M. 2021. "Triple-harmonic-droop control strategy for accurate harmonic power sharing in low-voltage islanded micro grids." IET Generation, Transmission & Distribution, 15(11), 1740-1751. https://doi.org/https://doi.org/10.1049/gtd2.12130

[25] Arif, A., Javaid, N.A., Aldegheishem A. and Alrajeh, N. 2021. "Big data analytics for identifying electricity theft using machine learning approaches in micro grids for smart communities." *Concurrency and Computation: Practice and Experience*, 33(17), e6316.

[26] Arif, M. S. B. and Hasan, M. A. 2018. "Micro grid architecture, control, and operation." In Hybrid-Renewable Energy Systems in Micro grids: 23-37. *Elsevier*.

[27] Atkar, D., Chaturvedi, P., Suryawanshi, H., Liserre, M., and Nachankar, P. 2022. "Adaptive Control Algorithm for Two Stage Integrated DC Transformer in DC Micro-Grid Applications." *IEEE Transactions on Industrial Electronics*.

[28] Azrik Roslan, M., Ahmed, K., Adam, G., Elkhateb, A., Issa, W. and Williams, B. 2022. "Semicentralized power sharing scheme for islanded parallel-connected inverters." *International Transactions on Electrical Energy Systems.*

[29] Balakrishnan, A. A. *Synthetic, Hierarchical Approach for Modelling and Managing Complex Systems' Quality and Reliability.* Thesis.

[30] Anand, V., Singh, V. and Mekhlief, S. 2022. *Power Electronics for Renewable Energy Systems. Renewable Energy for Sustainable Growth Assessment*: 81-117.

[31] Bayat, M., Koushki, M. M., Ghadimi, A. A., Tostado-Véliz, M. and Jurado, F. 2022. "Comprehensive enhanced Newton Raphson approach for power flow analysis in droop-controlled islanded AC micro grids." *International Journal of Electrical Power & Energy Systems*, 143, 108493.

[32] Bhattarai, R., Qi, J., Wang, J. and Kamalasadan, S. 2020. "Adaptive droop control of coupled micro grids for enhanced power sharing and small-signal stability." 2020 IEEE Power & Energy Society General Meeting (PESGM).

[33] Borghei, M. and & Ghassemi, M. 2021. "Optimal planning of micro grids for resilient distribution networks." *International Journal of Electrical Power & Energy Systems*: 128, 106682.

[34] Buraimoh, E., Aluko, A. O., Oni, O. E. and Davidson, I. E. 2022. "Decentralized Virtual Impedance-Conventional Droop Control for Power Sharing for Inverter-Based Distributed Energy Resources of a Micro grid." *Energies,* 15(12), 4439.

[35] Castillo-Calzadilla, T., Cuesta, M., Olivares-Rodriguez, C., Macarulla, A., Legarda, J. and Borges, C. 2022. "Is it feasible a massive deployment of low voltage direct current micro grids renewable-based? A technical and social sight." *Renewable and Sustainable Energy Reviews*: 161, 112198.

[36] Abdullah, A. A. and Hassan, T. M. 2022. "Smart grid (SG) properties and challenges: an overview." *Discover Energy*, 2(1): 1-11.

[37] Chen, L., Wang, Y., Lu, X., Zheng, T., Wang, J. and Mei, S. 2019. "Resilient active power sharing in autonomous micro grids using pinning-consensus-based distributed control." *IEEE Transactions on Smart Grid*, 10(6): 6802-6811.

[38] de Andrade, F., Castilla, M. and Bonatto, B. D. 2020. *Micro grids: operation and control methods. In Basic Tutorial on Simulation of Micro grids Control Using MATLAB® & Simulink® Software*: 1-12. Springer.

[39] Elgamal, M., Elmitwally, A. and Guerrero, J. 2022. "An adaptive multiagent control system for autonomous economic operation and resilience assurance in a hybrid-energy islanded micro grid." *International Journal of Electrical Power & Energy Systems*, 140, 108070.

[40] España, N., Barco-Jiménez, J., Pantoja, A. and Quijano, N. 2021. "Distributed population dynamics for active and reactive power dispatch in islanded micro grids." *International Journal of Electrical Power & Energy Systems,* 125, 106407.

[41] Fani, B., Zandi, F., & Karami-Horestani, A. (2018). An enhanced decentralized reactive power sharing strategy for inverter-based micro grid. International Journal of Electrical Power & Energy Systems, 98, 531-542.

[42] Feng, K. and Liu, C. 2022. "Multi-Rate Sampling Control Design and Stability Analysis for Frequency and Voltage Regulation in Islanded Micro grids." *IEEE Transactions on Sustainable Energy*.

[43] Gan, L. K., Hussain, A., Howey, D. A. and Kim, H.-M. 2018. "Limitations in energy management systems: A case study for resilient interconnected micro grids." I*EEE Transactions on Smart Grid*, 10(5): 5675-5685.

[44] Gao, F., Kang, R., Cao, J. and Yang, T. 2019. "Primary and secondary control in DC micro grids: a review." *Journal of Modern Power Systems and Clean Energy*, 7(2): 227-242.

[45] Garcés, A., Montoya, O. D. and Gil-González, W. 2022. "Power flow in bipolar DC distribution networks considering current limits." *IEEE Transactions on Power Systems*, 37(5): 4098-4101.

[46] Bharatee, A., Ray, P. K., Subudhi, B. and Ghosh, A. 2022. "Power Management Strategies in a Hybrid Energy Storage System Integrated AC/DC Micro grid: A Review." *Energies*, 15(19): 7176.

