Analysis of an Enhanced SEIG Model Including Iron Losses

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Abstract: This paper presents an enhanced dynamic model of a self-excited induction generator (SEIG) with iron losses. The iron losses are represented in the induction machine model with an equivalent resistance connected in parallel with the magnetizing reactance. Since these losses vary with the air-gap flux and the stator frequency, a series of no-load tests were performed using sinusoidal supply of various frequencies to determine this variation. The air-gap flux influence on the iron losses can be expressed by means of the corresponding iron loss current. Consequently, an enhanced induction generator model, including the equivalent iron loss resistance as a function of both stator frequency and iron loss current, was built in the MATLAB Simulink environment. In addition, this is, to the best knowledge of the authors, the first SEIG model which includes variable iron losses that is entirely built in MATLAB Simulink. The performance of the proposed model is analyzed through simulation under various operating conditions and compared with the conventional SEIG model in which the iron losses are neglected. Theoretical results obtained from the proposed model have been verified experimentally. It is shown that neglecting the iron losses could cause severe inaccuracies in the SEIG analysis, especially when a SEIG is driven by a variable speed prime mover such as wind turbine.

Key- Words: Self-excited induction generator, Efficiency, Iron losses, Wind turbine

1 Introduction
In general, a SEIG is an induction generator with capacitor excitation. Self-excitation process has been known since the 1930s [1], [2]. However, only recent research and developments spurred the growing global interest for a more effective utilization of SEIGs, particularly in stand-alone applications that employ wind or hydro power [3]. In such applications, of power up to 100 kW, induction generators offer several advantages compared with the conventional synchronous generators as can be found in [4]. On the other hand, they are characterized by poor voltage and frequency regulation and by low power factor.

In order for self-excitation to occur, an induction generator has to be driven by a prime mover and, additionally, a suitable capacitance has to be connected across the stator terminals. The process of the voltage build-up occurs until the voltage settles at a certain value, which is, for given speed and capacitance values, mainly determined by the magnetizing saturation. At no load, for a particular capacitance value, a corresponding minimum speed is defined and vice versa [1], [5]. Once the SEIG is loaded, because of a non-zero slip, both frequency and magnitude of the terminal voltage change, even if the speed of the prime mover is kept constant.

This paper focuses on the effect the iron losses have on the SEIG’s performance at various operating conditions. Often, for the sake of convenience, the iron losses are completely omitted from the SEIG’s performance analysis. However, even in the machines with low amount of iron losses, their impact is not negligibly small. Moreover, because of the detuning effect, neglecting the iron losses is not suggested if some kind of vector control system is utilized, as reported in [6]. While few works have been reported in which the iron losses are included in steady state or d-q axis models of a SEIG [3], [7], none of them considers the noteworthy influence of the stator frequency variation on the iron losses. In order to give a more accurate prediction of a SEIG’s performance, it is particularly important to consider this influence when a SEIG is driven by a variable speed prime mover. In this paper, an enhanced induction generator model, in which the iron losses are represented as a function of both air-gap flux and stator frequency, is proposed and analyzed.

2 Enhanced SEIG Model with iron losses
The iron losses are usually represented in the induction machine model with an equivalent resistance $R_m$ connected in parallel or in series with the magnetizing
reactance $X_m$ where the power loss of the equivalent resistance is equal to the total iron losses in the induction machine. Fig. 1 presents the conventional stationary reference frame ($\alpha$-$\beta$) model of an induction machine with the equivalent iron loss resistance added across the magnetizing branch. In addition, a parallel combination of an excitation capacitor and a resistive load is connected at the stator terminals. The load is connected across the capacitor through the switch $S$. However, the SEIG is always started at no load and it is loaded only when the steady state is reached.

