Reactive power analysis and frequency control of autonomous wind induction generator using particle swarm optimization and fuzzy logic

Ezzeddine Touti\textsuperscript{1,2}

Abstract
Wind generation system is becoming increasingly important as renewable energy sources due to its advantages such as low maintenance requirement and mainly it does not cause environmental contamination. This paper presents the improvement procedure of the transient state and the regulation of the output frequency by adjusting the terminal capacitor. The aim is to provide frequency control of a self-excited induction generator in remote site using different strategies which are based on the adjustment of the reactive power at the outputs of a three-phase self-excited induction generator. A thyristor controlled reactor and a switched resistive load will be used to control reactive power. The proposed particle swarm optimization algorithm technique, location of the thyristor controlled reactor device, and parameter value are optimized simultaneously. The results obtained by this strategy will be compared with those provided by the use of Fuzzy Logic Controller. This study will be conducted through the analysis of the frequency in the steady state and transient case using a developed induction generator numerical model built using MATLAB/Simulink. Simulation and experimental results will be exposed and analyzed considering a resistive inductive load on a laboratory test bench.

Keywords
Induction generator, transient enhancement, frequency control, fuzzy logic controller, particles swarm optimization

\textsuperscript{1}Electrical Department, Northern Border University, Arar, Saudi Arabia
\textsuperscript{2}Department of Electrical Engineering, University of Tunis, Tunisia, North Africa

Corresponding author:
Ezzeddine Touti, College of Engineering, Northern Border University, Khalidia 1321, Arar, Saudi Arabia.
Email: touti.these09@gmail.com
Introduction

For rural electrification, a large number of communities in isolated sites need renewable energy solutions (Hazra and Sensarma, 2010; Mingjun et al., 2016; Sarsing et al., 2014; Zhang and Ooi, 2013; Zhaoxia et al., 2018). In remote site, the wind turbine equipped with squirrel cage induction machine (IM) presents major benefits if extreme climatic conditions are considered or when the demand for electric power is limited. So for these reasons, the integration of IM in the wind turbines, where the power requested is relatively limited, has become competitive and that can explain their increasing in the electrical energy production (Enany, 2014; Goyal and Palwalia, 2016; Jazaeri and Chitsaz, 2012; Rahim et al., 2009; Yong et al., 2009). The IM is simple, reliable, and requires very little maintenance. It seems the most robust and common for wind energy systems. This induction generator (IG) needs an external supply on reactive power to produce a rotating magnetic flux wave (Ahmed et al., 2004). For this reason, it is necessary to connect capacitor to provide the required reactive power for the machine as well as the connected load. The use of the self-excited induction generator (SEIG) has been discovered for a few decades and was experienced at several remote sites, but the wave quality is not optimized. These difficulties are due to the inverse nature of the problem such as the voltage, the frequency, and the rotor sleep which are unknown at the beginning. In order to address and solve the problem of the unstable operation of this wind turbine generator, many papers propose control strategies and applications of different power electronic controllers for SEIG terminal voltage–frequency control (Aggarwal et al., 2017; Benghanem et al., 2013; Chauhan et al., 2010; Kumar and Palwalia, 2016; Ramirez and Torres, 2007; Rathore and Singh, 2017; Singh et al., 2004).

An innovative approach, based on a different IG single-phase equivalent circuit, is described in (Brudny et al., 2008). This solution consists on the use of a non-priority load which will be varied while keeping constant the argument of the total load and capacitor connected at the SEIG stator. The main objective of this work is to propose control strategies to increase the robustness of the regulation system. Also, the study of the transient enhancement of the SEIG by adjusting terminal capacitor connected across the stator terminals will be developed. This work is focused on studying the transient and the steady-state behavior of the SEIG when this one feed an inductive–resistive load.

The idea is to ensure dynamic variation of the capacitor $C$ in accord to the change of reactive power required by the load changes in order to enhance the voltage variation during the transient state.

Therefore, it is necessary to provide means of dynamic compensation of reactive power changes. The procedure is to use a thyristor controlled reactor (TCR) and a regulating impedance to adjust the reactive power at the SEIG outputs.

In this work, our contribution consists of developing a comparative study to analyze the operation of the generator in a controlled area where the frequency is almost constant without the need of a closed loop. For this purpose, the operating points of the SEIG are determined by means of a graphic study based on a theoretical development. Afterwards, one will do the same work using the particle swarm optimization (PSO) algorithm and the obtained results will be compared. Finally, one put the closed loop to control the frequency using a fuzzy logic controller (FLC) and one compare again the different obtained results.

The first section of this paper treats the SEIG operating point computing by means of PSO algorithm. The obtained results will be compared and approved by a numerical and graphical operating point determination. In a later section of this work, a developed strategy
based on the FLC to regulate the frequency will be analyzed. Finally, a comparative study to control the frequency and the reactive power at the outputs of the IG will be presented and examined. Computer simulations, experimental tests, and numerical analysis are carried out.

**Autonomous wind generator configuration**

The SEIG system configuration proposed for use in remote site is presented in Figure 1. Driven by the wind, this IG will provide electrical power to supply an inductive–resistive load. A capacitor bank of fixed capacitance $C_M$ provides the reactive power required by the machine and the load. This capacitor is placed in parallel with a regulating load ($Z_R$) to act as a variable capacitor which can provide dynamic compensation of the reactive power. In the test bench, a separately excited DC motor is used to ensure the wind turbine power. This motor is controlled by a pulse width modulation chopper, which allows the power regulation at the IG shaft.

The objective of the test bench configuration is to provide constant power on the common shaft of the IM and DC machines. Therefore, one performs a voltage and frequency regulation at the output of the SEIG without use of complicated power electronics systems (power electronic converters). In the case of a start-up, only the parameters which characterize the IM and those of the $R-L$ load and $C$ determine $\omega$, $s$ and therefore the angular rotor speed $\Omega'$. Consequently, the DC motor driving the asynchronous generator should not impose its parameters. In fact, at a given time interval, by analogy with the wind turbine blades, the mechanical power $P_w$ applied on the IG shaft should be constant. The other parameters such as, torque, voltage, and current result from the interaction between $P_w$, the generator, and the load.

**SEIG operating point computation**

In this section, we will present different methods to compute the operating point of the SEIG. To perform the transient and steady state studies of the IG, the SEIG modeling using space phasor formalism is numerically implemented. By means of the
concept of voltage source, Figure 2 presents the single-phase equivalent circuit of a three-phase IM with \( p \) pole pairs considering a parallel \((R-L)\) load (Brudny et al., 2008). To provide the required reactive power for self-excitation step and steady state operating, a capacitor is used in parallel with the load.

**Figure 2.** Single-phase equivalent circuit of SEIG. SEIG: self-excited induction generator.

**Figure 3.** Flow chart of PSO algorithm. PSO: particle swarm optimization.
Let us consider $S$ the slip obtained from rotor angular speed: $\Omega' = (1 - s)\Omega$ and the synchronous one: $\Omega = \omega/p$. By studying the time phasor diagram, developed in (Brudny et al., 2008) relative to the single-phase equivalent circuit given by Figure 2, it appears that the study of the real and imaginary parts of the complex variables leads to the following system

$$
\begin{align*}
\begin{cases}
s^2\omega^4 RLCA' + s^2\omega^2 LE'' - RA' + s\omega^2 LL^2 \rho^r - \omega^2 RLCD' + RD' + (R + r')Lr'^2 = 0 \\
s^2\omega^4 LA'' - s\omega^4 LB + s^2\omega^2 r'E' + s\omega^2 L^2 Rr' - \omega^2 LD'' + Rr'r'^2 = 0
\end{cases}
\end{align*}
$$

where the constants $A''$, $B$, $D''$, $E''$, $A'$, $D'$, and $E'$ are given by

$$
\begin{align*}
A'' &= L^2(1 + \lambda^i)[L^i(1 - (1 + \lambda^i)1 + \lambda^r)] - r^i RC(1 + \lambda^r) \\
B &= L^2 RCr^r, \\
D'' &= r'^2(L^i(1 + \lambda^i) + r^i RC), \\
E'' &= L^2(1 + \lambda^i)^2(R + r^i), \\
D' &= r'^2 L^i(1 + \lambda^i), \\
A' &= L^2(1 + \lambda^i)[L^i(1 - (1 + \lambda^i)(1 + \lambda^r))], \\
E' &= RLr'^2(1 + \lambda^r)^2
\end{align*}
$$

The equations of system 1 show that $\omega$ and $s$ depend only on $R$, $C$, $L$, and the machine parameters. Consequently, the IG will be locked on fixed $\omega$ and $s$ when these elements are chosen. In order to illustrate the different developments, the considered IG is characterized by the parameters denoted in Appendix A. The various parameters of the machine and that appearing in Figure 2 are given using the conventional no load and blocked rotor tests.

