PROCEEDINGS OF ECOS 2015 - THE 28TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 30-JULY 3, 2015, PAU, FRANCE

Energy efficiency on-site estimation of self-excited induction generator under internal fault conditions

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Abstract:

With the increasing concern over environmental issues and energy savings from improved energy efficiency, electricity consumption brings into focus the complete electrical machine cycle, i.e. manufacturing and materials, operation, monitoring and fault diagnosis. The increasingly application in distributed generation became the self-excited induction generator an important subject of research. Since the induction machine is mostly used as a motor, the data provided by manufacturers is mainly restricted to motor configuration efficiency values. Several works about the determination of induction motors efficiency were recently presented, however fewer considers the induction machine efficiency in generator mode and issues related to the rewind machine performance after failures. In this paper is presented a nonintrusive on-site efficiency estimation algorithm, the main strategy is based on the output to input power ratio determination. The algorithm is applied in healthy and faulty machines. The proposed methodology considers a model based least squares initial procedure in order to identify the main machine parameters, then, computational simulations of the induction machine dynamic model were applied in order to obtain the output to input power ratio determination. The overall on-site efficiency determination procedure is validated by means of a low power machine based implementation, where the input torque is estimated by means of an air-gap torque method validated in literature. As expected, the results of the work presents a clear relation between efficiency and fault conditions, furthermore, in order to observe the economic impact of the efficiency loss, generation process costs were calculated. Furthermore, a relationship between efficiency loss and gas emissions is presented. In this sense, the presented algorithm is suitable for conducting on-site energy audits in isolated generator systems, to guide the decisions regarding the investment in higher efficiency machines and to reduce gas emissions, in order to achieve a sustainable energy conversion process.

Keywords:

Self-excited induction generator (SEIG), on-site efficiency estimation, air-gap torque (AGT) estimation,
fault conditions, sustainability.

1. Introduction

Several studies recognize the potential of renewable energy in order to contribute to sustainable development [1,2]. Nevertheless, the development of cleaner energy technologies and energy conversion processes also involve conventional fossil fuels. In general, a method for sustainability analysis of electricity generation systems is not already established [3] and several interdisciplinary indicators are not considered in planning and implementation of power system projects. Availability and machine failures, greenhouse gas emissions, efficiency, land and water use, and social and political issues, are topics usually considered in the design of power generating systems, both centralized and decentralized.

This work deals with isolated power systems based on the induction generator, propounding a nonintrusive on-site efficiency estimation algorithm in order to attain a sustainable energy conversion process. The modules of the power system studied are defined in Fig. 1. Where the first module represent the source fuel based, the second is the induction generator, third one is the load and capacitor bank, and the last module is the efficiency estimator algorithm propounded in this work in order to achieve a sustainable energy conversion process.

Electric motors and generators are considered the central electric energy conversion devices. The induction motors have been the most widely used machines industrial applications for reasons of cost, size, weight and reliability. On the other hand, the induction machine certainly can compete with other generator technologies for small-scale generation. In this sense, the Self-excited induction generator (SEIG) has emerged as a promising subject of research due to its wide applications in decentralized power generation, leading the development of isolated power systems using both conventional and non-conventional sources of energy. As induction machines were introduced in industrial processes in a time of low cost energy and absence of major environmental concerns, this technology was directed toward robust and durable designs instead of efficient ones.

With the increasing concern over environmental issues and energy efficiency savings, electricity consumption brings into focus the complete electrical machines cycle design, i.e. manufacturing and materials, operation, monitoring and diagnosis. Literature has already reported works related to the improvement of the materials employed in electrical machinery manufacturing [4-7]. On the other hand, as several applications need precise control and health monitoring during operation, different works focused the development of technology applied into critical service systems. In this sense, the well-established condition monitoring techniques used in induction motors, mainly based on steady-state analysis, are recently being applied to induction generators [8-10]. Other studies related to the savings and efficiency improvements have been focused on diagnoses fault symptoms of electric machines, mainly in order to prevent costly system shutdowns or high generation costs [11-15]. The majority of the works consider faults related to loads, drives and internal components of the machine. They show, how efficiency guarantees high quality energy consumption by better energy conversion processes using improved design, condition monitoring and diagnosis

