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IDENTIFYING VOLTAGE AND FREQUENCY REGULATION CURVES OF SELF-EXCITED INDUCTION GENERATOR*

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Milan M. Radić[1], Zoran P. Stajić[1], Nataša Jovanović[2]

[1] University of Niš, Faculty of Electronic Engineering, Department of Power Engineering, Niš, Republic of Serbia
[2] University of Niš, Faculty of Mechanical Engineering, Department for Mechanical Constructions, Development and Engineering, Niš, Republic of Serbia

Abstract. *A simple method for computation of voltage and frequency regulation curves of a self-excited induction generator is presented in this paper. The method has been successfully exploited for identifying several different types of regulation curves of a 1.5 kW cage rotor self-excited induction generator. The proposed approach is universal and can be used for identification of any generator's regulation curves, if the parameters of the equivalent circuit are known. Information contained in these computed curves can be very useful while designing systems for automatic control of self-excited induction generators.*

Key words: *SEIG, induction machine, capacitor, voltage regulation, frequency regulation, Matlab Optimization Toolbox*

1. INTRODUCTION

The concept of self-excited induction generator (SEIG) has been recognized almost one century ago by Basset and Potter [1]. Until the last decades of the past century, this operating regime of induction machine was considered theoretically possible, but absolutely unacceptable for practical applications. Such negative opinion has been established at the

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Corresponding author: Milan M. Radić
Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Republic of Serbia
E-mail: milan.radic@elfak.ni.ac.rs
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first line due to the serious problems with voltage and frequency control. As a consequence, detailed descriptions and analyses of SEIG are very rare, even in contemporary literature units describing alternating current machines. Only few literature sources [2, 3] present positive examples of more detailed discussions on this subject. Other very important reason for neglecting SEIG as an acceptable solution for the off-grid electric power generation is the fact that any attempt to perform an accurate and reliable analysis of its operation, has been followed with serious mathematical difficulties. Greater interest for a self-excited regime of operation emerged along with the increased utilization of personal computers, but the first attempts of numerical calculations have been made using simplified equivalent circuits and long lasting and exhausting iterative methods [4, 5]. Modern numerical-based methods, developed for the purpose of solving systems of high-order nonlinear equations offer a new, more sophisticated approach in the analysis of a SEIG [6-8]. In recent years, great advances in theoretical research and steps towards practical improvements of performance have been made. The existing technical solutions for voltage and frequency control are nowadays mostly based on the intensive use of power electronics [9-12]. As it has been clearly mentioned in [13], there is still a significant work to be done in order to completely understand the nature of SEIG and to practically exploit its comparative advantages (low cost, simple and reliable construction and robustness) to the maximum. It is still interesting to search for less complex methods, in order to overwhelm weakness of voltage and frequency regulation.

During our previous research we have studied some important aspects of the SEIG operation. Investigation has been mostly directed towards identification and experimental verification of performance characteristics without any type of regulation [14-16]. In this paper we go one step further, trying to define a simple and universal method of computation in order to identify regulation curves that will result in constant voltage and constant frequency operation under variable loading conditions.

2. Computation of Regulation Curves

In our previous work, we have explained in details the mathematical model and optimization based approach that was used for the analysis of SEIG behavior under different operating conditions [14-16]. Such method of computation was originally proposed in reference [6], offering great simplifications in comparison to the previously exploited iterative methods. For the sake of clarity, some crucial steps have to be described here.

Self-excited induction generator is represented by the equivalent circuit shown in Fig. 1, which is a modified version of the standard „T" equivalent circuit of an induction machine. Although electric load of a three-phase generator can be asymmetrical in general, and can also contain inductive elements, for this occasion the consideration has been simplified, assuming that a symmetrical, three-phase resistive load is connected to the stator terminals.

The meanings of symbols used in Fig. 1 are defined as following: R_L is load resistance, R_s, X_{ls} are stator resistance and stator leakage reactance, R_r, X_{lr} are rotor resistance and leakage reactance (referred to stator), R_c, X_m are magnetizing resistance and variable (unknown) magnetizing reactance, X_C is capacitor reactance, F is per-unit value of actual stator frequency (calculated according to rated frequency f_n) and Ω is per-unit value of rotor speed (calculated according to rated synchronous speed n_s). It is important to notice that the values of all reactances from Fig. 1 are given for the rated frequency of the machine.