**PSO solution**

A PSO is one of the modern optimization techniques and can be applied on non-linear and non-continuous optimization problems with both continuous and discrete variables. It has been used in several applications (Babu et al., 2018; Bekakra and Ben Attous, 2014; Bharti et al., 2017; Manas, 2018; Ramdani et al., 2017; Wang and Singh, 2009). PSO is a population-based stochastic optimization technique developed by Kennedy and Eberhart in 1995, inspired by social behavior of bird flocking or fish schooling. In searching procedures by PSO, the particles are flown through the problem space by following the current optimum particles. Each particle keeps track of its coordinates, which are associated with the best solution that it has achieved so far. This solution is called personal best ($pbest$) and it is kept in the particle memory as the best position on the feasible search space. The best of value obtained so far by any particle in the group is commonly called the global best ($gbest$).

The basic concept behind the PSO technique consists of changing the velocity of each particle toward its $pbest$ and the $gbest$ positions at each iteration. The velocity and position of each particle can be modified according to the distance between its current position and $pbest$, and the distance between its current position and $gbest$. Using equation (3), a certain velocity that gradually gets close to $pbests$ and $gbest$ can be calculated. The current position (searching point in the solution space) can be modified by equation (4)

$$
v^{k+1}_{id} = v^k_{id} + c_1.r_1.(pbest_{id} - x^k_{id}) + c_2.r_2.(gbest - x^k_{id})
$$

(3)
\[ x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \]  \hspace{1cm} (4)

\[ i = 1, 2, \ldots, n \quad d = 1, 2, \ldots, m \]

where

- \( n \) number of particles in a population,
- \( m \) number of members in a particle (number of variables),
- \( v_i^k \) current velocity of particle \( i \) at iteration \( k \),
- \( v_i^{k+1} \) modified velocity of particle \( i \) at iteration \( k + 1 \),
- \( x_i^k \) current position of particle \( i \) at iteration \( k \),
- \( x_i^{k+1} \) modified position of particle \( i \) at iteration \( k + 1 \),
- \( r_1, r_2 \) random number between 0 and 1,
- \( pbest_i \) \( pbest \) of particle \( i \),
- \( gbest \) \( gbest \) of the population,
- \( c_1, c_2 \) acceleration constants.

The constants \( c_1 \) and \( c_2 \) represent the weighting of the stochastic acceleration terms that pull each particle toward the \( pbest \) and \( gbest \). The random numbers provide stochastic characteristics for the particles velocities in order to simulate the real behavior of the birds in a flock. An inertia weight parameter \( w \) was introduced in order to improve the performance of the original PSO model. This parameter provides a balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. The inertia weight parameter \( w \) often decreases linearly from \( w_{\text{max}} \) to \( w_{\text{min}} \) during a run. In general, the inertia weight \( w \) is set according to the following equation

\[ w = w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{k_{\text{max}}} \times k \]  \hspace{1cm} (5)

where \( k_{\text{max}} \) is the maximum number of iterations and \( k \) is the current number of iterations.

By incorporating this parameter into the velocity update equation (6), the modified velocity of each particle can be calculated as follows

\[ v_{id}^{k+1} = w.v_{id}^k + c_1.r_1.(pbest_{id} - x_{id}^k) + c_2.r_2.(gbest - x_{id}^k) \]  \hspace{1cm} (6)

**PSO algorithm.** The general PSO algorithm may be applied to any optimization problem. The steps of the algorithm can be represented as the flow chart shown in Figure 3. The whole PSO algorithm can be described in the following steps:

**Step 1: Initialization**

Initial conditions of searching points are usually generated randomly within their allowable ranges. For \( m \) variables in particle and \( n \) particles in population, the initial position of each
A particle can be expressed as the following form

$$x_i^0 = [x_{i1}^0, x_{i2}^0, x_{i3}^0, \ldots, x_{im}^0]$$  \hspace{1cm} (7)$$

where $x_d$ within the range $x_d^{\text{min}} \leq x_d \leq x_d^{\text{max}}$, $d = 1,2,\ldots,m$.

The initial velocity of each particle can be written as

$$v_i^0 = [v_{i1}^0, v_{i2}^0, v_{i3}^0, \ldots, v_{im}^0]$$  \hspace{1cm} (8)$$

where $v_d$ within the range $-v_d^{\text{max}} \leq v_d \leq v_d^{\text{max}}$

$$v_d^{\text{max}} = \beta (x_d^{\text{max}} - x_d^{\text{min}})$$  \hspace{1cm} (9)$$

where $\beta$ is a very well-defined ratio from the range of each variable. This factor determines the resolution. If $\beta$ is too high, particles might fly past good solutions. However, if $\beta$ is too small, particles may not explore sufficiently beyond local solutions. In many experiences with PSO, $\beta$ was often set at 10–20% of the dynamic range of the variable on each dimension.

**Step 2: Evaluation**

The current searching points are evaluated using the objective function of the target problem. The initial position $x^0$ is set as $pbest$. Set the particle associated with the best evaluation value among $pbests$ as the $gbest$. 

---

**Figure 4.** SEIG operating points. 
SEIG: self-excited induction generator.
Step 3: Modification of searching points

The current searching points are modified using the state equations (4) to (6) as follows

**Step 3a. Velocity updating**

The member velocity of each particle is modified according to equations (5) and (6) as

- If $v_{k+1}^d > v_{d}^{\text{max}}$, then set $v_{k+1}^d = v_{d}^{\text{max}}$
- If $v_{k+1}^d < -v_{d}^{\text{max}}$, then set $v_{k+1}^d = -v_{d}^{\text{max}}$

**Step 3b. Position updating**

Based on the updated velocities, each particle updates its position according to equation (4) as

- If $x_{k+1}^d > x_{d}^{\text{max}}$, then set $x_{k+1}^d = x_{d}^{\text{max}}$
- If $x_{k+1}^d < x_{d}^{\text{min}}$, then set $x_{k+1}^d = x_{d}^{\text{min}}$

$x_{i}^{k+1}$ must satisfy the problem constraints. If $x_{i}^{k+1}$ violates its constraints, then $x_{i}^{k+1}$ must be modified toward the near margin of the feasible solution.

**Step 3c. pbest and gbest updating**

Each particle is evaluated according to the updated position. If the evaluation value of each particle is better than the previous pbest, the current updated position is set to be pbest. If the best evaluation value among pbests is better than previous gbest, set the particle associated with it as the new gbest.

**Step 4: Stopping criterion**

If the number of iterations does not reach the maximum number of iterations, then go to step 3. Otherwise, the particle that generates the last gbest is the best evaluation and is considered as the optimal solution. After defining the variation range of $w$ and $s$ and their boundaries which are $[300 \text{ rd.s}^{-1}/316 \text{ rd.s}^{-1}]$ for the stator angular frequency $\omega$ and $[-8\%/-4\%]$ for the slip $s$, this approach allowed to find $\omega_{\text{ex}} = 313.235 \text{ rd.s}^{-1}$ and $s_{\text{ex}} = -6.03\%$.