Recently, some works focusing on induction machine efficiency estimation, [16-28], pointed out the considerable benefits in environmental and economic terms presented by modern fault detection strategies. The estimation of induction machine efficiency requires knowledge of at least two of the quantities input power, output power and total losses. Most of the studies are related to the efficiency estimation of the induction machine working as a motor [16-19]. Other works, comparing efficiency and constructive issues in motor and generator modes, under very specific operating conditions [20-22]. In general, a lack of references related exclusively to efficiency estimation of generator mode [20,23-24] became evident. The efficiency of an induction generator can be affected by different factors such as unbalance voltages and loads [26-27], noncritical internal faults [26], effects of the rewinding or repair processes of the machine [28], or due to inappropriate dimension of the machine. Moreover, operating conditions rarely meet the standard test conditions, some studies, [16,17], have presented differences among efficiency estimation methods and established standards, highlighting two mainly aspects [20]:

- As the induction machine usual application is in motor mode, the manufacturer’s catalogues simply mention motor efficiency values. However, the efficiency values for motor and generator modes are not necessarily the same.
- Low power rated machines could present lower efficiency values, where the efficiency for generator mode can drop several percent compared with motor mode.

The accurate knowledge of the induction generator efficiency strongly affects the energy savings calculations of the entire power generation system and relevant decisions, such as replacement of an existing machine [25]. Consequently, on-site efficiency monitoring of the SEIG is a necessity to identify the machines with lowest efficiencies and take an appropriate action. Numerous techniques for on-site efficiency estimation, with different levels of intrusion and accuracy, have been proposed. These methods can be classified as slip methods, current methods, simplified equivalent circuit methods, simplified loss segregation methods, nonintrusive air-gap torque (AGT) (NAGT) methods, and optimization-based methods.

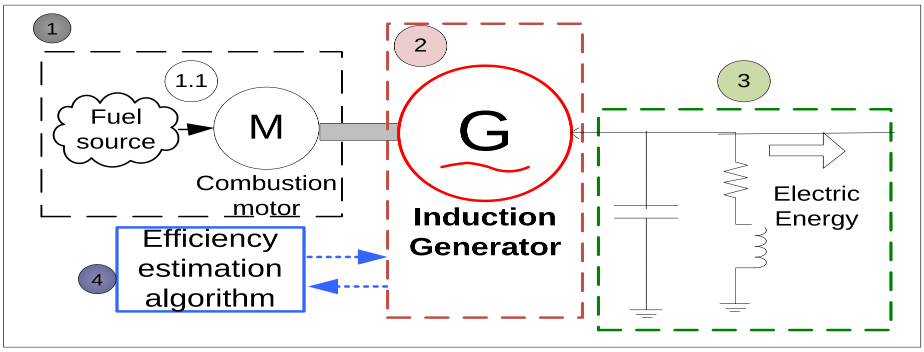


Fig. 1. Power system components

This paper presents a nonintrusive on-site efficiency estimation algorithm where the main strategy is based on the output to input power ratio determination. For the purpose of this paper, nonintrusive refers to electrical measurements at the terminals only with no mechanical measurement in a particular speed. The proposed methodology considers a model based least squares initial procedure in order to identify the main machine parameters, then, computational simulations of the induction machine dynamic model, under healthy and faulty conditions, in order to obtain the output to input power ratio determination. The overall on-site efficiency determination procedure is validated by means of a low power machine based implementation and the input torque estimation using a non-intrusive AGT method validated in literature.

The efficiency values are useful for analyze the economic impact as well as the gas emissions, regarding the efficiency loss in machines under faults. This analysis shows that the faulty machine has a negative impact on economic and environmental dimensions. In this sense, the aim of the efficiency estimation algorithm proposed is to achieve a sustainable energy conversion process.

This paper has been divided into 6 parts. Section 2 presents the dynamical model applied to study the healthy and faulty induction machine. Section 3 presents the efficiency estimation algorithm. Section 4, concisely describes the experimental platform. Section 5 shows the main results. Section 6 shows the impact analysis and finally, the conclusions are presented in section 7.

2. Self-Excited induction generator

Even though the synchronous generator has being most applied machine for generation purpose, last years the self-excited induction generator (SEIG) has become important due to low cost and robustness characteristics, and due to social and economic necessities, such as:

- The proliferation of settlements away from the large urban concentrations. This has led to demanding power plants (far from centralized power system) as other basic services.
- The decentralized power generation leading the development of isolated power systems using both conventional and non-conventional sources. Although the induction generator is more common in hydroelectric and wind power, it has been also used in small hydropower for the last decades [22]. Additionally, the SEIG is applied in isolated systems driven by diesel, biogas, natural gas, gasoline, and alcohol motors [29].

The following subsections describe the dynamic models applied in order to study de SEIG under healthy and faulty conditions considered in this paper.

