On the Use of a Dimmer for a Robust Frequency Control of a Self-Excited Three-Phase Induction Wind Generator

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Abstract

This paper concerns a three-phase self-excited induction generator used for autonomous power generation. It presents a robust control strategy which makes it possible to maintain the frequency quasi constant during the voltage regulation without any control loop on this variable. This strategy, which also prevents the machine disengagement, uses as power converter a simple dimmer. The obtained theoretical and/or numerical results are validated on a laboratory test bench that allows the analysis of this control law effectiveness.

Key words: Self excited induction generator, frequency control, voltage collapse, space phasor, dimmer.

I. INTRODUCTION

Traditionally the integration of Induction Machine (IM) in the wind turbines, especially when it is about isolated sites, where the power requested is relatively limited, has become competitive and that can explain their increasing in the electrical energy production [1]-[5]. The IM is simple, reliable and requires very little maintenance [6]-[10]. However, there are some difficulties with this IM when it operates in autonomous mode as, for example, frequency and voltage control [11]-[12]. Actually many papers propose control strategies and applications of different power electronic controllers for Self Excited Induction Generator (SEIG) terminal voltage-frequency control [13]-[14]. In most of the cases, controlled source inverters are used [15]-[18]. Other papers present the design and implementation of a SEIG electronic load controller which consists of a rectifier-chopper system feeding a resistive dump load [19]-[21]. Some works propose the use of the synchronous compensators based on STATCOM (Static Synchronous Compensator) to control the voltage and the frequency [22]. A voltage source pulse width-modulated inverter is used in [23]-[26] to control the voltage and the frequency at the SEIG outputs. The use of sliding mode controllers to analyze the IM dynamic response and its behavior during load changes is presented in [27]-[28]. These studies implement complex techniques. Nevertheless, these solutions increase the system cost and they are not easily possible in remote sites unreliable in critical locations.

To overcome these difficulties, and to increase the robustness of the regulation system, this paper proposes a control law developed for a parallel resistive-inductive load (R−L) supplied by SEIG and which can be considered as an introduction to the study of AC electrical motors loads. So, in this case, the SEIG can operate at quasi-constant frequency without any control loop. This new control law makes it possible also to prevent the voltage collapse. The control of the frequency for a simple load (resistive load R) using a specific law has been proposed in [29] showing that this type of control can be a solution for remote and isolated sites. The difficulty consists in adapting the law to the complexity of the 'real' loads because during the regulation an important transient state can appear, as the case of motors loads.

In this paper, it is assumed that L is constant and that the voltage regulation is realized acting only on R load. The first part concerns the steady state analysis which uses for the IM a single phase equivalent circuit defined from the concept of a voltage source. The new frequency control law for R−L load is also outlined and discussed. The second part deals with the SEIG modeling based on space vector formalism. The control law effectiveness is analyzed as well as its impact during transients. The numerical predictions obtained by the developed SEIG model are compared to experimental results in the last part where the test bench is also presented.

II. STEADY STATE ANALYSIS

A. Single Phase Equivalent Circuit Model for IM

Using the concept of voltage source, Fig. 1 presents the three-phase, p pole pair, rotor cage IM single phase equivalent circuit considering a parallel (R−L) load. The C capacity is used to provide the required reactive power for self excitation and steady state operating [30]-[31]. \( \omega \) represents the stator angular frequency (frequency f).

Let us point out that to distinguish the statoric and rotoric
variables, these last are labeled respectively with the superscript "sin" or "cos".

\[
\begin{align*}
\dot{L} &= \lambda^s L^s \\
\dot{I} &= \lambda^r L^s \\
\end{align*}
\]

where \( \lambda^s \) and \( \lambda^r \) are small compared to unity. It results that the constants \( A", B", D", E", A', D', E' \) are given by:

\[
\begin{align*}
A" &= L''^2 (1 + \lambda^r) \left( L^r \left( 1 - (1 + \lambda^r)(1 + \lambda^r) \right) - \right) \\
B &= L''^2 R C \lambda^r \\
D" &= r''^2 \left( L^r (1 + \lambda^r) + r'' R C \right) \\
E" &= L''^2 (1 + \lambda^r)^2 \left[ R + r'' \right] \\
\end{align*}
\]