[47] Ding, J., Qammar, A., Zhang, Z., Karim, A. and Ning, H. 2022. "Cyber Threats to Smart Grids: Review, Taxonomy, Potential Solutions, and Future Directions." Energies, 15(18): 6799.

[48] Gupta, A., Sharma, K. K. Kaur, G. 2022. *Micro grids—A Future Perspective. In Artificial Intelligence-Based Energy Management Systems for Smart Micro grids*: 103-126. CRC Press.

[49] Li, Y., Dong, P., Liu, M., and Yang, G. 2018. "A distributed coordination control based on finite-time consensus algorithm for a cluster of DC micro grids." I*EEE Transactions on Power Systems*, 34(3): 2205-2215.

[50] Zishan, F., Akbari, E., Montoya, O. D., Giral-Ramírez, D. A. and Molina-Cabrera, A. 2022. "Efficient PID Control Design for Frequency Regulation in an Independent Micro grid Based on the Hybrid PSO-GSA Algorithm." *Electronics,* 11(23): 3886.

[51] Hatefi Einaddin, A., Sadeghi Yazdankhah, A. and Kazemzadeh, R. 2017. "Power management in a utility connected micro-grid with multiple renewable energy sources." *Journal of Operation and Automation in Power Engineering*, 5(1): 1-10.

[52] He, W., Yu, M. and Yu, J. 2019. "Distributed finite-time active power sharing control with generation costs considered." *SN Applied Sciences,* 1(12). 1-10.

[53] Helmi, A. M., Carli, R., Dotoli, M. and Ramadan, H. S. 2021. "Efficient and sustainable reconfiguration of distribution networks via metaheuristic optimization." *IEEE Transactions on Automation Science and Engineering,* 19(1): 82-98.

[54] Huang, Z., Guo, Z., Ma, P., Wang, M., Long, Y. and Zhang, M. 2022. "Economic-environmental scheduling of micro grid considering V2G-enabled electric vehicles integration." *Sustainable Energy, Grids and Networks*, 32, 100872.

[55] Huo, Y., Bouffard, F. and Joós, G. 2022. "Integrating learning and explicit model predictive control for unit commitment in micro grids." *Applied Energy*, 306, 118026.

[56] Jasim, A. M., Jasim, B. H., Bureš, V. and Mikulecký, P. 2022. "A New Decentralized Robust Secondary Control for Smart Islanded Micro grids." *Sensors*, 22(22): 8709.

[57] Jeyaraj, P. R., Asokan, S. P. and Karthiresan, A. C. 2022. "Optimum power flow in dc micro grid employing bayesian regularized deep neural network." *Electric Power Systems Research*, 205, 107730.

[58] Jithin, S. and Rajeev, T. 2023. "A novel stability index-based virtual synchronous machine droop scheme for performance improvement of hybrid AC/DC micro grid under volatile loading conditions." *Electric Power Systems Research*, 214, 108901.

[59] Karthik, M. V. and Chaudhary, P. (2022). A novel integration of ANFIS-CRPSO based high power quality improvement in AC micro grids. Energy Systems, 1-26.

[60] Kermani, M., Adelmanesh, B., Shirdare, E., Sima, C. A., Carnì, D. L. and Martirano, L. 2021. "Intelligent energy management based on SCADA system in a real Micro grid for smart building applications." *Renewable Energy*, 171: 1115-1127.

[61] Ding, L., Han, Q.-L. and Zhang, X.-M. 2018. "Distributed secondary control for active power sharing and frequency regulation in islanded micro grids using an event-triggered communication mechanism." *IEEE Transactions on Industrial Informatics,* 15(7): 3910-3922.

[62] Kim, Y.-S., Hwang, C.-S., Kim, E.-S. and Cho, C. 2016. "State of charge-based active power sharing method in a standalone micro grid with high penetration level of renewable energy sources." *Energies*, 9(7): 480.

[63] Kulkarni, S. V., Gatade, S., Samanvita, N. and Gaonkar, D. 2022. *Comprehensive Strategy for Power Quality Improvement of Inverter Based Distributed Generation Systems.* In Emerging Research in Computing, Information, Communication and Applications:185-195. Springer.

[64] Kumar Prince, S., Prasad Panda, K., Naayagi, R., Sanjeevikumar, P., Khan, B., Affijulla, S. and Panda, G. 2022. "Challenges and Advancements in Protection of DC Micro grid System - A Comprehensive Review." *Energy Sources*, Part A: Recovery, Utilization, and Environmental Effects, 44(4): 10481-10505.

[65] Gupta, M., Tiwari, P., Viral, R. and & Shrivastava, A. 2022. *Performance Analysis of a Micro grid System Connected to a Grid Using EHO.* Smart Energy and Advancement in Power Technologies: Select Proceedings of ICSEAPT 2021 Volume 1, 926: 9.

[66] Li, X., Wang, J., Lu, Z. and Cai, Y. 2023. "A cloud edge computing method for economic dispatch of active distribution network with multi-micro grids." *Electric Power Systems Research,* 214, 108806.

[67] Li, X., Zeng, Y. and Lu, Z. 2022. "Decomposition and coordination calculation of economic dispatch for active distribution network with multi-micro grids." *International Journal of Electrical Power & Energy Systems*, 135, 107617.

[68] Li, X., Zhao, W. and Lu, Z. 2022. "Hierarchical Optimal Reactive Power Dispatch for Active Distribution Network with Multi-micro grids." *Journal of Electrical Engineering & Technology*: 1-14.

