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Using FLC, Design and Novel Control of a Variable Speed Cage Induction Generator

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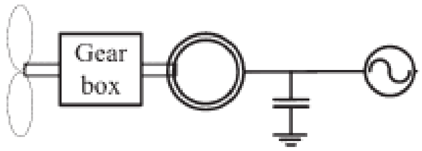
Abstract

This paper introduces a novel cage induction generator and presents a mathematical model, through which its behavior can be accurately predicted. The proposed generator system employs a three-phase cage induction machine and generates single-phase and constant-frequency electricity at varying rotor speeds without an intermediate inverter stage. The technique uses any one of the three stator phases of the machine as the excitation winding and the remaining two phases, which are connected in series, as the power winding. The two-series-connected-and-one isolated (TSCAOI) phase winding configuration magnetically decouples the two sets of windings, enabling independent control. Electricity is generated through the power winding at both sub and super-synchronous speeds with appropriate excitation to the isolated single winding at any frequency of generation. A dynamic mathematical model, which accurately predicts the behavior of the proposed generator, is also presented and implemented in MATLAB/Simulink. Experimental results of a 2-kW prototype generator under various operating conditions are presented, together with theoretical results, to demonstrate the viability of the TSCAOI power generation. The proposed generator is simple and capable of both storage and retrieval of energy through its excitation winding and is expected to be suitable for applications, such as small wind turbines and micro hydro systems.

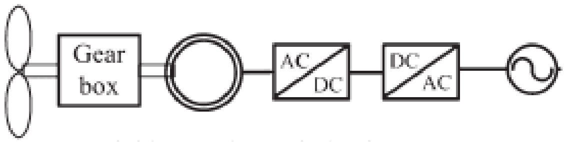
Keywords: FLC, TSCAOI, dynamic Model, Machine, Power Winding, Power Generation.

1. Introduction

THE use of renewable energy as an alternative to low cost fossil energy, which was in abundance, has never been considered as an economically viable option in the past. However, the excessive, unnecessary, and inefficient use of fossil energy has now become a global concern, owing to rapidly decreasing fossil resources, rising fuel prices, increasing demand for energy, and, more importantly, the awareness of global warming and environmental impact. Consequently, it has now become a common practice of governing bodies to place more emphasis on energy saving, harnessing renewable energy, and particularly on energy management through efficient generation, conversion, transmission, and distribution. This initiative incited a new area of active research and development within both academia and industry under the context of “green or clean or renewable” energy [1]–[3].



Fixed speed cage induction generator



Variable speed cage induction generator

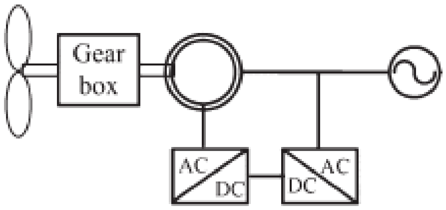


Figure 1: Typical induction generator systems used in wind turbines.

Mechanical-to-electrical energy conversion can be realized through a variety of techniques. These techniques vary from one to the other, owing to different levels of sophistication, characteristics, complexity, performance, cost, etc., and are suitable for a range of energy sources and applications from very low to very high power levels. Among the various renewable energy sources that are available, wind energy can be considered as a source that has been widely used. Wind turbine systems have been in use for power levels ranging from megawatts to microwatts, where miniature sensors are powered. In these wind turbine systems, various technologies have been employed to perform the mechanical-to-electrical energy conversion. Fig. 1 shows three electricity generation schemes, based on three phase induction generators, employed in typical wind turbine systems.

Fixed-speed cage three phase induction generators are well known for their simplicity and low cost and operated at constant rotor speed to generate electricity at constant frequency for both direct grid integration and standalone operation. Usually, they are excited through a bank of capacitors and are incapable of tracking maximum power that is available from the wind turbine when operated at constant speed Therefore, in order to extract maximum energy under varying wind speed conditions, an intermediate power conversion stage, comprising an alternating-current (ac)/direct-current (dc) and dc/ac back-to-back converter configuration, is employed between the generator and the grid or the load The intermediate stage allows for the variable-speed operation of the generator, but it essentially requires to be rated for the same or a fraction (in the case of doubly fed induction generators) of the power level of the generator itself. Thus, such an intermediate stage is often found to be economically unjustifiable for some applications, particularly at micro power levels.