![Stationary reference frame model of SEIG with equivalent iron loss resistance $R_m$](image)

Fig. 1 Stationary reference frame model of SEIG with equivalent iron loss resistance $R_m$

The mathematical model of an induction machine, obtained from Fig. 1, is presented by the following set of equations in the stationary $\alpha$-$\beta$ reference frame:

\[ u_{sa} = R_s i_{sa} + \frac{d\psi_{sa}}{dt} \]
\[ u_{sb} = R_s i_{sb} + \frac{d\psi_{sb}}{dt} \]
\[ 0 = R_s i_{ra} + \frac{d\psi_{ra}}{dt} + \omega_r \psi_{rb} \]
\[ 0 = R_s i_{rb} + \frac{d\psi_{rb}}{dt} - \omega_r \psi_{ra} \]
\[ \psi_{sa} = L_{soa} i_{sa} + L_{sm} i_{ra} \]
\[ \psi_{sb} = L_{soa} i_{sb} + L_{m} i_{rb} \]
\[ \psi_{ra} = L_{soa} i_{ra} + L_{m} i_{rb} + \psi_{rho} \]
\[ \psi_{rb} = L_{soa} i_{rb} + L_{m} i_{ra} + \psi_{rho} \]
\[ R_m i_{Rma} = L_m \frac{di_{ma}}{dt} \]
\[ R_m i_{Rmb} = L_m \frac{di_{mb}}{dt} \]
\[ i_{ma} + i_{Rma} = i_{sa} + i_{ra} \]
\[ i_{mb} + i_{Rmb} = i_{sb} + i_{rb} \]

\[ T_e = \frac{3}{2} p \frac{L_m}{L_r} \left[ \psi_{ra} (i_{sb} - i_{Rmb}) - \psi_{rb} (i_{sa} - i_{Rma}) \right] \]

where:

$u_{sa}$, $u_{sb}$, $i_{sa}$, $i_{sb}$, $\psi_{ra}$ and $\psi_{rb}$ are $\alpha$ and $\beta$ components of the stator voltage space-vector, the stator current space-vector and the stator flux linkage space-vector, respectively;

$I_{Rma}$, $I_{Rmb}$, $i_{ma}$ and $i_{mb}$ are $\alpha$ and $\beta$ components of the iron loss current space-vector and the magnetizing current space-vector, respectively;

$R_s$, $R_r$ and $R_m$ are the stator, rotor and iron loss resistance, respectively;

$L_{soa}$, $L_{soc}$ and $L_m$ are the stator leakage inductance, the rotor leakage inductance and the magnetizing inductance, respectively;

$\omega_r$ is the rotor angular speed expressed in electrical radians per second;

$T_e$ is the induced electromagnetic torque and $p$ is the number of the pole pairs.

In Eq. (4), $\psi_{rho}$ and $\psi_{rho}$ represent the residual rotor flux linkages along the $\alpha$ and $\beta$ axis, respectively.

The capacitor and load voltages are equal to the stator voltages and can be expressed as follows:

\[ u_{ca} = u_{sa} = \frac{1}{C} \int i_{ca} dt + u_{stao} \]
\[ u_{cb} = u_{sb} = \frac{1}{C} \int i_{cb} dt + u_{stbo} \]
\[ u_{Lr} = u_{sa} = R_i i_{Lr} \]
\[ u_{Lb} = u_{sb} = R_i i_{Lb} \]

where $u_{stao}$ and $u_{stbo}$ are the initial voltages along the $\alpha$ and $\beta$ axis capacitors, respectively, $C$ is the excitation capacitance and $R_i$ is the resistive load.

Furthermore, the stator currents can be expressed as the sum of the respective load and capacitor currents

\[ i_{sa} = i_{Lr} + i_{ca} \]
\[ i_{sb} = i_{Lb} + i_{cb} \]

The only additional data required in realization of the proposed model, by comparison with the conventional model, is the value of the equivalent iron loss resistance.

### 2.1 Determination of $R_m$ as iron loss current and stator frequency dependent parameter

As previously mentioned, if an induction generator is operating at variable flux levels and speeds, the iron loss resistance $R_m$ should be represented as a function of both stator frequency and air-gap flux. The air-gap flux influence on the iron losses is expressed by means of the iron loss current. The equivalent iron loss resistance has
to be identified experimentally. Hence, a series of standard no-load tests at various frequencies were performed to determine the aforementioned dependency. A synchronous generator, driven by a DC motor, was used to obtain sinusoidal supply at the induction machine terminals. The measured data were obtained by means of both Fluke 435 power quality analyzer and conventional analog ammeters, voltmeters and wattmeters. Frequencies encompassed within performed tests were from 10 Hz to 60 Hz.