2.1. Induction machine modeling

The electrical machines can be described as motor and generator as well; consequently, the induction machine can be described with the same set of equations, which govern its operation. However, in the case of the SEIG, the dynamics of self-excitation and load should be taken into account for the simulation process, more precisely: Load and self-excitation capacitor model, [30]; Mutual inductance (L_m) and magnetizing current (I_m) relation, that is the main factor in the dynamics of the voltage build up and stabilization in SEIGs, [29]; Stator voltages related to the self-excitation capacitor and load voltages [29-32].

The complete dynamic model of an induction machine is represented by the set of equations (1)-(4) expressed in dq-frame. Where, (1) is presented in the classical state-space equation form [ẋ] = [A][x]+[B][u], where the stator and rotor magnetic fluxes are the states, the matrix A the parameters of the machine, and stator voltages are the input. The rotor voltages are considered zero due to this work deals with a squirrel cage induction machine.

$$\begin{bmatrix} \dot{\phi}_{sd} \\ \dot{\phi}_{sq} \\ \dot{\phi}_{rd} \\ \dot{\phi}_{rq} \\ \dot{V}_{ld} \\ \dot{V}_{lq} \end{bmatrix} = \begin{bmatrix} \frac{R_s L_r}{\sigma L_m^2} & n\dot{\psi} & -\frac{R_s}{\sigma L_m} & 0 & -1 & 0 \\ n\dot{\psi} & \frac{R_s L_r}{\sigma L_m^2} & 0 & -\frac{R_s}{\sigma L_m} & 0 & -1 \\ -\frac{R_r}{\sigma L_m} & 0 & \frac{R_r L_s}{\sigma L_1^2} & n(\dot{\psi}-\omega_m) & 0 & 0 \\ 0 & -\frac{R_r}{\sigma L_m} & -n(\dot{\psi}-\omega_m) & \frac{R_r L_s}{\sigma L_m^2} & 0 & 0 \\ -\frac{L_r}{C\sigma L_m^2} & 0 & \frac{1}{C\sigma L_m} & 0 & -\frac{1}{RC} & 0 \\ 0 & -\frac{L_r}{C\sigma L_m^2} & 0 & \frac{1}{C\sigma L_m} & 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} \dot{\phi}_{sd} \\ \dot{\phi}_{sq} \\ \dot{\phi}_{rd} \\ \dot{\phi}_{rq} \\ V_{ld} \\ V_{lq} \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \quad (1)$$

$$\sigma = \frac{L_m^2 - L_s L_r}{L_m^2} \quad (2)$$

$$T = \frac{n(\phi_{rq}\phi_{sd} - \phi_{rd}\phi_{sq})}{\sigma L_m} \quad (3)$$

$$J\dot{\omega}_m + D\omega_m = n(T - T_L) \quad (4)$$

The magnetizing current, I_m, is defined in (5)

$$I_m = \sqrt{(i_{sd} + i_{rd})^2 + (i_{sq} + i_{rq})^2} \quad (5)$$

The nonlinear relationship between magnetizing inductance and magnetizing current, experimentally obtained, is represented by (6).

$$L_m = -0.0033306 \quad I_m{}^4 + 0.016567 \ I_m{}^3 - 0.03104 \ I_m{}^2 + 0.028038 \ I_m + 0.021841 \quad (6)$$

2.1.2. Stator Fault model

According to [32] the main types of faults studied in the literature are commonly categorized as electrical faults (short and open of windings, etc.) and mechanical faults (eccentricity rotor, broken rotor bar, end ring breakage, etc.), the last ones will be considered in future works.

The dynamic model of induction machine considers a symmetric machine, i.e. the same internal parameters values for each phase. According to [33] and [34] the most common failures of the induction machine produce an asymmetrical behavior of the machine depending on the fault location. This work aims to study two fault conditions located on the stator of the induction machine: poor windings connection and inter-turn short circuit.

As proposed in [34] without loss of generality, (1) is modified assuming that faults occur in the stator phase A. Under normal operating conditions, the stator impedances are equal in the three stator phases, i.e., $R_A = R_B = R_C$ and $L_A = L_B = L_C$. In dq frame, those variables are represented by R_S and L_S, respectively. In the presence of stator faults, the resistance and inductance of phase A are different from their equivalent parameters in phases B and C, i.e., $R_A \neq R_B = R_C$ and $L_A \neq L_B = L_C$, representing the asymmetry caused by the fault. Furthermore, the new values of the stator parameters, R_A and L_A, require changes in the magnetizing inductance and leakage coefficient values, Lm and σ respectively. Hence, the asymmetry produces some changes on the healthy machine model, as described by (7).