Induction generators have been also employed to generate single-phase electricity, particularly for standalone or residential use In and a self-excited and self regulated single-phase induction generator has been reported for the generation of single-phase electricity. In contrast, the analysis of the self-excitation of a dual-winding induction generator has been presented in This paper, which uses a single-phase cage induction machine with an auxiliary winding, has been extended by connecting an inverter to the auxiliary winding to achieve more flexibility in power control All these reported schemes employed a single-phase induction generator and an auxiliary winding in some cases or a three phase induction generator to generate single-phase electricity at constant or above synchronous speed.

In contrast with single-phase cage induction machines, three phase cage induction machines are less expensive and small in size for a similar power rating. According to literature, a single phase electricity generation scheme, based on a variable-speed three-phase cage induction machine without an intermediate inverter stage, is yet to be reported. This paper presents a novel technique whereby a three-phase cage induction machine can be used as a single-phase generator under both sub- and super-synchronous variable-speed conditions without an intermediate inverter stage. The technique uses one of the three windings in isolation for excitation and the remaining two, which are connected in series, as the power winding for the single-phase electricity generation. Alternatively, the two series-connected windings may be also used for excitation while the power is generated through the isolated single winding, as detailed in The three-phase cage induction machine is mathematically modeled in the proposed two-series connected- and-one-isolated (TSCAOI) phase winding configuration. The theoretical performance is investigated under varying operating conditions and compared with a prototype 2-kW single-phase electricity generator. Both simulated and experimental results are in good agreement and indicate that the machine can be operated both at sub- and super-synchronous rotor speeds to generate electricity at constant frequency. The proposed technique allows for both energy storage and retrieval through the excitation winding and is expected to gain popularity, particularly in small-scale applications, being relatively simple and low in cost.

2. WIND Power

Wind is abundant almost in any part of the world. Its existence in nature caused by uneven heating on the surface of the earth as well as the earth’s rotation means that the wind resources will always be available. The conventional ways of generating electricity using non renewable resources such as coal, natural gas, oil and so on, have great impacts on the environment as it contributes vast quantities of carbon dioxide to the earth’s atmosphere which in turn will cause the temperature of the earth’s surface to increase, known as the green house effect. Hence, with the advances in science and technology, ways of generating electricity using renewable energy resources such as the wind are developed. Nowadays, the cost of wind power that is connected to the grid is as cheap as the cost of generating electricity using coal and oil. Thus, the increasing popularity of green electricity means the demand of electricity produced by using non renewable energy is also increased accordingly.

Features of Wind Power Systems

There are some distinctive energy end use features of wind power systems

Most wind power sites are in remote rural, island or marine areas. Energy requirements in such places are distinctive and do not require the high electrical power.

I. A power system with mixed quality supplies can be a good match with total energy end use i.e. the supply of cheap variable voltage power for heating and expensive fixed voltage electricity for lights and motors.

II. Rural grid systems are likely to be weak (low voltage 33 KV). Interfacing a Wind Energy Conversion System (WECS) in weak grids is difficult and detrimental to the workers' safety.

III. There are always periods without wind. Thus, WECS must be linked energy storage or parallel generating system if supplies are to be maintained.

3. Power From The WIND

Kinetic energy from the wind is used to turn the generator inside the wind turbine to produced electricity. There are several factors that contribute to the efficiency of the wind turbine in extracting the power from the wind. Firstly, the wind speed is one of the important factors in determining how much power can be extracted from the wind. This is because the power produced from the wind turbine is a function of the cubed of the wind speed. Thus, the wind speed if doubled, the power produced will be increased by eight times the original power. Then, location of the wind farm plays an important role in order for the wind turbine to extract the most available power form the wind.

The next important factor of the wind turbine is the rotor blade. The rotor blades length of the wind turbine is one of the important aspects of the wind turbine since the power produced from the wind is also proportional to the swept area of the rotor blades i.e. the square of the diameter of the swept area.

Hence, by doubling the diameter of the swept area, the power produced will be four fold increased. It is required for the rotor blades to be strong and light and durable.

As the blade length increases, these qualities of the rotor blades become more elusive. But with the recent advances in fiberglass and carbon-fiber technology, the production of lightweight and strong rotor blades between 20 to 30 meters long is possible. Wind turbines with the size of these rotor blades are capable to produce up to 1 megawatt of power.