[69] Li, Y., Xu, Z., Xiong, L., Song, G., Zhang, J., Qi, D. and Yang, H. 2019. "A cascading power sharing control for micro grid embedded with wind and solar generation." *Renewable Energy*, 132: 846-860.

[70] Li, Y. and Yan, J. 2022. "Cybersecurity of smart inverters in the smart grid: A survey." *IEEE Transactions on Power Electronics*.

[71] Liang, X., Andalib-Bin-Karim, C., Li, W., Mitolo, M. and Shabbir, M. N. S. K. 2020. "Adaptive virtual impedance-based reactive power sharing in virtual synchronous generator controlled micro grids." *IEEE transactions on industry applications*, 57(1): 46-60.

[72] Ling, Y., Li, Y., Yang, Z. and Xiang, J. 2020). "A dispatchable droop control method for distributed generators in islanded ac micro grids." *IEEE Transactions on Industrial Electronics*, 68(9): 8356-8366.

[73] Liu, X., Liu, X., Jiang, Y., Zhang, T. and Hao, B. 2022. "PEDF (photovoltaics, energy storage, direct current, flexibility), a power distribution system of buildings for grid decarbonization: Definition, technology review, and application." *CSEE Journal of Power and Energy Systems*.

[74] Liu, X., Zhao, T., Deng, H., Wang, P., Liu, J. and Blaabjerg, F. 2022. "Micro grid energy management with energy storage systems: A review." *CSEE Journal of Power and Energy Systems.*

[75] Lu, J., Zhao, M., Golestan, S., Dragicevic, T., Pan, X. and Guerrero, J. M. 2021. "Distributed event-triggered control for reactive, unbalanced, and harmonic power sharing in islanded ac micro grids." *IEEE Transactions on Industrial Electronics,* 69(2): 1548-1560.

[76] MansourLakouraj, M., Shahabi, M., Shafie-khah, M. and Catalão, J. P. 2022. "Optimal market-based operation of micro grid with the integration of wind turbines, energy storage system and demand response resources." *Energy*, 239, 122156.

[77] Dsouza, A. K., Thammaiah, A. and Venkatesh, L. K. M. 2022. "An intelligent management of power flow in the smart grid system using hybrid NPO-ATLA approach." *Artificial Intelligence Review* 1-43.

[78] Prevedello, G. and Werth, A. 2021. "The benefits of sharing in off-grid micro grids: A case study in the Philippines." *Applied Energy*, 303, 117605.

[79] Maurya, R., Prakash, S. and Singh, A. K. 2022. "Challenges, Configuration, Control, and Scope of DC Micro grid Systems: A Review." *Journal of Electrical Engineering & Technology*: 1-20.

[80] Messaoudi, M. D., Menelas, B.-A. J. and Mcheick, H. 2022. "Review of Navigation Assistive Tools and Technologies for the Visually Impaired." *Sensors,* 22(20), 7888.

[81] Moretti, L., Polimeni, S., Meraldi, L., Raboni, P., Leva, S. and Manzolini, G. 2019. "Assessing the impact of a two-layer predictive dispatch algorithm on design and operation of off-grid hybrid micro grids." *Renewable Energy*, 143: 1439-1453.

[82] Muqeet, H. A., Javed, H., Akhter, M. N., Shahzad, M., Munir, H. M., Nadeem, M. U., Bukhari, S. S. H. and Huba, M. 2022. "Sustainable Solutions for Advanced Energy Management System of Campus Micro grids: Model Opportunities and Future Challenges." *Sensors*, 22(6): 2345.

[83] Nandhini, G. M. and Kannbhiran, A. (2022). "Power Electronics for Renewable Energy Systems." *Renewable Energy for Sustainable Growth Assessment*: 327-362.

[84] Nutkani, I. U., Loh, P. C. and Blaabjerg, F. 2013. "Distributed operation of interlinked AC micro grids with dynamic active and reactive power tuning." *IEEE transactions on industry applications*, 49(5): 2188-2196.

[85] Panigrahi, B. K., Bhuyan, A., Shukla, J., Ray, P. K. and Pati, S. 2021. "A comprehensive review on intelligent islanding detection techniques for renewable energy integrated power system." I*nternational Journal of Energy Research*, 45(10): 14085-14116.

[86] Parthasarathy, C., Hafezi, H. and Laaksonen, H. 2022. "Integration and control of lithium-ion BESSs for active network management in smart grids: Sundom smart grid backup feeding case." *Electrical Engineering*, 104(2): 539-553.

[87] Poudyal, A., Poudel, S. and Dubey, A. 2022. "Risk-based active distribution system planning for resilience against extreme weather events." *IEEE Transactions on Sustainable Energy*.

[88] Su, W., Huang, A. Q., Masrur, M. A., Srivastava, A. K., Bi, T. and Shi, D. 2022. "Special Section on Power Electronics-Enabled Smart Power Distribution Grid." *IEEE Transactions on Smart Grid*, 13(5): 3851-3856.

[89] Reddy, Y., Jithendranath, J., Chakraborty, A. K. and Guerrero, J. M. 2022. "Stochastic optimal power flow in islanded DC micro grids with correlated load and solar PV uncertainties." *Applied Energy*, 307, 118090.

[90] Rizvi, S. and Abu-Siada, A. 2022. "Active Power Sharing in a Micro-Grid with Multiple Grid Connections." *Designs*, 6(2), 24.

[91] Roy, T. K., Pramanik, M. A. H. and Ghosh, S. K. 2022. "Design of an integral terminal-based sliding mode controller for PV and BESS-based DC micro grids." *Energy Nexus*, 7, 100130.