$$\begin{bmatrix} \dot{\phi}_{sd} \\ \dot{\phi}_{sq} \\ \dot{\phi}_{rd} \\ \dot{\phi}_{rq} \\ \dot{V}_{ld} \\ \dot{V}_{lq} \end{bmatrix} = \begin{bmatrix} \frac{R_A L_r}{\sigma_A L_{mA}^2} & n\dot{\psi} & -\frac{R_A}{\sigma_A L_{mA}} & 0 & -1 & 0 \\ n\dot{\psi} & \frac{R_s L_r}{\sigma L_m^2} & 0 & -\frac{R_s}{\sigma L_m} & 0 & -1 \\ -\frac{R_r}{\sigma_A L_{mA}} & 0 & \frac{R_r L_A}{\sigma_A L_{mA}^2} & n(\dot{\psi}-\omega_m) & 0 & 0 \\ 0 & -\frac{R_r}{\sigma L_m} & -n(\dot{\psi}-\omega_m) & \frac{R_r L_s}{\sigma L_m^2} & 0 & 0 \\ -\frac{L_r}{C\sigma L_m^2} & 0 & \frac{1}{C\sigma L_m} & 0 & -\frac{1}{RC} & 0 \\ 0 & -\frac{L_r}{C\sigma L_m^2} & 0 & \frac{1}{C\sigma L_m} & 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} \dot{\phi}_{sd} \\ \dot{\phi}_{sq} \\ \dot{\phi}_{rd} \\ \dot{\phi}_{rq} \\ V_{ld} \\ V_{lq} \end{bmatrix} + \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \quad (7)$$

3. SEIG on-site efficiency estimation

The induction machine (IM) efficiency estimation requires the knowledge of at least two of these quantities: input power, output power and total losses. There are several standards for IM efficiency measurements. Most of these standards have more than one method for determining the efficiency, nevertheless, the two major ways of determining the efficiency of IM may be classified as follows: *Direct method:* measuring the output mechanical quantities and input electrical quantities and dividing the same. *Indirect method:* using some means to determine all the constituent losses in the motor and using their sum to calculate the efficiency.

The data required to be measured in the field and how difficult to perform the measurements determine the intrusiveness degree of an efficiency evaluation method.

There are several approaches to determine the field efficiency of IM [25-27]. In the plant, the induction motor field efficiency is determined based on the input measurements of motor, such as slip and current methods. Another usual way for motor field efficiency estimation is the equivalent-circuit-based method [25,36-37] using measured values (voltage, current, power and speed) without the need for measuring output power (torque). These methods still require measurements of stator resistance, stator winding temperature and motor speed which are impractical in many cases. Moreover, most of works are related to the efficiency estimation of the induction machine working as a motor [16-19]. Other works solely comparing efficiency and constructive issues in motor and generator modes under very specific operating conditions [20-22], but in general there is a lack of references related exclusively to efficiency estimation of generator mode [20,23-24]. Additionally, it is important to highlight that, the efficiency of an induction generator can be affected by many factors such as noncritical internal faults [26] and the effects of the rewinding and repair of the machine [28].

To overcome the above problems, this paper proposes a nonintrusive on-site SEIG efficiency estimation algorithm, where, the main strategy is based on the output to input power ratio determination [38], applied in healthy and faulty SEIGs. For the purpose of this paper, nonintrusive refers to electrical measurements at the terminals only, with no mechanical measurement in a particular speed. The overall on-site efficiency determination procedure is described following.

3.1. Fundamentals of the proposed algorithm

In this section, the fundamentals of the proposed efficiency estimation algorithm are discussed. The on-site algorithm for SEIG efficiency estimation is based in three basic modules: parameters identification procedure, torque estimation and output power measurement. The algorithm is resumed by the Fig. 2, and each module is described in the next subsections.

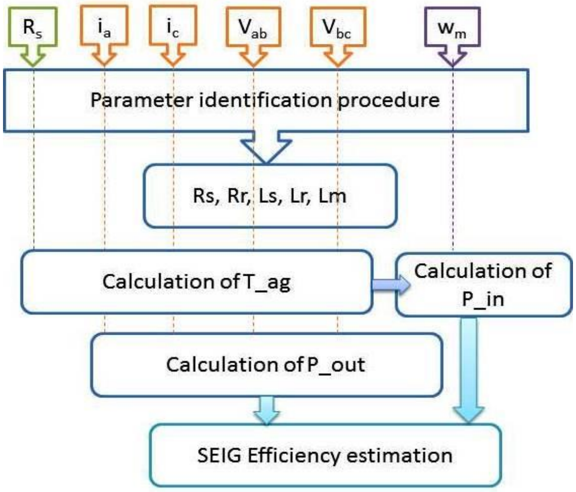


Fig. 2. SEIG Efficiency estimation algorithm

3.1.1. Parameter identification procedure.

The parameters required to specify the SEIG are: the stator resistance, R_s, the stator inductance, L_s, the rotor resistance, R_r. All those parameters can be determined from the free acceleration test data, based on [38], using the least squares estimation algorithm, with the machine working as a motor. The parameter identification procedure is realized with the machine working as a motor.

