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Effect of rotation on achieving constant voltage in three-phase self-excited induction generator for small scale wind turbines application

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Abstract

Three-phase Self-Excited Induction Generators (SEIGs) are commonly employed for electricity generation in remote or isolated areas. SEIGs are preferred in such regions due to their ability to create a magnetic field by adding a capacitor to one of their terminals. Nevertheless, a significant challenge in utilizing SEIGs is maintaining a consistent output voltage in the presence of load fluctuations. This study aims to investigate the impact of generator rotation on the SEIG's output voltage and determine the optimal rotation speed required for achieving a stable output voltage. Ensuring stable voltage regulation is crucial to guarantee the proper functioning of all loads connected to the SEIG. Furthermore, operating the SEIG in parallel with other generators is advantageous. The methodology employed in this study involves varying the load supplied by the SEIG at different capacitor values. Unwanted voltage variations occur due to load fluctuations within a generating system or SEIG. Adjustments to the generator's rotation speed are made to uphold a uniform voltage level. The variables considered in this study include the generator's rotation speed, capacitor size, and load fluctuations. Simulation results demonstrate that the SEIG's output voltage is affected by the generator's rotation speed, and maintaining a consistent voltage necessitates appropriate adjustments to capacitor values and generator speed. This research enhances understanding of SEIG characteristics and offers guidance on effective settings for maintaining a stable output voltage at various generator rotation speeds. Future research can focus on practically implementing these findings to enhance the performance of SEIGs in real-world applications.

Keywords:
Rotation effect, constant voltage, self-excited, three-phase, induction generators.

1 Introduction

The utilization of three-phase induction generators in rural electrification initiatives stemming from small scale wind turbine generation systems, has significant relevance and offers numerous advantages. Typically, these generators exhibit a high level of efficiency, enabling the efficient conversion of the limited wind energy available in rural areas into electricity [1,2]. Despite the relatively modest capacity of small scale wind turbine generators, three-phase induction generators possess the capability to generate sufficient power to fulfill the basic electricity requirements of rural communities [3]. They can cater to essential needs such as lighting, communication devices, and other fundamental necessities.

Additionally, three-phase induction generators boast a prolonged operational lifespan and require minimal maintenance, rendering them suitable for deployment in rural areas, which may pose accessibility challenges [4]. Their adaptability extends to both off-grid and grid-tied systems, contingent on the specific requirements and available infrastructure within the community [5]. The integration of small scale wind power plants equipped with three-phase induction generators has the potential to foster economic and social development in rural regions by facilitating access to dependable and cost-effective electricity [6]. The minimal maintenance requirements of three-phase induction generators represent a notable advantage, particularly in rural settings where technical resources may be scarce [7-8]. Through the combined utilization of small scale wind power plants and three-phase induction generators, rural communities can achieve enhanced accessibility to clean, dependable, and economically viable electricity, thereby contributing to the enhancement of quality of life and the promotion of sustainable development [9-11].

Currently, the utilization of electrical energy for human activities is primarily driven by electric motors, with induction motors constituting the majority [12]. Concurrently, there has been a rapid surge in the adoption of induction generators in small-scale power plants, particularly those leverage renewable energy sources [13]. An induction machine functions as either a motor or generator depending on the slip value [14]. In generator mode, the slip (S) is negative, whereas it is positive in motor mode [15].

Self-Excited Induction Generators (SEIG) have emerged as a pivotal solution in the pursuit of renewable energy [16-18]. Its principal advantage is its ability to self-excite by augmenting the rotor flux through the integration of capacitors on the stator coil terminal [19]. Consequently, SEIG has gained prominence for use in small-scale power plants powered by renewable sources, such as mini/small-scale wind turbines, ocean waves, biomass, and biogas [20,21]. Additional benefits of SEIG include its simple construction, compact size and weight, reliability, efficiency, ease of maintenance, and integrated circuit protection [22,23].

Mechanical energy from the prime mover propels the SEIG, with capacitor banks serving as an excitation system or reactive power generator to generate the required voltage [24]. Common issues encountered in SEIG-based generation include voltage and frequency fluctuations, both of which can detrimentally impact performance and efficiency [25,26]. This study scrutinized the influence of rotation on the SEIG output voltage, aiming to ensure voltage stability at its rated value (380 V). This paper discusses the impact of rotation on SEIG output voltage and seeks to identify the optimal generator rotation required to maintain a consistent output voltage.