The relationship between the powers produced by the wind source and the velocity of the wind and the rotor blades swept diameter is shown below.

$$P_{WIND} = \frac{\pi}{8} dD^2 V^3{}_{WIND}$$

The derivation to this formula can be looked up in It should be noted that some books derived the formula in terms of the swept area of the rotor blades (A) and the air density is denoted as δ.

Thus, in selecting wind turbine available in the market, the best and efficient wind turbine is the one that can make the best use of the available kinetic energy of the wind.

Wind power has the following advantages over the traditional power plants.

- Improving price competitiveness,
- Modular installation,
- Rapid construction,
- Complementary generation,
- Improved system reliability, and
- Non-polluting.

4. Proposed Novel Cage Induction Generator

Cage induction machines are undoubtedly the workhorse of the industry and can be still regarded as the main competitor to permanent-magnet machines. This is because they are self starting, rugged, reliable, and efficient and offer a long trouble free working life. Of these cage induction machines, three phase machines are significantly less expensive, more efficient, and smaller in frame size in comparison with their single-phase counterpart of similar power ratings. Consequently, three-phase cage induction motors are economically more appealing and have thus become the preferred choice for numerous applications, even at derated power levels as encountered in the Steinmetz configuration.

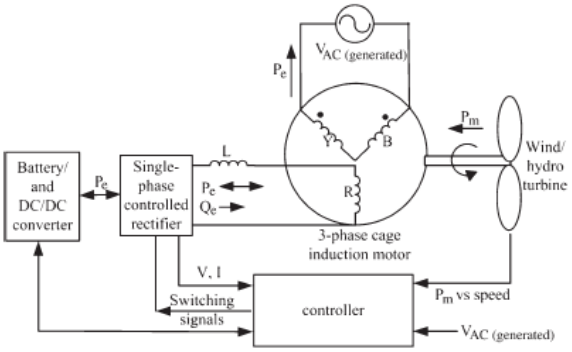


Figure 2: Proposed generator in TSCAOI winding configuration.

The novel technique proposed in this paper also uses a three phase cage induction machine, exploiting its economical advantage, to generate single-phase electricity at variable rotor speeds without an intermediate inverter stage. The technique configures the three stator windings of the three-phase cage induction machine in a novel way to create separate or rather decoupled excitation and power windings. In this configuration, any one of the three phase windings is solely used in isolation for excitation, whereas the remaining two are connected in series to generate power at a desired frequency while the rotor is driven at any given speed. Alternatively, the machine can be also configured in such a way that the two series-connected windings provide the excitation while the single winding generates. The proposed TSCAOI winding configuration of a three-phase cage induction machine is shown in Fig. 2. As mathematically shown in the following section, the TSCAOI winding configuration magnetically decouples both excitation and power windings from each other and thus allows for independent control as in the case of a single-phase induction motor with an auxiliary winding.

In the proposed technique, excitation for the generator is provided through the single winding, which is powered by a battery using either a simple square-wave inverter or a controlled rectifier. The former is the simplest and can be operated at the desired generation frequency using a less sophisticated controller to provide the reactive-power requirement of the generator. In the latter case, as shown in Fig. 2, the system is relatively sophisticated but facilitates bidirectional power flow, allowing for both energy storage and later retrieval. The level of excitation in both cases is governed by the voltage generated in the power winding. A controller, comprising of a voltage feedback, can be employed to regulate the excitation. The controller in the simplest form may provide only the reactive power requirement of the generator (not the load) and, at a more sophisticated level, may be used to control both the active- and reactive-power flows in accordance with the phase angle and the voltage magnitude between the inverter and the excitation winding.

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5. Mathematical Model

For the derivation of a model, it is assumed that the “α” axis of the “αβ” frame is aligned with phase “a” of the stator windings, as shown in Fig. 3(b). If the rotor phase “a” is assumed to be at angle ϕr from the axis, rotor quantities can be transformed into the “αβ” frame using the following transformation:

$$[K_r] = \frac{2}{3}\begin{bmatrix} \cos(\varphi_r) & \cos\left(\varphi_r + \frac{2\pi}{3}\right) & \cos\left(\varphi_r - \frac{2\pi}{3}\right) \\ \sin(\varphi_r) & \sin\left(\varphi_r + \frac{2\pi}{3}\right) & \sin\left(\varphi_r - \frac{2\pi}{3}\right) \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