3.1.2. Torque estimation.

According to [36], the air-gap torque (AGT) method requires the following data to be measured: line voltages, phase currents, rotor speed, and stator resistance. In order to reduce the degree of intrusiveness, there were applied the following modifications on this method:

- The rotor speed come from direct measurement, but it is used a cheaper very low resolution sensor (five pulses for revolution).
- The stator resistance value came from unpowered testing or through approximation from the nameplate data.
- A no-load test should be avoided due to its high intrusiveness. Instead, no-load data are obtained by next procedure: Nameplate R_s, estimated Ls ($L_S=V_S/I_S$), the other parameters are obtained by means of a least mean square method.

Finally, based on the approach presented by [39] applied in induction motors, the AGT is calculated based on (8). The measured signals are the stator voltages and currents signals. The AGT calculation includes the effects of the unbalanced supplies which is one of the advantages of this method:

$$T_{AG} = \frac{\mathrm{n}\sqrt{3}}{3}\left\{(2i_a + i_c)\cdot\int\left[v_{ca} - R_s(i_c - i_a)\cdot dt\right] - (i_c - i_a)\cdot\int\left[v_{ab} - R_s(2i_a + i_c)\cdot dt\right]\right\} \qquad (8)$$

Where: n is the number of pole pairs, i_a,i_c are the line currents, and V_{ab},V_{ca} are the line voltages.

The power transferred through the airgap is decribed by (9)

$$P_{T_{AG}} = \mathrm{T}_{AG}\omega_S = \mathrm{T}_{AG}\frac{\omega_R}{1-s} \qquad (9)$$

The input power of the SEIG, or the mecanical power, will finally described by meand of the next expresion: $P_{inSEIG} = \mathrm{T}_{AG}\omega_S + P_{losses}$ where P_{losses} represent the combined no-load losses which are assumed to be 3 % of rated output power, due to, according to [26], the friction and windage loss is 1.2% rated output power and and the stray-load loss is estimated as 1.8% rated output power (for low power machines). The positive sign of the expression define just the power direction due to the machine in working in generator mode.

3.1.1. Output power measurement.

The output power measurement is realized by means of the following equation: $P_{outSEIG} = \sqrt{3} V_l I_l \cos(\phi)$. The SEIG efficiency will be calculated based on the output to input power ratio: $\eta_{SEIG} = \frac{\mathrm{P}_{\mathrm{outSEIG}}}{P_{inSEIG}}$.

4. Experimental bench

Initial experimental results were obtained by using a modular bench work laboratory of electric machines (OPENLAB platform by DeLorenzo), the sensors applied for current and voltages measurements and the acquisition data system CompactDAQ. The OPENLAB is a set of components and modules of rotating electrical machines (DC and AC machines, and measurement modules).Voltage and current sensors, LEM-v25p and CSNE-151 respectively, were connected to the electrical machine terminals in order to conditioning the electrical signals according to the acquisition data platform requirements. The acquisition data platform is the Compact-DAQ from National Instruments. The chassis used is de NI-cDAQ-9172 and the modules NI 9201 and NI 9401 for analog and digital signals respectively.

The Fig. 3 shows the three-phase connection diagram of the induction machine studied configured as self-excited induction generator.

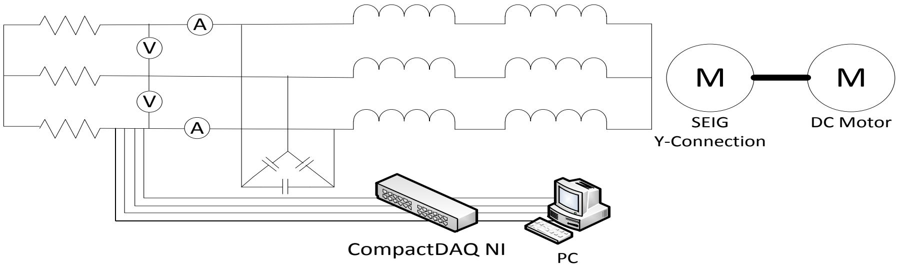
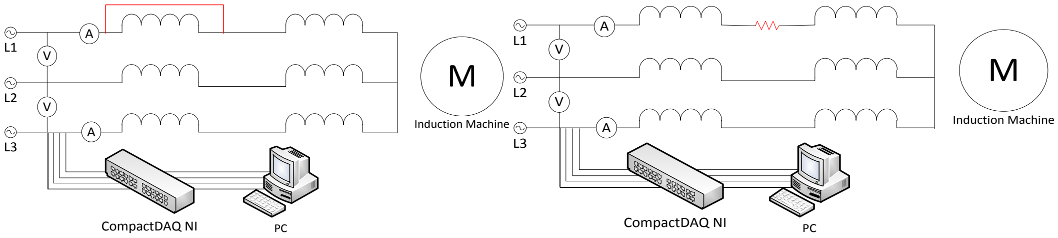


