Elaboration of the Minimum Capacitor for an Isolated Self Excited Induction Generator Driven by a Wind Turbine

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Abstract: In this paper, a detailed procedure is elaborated, based on evaluation of the roots in the characteristic equation of the stator current, to determine the proper capacitor bank that will be used to reach the self-excitation. For that, a d-q model of the self-excited induction generator under no load is presented using Matlab-Simulink to verify if the self-excitation comes true or not. This study illustrates furthermore, the influence of the magnetizing inductance on the voltage buildup.

1 INTRODUCTION

A wind turbine with Self-excited Induction Generator SEIGs is a subject that is gaining renewed interest with the increasingly frequent use of the asynchronous generator. In the field of renewable energies, in general, and that of wind turbines, in particular, has largely contributed to the development of the induction machine as a Self-excited Induction Generator thanks to its several advantages such as: very reliable and relatively inexpensive compared to other types of generators. It also has some mechanical characteristics which makes it very suitable for the conversion of wind energy (sliding of the generator as well as a certain capacity of overload), very high lifetime; non-existent maintenance (bearings ...), very simple, rugged, and produces high power per unit mass (N. M. Okana and al., 2015), (A.Abbou and al., 2013).
The self excited machine, in its operation in generator mode, poses a particular problem : it cannot start itself as a generator and needs an external source to perform this operation which is called self-excitation : it requires excitation current to magnetize the core and produce the rotating magnetic field. This current is supplied from an external source, for grid connected systems; however, this current is supplied from a battery of capacitors, for isolated system which is our case. When a charged capacitor is connected and the generator is driven by a prime mover, a transient exciting current will flow and produce a rotated magnetic flux, so as a result, the power will be generated and supplied to the external source.
Several approaches have been reported in previous studies to determine the sufficient value of the capacitance to stimulate a self excited induction generator (A.K and al., 1990), (N.H.Mal and al., 1986), (N.H.Malik and al., 1987), (M.Orabi and al., 2000), (S.S.Murthy al., 1982). Most of these approaches apply loop equations in the steady state model of per phase equivalent circuit such us : Nodal Admittance Approach, Loop Impedance Approach, and LC Resonance Principal. These kinds of approaches give the appropriate capacitance corresponding to the minimum capacitance in steady state analysis, but they are inapplicable for transient analysis.
The main purpose of this study is to present a new approach to determine the minimum capacitance required for excitation in a SEIG. For this, we should, first look behind its process and extract an accurate algorithm that will serve us to achieve the aim. For this, we have, first, recalled the basic concepts for modelling of RLC circuit, since this one is similar to the self-excited induction generator. Then, a review of the characteristic stator equation of the SEIG, the roots of this equation is discussed as well as the choice of the accurate capacitance.

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2 SELF EXCITED INDUCTION MACHINE

Basically, the mathematical model per phase of the self-excited induction generator is similar to the classical induction motor; the only difference is that the SEIG has a battery of capacitors linked to the stator terminal.

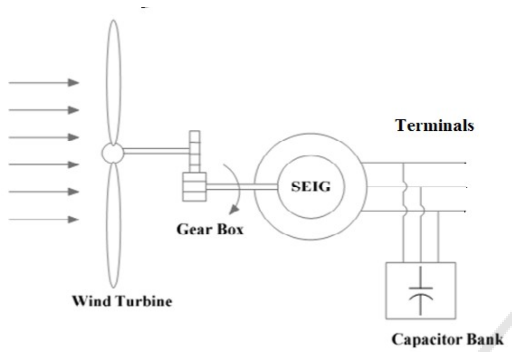

Figure 1: SEIG with a capacitor connecting across the stator terminal.

The equivalent circuit representation of an asynchronous machine is proper to use for steady state analysis. Nonetheless, the Park representation is used to model the SEIG beneath dynamic conditions.

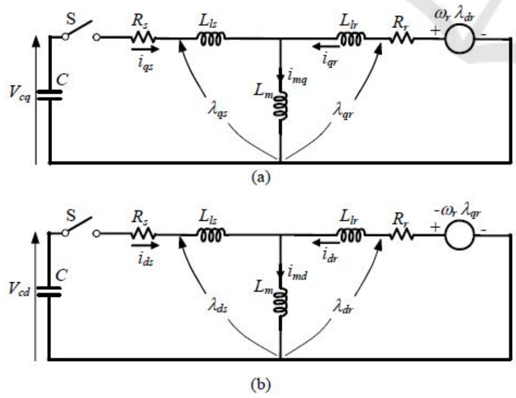

Figure 2: Park representation of the self induction generator in stationary frame (a) q-axis, (b) d-axis.

2.1 Modelling of the SEIG under No Load

Using the d-q representation in Figure 2, the induction machine can be modelled by equations (1) to (10),

From the stator side :

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{1}$$
$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{2}$$
$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \tag{3}$$
$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \tag{4}$$

From the rotor side :

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \tag{5}$$
$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \tag{6}$$
$$V_{dr} = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} + \omega_r \lambda_{qr} \tag{7}$$
$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} - \omega_r \lambda_{dr} \tag{8}$$

For the air gap flux linkage side :

$$\lambda_{dm} = L_m i_{ds} + L_m i_{dr} \tag{9}$$
$$\lambda_{qm} = L_m i_{qs} + L_m i_{qr} \tag{10}$$

The matrix equation for the d-q model of a self excited induction generator in the stationary stator reference frame using the SEIG model is given by (11).

$$\begin{pmatrix} R_s + pL_s + \frac{1}{pC} & 0 & pL_m & 0 \\ 0 & R_s + pL_s + \frac{1}{pC} & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_m \\ \omega_r L_m & pL_m & \omega_r L_m & R_r + pL_r \end{pmatrix} \begin{pmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{pmatrix} + \begin{pmatrix} V_{cq0} \\ V_{cd0} \\ -K_{qr} \\ K_{dr} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{11}$$

2.2 Analogy between RLC Circuit and SEIG

Basically, an induction machine can be modelled using RLC circuit elements. In fact, the behaviour and analysis of the self-excited induction generator is similar to an RLC circuit.

2.2.1 RLC Circuit Approach

Energy can be stored in an inductor as well as in a capacitor, at t = 0, two initial conditions, current might have been flowing in an inductor or initial voltage exist in a capacitor.

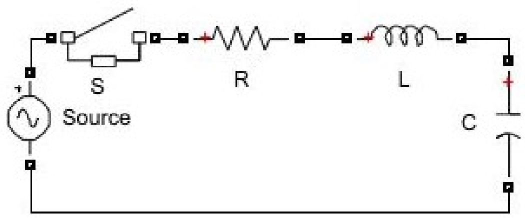

Figure 3: RLC circuitl.

Switch S is close : i(t) = 0; the voltage equation :

$$V_{co} = Ri(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)d(t) \tag{12}$$

Introducing the p operator (12) can be written as :

$$i(t) = \frac{pV_{co}}{pR + Lp^2 + \frac{1}{C}} \tag{13}$$

The characteristic equation is :

$$0 = pR + Lp^2 + \frac{1}{C} \tag{14}$$

The roots of this equation are :

$$p_1 = -\frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \tag{15}$$

$$p_2 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \tag{16}$$

If we suppose that :

$$\frac{R}{2L} \leq \frac{1}{LC}$$

Then the roots are complex, and can be expressed as :

$$p_1 = \psi + j\Omega \tag{17}$$

$$p_2 = \psi - j\Omega \tag{18}$$

ψ is always negative because the resistance R is positive, as result, with positive R will be a dampening of oscillation, the real part ψ represents the rate at which the transient decays, and Ω the imaginary part represents oscillation frequency.
In passive circuit like RLC all transient solutions have a negative ψ meaning that transient is reduced with the progression of time and finally will dampen to zero.

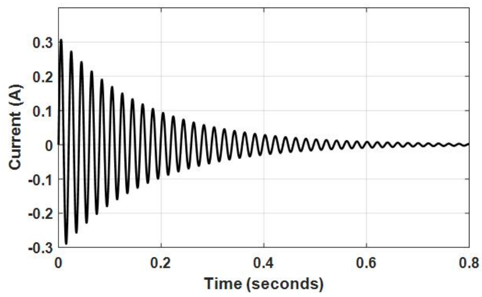

Figure 4: progression of current for a positive resistance value.

However, if ψ is positive, this implies the transient is growing with the progression of time.

