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Experimental Performance Evaluation of a Power Generation System Using SEIG

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***Abstract*—One of the working induction generators is the self-excited induction generator (SEIG). In the self-excited mode, the generator can produce its voltage and frequency and for this it requires a capacitor. Determination of exciting capacitance of the induction generator (IG) is very important in adjusting the capacitance size. The effect of varying the capacitance of this capacitor on the generated output power, voltage, and its frequency has been studied. Besides, these three factors also differ inside by the value of the capacitor, the speed of the generator, the size and the change of the load, and the parameters of the generator. For this purpose, an experimental system, which consists of an AC driver, an induction motor, an induction generator, a step-down transformer, an AC/DC converter, and a controller, was installed. Various loading and excitation capacitor configurations of the IG were also examined at load and no-load. Thus, the experimental analysis of the powers gathered from the output of the generator has been achieved.**

***Index Terms*—Generators, power systems, power generation and power capacitors.**

I. INTRODUCTION

Today's wind turbines are widely used in isolated small applications including remote communication systems, village electrification systems, and cathodic protection of underground pipelines. In these applications, the turbines must be operated at both an acceptable price and a lower maintenance cost. In asynchronous generators with the use of a gear box and hydraulic systems, there exists a mechanical weight in addition to the extra power loss. The most preferred control system in small powerful systems is the changing method of the exciting capacity. In exciting capacity changing system, the current control system with thyristor is not preferred because of a harmonic production [1]. They should also have simple, applicable, and low-cost control systems for asynchronous loads such as water and space (air) heaters, water pumps, ice making, electrolysis cells, and lights. In small powerful asynchronous generators, as load, fixed and changeable ones can be used. Water and air heaters, water pumps, and direct current motors can be examples of fixed loads. Changeable loads, on the other hand, are the cathodic preservation system, uncontrolled electrolyte coating cells, and lightning systems for homes. All these loads can be operated in low-quality electricity. Consequently, low-cost energy production can be achieved by low-cost wind turbines [2], [3].

From the literature, in small powerful wind turbines, it is seen that DC generator, PMSG, and SEIG are used. Because of its simplicity, reliability, and low-cost operation, an induction machine can be considered to be deployed as a generator in wind turbines for isolated power systems in remote areas [1]–[4].

Any induction motor can be activated independently from the grid by a propulsion machine or wind. To get output voltage from the machine, an exciting or magnetizing current is needed. This excitement is obtained by the capacitors. The voltage and frequency obtained from the output of the IG differ depending on the AC capacitor value, the state of the load, the rotor speed, and the parameters of the IG [5]–[8].

In this operation mode, the magnetizing current needed for SEIG is provided from AC capacitors connected to the machine terminals. Therefore, determination of an appropriate capacitance is the most important issue in case of possible frequency and voltage fluctuations resulting from the SEIG operation that determines its own frequency and voltage. Consequently, determination of the capacitance is the major interest of SEIG studies. A number of proposals and many theoretical approaches and studies for solving this problem can be found in [5]–[9].

From the literature, Mahato *et al*. analysed the transient behaviour of a one-phased induction generator with excitement. To do this analysis, a one-phased induction motor (IM) was used as a dynamic load. The IG was connected in star, and three pieces of capacitors were used for excitement [10]. Singaravelu and Velusami presented the capacitive VAR requirements to do the desired voltage regulation under changeable speed and load situations of the self-excited one-phased IG and three-phased SEIG with changeable number of poles [11]. Singh *et al*. described a generalized and efficient model of a six-phased SEIG. By taking advantage of this model, they carried out the performance analysis of the IG using excited capacitor topologies including simple shunt, short shunt, and long shunt [12]. Singh *et al*. used a SEIG for stand-alone renewable power systems. In this machine, they presented a simple method for determining the required serial and shunt capacitance in suitable values to provide voltage regulation or the initial self-excitement [13]. Kheldeun *et al*. presented the application algorithm to do the performance analysis of the SEIG [14]. Alolah and Alkanhal used an optimization

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method to determine the excitement capacitance values in suitable ones used in a three-phased SEIG [15]. Chen and Lai made a stable-state performance analysis of the stand-alone IG loaded with unbalanced loads and made self-excitation with unbalanced excitation capacitors [16]. Chen and Lai introduced a practical method that finds the minimum capacitance value required to get initial voltage in the IG with single capacitor for mono-phase load and excitation [17]. Ahmed *et al.* got the required minimum excitation capacitance value in the IG with squirrel-cage rotor and three-phase self-excitation by using nodal admittance analysis [18]. Ahmed *et al.* calculated the required minimum capacitance for three-phase SEIG used in variable-speed wind-turbine and made performance analysis [19]. Lopez and Almeida made voltage and frequency regulation analysis of SEIG used in wind-energy transformation systems [20]. Murty and others presented a new scheme for stand-alone single-phase SEIG. In this scheme, excitation capacitors were switched by means of a new designed electronic controller with thyristors [21]. In this way, it is possible to provide the required electricity at remote regions by connecting proper capacitors at stator outputs of the SEIG [22].