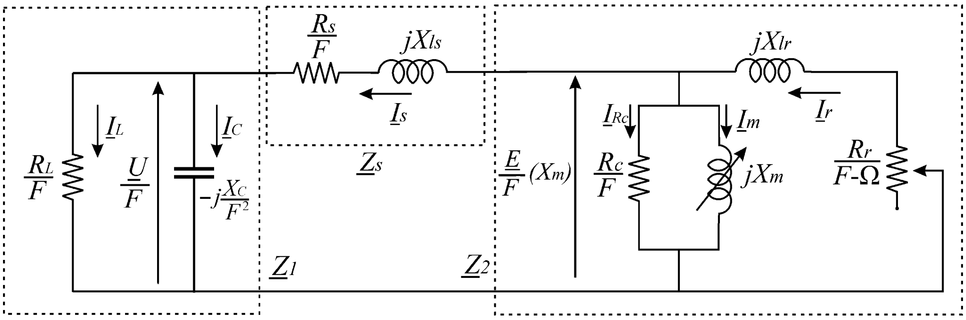

Fig. 1 Modified equivalent circuit of induction machine, suitable for analysis

The nonlinear function $E/F = f(X_m)$ representing normalized air-gap voltage is of crucial importance for accurate description of magnetic saturation, and it can be defined using the data obtained from ideal no-load test.

Since there is no external power supply, generally, voltage and frequency are not defined in advance. Instead, they have to be calculated, considering that all parameters of the equivalent circuit shown in Fig. 1 (except the actual value of the magnetizing reactance X_m, which depends upon the variable level of magnetic flux saturation) and rotational speed are known.

Loop impedance seen by stator current $\underline{I}_s$ is defined by

$$\underline{Z}_{lo} = \frac{R_s}{F} + jX_{ls} + \frac{R_L}{F} || \frac{-jX_C}{F^2} + \frac{R_c}{F} || jX_m || \left(\frac{R_r}{F-\Omega} + jX_{lr} \right) \tag{1}$$

and since in the electric circuit from Fig. 1 there are no voltage sources, it can be written:

$$\underline{Z}_{lo} \cdot \underline{I}_s = 0 \tag{2}$$

Knowing that stator current has to be greater than zero in the state of self-excitation, it is obvious that both real and imaginary parts of the loop impedance have to be equal to zero. This condition can be written as

$$\mathrm{Re}\{\underline{Z}_{lo}\} = 0 \tag{3}$$

$$\mathrm{Im}\{\underline{Z}_{lo}\} = 0 \tag{4}$$

thus defining two basic equations of a SEIG. The complete form of these equations is presented in [14], and since they are high degree, nonlinear equations of two unknown variables, F and X_m, they can not be solved in a closed form. It is necessary to exploit some of the available numerical methods in order to obtain the solution, and this can be successfully done using *fsolve* function from *Matlab Optimization Toolbox*.

For a properly chosen combination of externally controllable parameters, R_L, X_C and Ω, it is possible to calculate actual values of the unknown variables, F and X_m, thus allowing further calculation of actual stator voltage U, current I_s and generated power P_L.

If we consider that load resistance R_L is an independent variable (which is true in reality), its value can be varied across a chosen region, in small steps, using a program loop. The basic goal is to identify regulation curves that define how the other two externally controllable parameters X_C and Ω should be varied, in order to keep stator voltage and frequency at constant values, while R_L changes. For that purpose, system of Eqs. (3) and (4) have to be expanded with the equation

$$\left|\frac{\underline{Z}_1 E}{\underline{Z}_1 + \underline{Z}_s}\right| - U_{ref} = 0 \tag{5}$$

where U_{ref} is the desired constant voltage. It is also necessary to define the desired value of constant relative stator frequency $F = F_{ref}$. Solving the expanded system of nonlinear equations (3), (4) and (5), for a given triplet of (R_L, U_{ref}, F_{ref}) will result in the computation of the unknown triplet of values (X_m, X_C, Ω). After that, it is easy to calculate the necessary capacitance per phase as

$$C = \frac{1}{2\pi f_n X_C} \tag{6}$$

and the necessary rotor speed as

$$n = \Omega \cdot n_s \tag{7}$$

In this way, regulation curves $C = f(R_L)$ and $n = f(R_L)$ can be successfully identified.