In general, the iron losses found from no-load testing may be used for assessing performance during loading when an induction machine is driven up to rated load. The equivalent iron loss resistance and magnetizing reactance were identified from the measured data as described in [8]. Once when $R_m$ is identified in the frequency range of interest, it becomes possible to express it as both stator frequency and iron loss current dependent parameter. Obtained characteristics of $R_m$ versus no-load iron loss current $I_{Rno}$ with the operating frequency as parameter, are presented in Fig.2.

Consequently, final $L_m$ versus $I_m$ characteristic is given as an approximation of the measured characteristics as defined in [9] and [10]. Constant unsaturated value of the magnetizing inductance ($L_m^0$) is set as equal to 0.4058 H. However, SEIG’s equilibrium point is always located somewhere in the saturated part of the characteristic.

### 2.3 Simulink Model of SEIG

From Eqs. (1)-(6) and using Laplace transformation, four 2nd order differential equations are obtained as follows:

$$s^2 i_{s_{\alpha}} = \left( \frac{R_s}{L_{\alpha s}} + \frac{R_m}{L_m} \right) i_{s_{\alpha}} - \frac{R_m}{L_m} u_{s_{\alpha}}$$

$$s^2 i_{r_{\beta}} = \left( \frac{R_s}{L_{r_{\beta s}}} + \frac{R_m}{L_m} \right) i_{r_{\beta}} - \frac{R_m}{L_m} u_{r_{\beta}}$$

$$s^2 i_{s_{\beta}} = -\frac{R_m}{L_m} i_{s_{\beta}} - \frac{1}{L_{\alpha s}} u_{s_{\beta}}$$

$$s^2 i_{r_{\alpha}} = -\frac{R_m}{L_{r_{\alpha s}}} i_{r_{\alpha}} - \frac{1}{L_{r_{\alpha s}}} u_{r_{\alpha}}$$

where $K_{\alpha}$ and $K_{\beta}$ are constants, which represent the initial induced voltages due to residual magnetizing flux.

**Fig.3** Measured $L_m$ versus $I_m$ characteristics

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in the iron core along the α and β axis, respectively. Similar set of equations is given in [7], but it contains several algebraic sign errors which have been corrected.

Using Eqs. (11)-(14) simulation model of a SEIG is built in MATLAB Simulink environment. This is, to the best knowledge of the authors, the first SEIG model including variable iron losses that is entirely built in Simulink. The “SEIG-Rm” subsystem block, which represents the induction generator, is presented in Fig.4. Inputs to this block are \( \omega_r, K_{r_m}, K_{\phi_f}, u_{rs}, u_{ds}, C \) and \( R_{L_s} \), while the outputs are \( u_{ms}, u_{ds}, i_{sm}, i_{sd}, l_{r_m}, l_{r_f} \) and \( T_e \). The initial voltages along the α and β axis, the rotor speed and the capacitance are all presented by means of constant value blocks, while loading of the generator is implemented by means of a step function block. The stator angular frequency \( \omega_s \) is obtained by derivation of the stator voltage space-vector angle.

The equivalent iron loss resistance is obtained as the iron loss current used as the inputs. However, it is not advisable to use the minimum capacitance value because any change in load or rotor speed values may result in loss of excitation, while economically and technically it is not advisable to choose excessive capacitance values. In this paper, about 25% overestimated capacitances are used.

\[
C_{\text{min}} \approx \frac{1}{\omega r^2 L_m}. \quad (15)
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3.1 Simulation Results

The following simulation was carried out: the rotor speed is fixed at 140 rad/s and at \( t = 3 \) s, the SEIG is loaded with the resistive load of 150 Ω. The capacitance is fixed at 40 µF. Initial voltages along the α and β axis are fixed at 5 V.

The results obtained from running the simulation are shown in Figs. 5 to 9. It can be seen from Fig.5 that the inclusion of the iron losses into the model extends the magnetization process (about 0.4 s longer) and reduces the generated voltage magnitude. The maximum steady state difference between the two stator voltage space-vector magnitudes occurs while the SEIG is loaded and it is equal to 2.75 %. Moreover, there is a notable decrease of the stator voltage space-vector magnitudes (about 16 %) due to loading. The maximum steady state difference between the two stator current space-vector magnitudes also occurs while the SEIG is loaded and it is equal to 3.1 %. As it can be seen from Fig.7, inclusion of the iron losses increases the rotor current space-vector magnitude. However, this current is considerably smaller than the stator current and, hence, it has a considerably smaller impact on the overall losses.

