An Accurate Efficiency Calculation of Self-excited Induction Generator Including Effects of All Machine Parameters

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Abstract. In this paper an accurate method for efficiency calculation of self-excited induction generator (SEIG) at different operating conditions is proposed, considering the effect of stator and rotor iron core losses, stator and rotor circuits stray load losses, stator and rotor winding (copper) losses, mechanical losses, skin-effect losses, and skew-effect losses. The proposed procedure of efficiency calculation is based on the conventional machine tests such as no-load test, load test at variable supply voltage and temperature test without additional measurements. From these conventional tests, all the SEIG losses can be calculated accurately by their related formulas derived based on the SEIG equivalent circuit. The reduction of these losses causes an increase in the SEIG percentage efficiency, and this is a very important feature in electric energy saving by minimization of SEIG equivalent circuit components.

1. Introduction
The induction machine data of efficiency is provided by test and calculation procedures used by international standards, and the stray load losses represent an important key for accurate machine efficiency evaluation [1].

The efficiency of an electric SEIG represents the machine behavior during the energy conversion from mechanical power to electrical power, and can be defined as [1]:

\[ \eta = \frac{P_{\text{electrical}}}{P_{\text{mechanical}}} = \frac{P_{\text{electrical}}}{P_{\text{electrical}} + \text{total losses}} \]  

(1)

where \( P_{\text{electrical}} \) represents the output power at the SEIG terminals. \( P_{\text{mechanical}} \) represents the power absorbed by the SEIG from the prime-mover. The difference between these two powers is the total SEIG losses. The total losses can be subdivided as [2];

- stator copper loss (\( P_{\text{scu}} \));
- rotor copper loss (\( P_{\text{rcu}} \));
- iron core loss for both stator and rotor cores (\( P_{\text{ic}} \));
- mechanical (friction and windage) losses (\( P_{f\omega} \));
- stator stray loss (\( P_{\text{set}} \)) and rotor stray loss (\( P_{r\text{st}} \)).

The stator and rotor copper losses. Iron core losses and mechanical losses are called the conventional machine losses and can be determined by the D.C. stator resistance test, no-load test, and locked rotor test to perform the equivalent circuit per-phase of the machine.

The stray load losses are difficult to model and determine. These losses have been the object of many studies [3-9]. The IEEE standard 112-B defines these losses as the difference between the total measured losses and the determined conventional losses as [10]:

\[ P_{\text{test}} = (P_{\text{mechanical}} - P_{\text{electrical}}) - P_{\text{conventional}} \]  

(2)

Where

\[ P_{\text{conventional}} = P_{\text{scu}} + P_{\text{rcu}} + P_{\text{ic}} + P_{f\omega} \]  

(3)
The most important world standards for induction machine efficiency measurements are described in the literature [12-14]. The imposed zero no-load stray losses due to zero no-load torque in the IEEE Standard 112-B is not true and the assumption of constant percentage (0.5% of input power) in the IEC 34-2 standard is not correct, due to at no-load there are leakage fluxes, leakage voltage drops and hence leakage (stray) losses. These losses are not constant and depend on motor size and power. In this paper, according to [11], as a first time, the stray losses are represented by a modified equivalent series resistances ($R_{sat}$ and $R_{t2e}$) in the stator and rotor circuits, respectively, as shown in the machine equivalent circuit in figure (1). These resistances are derived from the power loss equation of stator and rotor iron cores, and these resistances are varied with supply voltage, supply frequency, and slip.

In this paper, an accurate method is proposed to determine the total stray losses ($P_{t2e}$) from the equivalent circuit of the figure (1). This equivalent circuit is proposed in [11] to determine the accurate parameters of the circuit. The efficiency of SEIG can be accurately determined by taking all the parameters of the equivalent circuit as a non-linear. These parameters really vary with the winding temperature, iron core temperature, the skin-effect phenomenon in the iron core and stator and rotor winding, slip, the magnetizing saturation, and the skew-effect phenomenon.

![Figure (1)](image)

Figure (1) The proposed equivalent circuit of self-excited induction generator for efficiency determination.

