Analytical Modeling and Lab-based Comparison of Series Connected Wound Rotor Induction Generator Performance with Ordinary Induction Generator at Standalone Operating Mode

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Abstract:
This paper proposes an analytical dynamic model for series connected wound rotor induction generator (SCWRIG) and investigates the experimental performance of SCWRIG and compares it with an ordinary induction generator (IG) at standalone operating mode. After introducing the structure of series connected wound rotor induction generator and its different modes of performance, a suitable dynamic model is proposed for this machine. The results of experimental investigations indicate that series connected induction generator and ordinary induction generator have some similar behaviors. But, SCWRIG has higher speed range without any need to gearbox and capability of operating at higher voltage levels. So it may be proposed as a new suitable candidate for wind power generation at regions with high-speed wind.

Keywords: series connected wound rotor induction generator; lab results; wind generator

1. Introduction

Nowadays, everybody is aware of the importance of induction machines; such that induction motors consist 70% of the motors used in industry [1] and induction generators play an important role in wind power generation [2]. With respect to the increasing rise of the importance of renewable energies, particularly wind energy, induction machines in generator state are given more attention. Therefore, conducting researches and presenting new achievements and findings in this domain is even more needed. Series connected wound rotor induction generator (SCWRIG) can be presented as an equipment which has recently been studied and yet it needs more research [3].

The reason for rapid progress in wind power technologies is the environmental and economic issues [4]. Therefore, it is of great importance to study the connection of these turbines to the network [5]. The technology of wind turbines includes constant and variable speed wind turbines [2]. Due to being economic, resistant and having easier installation, most wind turbines that are installed today are chosen among constant speed ones [6].

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Squirrel cage induction machines are being frequently used in industry due to having low price, resistance and easy maintenance. These advantages make this machine a proper choice to be used in constant speed wind systems. The modeling and analysis of wind farms with fixed speed wind turbines implemented with squirrel cage induction generator (SCIG) has been the subject of numerous publications (e.g. [6-9]). Nowadays, change in the structure of wind farm generators is being made rapidly and newer ones are replacing the old generators.

Accordingly, this paper is an attempt for the dynamic modeling, analysis and experimental study of a new candidate for wind power generator called series connected wound rotor induction machine. It also aims at analyzing the feasibility of using it as a wind generator when connected to the grid. Most papers on this machine have been delivered in motor state [10-18] and fewer researches have been done on generator state to date [19-22].

Analysis of the behavior and performance of wind generators requires proper models. The reason for that is the fluctuating nature of the input wind power to their turbines and the transient behavior resulted from it. The dynamic behavior of series connected induction machine can be explained by differential equations. Due to the dependence on time and speed variations of the rotor, these differential equations are so complicated.

Also, due to lack of proper knowledge of series connected wound rotor induction machine at generator state, the need to carry out lab researches and compare its performance with ordinary generators is so necessary. Hence, the lab performance of series connected wound rotor induction generator is also studied and compared with ordinary induction generator in this study.

Introducing of SCWRIG as a new candidate for wind power generation is the main contribution of this paper.

The results of this study indicate that series connected wound rotor induction generator has a behavior similar to that of induction generator. Yet, the differences between these two generators have been studied as well. As shown later, this generator can operate at higher voltage level and higher wind speed.

In section 2, series connected wound rotor induction machine is introduced and its different modes of operation is shortly explained. A suitable dynamic model is proposed for system in section 3. Some of analytical results are shown in section 4.

Laboratory equipment's arrangement developed for this study and the experimental results are presented in Section 5. Finally, concluding remarks are drawn in section 6.

2. General aspects of series connected wound rotor induction machine

According to Fig. 1, Series Connected Wound Rotor Induction Machine (SCWRIM) is a wound rotor induction machine whose rotor and stator windings have been series connected with the sequence of two converse phases. This machine functions at two performance modes of asynchronous and super synchronous in a wide range of speeds [10-18] and it seems to be proper for converting wind energy to electric energy.

SCWRIM, such as most electromagnetic convertors, is able to function as motor or generator.

It is obvious that this machine behaves similar to ordinary induction machine at under synchronous speed and it is able to operate and function [3, 10].

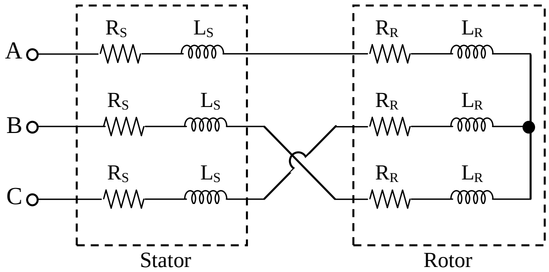

Fig (1): The connection of SCWRIM windings

In super synchronous mode, it is able to function twice as much as synchronous speed. However, this mode needs an exterior primary propellant. Yet, it has unstable performance in this mode and it is in ever-need of controller design [10]. Discussion about different modes of operation in this machine is out of scope of this paper. References [10-22] may be suggested for further reading.

These machines are able to function at invariant referent frequency at speeds higher than the synchronous machines and ordinary induction machines. Since stator and rotor windings are series connected, this machine is able to function at higher voltage levels without influencing on conductor insulation class [3, 18].

Another characteristic of this generator that distinguishes it from ordinary induction generators is its higher performance speed. The turn ratio of rotor to stator plays an important role in this machine [18].

3. Dynamic Modeling of study system

The proposed dynamic model is derived from the sample system configuration shown in Fig (2). This system includes two buses. Series connected wound rotor induction generator (SCWRIG) is connected to the local bus. Then, local bus is connected to the load bus via a short transmission line. Also, local bus is implemented with a capacitor bank.

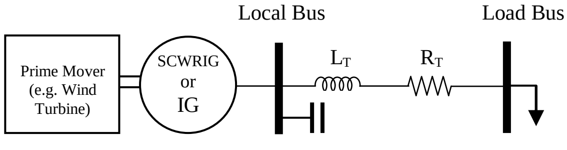

Fig (2): Sample study system configuration

In the following, the sample system elements are modeled and then dynamic model of the whole system is obtained by aggregating the individual component models. Based on the proposed model, a set of differential equation is obtained.

3.1. Dynamic model of series connected wound rotor induction generator (SCWRIG)

In general, the differential equations of the series connected induction generator can be written as below [3, 20]:

$$V_q = -R_a i_q - \omega_e(2L_m + L_s)i_d - (\omega_r - \omega_e)(2L_m + L_r)i_d - L_q p(i_q) \quad (1)$$

$$V_d = -R_a i_d + \omega_e(L_s)i_q + (\omega_r - \omega_e)(L_r)i_q - L_d p(i_d) \quad (2)$$

where ω_e is angular synchronous speed, ω_r is angular rotor speed, L_m, L_s and L_r are mutual, stator and rotor inductances respectively and p is derivative operator. By assuming unit value for turn ratio of rotor to stator windings, the parameters L_d, L_q and R_a in (1) and (2) can be given by [3, 20]:

$$\begin{aligned} L_q &= L_s + L_r \\ L_d &= L_s + L_r + 4L_m \\ R_a &= R_s + R_r \end{aligned} \quad (3)$$

where R_s and R_r are stator and rotor winding resistances. The electromagnetic torque equation can be written as (4):

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{4}\right)\left(L_d - L_q\right) \quad (4)$$

where P is number of poles. The torque equation for this machine in generator state is obtained from (5).

$$T_L - T_e = Jp\omega_r + B\omega_r \quad (5)$$

where T_L, J and B are mechanical torque, moment of inertia and damping constant respectively.

In general, the differential equations of the series connected wound rotor induction generator can be written as [3, 20]:

$$p[i] = [L]^{-1}([V] - [R][i] - [G][i]) \quad (6)$$

3.2. Dynamic model of ordinary induction generator (IG)

The differential equations of the ordinary induction generator can be written as [3]:

$$V_{ds} = -R_s\, i_{ds} - \omega_e \lambda_{qs} - p\lambda_{ds} \quad (7)$$

$$V_{qs} = -R_s\, i_{qs} + \omega_e \lambda_{ds} - p\lambda_{qs} \quad (8)$$

$$V_{dr} = -R_r\, i_{dr} - (\omega_e - \omega_r)\lambda_{qr} - p\lambda_{dr} \quad (9)$$

$$V_{qr} = -R_r\, i_{qr} + (\omega_e - \omega_r)\lambda_{dr} - p\lambda_{qr} \quad (10)$$

where:

$$\begin{aligned} \lambda_{ds} &= L_s i_{ds} + L_m(i_{ds} + i_{dr}) \\ \lambda_{qs} &= L_s i_{qs} + L_m(i_{qs} + i_{qr}) \\ \lambda_{dr} &= L_r i_{dr} + L_m(i_{ds} + i_{dr}) \\ \lambda_{qr} &= L_s i_{qr} + L_m(i_{qs} + i_{qr}) \end{aligned} \quad (11)$$

where the above machine parameters have the same definition as SCWRIG.

