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Voltage and Frequency Control of Wind-Powered Islanded Microgrids based on Induction Generator and STATCOM

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Abstract—This paper presents a comprehensive modeling of a three-phase cage induction machine used as a self-excited squirrel-cage induction generator (SEIG), and discusses the regulation of the voltage and frequency of a self-excited SEIG based on the action of the static synchronous Compensator (STATCOM). The STATCOM with the proposed controller consists of a three-phase voltage-sourced inverter and a DC voltage. The compensator can provide the active and reactive powers and regulate AC system bus voltage and the frequency, but also may enhance the load stability. Moreover, a feed forward control method for the STATCOM is introduced and applied for controlling the SEIG’s terminal voltage using a two-degree of freedom RST controller. Simulation results for the steady-state operating condition and transient operating conditions for the system subjected to a wind reference step change, and a step load change are presented to demonstrate the effectiveness of the proposed controller.

Keywords— STATCOM, voltage control, frequency control, islanded generation, induction generator

I. INTRODUCTION

Due to the rapid depletion of conventional fuels and the quick growth of environmental protection concepts, renewable energy sources have been extensively developed and studied in the whole world. Wind, bio, hydro and solar energy are in the forefront with fairly mature technologies adaptable to the field [1]. Wind energy is, for many reasons, one of the most promising renewable energy sources; it comprises a wind turbine, an electric generator, a power electronic converter and the corresponding control system [2]. In this sense, self-excited induction generators (SEIG) are good candidates for wind powered electricity generation especially in remote areas, because they do not need an external power supply to produce the excitation magnetic field [3]. The performance of voltage and frequency in isolated induction generator may vary according to the speed of the rotor and the load connected to the generator, due to a decrease in the speed of the rotating magnetic field [4]. The wind turbine can be designed to operate at a constant speed or variable speed. The frequency of the isolated induction generator varies with the load demand, and therefore its application should be to supply equipment insensitive to frequency variations, such as heaters, water pumps, lighting, charging battery, etc. But the major disadvantage of SEIG, is its poor voltage and frequency regulation under source and load perturbations, which may limit its use in isolated and scattered generation areas, such as wind and micro hydro renewable energy sources [5]. For applications that require constant voltage and frequency, the stator voltage isolated induction generator should be controlled to stay at a given reference value. A SEIG can be controlled by varying the rotor resistance of a SEIG sliding ring, but it requires more maintenance than a squirrel cage rotor due to sliding rings [6]. In a SEIG, a rotor squirrel cage is preferable to a wound rotor because the rotor squirrel cage has higher thermal-order potential and require less maintenance [7]. In addition, SEIGs are more robust and cheaper than other electrical machines for the same power rating. They require less maintenance once built with a squirrel-cage. However, at start-up, the induction generator requires a reasonable amount of reactive power which must be fed externally to establish the magnetic field necessary to convert the mechanical power from its shaft into electrical power [3]. This reactive power can be supplied by a bank of capacitors connected across its terminals that must remain permanently connected to the stator windings responsible for the output voltage control [8]. Fig.1 shows the stator side of the generator, a capacitor bank used for the excitation, the STATCOM, and the consumer load.

This paper introduces a voltage and frequency control of a wind-power islanded microgrid by using a STATCOM. A mathematical model of the proposed system is developed. The STATCOM is controlled by using a feed-forward and two
feedback control loops. The RST controller is proposed in order to obtain a good performance. Therefore, a control scheme is required to regulate the output voltage to meet the constant voltage demand. The simulation results using MATLAB® environment are carried out and thoroughly discussed and included in this paper.

II. MATHEMATICAL MODEL OF A SEIG

The modeling of the three-phase squirrel cage induction generator is performed through the Clarke and Park transformations in the synchronously rotating reference frames and the relevant volt-ampere equations are written as [9] (variable are defined in Appendix):

\[ \mathbf{V} = [\mathbf{R}] \mathbf{I} + \left[ L \right] \frac{d}{dt} \mathbf{I} + \omega_r [\mathbf{G}] \mathbf{I} \quad (1) \]

from which, the current derivative can be expressed as:

\[ \frac{d}{dt} [\mathbf{I}] = \left[ L \right]^{-1} \{ [\mathbf{V}] - [\mathbf{R}] [\mathbf{I}] - \omega_r [\mathbf{G}] [\mathbf{I}] \} \quad (2) \]

\[ \frac{d}{dt} [\mathbf{I}] = -\left[ L \right]^{-1} \{ [\mathbf{R}] [\mathbf{I}] + \omega_r [\mathbf{G}] [\mathbf{I}] - [\mathbf{V}] \} \quad (3) \]

A. Magnetizing inductance

The SEIG operates in the saturation region and its magnetizing characteristics are non-linear in nature. The magnetizing current should be calculated at every step of integration in terms of the stator and rotor d-q currents as:

\[ I_m = \sqrt{(I_{ds} + I_{dq})^2 + (I_{qs} + I_{qr})^2} \quad (4) \]

Fig. 2. Comparative study between linear and saturation state

Fig. 2 shows the evolution of magnetizing inductance \( L_m \) and dynamic inductance \( L \) as a function of the magnetizing current \( I_m \) module of SEIG. When the operating point is reached, the machine delivers a voltage to the stator, which effective value is constant. The simulation of the phenomenon of self-excitation of the asynchronous machine with capacitors cannot be achieved with this model since it is the saturation itself that sets the steady state operating point.

The magnetizing inductance is calculated from the magnetizing characteristics and it is obtained by synchronous speed test for the machine. For the test machine rated at 3.5 kW, it is defined as:

\[ L_m = 0.63 \tan(0.15I_m) / I_m \quad (5) \]

B. Electromagnetic torque

The developed electromagnetic torque \( T_e \) of the SEIG is:

\[ T_e = (3P/4)L_m (I_{qs} I_{ds} - I_{ds} I_{qr}) \quad (6) \]

The Torque balance \( T_{shaft} \) equation is:

\[ T_{shaft} = T_e + J(2/P) \frac{d}{dt} \omega_r \quad (7) \]

With \( P \): number of pole pairs; and \( J \): Inertia of the induction machine.

C. Excitation system model

Equations (7) and (8) represent the self-excitation capacitor currents and voltages in d-q axes representation.

\[ \begin{align*}
I_{ds} &= I_{cd} + I_{id} \\
I_{qs} &= I_{cq} + I_{iq}
\end{align*} \quad (8) \]

\[ \begin{align*}
\frac{d}{dt} V_{ld} &= \frac{1}{C_{ex}} I_{ds} - \frac{1}{C_{ex}} I_{ld} \\
\frac{d}{dt} V_{lq} &= \frac{1}{C_{ex}} I_{qs} - \frac{1}{C_{ex}} I_{lq}
\end{align*} \quad (9) \]

With \( I_{cd}, I_{cq} \) representing the capacitor currents, \( I_{ld}, I_{lq} \) representing the grid inductor currents, and \( C_{ex} \) representing the capacitor excitation.

D. R-L load model

Equations (10) and (11) represent the d-q axes load voltages and currents.

\[ \begin{align*}
V_{ld} &= R I_{ld} + \frac{L}{d} \frac{d}{dt} I_{ld} \\
V_{lq} &= R I_{lq} + \frac{L}{d} \frac{d}{dt} I_{lq}
\end{align*} \quad (10) \]

\[ \begin{align*}
\frac{d}{dt} I_{ld} &= \frac{L}{R} V_{ld} - \frac{R}{L} I_{ld} \\
\frac{d}{dt} I_{lq} &= \frac{L}{R} V_{lq} - \frac{R}{L} I_{lq}
\end{align*} \quad (11) \]