According to the TSCAOI configuration, the relationship between the voltages and the currents in the power and excitation windings and those in the stator-phase windings can be given by

$$[v_{s,\mathrm{eo}}] = [Q][v_{s,\mathrm{abc}}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$[i_{s,\mathrm{eo}}] = [Q][i_{s,\mathrm{abc}}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where

$$[v_{s,\mathrm{eo}}] = \begin{bmatrix} v_{se} \\ v_{\mathrm{so}} \end{bmatrix} \quad [i_{s,\mathrm{eo}}] = \begin{bmatrix} i_{se} \\ i_{\mathrm{so}} \end{bmatrix} \quad [v_{s,\mathrm{abc}}] = \begin{bmatrix} v_{\mathrm{sa}} \\ v_{\mathrm{sb}} \\ v_{\mathrm{sc}} \end{bmatrix}$$

$$[i_{s,\mathrm{abc}}] = \begin{bmatrix} i_{\mathrm{sa}} \\ i_{sb} \\ i_{\mathrm{sc}} \end{bmatrix} \quad [Q] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -1 \end{bmatrix} \quad [\mathrm{Q}]^{-1} = [\mathrm{Q}]^{\mathrm{T}}.$$

A three-phase cage induction machine can be represented in the “abc” frame by the following standard equations:

$$[v_{s,\mathrm{abc}}] = [R_s][i_{s,\mathrm{abc}}] + p\left\{[L_s][i_{s,\mathrm{abc}}]\right\} + p\left\{[L_{\mathrm{sr}}][i_{r,\mathrm{abc}}]\right\} \quad \ldots\ldots\ldots\ldots(4)$$

$$[v_{r,\mathrm{abc}}] = [R_r][i_{r,\mathrm{abc}}] + p\left\{[L_{\mathrm{sr}}]^T[i_{s,\mathrm{abc}}]\right\} + p\left\{[L_r][i_{r,\mathrm{abc}}]\right\} \quad \ldots\ldots\ldots..(5)$$

where p is the differential operator, [vr,abc] and [ir,abc] are defined according to [vs,abc] and [is,abc], respectively, [vr,abc] = 0 for cage machines, and

$$[R_s] = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \qquad [R_r] = \begin{bmatrix} r_r & 0 & 0 \\ 0 & r_r & 0 \\ 0 & 0 & r_r \end{bmatrix}$$

$$[L_s] = \begin{bmatrix} (L_{\mathrm{ls}} + L_{\mathrm{ms}}) & -L_{\mathrm{ms}}/2 & -L_{\mathrm{ms}}/2 \\ -L_{\mathrm{ms}}/2 & (L_{\mathrm{ls}} + L_{\mathrm{ms}}) & -L_{\mathrm{ms}}/2 \\ -L_{\mathrm{ms}}/2 & -L_{\mathrm{ms}}/2 & (L_{\mathrm{ls}} + L_{\mathrm{ms}}) \end{bmatrix}$$

$$[L_r] = \begin{bmatrix} (L_{\mathrm{lr}} + L_{\mathrm{mr}}) & -L_{\mathrm{mr}}/2 & -L_{\mathrm{mr}}/2 \\ -L_{\mathrm{mr}}/2 & (L_{\mathrm{lr}} + L_{\mathrm{mr}}) & -L_{\mathrm{mr}}/2 \\ -L_{\mathrm{mr}}/2 & -L_{\mathrm{mr}}/2 & (L_{\mathrm{lr}} + L_{\mathrm{mr}}) \end{bmatrix}$$

$$[L_{\mathrm{sr}}] = L_{\mathrm{ms}} \begin{bmatrix} \cos\left(\varphi_r\right) & \cos\left(\varphi_r + \frac{2\pi}{3}\right) & \cos\left(\varphi_r - \frac{2\pi}{3}\right) \\ \cos\left(\varphi_r - \frac{2\pi}{3}\right) & \cos\left(\varphi_r\right) & \cos\left(\varphi_r + \frac{2\pi}{3}\right) \\ \cos\left(\varphi_r + \frac{2\pi}{3}\right) & \cos\left(\varphi_r - \frac{2\pi}{3}\right) & \cos\left(\varphi_r\right) \end{bmatrix}$$