Ordinary induction generator (IG) has similar torque equation, i.e. (5), and the same differential equations, i.e. (6), but with different values for coefficient matrixes [3].

$$V = \begin{bmatrix} V_{dt} & V_{qt} & 0 & 0 \end{bmatrix}^T \quad (12)$$

$$i = \begin{bmatrix} i_{ds} & i_{qs} & i_{dr} & i_{qr} \end{bmatrix}^T \quad (13)$$

$$L^{-1} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (14)$$

$$G = \begin{bmatrix} 0 & \omega_e L_s & 0 & \omega_e L_m \\ -\omega_e L_s & 0 & -\omega_e L_m & 0 \\ 0 & (\omega_e - \omega_r)L_m & 0 & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & 0 & -(\omega_e - \omega_r)L_m & 0 \end{bmatrix} \quad (15)$$

3.3. Dynamic model of the transmission line

The transmission line has the impedance of $Z_T = R_T + jX_T$ and injects the i_t current to the load bus. Transmission line equations, in synchronous reference frame, are given by [3]:

$$V_{dt} = V_d^{Load} + R_T i_{dt} - \omega_s L_T i_{qt} + L_T\, pi_{dt} \quad (16)$$

$$V_{qt} = V_q^{Load} + R_T i_{qt} + \omega_s L_T i_{dt} + L_T\, pi_{qt} \quad (17)$$

Transmission line current (or load current) depends on SCWRIG (or IG) current as follow:

$$i_T = i_{Load} = i - i_c \quad (18)$$

V_d^{Load} can be derived from load model by a simple equation.

3.4. Dynamic model of the whole system

By using pervious equations, dynamic model of the whole system is obtained by aggregating the dynamic models of individual components as shown in (19). The dynamics of the whole system can be modeled by parameter dependent differential equations (DE).

$$\dot{X} = f(X, \mu) \quad (19)$$

The state variables are i_d, i_q, V_{dt}, V_{qt} and ω_r. These equations can be solved using order four Rang-Kutta method.

4. Analytical Results

To investigate analytical system performance, several simulations are performed. The initial conditions of the state variables are needed for the numerical solution of the system's differential equations. The initial values of these variables determine the transient state of the beginning of the equations solution. In order to make the results more authentic, the primary speed of the machine was adjusted equal to the synchronous speed and its primary currents were set equal to zero. Fig (3) indicates the series connected wound rotor induction generator speed from the beginning of solution process with primary speed is equal to synchronous speed.

According to the figure, after a little drop in primary speed, the generator speed rises gradually and transcends the synchronous speed [3, 21].

Fig (4) shows the variation of electrical torque of SCWRIG. The value of this torque, after a primary transient state, reaches 10 N.m in about 0.1 seconds. According to the figure, the series connected wound rotor induction generator has a high transient torque.

Fig (5) shows the torque-slip characteristic curve for SCWRIG.

Fig (6) shows the variation of electrical torque of ordinary induction generator (IG). Fig (7) shows the torque-slip characteristic curve for IG.]