In this study, a new low-cost experimental system to determine the appropriate capacitance of an SEIG is introduced. For this purpose, a simple and applicable electronic control technique to determine the capacitor requirements for the self-excitation process in a three-phase isolated IG has been carried out in the laboratory environment. Performance evaluation and experimental analysis of the output power results are presented.

II. SELF-EXCITED INDUCTION GENERATOR

Self-excitation term has primary importance for generating voltage in an IG. The required states for self-excitation in the IG are: the rotor must be driven by turning with an outside machine or wind power, proper capacitor must be connected to stator output in accordance with each number of revolution for taking magnetizing current, direct current must be applied to stator findings temporarily or before the induction generator is connected to the system, and it must be operated at three-phase grid at least once for providing remanence.

As induction generator that has remanence property at stator magnetic circuit is turned by a turbine, the oscillation is occupied between capacitor windings and stator windings mutually. Oscillation frequency and voltage value, remanence value, and capacitance at the beginning revolution number of generator are formed according to load variables connected to the generator; if there is enough capacitance but no load, voltage value may reach uncontrolled values [5].

The maximum value of the voltage increase is changed according to saturation value of the core and capacitance value of the AC capacitors. In this application, the excitation capacitors are connectable in star or delta. When the capacitors are star-connected, the voltage of each capacitor will be reduced as according to the delta connection. In this case, as can be seen from the formula, one- third of the reactive power is produced in the star connection in comparison with delta connection and no more than triple capacitors are required in star connection. This state is not economical. On the other hand, the time to break down the capacitor is strongly dependent on the operating voltage. Therefore, the capacitors were connected in star to provide long-term operation in the experimental setup system [5].

The typical equivalent circuit of an induction generator is shown in Fig. 1. In this circuit, R_1 and R_2 are stator and rotor resistances, jX_1 and jX_2 are stator and rotor reactance, and R_m and jX_m are magnetization reactance and resistance, respectively.

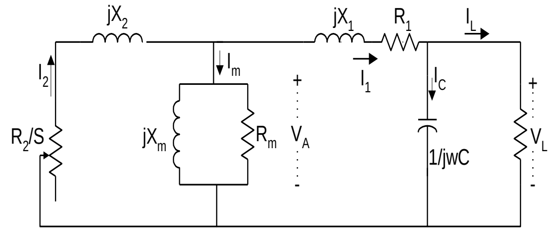

Fig. 1. Per-phase equivalent circuit of IG.

The excitation capacitance to provide reactive power for the IG is calculated by the following equations [23]–[26]

$$\sum S_o = \sqrt{3} V_l I_l, \; i = 1, 2, \ldots N. \tag{1}$$

The apparent power at no load equals the reactive power provided by excitation capacitors

$$\sum Q = \sum S_o. \tag{2}$$

Reactive power per phase is

$$Q_p = \frac{Q}{3}. \tag{3}$$

The value of star-connected capacitor is calculated by the following equations:

$$V_p = \frac{V_l}{\sqrt{3}}, \tag{4}$$

$$I_p = \frac{Q_p}{V_p}, \tag{5}$$

$$X_c = \frac{V_p}{I_p} = \frac{1}{2\pi f C}, \tag{6}$$

$$C = \frac{I_p}{2\pi f \, Vp}. \tag{7}$$

Using the above equations, the capacitance value for the induction generator used in the experiment can be easily calculated at various operation frequencies, which range between 30 Hz and 60 Hz with 5 Hz steps. For the 30 Hz, 50 Hz, and 60 Hz operating frequencies, the capacitor values were found to be 41 µF, 24 µF, and 11 µF, respectively.

III. THE EXPERIMENTAL SYSTEM

The experimental system is shown in Fig. 2; to represent the small wind turbines, a three-phase, 1 kW, squirrel-cage induction machine driven by a 0 Hz–200 Hz, 1.1 kW AC driver was used. A load can be supplied from the IG driven by wind turbine. If the generator is producing sufficient power, the load will be supplied entirely from the generator. If the output power of IG exceeds the demand of the load, the load switch is turned off. As an IG, another three-phase, 750 W, 3000 RPM induction machine was used and coupled to induction motors. To provide reactive power to the IG, four sets of 4 μF, 8 μF, 12 μF, and 24 μF capacitors were connected across the stator windings by controlled relays. The operating voltage of all the capacitors is 400 V. Hence, the voltage value at the windings of induction generator reached $400\sqrt{3}=692$ Volt; to prevent breakdown, the capacitors were connected in star. Another component is the step-down transformer used to reduce the voltage produced by the generator windings. Then, the voltage is rectified by a three-phase half-wave rectifier.