The quantities \( A', D', E' \) result from \( A", D", E" \) considering \( r'' = 0 \). The \( T_e \) IM electromagnetic torque can be expressed from the cross product [32]:

\[
T_e = k E^x (s) \times E^s (r) 
\]

where: \( k = 3 p / \omega X^s \). One can express the output \( V^s \) to SEIG RMS voltage from \( T_e \) :

\[
V^s = \sqrt{RL} \frac{T_e \omega - r''^2 + s^2 L^2 (1 + \lambda^r)^2 \omega^2}{3p \left( L^r \omega^2 + R^2 (LC\omega^2 - 1)^2 \right)} 
\]

\( T_e \) is related to \( P_w \) wind power which acts on the blades:

\[
P_w = (T_e + T_f) \Omega'
\]

where \( T_f \) represents the SEIG friction and windage torque.

**B. Identification of Operating Points (OP)**

According to system (5), it can be seen that \( \omega \) and \( s \) depend only on \( R \), \( C \), \( L \) and the IM parameters. Consequently, when these elements are imposed, the SEIG will be locked on fixed \( \omega \) and \( s \) regardless of \( P_w \). This latter will affect only \( V^s \). In order to illustrate the different developments, the considered IM is characterized by rated values denoted in appendix, if necessary, using the lower index "rat". For experiments, in order to prevent the IM from high damaging transients which appear during \( P_w \) and load changes, but also to avoid magnetic saturation, stator windings are star connected. The \( R \), \( C \) and \( L \) are chosen such as the electrical reference Operating Point (OP), denoted with the lower index " ref ", is decreased from the rated values by a \( \sqrt{3} \) ratio. The conventional no load and blocked rotor tests give the various parameters shown in the appendix.

1. **Approximately determination of OP**

When \( r'' \), \( \lambda^s \) and \( \lambda^r \) (denoted parasitic terms) are neglected, \( \omega \) and \( s \) can be identified with \( \omega_0 \) and \( s_0 \):

\[
\begin{align*}
\omega^2 R L C + R D' + (R + r') L r''^2 &= 0 \\
\omega_0^2 R L C' + r''^2 &= 0 \\
\omega_0^2 L A' + s^2 \omega_0^2 L^r B + s^2 \omega_0^2 L^2 R r''^2 &= 0 \\
\omega_0^2 L D'' + R r''^2 &= 0 \\
\end{align*}
\]
\[
\begin{align*}
\omega_0 &= \sqrt{\left( L' + L \right) / L' \cdot LC} \\
\omega_s &= -e^{\omega_0 t} / R 
\end{align*}
\] (11)

The analysis is performed at a frequency close to \( f_{ref} \), keeping \( s \) in the machine physical limits (\( s > -15\% \)). In order to really distinguish the case of a only resistive load, the load power factor is assumed in this case to be weak. For a value close to 0.45, using (11) one can obtain for \( L = L_0 = 170 \text{ mH} \), \( R = R_0 = 111 \Omega \), \( C = C_0 = 87.5 \mu F \), the \textbf{OP} characterized by: \( \omega_0 = 298 \text{ rds}^{-1} \), \( f_0 = 47.43 \text{ Hz} \), \( s = s_0 = -5.4\% \).

\textit{2- Exactly determination of \textbf{OP}}

In order to define the \( \omega_{ex} \) and \( s_{ex} \) exact values, the parasitic elements must be considered. So an iterative (Newton-Raphson) or graphical methods have to be used to solve system (5). In this paper only this last solution is presented. Considering the first equation of system (5), the following equation is obtained:

\[ M_1 \omega^4 + N_1 \omega^2 + P_1 = 0 \] (12)

Where \( M_1, N_1 \) and \( P_1 \) are given by:

\[ M_1 = LRC^2 A^2 \]  \[ N_1 = (L \omega^2 s - R^2 A^2) s^2 + LL^2 e^{-\omega} s - RLCD' \] (13)

\[ P_1 = R D^2 + L (R + r^2) e^{-\omega^2} \]