In these equations, parameters rs, rr, Lls, Lms, Llr, Lmr, and Lsr are the stator resistance, the rotor resistance, the stator leakage, the stator magnetization, the rotor leakage, the rotor magnetization, and the stator-to-rotor mutual inductance referred to the stator side, respectively. The stator and rotor parameters in the “abc” frame can be now transformed into the “eo” and “αβ” frames, respectively, i.e.,

$$\begin{aligned} [v_{s,\mathrm{eo}}] = {} & [Q][R_s][Q]^{-1}[i_{s,\mathrm{eo}}] + [Q]p\left\{[L_s][Q]^{-1}[i_{s,\mathrm{eo}}]\right\} \\ & + [Q]p\left\{[L_{\mathrm{sr}}][K_r]^{-1}[i_{r,\alpha\beta}]\right\} \end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

$$\begin{aligned} [v_{r,\alpha\beta}] = {} & [K_r][R_r][K_r]^{-1}[i_{r,\alpha\beta}] + [K_r]p\left\{[L_{\mathrm{sr}}]^T[Q]^{-1}[i_{s,\mathrm{eo}}]\right\} \\ & + [K_r]p\left\{[L_r][K_r]^{-1}[i_{r,\alpha\beta}]\right\}. \end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots.(7)$$

After lengthy manipulations with appropriate substitutions, (6) and (7) can be rewritten the following (8) and (9).

$$\begin{aligned}0 &= L_{\mathrm{ms}}\omega_r \begin{bmatrix} 0 & \sqrt{3} \\ -1 & 0 \end{bmatrix} [i_{s,\mathrm{eo}}] \\ &+ L_{\mathrm{ms}} \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{3} \end{bmatrix} p[i_{s,\mathrm{eo}}] r_r [i_{r,\alpha\beta}] \\ &+ \left(L_{\mathrm{lr}} + \frac{3}{2}L_{\mathrm{ms}}\right)\omega_r \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} [i_{r,\alpha\beta}] \\ &+ \left(L_{\mathrm{lr}} + \frac{3}{2}L_{\mathrm{ms}}\right) p[i_{r,\alpha\beta}]\end{aligned}$$

……..(8 & 9)

Where ωr is the rotor speed in electrical radians per second.

From (8) and (9), it is evident that the excitation and power windings are decoupled. To complete the machine model, it is necessary to select state variables and derive the appropriate equations for integration. In this case, the elements of the machine current vector are chosen as the state variables.

Equation (10) shows the state space model using the winding currents as the phase vector, as derived from (8) and (9), i.e.,

$$p[i] = [A][i] + [B][v]$$

………………………………..….(10)

Where the parameters are shown at the bottom of the page.

The electromagnetic torque of the machine can be derived from

$$T_e = \frac{P}{2}[i_{s,\mathrm{abc}}]\frac{\partial}{\partial\varphi_r}\left\{[L_{\mathrm{sr}}][i_{r,\mathrm{abc}}]\right\}$$

…………………….(11)

Where P denotes the number of poles. Equation (11) in “abc” quantities is transformed into the “eo” and “αβ” frames and can be given by

$$T_e = \frac{P}{2}L_M(\sqrt{3}i_{\mathrm{so}}i_{r\alpha} - i_{\mathrm{se}}i_{r\beta}).$$

………………………(12)

Equation (12) represents the torque components due to both load and excitation currents. At the steady state, the torque given in (12) is equal to the turbine torque. The equation of the motion of the generator is given by

$$p\omega_r = \frac{P}{2}\frac{1}{J}(T_P - T_e)$$

……………………………………(13)

Where J (in kg · m2) is the inertia and Tp (in nanometers) is the torque of the prime mover.

