Experimental determination of minimum capacitor for self-excitation of induction generators

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ABSTRACT

This article addresses the issue related to determining the minimum capacitor required for the self-excitation of an induction generator. The determination of the minimum capacitance required for the self-excitation of a self-excited induction generator has already been the subject of several previous studies. It has been shown that the minimum capacitance depends on the rotation speed and the remanent magnetism. The study carried out in this paper shows that, in addition to the rotation speed and the remanent magnetism, there is a third parameter that has an influence on the self-excitation process, which is the acceleration or, in other words, the rotation speed ramp-up. In this paper, several experimental self-excitation tests for different values of the rotation speed ramp-up are carried out, leading to new characteristics of the minimum self-excitation capacitance as a function of the rotation speed. The results obtained from simulation and experimental studies prove the efficacy of the proposed approach.

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1. INTRODUCTION

The use of wind power to generate electricity as an ecological alternative source to fossil fuels and nuclear energy is nowadays undergoing great development. Indeed, new units for the conversion of renewable energy into electrical energy are taking place. They are in the form of micro-power stations and are either intended to serve as a back-up source to other sources or are specifically designed for stand-alone operation to supply sites isolated from the electricity grid [1], [2].

In the case of stand-alone systems, various electric generators are used. However, for reasons of reliability and robustness, self-excited induction generators are still widely utilized. A capacitor self-excited asynchronous generator (SEIG) offers certain advantages over a conventional synchronous generator as an isolated electrical power source. These advantages include reduced unit cost, a brushless rotor, the absence of a separate DC source, and ease of maintenance [3]–[6]. In this modes, capacitors are utilized to provide the requisite reactive power for self-excitation of the induction generator [7]. In these situations, the generator adjusts its operational frequency in line with the rotational speed and load demands [8]. However, maintaining voltage regulation within autonomous self-excited induction generators (SEIGs) is of paramount importance to ensure stable and reliable power generation [9]. Various voltage regulation systems for SEIGs rely on automatic adjustment of capacitor capacity. SEIG voltage regulation can be enhanced through shunt or series compensation techniques. Technological advancements, particularly the use of thyristors and power converters, have facilitated the deployment of devices such as the thyristor-based phase-controlled reactor (FC-TCR). In this context, the induction generator no longer requires a capacitor bank for self-excitation, as the reactive power needed for both the generator and the loads is supplied by the TCR-FC. Furthermore, static synchronous compensators (STATCOMs) offer two topologies used in SEIG voltage control [10]–[13]. The first topology is based on a current-controlled voltage source converter, while the second utilizes a static current compensator. Moreover, the series static compensator (SSC) has demonstrated its efficiency in optimizing voltage profiles within electrical systems. The literature has also explored different control strategies, encompassing both voltage and frequency regulation [12], [13].

The phenomenon of self-excitation in induction machines is nowadays well known. It requires three conditions simultaneously [2], [14]–[17]. The existence of a reactive energy source (capacitors in the case of stand-alone operation), the existence of a remanent magnetism and sufficient rotation speed; for a given value of capacitor capacitance, there is a lower limit of rotation speed below which self-excitation will not occur. Studies have shown the influence of each of these three conditions on the self-excitation delay of induction generators and on the amplitude of the generated voltages [18].

This article presents a theoretical study followed by an experimental validation aimed at highlighting a fourth factor in the self-excitation delay of SEIG. The parameter under investigation is the acceleration or transient rotational speed. In the literature, several studies have been conducted to determine the minimum required capacitance value for ensuring self-excitation of an asynchronous generator at a given rotational speed [1], [15], [17], [19], [20]. The procedure involves setting the rotational speed and then varying the capacitance of the capacitors until self-excitation occurs [21]. Thus, a curve representing the minimum self-excitation capacitance as a function of rotational speed can be plotted. We have observed that this technique does not take into account the influence of acceleration on the self-excitation phenomenon. In this context, for our contributions, we fix the capacitance of the capacitors and vary the rotational speed from zero until the occurrence of the self-excitation phenomenon. The objective of this technique is to plot the characteristic of the minimum capacitance as a function of rotational speed and demonstrate the influence of acceleration on the self-excitation phenomenon. In order to compare the experimental and theoretical results, a dynamic model of the self-excited asynchronous generator is developed using Matlab-Simulink. This model is valid both in transient conditions to evaluate excitation delays and in steady-state conditions to assess the generated voltage amplitudes.