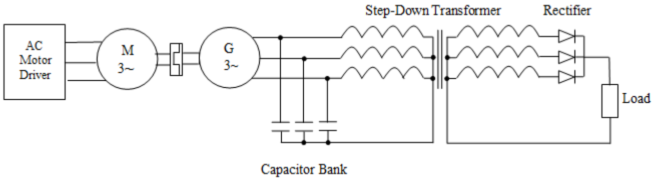

Fig. 2. Experimental setup scheme.

Since the excitation capacitance required for the generator changes according to the frequency and load, the ladder control system given above is used to supply all possible capacitance demands in a binary-coded system. Maximum 16 different capacitances are obtained in the ladder-control system. When the generator power is increased, this system that is enough in small power generators is varied with 32 or 64 different capacitances. Capacitance controls that have more different values can be made considering alternation boundaries in wind speeds. In Fig. 2, an AC motor driver is used to obtain variable wind speed.

The block diagram of the proposed system is shown in Fig. 3. In the generating system, a capacitor bank is connected to the generator terminal. The capacitors were arranged in 1-2-4-8 binary number system using capacitor-relaying circuit. Thus, 15 different capacitor values were obtained. For this purpose, a counter is used in the system. When the generator is operated at low speeds, the controller connects more capacitors in parallel to the terminals of the induction generator to provide more self-excitation current. On the other hand, to avoid switching on of the capacitors frequently, the count range of the counter must be determined considering the discharge time over the resistances.

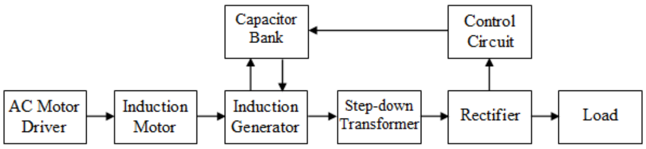

Fig. 3. Block diagram of the experimental setup system.

Figure 4 shows block diagram of the control circuit. The controller compares the output voltage value of the rectifier with a reference voltage value and adjusts the parallel capacitor number connected across the machine terminals to maintain a constant output voltage at various speeds and loads. The rectifier voltage is adjustable by a voltage divider using a variable resistance for comparison with the reference voltage. In Figure 4, a Proportional Controller is used for the control circuit.

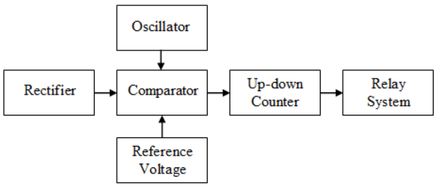

Fig. 4. Block diagram of the control circuit.

IV. EXPERIMENTAL ANALYSIS RESULTS

Figure 5 shows the variation of output DC power of the rectifier with values of frequency at different excitation capacitors at load operation. The generated output DC power increases as the frequency is increased for capacitor values between 4 μF and 24 μF shown in Fig. 5. But, at a capacitor value of between 24 μF and 48 μF, the rectifier output DC power decreases after the frequency of 45 Hz. This implies that because the maximum value of excitation capacitor is 24 μF, after this value, the excitation capacitors behave as loads.

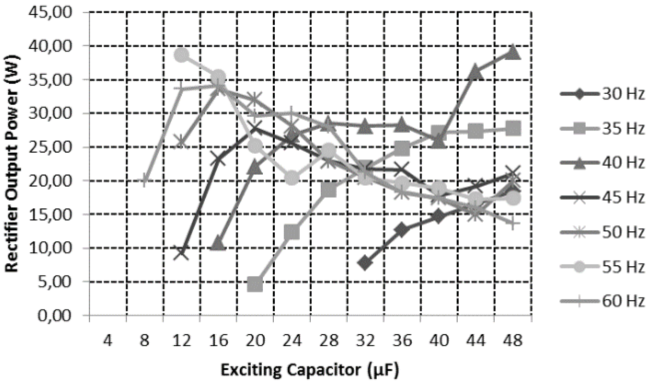

Fig. 5. Output DC power characteristic of rectifier at load.

In this study, a fixed resistor is used as the load. Load effect against power is not observed since load changes are not formed. However, fixed loads are not always possible in the small power applications; control system also works in the variable loads. What is needed in the control system is to hold voltage in the fixed range. But when the load exceeds the mechanical power of the IG, feedback current control must also be added to the system since there is an over load in the windings.

Figure 6 shows the variation of output of induction generator with values of frequency at different excitation capacitors at load operation. The generated power increases as the frequency is increased for capacitor values between 4 μF and 24 μF as the rectifier output.