Fig. 3. Scheme applied for experimental purposes

4.1. Stator faults scheme

In order to study the SEIG under stator faults, some adjustments were applied in the stator circuit. The Fig. 4 present the schemes of the stator faults studied in this work. Those figures explain graphically the changes applied on the phase A of the induction machine stator in order to study the considered faults. Those adjustments were possible due to the machine stator has two windings per phase.



a. Inter-turn short circuit b. Poor winding connection

Fig.4 Experimental scheme applied for stator faults

5. Main results and validation.

This section presents the simulation and experimental results of the SEIG efficiency estimation algorithm proposed. The machine parameters are presented in annex.

5.1. Simulation results

The proposed method was initially tested in computational simulations of the dynamic model described in sections 2.1 and 2.2, for the three conditions studied in this work: healthy machine, inter-turn short circuit on the stator windings and poor winding connection. The results, presented in Fig.5, shows that under normal conditions the efficiency value is around 54%, decreasing under fault conditions, around 46% and 53% for inter-turn short circuit and poor winding connection respectively. The inter-turn short circuit on the stator presents the greatest efficiency loss, almost 8% less than under normal conditions.

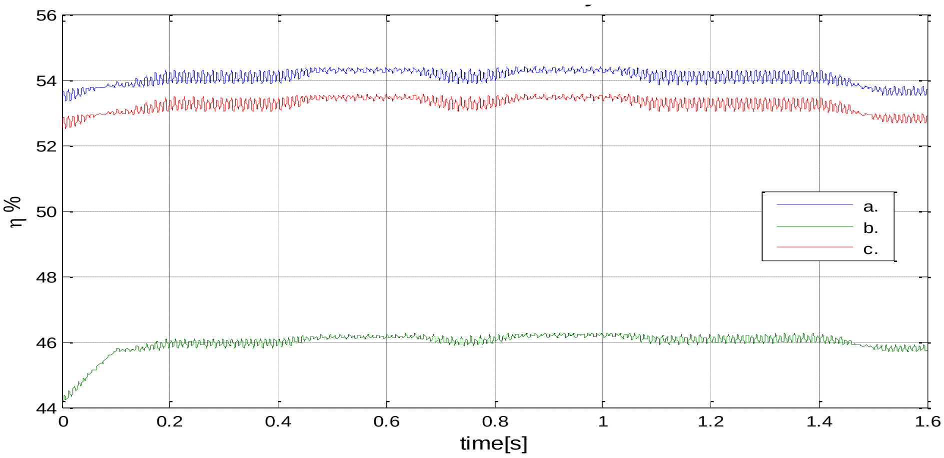


Fig. 5. Simulation results of SEIG Efficiency. a. Healthy machine, b. Inter-turn short circuit, c. Poor winding connection

5.2. Experimental Results

The simulated results have been validated by means of a low power laboratory machine (42V/14A) and an acquisition data system, both described in section 4. The results presented in Fig. 6 shows the three conditions studied. Low efficiency values are clearly observed for the faulty machine, as in the simulation case. For normal conditions, the on-site efficiency value is around 51 and 53%. The efficiency oscillates between 47 and 51% for the poor winding connection case. Finally, the intern-turn short circuit presents the lowest efficiency values, between 42 and 45%.

Bearing in mind the induction machine theory, it is important to consider a suitable speed operation point, which fits the better performance for the machine, i.e. not near from the synchronous frequency.

