# Performance Analysis of Three Phase Induction Generators During Fault

Dawit Seyoum
Central Queensland University,
Rockhampton, Australia
d.seyoum@cqu.edu.au

Peter Wolfs
Central Queensland University,
Rockhampton, Australia
p.wolfs@cqu.edu.au

Nasser Hoessein Zadeh Central
Queensland University,
Rockhampton, Australia
n.zadeh@cqu.edu.au

## ABSTRACT

*Three phase induction generators can be utilized to generate electrical power in nonconventional energy conversion systems. With low penetration of induction generators the practice has been to disconnect induction generators from the grid during a network fault. However with an increase in the use of induction generators the induction generators are required to operate during faults and to assist in stabilizing the grid voltage and frequency. During a network fault an induction generator will experience decreased stator voltage and flux with a severity depending on the location of the fault.*

*This paper deals with the performance analysis of different induction generator schemes for grid-connected as well as isolated system applications during electrical faults and after clearance of the fault.*

## 1. INTRODUCTION

Three phase induction generators are good candidates to generate electrical power in non-conventional energy conversion systems. Induction machines are more robust and cheaper than other electrical machines for the same rating. They need less maintenance when manufactured with a squirrel cage rotor. There is no need for synchronization. Depending on the condition of operation the induction machine can be used as a motor or generator.

For a grid connected induction generator electrical connection to the grid network can be done by closing the circuit breaker with zero flux while rotating at rated speed [1]. There will be large inrush current decaying to the normal magnetizing current in a few cycles. If there is no mechanism to control the large inrush current, it will create a voltage dip in the system

However for an isolated self-excited induction generator excited by ac capacitors the procedure of operation is first the generator has to rotate at rated speed second the capacitors are connected to the stator terminals of the generator and voltage will start to build up starting from the remnant magnetic flux in the iron core or from initial charge in the capacitors. Finally the generator is connected to the load when the voltage build up reaches rated voltage or its steady state value [2]. The self-excited induction generator can be also excited by a single DC capacitor and three phase inverter/rectifier. In this case initiation of voltage build up is dependent on initial DC voltage in the DC capacitor [3].

When there is fault at the terminals of self excited induction generator the voltage will collapse and as a result the magnetic flux in the core will not exist. This will stop the continuity of generation of electrical power after the fault. The inherent characteristic of an isolated self excited induction generator gives rise to a self protecting mechanism during faults. After the fault, whether it is cleared or not, reconnection to the load is only possible by following the procedures that should be done in starting an isolated self excited induction generator. As a result automatic reconnection is not possible.

However in grid connected induction generators the study of their performance characteristics is important during electrical faults and after clearance of the fault. Based on critical angular speed and critical clearing time the analysis of steady state stability limit and transient stability limit of induction generators has been developed in a similar way to the well established synchronous generator stability limit analysis [4]. But this stability limit based on the increase in angular speed is not of practical concern as there are also mechanical arrangements to protect the rotor from exciding the rated angular speed of the speed.

Induction generators have received more attention in wind powered electric generating plants. With low penetration of wind power the practice has been to disconnect wind turbines from the grid during a network fault. However with an increase in the use of wind power the wind powered generators are required to operate during faults and to assist in stabilizing the grid voltage and frequency. Different countries have varying connection requirements. For example in Australia, significant grid connected units of any generation type must ride through 0% voltage for 175ms without being isolated from the grid [5].

Induction generator generators require external reactive power source for their excitation. When the voltage at the terminals of the induction generator drops the magnetic flux in the core will drop which will force the internally generated voltage to drop. After clearance of the fault the grid voltage will rise to its rated value. Hi current will be drawn from the grid to excite the induction generator.

To solve the problem associated with the drop in the magnetic flux in the induction generator there should be a way of maintaining the magnetic flux at its rated value. This can be implemented by supplying excitation through the rotor of the induction generator in doubly-fed wound rotor induction generator [6] or through a second stator winding in brushless doubly-fed induction generator with twin windings in the stator [7]. During fault the excitation will come from a charged DC capacitor and fed to the generator via an inverter.

This paper deals with the performance analysis of different induction generator schemes for grid-connected as well as isolated system applications during electrical faults and after clearance of the fault. The relevant Australian grid connection rules relevant to the issues discussed in this paper are given.

## 2. RELEVANT RULES TO CONNECT GENERATING UNITS TO THE GRID

Each country has a rule to connect generating unit to the grid. Some of the relevant points in connecting induction generating unit to the grid in relation to disturbance ride through taken from the National Electricity Rules (extracted from clauses S5.2.5.3 and S5.2.5.4) [8] are:

(a) The voltage dip caused by a transmission system fault which causes voltage at the connection point to drop to zero for up to 0.175 seconds in any one phase or combination of phases, followed by a period of ten seconds where voltage may vary in the range 80-110 percent of the nominal voltage, and a subsequent period of three minutes in which the voltage may vary within the range 90-110 percent of the nominal voltage.

(b) Each generating unit must be capable of continuous uninterrupted operation during and following a loading level reduction directly imposed from the power system in less than 10 seconds from a fully or partially loaded condition provided that the loading level reduction is less than 30 percent of the generating unit's nameplate rating and the loading level remains above minimum load.

During fault, as shown in Fig. 1, the output power from the induction generator will be reduced and as a result the rotor speed will increase. The angular rotor speed stability limit of induction generators is much higher than the rated angular rotor speed [4]. Therefore the increase in angular rotor speed should be monitored using mechanical regulators to satisfy the mechanical rating of the system. The main issue of stability related to grid connected induction generators is the voltage stability to decide whether the induction generator will be able to continue to generate power after the fault is cleared.

## 3. MODELLING OF INDUCTION GENERATORS

The modelling of an induction generator is the same as the general induction machine modelling. The d-q equivalent circuit of an induction machine when the rotor and start variables are referred to a stationary reference frame fixed in the stator is given in Fig. 2.

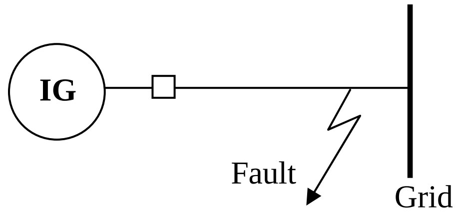


Figure 1: Induction generator connected to a grid during fault

Using Fig.2 the following equation, Equation 1, can be derived.

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m & 0 \\ 0 & R_s + pL_s & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (1)$$

Where $\omega_r$ is the electrical rotor speed.

$R_r$ - rotor winding resistance, Ω
$L_{lr}$ - rotor leakage inductance, H
$v_{qs}$ - q-axis stator voltage
$v_{ds}$ - d-axis stator voltage
$v_{qr}$ - q-axis rotor voltage
$v_{qr}$ - d-axis rotor voltage
$i_{qs}$ - q-axis stator current
$i_{ds}$ - d-axis stator current
$i_{qr}$ - q-axis rotor current
$i_{qr}$ - d-axis rotor current
$\omega_r$ - is the electrical rotor speed, rad/s
$R_r$ - rotor winding resistance, Ω
$L_{lr}$ - rotor leakage inductance, H
$R_s$ - stator winding resistance, Ω
$L_{ls}$ - stator leakage inductance, H
$L_m$ - magnetising inductance, H
$L_s$ - $L_{ls} + L_m$
$L_r$ - $L_{lr} + L$
$p = d/dt$

For doubly fed induction machine referring the stator voltage and current to the stationary stator reference frame and the rotor voltage and current to a reference frame rotating at an electrical rotor speed, the equations relating the voltages and currents are given as[9]:

$$\begin{bmatrix} v_{sD} \\ v_{sQ} \\ v_{r\alpha} \\ v_{r\beta} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m\cos\theta_r & -pL_m\sin\theta_r \\ 0 & R_s + pL_s & pL_m\sin\theta_r & pL_m\cos\theta_r \\ pL_m\cos\theta_r & pL_m\sin\theta_r & R_r + pL_r & 0 \\ -pL_m\sin\theta_r & pL_m\sin\theta_r & 0 & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{r\alpha} \\ i_{r\beta} \end{bmatrix} \quad (2)$$

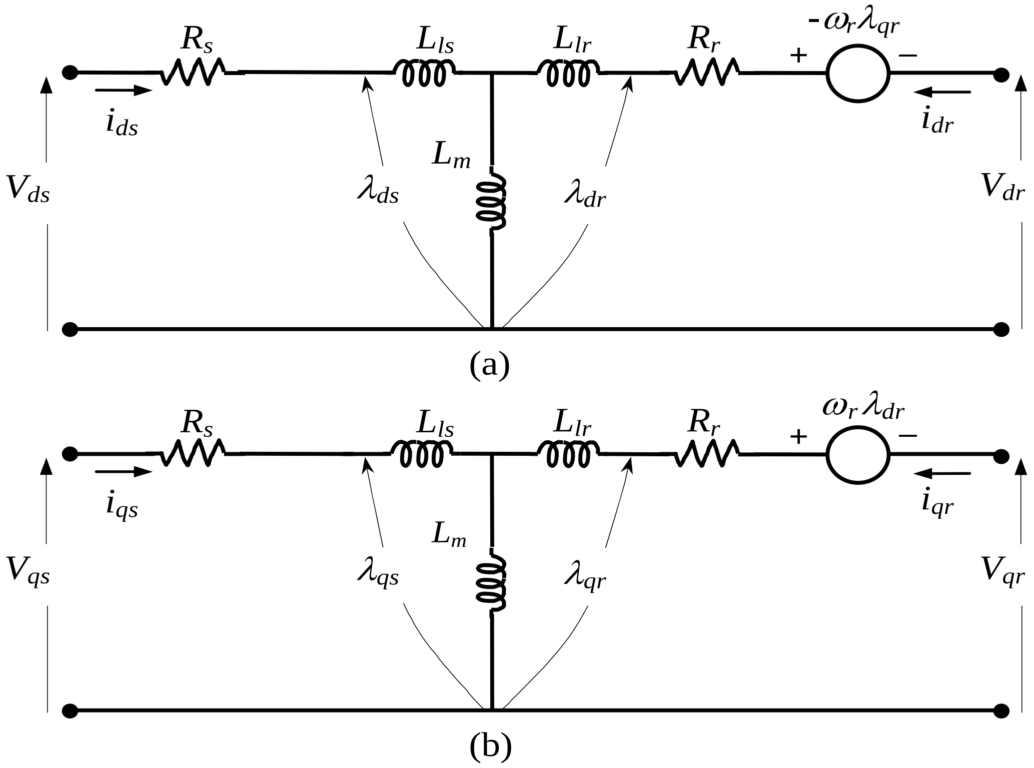


Figure 2: D-Q representation of induction machine in the stationary reference frame (a) d-axis circuit (b) q-axis circuit

Where $\theta_r$ is the electrical rotor angle.

$v_{sD}$ - D-axis stator voltage
$v_{sQ}$ - Q-axis stator voltage
$v_{r\alpha}$ - $\alpha$-axis rotor voltage
$v_{r\beta}$ - $\beta$-axis rotor voltage
$i_{sD}$ - D-axis stator current
$i_{sQ}$ - Q-axis stator current
$i_{r\alpha}$ - $\alpha$-axis rotor current
$i_{r\beta}$ - $\beta$-axis rotor current

The parameters of the induction generator used in this paper have been obtained by conducting tests when it is used as a motor. The traditional tests used to determine the parameters are the open circuit (no load) test and the short circuit (locked rotor) test. The induction machine used as induction generator in this investigation is a three-phase squirrel cage 22kW WEG induction motor with specification on the name plate: 4 pole, 415V delta connected, 41A, 22kW, 50Hz, 1470rpm. The parameters are obtained by conducting parameter determination tests on the above mentioned induction machine. The parameters obtained from the test at rated values of voltage and frequency are $L_{ls}$=$L_{lr}$=8.5mH, $L_m$=140mH, $R_s$=0.5Ω $R_r$=0.36Ω. For self excited induction generator application the variation of $L_m$ with current has been taken into consideration.

## 4. Isolated Self-Excited Induction Generator

An isolated three phase self-excited induction generator is excited by three ac capacitors connected at the stator terminals, shown in Fig. 3, or a single DC capacitor connected to the stator terminals via inverter/rectifier power converter, shown in Fig. 4..

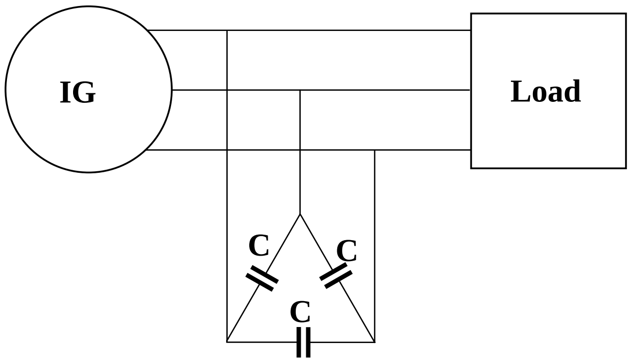


Figure 3: Induction generator excited with ac capacitors

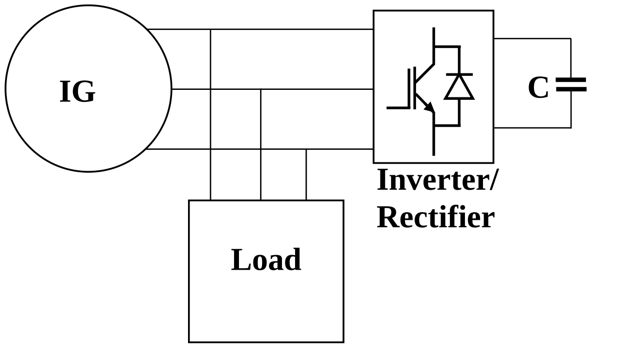


Figure 4: Induction generator excited by Inverter/rectifier

## 5. FAULT ON THE LINES OF STATOR SUPPLIED INDUCTION GENERATOR

When there is fault close to the induction generator high current will flow to the point of fault and the terminal voltage at the terminals of the induction generator will drop. As the only source of excitation to produce the magnetic flux required for the operation of the induction generator is coming from the stator terminals, any drop in terminal voltage will create a drop in the magnetic flux.

The simulation results for a fault accruing at about 0.5sec and close to the terminals of the induction generator are shown in Fig. 5, for current, and in Fig. 6, for voltage. The current waveform, shown in Fig. 7 and voltage waveform, shown in Fig. 8 are for a fault further from the induction generator.

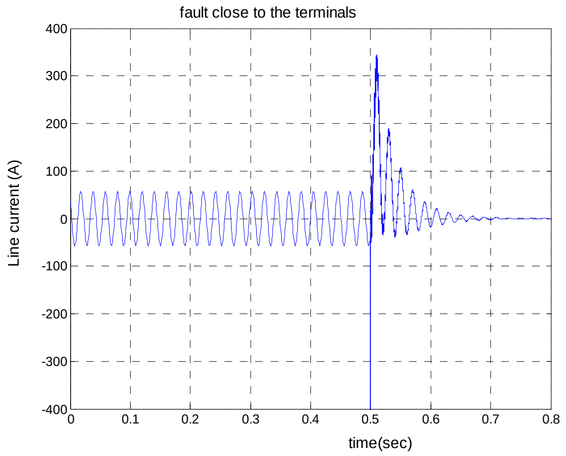


Figure 5: Current waveform for a fault close to the induction generator

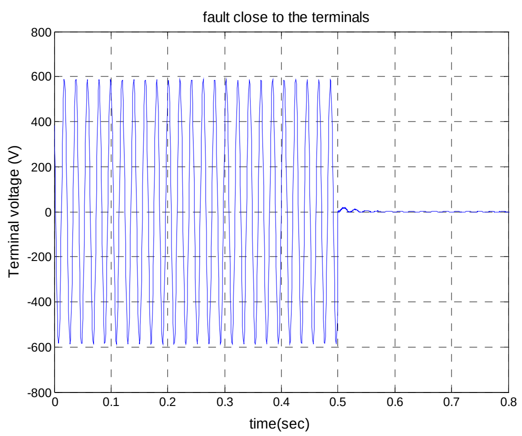


Figure 6: Voltage waveform for a fault close to the induction generator

The stator flux linkage associated with the fault further from the induction generator is given in Fig. 9. The negative offset just after the fault happened (at about 0.5 sec) is due to numerical integration error [10]. The flux linkage wave form for the fault close to the induction generator is not shown because the value after the fault is almost zero, difficult to see its magnitude on a figure size given in this paper.

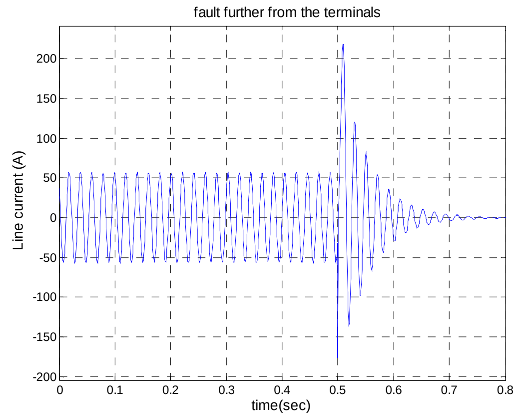


Figure 7: Current waveform for a fault further from the induction generator

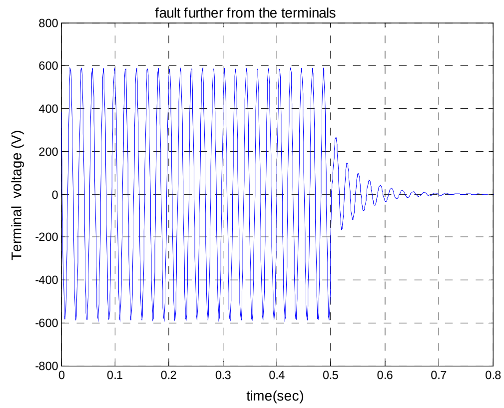


Figure 8: Voltage waveform for a fault further from the induction generator

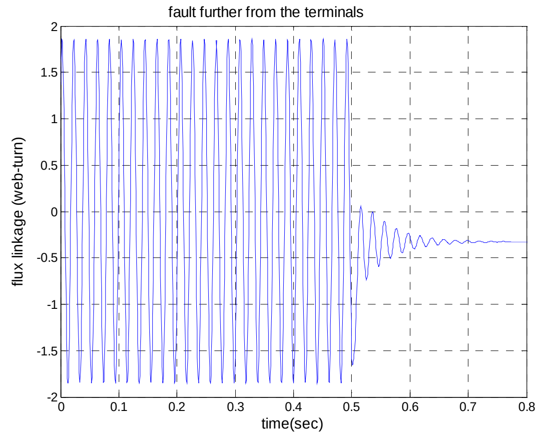


Figure 9: flux linkage waveform for a fault further from the induction generator

During the fault the value of the flux has dropped significantly even if the fault is cleared quickly. For an isolated self excited induction generator once fault occurs all the operation has to be stopped and restarted again.

Based on the National Electricity Rules the grid connected induction generator should be able to ride through any fault, including zero voltage at the connection point, for 175ms without being isolated from the grid. When the fault is cleared with in 0.175seconds the magnetic flux in the induction machine has dropped significantly. Hence the induction machine will draw high inrush current for its excitation. An induction generator drawing all of the excitation current required for re-magnetisation from its stator terminals will reduce the network voltage after the fault clearance.

Due the fault the circuit breaker may open the lines. The voltage and flux linkage waveforms of the induction generator, when the lines are opened just before 0.5sec, are given in Fig. 10 and Fig. 11 respectively.

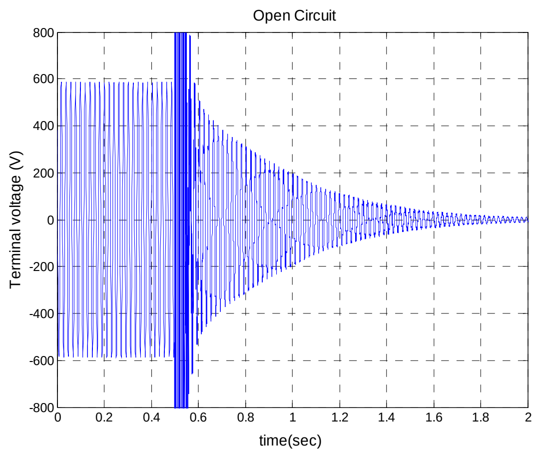


Figure 10: Voltage waveform when the lines are opened

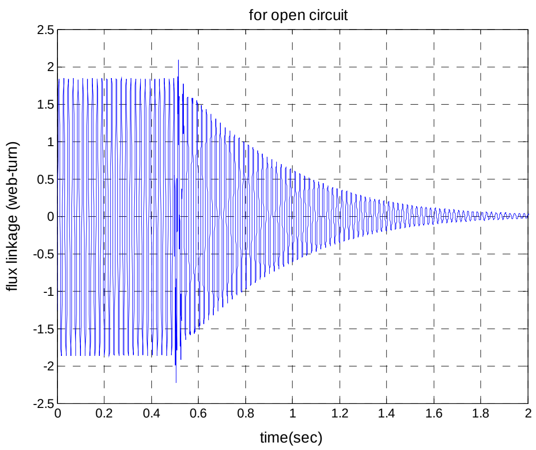


Figure 10: flux linkage waveform when the lines are opened

When the circuit breaker closes the line high inrush current will be withdrawn from the grid. Hence for a stator a stator excited induction generator, whether the line is opened or still connected during the fault, it will not be able to satisfy the National Electricity Rules.

## 6. DOUBLY FED INDUCTION GENERATOR

There are two types of arrangements of doubly fed induction generator. The first one is implemented by supplying additional excitation through the rotor of the induction generator in a wound rotor induction generator, as shown in Fig. 12. The second one is implemented by special induction generator having twin windings in the stator, ash shown in Fig. 13.

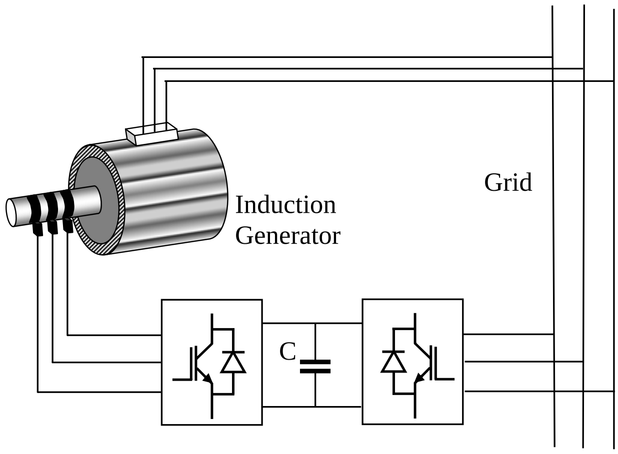


Figure 12: Doubly-fed wound rotor induction generator

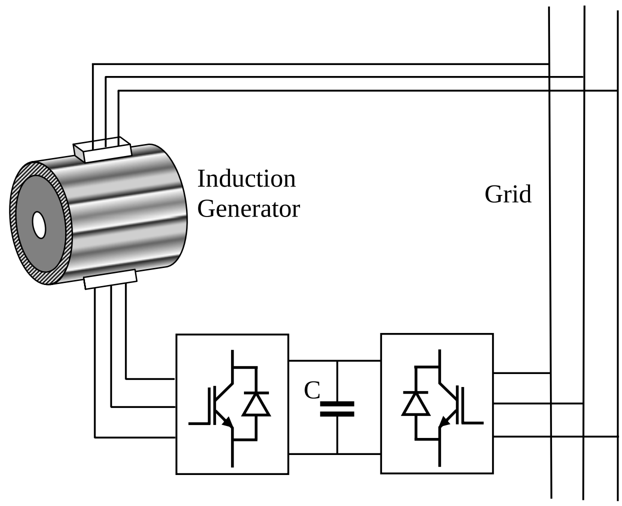


Figure 13: Brushless doubly-fed (twin stator winding) induction generator

In both types of doubly fed induction generators the reactive current required to produce magnetic flux from the stator terminals directly connected to the grid or from the inverter. The DC capacitor will be charged from the grid through the grid side converter. When there is fault the stator terminal voltage will be dropped but the magnetic flux will not drop as the DC capacitor will be used as a reactive current source to maintain the flux in the generator.

Using doubly-fed induction generators it is possible satisfy the National Electricity Rules. The doubly-fed wound rotor induction generator, shown in Fig. 12, is the most commonly used because it is the normal wound rotor induction machine. However for the brushless doubly-fed (twin stator winding) induction generator the induction machine should be specially designed and manufactured.

## 7. CONCLUSIONS

The performance analysis of different induction generator schemes for grid-connected as well as isolated system applications during electrical faults and after clearance of the fault has been discussed and simulation results have been shown.

The National Electricity Rules related to induction generating units that will be connected to the grid can be satisfied only if the induction generators are implemented using doubly-fed induction generators.

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