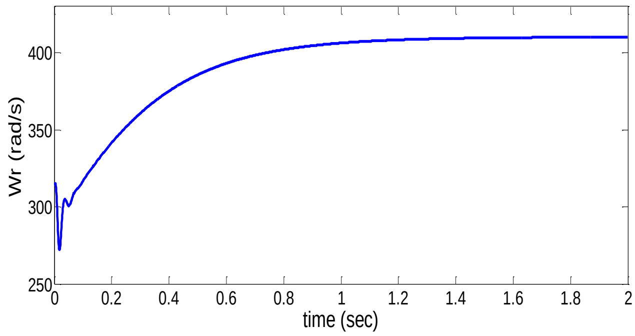

Fig (3): SCWRIG rotor angular speed

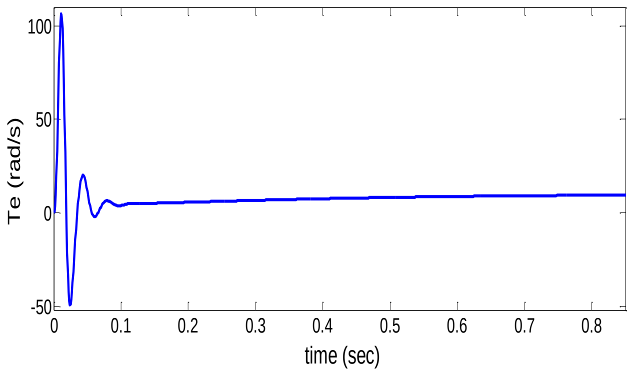

Fig (4): Electrical Torque of SCWRIG

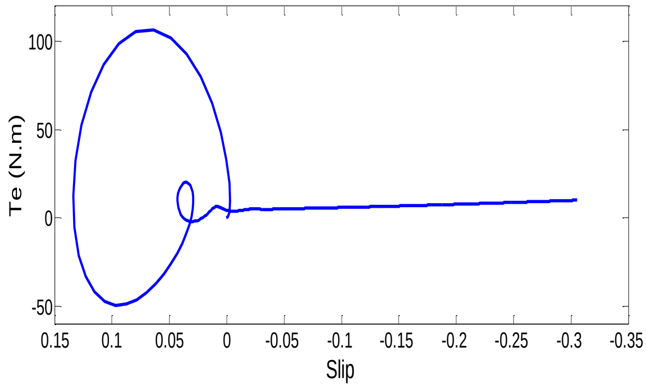

Fig (5): SCWRIG torque-slip characteristic curve

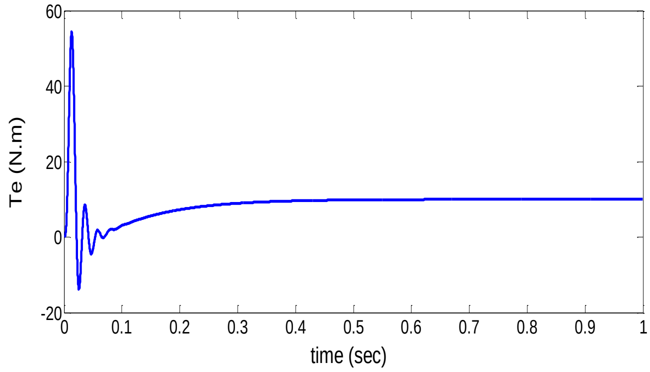

Fig (6): Electrical Torque of IG

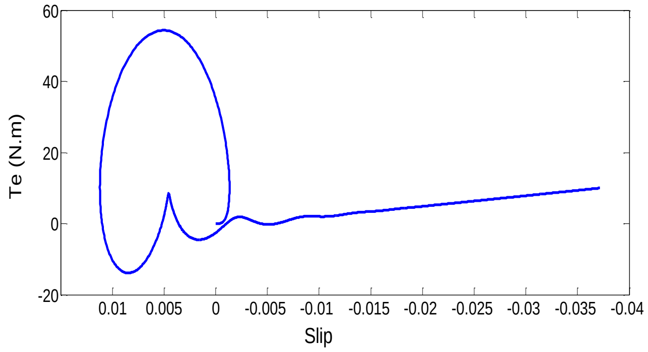

Fig (7): IG torque-slip characteristic curve

5. Laboratory test system

Lab facilities and arrangement of laboratory equipments developed in this study are shown in Fig (8) and Fig (9) respectively [3, 22]. A 200 W, 380/220 v, 50 Hz, 1340 rpm wound rotor induction machine (WRIM) is used as basic generator. By changing the connection of WRIM windings, this machine can act as SCWRIG or IG. The prime mover of this generator is a dc motor. In order to operate this machine at standalone mode, three capacitors with the capacity of 20 μF are connected at local bus [3, 22].

Fig (8): Test system at the Laboratory

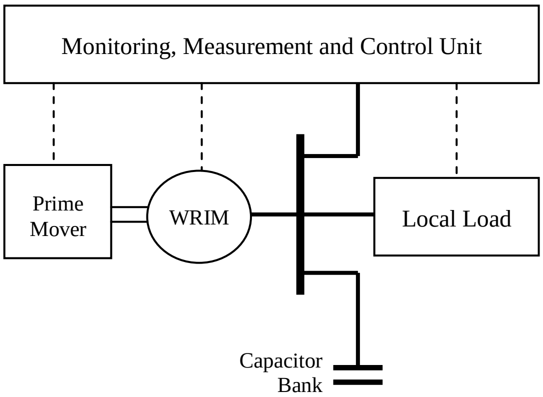

Fig (9): Laboratory arrangement of test system

6. Lab results

In these experiments, the behavior of series connected wound rotor induction generator and induction generator at different loads and in stand alone state have been studied.