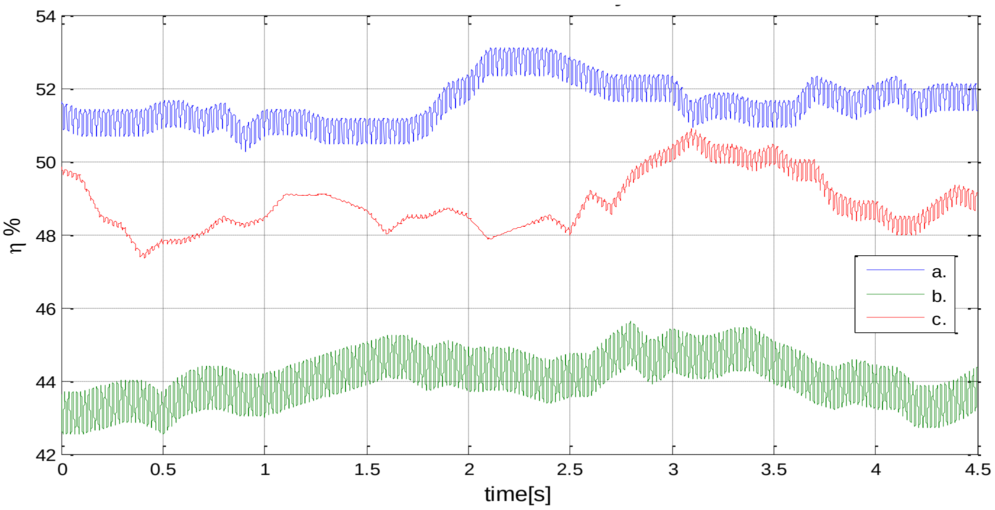


Fig. 6. Experimental results of SEIG Efficiency. a. Healthy machine, b. Inter-turn short circuit, c. Poor winding connection

6. Impacts analysis

This section presents the impacts caused by the efficiency loss under fault conditions. The aim of this section is to explain how the accurate knowledge of the induction generator efficiency affects the energy savings calculations of the entire power generation.

The aim of the efficiency estimation algorithm is to observe the economic and environmental impact of the efficiency loss, for conducting on-site energy audits in isolated generator systems. The Fig. 7 summarizes this idea.

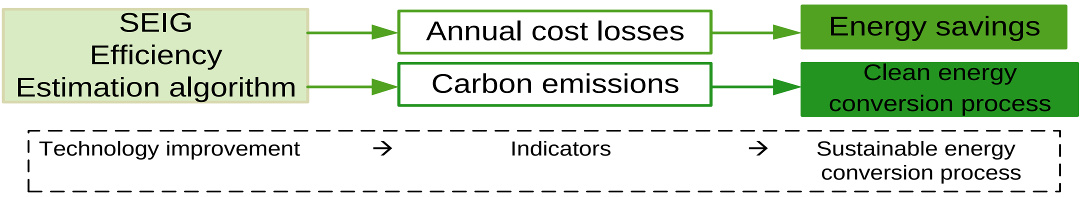


Fig. 7. Impact assessment indicators of SEIG Efficiency algorithm

6.1. Economic impact of efficiency

In order to observe the economic impact of the efficiency decrement it was calculated the annual cost losses (A_{losses}), based on the approach presented by [33] to compare normal machines with more efficient ones. The savings were calculated based on (12).

$$A_{losses}(R\$) = P_{outSEIG} h_r C \left(\frac{1}{E_f} - \frac{1}{E_h} \right) \qquad (12)$$

Where h_r is the annual operating hours, C is the average of energy cost (R$/KWh), E_f is the machine efficiency under faults and E_h is the machines efficiency in healthy conditions.

This indicator is also applied in order to notice the difference between consider an approximation or the accurate value of efficiency. Assuming an average energy cost of 0.3 R$/KWh and 8000 operating hours per year, the savings considering a constant value of efficiency are presented following:

Inter-turn short circuit $$A_{losses}(R\$) = 60 \times 8000 \times 0.3 \left(\frac{1}{0.44} - \frac{1}{0.52} \right) = 44055.94 R\$$$

Poor winding connection $$A_{losses}(R\$) = 60 \times 8000 \times 0.3 \left(\frac{1}{0.48} - \frac{1}{0.52} \right) = 20192.30 R\$$$

We observe that even a 4% less efficient machine produce almost double extra costs in a year.

In the other hand, considering the accurate value of efficiency, as showed in Fig. 8, we notice that for the inter-turn short circuit case the A_{losses} range is between 32800 and 60550 R$. For the poor winding connection case the A_{losses} values varies between 3200 and 29500R$. Those grater ranges of A_{losses} calculations made us realize the importance of the accurate value of the SEIG efficiency.

6.2. Environmental impact of efficiency

The environmental impacts were analyzed by considering the assumptions that the generator is driven by a diesel motor. Under fault conditions, the power generated value is smaller than under normal conditions. Consequently, under fault conditions, more fuel is required to generate the same amount of energy produced in normal conditions. The carbon emissions factor for natural gas is 0.00005508 [tC/kWh]. This indicator quantifies the tons of carbon (present in CO, CO2 and CH4) emitted for each fuel per unit of energy. With all those assumptions, the carbon emissions are calculated, for the three conditions studied in this work, by means of KWh×tC×h, where h is the quantity of operation hours.