Taking into account that \( M_1 \) is negative and that the quantity under the radical is greater than unity, considering only the positive \( \omega \) value, the root of (12) can be expressed as:

\[ \omega_1 = \left[ -N_1 \left( 1 + \sqrt{1 - 4M_1 P_1 / N_1^2} \right) / 2M_1 \right]^{1/2} \] (14)

Similar considerations lead to the \( \omega_{2(1 \text{ or } 2)}^2 \) roots of the second equation of (5):

\[ \omega_{2(1 \text{ or } 2)}^2 = \left[ -N_2 \left( 1 + \sqrt{1 - 4M_2 P_2 / N_2^2} \right) / 2M_2 \right]^{1/2} \] (15)

where:

\[ M_2 = L s (A^2 s - B) \]  \[ N_2 = r^2 E^2 \cdot s^2 + L^2 e^{\omega} s - LD' \] \[ P_2 = R e^{\omega^2} s \]

(16)

The lower index \( 1 \) between brackets in (15) is associated with the sign \( + \) before the radical whereas the subscript \( 2 \) corresponds to the sign \( - \). Let us point out that \( M_2 \) has a positive value only for: \( 0 > s > s^* \) where: \( s^* = B / A \). That means that \( \omega_{2(1)} \) only exists in this range of \( s \) variations whereas \( \omega_{2(2)} \) exists for \( s \) between -1 and 0 as it appears in Fig. 2 plotted for \( R_0 \), \( L_0 \) and \( C_0 \) (\( s^* = -35.8\% \)).

As the \textbf{OPs} are given by the intersections of \( \omega_0 \) with \( \omega_{2(1)} \) and \( \omega_{2(2)} \), it appears that \( \omega_{2(2)} \) does not intervene in the \textbf{OP} definition. It results that only two \textbf{OPs}, tied to \( \omega_{2(1)} \) have to be considered. The \textbf{OP ‘A’}, whose coordinates are \( s_{ex} = -6.03\% \) and \( \omega_{ex} = 313.2 \text{ rds}^{-1} \), is placed in \( \omega_{2(1)} \) characteristic located around \( \omega_{min} \) where the variations of \( \omega \) are relatively restricted. \( \omega_{min} \) is the minimal stator angular frequency. This region, described as stable operating zone, is limited on the left considering the \textbf{SEIG} energetic performances. On the right the limitation is imposed by the frequency increase. Let us point out that for \( P_w = 1884 W \), (9) and (10) lead to \( V^* = V_{ref}' \). The \textbf{OP ‘B’} is characterized by high \( \omega \) and \( s \) values which may damage the \textbf{SEIG} energetic performance. However, stability elementary considerations show that this \textbf{OP} is in the region qualified as unstable of \( T_{ex}(s) \) characteristic. So, practically, this \textbf{OP} will not be considered. In order to appreciate the \( L \) impact on the \textbf{OPs}, one have depicted in Fig. 3 the cases for \( L = 100 H \), \( 1H \), \( 10H \) and \( 100H \). The latter case (\( L = 100H \)) can be assimilated to a resistive load. The system (11) shows that \( R = R_0 \), whereas \( C \) must take respectively the values \( C_0 = 32.52 \mu F \), \( 22.4 \mu F \) and \( 21.37 \mu F \). One can note that, regardless of the \( L \) value, \( \omega_{2(2)} \) never acts on the \textbf{OP} definition. Consequently, \( \omega_{2(2)} \) will not be considered in the following developments. Moreover, it appears that \( \omega_{ex} \) increases with \( L \) whereas \( s_{ex} \) keeps practically constant value. Finally it is noted that the range for \( \omega \) nearly constant increases as \( L \) decreases. This can be considered as benefit if there is no adverse effect on the energy performance mentioned above.

![Fig. 2. Operating points for \( R_0 \), \( C_0 \) and \( L_0 \)](Image 325x569 to 527x732)
C. SEIG operating at quasi constant frequency

The \( \omega \) relationship established for a \( R \) load makes it possible to show that \( f \) can be maintained quasi constant for \( R \) changes when the product \( RC \) is kept constant. It results that this condition can also be written as:

\[
RC \omega = \text{cst}
\]  
(17)

which, physically, corresponds to a constant argument of the elements connected to the SEIG outputs. One can define a similar law considering a parallel \( R-L \) load. It suffices to define an equivalent \( \gamma \) capacity to the parallel \( C-L \). It comes:

\[
\gamma = \left[ L C \omega^2 - 1 \right] / L \omega^2
\]  
(18)

It results that (17) can be written as:

\[
R \left[ L C \omega^2 - 1 \right] / L \omega = \text{cst}
\]  
(19)

Starting from OP ‘A’ obtained for \( R_0 \), \( L_0 \) and \( C_0 \), a \( R \) change must be accompanied by a \( L \) and \( C \) changes in order to obtain a new \( \omega \) practical value close to the initial one. That needs to satisfy the following equality:

\[
R_0 \left[ L_0 C_0 \omega^2 - 1 \right] / L_0 = R \left[ L C \omega^2 - 1 \right] / L
\]  
(20)

As it is assumed that the stator voltage control is performed only adjusting \( R \), \( L \) is constant and (20) is satisfied changing only \( C \). In these conditions, (20) can be written as:

\[
R_0 \left[ L_0 C_0 \omega^2 - 1 \right] = R \left[ L C \omega^2 - 1 \right]
\]  
(21)

To exploit (21), one has to choose the \( \omega \) value which has to be used for the \( C \) determination. As \( \omega_{\text{ex}} \) is, a priori, unknown, \( \omega_{\text{ref}} = \omega_{\text{rat}} \) is considered. For two values for the \( R \) changes between about \( \pm 20\% \) from \( R_0 \) (these values are compatible with those ones considered during experiments), the corresponding \( C \) values which satisfied (21) are shown along the diagonal of Table I. Let us point out that the use of \( \omega_{\text{ex}} \) for these determinations leads to practical same values for \( C \) because \( \omega_{\text{rat}} \) is very close to \( \omega_{\text{ex}} \).

<table>
<thead>
<tr>
<th>( R ) (( \Omega ))</th>
<th>Case 00</th>
<th>Case 10</th>
<th>Case 11</th>
<th>Case 20</th>
<th>Case 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 = 111 \Omega )</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>( R_1 = 132 \Omega )</td>
<td>Case 10</td>
<td>Case 11</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>( R_2 = 86 \Omega )</td>
<td>Case 20</td>
<td>-----</td>
<td>Case 22</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

In this table, the selected values are chosen in order to satisfy the conditions of the operating point determination presented in section B. The OP position variations for only \( R \) load changes (\( L \) and \( C \) constant) are shown in Fig. 4.a for \( R_0, R_1 \) and \( R_2 \). The results presented in Fig. 4.b concern these \( R \) changes with variable \( C \) and, consequently, respectively the quantities \( C_0, C_1 \) and \( C_2 \). One can observe that applying the \( f \) frequency control law makes it possible to practically confuse the three characteristics in the controlled zone described in Fig. 2. To better appreciate the law effectiveness, Fig. 5 presents the \( \omega \) (Fig. 5.a) and \( \Omega' \) (Fig. 5.b) variations for \( R \in [85 \Omega \pm 135 \Omega] \).
Two cases are considered: only $R$ changes and the pair $(R, C)$ changes. If the latter varies respecting the suggested law, it appears that it is possible to reduce in a ratio close to 2 the $f$ variations. The $R$ and $C$ changes are accompanied by simultaneous variations so that $\Omega'$ is maintained nearly constant. In considered study case, $sV$ has also be determined assuming that $wP$ is constant and equal to $1884W$. The $sV$ variations are practically independent of the used strategy and are included between $191V (R = 85Ω)$ and $248V (R = 135Ω)$. This shows that regulating the SEIG output voltage by acting on $R$ value is perfectly suited.

### III. SEIG MODELLING

#### A. Mathematic formulation

This modelling is performed considering a two pair pole IM with three-phase equivalent rotor winding. The rotor and stator spatial reference ($d'$ and $d''$) are confused with the rotor and stator phase 1 axes. In order to take into account the SEIG self-excitation, a rotor residual magnetic field is created by means of a three phase fictitious winding, distributed on the rotor like the equivalent rotor winding. The variables corresponding to these fictitious windings are labeled with the superscript "a". These coils of $n^a$ turns are supplied by $i_q^a$ DC currents ($q=1, 2$ or $3$) with a null sum.

The stator space phasor variables defined relatively to $d'$ are denoted $\bar{X}^s$. In the same way, a rotor space phasor variable defined relatively to $d'$ is written: $\bar{X}^r$. $\bar{X}^a$ can be deduced from $\bar{X}^s$ using variable change: $\bar{X}^a = \bar{X}^s \exp(-j\theta)$ where: $\theta = \theta_0 + \omega't$ is the spatial angular gap between $d'$ relatively to $d''$ and $\omega' = p\Omega'$.

In these conditions, the IM voltage equations written in the rotor reference frame are given by:

$$
\begin{align*}
\frac{dv^r}{dt} & = r^r i^r + j\omega' \bar{X}^s \\
\frac{dv^s}{dt} & = r^s i^s + j\omega' \bar{X}^s \\
\frac{dv^a}{dt} & = r^a i^a + j\omega' \bar{X}^s
\end{align*}
$$

(22)

The quantities $r$ are the per phase winding resistances, $\bar{X}$ define the winding linked flux space phasors:

$$
\begin{align*}
\bar{X}^r & = L^r (1 + \lambda^r) i^r + M^{ra} i^s + M^{ar} i^r \\
\bar{X}^s & = L^s (1 + \lambda^s) i^s + M^{as} i^s + M^{sa} i^r \\
\bar{X}^a & = L^a (1 + \lambda^a) i^a + M^{aa} i^s + M^{sa} i^r
\end{align*}
$$

(23)

where $L$ (that appear in (23)) are the main winding cyclic inductances, the $M$ quantities denote the mutual inductances between the windings and $\lambda^a = l^a / L^a$ is the coefficient which characterizes the fictitious winding leakage inductances. Let us point out that initially, $\lambda'$ has been defined from $L' : \lambda' = l' / L'$, where $l'$ and $L'$ are proportional to the squared $n^a$ statoric per phase effective turn number. As $l'$ and $L'$ are proportional to the squared $n^r$ rotoric per phase effective turn number, $\lambda'$ is also given by: $\lambda' = l' / L'$. To these IM equations must be added a relationship tied to the components connected at SEIG outputs. Fig. 1 leads to:

$$
\tilde{i}^s = -(\tilde{i}_R + \tilde{i}_C + \tilde{i}_L)
$$

(24)

Moreover, to model this SEIG during transients as well as during steady states, a mechanical relationship has to be considered:

$$
T_w = T_e + T_f + J \frac{d\Omega'}{dt}
$$

(25)

$J$ is the overall system inertia. $T_w$ results from $P_w : T_w = \frac{P_w}{\Omega'}$. $T_e$ is defined by the cross product:

$$
T_e = 3 p (\bar{X}^s \times \tilde{i}^s) / 2
$$

(26)
Taking into account that all the main and mutual inductance coefficients are constants (because saturation is neglected) and that the \( \dot{T}^a \) time derivative is null, make it possible an easy numerical implementation of these equations. During the SEIG self excited step, the \( i_q^a \) currents are such as:

\[
\left| i_q^a \right| = 0.2 \text{ A and null after this step.}
\]

The following presented results concern the variations of \( \left| r^o \right| = \left| r^s \right| \) modulus (solid line) expressed in (volts) and those of \( \omega' \) (dashed line) expressed in (rd.s\(^{-1}\)). The variations of the last variables are shown versus time expressed in seconds (s).

B. SEIG Startup

For a constant power \( P_w = 1884 \text{ W} \) applied to SEIG shaft the variations of presented variables during startup are shown in Fig. 7 for \( R_0, L_0, C_0 \). The steady state, that appears at \( t = 6 \text{ s} \), is reached when \( \dot{T}^s, \dot{T} \) and \( \ddot{V}^s \) possess constant moduli and turn at the same \( s \omega \) speed. It appears that in steady state, \( s \omega = 18.9 \text{ rds}^{-1} \) for \( \omega = 314.2 \text{ rds}^{-1} \), \( s = 5.4\% \) and \( \dot{V}^s = 223 \text{ V} \). An important voltage peak value appears during the transient which can damage the SEIG.

Consequently, in practice, a device must be added in order to protect the IM and the components connected at its outputs. That justifies the choice made in this study: \( V_{\text{ref}}^s < V_{\text{rat}}^s \).

C. Transient state for Constant Shaft Power \( P_w \)

The curves shown in Fig. 8 present an example of \( \left| r^s \right| \) and \( \omega' \) variations with time for constant \( P_w \) equal to \( 1884 \text{ W} \) and for a \( R \) change at \( t = 8 \text{ s} \). Fig. 8.a is relative to the case 00 \( \rightarrow \) case 20 change but Fig. 8.b concerns the case 00 \( \rightarrow \) case 22 change. It appears first that the maximum variations of \( \left| r^s \right| \) and \( \omega' \) are reduced when the suggested law is used. On the other hand, this law leads to an important increase in the speed when \( C \) is kept constant. In fact, this latter increases by 5.24\% in the steady state speed in Fig. 8.a and 0.12\% in Fig. 8.b.

The obtained simulation results show that considering (21) the frequency can be maintained quasi constant with a transient state improved.

D. Transient state for variable Shaft Power \( P_w \)

In steady state, for \( R_0, L_0, C_0 \) and \( P_w = 1884 \text{ W} \), it is assumed that at \( t = 8 \text{ s} \), \( P_w \) varies taking the \( 2204 \text{ W} \) value. The regulation occurs at \( t = 8.05 \text{ s} \). Fig. 9.a shows the variations of \( \omega' \) and \( \left| r^s \right| \) when only \( R \) changes (case 00 to case 20, Table I) in order to keep \( \left| r^s \right| \) constant. First of all, one notes the relatively high transients on speed and voltage. If the new steady state is characterized by a voltage which is nearly identical to that existing before the state change, it is not the case for the speed which increase considerably decreasing \( s \) (from \( -6.03\% \) to \( -7.75\% \)). Fig. 9.b shows these variable variations when \( R \) and \( C \) vary simultaneously: case 00 \( \rightarrow \) case 22. The voltage regulation is also effective with, however, strongly attenuated transients in
amplitude and duration. The final steady state is characterized by a speed close to that existing before the $P_w$ change.

![Fig. 9. Variations of $\omega'$ and $|v'|$ for $P_w$ change from 1884W to 2204 W: (a) only $R$ changes; (b) $R$ and $C$ change](image)

$E. \text{ Voltage Collapse}$

Starting from steady state corresponding to case 00 and $P_w = 1884W$, it is assumed that at $t = 8s$, $R$ varies taking the 61Ω value. Fig. 10.a shows the variable variations with time which correspond to a voltage collapse characterized by a voltage drops and an IM acceleration. The same switching to $R = 61Ω$ accompanied by a $C$ change according to the suggested law, is presented in Fig. 10.b. It appears that following a relative severe transient on the voltages, the SEIG manages to return to an operational steady state with a decrease of the voltage and an increase of the rotor angular speed (from $\omega' = 332.1 rds^{-1}$ to $\omega' = 345.1 rds^{-1}$). However, the $\omega'$ variation has a slight influence on the $f$ modification (frequency changes from $f = 49.8 Hz$ to $f = 49.3 Hz$) because the slip $s$ is changed to reach $s = -11.25 \% \ (\omega = \omega'(1-s) = 310.1 rds^{-1})$.

IV. EXPERIMENTAL STUDY

A. Test bench presentation

In order to validate the analytical and numerical results, a test bench (Fig. 11) is used. It consists of DC motor which operates at constant magnetic flux $\phi$, mechanically associated with an IM which operates as a SEIG. There are two problems to implement such a system: the first consists in providing a $P_w$ control on the IM shaft, the second is to provide a variable $C$ capacitor which changes with $R$ according to the relationship (21).

1) Regulation of $P_w$

In order to control $P_w$, the DC motor is connected at chopper outputs supplied with constant $U_0$ DC voltage. This chopper is controlled by a data acquisition numerical system (dSPACE & Matlab) which samples the $i_{DC}$ current of the DC motor. The dSPACE system uses as input $i_{DC}$ in order to provide a $\beta$ analogical signal which controls the chopper operating. This machine is compensated which allows to neglect the inductive effects.
The DC machine electromagnetic torque is given by:

$$T_{DC} = K_{DC} \phi$$  \hspace{1cm} (27)

where $K_{DC} = K' \phi$, $K'$ being a constant tied to the DC machine design. In the operating range considered for this analysis, the $T_{JDC}$ SEIG friction and windage torque can be assumed constant.

The torque which acts on the IM shaft is given by:

$$T_w = T_{DC} - T_{JDC}$$  \hspace{1cm} (28)

The $P_w$ power results from the relationship:

$$P_w = \beta U_0 \phi_{DC} - R_{DC} i_{DC}^2 - T_{JDC} \Omega'$$  \hspace{1cm} (29)

where $R_{DC}$ is the DC machine armature resistance. Given $U_0$, $T_{JDC}$, $R_{DC}$ and $i_{DC}$, the dSPACE system can computes $\beta$ from (29) in order to control $P_w$.

In (29), the speed $\Omega'$ is estimated using the relationship:

$$\Omega' = (\beta U_0 - R_{DC} i_{DC}) / K_{DC}$$  \hspace{1cm} (30)

It should be noted that the different parameters of this practical bench will be given in the appendix.

2) Capacitor variation

For a given $R-L$ load, the first step consists of finding by numerical simulation adequate pairs $(R, C)$ using the analytical method described in section II. This leads to some OP within the zone which can be described as stable (Fig. 2). The voltage regulation is performed with $R$ variations using controlled mechanical switches (Fig. 11). For this application, several $R$ discrete values are used. The $C$ changes are obtained using a fixed capacitor $(C_M > C)$ parallel connected with a fixed $L_R$ inductance series connected with a dimmer as shown in Fig. 12. That leads, for given frequency close to $f_{rat}$, to different $\alpha$ dimmer firing angles whose values have to be computed and incorporated in the «control logic» block (Fig. 11). The developments realized for the $\alpha$ calculus are those presented in [33].

B. Validation of numerical model in steady state

The experiment has been done at the same constant $P_w$ equal to 1884W with a starting point relative to $R_0$, $L_0$ and $C_0$. The changing limits values given in section II are those corresponding to case 22 and case 11 (Table I). The values, presented in Table II, show the $f$ and $\Omega'$ variations with $R$ changes taking into account the theoretical and experimental values.

One can note that $f$ presents weak variations between theoretical and experimental values which seems to be compensated following the $s$ variations as it can be shown in the variation of $\Omega'$ values. The theoretical and experimental $\Omega'$ variations are nearly very close. One can remark here a robust frequency control obtained by capacity variation using the suggested law given by (21).

C. Validation of numerical model during transients at constant $P_w$

The curves presented in Fig. 13 show the $|F'|$ variations

<table>
<thead>
<tr>
<th>Experimental values</th>
<th>Theoretical values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$ Hz</td>
<td>$s$</td>
</tr>
<tr>
<td>R=111 C=87.5</td>
<td>49.8</td>
</tr>
<tr>
<td>R=132 C=83.1</td>
<td>50.3</td>
</tr>
<tr>
<td>R=86 C=95.5</td>
<td>49.6</td>
</tr>
<tr>
<td>R=132 C=87.5</td>
<td>48.9</td>
</tr>
<tr>
<td>R=86 C=87.5</td>
<td>51.3</td>
</tr>
</tbody>
</table>

Fig. 11. Test bench schematic diagram

Fig. 12. Variable C capacitor realization
when $R$ changes for constant $P_w$ equal to 1884W. This example corresponds to that presented in section III.C. Fig. 13.a is relative to the case 20 and Fig. 13.b concerns a change to the case 22. In Fig. 13.a, the SEIG reaches the steady state after a transient relatively large. This transient state is accompanied by important overvoltage which may trigger the protection systems leading to the disconnection of the SEIG. Fig. 13.b shows a reduced $|\bar{r}^s|$ variations (decreased to half) during transient state.