2 Experimental Procedures

As illustrated in Fig. 1, a three-phase induction motor has the capability to function as a Self-Excited Induction Generator (SEIG) when its rotor is propelled at an appropriate speed by wind energy, and its excitation is induced by linking a three-phase capacitor bank to the stator terminal to initiate voltage buildup and regulation to achieve a nominal terminal voltage value [27].

An induction machine can function as either a motor or a generator depending on the slip value, as illustrated in Fig. 2. In the generator mode, the slip (S) is negative, whereas in the motor mode, it is positive, as shown in Eq. 1, where S represents the slip, N_s denotes the stator synchronous/rotating field speed, and N_r signifies the rotor speed [3].

$$S = \frac{N_s - N_r}{N_s} \times 100\% \tag{1}$$

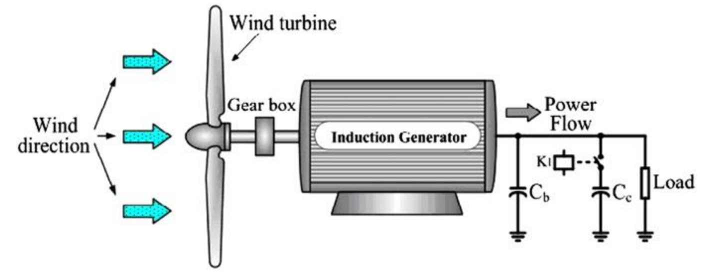

Fig. 1. Induction generator that is self-excited and powered by wind energy [27].

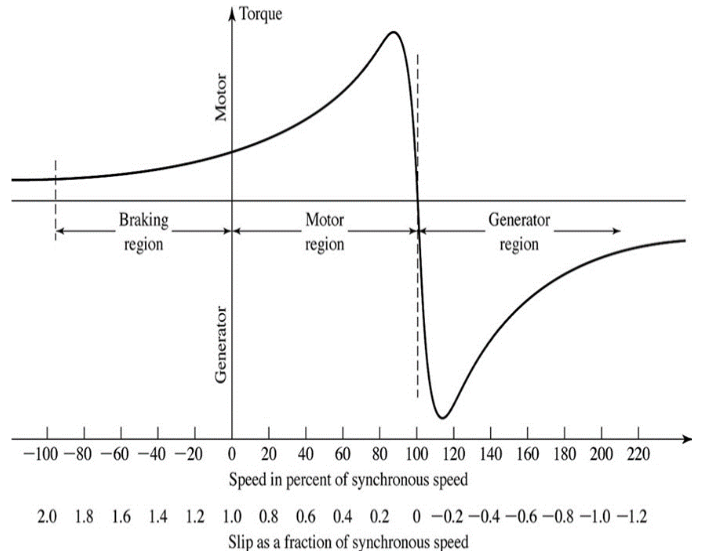

Fig. 2. Induction machine working area [28].

This paper discusses the impact of the prime mover rotation speed on the voltage of a self-excited three-phase induction generator (SEIG) through load and excitation capacitor value variations, aimed at maintaining a constant voltage of 380 V. The influence of adjusting capacitor size and prime mover rotation to the appropriate values for voltage maintenance at its rating will also be examined [29].

The DC motor, serving as the prime mover, transfers mechanical or kinetic energy to the SEIG, as shown in the flow chart (Fig. 3). The DC motor used was a permanent-magnet DC motor. The speed of this type of DC motor was regulated by adjusting the terminal voltage. The DC motor used as a prime mover in this research can be replaced by a wind turbine or water turbine under the conditions of application.

The flowchart delineates the research stages undertaken, encompassing problem identification, tool and material collection, self-excited induction generator design, work analysis, and data organization.

2.1 System Configuration

This stage involves calculation of the minimum capacitor value applicable to an induction generator. The objective is to ascertain the lowest value of capacitor that enables the induction generator to function and produce voltage [10]. The specifications for an induction motor functioning as a generator include a power of 0.35 kW (P_{nom}), power factor of 0.8 ($\cos\phi$), frequency of 50 Hz, motor rotation of 1410/1630 RPM, and an input power (P_{input}) of 0.4375 kW. The Direct Current (DC) motor specifications were 0.4 kW, 180, and 2500 RPM. The DC motor specifications are chosen so that it can drive the SEIG according to its needs.