First, various loads' impedance (resistances) were set equal to their maximum values, then, the voltage was set constant at a desirable value [3, 22]. As resistance decreases, which causes variations in output current, the results were recorded.

7. Resistive load

In this experiment, the performance of the induction machine at normal mode and SCWRIG mode with different resistive load was studied. As the load increases, voltage drop in series connected wound rotor induction generator is less than induction generator, while its behavior is similar (Fig. 10).

Fig (11) shows the comparison of output active power for these two generators. The generated active powers by SCWRIG and IG have a similar behavior. In this experiment, the ordinary induction generator (IG) injects more active power to the network.

Fig (12) shows machine speed variation as a function of the resistive load current.

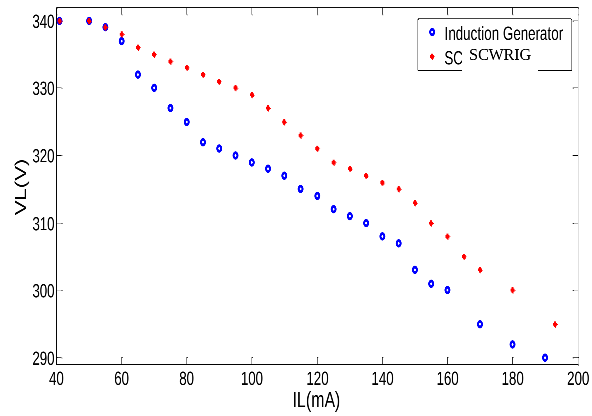

Fig (10): Load voltage variations of SCWRIG and IG at different resistive load

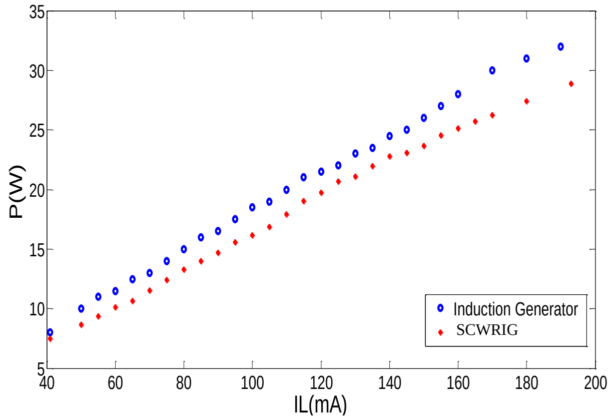

Fig (11): Load power variations of SCWRIG and IG at different resistive load

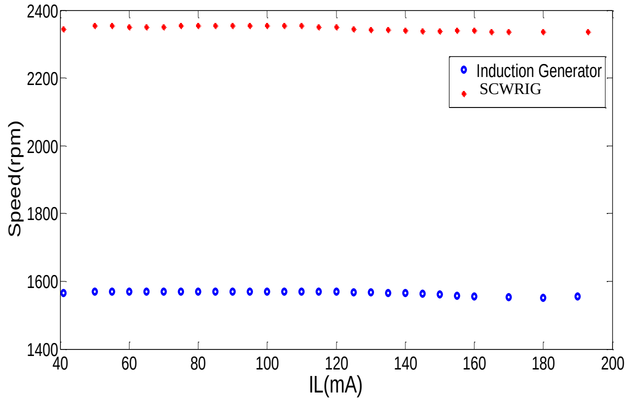

Fig (12): SCWRIG and IG speed variations at different resistive load

According to the figure, series connected wound rotor induction generator has higher operating speed than induction generator. As a result, this generator can be used at higher speeds. The results of this experiment give same response in all modes. Also, the frequency of two machines is almost constant.

7.1. Resistive-capacitive load

In these experiments, three capacitors with the capacity of 2.7μF were used in series connection with variable resistive load. According to Fig. 13, the generated voltage increases after a slight drop in series connected induction generator, while induction generator (IG) has more voltage drop [3, 22].