All regulation curves computed and presented in this paper are valid for a laboratory three-phase squirrel cage, Y-connected induction machine with rated data of 1.5 kW, 380 V, 50 Hz, 3.2 A, 2860 rpm (values for a motoring mode of operation). Parameters of the equivalent circuit have been obtained from no-load and locked rotor test, and their values are: $R_s = 4.05\Omega$, $R_r = 2.75\Omega$, $R_c = 1200\Omega$, $X_{ls} = 4.34\Omega$, $X_{lr} = 2.77\Omega$.

Nonlinear function $E/F = f(X_m)$ of the test machine is represented in the form of the third-degree polynomial function:

$$\frac{E}{F} = 348.1 - 2.34X_m + 0.0156X_m^2 - 0.00004861X_m^3 \tag{6}$$

whose graphic representation can be found in [15].

3. Simultaneous Voltage and Frequency Regulation

Keeping stator voltage and frequency at constant, rated values, while the load resistance changes, would be ideal for practical applications of a SEIG. That was the reason why the desired voltage and frequency have been set to $U_{ref} = U_n = 380\ V$ and $F = 1$ (i.e. $f = f_n$), during the first part of the investigation. The value of load resistance has been varied in small steps (of approximately 1 Ω), using the program loop. The starting computational point was set as R_{Lmax} = 600 Ω and computation ended at R_{Lmin} = 70 Ω. The computed regulation curves are shown in Fig. 2.

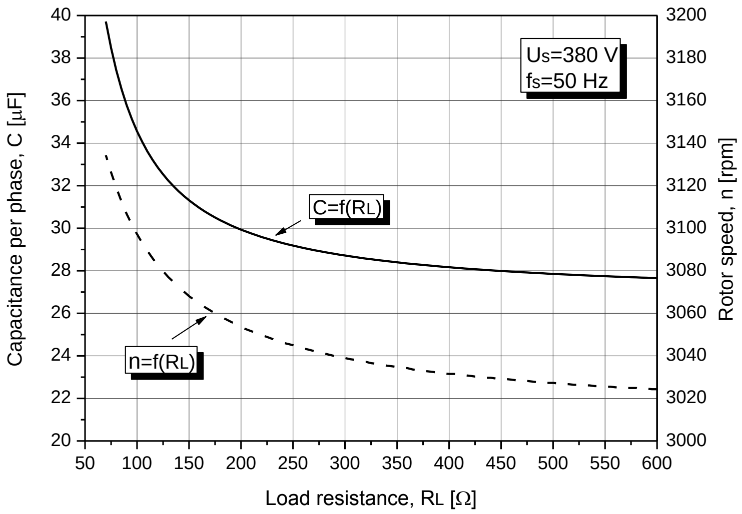

Fig. 2 Regulation curves for constant voltage and constant frequency operation

The presented curves clearly indicate that, if both rotor speed and capacitance are varied according to the calculated functional dependencies, voltage and frequency will remain constant, regardless of load variations. The decrease of load resistance has to be followed by simultaneous increase of rotor speed and connected capacitance.

An alternative, and perhaps more comprehensive form of the mentioned regulation curves, can be obtained if the variations of capacitance and rotor speed are presented as the functions of the generated power P_L (see Fig. 3).

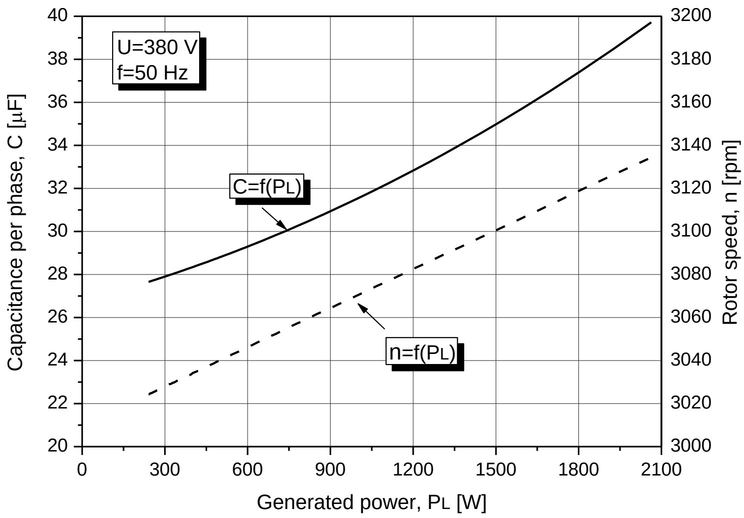

Fig. 3 Constant voltage and constant frequency operation regarding generated power

From the Fig. 3 one can see that in order to keep voltage and frequency at constant values, rotor speed has to be increased with the growth of the generated power, at an almost ideally linear law. The regulation curve of the capacitor has a similar nature, however, it is somewhat more complex, and deviates from linear, especially at higher values of P_L.

