Performance Enhancement of Grid-Connected Fixed Speed Wind Energy Conversion Systems (WECS)

S. Sugiarto, A. Abu-Siada and S. Islam

Abstract—**Wind power generation is regarded as the most promising of all renewable energy supply to meet the global commitment to climate change. Of all wind power technologies, the fixed speed system employing the rugged Squirrel Cage Induction Generators (SCIGs) are the cheapest and simplest for grid connection. While the self excitable induction generator behavior in stand alone circumstances has been studied in detail, not much attention has been given to the efficiency optimization of the grid connected wind turbine driven SCIGs. In this paper, a novel optimal energy extraction scheme of fixed speed system is proposed within the tolerable speed and voltage range of the SCIGs. The proposed technique doesn't employ any expensive power converter or inverter arrangements but exploits the capability of the existing equipment.**

I. INTRODUCTION

THE current climate change initiatives has prompted rapid development of many renewable energy systems, including the wind energy conversion system, for integration into the current power system [1]. High penetration of wind energy into the current grid is prevented by many reasons, especially the high capital and maintenance cost of the system [2]. To some extent this is mitigated by utilizing SCIGs. The use of SCIG in wind energy generation is widely accepted as a simple and cheap option, as it is reliable and requires very little maintenance due to its brushless rotor. Hence, it offers significant cost advantage over other type of generators [1].

The grid or the power system strictly requires a fixed frequency and voltage with some degree of tolerance. This regulation is especially important now as power generation becomes more deregulated. The grid also regulates the reactive power requirement of the WECS to ensure power quality and efficiency is maintained at a high level.

With the increasing cost of energy in the modern world, it is important, now more than ever, to ensure that power system, from generation, transmission, distribution to consumption, is kept at its maximum possible efficiency. This paper is intended to address the possibility of realizing this efficiency maximisation by maintaining system simplicity yet maximising delivered power to the grid.

II. PROPOSED SYSTEM

The WECS proposed in this paper is configured as shown in Fig 1. The wind kinetic energy captured in the wind turbine drives a rotor that is mechanically coupled to the SCIG. The SCIG is configured to operate as a fixed-speed generator and utilizes variable capacitors for excitation and reactive power support. The capacitors are sized to provide the suitable reactive requirement of the IGs with additional capacity to temporarily help support reactive requirement of the local load. The SCIG is grid-connected without power electronic converter and hence the grid governs a fixed voltage fixed frequency operating point for the system and the SCIG can only run with a limited rotor speed variation, which is governed by the slip. The voltage variation is compensated by the tap changing transformer, which will keep the voltage at the grid side constant, within the tap changer's operational constraint, while providing some tolerance in voltage variation at the terminal of the SCIG.

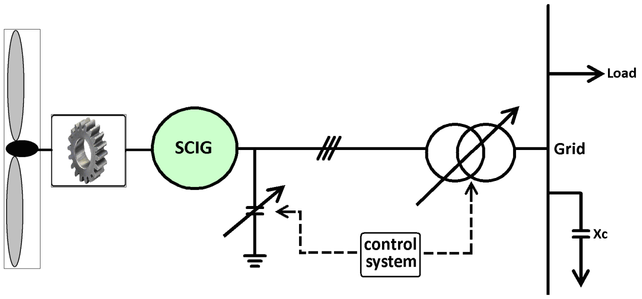

Fig 1. Schematic of proposed model

The variable capacitors and tap changing transformer will be controlled through a supervisory control system. By performing some voltage control on the SCIG, it is possible for more power to be transferred to the grid. As the SCIG is grid-connected, the voltage at the IG terminal is rigidly governed by the grid and the number of turns of the transformer. Hence, by controlling this turn ratio appropriately, it is possible for the terminal voltage of the IG to vary within reasonable limit to allow more efficient power transfer to the grid, while ensuring that the voltage at the grid side stays constant by the action of the tap changer, which works as an AC-AC converter. Due to the characteristics of both the wind turbines and the IG it is revealed that there is a limited opportunity to vary the speed and voltage to obtain significant gain in energy output without sacrificing grid requirements. The main components of this proposed system are explained below.