[92] Rüther, T., Mößle, P., Mühlbauer, M., Bohlen, O. and Danzer, M. A. 2022. "Iterative Dynamic Programming—An Efficient Method for the Validation of Power Flow Control Strategies." *Electricity*, 3(4): 542-562.

[93] Sadeghian, M. and Fani, B. 2017." *Advanced localized reactive power sharing in micro grids. Electric Power Systems Research*, 151: 136-148.

[94] Salah, B., Hasanien, H. M., Ghali, F. M., Alsayed, Y. M., Abdel Aleem, S. H. and El-Shahat, A. 2022. "African Vulture Optimization-Based Optimal Control Strategy for Voltage Control of Islanded DC Micro grids." *Sustainability*, 14(19), 11800.

[95] Sampaio, F. C., Tofoli, F. L., Melo, L. S., Barroso, G. C., Sampaio, R. F. and Leão, R. P. S. 2022."Adaptive fuzzy directional bat algorithm for the optimal coordination of protection systems based on directional overcurrent relays." *Electric Power Systems Research*, 211, 108619.

[96] Sellamna, H., Pavan, A. M., Mellit, A. and Guerrero, J. M. 2020. "An iterative adaptive virtual impedance loop for reactive power sharing in islanded meshed micro grids." *Sustainable Energy, Grids and Networks*, 24, 100395.

[97] Serrano-Fontova, A. and Azab, M. 2022. "Development and performance analysis of a multi-functional algorithm for AC micro grids: Simultaneous power sharing, voltage support and islanding detection." *International Journal of Electrical Power & Energy Systems*, 135, 107341.

[98] Shahgholian, G. 2021. "A brief review on micro grids: Operation, applications, modeling, and control." *International Transactions on Electrical Energy Systems*, 31(6), e12885.

[99] Shi, M. S., Huang, Y. and Lin, H. 2022. "Research on power to hydrogen optimization and profit distribution of micro grid cluster considering shared hydrogen storage." *Energy*, 126113.

[100] Srivastava, I., Bhat, S., Vardhan, B. S. and Bokde, N. D. 2022. "Fault Detection, Isolation and Service Restoration in Modern Power Distribution Systems: A Review." *Energies*, 15(19), 7264.

[101] Su, M., Zhang, K., Sun, Y., Han, H., Shi, G. and Fu, S. 2022. "Coordinated control for PV-ESS islanded micro grid without communication." *International Journal of Electrical Power & Energy Systems*, 136, 107699.

[102] Thirunavukkarasu, G. S., Seyedmahmoudian, M., Jamei, E., Horan, B., Mekhilef, S. and Stojcevski, A. 2022." Role of optimization techniques in micro grid energy management systems—A review." *Energy Strategy Reviews,* 43, 100899.

[103] Twaisan, K. and Barışçı, N. 2022. "Integrated Distributed Energy Resources (DER) and Micro grids: Modeling and Optimization of DERs." *Electronics,* 11(18), 2816.

[104] Vaidya, S., Somalwar, R. and & Kadwane, S. G. 2016. *Review of various control techniques for power sharing in micro grid.* 2016 International Conference on Global

Trends in Signal Processing, Information Computing and Communication (ICGTSPICC).

[105] Wiegel, F., Wachter, J., Kyesswa, M., Mikut, R., Waczowicz, S. and Hagenmeyer, V. 2022. "Smart Energy System Control Laboratory–a fully-automated and user-oriented research infrastructure for controlling and operating smart energy systems." *at-Automatisierungstechnik*, 70(12): 1116-1133.

[106] Wu, Q., Xue, F., Lu, S., Jiang, L., Huang, T., Wang, X and Sang, Y. 2023. "Integrated network partitioning and DERs allocation for planning of Virtual Micro grids." *Electric Power Systems Research*, 216, 109024.

[107] Xu, W., Li, J., Dehghani, M. and GhasemiGarpachi, M. 2021. "Blockchain-based secure energy policy and management of renewable-based smart micro grids." *Sustainable Cities and Society*, 72, 103010.

[108] Yan, L., Sheikholeslami, M., Gong, W., Shahidehpour, M. and Li, Z. 2022. "Architecture, Control, and Implementation of Networked Micro grids for Future Distribution Systems." *Journal of Modern Power Systems and Clean Energy*, 10(2): 286-299.

[109] Yang, W-M., Wang, X.-G., Li, X.-Y., & Liu, Z.-Y. (2014). An active power sharing method among distributed energy sources in an islanded series micro-grid. Energies, 7(12), 7878-7892.

[110] Yu, H., Niu, S., Shang, Y., Shao, Z., Jia, Y. and Jian, L. 2022. "Electric vehicles integration and vehicle-to-grid operation in active distribution grids: A comprehensive review on power architectures, grid connection standards and typical applications." *Renewable and Sustainable Energy Reviews*, 168, 112812.

[111] Rosero, D., Díaz, N. and Trujillo, C. 2021. "Cloud and machine learning experiments applied to the energy management in a micro grid cluster." *Applied Energy*, 304, 117770.

[112] Zhang, J., She, B., Peng, J. C.-H. and Li, F. 2022. "A distributed consensus-based optimal energy management approach in DC micro grids." *International Journal of Electrical Power & Energy Systems*, 140, 108015.

[113] Zhong, C., Li, H., Zhou, Y., Lv, Y., Chen, J. and Li, Y. 2022. "Virtual synchronous generator of PV generation without energy storage for frequency support in autonomous micro grid." *International Journal of Electrical Power & Energy Systems*, 134, 107343.

[114] Zhou, J., Sun, H., Xu, Y., Han, R., Yi, Z., Wang, L. and Guerrero, J. M. 2021. "Distributed power sharing control for islanded single-/three-phase micro grids with admissible voltage and energy storage constraints." *IEEE Transactions on Smart Grid*, 12(4): 2760-2775.

[115] Zhou, J., Zhang, H., Sun, Q., Ma, D. and Huang, B. 2017. "Event-based distributed active power sharing control for interconnected AC and DC micro grids." *IEEE Transactions on Smart Grid*, 9(6): 6815-6828.

[116] Zhu, Y., Liu, B., Wang, F., Zhuo, F. and Zhao, Y. 2015. *A virtual resistance based reactive power sharing strategy for networked micro grid.* 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia).

[117] https://www.aemc.gov.au/energy-system/electricity/electricity-system/NEM

[118] https://www.westernpower.com.au/our-energy-evolution/grid-technology/microgrid-technology/

[119] https://www.westernpower.com.au/media/5967/kalbarri-microgrid-fact-sheet-20220203.pdf

[120] https://smartgrid.ieee.org/images/files/pdf/IEEE_QER_Microgrids_October_3_2014.pdf

[121] https://www.wa.gov.au/system/files/2021-12/Final-DMG-Presentation-Forum-17November2021b.pdf

[122] https://www.pv-magazine-australia.com/2019/12/16/was-largest-battery-on-the-way-to-kalbarri-microgrid/

[123] Kermani, M., Adelmanesh, B., Shirdare, E., Sima, C. A., Carnì, D. L. and Martirano, L. , 2021. "Intelligent energy management based on SCADA system in a real Microgrid for smart building applications." *Renewable Energy*, vol. 171: 1115-1127.

[124] Arif, A., Javaid, N., Aldegheishem, A. and Alrajeh, N. 2021. "Big data analytics for identifying electricity theft using machine learning approaches in microgrids for smart communities," *Concurrency and Computation: Practice and Experience,* vol. 33, no. 17: e6316,

[125] Prevedello, G. and Werth, A. 2021. "The benefits of sharing in off-grid microgrids: A case study in the Philippines." *Applied Energy*, vol. 303: 117605.

[126] Kraiem, Y., Krim, S. and Mimouni, M. F. "Optimization of an adaptive droop control and powers allocation for a distributed generator under loads and grid uncertainties." *Sustainable Energy, Grids and Networks*, vol. 32: 100950, 2022/12/01/ 2022, doi: https://doi.org/10.1016/j.segan.2022.100950.

[127] Villalón, A., C. Muñoz, Muñoz, J. and Rivera, M. 2023."Fixed-Switching-Frequency Modulated Model Predictive Control for Islanded AC Microgrid Applications," *Mathematics*, vol. 11, no. 3: 672.

[128] Kherbachi, A., Chouder, A., Bendib, A. and Ahmed, H. 2023. "Improved power computation method for droop-controlled single-phase VSIs in standalone microgrid considering non-linear loads." IET *Generation, Transmission & Distribution*.

[129] Roozbehani, S., Kordkandi, R. D. and Hagh, M. T. "An Overview of Modeling and Control of Grid-Forming Inverters," *Grid-Forming Power Inverters*: 79-106.

[130] Prakash, V. and Pandzic, H. 2023. "Fast frequency control service provision from active neighborhoods: Opportunities and challenges," *Electric Power Systems Research*, vol. 217: 109161.

[131] Fazal, S., Haque, M. E., Arif, M. T., Gargoom, A. and Oo, A. M. T. 2023."Grid integration impacts and control strategies for renewable based microgrid." *Sustainable Energy Technologies and Assessments*, vol. 56: 103069.

[132] Ghasemi, N., Ghanbari, M. and Ebrahimi, R. 2023. "Intelligent and optimal energy management strategy to control the Micro-Grid voltage and frequency by considering the load dynamics and transient stability." *International Journal of Electrical Power & Energy Systems*, vol. 145: 108618.

[133] Sathish, C., Chidambaram, I. and Manikandan, M. 2023. "Intelligent cascaded adaptive neuro fuzzy interface system controller fed KY converter for hybrid energy based microgrid applications." Electrical *Engineering & Electromechanics*, no. 1: 63-70.

[134] Mustafa, G., Ahmad, F., Zhang, R., Haq, E. U., and Hussain, M. 2023. "Adaptive sliding mode control of buck converter feeding resistive and constant power load in DC microgrid." *Energy Reports*, vol. 9: 1026-1035.

[135] Montenegro-Oviedo, J. A., Ramos-Paja, C. A., Orozco-Gutierrez, M. L., Franco-Mejía, E., and Serna-Garcés, S. I. 2023. "Adaptive Controller for Bus Voltage Regulation on a DC Microgrid Using a Sepic/Zeta Battery Charger/Discharger," *Mathematics*, vol. 11, no. 4: 793.

[136] Abbasi, M., Abbasi, E., Li, L., Aguilera, R. P., Lu, D and Wang, F. 2023. "Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods." *Energies*, vol. 16, no. 1: 484.

[137] Skiparev , V et al. 2023."Virtual Inertia Control of Isolated Microgrids Using an NN-Based VFOPID Controller." *IEEE Transactions on Sustainable Energy.*

[138] Zadehbagheri, M., Sutikno, T., Kiani, M. J., and Yousefi, M. 2023. "Designing a power system stabilizer using a hybrid algorithm by genetics and bacteria for the multi-machine power system." *Bulletin of Electrical Engineering and Informatics,* vol. 12, no. 3: 1318-1331.