**Graphical solution**

In this section, one presents another procedure to solve the equation system given by equation (1). This method can approve the solutions detailed by graphical method and PSO in the previous section. The resolution of the equation system (equation (1)) leads to the characteristics shown in Figure 4. There are two possible operating points (points A and B) resulting from the characteristics intersections. Implicitly it means that wind generator operation is possible only if $w$ and $s$ satisfy the two equations of this system. Let us consider that $\omega_1$ and $\omega_2$ are the composed solutions considered in the following study. The operating point (OP) “A”, whose coordinates are $s_{\text{ex}} = -6.029\%$ and $\omega_{\text{ex}} = 313.3 \text{ rd.s}^{-1}$, is placed in the characteristic located around $\omega_{\text{min}}$ where the variations of $\omega$ are relatively restricted. $\omega_{\text{min}}$ is the minimal stator angular frequency given by

$$\omega_{\text{min}}^2 = (s^2 r^4 E' + sL^2 R^2 - LD'')/[sL(B - sA'')]$$  (10)
and the slip $s$ is expressed as

$$s = \frac{A''D''L}{L^2 R^{r''r} A'' + BE^{r''}} \left[ 1 + \left( 1 - \frac{B(L^{r''2} R^{r''r} A'' + E^{r''} B)}{A''^2 D'' L} \right)^{1/2} \right] \tag{11}$$

This area, which contains the operating point $A$, is classified as stable operating zone. The $B$ operating point is characterized by high values of $\omega$ and $s$ which affect directly the stator voltage value. For this reason, this solution is not considered. For each machine, $L$, $R_0$, and $C_0$ values are chosen in order to place the operating point $A$ in the flattened zone of the curve.

In our case, the numerical application values for considered machine leads to $R = R_0 = 110 \ \Omega$, $C = C_0 = 87.7 \ \mu F$, and $L = 170 \ \text{mH}$. The analytical developments based on the properties which characterize the $A$ operating point show that is possible to keep $\omega$ quasi-constant, close to $\omega_{ex}$, for $R$ changes when $\tan \phi$ keeps a constant value, where $\phi$ is the argument of the $R-L-C$ parallel connected. This strategy is developed in (Touti et al., 2014) and needs to change $C$ with $R$ according to the following equality

$$C = \frac{(R + R_0(LC_0\omega_{ref}^2 - 1))}{LR\omega_{ref}^2} \tag{12}$$

**Impact of $L$ load on the operating point.** Considering the machine already presented, we are interested in demonstrating how the operating point is located when the load $L$ varies. Indeed, to appreciate the impact of the $L$ values on the situation of the different operating points which leads to fix the range of $L$ variation, we have taken the initial objectives of the study which consisted in analyzing the behavior of the system when it was connected to the output of the wind generator, an inductive load such as asynchronous motor or pump.

By definition, the pump power must be lower than that of the wind turbine. This peculiarity will be explained by a great magnetizing inductance of the pump compared to that of the wind generator ($L^2 = 0.534 \ \text{H}$). It should be noted that the resistance $R_0 = 110 \ \Omega$ is, implicitly, assumed to be constituted of a fixed resistor connected in parallel with the quantity internal resistance of the pump rotor. The cases we are going to deal with are as follows:

- $L = 0.17 \ \text{H}$: Value which is originally chosen
- $L = 0.55 \ \text{H}$: Which corresponds to a pump with power similar to that of the wind turbine
- $L = 1 \ \text{H}$: Corresponds to a pump with power that is two times lower compared to the wind turbine
- $L = 100 \ \text{H}$: Corresponds to a flow on an almost pure resistive load

In order to obtain meaningful comparisons, the values of $C$ and $R$ are adjusted to obtain the same values of $\omega_0$ and $s_0$, similar to those previously defined. The obtained results are gathered in Table 1. One can notice that $\omega_{ex}$ increases with the increase of $L$, whereas $s_{ex}$ keeps a quasi-constant value.
This phenomenon leads to a stable operating system for low values of load $L$. Indeed, a change in the load state accompanied by a decrease in the slip makes it possible to keep the angular frequency values at a reasonable value even if $s$ is very small. At the same time, $x$ takes relatively high values for a small change in $s$ when $L$ is large.

**Impact of $L$ load on the $C$ capacitor.** In practice, the value of $L$ can vary due to the voltage variation. If this variation is significant, it must be taken into account for the computation of the $C$ capacity which provides the reactive power. The relationship (12), used for $C$ calculating, takes into account the possible variations of both $L$ and $R$. In order to appreciate the $L$ impact on the OPs, it has been depicted in Figure 5 the cases for $L$ taking successively the values 0.136 H, 0.17 H, and 0.204 H. Taking into account the initial OP which is characterized by: $R_0 = 110 \, \Omega$, $C_0 = 87.7 \, \mu F$, and $L_0 = 170 \, \text{mH}$, Figure 5 presents the $C$ evolution versus $R$ for different $L$ values.

It is noted that for the same value of $R$, the increase of $L$ causes the decrease of $C$. Therefore $\omega$ takes relatively high values. This can be considered as an adverse effect on the energy performance of the SEIG. For this reason, when $L$ varies, $R$ and $C$ have to be changed according to the relationship (12). This procedure is the aim of the following section.

| $L$ (H)  | $R_0$ (Ω) | $C_0$ (μF) | $\omega_0$ (rd/s) | $s_0$ (%) | $\omega_{ex}$ (rd/s) | $s_{ex}$ (%) |
|----------|-----------|------------|-------------------|---------|---------------------|-------------|
| 0.17     | 111       | 87.3       | 298               | -5.4    | 314                 | -6.01       |
| 0.55     | 111       | 41.6       | 298               | -5.4    | 332                 | -6.02       |
| 1        | 111       | 32.3       | 298               | -5.4    | 344                 | -6.02       |
| 100      | 111       | 21.2       | 298               | -5.4    | 374                 | -6.05       |

**Figure 5.** Impact of $L$ load on the $C$ evolution according to $R$. 

| $L$ (H)  | $R_0$ (Ω) | $C_0$ (μF) | $\omega_{ex}$ (rd/s) | $s_{ex}$ (%) |
|----------|-----------|------------|----------------------|-------------|
| 0.136    | 110       | 87.7       | 314                  | -6.01       |
| 0.17     | 110       | 87.7       | 332                  | -6.02       |
| 0.204    | 110       | 87.7       | 344                  | -6.02       |

| $L$ (H)  | $R_0$ (Ω) | $C_0$ (μF) | $\omega_{ex}$ (rd/s) | $s_{ex}$ (%) |
|----------|-----------|------------|----------------------|-------------|
| 0.136    | 170       | 32.3       | 344                  | -6.02       |
| 0.17     | 170       | 32.3       | 374                  | -6.05       |
| 0.204    | 170       | 32.3       | 374                  | -6.05       |

| $L$ (H)  | $R_0$ (Ω) | $C_0$ (μF) | $\omega_{ex}$ (rd/s) | $s_{ex}$ (%) |
|----------|-----------|------------|----------------------|-------------|
| 0.136    | 204       | 32.3       | 374                  | -6.05       |
| 0.17     | 204       | 32.3       | 374                  | -6.05       |
| 0.204    | 204       | 32.3       | 374                  | -6.05       |
Reactive power adjustment

Static reactive power compensators or static VAR compensator (SVC) are shunts generating or absorbing reactive power. They can be used to control the voltage, at the points where they are connected, by injecting active or reactive current (Bouzid et al., 2012; Gelen and Yelcinoz, 2010). We can therefore identify them as variable impedance that can be sometimes inductive or capacitive load. The SVC is consisting of capacitors and inductances which are controlled by thyristors. They can allow the voltage regulation by controlling the reactive power quantity which will be provided or removed. The SVC can be considered as variable impedance which may response quickly to modification due to the sudden load variations. The current flowing through the reactance is variable between zero and its maximum value via the regulation of the thyristor firing angle.

Fixed capacitor TCR configuration

The fixed capacitor thyristor controlled reactor configuration (FC-TCR), shown in Figure 6, is used during our carried out study. It is made up of a fixed capacitor in parallel with the TCR which makes it possible to take advantage of existing capacitors for self-excitation IG. It suffices to choose a maximum value of all the capacitors necessary to supply the reactive power demanded by the machine as well as the neighboring charges. This configuration is used when the absorption and production of reactive energy is necessary. The value of the TCR reactance is variable and depends on the firing angle of the thyristors (Haque et al., 1985). Therefore the reactive power absorbed by the TCR is variable. The value of the inductance increases with the increase of the firing angle. This increase causes the decrease of the reactive power which will be absorbed.

Variable capacitor design

The configuration shown in Figure 6 is used when the production of reactive power or alternatively, absorption and production are needed. For a given $R-L$ load, the first step consists on finding by numerical simulation adequate pairs $(R,C)$ using the analytical method already described. The $C$ changes are obtained using a fixed capacitor $C_M$ parallel
connected with an $L_R$ inductance series connected with a dimmer. The aim is to control the $C$ variations after $R$ changes from the initial values when these operating point change. This procedure is realized by means of a regulating impedance made up of inductor $L_R$ in series with resistor $R_R$ as shown in Figure 6. The curves of the $v'(\theta)$ voltage and the $i'(\theta)$ current through the branch $R_{LR}-L_R$ are given in Figure 7. In this Figure, one showed the firing angle $\psi$, the current cancellation angle in the considered phase $\beta$, the current cancellation angle in the third phase $\theta_1$, and the control practical angle $\alpha$.

Let us assume that $L_R$ absorbs a part of reactive power which is provided by the total capacitor $C_M$, the capacitance of capacitor removed $C(\psi)$ will be expressed as

$$C(\psi) = \frac{3\sin\phi_1}{2\omega\pi \sqrt{R_{LR}^2 + (L_R\omega)^2}} \left( \left( \theta_1 - \psi + \frac{\pi}{4} - \frac{1}{2}\sin2\left( \theta_1 + \frac{2\pi}{3} \right) + \frac{1}{2}\sin2\psi \right)^2 + \frac{1}{4}(\cos2\psi - \cos2(\theta_1 + \frac{2\pi}{3}))^2 \right)^{\frac{1}{2}}$$

(13)

where $\phi_1$ is given by

$$\phi_1 = \tan^{-1}(L_R\omega/R_{LR})$$

(14)

Taking into account the relationship (13), the maximum capacitance $C_M$ for each phase is modified via the used dimmer to an equivalent value $C_{eq}$ given by

$$C_{eq}(\psi) = C_M - C(\psi)$$

(15)

### Influence of distorting regime

In order to analyze the inductive nature of the circuit and to calculate the $C$ capacitor with accurate values, we will propose an approach which takes into account the distorting
regime. Given the symmetry of the dimmer control signals, Fourier analyzes spectrum contains only the odd harmonics. The different powers are expressed by

\[
\begin{align*}
    P_{2h+1} &= \sum_{h=0}^{n} \left( \frac{V_{2h+1}^2}{\sqrt{R_{L,R}^2 + ((2h+1)\omega L_R)^2}} \right) \cos(\tan^{-1}(2h+1)\omega L_R/R_{L,R}^2) \\
    Q_{2h+1} &= \sum_{h=0}^{n} \left( \frac{V_{2h+1}^2}{\sqrt{R_{L,R}^2 + ((2h+1)\omega L_R)^2}} \right) \sin(\tan^{-1}(2h+1)\omega L_R/R_{L,R}^2) \\
    S_{2h+1} &= \sqrt{\sum_{h=0}^{n} V_{2h+1}^2 \sum_{h=0}^{n} P_{2h+1}^2}
\end{align*}
\]

The distorting power is defined by

\[
D_{2h+1} = \sqrt{S_{2h+1}^2 - P_{2h+1}^2 - Q_{2h+1}^2}
\]

Where

\[
\begin{align*}
    V_{2h+1}' &= \sqrt{\left( A_{2h+1}^2 + B_{2h+1}^2 \right)/2} \\
    I_{2h+1}' &= V_{2h+1}'/\sqrt{R_{L,R}^2 + ((2h+1)\omega L_R)^2}
\end{align*}
\]

and \( A_{2k+1}, B_{2k+1} \) are given by

\[
\begin{align*}
    A_{2h+1}^2 &= \frac{2V^2}{\pi^2} \left( \frac{\sin2h\beta - \sin2h\psi}{2h} - \frac{\sin(2h+1)\beta - \sin(2h+1)\psi}{2(h+1)} \right)^2 \\
    B_{2h+1}^2 &= \frac{2V^2}{\pi^2} \left( \frac{\cos2h\beta - \cos2h\psi}{2h} + \frac{\cos(2h+1)\psi - \sin(2h+1)\beta}{2(h+1)} \right)^2
\end{align*}
\]

Let us assume that distorting power is a reactive power, so the capacitance of the corresponding capacitor can be expressed as

\[
C_{\text{def}}(\psi) = D_{2h+1}/V^2\omega
\]

In our study of three-phase system, there is no harmonic 3 and multiple of 3 (\( D_{2k+1} = D_{1,5,7,...} \)). Consequently, the relationship (17) must be calculated without considering these harmonic. Therefore, the relationship (15) can be written as

\[
C_{\text{eq}}(\psi) = C_M - C(\psi) - C_{\text{def}}(\psi)
\]

So the variation of the R load is accompanied by a change of a final equivalent capacitor \( C_{\text{eq}}(\psi) \) through changing the firing angle \( \psi \). In this case, the equivalent reactive power
available on the isolated grid will be defined by

\[ Q_{eq} = U^2 \omega C_{eq}(\psi) \]  

(22)

In practice, the evolution of \( \psi \) depends on the previously calculated values in order to ensure a relative voltage stability obtained by coupling or decoupling the non-priority loads.

**Simulation results**

**SEIG modeling**

The asynchronous generator modeling is carried out using an analytical model based on space vector formalism to study the transient and steady state. The rotor and stator spatial reference \((d^s, d^r)\) are tied to the rotor and stator phase 1 axes. Let us consider \(\tilde{x}^s\) the stator space phasor variables which are defined relatively to \(d^s\) while \(\tilde{x}^r\) expresses the rotor space phasor variables defined relatively to \(d^r\). The stator space phasor variables defined relatively to the spatial reference \(d^r\) are denoted \(\tilde{x}^{ts}\). Therefore \(\tilde{x}^{ts}\) can be deduced from \(\tilde{x}^s\) using the expression

\[ \tilde{x}^{ts} = \tilde{x}^s \exp(-j\theta) \]  

(23)

where \(\theta = \omega t + \theta_0\) is the spatial angular gap between \(d^r\) relatively to \(d^s\) and the synchronous speed is defined by \(\Omega = \omega/p\). \(p\) is the number of pole pairs of the machine and \(\Omega'\) represents the rotor angular speed which is given by \(\Omega' = (1 - S)\Omega\) where \(S\) denotes the slip. The voltage equations written in the rotor reference frame are given by

\[
\begin{align*}
\dot{\psi}^{ts} &= r^s i^{ts} + \left( \frac{d L^s}{di_m} + \gamma L^s \right) \cdot \left( -\frac{r^r}{K_{2r}} \tilde{i}^{tr} \right) + \left[ \frac{d L^s}{di_m} + L^s + \ell^r - \frac{K_1r}{K_{x}} \left( \frac{d L^s}{di_m} + \gamma L^s \right) \right] \frac{d i^{ts}}{dt} \\
&+ j \omega' (L^s + \ell^r) \tilde{i}^{tr} + \gamma L^s \tilde{i}^{tr} + \chi L^s \tilde{i}^{ta} \\
0 &= r^r \tilde{i}^r + \left( \beta \frac{d L^s}{di_m} + \gamma L^s \right) \frac{d i^{ts}}{dt} + \left( \beta \frac{d L^s}{di_m} + \delta L^s + \ell^r \right) \frac{d \tilde{i}^r}{dt}
\end{align*}
\]  

(24)

While the equations of the fluxes linked by the stator, the rotor, and the fictitious windings can be expressed as

\[
\begin{align*}
\frac{d \tilde{\phi}^{ts}}{dt} &= \frac{d L^s}{di_m} \left[ \frac{d i^{ts}}{dt} + \gamma \tilde{i}^{tr} + \chi \tilde{i}^{ta} \right] \cdot \left[ \frac{d i^{ts}}{dt} + \frac{d \tilde{i}^r}{dt} \right] + (L^s + \ell^r) \frac{d i^{ts}}{dt} + \gamma L^s \frac{d \tilde{i}^r}{dt} \\
\frac{d \tilde{\phi}^r}{dt} &= \frac{d L^s}{di_m} \left[ \frac{d \tilde{i}^{tr}}{dt} + \gamma \tilde{i}^{ts} + \eta \tilde{i}^{ta} \right] \cdot \left[ \frac{d i^{ts}}{dt} + \frac{d \tilde{i}^r}{dt} \right] + (\delta L^s + \ell^r) \frac{d \tilde{i}^r}{dt} + \gamma L^s \frac{d i^{ts}}{dt} \\
\frac{d \tilde{\phi}^a}{dt} &= \frac{d L^s}{di_m} \left[ \frac{d i^{ts}}{dt} + \gamma \tilde{i}^{ts} + \eta \tilde{i}^{tr} \right] \cdot \left[ \frac{d i^{ts}}{dt} + \frac{d \tilde{i}^r}{dt} \right] + \gamma L^s \frac{d i^{ts}}{dt} + \eta L^s \frac{d \tilde{i}^r}{dt}
\end{align*}
\]  

(25)
where

\[
\begin{aligned}
\alpha &= \tilde{t}^s + \gamma \tilde{i}^r + \chi \tilde{a}, \\
\beta &= \delta \tilde{i}^r + \gamma \tilde{t}^s + \eta \tilde{a}, \\
K_{1r} &= \beta \frac{dL_s}{dm} + \gamma L_m, \\
K_{2r} &= \beta \frac{dL_s}{dm} + \delta L_s + \rho
\end{aligned}
\]  

(26)

The parameters met in equation (26) are given by: \( \gamma = 1/\sqrt{2} \), \( \delta = \frac{1}{2} \), \( \chi = \sqrt{L^a/L^s} \), \( \eta = \sqrt{L^a/2L^s} \), and \( \zeta = L^a/L^s \).

This model is developed in order to take into account the saturation effect. Nevertheless, in this study, the SEIG model is developed without considering the saturation effect. So, in these conditions, \( L^s \) is considered constant and equal to 0.534 H.

**Impact of the load on the voltage and the frequency**

In this section, the given simulation results present the variations of the space vector modulus (Figure 8(a)) and those of the rotor angular speed (Figure 8(b)). The steady state is reached when \( \tilde{t}^s, \tilde{i}^r, \) and \( \tilde{v}^a \) possess constant moduli and turn at the same speed \( s \omega_0 \). This steady state is characterized by the values \( s\omega_0 = 19 \text{ rd/s} \) and \( \omega^' = 332.1 \text{ rd/s} \), which lead to \( \omega = 313.1 \text{ rd/s} \), the slip \( s = 6.06\% \), and \( V^s = 224 \text{V} \). The study is carried out considering the case where the load changes, whereas the capacitor is kept constant and the case with changing the capacitor. During the load tilting from an initial state to another, Figure 8 (a) shows a significant improvement of transient voltage stability when the capacitor is modified according to the relationship given by the relationship (12). Whereas, one can remark a relative severe transient on the voltage when the capacitor is kept constant. The variation of the rotor angular speed is presented by Figure 8(b). During the load tilting, one can see a marked improvement of the transient and the maximum variations is reduced when the capacitor is modified, introduced by the use of dimmer and a regulating impedance \( Z_R \). The continuous compensation of reactive power during load changes enables a transient improvement for load and wind power variations.
Load variation at various capacitor state

The instantaneous line-to-line voltage is presented in this section. For a constant wind power 1800 W applied to the SEIG shaft, the variations of the stator voltage at constant $C$ value are shown in Figure 9. The steady state is characterized by a stator line-to-line voltage $U = 550 \text{ V}$ and a stator angular frequency $\omega = 313.1 \text{ rd.s}^{-1} (49.8 \text{ Hz})$. The analysis is performed by considering a resistive inductive load while driving the SEIG by constant power across its shaft. The case of a load variation is presented in Figure 9(a) at $t = 7s$. This Figure shows a simulation of the stator instantaneous line-to-line voltage considering an increase in the resistive load (from $R_0 = 110 \Omega$ to $R_2 = 85.5 \Omega$) at constant $C = 87.7 \mu\text{F}$. It is noticed that, during the load tilting, the voltage tends to decrease with strong oscillations during the transient state because the reactive power provided by $C$ is kept constant. This can be dangerous for the machine and the neighboring devices. On the other hand, the case of a load variation with considered value of the capacity is presented in Figure 9(b). This Figure shows a simulation of the stator instantaneous line-to-line voltage considering an increase in the resistive load while varying $C$ (from 87.7 $\mu\text{F}$ to 95.8 $\mu\text{F}$). It is remarked an enhancement during the transient. One can notice, by means of $C$ variation, an oscillations improvement and a short transient explained by continuous exchange of variable reactive power between the loads when $R$ values change.

One can conclude that changing $C$ with $R$ variation in accord to relation (17) is necessary and it improves the voltage and the frequency stability. So in the case of power wind variation, it is possible to ensure the voltage control by changing the $R$ value (active power) and it is possible to keep quasi-constant the frequency by adapting $C$ respecting relation (22). This adaptation can be ensured by TCR system that feeds regulating inductive load placed in parallel with $C_M$ in order to modify the reactive power and therefore the equivalent capacity $C_{eq}$.

SEIG frequency regulation

The wind turbine equipped with IG is considered as a nonlinear system. This system presents a marked fluctuation in the magnitude and frequency of the voltage at the outputs of the SEIG. Taking into account the benefits related to the FLC (Galdi et al., 2008;
Lin et al., 2007), its use seems to be a good alternative for regulating the frequency because of the linear controller presents difficulties especially for transient states. The configuration of the considered system is given by Figure 10. The fuzzy controller uses the measured $f$ frequency compared with a reference $f_{ref}$. It can involve three levels: measured signals preprocessing, application of the fuzzy rules set, and the decisional and final processing level. It can be implemented easily using a low-cost microprocessor. The fuzzy controller generates a control signal which will be transformed into an analog signal (0–10 V). This signal is proportional to the firing angle applied to the TCR. By this procedure, the reactive power delivered by the $C_M$ capacitor and consumed by the inductance $L_R$ placed in series with a dimmer will be regulated. The fuzzy controller considered in the studied control scheme is the Mamdany type.

Considering this configuration for SEIG frequency regulation, the gains at the input and the output of the fuzzy controller are respectively 0.279, 0.988, and 3.799. These gains evaluation are based on the experiment in order to lead to the desired quality setting. In this case, the triangular functions are chosen with normalized interval. The considered error is in the range $[-2.9\% \text{ to } 2.9\%]$ and $[-29\% \text{ to } 29\%]$ for error variation. The linguistic variables utilized in the membership functions are BN, MN, SN, JZ, SP, MP, and BP where BN means “Big Negative”, BP “Big Positive”, MN “Medium Negative”, MP “Medium Positive”, SN “Smaller Negative”, SP “Smaller Positive”, and JZ “Just Zero”. Figure 11 shows the membership functions of the used FLC input. Whereas, the membership functions of the output is given by Figure 12. Then, the rule-based fuzzy models are summarized and listed in Table 2.

The simulation results of the frequency evolution during a sudden change of the load are presented in Figure 13. It is remarked that the transient state is characterized by a strong oscillation when the capacitor is kept constant (red dotted line). Whereas, one can notice an improvement of the transient if the FLC is used. In fact, the latter has a less oscillations in the amplitude and less duration. But when the proportional integral (PI) controller is used, the curve presents a smaller gap (continuous line).
Table 3 gives theoretical values, those obtained by FLC and PI controller. According to these results, one can remark that the frequency extreme variation is obtained for the first case where the capacitor is kept constant. Whereas, the use of fuzzy controller can improve the frequency variation (from 50 Hz to 49.93 Hz).

By against for the same change of the load, the frequency scales from 49.88 Hz to 49.12 Hz. One can conclude that the frequency values obtained using FLC are very close. These results show that the FLC controller acts properly for the stabilization of the frequency.

**Figure 11.** Input membership functions.
BN: Big Negative; MN: Medium Negative; SN: Smaller Negative; JZ: Just Zero; SP: Smaller Positive; MP: Medium Positive; BP: Big Positive.

**Figure 12.** Output membership functions.
BN: Big Negative; MN: Medium Negative; SN: Smaller Negative; JZ: Just Zero; SP: Smaller Positive; MP: Medium Positive; BP: Big Positive.
Table 2. Linguistic rule.

| de | BN | MN | SN | JZ | SP | MP | BP |
|----|----|----|----|----|----|----|----|
| BN | BN | BN | BN | BN | MN | SN | JZ |
| MN | BN | BN | BN | MN | SN | JZ | SP |
| SN | BN | BN | MN | SN | JZ | SP | MP |
| JZ | BN | MN | SN | JZ | SP | MP | BP |
| SP | MN | SN | JZ | SP | MP | BP | BP |
| MP | SN | JZ | SP | MP | BP | BP | BP |
| SP | JZ | SP | MP | BP | BP | BP | BP |

BN: Big Negative; MN: Medium Negative; SN: Smaller Negative; JZ: Just Zero; SP: Smaller Positive; MP: Medium Positive; BP: Big Positive.

Figure 13. Rotor angular speed behavior during a sudden load variation.

Table 3. Angular frequency variation with different control strategies.

|                | C (μF) | R (Ω) | ω (rd.s⁻¹) | F (Hz) | S (%) |
|----------------|--------|-------|-------------|--------|-------|
| Numerical values at C constant | 87.7   | 110   | 313.3       | 49.88  | –6    |
|                | 131    | 308.5 | 49.12       | –5     |
|                | 85.5   | 323.2 | 51.46       | –7.7   |
| Obtained values using FLC | 87.3   | 110   | 314.2       | 50     | –6.01 |
|                | 84.9   | 131   | 313.7       | 49.93  | –5.1  |
|                | 96     | 85.5  | 307         | 48.86  | –7.7  |
| Obtained values using PI controller | 88.5   | 110   | 312.29      | 49.72  | –6    |
|                | 85.5   | 131   | 313.19      | 49.87  | –5    |
|                | 96.3   | 85.5  | 306.61      | 48.82  | –7.7  |

FLC: fuzzy logic controller.
Experimental results

The test bench, shown in Figure 14, is used to emulate the wind turbine operating based on a self-excited asynchronous generator in remote site. In the case of real operation, the IG is driven by the wind which will provide, through the blades, the mechanical power on the common shaft. This laboratory prototype of the proposed SEIG system has been developed to test the performance of the integrated system and to carry out the practical study of the IG. A DC motor fed by a DC power supply and controlled by a dSPACE system via a pulse width modulation (PWM) chopper is used in this test bench. The capacitor bank is placed in parallel with the load will allow the supply of the reactive power required by the IM as well as the load.

Impact of the load change

Figure 15(a) shows the stator voltage experimentally measured at the SEIG outputs during the R load variation while keeping $C$ at constant value. This test is carried out at 1800 W.
input wind power in the SEIG shaft. This experimental result confirms clearly that the line-to-line SEIG outputs stator voltage is stabilized at 550 V in steady state before load variation. Compared to stator voltage evolution simulated in Figure 9(a), one can remark the same behavior during transient state for the same resistive load variation (from $R_0 = 110 \Omega$ to $R_2 = 85.5 \Omega$). Whereas Figure 15(b) presents the line-to-line stator voltage measured at the SEIG outputs during the $R$ load variation while changing the $C$ capacitor. As a result, the stator voltage tends to decrease slowly with marked improvement of the transient oscillations when adjusting the reactive power by varying $C$ values. This case is simulated and presented in Figure 9(b).

The simulation and experimental tests show that the capacitor variation is very interesting for voltage and frequency regulation in remote site. In fact, it is noticed, strong oscillations during the transient state which may cause the SEIG disengagement when the capacitor is kept constant. For this reason, it is recommended to change the $C$ capacitors at any change of the load with the appropriate values in order to avoid the voltage collapse and consequently the dropping out of the machine.

**Dynamic stability analysis**

In remote site, the asynchronous generators need an external supply to provide the reactive power which is necessary for production of the rotating magnetic flux. An IM can operate as a self-excited generator when its rotor is driven by an external prime mover and its excitation is provided by placing capacitor bank at the stator outputs.

To avoid the generator dropping out when it is used in an off grid configuration, the wind generator requires an accurate reactive power regulation. The procedure used in this work consists on the use of the SVC devices, which is composed of FC-TCR as it is presented in Figure 6. The SVC when connected in shunt in the system can provide fast and smooth reactive power control. Also, it can effectively control the system voltage level during the IGs operation. This strategy consists on the variation of the capacitor $C$ with load variation according to the law given by the equation (12) to avoid the voltage instability, even its collapse. When the operating point is chosen and kept in the flattened zone shown in Figure 4, the frequency at the output of the generator is kept constant.

Figure 16(a) and (b) shows the frequency before and after a load variation when the capacitor $C$ is changed according to the equation (12). As it is remarked, the frequency is kept quasi-constant (from 1/20.16 ms to 1/20.08 ms) during this load variation.

However, Figure 17(a) and (b) presents a dynamic behavior following a sudden and strong change of the load. As is shown in Figure 17(a), the IG continues to work with significant variation in voltage and sharp oscillations at its outputs. However, Figure 17(b) presents a voltage collapse following the same change of the load, but the capacitor is kept constant which causes the machine dropping out.