Consequently, the minimum capacitor value and reactive power required by the machine when operating as an induction motor can be calculated as $Q_m = P_1 \tan\phi = 0.4375 \tan 36.8 = 0.328125$.

When operating as an SEIG, this can be demonstrated through Eq. 2, the sewing of Q_{total} (Eq. 3).

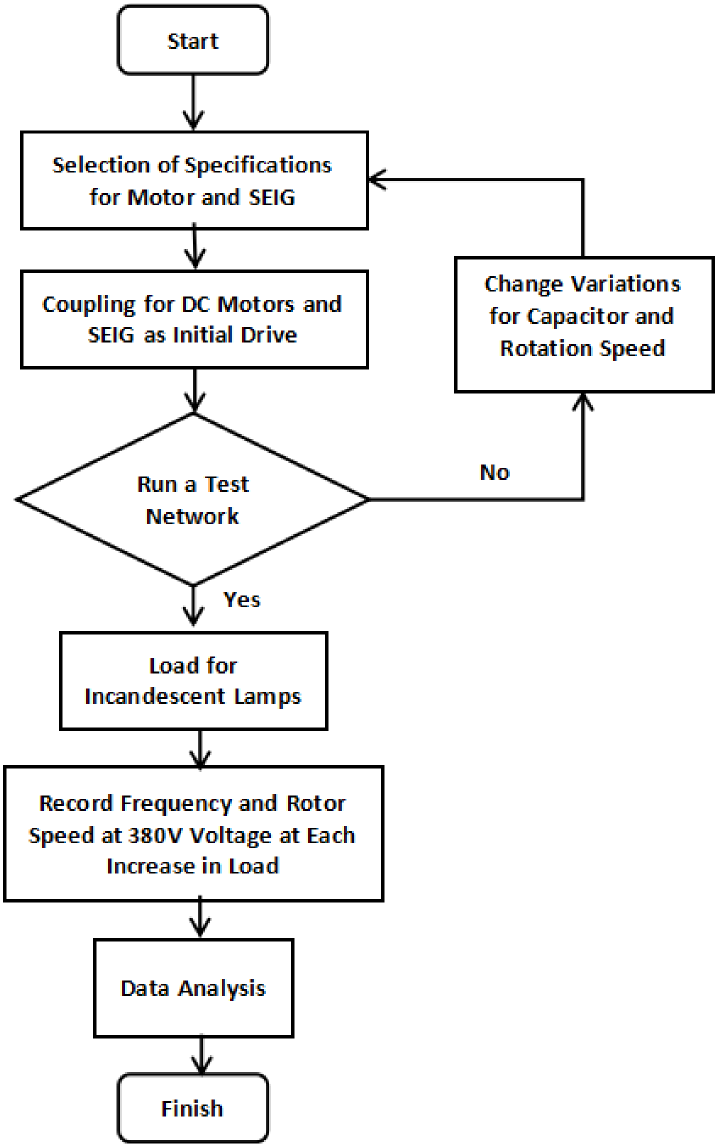

Fig. 3. Flowchart for achieving constant voltage in self-excited three-phase induction generators.

$$Q_g = P_2 \tan\phi = 0.35 \tan 36.8° = 0.2625 \text{ kVAR} \quad (2)$$

$$Q_{total} = Q_m + Q_g = 0.590625 \text{ kVAR} \quad (3)$$

$$C_{\gamma}/phase = Q/3 \cdot V^2 \cdot 2\pi f = 12.95\ \mu\text{F} \quad (4)$$

Since this study employs a parallel capacitor configuration (Fig. 4 and Fig. 5), the minimum capacitor suitable for an induction generator is calculated as 12.95 μF × 3 = 38.85 μF, rounded to 39 μF.

Fig. 4. Design results of applying capacitor circuit to induction generator.

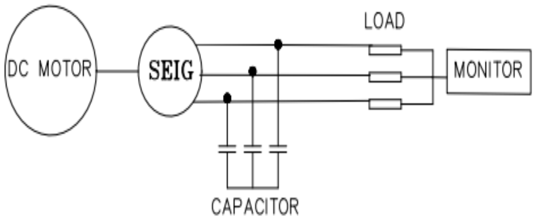

Fig. 5. Induction generator circuit design.