Fig (14) indicates the comparison of reactive power variations between series connected wound rotor induction generator and induction generator; the two generators have similar behaviors. The induction generator absorbs a little more reactive power from the network than series connected wound rotor induction generator.

Fig (15) shows the active power generation difference between the two generators.

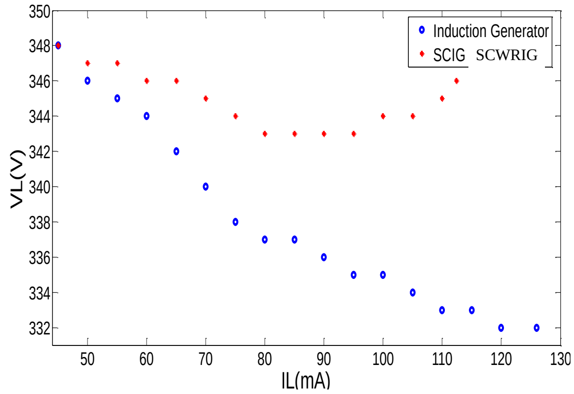

Fig (13): Variations of voltage versus output current of induction generator and SCWRIG at different resistive-capacitive load

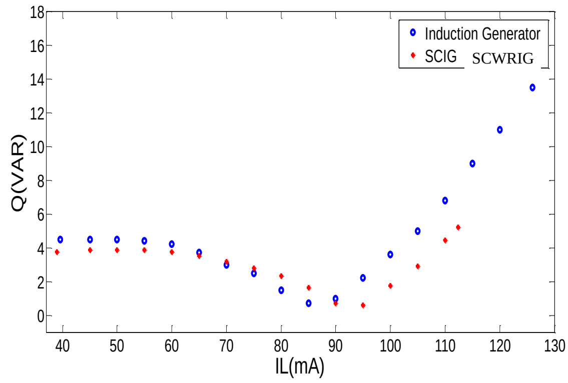

Fig (14): Reactive power variations at different resistive-capacitive load for SCWRIG and IG

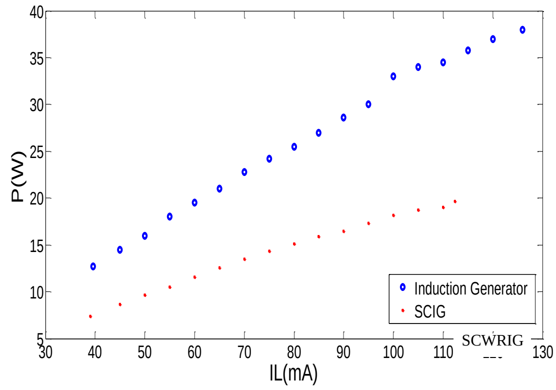

Fig (15): Output active power versus resistive- capacitive load current

The generated active power in induction generator at resistive-capacitive load is far higher than series connected induction generator. However, it should also be taken into consideration that the turn ratio of rotor to stator in these experiments is 0.5, and as this ratio increases, the performance of the series connected wound rotor machine enhances [3, 22].

7.2. Resistive- inductive load

In this experiment, three inductors with the inductance of 2.5mH are connected in series with variable resistive load. Resistive-inductive load, due to having more similarity to real loads, is more important. Fig. 16 shows the amount of voltage drop for two generators. As it could be observed, series connected generator shows less voltage drop as compared to ordinary induction generator. According to Fig. 16 to Fig. 18, series connected induction generator and ordinary induction generator show similar behavior in this type of load.

Fig (17) shows the comparison between the amounts of generated active power of ordinary induction generator with that of series connected induction generator. The amount of generated power decreases after a specific deal. Yet, the beginning of this decrease occurs a bit later in series connected induction generator than in ordinary induction generator [3, 22].

Fig (18) shows the absorbed reactive power for two generators. According to figure, the amount of reactive power absorbed by series connected induction generator is much less than induction generator.

An interesting fact about SCWRIG is its voltage built up process. As it could be observed from Fig (19), this type of generator is not able to generate voltage up to a specified speed, and voltage increases suddenly after that speed, whereas, this process occurs at lower speed for IG. However, it should be taken into consideration that these experiments have carried out in standalone mode [3, 22].