The skew factor of the rotor circuit is given as:

$$K_{trq} = \frac{\sin(\frac{\pi P_p}{2Q_r})}{\left(\frac{P_r}{Q_r}\right)}$$

(4)

$p_p$ = number of pole-pairs of the machine, $Q_r$ = the number of rotor slots.

$$R_{ic} = \frac{R_{sic}}{R_{ric}} = \frac{R_{sic}(R_{mic}/s^2)}{[R_{ric}+R_{mic}/s^2]} = \frac{R_{mic}}{(1+s^2)}$$

(5)

The skew effect added an extra leakage reactance in the rotor circuit and can be determined as:

$$x_{t rq} = X_m \cdot \left(\frac{1}{X_{sq}} - 1\right)$$

leakage reactance due to rotor skew effect

(6)

where $X_m$ is the magnetizing reactance per phase.

2. The Proposed Efficiency Calculation Procedure

Although the IEEE standard 112-B assumes zero stray losses at no-load and assumes the stray load losses as a function of squared load torque instead of squared load current with a negative intercept of the regression with zero torque line, but it can be considered the most suitable standard for the stray load loss measurement and for the machine efficiency evaluation when compared with the other standard. The IEC 34-2 and JEC 37 overestimate the machine efficiency because they define and
assume that the stray losses are 0.5% of input power in IEC 34-2 standard and are neglected in JEC 37 standard instead of measuring the stray load losses.

An accurate stray loss determination is mandatory to obtain significant values of motor efficiency. The stray loss measurements are not simple to perform, and they are strongly influenced by the errors of measurement. The most critical quantities that affect the stray losses are the input power, load current, and output power, which have to be measured with very high accuracy. Also, the temperature effect on the copper losses and iron core losses, the skin-effect, the rotor skewing effect, the magnetizing saturation, and slip must be taken into consideration for accurate efficiency calculation.

The main tests done on the machine are as follow:

i) DC resistance test; in this test, the stator resistance at ambient temperature can be determined.

ii) Temperature test; this test is used for temperature correction of the stator winding resistance and iron core resistance.

iii) Variable load test; the machine is loaded with six load points ranging from 150% down to 25% of full load. From this test, the stator and rotor copper losses and stray losses are calculated.

iv) No-load test; the test is done without coupling the machine with the load. The tested machine is then run at rated supply voltage and frequency.

Then the supply voltage can be ranging from 125% down to 25% of rated value for determination of iron core resistance and mechanical (friction and windage) loss resistance.

The efficiency determination method based on loss segregation is known to be accurate. From the equivalent circuit of the figure (1), there are seven categories of losses in the motor: \( P_{scu} \) = the stator copper loss; \( P_{str} \) = the stator stray loss; \( P_{sc} \) = the stator iron core loss; \( P_{rcu} \) = the rotor copper loss; \( P_{rs} \) = the rotor iron core loss; \( P_{fr} \) = the rotor stray loss and \( P_{fw} \) = the friction and windage loss. The stator iron core loss and rotor iron core loss can be added together as iron core loss and can be represented by an equivalent resistance \( R_{ic} \) as shown in figure (1). The power flow of these losses is shown in figure (2), where \( P_{in} \) is the mechanical input power to the SEIG, \( P_{ag} \) is the air-gap power and \( P_{out} (P_{elec}) \) is the electrical output power at the SEIG terminals.

![Figure (2) The Power flow diagram of the induction generator.](image-url)
The machine losses can be calculated as [11]:

**i. Stator copper loss**: These losses can be calculated from the DC test resistance of the stator phase \( R_s \) and by measuring the stator phase current \( I_s \), taking the effect of temperature rise and skin-effect as:

\[
P_{scu} = 3 \cdot I_s^2 \cdot R_s(o) \cdot K_{se} \cdot [1 + \alpha_s \Delta T]
\]

Where \( R_s(o) \) is the stator resistance at ambient temperature, \( K_{se} \) is the skin-effect correction factor [11], \( \alpha_s \) is the thermal temperature coefficient of copper material, and \( \Delta T \) is the difference between the measured and ambient or reference temperature.

**ii. Stator stray loss**: These losses can be calculated from the measured stator phase current and the calculated stator stray loss resistance \( R_{sst} \) as [11]:

\[
P_{sst} = 3 \cdot I_s^2 \cdot R_{sst}
\]

Where \( R_{sst} \) is the equivalent stator series stray loss resistance and can be calculated as:

\[
R_{sst} = (X_{fs})^2 \cdot R_s / [R_s^2 + (X_{fs})^2]
\]

Where \( R_s \) = the measured stator winding resistance.

\( X_{fs} \) = the calculated stator leakage reactance from the no-load and blocked rotor test.