This study shows that this procedure of changing the $C$ capacitor with $R$ changes according to the law given by equation (12) enhances the system stability and reveals the operating zones where the SEIG behavior can be controlled. It also proved operation at a quasi-constant frequency without the need of a control loop. This control law enhances also the transient state. For strong $R$ variations, this control strategy prevents the voltage collapse through changes of the reactive power supplied by the capacitor bank. This reactive power must vary continuously with load variations. In the test bench, the reactive power variation is ensured by a three-phase dimmer.
Reactive power analysis and C capacitor computing

Considering the SEIG operation in remote site, maintaining a constant voltage is ensured by a discrete variation of the resistive load via controlled switch. This load variation concerned only the consumers who are not priority and they can be disconnected or introduced in accord to the wind power changes. According to the relationship (13), the \( R \) load variation is accompanied by a capacitor change \( C = C_{eq}(\psi) \) through changing the firing angle \( \psi \). In this case, the equivalent reactive power available on the isolated grid is defined in equation (22). In practice, the evolution of \( \psi \) depends on the previously calculated values in order to ensure a relative voltage stability obtained by coupling or decoupling the non-priority loads. The equivalent capacitor \( C_{eq} \) can be determined by the equation (21). This capacitor depends on the firing angle \( \psi \). The experimental study considers that the regulating load consists of an inductance \( L_R = 145 \text{ mH} \) in series with a resistance \( R_{LR} = 1.05 \Omega \). For the considered load (\( \phi = 88.7^\circ \), \( Q = 43.36 \)), it is possible to work in mode 1 for \( 88.7^\circ < \psi < 120^\circ \). Figure 18 shows the waveforms obtained (voltage and current) for a firing angle \( \psi = 1.73 \text{ rd (5.52 ms)} \).

**Figure 16.** Generator stator voltage variation: (a) before load variation and (b) after load variation.

**Figure 17.** Stator voltage at strong load variation: (a) with changing the C capacitor and (b) with constant C capacitor.
The current cancellation angle $\theta_1$ in the third phase is given by

$$\sin \left( \theta_1 - \varphi - \frac{4\pi}{3} \right) e^{\theta_1 - \varphi} = -\sin(\varphi - \rho) \frac{1 - 2e^{-\pi/3Q}}{2 - e^{-\pi/3Q}}$$  \hspace{1cm} (27)$$

In our case, $\theta_{1,\text{the}} = 2.41 \text{ rd}$ for a measured practical angle $\theta_{1,\exp} = 2.47 \text{ rd}$. These angles are shown in Figure 19. The current cancellation angle in the first phase $\beta_{\text{the}}$ is given by

$$\beta = \psi + \pi + \alpha = \theta_1 + (2\pi/3)$$  \hspace{1cm} (28)$$

In the studied case, $\beta_{\text{the}} = 4.51 \text{ rd} (14.37 \text{ ms})$ for a measured practical angle $\beta_{\exp} = 4.58 \text{ rd} (14.6 \text{ ms})$.

Figure 20 shows the voltage and current experimental waveforms considering phase 1. For $\psi = \psi_{\text{lim}} = 120^\circ$, it can be noticed that the current has a low value which confirms the
choice of working in mode 1. According to the relationship (21), for \( \psi = 1.73 \) \( \text{rd} \), the capacitance value of resulting theoretical capacitor is \( C_{\text{the}} = 41.3 \) \( \mu F \) for a measured value \( C_{\text{mes}} = 48.9 \) \( \mu F \) (\( Q_L = 2500 \) VAR, \( \omega = 314 \) \( \text{rd.s}^{-1} \), and \( U = 403.5 \) V).

Therefore, the capacitance of the equivalent capacitor corresponding to the reactive power consumed by the regulating load is \( C_{\text{exp}} = C_{\text{the}} - C_{\text{mes}} = 102 \) \( \mu F \) - 48.9 \( \mu F \). Taking into consideration the relation (20), the capacitance of the equivalent capacitor corresponding to the distorting power is \( C_{\text{def}} = 11.8 \) \( \mu F \). Thus, the resulting capacitance of the equivalent capacitor at the generator terminals is \( C_{\text{eq}} = C_{\text{the}} + C_{\text{def}} = 53.1 \) \( \mu F \). In order to validate the relationship already mentioned, several firing angle values have been checked. The obtained values are presented in Table 4 where the distorting power computing is stopped for \( n = 7 \) (\( D_{1,5,7} \)).

As previously mentioned, with this computing method, theoretical capacitance values \( C_{\text{eq}} \) are close to experimental measured values \( C_{\text{exp}} \) as indicated in Table 4.

To predict the impact of the TCR on the signals quality of the generator, some measures were carried out at the SEIG outputs. Figure 21 shows the instantaneous evolution of the current (curve 3), the voltage at the output of the IG (curve 1), the current absorbed by the regulating impedance (curve 4), and the voltage at the terminals of this impedance (curve 2).

**Figure 20.** Waveforms for \( \psi \approx 120^\circ \).

**Table 4.** Theoretical and experimental capacitor values.

|                  | Test 1 | Test 2 | Test 3 |
|------------------|--------|--------|--------|
| \( \psi \) [\( \text{rd} \)] | 1.98   | 1.73   | 1.56   |
| \( \theta_{\text{the}} \) [\( \text{rd} \)] | 2.19   | 2.41   | 2.58   |
| \( \theta_{\text{exp}} \) [\( \text{rd} \)] | 2.27   | 2.47   | 2.6    |
| \( \beta_{\text{the}} \) [\( \text{rd} \)] | 4.28   | 4.51   | 4.67   |
| \( \beta_{\text{exp}} \) [\( \text{rd} \)] | 4.33   | 4.58   | 4.71   |
| \( C_{\text{the}} \) [\( \mu F \)] | 6.1    | 11.8   | 1.6    |
| \( C_{\text{def}} \) [\( \mu F \)] | 16.9   | 41.3   | 67.1   |
| \( C_{\text{exp}} \) [\( \mu F \)] | 23     | 53.1   | 68.7   |
| \( C_{\text{eq}} \) [\( \mu F \)] | 22.5   | 53.1   | 69.7   |
In this case, the $v_1$ voltage and the $i_1$ current measured across the regulating impedance correspond to a thyristor firing angle of the dimmer $\psi = 107.28^\circ$ (5.96 ms, Figure 21(a)) and $\psi = 111.6^\circ$ (6.2 ms, Figure 21(b)).

These quantities are measured directly on phase 1 of the generator without making the transformations to the space vectors to verify the impact of the use of the TCR on the quality of the signals delivered by the SEIG. The curves plotted in Figure 21 show that the stator voltage and current measured at the outputs of the generator are very slightly modified by the use of the dimmer.

**Conclusion**

In this paper, a robust strategy to enhance the transient state of the SEIG equipping a remote site was developed and analyzed. This study was developed to demonstrate the importance of the reactive power adjustment by varying $C$ value at the stator of the SEIG which supplies an inductive–resistive load in remote site. Some methods such as Newton–Raphson method, PSO method, and graphical development are used to determine the best operating point of the SEIG. Through this analysis, it was revealed that any change of $R$ load accompanied by $C$ capacitor variation can enhance the transient state and can make easy the control of the sudden voltage variations at the SEIG outputs which can cause the voltage collapse. The variable capacitor was obtained by adjusting a fixed capacitors battery while using a dimmer feeding an inductive regulation load. Also in this paper, it was presented an approach able to estimate the equivalent capacitor at the SEIG terminals considering the thyristors firing angle of the dimmer. To perform the transient and steady state studies of the IG, the SEIG modeling using space phasor formalism was numerically implemented. By means of this model, a fuzzy logic and PI controllers were simulated. These results show that the FLC controller acts properly for the stabilization of the frequency and the improvement of the transient state. The numerical simulations and experimental tests have demonstrated that this strategy can carry a significant improvement during transient state and consequently can avoid the SEIG collapse.

A major perspective of this work is to study and design a system for the smooth self-starting of the SEIG. This will prevent overvoltage that appear in the stator of the machine and may cause its stall or destruction of nearby equipment. In this context, we must think to make a thorough study of the starting of the wind generator to avoid significant variations.
in voltage and current that can trigger protections or disrupt electronic equipment. Another future work consists on the procedure of merging of two or more renewable energy sources, such as solar photovoltaic (PV) system, storage battery, and Wind IG, which can provide better power stability and reliability. Indeed, the operation of such hybrid system becomes more economical since the weakness of one source can be complemented by the strength of the other one.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors gratefully acknowledge the approval and the support of this research study by the Grant No. 7527-ENG-2018–1-8-F from the Deanship of Scientific Research at Northern Border University, Arar, KSA.