[139] Van, L. P., Do Chi, K., and Duc, T. N. 2023. "Review of hydrogen technologies based microgrid: Energy management systems, challenges and future recommendations." *International Journal of Hydrogen Energy*.

[140] Cai, W., Kordabad, A. B. and Gros, S. 2023. "Energy management in residential microgrid using model predictive control-based reinforcement learning and Shapley value." *Engineering Applications of Artificial Intelligence*, vol. 119: 105793.

[141] Pontes L. et al. 2023. "Operational Data Analysis of a Battery Energy Storage System to Support Wind Energy Generation." Energies, vol. 16, no. 3: 1468.

[142] Yahya M. G., and Yahya, M. G. 2023. "Modified PDPWM control with MPPT algorithm for equal power sharing in cascaded multilevel inverter for standalone PV system under partial shading." *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1: 533.

[143] Shezan S. A. et al. 2022. "Selection of the best dispatch strategy considering techno-economic and system stability analysis with optimal sizing." *Energy strategy reviews*, vol. 43: 100923.

[144] Zhang, L., Guo, Q., Liu, M., Yang, N., Gao, R. and Sobhani, B. 2023. "Optimal dispatch of dynamic power and heat considering load management, water pump system, and renewable resources by grasshopper optimization algorithm." *Journal of Energy Storage*, vol. 57: 106166.

[145] M. Mangaraj, J. Sabat, and Chahattaray, A. K. 2022. *A Comparative Simulation Study Between ZSI and BB-ZSI Based Distribution Static Compensator for Power Quality Improvement in Power Distribution Network. Recent Advances in Power Electronics and Drives*. Select Proceedings of EPREC 2022: Springer, 2023: 171-181.

[146] Malan, A. J., Jané-Soniera, P., Strehle, F. and Hohmann, S. 2023. "Passivity-based power sharing and voltage regulation in DC microgrids with unactuated buses." *arXiv* preprint arXiv:2301.13533.

[147] Li, Z., Li, H., Zheng, X. and Gao, M. 2023. "Virtual model predictive control for virtual synchronous generators to achieve coordinated voltage unbalance compensation in islanded micro grids," *International Journal of Electrical Power & Energy Systems*, vol. 146: 108756.

[148] Liu Z. et al. 2023. "An adaptive multi-mode switching control strategy to improve the stability of virtual synchronous generator with wide power grid strengths variation." *IET Generation, Transmission & Distribution*, vol. 17, no. 2: 307-323.

[149] Jithin, S. and Rajeev, T. 2023. "A novel stability index-based virtual synchronous machine droop scheme for performance improvement of hybrid AC/DC microgrid under volatile loading conditions." *Electric Power Systems Research*, vol. 214: 108901.

[150] Zheng, M., Zou, Z., Lu, Q., Li, Y., and Shen, Y. 2023. "A Simple Modified Deadbeat Direct Thrust Control for Permanent Magnet Linear Synchronous Machine Considering Parameter Asymmetry." *IEEE Transactions on Industry Applications.*

[151] Zhang, J., Sun, B., and Zhao, D. 2023. "A Novel Event-Triggered Secondary Control Strategy for Distributed Generalized Droop Control in Microgrid Considering Time Delay." *IEEE Transactions on Power Electronics*.

[152] Ibraheem, M. I., Edrisi, M., Gholipour, M. and Alhelou, H. H. 2023. "A Novel Frequency Regulation in Islanded Microgrid using Sliding Mode Control with Disturbance Observers considering Storages and EVs." *Computers and Electrical Engineering*, vol. 105, p. 108537.

[153] Merabet, A., Ahmed, K. T., Ibrahim, H., Beguenane, R. and Ghias, A. M. 2017. "Energy management and control system for laboratory scale microgrid based wind-PV-battery." *IEEE transactions on sustainable energy*, vol. 8, no. 1: 45-154.

[154] Dufo-Lopez, R., Cristobal-Monreal, I. R., and Yusta, J. M. 2016. “Stochastic-heuristic methodology for the optimisation of components and control variables of PV-wind-diesel-battery stand-alone systems." *Renewable Energy*, vol. 99: 919-935.

[155] Kumar, K., Babu, N. R. and Prabhu, K. 2017. "Design and analysis of an integrated Cuk-SEPIC converter with MPPT for standalone wind/PV hybrid system." *International Journal of Renewable Energy Research* (IJRER), vol. 7, no. 1: 96-106.

[156] Li, J., Xiong, R., Yang, Q., Liang, F., Zhang, M.and Yuan, W. 2017. "Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system." *Applied Energy*, vol. 201: 257-269.

[157] Li, J., Yang, Q., Robinson, F., Liang, F., Zhang, M. and Yuan, W. 2017. "Design and test of a new droop control algorithm for a SMES/battery hybrid energy storage system." *Energy*, vol. 118: 1110-1122.

[158] Powell, K. M., Rashid, K., Ellingwood, K., Tuttle, J. and Iverson B. D. 2017. "Hybrid concentrated solar thermal power systems: a review." *Renewable and Sustainable Energy Reviews*, vol. 80: 215-237.

[159] Ciocan, A., Balan, M., Pislaru, M., Rizoiu, A. and Constantin, A. 2017. "A HYBRID ENERGY STORAGE SYSTEM AND CONTROL STRATEGY FOR STAND-ALONE APPLICATIONS USING RENEWABLE ENERGY SOURCES." *Progress of Cryogenics & Isotopes Separation*, vol. 20, no. 1.