**iii. Stator iron core loss**: This loss can be determined from the no-load test by calculating the magnetizing voltage per phase \( V_g \) and the iron core resistance of the stator as:

\[
P_{sic} = 3 \cdot V_g^2 / R_{sic}
\]

\[
V_g = X_m \cdot I_m = X_m \cdot I_o \cdot \sin \phi_o
\]

\[
I_m = \sqrt{(Q_{nl} - I_s^2 \cdot X_{fs}) / X_m}
\]

Where \( R_{sic} \) is the stator iron core resistance measured from the no-load test at zero slip by rotating the machine at synchronous speed.

\( V_g \) = the air-gap voltage calculated from equivalent circuit parameters.

Where \( Q_{nl} \) = the no-load reactive power (VAR) per phase.

**iv. Rotor iron core loss**: This loss can be calculated from the magnetizing or air-gap voltage \( V_g \) and the rotor iron core resistance \( R_{ric} \) as [11]:

\[
P_{ric} = 3 \cdot V_g^2 / R_{ric}
\]

\[
R_{ric} = R_{sic} / S^2
\]

**v. Rotor copper loss**: This loss can be calculated from the measured stator phase current, no-load current and the rotor phase resistance referred to the stator as [11]:

\[
P_{rcu} = 3 \cdot I_r^2 \cdot \tilde{R}_{r(t)}
\]

\[
I_r^2 = (I_s + I_d)
\]

\[
\tilde{R}_{r(t)} = R_{r(o)} / \alpha_{rk} \cdot [0.5 + 0.5 \cdot \sqrt{S_r/S_m}(1 + \alpha_r \Delta T)]
\]

Where \( \tilde{R}_{r(t)} \) is the rotor resistance at ambient temperature, \( K_{sk} \) is the skew factor given in [11], \( S_r \) is the rated slip, \( S_m \) is the slip at maximum torque [11], \( \alpha_r \) is the rotor thermal temperature coefficient of the aluminum bar material, and \( \Delta T \) is the difference between the measured and reference temperature.

**vi. Rotor stray loss**: This loss can be calculated from the determined rotor current, and rotor series stray loss resistance as [11]:

\[
P_{rst} = 3 \cdot I_r^2 \cdot R_{rst}
\]

Where \( R_{rst} \) = the rotor equivalent series of stray loss resistance and can be calculated as:
vii. Friction and windage loss: This loss can be measured by subtracting the no-load loss at synchronous speed from the no-load loss at rated speed. Also, these losses can be calculated at any speed and magnetic saturation of the machine as:

\[ P_{fω} = 3 \cdot \frac{V_f^2}{R_fω} \]  

Where \( R_{fω} \) is the friction and windage loss resistance and can be calculated from the no-load test as:

\[ R_{fω} = 3 \cdot \frac{V_f^2}{P_{fω}} \]  

Where \( P_{fω} \) is the friction and windage losses at no-load.

The SEIG output power can be measured or can be calculated as:

\[ P_{out} = 3 \cdot V_{ph} \cdot I_ξ \cdot \cos φ_ξ \]  

The SEIG efficiency is given as:

\[ η% = \frac{P_{out}=P_{se}}{P_{out}+\text{total losses}} \cdot 100 \]  

Where the total SEIG losses can be given as:

\[ \text{Total losses} = P_{g} = (P_{ic} + P_{se} + P_{ic} + P_{cu} + P_{ref} + P_{fω}) \]  

Where \( P_{se} + P_{ic} = P_{ic} \) total iron core loss

Also, the SEIG efficiency can be calculated from the equivalent circuit of the figure (1) as:

\[ η% = \frac{P_{out}}{P_{in}} \cdot 100 = \frac{3 \cdot V_{ph} \cdot I_ξ \cdot \cos φ_ξ}{3 \cdot I_ξ \cdot 8_ξ \frac{(1-s)}{s}} \cdot 100 \]  

where \( I_ξ \) is the load current per phase given as:

\[ I_ξ = \frac{V_{ph}}{Z_ξ} \]  

\( \cos φ_ξ \) is the load power factor given as:

\[ \cos φ_ξ = \frac{R_ξ}{R_ξ} \]  

\( I_r \) is the total generated rotor current per phase and can be derived as:

\[ I_r = \left[ \frac{P_{mech}}{R_ξ \cdot (1-s)/s} \right]^{\frac{1}{2}} \]  

The source resistance \( R_ξ \cdot (1-s)/s \) can be derived as:

\[ R_ξ \cdot (1-s)/s = \frac{1}{1/\left(\frac{R_ξ}{R_ξ \cdot (1-s)/s} - R_{ref}\right) - (1/R_fω)} \]  

The whole power factor of SEIG can be derived as:

The total equivalent circuit impedance \( (Z_{eq}) \) from the rotor side can be derived from the figure (1) as:

\[ Z_{eq} = \frac{V_ξ}{I_{r2}} + \left[ \frac{8_ξ}{X_{r2}} + \left( X_{fr2} + X_{fr2} \right) \right]^{\frac{1}{2}} \]  

where \( V_ξ \) can be calculated from equation (11).