3 Results and Discussion

This research focuses on investigating the impact of the prime mover's rotational speed on achieving a consistent voltage at its rating (380 V) across test loads of 5, 15, 25, 40, and 60 Watts, along with variations in capacitor values of 45, 50, 55, and 60 µF, respectively, per phase. The lamp was chosen as a load because it does not require a large current when turned on.This test was carried out in the Basic Electrical Energy Laboratory, Department of Electrical and Computer Engineering, Faculty of Engineering.

3.1 Capacitor at 45 µF

The results of testing the effect of rotational speed on SEIG voltage with an excitation capacitor of 45 µF and load variations of 5, 15, 25, 40, and 60 Watts yielded speed values of 1706, 1733, 1760, 1798, and 1820 RPM, respectively, for each load. This rotor speed is greater than the speed of the stator rotating field; this indicates that the slip value is negative

These speeds were obtained sequentially from 5 to 60 Watts. The rotational speeds recorded during the experiment consistently exceeded the synchronous speed, indicating negative slip and activation of the generator mode [30,31]. Analysis of the test results with a 45 µF capacitor indicates that, as the load increases, the rotational speed required to maintain the voltage constant at its 380 V rating also increases. Notably, the rotational speed observed during a 25 Watts load variation surpassed that observed during a 5 Watts load variation. Further details of the initial experiments are presented in Fig. 6 and Table 1.

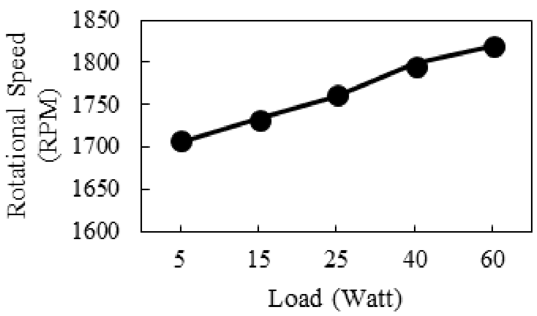

Fig. 6. Effect of rotational speed on voltage of induction generator with 45 µF excitation capacitor.

Table 1. Capacitor excitation at 45 µF

Load (Watt)	Current (A)	Frequency (Hz)	Rotational speed (RPM)
5	0.07	45.54	1706
15	0.09	45.83	1733
25	0.11	45.98	1760
40	0.17	46.06	1798
60	0.21	46.18	1820

3.2 Capacitor at 50 µF

The results of testing the effect of rotational speed on SEIG voltage with an excitation capacitor of 50 µF and load variations of 5, 15, 25, 40, and 60 Watts yielded speed values of 1650, 1681, 1692, 1710, and 1742 RPM, respectively, for each load. These speeds were recorded sequentially from 5 to 60 Watts. Throughout the experiment, the rotational speeds consistently exceeded synchronous speed, indicating negative slip and active generator mode [32]. The test results with a 50 µF capacitor demonstrated a direct proportionality between load magnitude and rotational speed required to maintain a constant voltage at a rating of 380 V; higher loads necessitated higher speeds. A comparison of the experimental data reveals that the rotational speed is lower at a 5 Watts load variation than at a 25 Watts variation. For more detailed results from the second experiment, refer to Fig. 7 and Table 2.

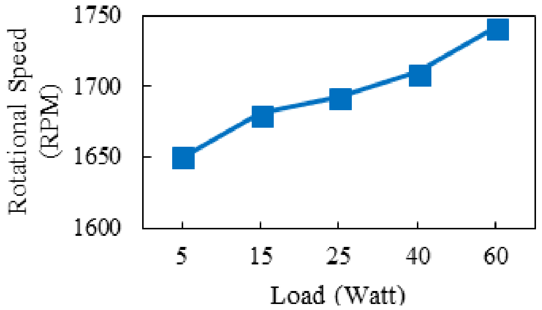

Fig. 7. Effect of rotational speed on voltage of induction generator with 50 µF excitation capacitor.