**ORCID iD**

Ezzeddine Touti  
https://orcid.org/0000-0002-5328-9528

**References**

Aggarwal M, Singh M and Gupta SK (2017) Performance enhancement of wind energy system with distribution static compensator. *Indian Journal of Science and Technology* 10(30): 1–8.

Ahmed T, Noro O, Hiraki E, et al. (2004) Terminal voltage regulation characteristics by static var compensator for a three phase self-excited induction generator. *IEEE Transactions on Industry Applications* 40(4): 978–988.

Babu TS, Prasanth Ram J, Dragicevic T, et al. (2018) Particle swarm optimization based solar PV array reconfiguration of the maximum power extraction under partial shading conditions. *IEEE Transactions on Sustainable Energy* 9(1): 74–85.

Bekakra Y and Ben Attous D (2014) Optimal tuning of PI controller using PSO optimization for indirect power control for DFIG based wind turbine with MPPT. *International Journal of System Assurance Engineering and Management* 5(3): 219–229.

Benghanem M, Bouzid AM, Bouhamida M, et al. (2013) Voltage control of an isolated self-excited induction generator using static synchronous compensator. *Journal of Renewable and Sustainable Energy* 5: 1–15.

Bharti OP, Saket RK and Nagar SK (2017) Controller design for doubly fed induction generator using particle swarm optimization technique. *Renewable Energy* 114: 1394–1406.

Bhim S, Murthy SS and Sushma GA (2006) Voltage and frequency controller for self-excited induction generators. *Electric Power Components and Systems* 34: 141–157.

Bouzid AM, Benghanem M, Hamane B, et al. (2012) Current control of the isolated self-excited induction generator using shunt active filter. *Energy Procedia* 18: 349–358.

Brudny JF, Pusca R and Roisse H (2008) Wind turbines using self-excited three-phase induction generators: An innovative solution for voltage-frequency control. *The European Physical Journal Applied Physics* 43: 173–187.

Chauhan YK, Jain SK and Singh BA (2010) Prospective on voltage regulation of self-excited induction generators for industry applications. *IEEE Transactions on Industry Applications* 46(02): 720–730.
Enany MA (2014) Steady state modeling and ANFIS based analysis of self-excited induction generator. *Wind Engineering* 38(3): 349–358.

Galdi V, Piccolo A and Siano P (2008) Designing an adaptive fuzzy controller for maximum wind energy extraction. *IEEE Transactions on Energy Conversion* 23(2): 559–569.

Gelen A and Yalcinoz T (2010) Experimental studies of scaled-down TSR-based SVC and TCR-based SVC prototype for voltage regulation and compensation. *Turkish Journal of Electrical Engineering* 18(02): 147–157.

Goyal SK and Palwalia DK (2016) A comprehensive analysis of optimal performance parameters of stand-alone generator. *Indian Journal of Science and Technology* 9(25): 1–13.

Haque SE, Malik NH and Sheferd W (1985) Operation of a fixed capacitor thyristor controlled reactor power factor compensator. *IEEE Transactions on Power Apparatus and Systems* 104(6): 1385–1390.

Hazra SP and Sensarma S (2010) Self-excitation and control of an induction generator in a stand-alone wind energy conversion system. *IET Renewable Power Generation* 4(4): 383–393.

Jazaeri M and Chitsaz H (2012) A new efficient scheme for frequency control in an isolated power system with a wind generator. *Electric Power Components and Systems* 40: 21–40.

Kennedy J and Eberhart R (1995) Particle swarm optimization. In: *In proceeding of IEEE international conference on neural networks*, Perth, Australia, 1995, 4, pp.1942–1948. Perth, WA, Australia: IEEE.

Kumar P and Palwalia DK (2016) Static voltage and frequency regulation of standalone wind energy conversion system. *Indian Journal of Science and Technology* 9(29): 1–6.

Lin F-J, Huang P-K, Wang C-C, et al. (2007) An induction generator system using fuzzy modeling and recurrent fuzzy neural network. *IEEE Transactions on Power Electronics* 22(01): 260–271.

Manas M (2018) Optimization of distributed generation based hybrid renewable energy system for a DC micro-grid using particle swarm optimization. *Distributed Generation and Alternative Energy Journal* 33(4): 7–25.

Mingjun L, Wenyuan L, Juan Y, et al. (2016) Reliability evaluation of tidal and wind power generation system with battery energy storage. *Journal of Modern Power Systems and Clean Energy* 4(4): 636–647.

Rahim AHMA, Ahsanul Alam M and Kandlawala MF (2009) Dynamic performance improvement of an isolated wind turbine induction generator. *Computers & Electrical Engineering* 35: 594–607.

Ramdan BA, Koad AFZ and El-Shahat A (2017) A novel MPPT algorithm based on particle swarm optimization for photovoltaic systems. *IEEE Transactions on Sustainable Energy* 8(2): 468–476.

Ramirez JM and Torres ME (2007) An electronic load controller for the self-excited induction generator. *IEEE Transactions on Energy Conversion* 22(2): 546–548.

Rathore UC and Singh S (2017) Control topologies for 3-phase SEIG used in small hydro power plant feeding isolated domestic load in remote mountainous region. *Indian Journal of Science and Technology* 10(31): 1–7.

Sarsing G, Gurumoorthy B, Murthy SS, et al. (2014) Efficient voltage regulation scheme for three-phase self-excited induction generator feeding single-phase load in remote locations. *IET Renewable Power Generation* 8(2): 100–108.

Singh B, Murthy SS and Gupta S (2004) Analysis and design of an electronic load controller for self-excited induction generators. *IEEE Transactions on Energy Conversion* 21(1): 285–293.

Touti E, Pusea R, Manata JP, et al. (2014) On the use of a dimmer for a robust frequency control of a self-excited three-phase induction wind generator. *Journal of Power Electronics* 12(4): 1–12.

Wang L and Singh C (2009) Multicriteria design of hybrid power generation systems based on a modified particle swarm optimization algorithm. *IEEE Transactions on Energy Conversion* 24(1): 63–172.

Yong L, Yuwen H, Huang W, et al. (2009) The capacity optimization for the static excitation controller of the dual-stator-winding induction generator operating in a wide speed range. *IEEE Transactions on Industrial Electronics* 56(2): 530–541.

Zhang Y and Ooi BT (2013) Stand-alone doubly-fed induction generators with autonomous frequency control. *IEEE Transactions on Power Delivery* 28(2): 752–760.
Zhaoxia J, Jisong Z and Rongxing H (2018) Sizing optimization for island micro-grid with pumped storage system considering demand response. *Journal of Modern Power System Clean Energy* 6(4): 791–801.

**Appendix A**

The considered induction machine is characterized by

\[
\begin{align*}
380 \text{ V} / 660 \text{ V}, & \quad 7.3 \text{ A} / 4.2 \text{ A}, \quad \cos \phi = 0.8, \quad p = 2, \quad 50 \text{ Hz}, \quad r^f = 3 \Omega, \quad 1420 \text{ rpm}, \\
6kW, & \quad r^s = 8.66 \Omega, \quad f^s = 24.24 \text{ mH}, \quad C_M = 113 \mu \text{F}, \quad f^r = 36.36 \text{ mH}, \quad J = 0.05 \text{ kg.m}^2, \\
L_R & = 215 \text{ mH}, \quad R_{LR} = 6.1 \Omega, \quad L^r = 267 \text{ mH}, \quad M^{sa} = 100 \text{ mH}, \quad M^{sr} = 377 \text{ mH}, \\
M^{ra} & = 70.6 \text{ mH}, \quad L^a = 18.7 \text{ mH}, \quad f^a = 18.7 \text{ mH}, \quad r^a = 10 \Omega, \quad X^a = L^a \omega.
\end{align*}
\]