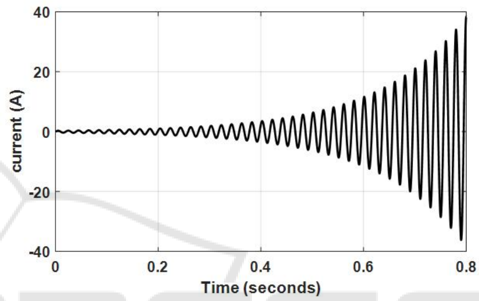

Figure 5: progression of current for a negative resistance value.

We can describe the self-excitation in an induction generator as the growth of current and the associated increase in the voltage across the capacitor without an external excitation system.
Transients that grow in magnitude (self-excitation) with positive real part of the roots can only be happening if there is an external energy source that is able to cover all the losses associated with the rising current, the SEIG is able to have a growing transient because of the external mechanical energy source.

2.2.2 Projection of the RLC Approach on the SEIG

We can deal with the circuit of the SEIG by using the same approach as well as the circuit of the RLC.

The matrix (11) can be written as :

$$\begin{pmatrix} R_s + pL_s + \frac{1}{pC} & 0 & pL_m & 0 \\ 0 & R_s + pL_s + \frac{1}{pC} & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_m \\ \omega_r L_m & pL_m & \omega_r L_m & R_r + pL_r \end{pmatrix} \begin{pmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{pmatrix} = \begin{pmatrix} -V_{cq0} \\ -V_{cd0} \\ K_{qr} \\ -K_{dr} \end{pmatrix} \tag{19}$$

When a balanced three phase system is transformed into a two-axis system, the stator currents i_{qs} and i_{ds} have similar waveforms.

$$i_{qs} = \frac{numerator}{k_8p^8 + k_7p^7 + k_6p^6 + k_5p^5 + k_4p^4 + k_3p^3 + k_2p^2 + k_1p^1 + k_0p^0} \tag{20}$$

The characteristic equation of the current can be obtained from the expression of the current transfer function (20).

$$k_8p^8 + k_7p^7 + k_6p^6 + k_5p^5 + k_4p^4 + k_3p^3 + k_2p^2 + k_1p^1 + k_0p^0 = 0 \tag{21}$$

With :

$$k_8 = A^2$$
$$k_7 = 2AB$$
$$k_6 = 2ADB^2$$
$$k_5 = 2BD + AE$$
$$k_4 = 2AF + 2BE + D^2 + G^2$$
$$k_3 = 2BF + 2DE$$
$$k_2 = 2DF + E^2$$
$$k_1 = 2EF$$
$$k_0 = F^2$$

And :

$$A = C\left(L_r^2L_s - L_m^2L_r\right)$$
$$B = C\left(L_r^2R_s + 2R_rL_rL_s - L_m^2L_r\right)$$
$$D = C(2R_rR_sL_r + (R_r^2 + \omega_r^2 + L_r^2)L_s - L_m^2\omega_r^2L_r) + L_r^2$$
$$E = CR_s(R_r^2 + \omega_r^2 + L_r^2) + 2R_rL_r$$
$$F = R_r^2 + \omega_r^2 + L_r^2$$
$$G = CL_m^2R_r\omega_r$$

This characteristic equation for the current can be solved using different ways, for our case, the roots are obtained numerically using the root function in Matlab.
When (21) is factorized, it gives :

$$(p - \psi_1 + j\Omega_1)(p - \psi_1 - j\Omega_1)$$
$$(p - \psi_2 + j\Omega_2)(p - \psi_2 - j\Omega_2)$$
$$(p - \psi_3 + j\Omega_3)(p - \psi_3 - j\Omega_3)$$
$$(p - \psi_4 + j\Omega_4)(p - \psi_4 - j\Omega_4) = 0 \tag{22}$$

If any of the roots in the equation has a positive real value, then there is a self-excitation. To determine the required capacitor for an induction generator running at the given rotor speed, the roots values are computed by increasing the capacitor value until one of the real parts of the roots becomes positive.

2.3 Algorithm to Determine the Minimum Capacitance

In order to determine the accurate capacitor value, an algorithm is elaborated and programmed using Matlab as shown in flow chart figure 6 :

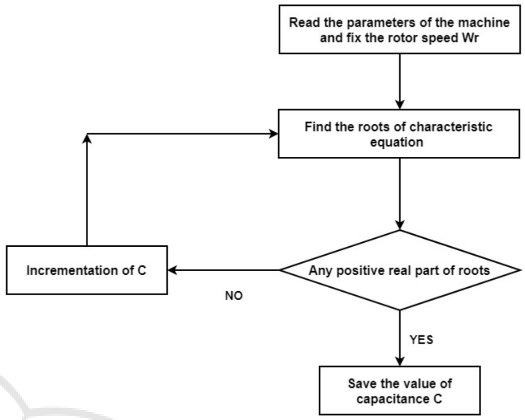

Figure 6: Flow chart to determine the minimum capacitance at a given rotor speed at no load.

The minimum capacitance required for a given rotor speed of induction generator, can be found by fixing the rotor speed and then increasing the value of the capacitance until one of the real parts of the roots becomes positive. The value of capacitance makes that happen is the minimum value of capacitance required for self-excitation.

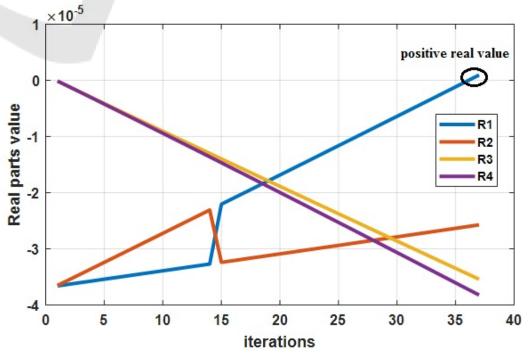

Figure 7: progression of real part value when capacitance C increased.

As it is shown in figure 7 all the real parts of the roots start with a negative value, so the waveform will dampen with time and there will be no transients. After some iterations, the algorithm returns one of the real part greater than zero and that by determining the appropriate capacitance value that makes the self-excitation achieve.

2.4 Characteristic of Magnetizing Inductance

In the modelling of an induction machine, it is essential to determine the magnetizing inductance Lm at rated voltage and rated frequency. In the SEIG, the variation of Lm is the major element in voltage build up and its stabilization. Magnetizing inductance is determined by driving the asynchronous machine at synchronous speed and taking measurements when the applied voltage was varied from zero to 120% of the rated voltage. The variation of Lm measured at rated frequency of the induction machine used in this study is given by (B.Singh al., 1998) :

$$L_m = 0.00016 I_m^3 - 0.002 I_m^2 + 0.005 I_m + 0.205 \quad (23)$$

The expression of Lm is elaborated experimentally as a function of magnetizing current Im, however, in this investigation, we are looking for the expression of magnetizing inductance as a function of voltage V_0, for that, we use equations below to convert from L_m = f(I_m) to L_m = f(V_0).

$$Z_0 = \sqrt{R_s^2 + ((L_s + L_m)2\pi f)^2} \quad (24)$$

$$V_0 = Z_0 I_m \quad (25)$$

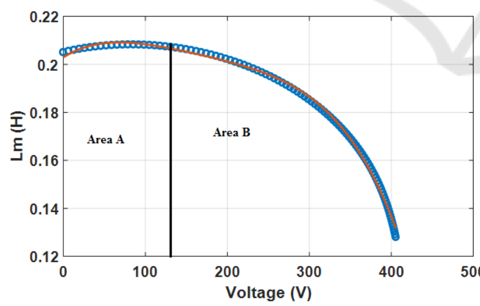

Figure 8: variation of Lm as function of voltage.

Where the blue dots are experimental results and the red curve is a fourth order curve fit given by :

$$L_m = -0.003 V_0^4 - 0.01 V_0^3 - 0.013 V_0^2 - 0.02 V_0 + 0.19$$

The magnetizing inductance varies with voltage as shown in Figure 8. At the start of self-excitation where the voltage is near to zero, Lm is close to 0.205H. Once self-excitation begins, the generated voltage will develop and thenL_m also increases. When there is an increase in L_m, it increases the value of the positive real root of the characteristic equation and consequently the generated voltage grows faster. Then, L_m decreases while the voltage continues to grow until it reaches its steady state value determined by : the L_m value, capacitance and the rotor speed.

2.5 Impact of Lm on Voltage Build-up

According to the previous figure, we can divide the curve in stable an instable area B and A. If the SEIG starts to generate in region A, a small loss in speed will cause a drop in voltage and this will bring a decrease in L_m, which in turn decreases the voltage, and finally the voltage will dampen to zero. Once the voltage dampens, there is no transient phenomenon and there will not be voltage build up even if the speed increases once again to its initial value as shown in figure 9.

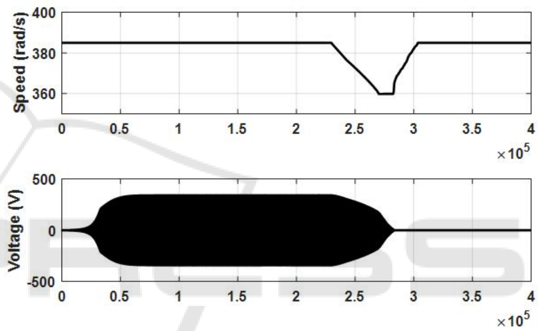

Figure 9: decrease in rotor speed and its effect on generation of voltage in the unstable area A.

Area B is a stable operating region. When the speed of the prime mover decreases, voltage will decrease, and L_m increases, which yield the SEIG to continue to operate at a lower voltage as shown in Figure 10.

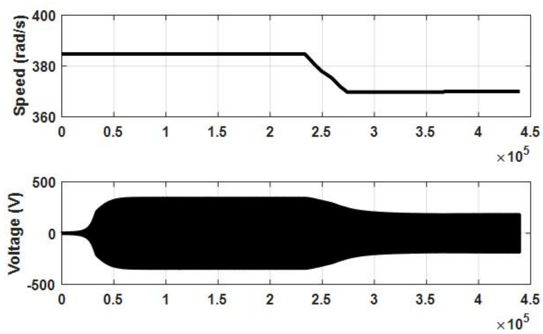

Figure 10: reduction of the rotor speed and its impact on generation of voltage in the stable area B.

The growth in L_m means an increase in the positive real roots of the characteristic equation.

3 SIMULATION RESULTE

The induction machine used as the SEIG in this study is a three-phase induction motor with specifications (APPENDIX-table 1). When the induction machine is driven by a prime mover, the voltage will start to develop at a corresponding minimum capacitance at a giving rotor speed. This capacitance is obtained by solving the roots of the 8th order polynomial equation given by (21) and then searching if there is a positive real part of the roots. The curve in figure 11 gives the values of minimum capacitance at different rotor speed at no load.

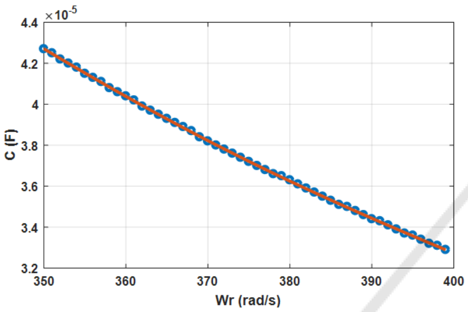

Figure 11: minimum capacitance as function of rotor speed at no load.

In this investigation, the minimum capacitance required has a value of 35.3 μF . The figure 12 shows the progression of different waveform of current and voltage of the SEIG.

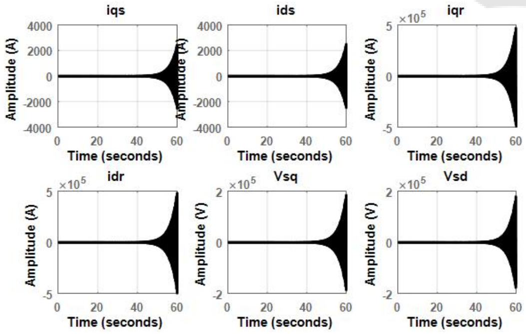

Figure 12: progression of current and voltage waveform with capacitance value C = 35.3 μF.

As we notice the transients are growing with the progression of time, in theory, these transients will increase to infinity, but in this case, it will increase until the circuit is saturated so the self-excitation is achieved. If we reduce the capacitance value from 35.3 μF to 30.5 μF the self-excitation does not come true as shown in figure 13, and this value of 30.5 μF yield to a characteristic equation with roots which have a negative real part.

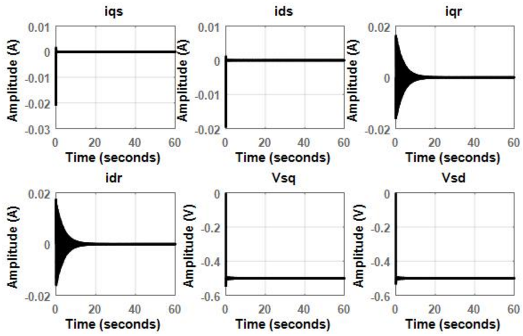

Figure 13: progression of current and voltage waveform with capacitance value C = 30.5 μF.

In order to visualize the voltage, a Simulink model of the SEIG at no load is developed using matrix (19) as shown in figure 14, this model gives us the possibility to visualize the dynamic of our system and the impact of capacitance value on voltage build up.

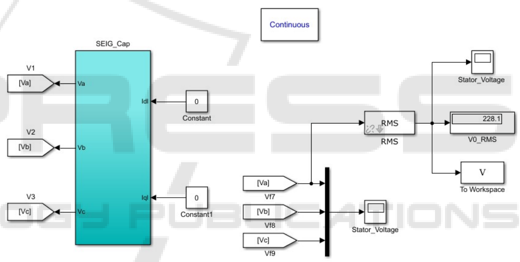

Figure 14: model of the SEIG at no load.

The voltage curve is given by the figure 15. According to this curve, we can notice that we have a voltage build up at the choosing rotor speed and this validate the value of capacitance giving by the algorithm developed in this study.

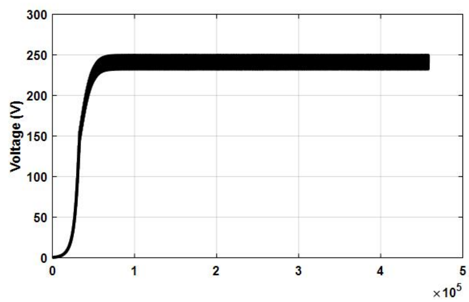

Figure 15: voltage progression of the SEIG at no load with capacitance value of C = 35.3 μF.

To confirm that 35.5 μF is the minimum value, we reduce another time the capacitance value to 30.5 μF. The figure 16 shows that the voltage collapses because the loss of the self-excitation phenomenon and that return to the roots of the characteristic equation.

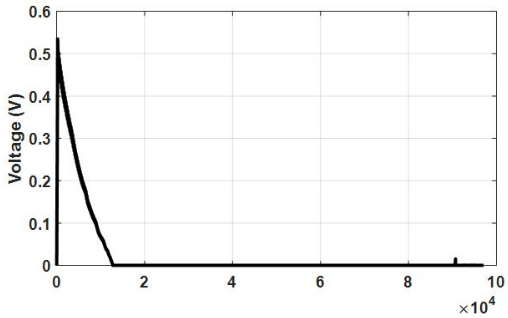

Figure 16: none build-up of the voltage of the SEIG at no load with capacitance Value of C = 30.5 μF.

4 CONCLUSION

In this study, a simple algorithm is proposed to obtain the minimum requirement of the capacitance for self excited induction generator under no-load conditions for different speeds. This study demonstrates, also, how excitation capacitance and prime mover speed affect the steady state performance of SEIG. The minimum value of the excitation capacitor must be properly calculated in order to assure an effective starting of the SEIG. Furthermore, it was concluded that SEIG has a critical excitation capacitor value at constant rotor speed. We notice that the output voltage magnitude follows the variation of the rotor speed, decreasing the rotor speed will lead to decrease the output voltage. This reveals the voltage regulation issue of the self-excited induction generator when it is used for wind application. Consequently, if our steady state point is located in the stable area of Lm curve, we can have proportionally between voltage and rotor speed, however, if we are located in the instability area a decrease in rotor speed will lead to a collapse of the voltage, thereafter, demagnetization of our induction machine.

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APPENDIX

Rated power	15 KW
Voltage	440V Y
Frequency	50 Hz
Pair pole	4
Rated speed	385 rd/s
Stator resistance	0.696 Ω
Rotor resistance	0.743 Ω
Inductance stator	1.1 mH
Inductance rotor	1.1 mH

Table 1: Induction generator parameters.