These conclusions have great theoretical significance because they show that SEIG can be considered as an equivalent of synchronous generator, if adequate regulation of speed and capacitance is applied simultaneously. While continual regulation of generator's turbine is not especially difficult, practical problems can be expected during the attempt to continually regulate capacitance connected to the stator terminals (using power electronic components such as thyristors, for example). For the sake of reliable operation, it would be more convenient to exploit a discrete type of capacitance regulation, using several carefully chosen steps of total capacitance. This approach could be the subject of a detailed investigation in some future work.

4. Regulation of Voltage Using Only Turbine's Speed Control

Although results presented in the previous section are of significant theoretical importance, sometimes it is not necessary to regulate both voltage and frequency in practical applications. Pure resistive loads (e.g. used in lighting or heating applications) are not sensitive to frequency variations. In such cases, generator could operate with the fixed capacitor bank connected to the stator, while the speed of a turbine still has to be regulated. The purpose of the investigation described in this section was to define single regulation curve $n = f(R_L)$, corresponding only to the criterion $U = U_{ref} = const$, while the stator frequency is allowed to be variable. In order to investigate the manner in which the chosen value of the fixed capacitance affects the described regulation curve, three different computations have been performed, using three different values of capacitance per phase $C_1 = 40\,\mu F$, $C_2 = 30\,\mu F$ and $C_3 = 20\,\mu F$. The results are shown in Figs. 4 and 5.

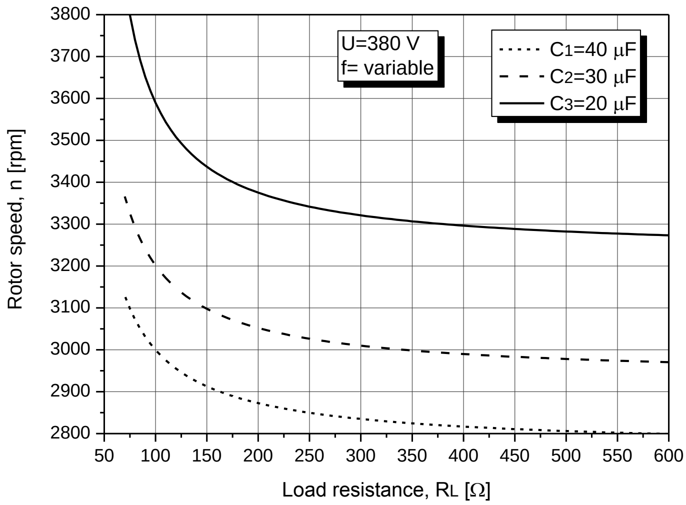

Fig. 4 Computed regulation curves $n = f(R_L)$, while $C = const$, for constant voltage and variable frequency operation

From the Fig. 4 it s clear that applying of appropriate turbine regulation will result in operation with constant voltage, even when capacitance is held at constant value. The basic principle is that the decrease in load resistance has to be followed by the increase of rotor speed. However, the rate of speed increasing is somewhat greater compared to the previously studied case characterized with simultaneous capacitance and speed regulation. This fact can be better observed from Fig. 5, since it is obvious that the desired rotor speed is not a linear function of generated power anymore. This effect is especially emphasized in the region characterized by high values of the generated power, and the lower value of fixed capacitance connected to the stator.

Operation with lower fixed capacitance generally results in greater demands for rotor speed increase, since the complete regulation curve is shifted to the region characterized by higher speed.

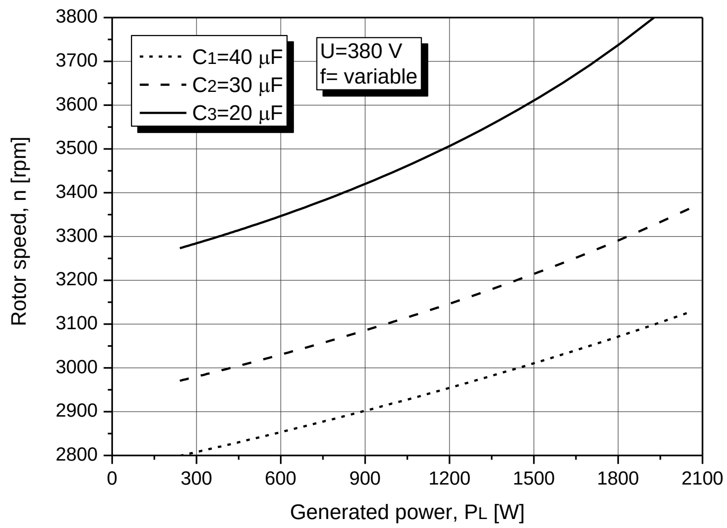

Fig. 5 Computed regulation curves $n = f\,(P_L)$, while $C = const$, for constant voltage and variable frequency operation