6. Simulation Results

Simulink Circuit

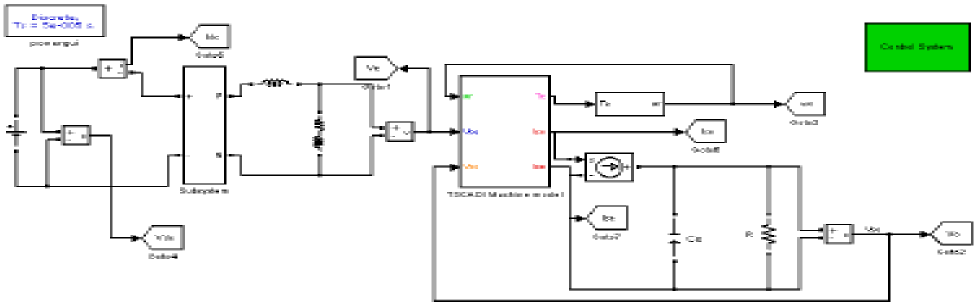


Fig.9 simulation diagram of proposed system

Figure 3: Excitation current for different rotor speeds and loads

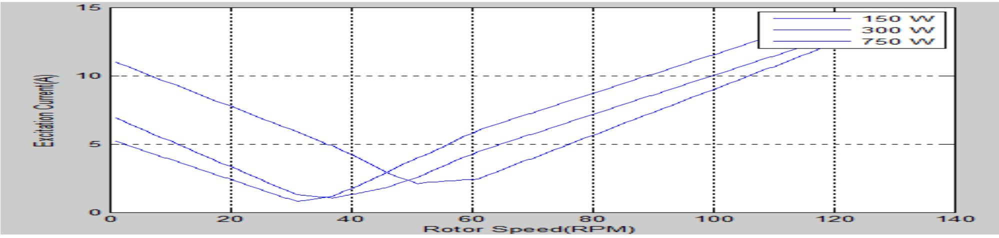


Figure 4: Excitation voltage for different rotor speeds and loads

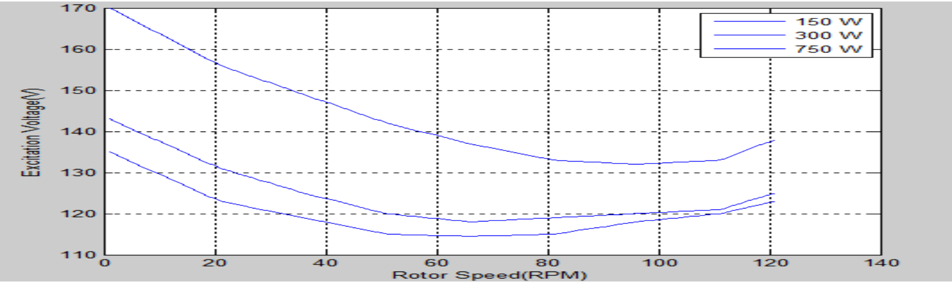
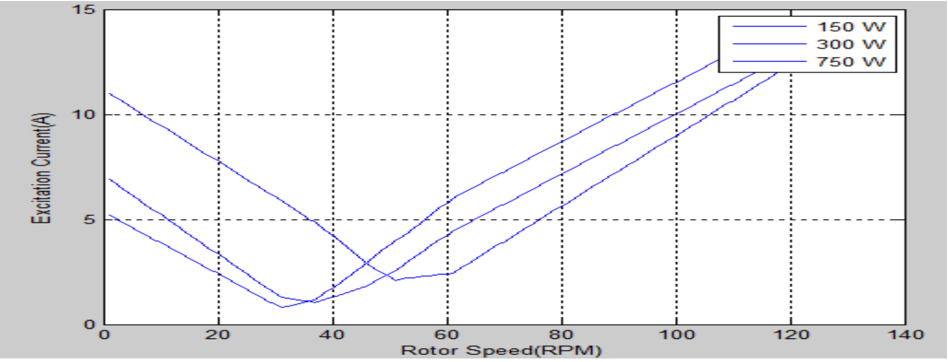
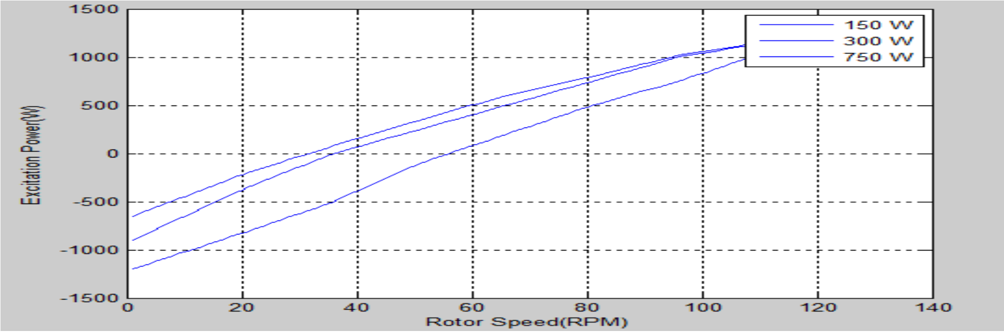