Table 2. Capacitor excitation at 50 µF

Load (Watt)	Current (A)	Frequency (Hz)	Rotational speed (RPM)
5	0.05	43.63	1650
15	0.08	44.02	1681
25	0.10	44.12	1692
40	0.12	44.30	1710
60	0.20	44.52	1742

3.3 Capacitor at 55 µF

In the third experiment, utilizing a 55 µF excitation capacitor, yielded results identical to those of the 5 and 50 µF excitation capacitor experiments, indicating a direct proportionality between rotational speed and load magnitude. This experiment underscores the influence of excitation capacitor size on rotational speed, as observed in the trend where larger excitation capacitors correspond to lower rotational speed values. The detailed results of the third experiment are presented in Fig. 8 and Table 3.

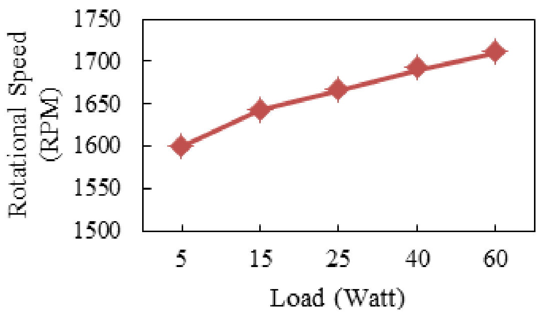

Fig. 8. Effect of rotational speed on the voltage of an induction generator with the 55 µF excitation capacitor.

Table 3. Capacitor excitation at 55 µF

Load (Watt)	Current (A)	Frequency (Hz)	Rotational speed (RPM)
5	0.05	41.33	1600
15	0.08	41.86	1642
25	0.10	42.40	1666
40	0.12	42.52	1689
60	0.20	44.82	1710

3.4 Capacitor at 60 µF

The results of testing the effect of rotational speed on SEIG voltage with a 60 µF excitation capacitor and load variations of 5, 15, 25, 40, and 60 Watts yielded speed values of 1598, 1612, 1632, 1655, and 1687 RPM, respectively, for each load in sequence from 5 to 60 Watts. Notably, the rotational speed obtained in the fourth experiment was the lowest among the three previous experiments because of the inverse proportionality between the excitation capacitor value and rotational speed [33-35]. The comprehensive experimental results of the 60 µF capacitor are illustrated in Fig. 9 and Table 4.

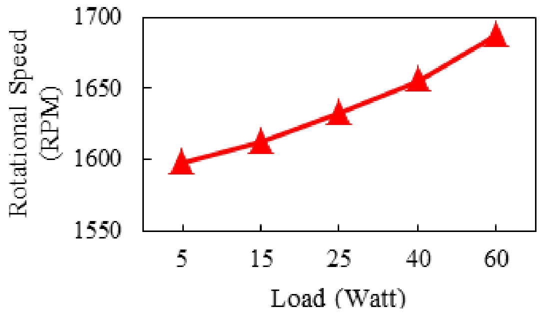

Fig. 9. Effect of rotational speed on the voltage of an induction generator with the 60 μF excitation capacitor.

Table 4. Capacitor excitation at 60 μF

Load (Watt)	Current (A)	Frequency (Hz)	Rotational speed (RPM)
5	0.07	39.93	1598
15	0.08	40.13	1612
25	0.10	40.34	1632
40	0.12	41.57	1655
60	0.20	41.65	1687

4 Conclusion

The impact of rotation on SEIG output voltage and the identification of optimal generator rotation for maintaining a constant output voltage have been investigated. It can be concluded that a larger excitation capacitor value results in a lower rotational speed requirement to attain a constant voltage at its rating. The speed values of the induction generator, capacitors, and loads supplied by the SEIG were interconnected variables. Load fluctuations typically lead to voltage variations, an undesirable occurrence in generating systems or SEIGs. The generator rotation settings were adjusted to achieve a stable voltage level. Factors being examined include generator rotation, capacitor size, and load fluctuations. Simulation results indicate that SEIG output voltage is influenced by generator rotation, and maintaining a consistent output voltage requires appropriate adjustments to capacitor values and generator speed. This study improves understanding of SEIG characteristics and provides guidance for effective settings to ensure a constant output voltage across various generator rotation speeds. Based on the experiments carried out, setting the capacitor value is easier to do when compared to setting the generator rotation to get a constant voltage.Future research should focus on frequency regulation to obtain a constant frequency. In addition, these findings can be used to improve SEIG performance in real-world applications.

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