2. SYSTEM DESCRIPTION AND MODELLING

The proposed method will be tested in a dedicated control scheme for a SEIG driven by a DC motor. The SEIG is connected to a variable capacitor bank for self-excitation. Figure 1 illustrates the overall system diagram under study. The dynamic model of the SEIG is derived from the electrical and magnetic equations to which we add the self-excitation equations. The SEIG equations and parameters used in this study are the same as those used in our previous works [22], [23].

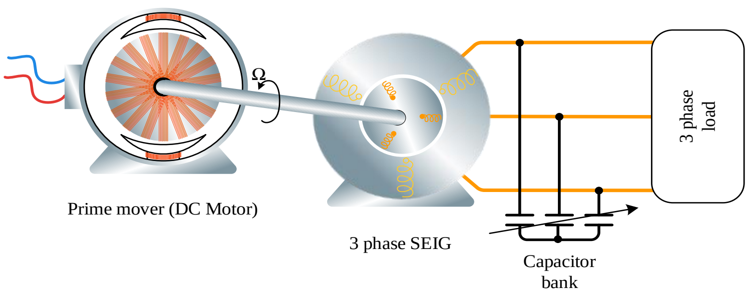

Figure 1. Overall diagram of the studied system

The equivalent circuit shown in Figure 2 is the classical equivalent diagram of an induction machine to which we have added a self-excitation capacitor in the stator branch. At no load, the rotor current is low compared to the stator current and the magnetising current. The rotor branch will then appear as an open circuit and the equivalent circuit of Figure 2 will be reduced to a single branch as shown in Figure 3 [23], with Rs: stator resistance, Xs: stator leakage reactance, Xm: magnetising reactance, and Xc: capacitor reactance.

From Figure 3, we can write:

$$-j.X_c.I_s + (R_s + j.X_s).I_s + j.X_m.I_m = 0 \quad (1)$$

as: $I_s = I_m$, therefore

$$\left(R_s + j(X_s. + X_m - X_c)\right).I_s = 0 \quad (2)$$

this leads to:

$$\begin{cases} R_s = 0 \\ X_s + X_m - X_c = 0 \end{cases} \Rightarrow X_c = (X_s. + X_m) \quad (3)$$

$$\frac{1}{C.\omega_r} = L_m.\omega_r \quad \Rightarrow C = \frac{1}{L_m.\omega_r^2} \quad (4)$$

From (4), we plot the theoretical characteristic which gives the minimum capacitance of self-excitation as a function of the rotation speed. Given that the value of the magnetising inductance L_m to be taken into account is the one corresponding to the linear zone of the no-load characteristic $L_m(i_m)$, i.e. the initial value of L_m [24], [25].

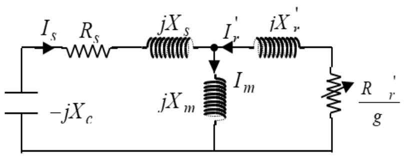

Figure 2. Equivalent circuit of SEIG

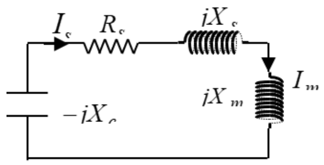

Figure 3. Simplified equivalent circuit of the SEIG

3. EXPERIMENTAL TEST BENCH

In order to demonstrate the influence of the slope of the rotation speed increase on the value of the self-excitation capacitance, an experimental test bench was prepared. It consists of a 1.1 kW squirrel cage induction machine driven by a 3 kW DC motor and a three-phase variable capacitance bank. A dynamo-tachometer mounted on the shaft is used to visualize the speed. A voltmeter is employed to assess the occurrence of self-excitation. Figure 4 displays a photograph of the experimental test bench.

Capacitor capacitance limits depend on generator rotation speed and power. For a 1.1 kW induction generator and for a speed of 1500 rpm, the minimum capacity is around 20 µF. The maximum limit of the capacitance is dictated by the magnitude of the generated voltage which should not exceed the nominal value.

The working method employed during the experimental tests follows a well-defined process. First and foremost, we initially determine the excitation capacity value using a random selection. Subsequently, in a progressive manner, we increase the rotational speed of the machine until reaching the optimal excitation point of the generator. Through this testing approach, we are able to accurately determine the optimal value of the excitation capacity.

Figure 4. Photograph of the experimental test bench

4. RESULTS AND DISCUSSION

The experimental characteristic is obtained by fixing the value of the capacitance and gradually increasing the rotation speed until excitation occurs, and then noting the speed corresponding to the beginning of the excitation. Figure 5 shows the characteristic of the minimum capacitance of self-excitation as a function of the rotation speed, obtained experimentally and theoretically.