This is an improvement obtained by the use of the proposed law. So one can remark that these experimental results are close to those obtained by simulation (Fig. 8) with transient state duration slightly greater in the experimental case.

For validation of $P_w$ control law, the case corresponded to a load variation (case 00 to case 22) considering $P_w$ constant is shown in Fig. 14. The curves are plotted in per unit taking into account the variable values obtained before transient as references: $P_{wref}^*=1884W$, $|\bar{r}^s|_{ref}=315V$, $i_{DCref}=10.7A$ and $U_{DCref}^*=197V$.

However these curves are delayed with adapted coefficients in order to keep the figure clarity. In Fig. 14, the per unit values are multiplied by: 1 for $|\bar{r}^s|$, 1.55 for $U_{DC}$, 1.65 for $i_{DC}$ and 2 for $P_w$.

It can be noticed that during the load changes, the average $i_{DC}$ and $U_{DC}$ values are modified but $P_w$ is maintained at quasi-constant value by dSPACE control. One notes a decrease of $|\bar{r}^s|$ values with weak variations during transient regime. In this case only the frequency is kept constant. These measured values correspond to the case also simulated in Fig. 8.b.

D. Validation of numerical model during transients at variable $P_w$

The variable variations when $P_w$ varies and the load changes from case 00 to case 22 is shown in Fig. 15. The curves are plotted in per unit values and are multiplied by the same coefficient as used in Fig. 14. This case validates the $|\bar{r}^s|$ regulation law as simulated in Fig. 9. b. For this case the transient state is improved, $|\bar{r}^s|$ is stabilized and $f$ kept constant value.

### Table II

<table>
<thead>
<tr>
<th>Studied Tests</th>
</tr>
</thead>
</table>

**Fig. 13.** Variations of $|\bar{r}^s|$ at constant $P_w$: - (a) Only $R$ changes, - (b) change of $R$ and $C$
Presented study was developed to ensure a robust frequency control for a Self Excited Induction Generator which supplies a $R-L$ load connected in parallel with capacitor banks. The steady state analysis developed in the paper uses the single-phase equivalent circuit definition taking into account the concept of induced voltage source and the IM space vector formalism. This analysis shows that the presence of $L$ component in the load enhances naturally the system stability and reveals the operating zones where the SEIG behavior can be controlled. It was also revealed the operating at quasi constant frequency without need of a control loop of the latter. This has been possible by means of changing the $C$ capacitor with $R$ changes, in the case of load variations, according to the defined law presented in the paper. This control law enhances also the transient state. For the strong $R$ variations, this control strategy will prevent the voltage collapse through changes of the reactive power supplied by the capacitor bank. This reactive power must vary continuously with the load variations according to the law already studied. So in the test bench, the reactive power variation is ensured by a three-phase dimmer. The experimental tests have validated the analytical control law variation is ensured by a three-phase dimmer. The transient state analysis developed in the paper. The test bench and induction machine are characterized by:

**Fig. 15.** $U_{DC}$, $i_{DC}$ and $P_{e}$ variations for variable $P_{e}$

### REFERENCES


$$L' = 534mH \quad r' = 8.66\Omega \quad r'' = 6\Omega \quad l' = 24.24mH \quad l'' = 36.36mH \quad \lambda' = 0.0454 \quad \lambda'' = 0.068 \quad I_{DC_{ref}} = 23A \quad R_{DC} = 0.63\Omega \quad T_f = 1.3Nm \quad \Gamma_{fDC} = 0.9Nm \quad K_{DC} = 1.26 \quad U_{0} = 280V \quad U_{DC_{ref}} = 220V \quad L_R = 215mH \quad C_M = 113\mu F$$

The rated values are : $380V / 660V \quad 7.3A / 4.2A \quad 50Hz \quad 1420rpm$, but the reference values are : $V'_{ref} = 223V \quad s'_{ref} = 5.4\% \quad I_{ref}' = 2.42A \quad \omega_{ref} = \omega_{rat} = 314.2rds^{-1}$.


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