A. Squirrel Cage Induction Generator

An induction machine can work as a generator if the required amount of reactive power is supplied to sustain the excitation requirement, while the rotor speed is maintained by

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some prime mover above the synchronous speed. This is as shown in Fig 2.

When the generator is connected to the grid, theoretically, it is possible for this reactive power requirement to be supplied by the grid. However, due to the connection regulation, it is required that at the point of common coupling a certain power factor is maintained. This means that the generator is not allowed to take reactive power from the grid and have to be self-sufficient through the utilization of excitation capacitors.

Utilising squirrel-cage induction machine as self-excited induction generator is beneficial as it has high power density and simple construction. Furthermore, the self-excitation characteristics causes the voltage to collapse rapidly when overloaded, thus providing self-protection.

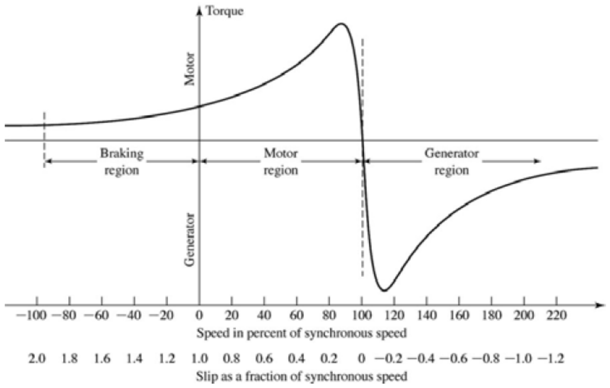

Fig 2. Torque-slip characteristic of an induction machine [3]

B. *On load tap changing transformer*

OLTC transformer is normally used to maintain the load bus voltage within its permissible limits despite any load changes. The utilization of OLTC transformer on different static loads namely; constant power (CP), constant current (CI) and constant impedance (CZ) had major effect on the maximum power transfer limit in the power system, from the generation to the load centre through the OLTC transformer branch. In the proposed system, transformer with tap changer is utilised to maintain a predetermined voltage level at the grid side allowing a limited voltage variation on the generator side.

Power transfer from generators to load centres affects load bus voltages and tap changing transformer is capable of maintaining this bus voltage. Using this same principle, this transformer is believed to maintain voltage when there is change in the supply instead of change in load. This means its capability of extending power transfer capability of the system [4] can also be applied to the proposed system of variable supply. Due to this reason, the tap changing transformer will be utilised together with the variable capacitors in improving the efficiency of the WECS with fixed speed SCIG.

1) *Constant Power (CP) Load:*

The limit of power transfer to the constant power load depends on the degree of reactive power compensation through the capacitor bank, OLTC transformer setting and load bus voltage. Fig 3 shows the effect of OLTC transformer tap ratio on the maximum power transfer for compensated and uncompensated load (X_c=10 pu. and X_c=∞ respectively). For both cases the maximum power transfer limit is increased by increasing the tap ratio. Once the optimal power is reached (0.5 pu. in case of uncompensated load and 0.56 pu. in case of compensated load) the power slightly decreases with the increase of tap ratio.

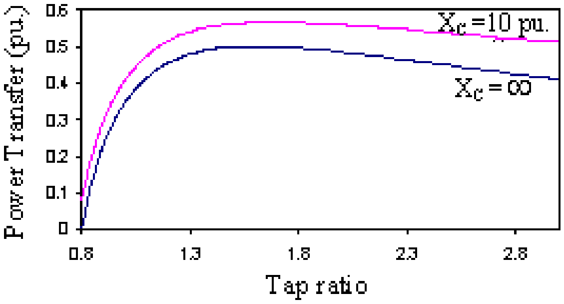

Fig 3. Effect of OLTC on power transfer to the CP load (K=0.75, X_T=0.5 pu., V_r=0.8 pu.) [4]

Fig 4 shows the PV curve for the uncompensated load for different tap ratios. The figure shows that the maximum power limit is constant and equal 0.5 pu. in all cases.

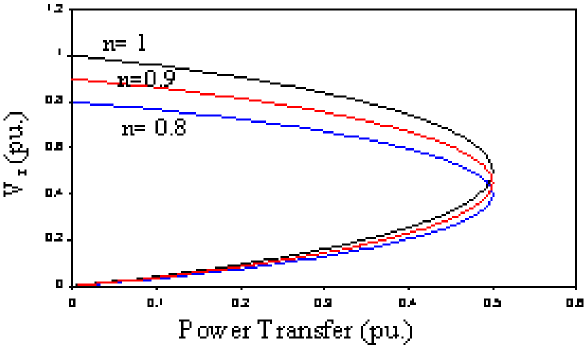

Fig 4. P-V curve at different tap ratios (X_c=∞) [4]

The PV curves in Figures 5 and 6 show that the maximum power transfer limit to a compensated load can be increased by either increasing the tap ratio of OLTC transformer or by increasing the degree of compensation.

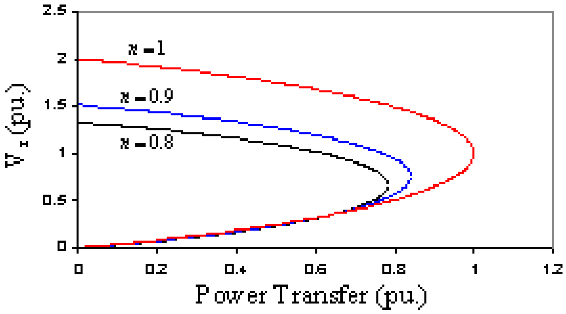

Fig 5. P-V curve at different tap ratios (X_c=1 pu) [4]

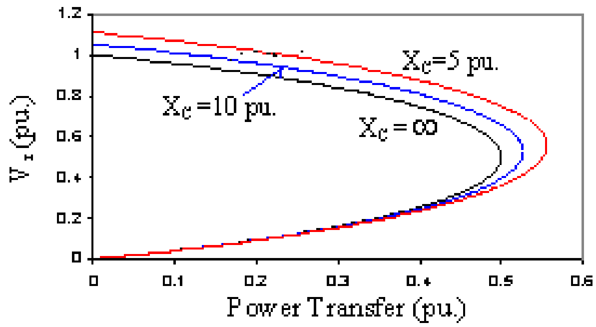

Fig 6. P-V curve at different load compensation (n=1) [4]

2) Constant Current (CI) Load

Fig 7 shows the effect of OLTC transformer tap ratio on the power transfer limit to constant current load. The maximum power transfer limit is increasing with the increase of the tap ratio. When the maximum limit is reached (0.5 pu. in case of uncompensated load and 0.62 pu. in case of compensated load), the power is decreasing with the increase of tap ratio. The shunt capacitor increases the power transfer limit and shifts the optimal setting of OLTC transformer to a higher value.

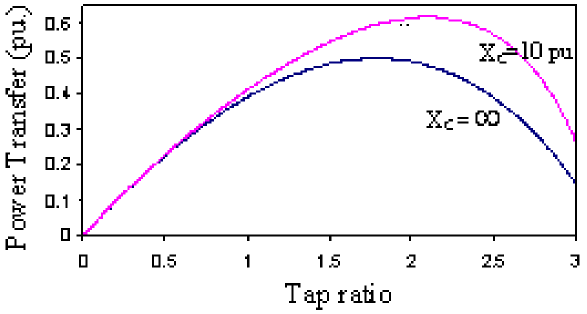

Fig 7. Effect of OLTC on power transfer to the CI load [4]

3) Constant Impedance (CZ) Load

Fig 8 shows the effect of OLTC transformer tap ratio on the power transfer limit to constant impedance load. Power is increasing with the increase of OLTC transformer tap ratio till the optimal power is reached then the power is decreasing with the increase of tap ratio. The optimal power in case of uncompensated load ($X_c = \infty$) is 0.5 pu. corresponding to 1.72 tap ratio. However, the maximum power for a compensated load ($X_c = 10$ pu.) is 0.62 pu. corresponding to 2.1 tap ratio.

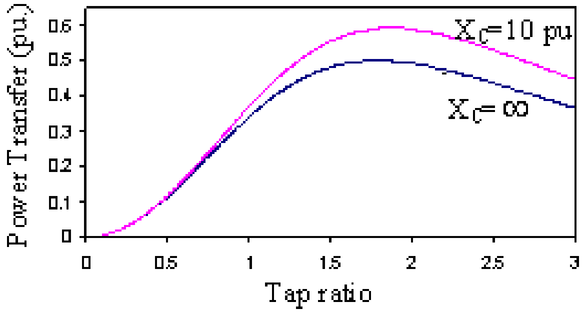

Fig 8. Effect of OLTC on power transfer to the CZ load [4]

C. OLTC transformer Test System

To show the effectiveness of OLTC transformer in optimizing power transfer capability, a test system is investigated. Fig 9 shows a one-line diagram of the test system. The system consists of 6-nodes, 7 lines, two transformers OLTC transformer, two generators and four loads [4]. The two OLTC transformers are varied one at a time, during the calculation of the maximum power transfer to the load centers.

The results obtained by using the conventional methodology cover a wide range of operating conditions. A sample of the training results is shown in Figures 10-15. These results are presented to explore the effect of both OLTC transformer settings and the load model on the maximum power transfer.

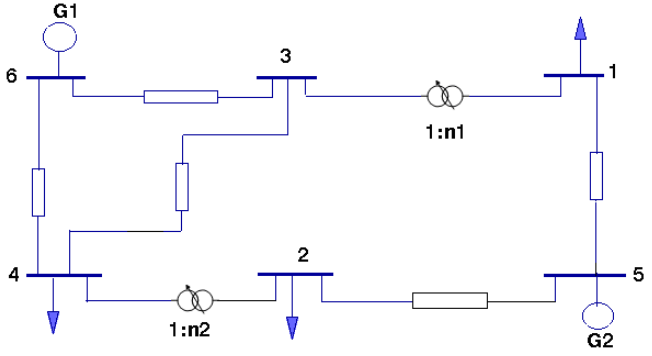

Fig 9. One line diagram of the test system [4]

Figures 10-12 show the relation between the power transfer and the transformer tap ratio n at the three load buses (1, 2& 4) with the loading condition $P_L = Q_L = 0.35$ pu.(pf= 0.707 lag), for the three different load models (CP, CI & CZ). From these figures, it can be seen that the optimum value of n and the corresponding maximum power transfer are different for the three load models.

Figures 13-15 present similar results at another loading condition $P_L = 0.8$ pu. and $Q_L = 0.13$ pu. (pf = 0.987 lag). It can be seen from these figures that the maximum power transfer limit is higher at this operating condition than the previous case and the OLTC transformer setting n1 has a strong effect on the load at bus 1 which is similar to the effect of n2 on the load at bus 2. On the other hand, the OLTC transformer setting n2 has a unique correlation and effect on the load at bus 4. These figures prove that the power transfer limit is affected by the OLTC transformer setting for all load models.

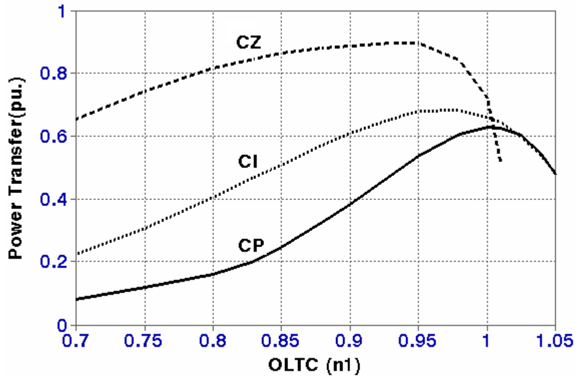

Fig 10.Effect of OLTC (n1) on Power transfer to load 1 [4]

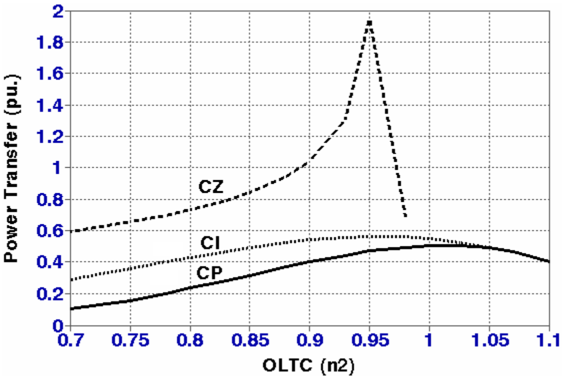

Fig 11. Effect of OLTC (n2) on Power transfer to load 2 [4]

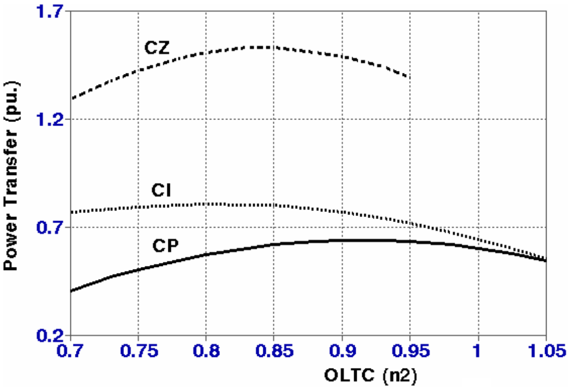

Fig 12. Effect of OLTC (n2) on Power transfer to load 4 [4]

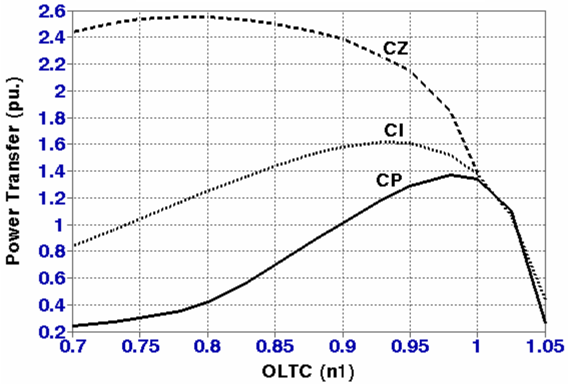

Fig 13. Effect of OLTC (n1) on Power transfer to load 1 [4]

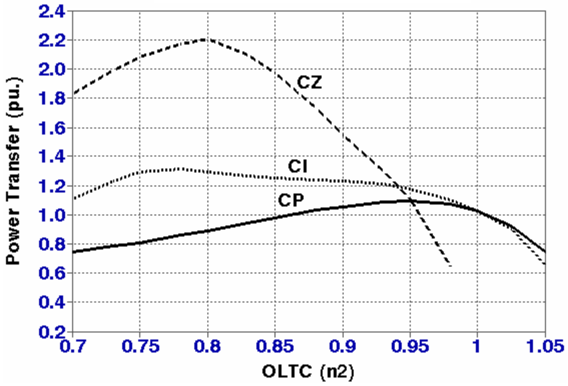

Fig 14. Effect of OLTC (n2) on Power transfer to load 2 [4]

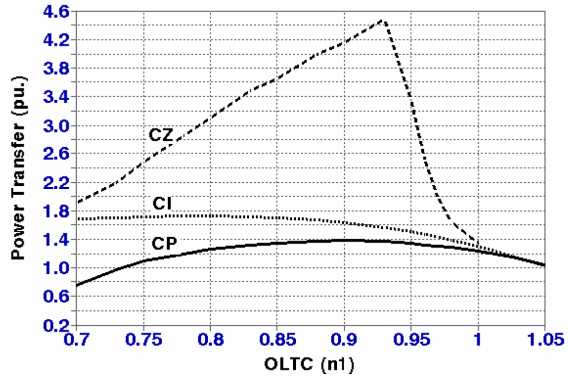

Fig 15. Effect of OLTC (n1) on Power transfer to load 4 [4]

From these results, it can be seen that before the reverse points are reached, the upward of OLTC transformer operation increases the maximum power transfer to the load centre. Also these results give an indication that the maximum point of power transfer and thus the levels of these powers are different for different load models.

III. SYSTEM OPERATION

The system is proposed to operate in the small window of the fixed speed region as shown in Fig 16 by the grey shaded area. The turbine output power is computed using the data from Vestas V82-1.63MW wind turbine specification [5]. The dashed line shows that by controlling the stator terminal voltage it is possible to move the point of operation at any particular wind speed. Within the tolerable fixed speed region, output power can be significantly improved, as shown by the green shaded area, by adjusting the terminal voltage of the SCIG. The key for significant gain is the high slope of the induction generator's torque-speed curve as shown in Fig 2 and Fig 16. The method of stator terminal voltage adjustment to vary output power and generator torque can be found in Fig 17 [6].

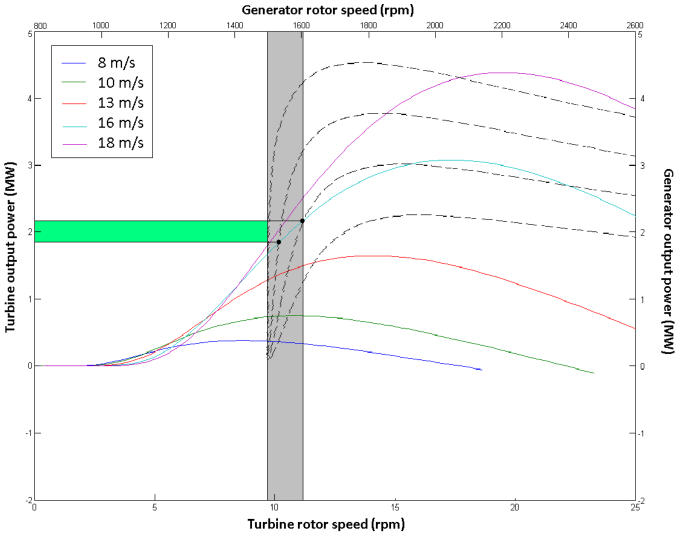

Fig 16. System operation region

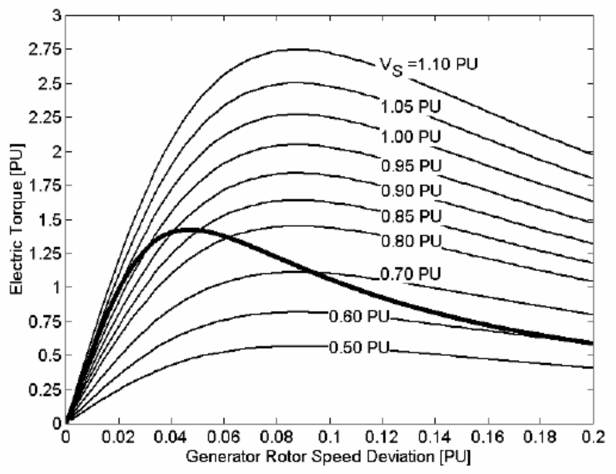

Fig 17. Electric torque versus generator rotor speed calculated at a constant stator terminal voltage [6]

IV. PSIM SIMULATION

Simulation of a scalable SCIG operated as a grid-connected IG has been performed on PSIM® simulation platform. The wind turbine is modeled from a 3kW Westwind turbine specification with power curve shown in Fig 18 [7]. The simulation model is shown in Fig 21 and consists of a wind turbine model that is mechanically coupled with the shaft of an SCIG though a gear box. The stator of the SCIG is connected to the grid through a transformer of variable turns ratio to simulate OLTC transformer, a local load and a capacitor bank.

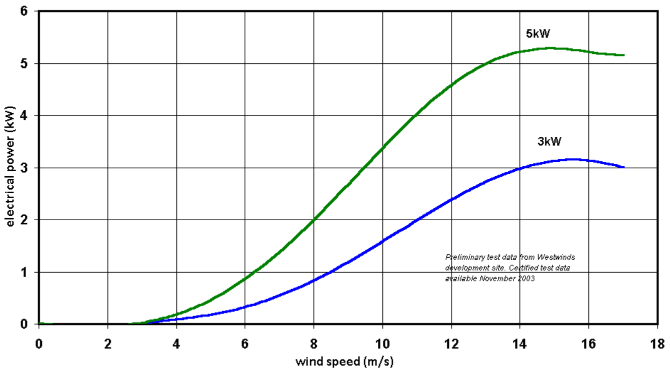

Fig 18. Westwind 3kW wind turbine power [7]

In PSIM, an SCIG generates power when supplied by a negative torque on its shaft. Due to the placement direction of the meters, power is negative when generated by the SCIG and positive when consumed by the SCIG. The gearbox is tuned to optimize the operation at a wind speed of 8m/s, which will make cp value ranging at 0.45. The SCIG has a rated voltage at 440V and a base turn ratio of 1:1 is used for the transformer. A snapshot of a simulation result is shown in Fig 19 and 20. From these figures, it can be seen that after an approximately 3s initialization period, the turbine model supplies negative torque to the SCIG, which in turn generates real power to the grid and consumes reactive power from the grid.

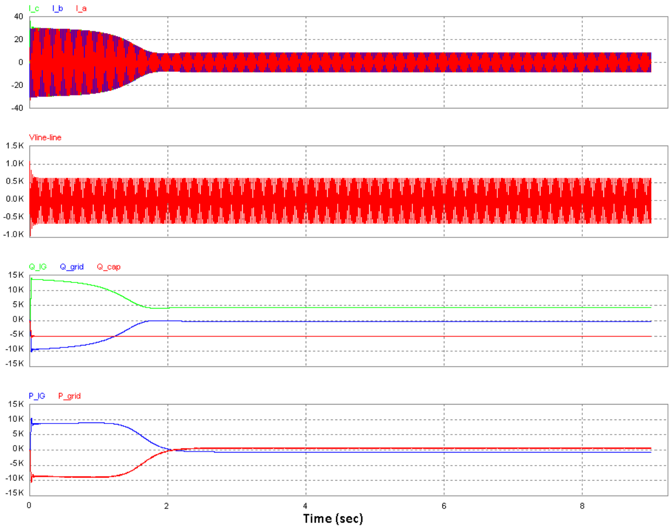

Fig 19. PSIM simulation results showing the initialization and power transfer of the system

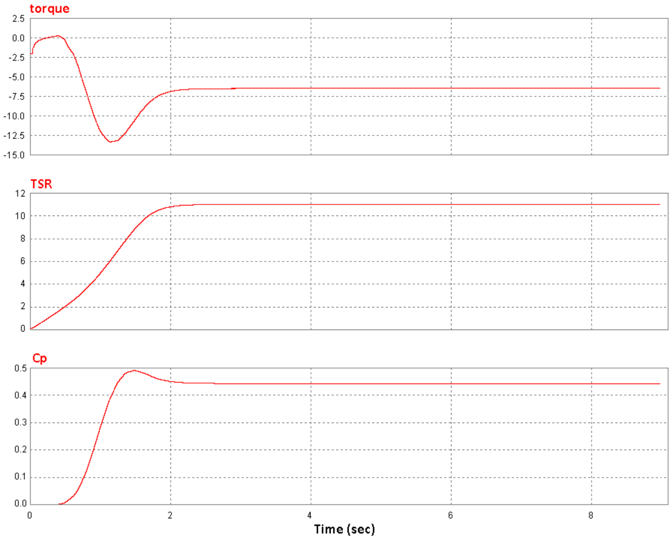

Fig 20. PSIM simulation results showing the negative torque, Tip Speed Ratio (TSR) and cp