The total equivalent resistance from the SEIG equivalent circuit can be derived as:

\[ R_{eq} = \left( \frac{R_ξ}{K_{Rξ}} \right) + \frac{P_{out} + P_{cu} + P_{ref}}{2 \cdot I_{r2}^2} \]  

The stator copper and stray losses depend on the stator phase current \( I_s = I_{ph} \) and this current can be derived as:

\[ I_s = [I_ξ \cdot \cos φ_ξ]^{\frac{1}{2}} + [(-I_ξ + I_ξ \cdot \sin φ_ξ)]^{\frac{1}{2}} \]  

The net rotor current \( I_{r2} \) can be derived from the equivalent circuit of the figure (1) as:

\[ I_{r2} = I_r - I_{r1} \]
Where $I_{r1}$ is the total generated-rotor current calculated by equation (26) and $I_{r1}$ is the current lost to compensate for the friction and windage losses and can be derived as:

$$I_{r1} = \left[\frac{P_{mech} \cdot \hat{R}_r (1 - s) / (3 \cdot s \cdot \omega)}{\hat{R}_r \omega}\right]^\frac{1}{2}$$  \hspace{1cm} (35)

$I_c$ is the reactive current in the excitation capacitance of the SEIG and can be calculated as:

$$I_c = \frac{V_{ph}}{X_e}$$  \hspace{1cm} (36)

Then, the whole power factor of SEIG can be calculated as:

$$P \cdot f = \cos \phi = R_{eq} / Z_{eq}$$  \hspace{1cm} (37)

The steady-state electromagnetic torque of SEIG can be calculated in terms of air-gap power and angular frequency as:

$$T_e = \frac{P_{eg}}{\omega_x} = -\frac{3 f \cdot R_x \cdot \hat{E}_{eq} (s, \omega_x)}{s \cdot \omega_x}$$  \hspace{1cm} (38)

The angular frequency ($\omega_x$) is given as:

$$\omega_x = (2\pi f) \text{ rad./sec.}$$  \hspace{1cm} (39)

3. Results and Discussion

Equivalent circuit components of fig.(1) are simulated in Matlab/Simulink Block-Set, and the simulating results of SEIG performance are compared with experimental results, which are obtained from an experimental setup consists of induction machine used as a SEIG and DC machine used as prime-mover.

All the specifications and parameters of these machines are given in reference [11].

Figs (3-6) show the variation of SEIG terminal voltage, output power, power factor, and efficiency with load current, respectively. From these simulation and experimental results, there is a high agreement between these results of machine performance, and this proves the validity of the proposed efficiency calculation method for high accuracy of SEIG performance calculation. The discrepancy in the results at high load currents is due to the saturation effect of cross-coupling magnetizing inductance and saturation in leakage inductances are not considered in the simulation model.

**Figure (3)** Variation of machine terminal voltage with load current.
4. Conclusion
All the SEIG equivalent circuit components are measured and calculated accurately to achieve excellent efficiency calculation considering the effect of copper losses, iron core losses, stray load losses, friction and windage losses, skin-effect losses, and skew-effect losses. All these losses of the SEIG are calculated accurately by their derived formulas due to the efficiency calculation depends directly on the adding of these losses. These losses can be minimized by choosing appropriate equivalent circuit components. There are many effects that influence and minimize these losses, such as:

i. The reduction of copper or winding losses can be achieved by increasing winding cross-sectional area and improving the slot design.

ii. The reduction of iron core losses can be achieved by using thinner laminations.

iii. The mechanical losses can be improved by using lower friction bearings and good cooling fans.

iv. The stray losses are produced due to the leakage fluxes and by good design of winding end-turn, can be reduced and limited.
The accuracy of machine efficiency measurement is highly affected by the type of instrumentation and calibration.

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