Thus, the minimum capacitance of self-excitation $C_{\_min}$ is inversely proportional to the square of the rotation speed. Figure 5 shows a good agreement between the experimental and theoretical characteristics. It is important to highlight that, when plotting the experimental characteristic of $C_{min}(\omega_r)$, the increase in speed was deliberately made very slow to correctly assess the value of the speed corresponding to the start of self excitation.

For a thorough analysis, we replicated the previous experiment while accelerating the process at a faster rate, which led to significantly distinct outcomes. To achieve this, while maintaining a constant capacity, we conducted three tests by progressively increasing the acceleration rate. This approach allowed us to highlight the substantial impact of acceleration on the self-excitation process.

We set the capacitance to a given value and, by means of the DC motor, we gradually increase the rotation speed of the motor-SEIG set until the voltmeter starts to deviate, this is the beginning of self-excitation. The rotation speed evolves approximately in a ramp from zero to the value corresponding to self-excitation. We carry out three tests by acting on the slope of this speed ramp up. We will thus speak about slow slope, medium slope and high slope.

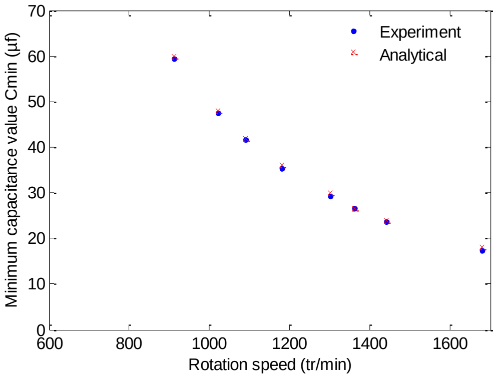

Figure 5. C_min versus rotation speed characteristic

Figure 6, shows the evolution of the rotation speed versus time for three different slopes, which are noted respectively: low, medium and high slope. Figure 7, shows the rotational speed curve versus time with the same slope but with different self-excitation capacitance (C = 42 µF and C = 48 µF). We can see steady state of rotation speed is inversely proportional to capacitance.

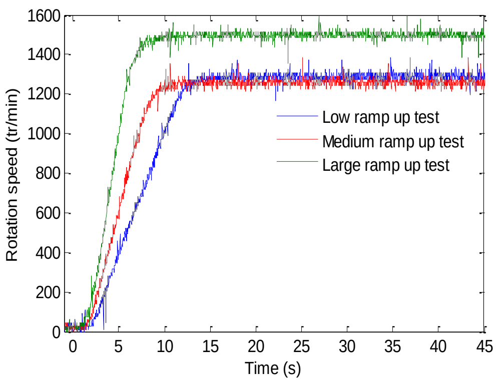

Figure 6. The evolution of rotation speed versus time for the 3 degrees of the speed ramp up and C = 48 µF

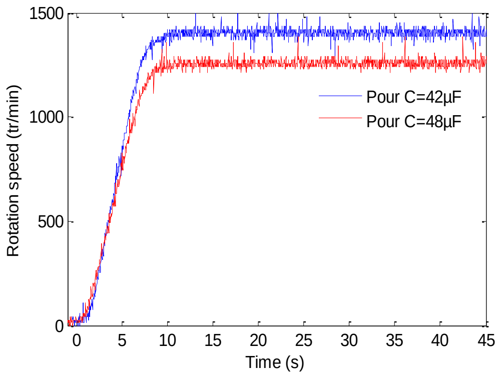

Figure 7. The evolution of rotation speed versus time, medium ramp up test, for C = 42 µF and C = 48 µF

Thus, for each value of capacitance, three tests are carried out, corresponding to the low, medium, and high slopes, respectively. Table 1 shows the results of these three tests. In order to better highlight and interpret the obtained results presented in Table 1, we deemed it important to plot them on graphs for the three speed slopes.

Figures 8, 9 and 10 depict the minimum self-excitation capacity characteristics as a function of rotational speed for low-ramp, medium-ramp, and high-ramp tests, respectively. According to the three latest figures, we observe a satisfactory agreement between the results obtained from the simulations and those obtained from the experimental tests conducted in the laboratory. This convergence thereby validates the results of the simulations.

Table 1. Rotation speed versus excitation capacitance, for three speed ramp ups

Minimum capacitance C_min (µF)	Rotational speed in rpm Low ramp up	Medium ramp up	Large ramp up
24.2	1420	1344	1300
26.5	1360	1240	1200
28.1	1320	1200	1170
30.2	1280	1170	1110
32.8	1240	1128	1090
34.8	1200	1104	1060
36	1188	1080	1038
38.88	1130	1040	992
42.3	1094	1000	940
44.8	1060	960	900
46.7	1040	920	860
48.2	1000	900	840
50.8	980	860	800
53.1	960	834	780
56.1	940	786	764
60.1	922	754	720
62.7	910	738	700
66.3	890	720	694

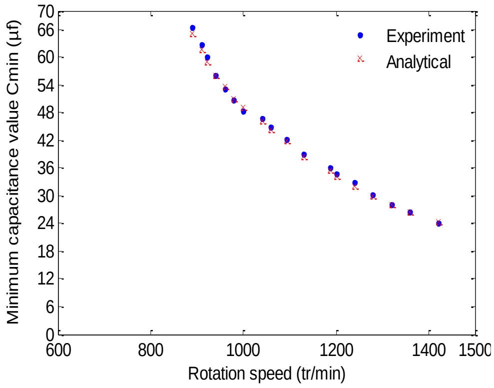

Figure 8. C_min versus speed characteristic, low ramp up test

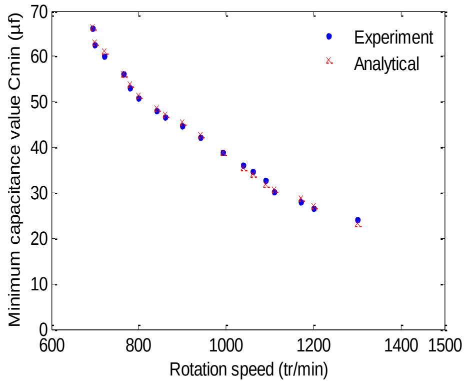

Figure 9. C_min versus speed characteristic, medium ramp up test

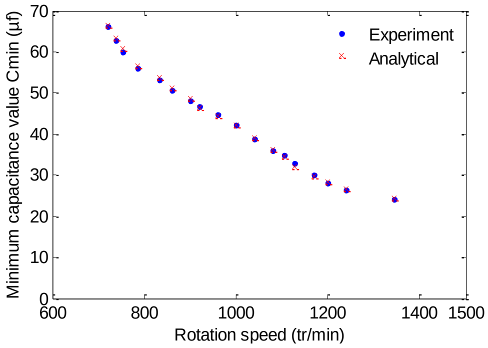

Figure 10. C_min versus speed characteristic, large ramp up test

We have grouped all the experimental results obtained in Figure 11, in order to compare them using various measures. The graph clearly shows that, when the capacity and rotation speed are kept constant, a steeper acceleration slope corresponds to a reduced value of self-excitation capacity. The obtained results conclusively demonstrate the idea implemented in this article. Indeed, this study highlights the importance of considering the acceleration parameter for self-excitation of induction generators.

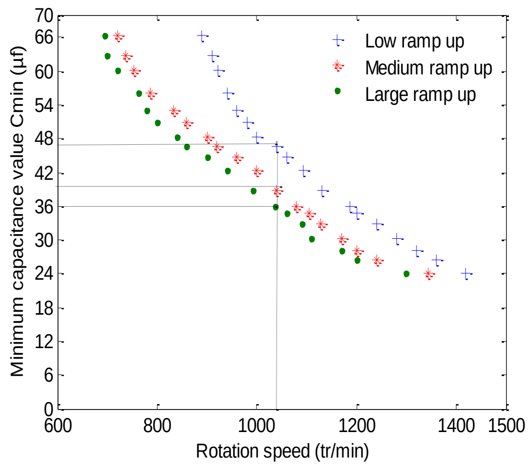

Figure 11. Comparison of the experimental characteristics of C_min versus rotation speed for the 3 degrees of the speed ramp up

5. CONCLUSION

This paper has been devoted to the theoretical and experimental study of the conditions necessary for the self-excitation of a self-excited induction generator (SEIG). Particular emphasis has been placed on the characteristic that determines the minimum capacitance required for self-excitation as a function of rotation speed. Based on the equivalent circuit of the SEIG operating at no load and with some justified simplifications, a simple theoretical relationship describing the minimum self-excitation capacitance as a function of rotation speed has been established. The comparison between the theoretical and experimental results shows a good agreement. Furthermore, a dynamic model of the SEIG was developed in MATLAB-Simulink to assess both the self-excitation delays and the amplitudes of the generated voltages.

Subsequently, a series of experimental tests were carried out to investigate the influence of the speed rise slope (acceleration) on the characteristic determining the minimum self-excitation capacitance as a function of rotation speed. By considering the acceleration, new characteristics were plotted. The main result of these new tests can be summarized as follows: for the same steady-state value of the rotation speed, the value of the minimum capacitance for self-excitation depends on the slope at which the speed evolves towards steady-state. The higher the slope of the speed increase, the lower the minimum capacitance required for self-excitation.

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