Generating electric power at higher values of rotor speed, while using lower values of fixed capacitor bank has certain advantages that can be clearly observed from Fig. 6. Knowing that stator current must not exceed the rated value of $I_n = 3.2\,A$ during the continual operation, it is obvious that with the fixed capacitance $C_1 = 40\,\mu F$ connected to the stator, generator can deliver maximum power of $P_{L1\max} \approx 1.2\,kW$. This value is lower than the rated power for the motoring mode of operation. On the contrary, if the lower value of capacitance $C_3 = 20\,\mu F$ is chosen, stator current is generally lower for any value of the generated power. In other words, for the same value of stator current, generator will be able to deliver more active power to the load. Rated stator current will be reached at $P_{L3\max} \approx 1.8\ \ kW$! This situation can be explained by the fact that at higher rotor speed frequency is also higher. The increased frequency at the constant value of stator voltage consequently results in lower magnetizing current, thus making more of stator's apparent power available for electromechanical conversion.

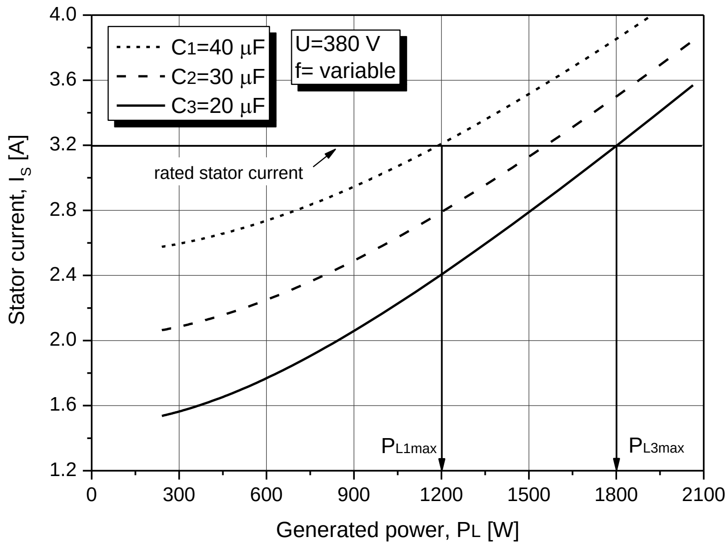

Fig. 6 Computed stator current for constant voltage regulated by speed of a turbine and variable frequency operation

5. CONCLUSION

In this paper we have presented a very simple and efficient method for the computation of regulation curves of self-excited induction generator. The proposed approach is based on the utilization of *Matlab Optimization Toolbox* function *fsolve* which easily generates solutions of a system of three high degree nonlinear equations. The method of calculation is universal and can be applied to any induction machine with the known parameters of the equivalent circuit, resulting in the identification of regulation curves.

At the first part of investigation we have studied the possibility of simultaneous voltage and frequency control, by means of continual control of turbine speed and total capacitance connected to the stator. The desired regulation curves have been successfully identified and results have shown that, if proper control system is applied, self-excited induction generator can operate with performance characteristics equivalent to any synchronous generator. This conclusion at the first line regards the fact that even with variable resistive load connected to the stator, electric power can be generated at constant voltage and frequency.

We have further investigated a simplified method of control, considering constant voltage but variable frequency operation. The results of this investigation have shown that generator's voltage could be kept at the desired value if the increase of electric load was followed by adequate increase of rotor speed, even if excitation capacitor had a constant value. Another important conclusion originating from this part of investigation is that generator can deliver more active power if a lower value of fixed excitation capacitance is chosen. On the other hand, direct consequence of such a choice is the demand for operation at higher rotor speed.

Although th e exact regulation system has not been proposed in this paper yet, authors strongly believe that the presented results are of great significance for the future work.

Further investigation will be directed towards the development and synthesis of new types of reliable, low-cost automatic control systems for practical application in self-excited induction generators.

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