[160] Derrouazin, A., Aillerie, M., Mekkakia-Maaza N., and Charles, J-P. 2017. "Multi input-output fuzzy logic smart controller for a residential hybrid solar-wind-storage energy system," Energy Conversion and Management, vol. 148: 238-250.

[161] Vincent, F. Y., Le, T. H. A. and Gupta, J. N. 2023. "Sustainable microgrid design with peer-to-peer energy trading involving government subsidies and uncertainties." Renewable Energy.

[162] Liu, S., Miao, H., Li, J. and Yang, L. 2023. "Voltage control and power-sharing in DC Microgrids based on voltage-shifting and droop slope-adjusting strategy." *Electric Power Systems Research*, vol. 214: 108814.

[163] Arabpour A. and Hojabri, H. 2023. "An improved centralized/decentralized accurate reactive power-sharing method in AC microgrids." *International Journal of Electrical Power & Energy Systems*, vol. 148: 108908.

[164] Olives-Camps, J. C., del Nozal, Á. R., Mauricio, J. M. and Maza-Ortega, J. M. 2023. "A holistic model-less approach for the optimal real-time control of power electronics-dominated AC microgrids." *Applied Energy*, vol. 335: 120761.

[165] Sánchez-Herrera, M. R., Márquez, M. and de la Torre, L. 2023. "Secure and Private Internet of Things for Industry, Training, and Homes: A Communications Solution for Connected Devices." *IEEE Industrial Electronics Magazine*.

[166] Sengupta, J., Ruj, S. and Bit, S. D. 2023. "FairShare: Blockchain Enabled Fair, Accountable and Secure Data Sharing for Industrial IoT." *IEEE Transactions on Network and Service Management*.

[167] Zhang, B., Hu, W., Ghias., A. M., Xu, X. and Chen, Z. 2023. "Multi-agent deep reinforcement learning based distributed control architecture for interconnected multi-energy microgrid energy management and optimization." *Energy Conversion and Management*, vol. 277" 116647.

[168] Babayomi, O., Zhang, Z., Dragicevic, T., Hu, J. and Rodriguez, J. 2023. "Smart grid evolution: Predictive control of distributed energy resources—A review." *International Journal of Electrical Power & Energy Systems*, vol. 147: 10881.

[169] Naderi, M., Shafiee, Q., Blaabjerg, F. and Bevrani, H. 2023. "Synchronization Stability of Interconnected Microgrids with Fully Inverter-Based Distributed Energy Resources." *Journal of Modern Power Systems and Clean Energy*.

[170] Su W. and Shi, Y. 2023. "Distributed energy sharing algorithm for Micro Grid energy system based on cloud computing." *IET Smart Cities*.

[171] Wang, Y., Rousis, A. O., Qiu, D. and Strbac, G. 2023. "A stochastic distributed control approach for load restoration of networked microgrids with mobile energy storage systems." *International Journal of Electrical Power & Energy Systems,* vol. 148: 108999.

[172] Perez, F., Damm, G., Verrelli, C. M. and Ribeiro, P. F. 2023. "Adaptive Virtual Inertia Control for Stable Microgrid Operation Including Ancillary Services Support." *IEEE Transactions on Control Systems Technology*.

[173] Song, Y., Sahoo, S., Yang, Y. and Blaabjerg, F. 2023. "Conditional Droop Adjustment for Reliability-Oriented Power-Sharing in Microgrids." *IEEE Transactions on Circuits and Systems II: Express Briefs*.

[174] Zhou J. et al. 2021. "Distributed power-sharing control for islanded single-three-phase microgrids with admissible voltage and energy storage constraints." IEEE Transactions on Smart Grid, vol. 12, no. 4: 2760-2775.

[175] Poudyal, A., Poudel, S. and Dubey, A. 2022. "Risk-based active distribution system planning for resilience against extreme weather events." *IEEE Transactions on Sustainable Energy*.

[176] Parthasarathy, C., Hafezi, H. and Laaksonen, H. 2022. "Integration and control of lithium-ion BESSs for active network management in smart grids: Sundom smart grid backup feeding case." *Electrical Engineering*, vol. 104, no. 2: 539-553.

[177] Garcés, A., Montoya, O. D. and Gil-González, W. 2022. "Power flow in bipolar DC distribution networks considering current limits." *IEEE Transactions on Power Systems*, vol. 37, no. 5: 4098-4101.

[178] Roy, T. K., M. Pramanik, A. H. and Ghosh, S. K. 2022. "Design of an integral terminal-based sliding mode controller for PV and BESS-based DC microgrids." *Energy Nexus*, vol. 7: 100130.

[179] Sedhom, Bishoy, E., El-Saadawi, Magdi, M., M. and Elhosseini, Mostafa, A. and Saed, Mohammad A. 2019. “A harmony search-based H-infinity control method for islanded microgrid.” *ISA Transactions*, 99: 252-269,

[180] Sedhom, Bishoy, E., El-Saadawi, Magdi, M. and Hatata, Ahmed Y. 2020. “H-Infinity versus model predictive control methods for seamless transition between islanded- and

grid-connected modes of microgrids.” *IET Renewable Power Generation*, vol. 14 Iss. 5: 856-870.

[181] https://www.globenewswire.com/news-release/2022/06/06/2456587/0/en/Microgrid-Global-Market-Report-2022.html

[182] https://www.c2es.org/content/microgrids/

[183] *INTERCONNECTOR CAPABILITIES FOR THE NATIONAL ELECTRICITY MARKET*, Published November 2017.