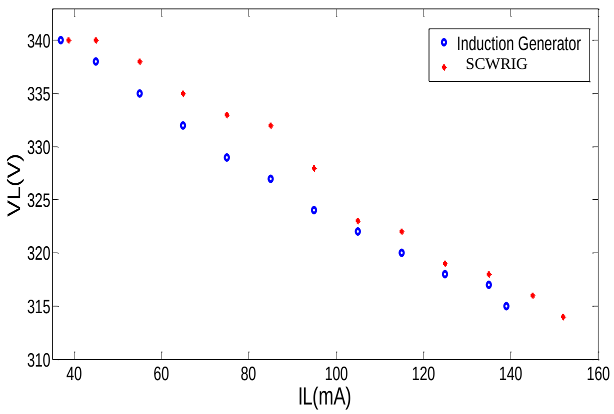

Fig (16): Variations of voltage versus output current of ordinary induction generator and SCWRIG at different resistive-inductive load

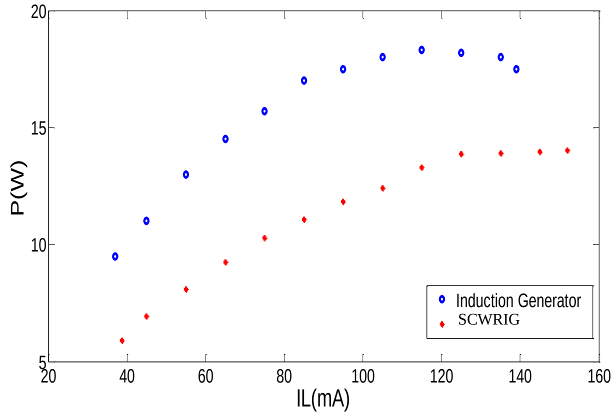

Fig (17): Output active power versus resistive-inductive load current

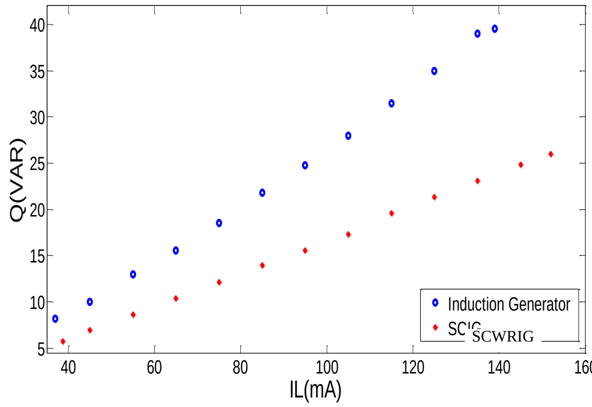

Fig (18): Reactive power variations at different resistive-inductive load for SCWRIG and IG

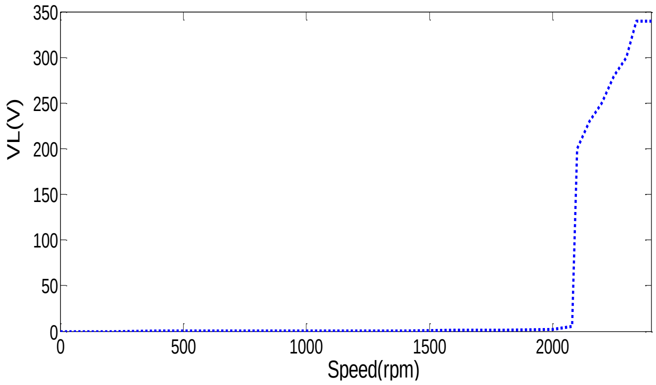

Fig (19): Speed-voltage curve of SCWRIG at resistive-inductive load

8. Conclusions

In this paper, a suitable analytical model is proposed for series connected wound rotor induction generator (SCWRIG). The lab performance of SCWRIG was studied and compared against the behavior of ordinary induction generator (IG). As it was shown in the results of experiments, the performance of series connected wound rotor induction generator is almost similar to ordinary induction generator. Yet, it is different in performance, including higher performance speed, capability of working at higher voltage level.

In resistive-inductive loads, which have more similarity to real lods, the series connected wound rotor induction generator has a much better performance than that of ordinary induction generator.

In standalone mode, voltage built up process of SCWRIG is far different from that of IG. The beginning of voltage built up process in this generator occurs at higher speed as compared to IG, and also the primary propellant speed and the value of capacitors have significant influence on this process.

Finally, the experimental results show that series connected wound rotor induction generator can be proposed as a suitable candidate for wind power generation. Of course, further consideration may be taken into account.

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