Figure 7 shows the variation of output of induction generator with values of frequency at different excitation capacitors at no-load operation. In this operation the only load is the excitation capacitors. Thus, power is reactive power and belongs to capacitor values and frequency.

Figure 8 shows changes in the rectifier output current that is under fixed load resistor with excitation capacitance at different operating frequencies. Changing the excitation capacitance also changes the rectifier output voltage. Therefore, the current is drawn by the load changes.

As can be seen in Fig. 9, as the value of excitation capacitance increases in each cycle, ns-nr value increases according to load increase. Load that increases according to rectifier output voltage also increases shift value.

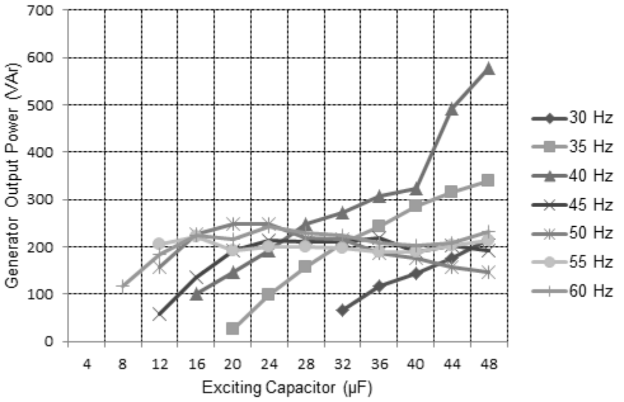

Fig. 6. Generator output reactive power at load.

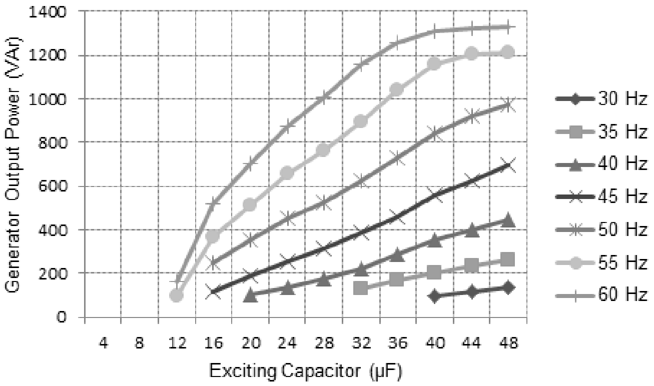

Fig. 7. Generator output reactive power at no-load.

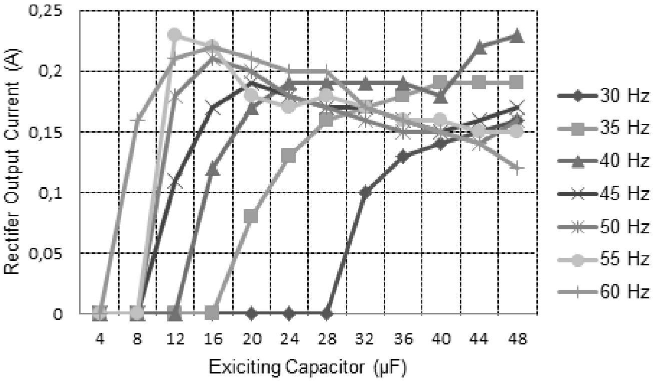

Fig. 8. Rectifier output current for exciting capacitor.

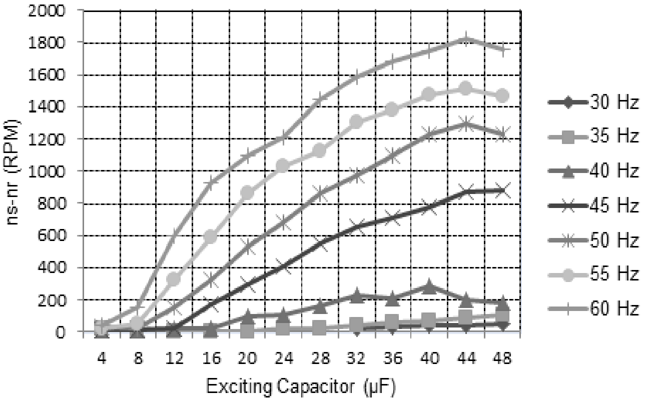

Fig. 9. Difference of stator magnetic rotary field by rotor mechanical return value.

V. CONCLUSIONS

In this study, the output power for induction generator is adjusted simply and reliably. In isolated remote areas, for small application, it is quite difficult to supply the low-quality power necessary from the low-voltage power distribution grid. In these cases, the electric power may be produced with low cost and easily controllable generation system. For this purpose, the designed and realized induction generator and control system have sufficient performance and they may be used for the isolated small wind power applications. This practical system was operated without any problems at various limited frequencies and loads. But, for other functional applications, some improvements are necessary in the number of capacitor banks and the sensitivity of the control system.

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