[184] Jiang, J., et al. 2023. "Strategic active and reactive power scheduling model for community energy systems in day-ahead distribution electricity market." *Applied Energy*. 336. 120558. 10.1016/j.apenergy.2022.120558.

[185] Ghiasi, M., Niknam T.. 2023. "Multipurpose FCS model predictive control of VSC-based microgrids for islanded and grid-connected modes." *IEEE Systems Journal*. 17(2), 2558-2569. https://doi.org/10.1109/JSYST.2022.3215437.

[186] T. Wang, D. O’Neill and H. Kamath. 2015. "Dynamic Control and Optimization of Distributed Energy Resources in a Microgrid," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2884-2894, doi: 10.1109/TSG.2015.2430286.

[187] Kanche A., P.K. Dash. 2024. “A new approach for active and reactive power management in renewable based hybrid microgrid considering storage devices.” Applied Energy, Volume 367, 123429, ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2024.123429.

[188] Hafez, W.A., et al. 2022. "Droop-based frequency controller for parallel operation of VSCs and SG in isolated microgrids." *23rd International Middle East Power Systems Conference (MEPCON)*, Cairo, Egypt, pp. 01-06, doi:10.1109/MEPCON55441.2022.10021786.

[189] Rosini A., Labella A, Bonfiglio A, Procopio R, Guerrero JM. 2021. “A review of reactive power sharing control techniques for islanded microgrids.” *Renew Sustain Energy Reviews*, vol. 141, 110745. ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.110745.

[190] Ahmed M., Meegahapola L. 2020. "Stability and Control Aspects of Microgrid Architectures–A Comprehensive Review." *IEEE Access*, vol. 8, pp. 144730-144766, doi: 10.1109/ACCESS.2020.3014977.

[191] Zhang L, Zheng H, Wan T, Shi D, Lyu L, Cai G. 2021. “An integrated control algorithm of power distribution for islanded microgrid based on improved virtual synchronous generator.” *SIET Renewable Power Generation,* vol. 15, iss. 12: 2674 - 2685. **https://doi.org/10.1049/rpg2.12191**

[192] Alireza A., Hossein H. 2023. “An improved centralized/decentralized accurate reactive power sharing method in AC microgrids.” *International Journal of Electrical Power and Energy Systems,* Vol. 148, no. 108908, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2022.108908.

[193] Dong L., Lin H., 2024. “A coordinated active and reactive power optimization approach for multi-microgrids connected to distribution networks with multi-actor-attention-critic deep reinforcement learning.” *Applied Energy*, vol. 373, 123870, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2024.123870.

[194] Zong S., Cao J., 2023, “Adaptive normalized droop control for low-voltage hybrid microgrid interlinking converter.” *Energy Reports*, vol. 9, Supplement 7, pp. 1377-1388, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2023.04.178.

[195] Sun, X., Qiu, J., Ma, Y., Tao, Y., Zhao, J. and Dong, Z., 2022. “Encryption-based coordinated volt/var control for distribution networks with multi-microgrids.” *IEEE Transactions on Power Systems*, *38*(6), pp. 5909-5921.

[196] Z. Yi, W. Dong and A. H. Etemadi. 2018. "A Unified Control and Power Management Scheme for PV-Battery-Based Hybrid Microgrids for Both Grid-Connected and Islanded Modes," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 5975-5985, doi: 10.1109/TSG.2017.270033.

[197] Karimi Y., Oraee H. 2017. “Decentralized method for load sharing and power management in a PV/battery hybrid source islanded microgrid,” *IEEE Trans. Power Electron.*, vol. 32, no. 5, pp. 3525–3535.

[198] B. Ping, X. Zhang. 2020. "Voltage control strategy for integrated medium and low voltage distribution network based on active-reactive power coordination optimization," *2020 Chinese Automation Congress (CAC)*, Shanghai, China, pp. 1187-1192, doi: 10.1109/CAC51589.2020.9327715.

[199] Saeed M., Fangzong W. 2021. "A Review on Microgrids’ Challenges & Perspectives." *IEEE Access*, vol. 9, pp. 166502-166517, 2021, doi: 10.1109/ACCESS.2021.3135083.

[200] D. E. Olivares *et al*. 2014. "Trends in Microgrid Control," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1905-1919, doi: 10.1109/TSG.2013.2295514.

8. Appendix A

Modelling parameters used in developing the micro grid model are given in Table 8-1 to Table 8-4.

Table 8-1. Transmission Lines.

Lines	Z1 (Ohm)	R1 (Ohm)	X1 (Ohm)
Line1	0.3318	0.15	0.296
Line2	0.3318	0.15	0.296
Line	1.4724	1.46	0.191
FL2	4.4440	3.56	2.66
FL3	4.4440	3.56	2.66
Line(2)	1.4724	1.46	0.191
Line(4)	1.4724	1.46	0.191
Line3 (Configuration 3)	0.3318	0.15	0.296

Table 8-2. Transformers.

Transformers	MVA	Voltage (kV/kV)	Vector Group	%Z
T2(1)	15	69/13.8	Dyn0	8
T13	4	13.8/4.14	YNyn0	3
T3(1)	4.5	13.8/4.14	YNyn0	3
T3(2)	3.5	13.8/4.14	YNyn0	3

Table 8-3. Loads.

Loads	MW	MVAr
Load1	3	0.9
Load2	2	0.3
Load3	1.8	0.6
Load4(Configuration 3)	1.2	0.1

Table 8-4. Generators.

Active Power from DDGU	MW	MVAr
G1	2	0.6
G2	2.2	0.7
G3	1.2	0.6