In addition, SEIG’s efficiency is calculated as the ratio between the electrical output power and the shaft input power. Hence, the calculated efficiencies are 87.1 % for the conventional model and 74.7 % for the proposed model. This large efficiency deterioration of 12.4 % is due to iron losses only.

Similar results were obtained with different simulated rotor speeds, capacitances and loads, but were not included in this paper due to the paper size limitation.

3 Performance Analysis of the Enhanced SEIG Model

In order to evaluate the validity of the proposed SEIG modeling approach, performance of the proposed simulation model is analyzed under various operating conditions and compared with the conventional SEIG model in which the iron losses are entirely neglected. In addition, in order to determine the level of the analysis accuracy, the proposed model is verified experimentally. Parameters of the induction machine used as the SEIG in this investigation are given in Appendix.

The approximate minimum capacitance value required for self-excitation to occur under no load conditions can be calculated as follows, [7]

\[
C_{\text{min}} \approx \frac{1}{\omega r^2 L_m}. \quad (15)
\]

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In general, when $R_m$ is neglected, generated voltage and output power of a SEIG are higher than for the case when $R_m$ is included. However, in this paper, the highest difference between the generated voltage/current magnitudes obtained for the SEIG used in this investigation is within 5 %, which can be interpreted as negligible.

### 3.2 Experimental Results

The following experiment was carried out: the rotor speed is held constant at 126 rad/s and at $t = 4$ s, the SEIG is loaded with the resistive load of 221 Ω. The capacitance is fixed at 50 µF.

Experimentally obtained results are shown in Figs. 10 to 12. All of the measured quantities were collected by means of the digital signal processor (dSpace DS1104 microcontroller board). In addition, the above mentioned operating regime was also simulated by using both conventional and proposed model. As it can be seen from Figs. 11 and 12, there is a certain discrepancy between the measured and simulated voltages and currents due to additional losses in the actual machine and even due to inaccurately defined initial voltages. However, the discrepancy is evidently smaller within the proposed model. The maximum steady state difference between the measured stator voltage space-vector magnitude and the one obtained from the proposed model occurs while the SEIG is loaded and it is equal to 5.53 %. The maximum steady state difference between the measured stator current space-vector magnitude and the one obtained from the proposed model also occurs while the SEIG is loaded and has a percentage value of 5.32 %. The stator voltage space-vector magnitudes are decreased due to loading by 10.16 % - obtained from the measurement and by 8.69 % - obtained from the proposed model. Connecting the load at the stator terminals resulted in the 2 % speed transient drop and, consequently, in the 5.6 % voltage magnitude undershoot. In simulations, the speed is held constant regardless of the load connected and, hence, no voltage undershoot occurred.
Conclusion

In this paper, a new approach in modeling the iron losses of an induction generator is suggested, resulting in an enhanced SEIG model in which the iron losses are represented as a function of the stator frequency and the iron loss current. The proposed model of a SEIG was built in Simulink and it is, probably, the first such model. Based on the carried simulations several important conclusions are drawn.

Significance of taking the iron losses into account is most emphasized when analyzing the impact they have on the overall efficiency. Because of the impact they can have on the efficiency, inclusion of the iron losses into the model is mandatory when analyzing a SEIG’s efficiency. In order to obtain more accurate representation of the iron losses, it is also important to express them not only as a function of the air-gap flux, i.e. the iron loss current, but also as a function of the stator frequency, especially when it varies considerably.

On the other hand, if only generated voltages and currents are of interest, the conventional SEIG model could be used instead.

Finally, the comparison has showed a remarkable agreement between the simulation and experimental results.

Appendix (Induction machine parameters):

\[ P_n = 1.5 \text{ kW}, \quad U_n = 380 \text{ V}, \quad p = 2, \quad Y, \quad I_n = 3.81 \text{ A}, \]
\[ n_n = 1391 \text{ r/min}, \quad L_m' = 0.4058 \text{ H}, \quad L_{as} = 0.01823 \text{ H}, \]
\[ L_{or} = 0.02185 \text{ H}, \quad R_s = 4.293 \Omega, \quad R_r = 3.866 \Omega \text{ (at 20 °C)}, \]
\[ T_n = 10.5 \text{ Nm}, \quad J = 0.0071 \text{ kgm}^2. \]

References: