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Performance Improvement of Low Power Wind-Driven Wound Rotor Induction Generators with Combined Input Voltage and Slip Power Control

M. Munawar Shees[1,2], A. F. Almarshoud[2], M. S. Jamil Asghar[3]
[1] Singhania University, Jhunjhunu, Rajasthan, India
[2]College of Engineering, Qassim University, Buraidah, K.S.A.
[3]Electrical Engineering Department, Aligarh Muslim University, Aligarh, U.P., India

Abstract:- Various techniques have been employed to optimize the performance of wound rotor induction generator (WRIG) based wind power generation systems. Input voltage control was used for the improvement of power factor in grid-connected induction generators. However, in this case, efficiency reduces drastically due to high output current. Moreover, the control range is limited. The conventional rotor resistance control had also been used for wind-driven WRIG. But, with this, the input power factor becomes very poor. In this paper, a new control method is proposed where both input voltage and slip power control are combined to achieve better performance. For each operating point an optimum input voltage is set and slip is controlled by rotor resistance such that the maximum efficiency is obtained. Moreover, both power factor and efficiency are improved for a wide range of speed variations. Also the reactive power demand is reduced throughout the range of effective speed which is compensated by optimum fixed capacitors. This scheme is useful for low power wind energy conversion system (WECS) where wind speed varies over wide range. Simulation model for the proposed schemes are developed using MATLAB and the performance of the induction generator under various wind conditions are studied with this model. Also the performance characteristics of the proposed schemes are experimentally verified. The proposed control schemes are simple as well as cheap.

Index Terms:- Combined input voltage and slip power control, Wound Rotor Induction generator (WRIG), MATLAB, Slip power control, Renewable energy sources (RES), Wind energy conversion system (WECS).

I. INTRODUCTION

The increasing energy demand throughout the world, the air pollution produced by burning of fossil fuels as well as the depletion of fossil fuels and the growing doubt about the safety of nuclear power led to a growing demand for the wider use of renewable energy sources (RES). Wind power is one among the leading renewable energy sources, which can overcome the concern of energy shortage in future. Wind power has proven to be a potential clean renewable source for generation of electricity with minimal environmental impact. This has a great impetus for interest in the wind energy conversion system (WECS) as potential power source. With the priority status accorded to it in many countries, the share of wind power in relation to overall installed capacity has increased significantly, while in some of the countries, it is approaching to 50% mark [1]. The wind energy will be able to contribute at least 12% of global electricity consumption by the year 2020 [2].

Grid-connected induction generators have many advantages over synchronous generators. It does not require separate field circuit. A controlled synchronization with grid is not required. The ac line regulates the frequency and output voltage of the induction generator, eliminating the need for expensive and complex electronic conversion equipment. Moreover, it is not necessarily to be operated at fixed speed as in case of synchronous generator. The operating speed of the induction generator is self-adjustable according to the variation in the input torque. This also reduces the wear and tear on the gearbox [3,4]. When input torque increases beyond push-over torque, power generation starts and machine speed increases. The main demerit is, it requires reactive (lagging) power, which is to be supplied externally (e.g. by capacitor bank)[4].

Variable speed wind turbine has the advantages of maximum energy capture and reduction of the aerodynamic noise levels produced by wind turbines which is more significant in low wind speeds[5].The gearbox of a wind turbine has single gear ratio between the rotation of the rotor (turbine) and the induction generator. Therefore, either the control has to be applied on the generator itself or by pitching the rotor-blades out marginally or fully, as required. However, an electrical control is preferable and the easy option left, especially at low wind speeds. The conventional rotor resistance control had been used with WRIG for wind power generation. But, the main demerit of this system is its very low input power factor. Moreover, the efficiency also becomes poor [6]. Often, an ac voltage regulator is used for soft switching to reduce the extra wear on the gearbox at the time of cut-in of the generator. The voltage control by an ac voltage regulator had been suggested earlier to improve the power factor. However, in this case the efficiency drops drastically and control range is also limited [7,8]. Moreover, the total harmonic distortion (THD) also increases with the increase of triggering angle or at low output voltage [9].

Most of the doubly-fed induction generators (DFIG) and synchronous generators, incorporate sophisticated power electronic control systems. However, DFIG is capable to control both active and reactive power independently [10]. The dynamic voltage restorer is also used for active and reactive power control for wind turbine based power generation system [11].

To optimize the performance of wind power generation various techniques have been employed. The dual stator-winding induction generator with static excitation controller is one among the various optimum schemes [12]. Recently the performance of wound-rotor induction motor had been greatly enhanced by the combination of input voltage control and slip power control [13]. In this paper this technique is extended for wind-driven WRIGs to improve both efficiency and power factor, over a wide range of speed. Moreover, another scheme is also proposed in which fixed capacitors are connected in parallel with the rotor external resistances to compensate the reactive power demand of the induction generator. Therefore no separate control of reactive power is needed. Here, the induction generator is made to operate at its optimum point, therefore optimum performance is achieved. A comparison of the proposed schemes with conventional rotor resistance control scheme is also presented.

II. CONVENTIONAL SLIP POWER CONTROL SCHEME

In the conventional slip power control scheme using rotor resistance control method, the speed of the induction machine is controlled by varying the external resistance, which is inserted in the rotor circuit. Figure 1 shows the slip power control scheme for wound rotor induction generator. However, in this type of control, there is substantial loss in the external resistors at higher speeds which reduces the overall efficiency of the system [14]. The torque-speed characteristic of a wound rotor induction generator (WRIG) with slip power control is shown in Fig. 2. It also indicates the different operating points of WRIG under different wind speeds.

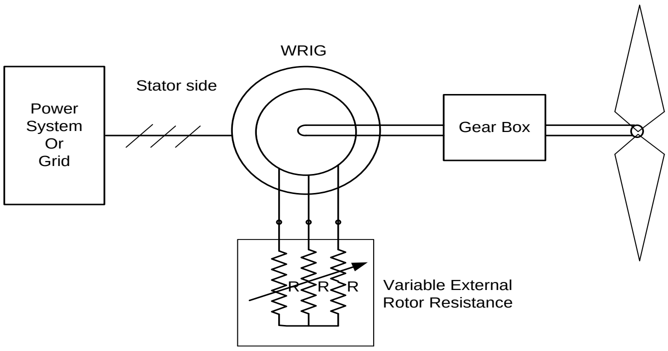

Fig. 1 : Slip power control scheme of a wound rotor induction generator

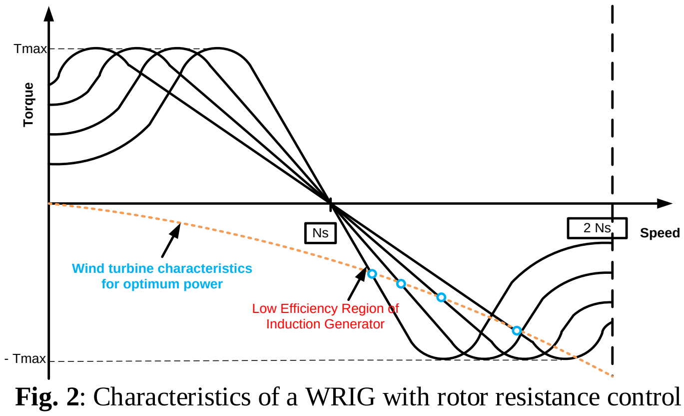

Fig. 2: Characteristics of a WRIG with rotor resistance control

III. PROPOSED SCHEME

In the proposed scheme, the characteristic of WRIG is matched with the characteristic of a wind turbine using combined input voltage and slip power control. Figure 3 shows the circuit topology of the proposed scheme. Here, the slip power controller circuit controls the power in the rotor circuit by varying the external resistance in the rotor circuit. The input voltage is controlled by using an auto transformer or an ac voltage regulator. For a particular wind speed, a particular regulated input ac voltage is applied to the stator of WRIG and a fixed external resistance is put in the rotor circuit such that characteristics of WRIG and wind turbine are matched as shown in Fig. 4. Here, the maximum torque of WRIG matches with the available optimum torque of the wind. Moreover, the efficiency of an induction machine is maximum when the machine is operated at or near the maximum torque condition. In this way, both efficiency and power factor improve for the whole range of control.

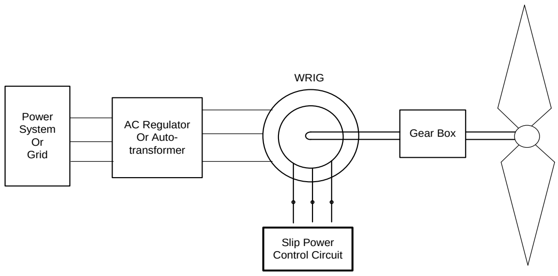

Fig. 3: Circuit topology of the proposed scheme

The different topologies for the slip power control circuit are shown in Fig. 5.

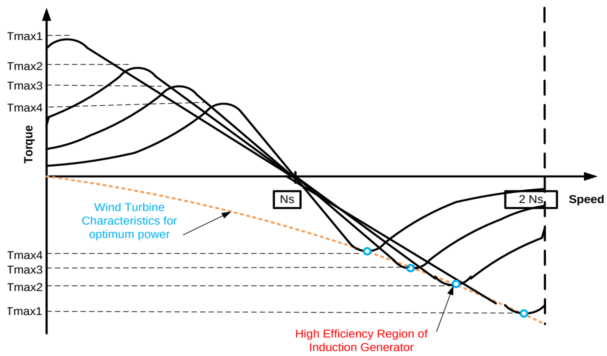

Fig. 4: Characteristics of a WRIG with rotor resistance as well as stator voltage control

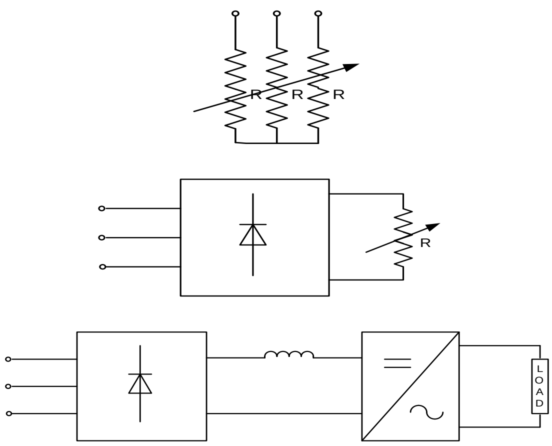

Fig. 5: Circuit topologies of the slip power controller circuit

IV. SIMULATION MODEL

The power system is simulated with three-phase voltage source which is connected to the stator of (WRIG) asynchronous machine in SI unit (Fig. 6). The asynchronous machine is modeled in a dq-abc reference frame. The torque is applied to the WRIG as input mechanical torque 'T_m' through a constant block. The rotor is connected to a three-phase RLC branch which is connected in star. To make it pure resistive, only R is selected from its options. Various measurement blocks such as, V-I, P-Q,V, I, T, ω_m, displays, scopes etc are placed at proper locations. For a particular torque the speed of WRIG is matched with the speed-torque characteristics of wind turbine by varying stator voltage and external rotor resistance. Under different torque conditions, the power transferred from the WRIG to grid or power system is simulated (Fig. 6). The simulated results of waveforms of stator voltage, stator current, and power fed to grid are obtained, which are shown in Fig. 7.

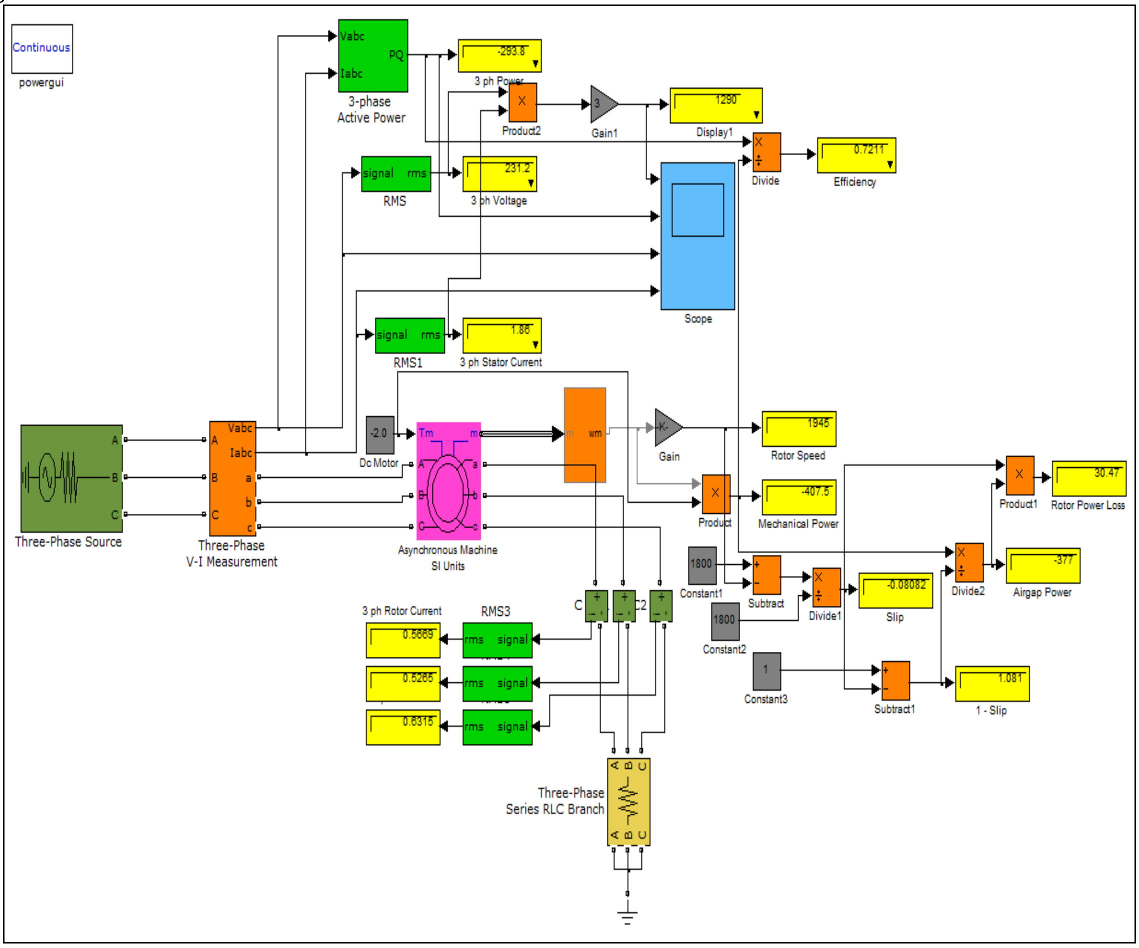

Fig. 6: MATLAB Simulation model of the proposed system feeding power into the grid.

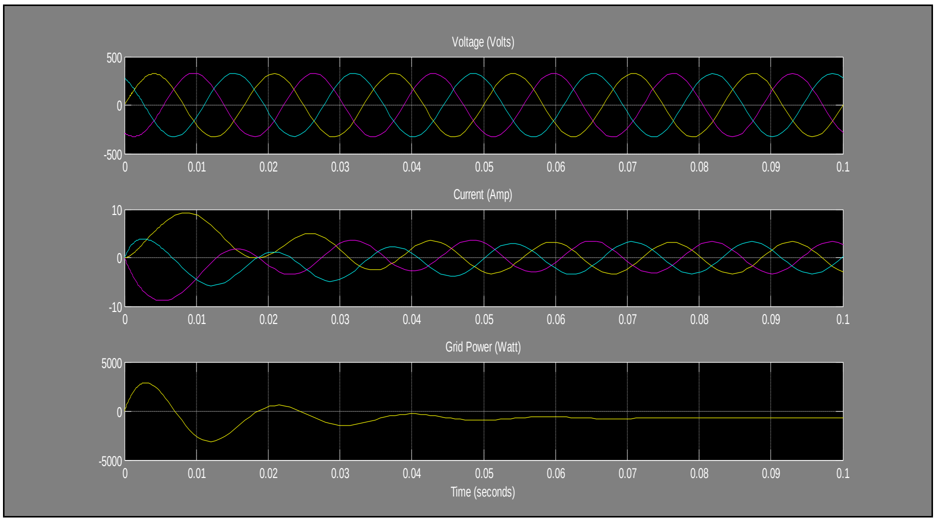

Fig. 7: Waveform showing stator voltage, stator current and power fed to grid

A 1KW, WRIG based wind turbine system is used for the present study. The results obtained using the proposed simulation model of WRIG feeding power to the grid, are given in Table I and Table II.

TABLE I: SIMULATION RESULT OF SLIP POWER CONTROL

Speed (rpm)	Controller Efficiency (%)	Power Factor	Stator Current (Ampere)	Power fed to grid, P (Watt)	% of power loss in external resistor w.r.to P
1860	95.45	0.175	1.812	220.7	2.04
1918	92.46	0.188	1.823	239.5	5.85
1973	88.97	0.202	1.834	257.9	9.39
2026	86.23	0.201	1.844	275.3	12.77
2080	83.51	0.225	1.856	292.3	16.21
2130	81.50	0.238	1.868	310.8	19.21
2180	79.58	0.249	1.884	328.2	22.28
2230	77.77	0.260	1.895	344.9	25.40

TABLE II: SIMULATION RESULT OF COMBINED INPUT VOLTAGE AND SLIP POWER CONTROL

Speed (rpm)	Controller Efficiency (%)	Power Factor	Stator Current (Ampere)	Power fed to grid, P (Watt)	% of power loss in external resistor w.r.to P
1860	97.36	0.35	1.42	244.6	0.05
1918	95.92	0.48	1.38	265	1.50
1973	92.72	0.48	1.42	281.3	5.04
2026	89.77	0.47	1.46	296.6	8.56
2080	86.51	0.46	1.51	313.2	12.19
2130	84.43	0.45	1.55	329.8	15.51
2180	82.13	0.44	1.59	345.9	18.81
2230	79.98	0.43	1.64	362.1	22.06

V. EXPERIMENTAL SET-UP

A 1kW, star-connected, WRIG is mechanically coupled to a Machine Test System which consists of a Drive and Brake unit and a Control unit which can operate the machine in all the four quadrants. The stator of the induction machine is connected to a three phase ac supply through a three-phase auto-transformer and a multifunction meter which can measure active power, reactive power, power factor, frequency, voltage, current etc. Rotor is connected to a three phase variable resistor box. The D & B unit is a cradle-type three-phase asynchronous machine with integrated torque pick-up for connection to the control unit. This special machine is equipped with sufficient power and torque reserves to brake or drive a 1kW machine. The control unit is a microcontroller-controlled device with integrated frequency converter for power supply and control of the D & B unit and display of speed and torque measured values. Both the conventional slip power control scheme as well as the proposed scheme (combined input voltage and slip power control) has been experimentally tested in the laboratory.

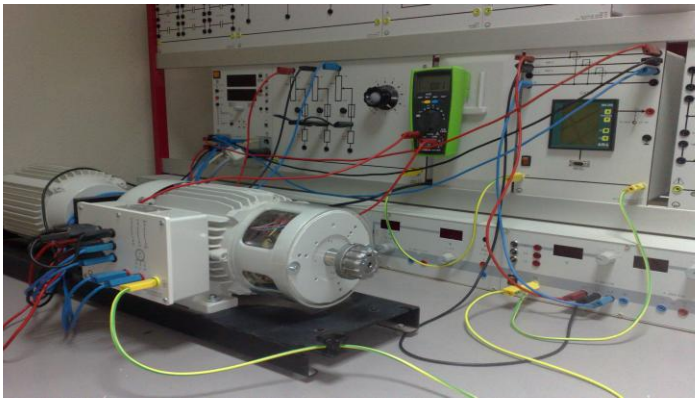

Fig. 8: Experimental set-up for the proposed scheme

TABLE III: EXPERIMENTAL RESULT OF SLIP POWER CONTROL

Speed (rpm)	Controller Efficiency (%)	Power Factor	Stator Current (Ampere)	Power fed to grid, P (Watt)	% of power loss in external resistor w.r.to P
1860	97.35	0.14	1.84	186	0.50
1918	90.71	0.15	1.86	203	7.87
1973	86.94	0.16	1.87	221	12.56
2026	83.80	0.18	1.88	241	16.79
2080	80.64	0.19	1.89	256	21.38
2130	79.09	0.20	1.91	271	22.24
2180	76.45	0.22	2.01	308	28.13
2230	74.80	0.23	2.0	323	30.97

TABLE IV: EXPERIMENTAL RESULT OF COMBINED INPUT VOLTAGE AND SLIP POWER CONTROL

Speed (rpm)	Controller Efficiency (%)	Power Factor	Stator Current (Ampere)	Power fed to grid, P (Watt)	% of power loss in external resistor w.r.to P
1860	96.85	0.48	1.09	229	0.24
1918	94.09	0.53	1.15	246	3.23
1973	90.94	0.53	1.18	264	6.86
2026	87.88	0.53	1.21	279	10.60
2080	85.31	0.51	1.25	299	13.98
2130	83.91	0.49	1.29	317	15.94
2180	82.61	0.48	1.32	332	17.79
2230	81.39	0.47	1.38	349	19.64

The comparision of both simulated and experimental results are shown in Figs. 9-13. It is evident that the overall performance of WRIG by the proposed control scheme improves significantly.

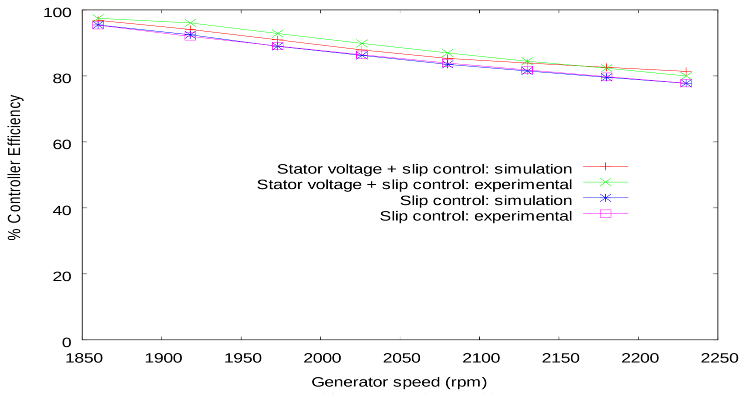

Fig. 9: Controller efficiency for different speed

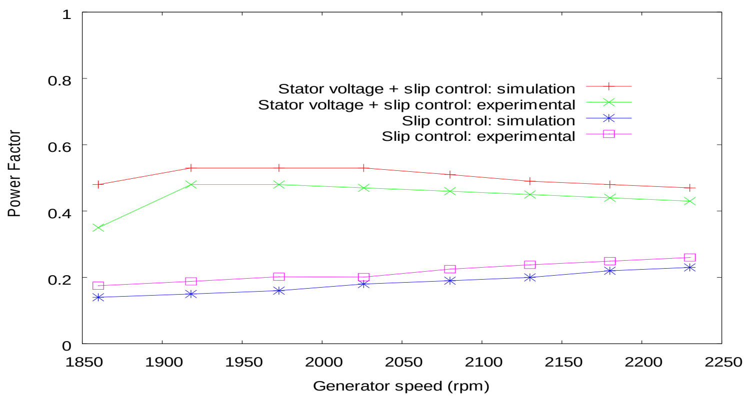

Fig. 10: Power factor for different speed

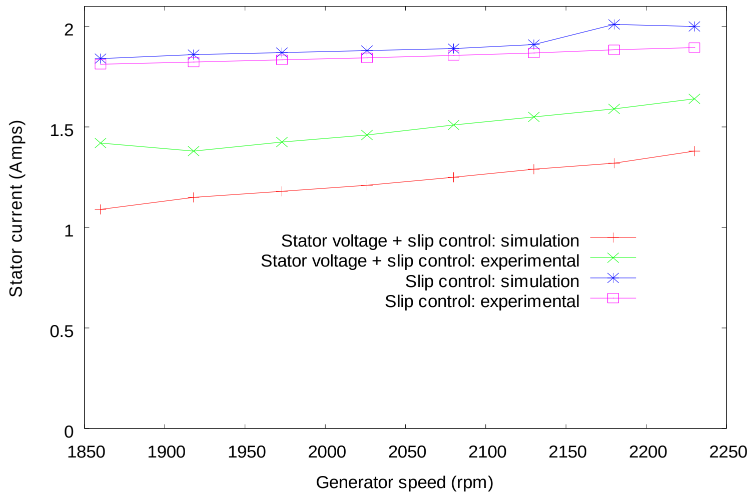

Fig. 11: Stator current for different speed

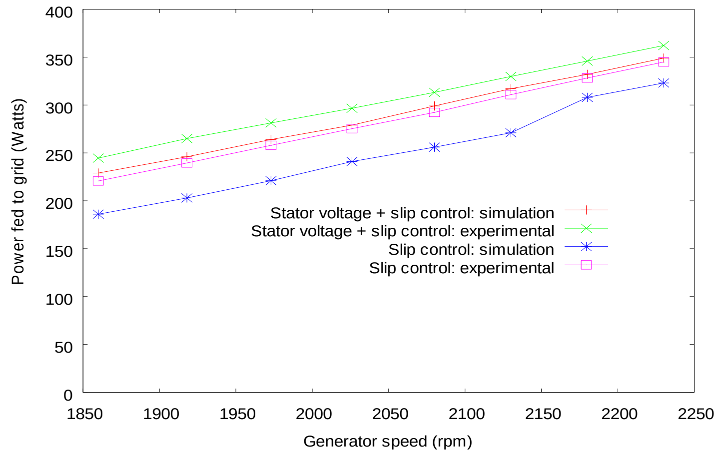

Fig. 12: Power fed into grid for different speed

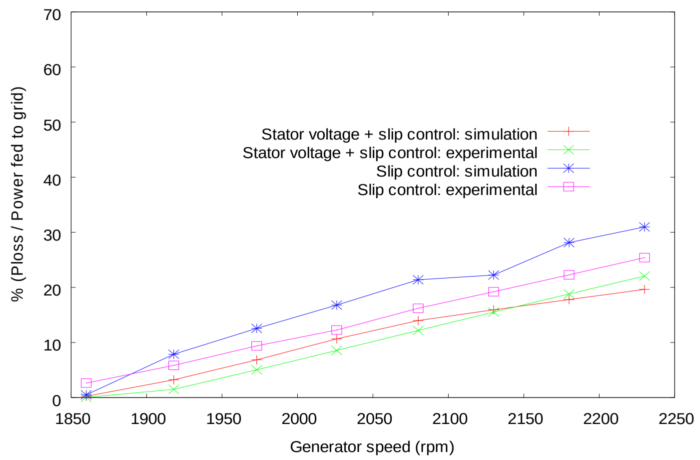

Fig. 13: Percentage of power loss in the external resistor with respect to power fed to grid for different speed

VI. REACTIVE POWER COMPENSATION

To improve the performance of the system further and to compensate the reactive power required by the system, reactive power compensation is done with the proposed control. Fixed capacitors are connected across the rotor external resistors of WRIG as shown in Fig. 14. However, it is found that the performance improves only for an optimum value of the capacitance for a particular system. An optimum value of capacitor is found through simulation.

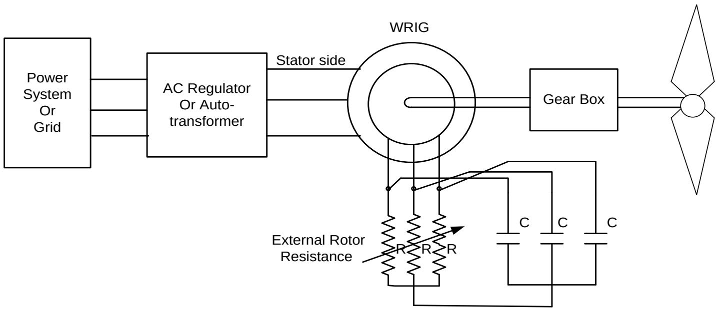

Fig. 14 : Circuit topology of the proposed scheme with capacitor

In the MATLAB simulation model of the proposed system with reactive power compensation, for the parallel RLC branch connected to the rotor of WRIG, option of RC is chosen. Then the optimum value of the capacitor is found by the simulation with trial & error method. The results obtained for an optimum value of capacitor are given in Table V. The simulation results are verified experimentally as well and tabulated in Table VI.

TABLE V: SIMULATION RESULT OF COMBINED INPUT VOLTAGE AND SLIP POWER CONTROL WITH 1MF CAPACITOR

Speed (rpm)	Controller Efficiency (%)	Power Factor	Stator Current (Ampere)	Power fed to grid, P (Watt)	% of power loss in external resistor w.r.to P
1860	97.34	0.37	1.4	244	0.05
1918	95.92	0.49	1.377	265.5	1.50
1973	94.06	0.52	1.34	285.8	3.44
2026	91.58	0.625	1.155	312	6.07
2080	88.68	0.79	1.118	332.6	9.49
2130	85.76	0.91	1.169	348.4	13.29
2180	83.01	0.962	1.318	359.9	17.22
2230	80.63	0.978	1.533	366.5	20.95

TABLE VI: EXPERIMENTAL RESULT OF COMBINED INPUT VOLTAGE AND SLIP POWER CONTROL WITH 1MF CAPACITOR

Speed (rpm)	Controller Efficiency (%)	Power Factor	Stator Current (Ampere)	Power fed to grid, P (Watt)	% of power loss in external resistor w.r.to P
1860	96.85	0.48	1.09	229	0.24
1918	94.30	0.54	1.14	246	3.00
1973	91.28	0.55	1.13	265	6.40
2026	88.15	0.59	1.11	286	10.15
2080	85.22	0.63	1.05	306	13.86
2130	83.83	0.7	1.1	326	15.65
2180	82.47	0.84	1.2	346	17.36
2230	81.30	0.96	1.3	363	18.93

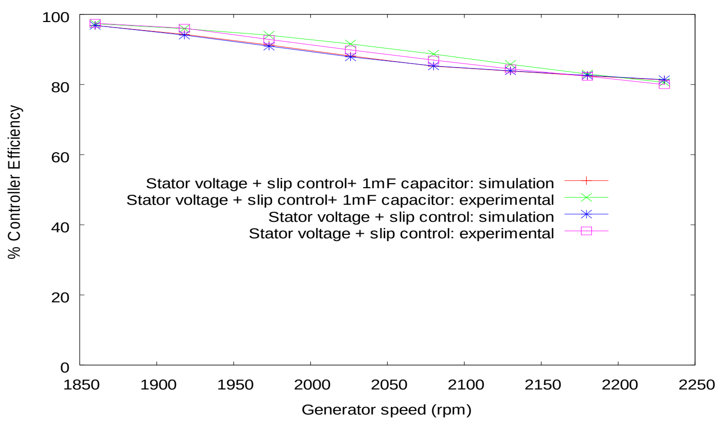

Fig. 15: Controller efficiency for different speed

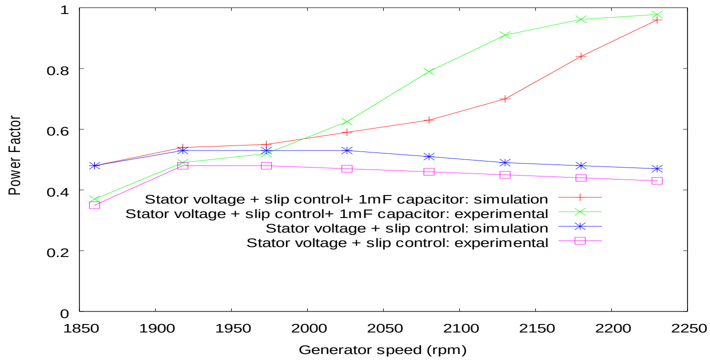

Fig. 16: Power factor for different speed

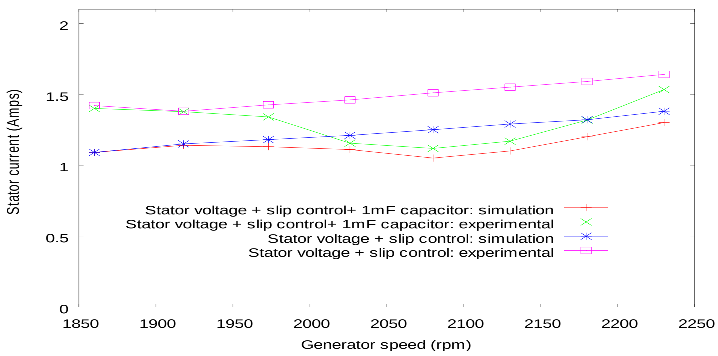

Fig. 17: Stator current for different speed

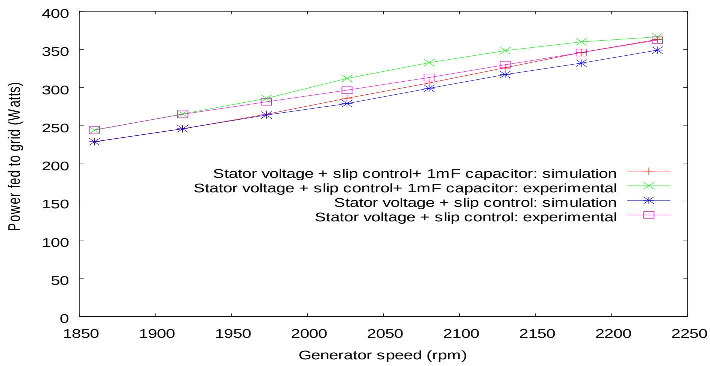

Fig. 18: Power fed into grid for different speed

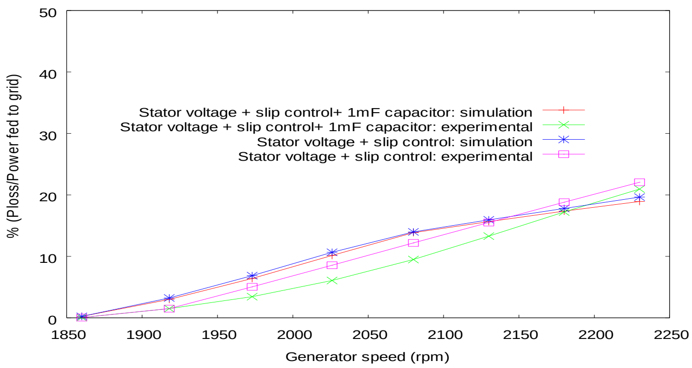

Fig. 19: Percentage of power loss in the external resistor with respect to power fed to grid for different speed

VII. CONCLUSION

In this paper, a combined input voltage and slip power control scheme is adopted for a low wind power based wound rotor induction generator system. It is evident from the simulated and experimental results that the proposed control scheme is quiet effective for grid connected induction generators. Here, both efficiency and power factor have been improved in comparison to a conventional slip power control scheme. Moreover, there is a significant reduction in the line current and increase in the active power supplied to the grid. The reactive power (inductive) demand has also reduced, as the power factor improves throughout the range of operation and which does not vary appreciably with the wind speed. Using the simulation model, an optimum value of capacitance has been found to compensate the reactive power throughout the range of control. This scheme is useful for wind energy conversion system (WECS) where wind speed varies over wide range.

VIII. APPENDIX

WOUND ROTOR INDUCTION MACHINE DATA: 1kW, three phase, 60Hz, 400V, 2.8A, 1690rpm, star connected: Stator resistance, $R_1 = 6.28\ \Omega$, Stator reactance, $X_1 = 15.9\Omega$, ecnatsiser rotoR, $R_2 = 1.5\ \Omega$, Rotor reactance, $X_2 = 3.6\ \Omega$, and Mutual reactance, $X_m = 118.01\Omega$

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