Table 1. Tons of Carbon emitted during 8000 hours of work in normal and faulty.

SEIG operating condition	*Extra Power required*	*Emission [tC]*
Healthy	0 KWh	26438
Poor winding connection on the stator windings	8 KWh	29963
Inter-turn short circuit on the stator windings	14 KWh	32607

The results presented in Table 1 shows a relationship between fault conditions and carbon emissions, which could be detected by means of the efficiency estimation procedure, specifically in the stage of the output power calculation.

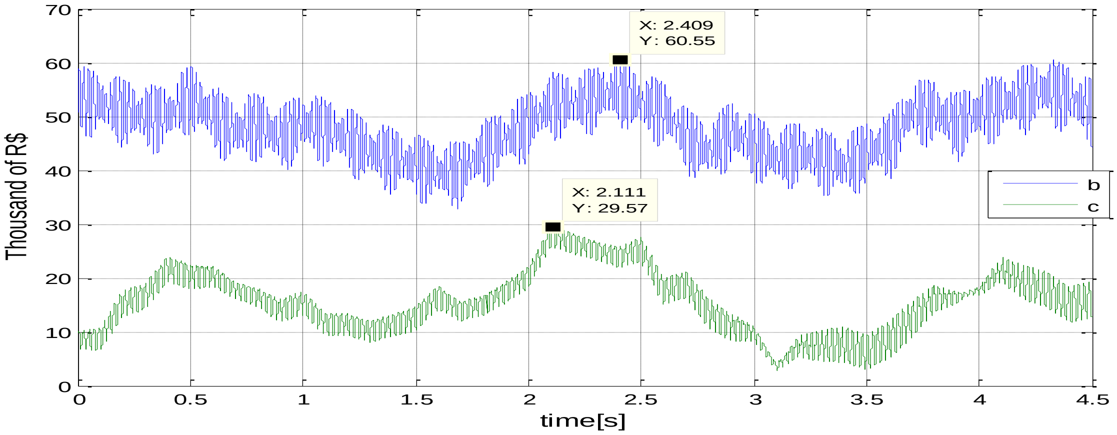


Fig. 8. A_{losses} of SEIG. b. Inter-turn short circuit, c. Poor winding connection

7. Conclusions

This paper propose an online nonintrusive method for SEIG efficiency estimation, based on air-gap torque, by using only generator terminal quantities, a very low resolution optical encoder and a simple parameter identification method without rotor lock test. The work is focused on machines operating under faults. The efficiency estimation algorithm was firstly applied in computational simulation of the dynamic models. Then, it has been experimentally validated by means of a small induction generator, working under healthy and fault conditions. The method could be applied without interfere on the generator operation.

According to the importance of the interdisciplinary contributions in the energy field, this method is intended to be a low cost energy evaluator based on currents, voltages and a cheaper low resolution optical encoder. In this sense, the economic and environmental impacts were analyzed by means of two indicators: Annual losses costs (A_{losses}) and carbon emissions. In the A_{losses} case, we observe that even a 4% less efficient machine produce almost double extra costs in a year. Furthermore, considering the accurate value of efficiency, we notice that the A_{losses} range is greater than considering approximated values, this fact could lead to wrong audits, highlighting the importance of accurate value of the SEIG efficiency. On the other hand, considering the SEIG is driven by a diesel motor, due to the decrease in efficiency caused by faults, a larger amount of fuel to generate the energy is required, that results in a higher amount of carbon emissions.

As a future work is extended to include the rotor faults and implement the complete procedure on a digital signal processor. Finally, it is necessary to define the perceptual error of the method in several low power machines and to include more indicators in order to improve the impacts analysis.

Due to technological, economic and environmental dimensions are important in the energy conversion process, all those considerations indicate how the efficiency estimation algorithm could lead to increase the energy savings and a clean energy conversion process, attaining in this way a sustainable isolated power system.

Acknowledgments

Authors thank to the UFABC University and CAPES for economic support.

Annex

Table 2. SEIG parameters

Parameters	*values*	*Parameters*	*values*
Dv [Nm/s]	0.0003195		*Poor winding connection*
J [Nm^2/s]	0.0016759	Rsa [Ω]	1.78
Lm [mH]	70.76	Lsa [mH]	72.33
Lr [mH]	72.77		*Inter-turn short circuit*
Ls [mH]	74.55	Rsa [Ω]	0.88
Rr [Ω]	0.71	Lsa [mH]	68.89
Rs [Ω]	1.17		

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