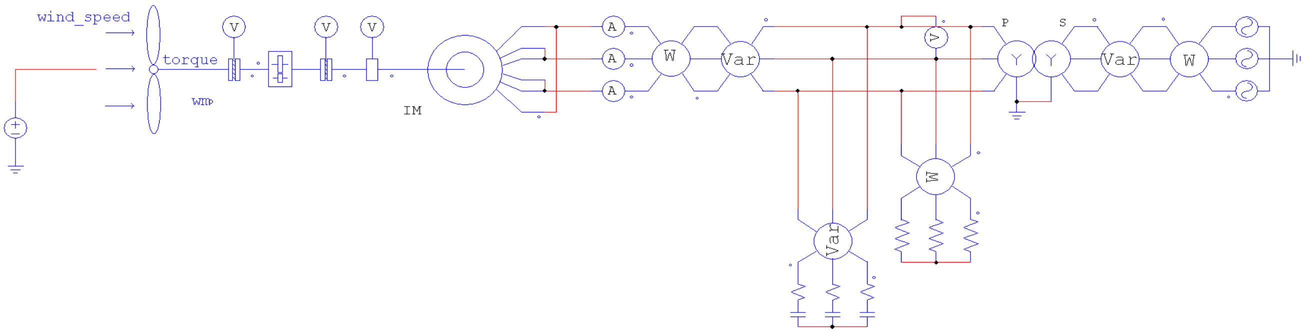

Fig 21. PSIM simulation model

Fig 22 shows the result of terminal voltage control of the SCIG. When the terminal voltage is increased, the real power generated by the SCIG also increases until it reach an optimum operating point from where increasing the terminal voltage will result in the decrease of SCIG generated power. The maximum power generated is less than the rated power due to losses in the system. This method of optimizing the power transfer to the grid also results in the variation of reactive power requirement of the SCIG. Due to this reason, to maintain an acceptable power factor at the point of common coupling, it is essential that the capacitor bank is varied accordingly to provide reactive power support.

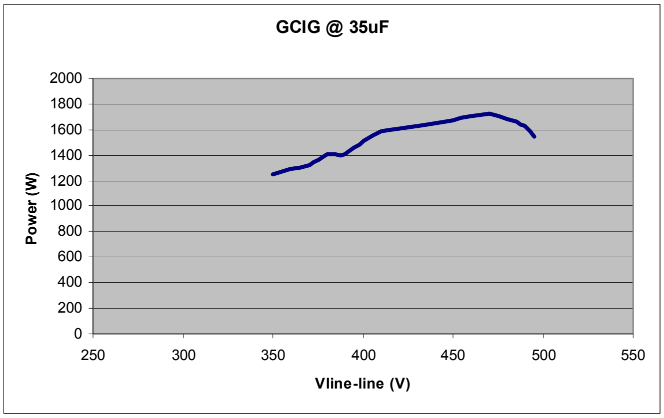

Fig 22. PSIM simulation results showing CGIG terminal voltage control

V. CONCLUSIONS

The utilization of variable capacitors and OLTC transformer in tandem can significantly improve the power transfer capability of a WECS with fixed speed SCIG, within a tolerable window of opportunity. Only minor modification, in the form of a global controller that will control the values of excitation capacitor as well as the tap position of the transformer, needs to be added to the existing system. It was noted that in all the different load models, the power transfer limit is increased by increasing the degree of compensation i.e. decreasing the value of X_c. When the load power can not be met with the increasing the compensation degree, the power can be increased by increasing the OLTC transformer tap ratio. Further research and hardware testing are currently undertaken by the authors of this work to ensure further validity of this finding and to design an appropriate control scheme for this system with various load types.

VI. REFERENCES

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