Figure 5: Excitation current for different rotor speeds and loads

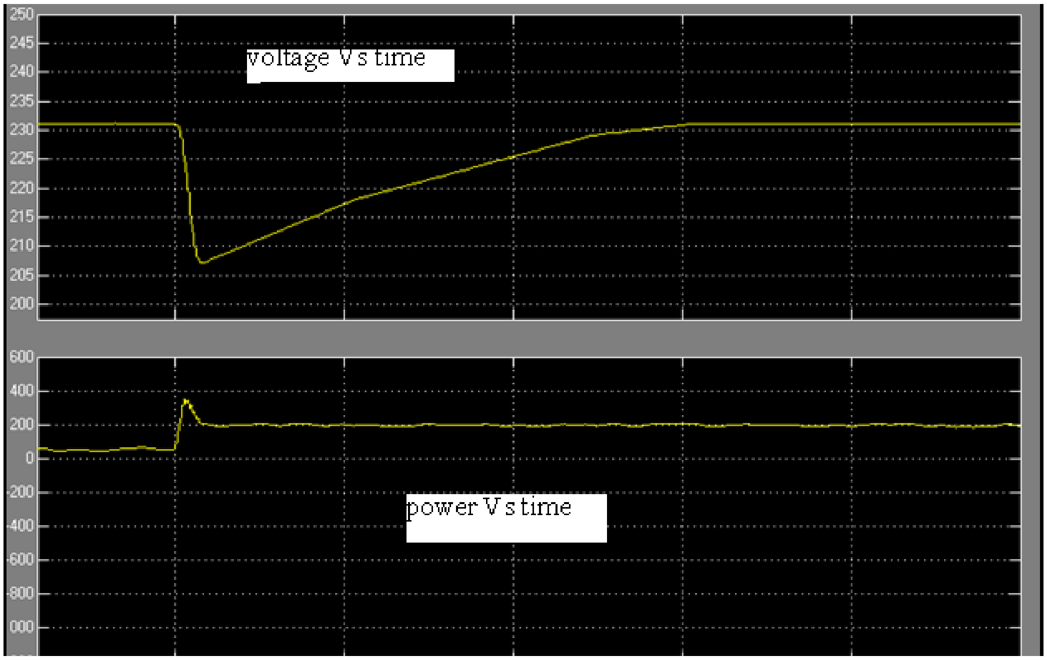


Excitation Power for Different Rotor Speeds and Loads



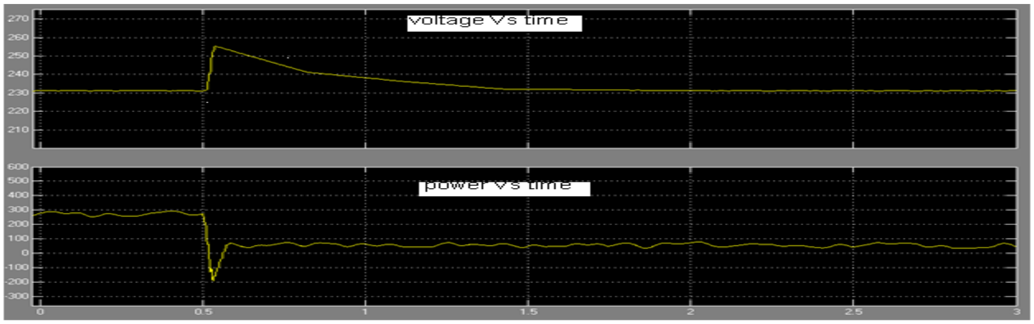
Increase in the Load

The output voltage and the reactive power supplied by the excitation source when the generator is subjected to an Increase in the load at approximately 0.5 s.



Reduction in the Load

As expected, an increase in the load voltage is observed, but it is restored to its original value by reducing the amount of reactive power injected into the generator.



7. Conclusion

A novel winding configuration that facilitates the generation of single-phase electricity from standard three-phase cage induction machines at variables speeds has been described, and a mathematical model, which predicts its behavior, has been also presented. The validity of the proposed concept of generation has been verified using simulations and experimental evidence of a prototype 2-kW generator. Both simulations and measured results indicate that the technique is viable and allows for the generation of electricity at constant frequency while the cage induction machine is operated at both sub- and super synchronous speeds. The proposed generator is easy to implement and low in cost. It can be used for both energy storage and retrieval through its excitation winding, and it is an ideal candidate for small-scale renewable energy applications.

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