III. SYSTEM CONFIGURATION AND CONTROL SCHEME

The STATic COMpensator (STATCOM) is designed to regulate the line voltage at the Point of Common Coupling (PCC), by injecting or absorbing a certain amount of reactive power. It can balance loads or compensate load reactive power by producing the desired amplitude and phase of inverter output voltage [10]; it may also be used for additional tasks such as stabilization of power system. The STATCOM is playing increasingly important roles in reactive power provision, which is why it receives considerable attention due to the urgent requirement for tackling the voltage fluctuation problems. The topology of the SEIG - STATCOM presented in this paper is depicted in Fig.3. The compensator consists of a voltage source converter, a DC voltage, an inductance, \( L_{sh} \) (representing the leakage inductance of the transformer and line) and a resistor, \( R_{sh} \) (representing the inverter and transformer conduction losses) on the AC side. STATCOM is connected in parallel with a fixed capacitor and load. In order to obtain a rated voltage at no load, the suitable capacitor bank is needed. Synchronous frame (dq) control is used so that the reference currents that control the reactive power and consequently the generated voltage become simple, effective and easy to tune. Feed forward loops of \( i_d^* \), \( i_q^* \) and \( V_q \) are...
used to minimize the coupling effect between $i_d$ and $i_q$. The voltage at the DC bus is relatively smooth due to the battery [11, 12].

A. Voltage and frequency control

The voltage control is performed according to the following steps:

- The regulation of the load voltage/frequency is performed by comparing the actual voltage/frequency to a desired reference value.
- The error between the two voltages goes through a PI controller. The regulation of the load voltage/frequency is controlled by the PI controller and with regulation. It is based on the pole placement theory. The RST controller is used with both control loops and it is implemented in continuous form. The block diagram of a system with its RST controller used in the inner loop is shown in Fig 5.

The active power $P_a$ and reactive $Q$ power are expressed by

$$Q = \frac{1}{2}E_d I_d \quad P_a = \frac{3}{2} E_d I_q$$  \hspace{1cm} (14)

IV. DESIGN OF THE RST CURRENT CONTROLLER

The objective of this section is to obtain the RST current controller ($i_d$ and $i_q$). This type of controller is a structure with two degrees of freedom as compared to a one degree of freedom structure. Its main advantage is that it allows the designer to specify performances independently with reference trajectory tracking (reference variation) and with regulation. It is based on the pole placement theory. The RST controller is used with both control loops and it is implemented in continuous form. The block diagram of a system with its RST controller used in the inner loop is shown in Fig 5.

$$Y_{ref} = \frac{B T}{(A S+B R)} Y_{ref} + \frac{R S}{(A S+B R)^2}$$  \hspace{1cm} (16)

By applying the Bezout equation, we have

$$D = A S + B R = C F$$  \hspace{1cm} (17)

Where $C$ is the command polynomial and $F$ is the filtering polynomial. In order to have good adjustment accuracy, we choose a strictly proper regulator. So if $A$ is a polynomial of degree $n$ ($\text{deg}(A) = n$) we must have:

$$\text{deg}(D) = 2n + 1; \quad \text{deg}(S) = \text{deg}(A) + 1;$$

$$\text{deg}(R) = \text{deg}(A)$$  \hspace{1cm} (18)

To find the coefficients of polynomials $R$ and $S$, the robust pole placement method is adopted with $T_c$ as control horizon and $T_f$ as filtering horizon.

$$\begin{align*}
A &= a_1 s + a_0 \\
B &= b_0 \\
D &= d_3 s^3 + d_2 s^2 + d_1 s + d_0 \\
R &= r_1 s + r_0 \\
S &= s_2 s^2 + s_1 s + s_0
\end{align*}$$  \hspace{1cm} (19)
We have $P_c = -1/T_c$ pole of polynomial order $C$, and $P_f = -1/T_f$ double pole of the polynomial filter $F$. The pole $P_c$ must improve the speed response of the system and is generally chosen $2$–$5$ times greater than the pole of $P_a = -R_{sh}/L_{sh}$. $P_f$ is generally chosen $3$–$5$ times smaller than $P_c$. According to the robust pole placement strategy, the polynomial $D$ can be written as:

$$D = \left(s + \frac{1}{P_c}\right)^2$$

(20)

$$R_c = 5P_a = -\frac{2\omega}{L_{sh}}$$

(21)

To improve the speed response of the system, we adopt the following conditions:

$$D = (s - 5P_a)(s - 15P_a)^2$$

(22)

By identifying equations (14) and (21), we deduce the coefficients of the polynomial $D$, which are linked to the coefficients of $R$ and $S$ by the Sylvester matrix. Thus, we can determine the parameters of the RST controller as follows:

$$
\begin{align*}
    d_3 &= a_1s_2 \rightarrow s_2 &= \frac{d_1}{a_1} \\
    d_2 &= a_4s_1 \rightarrow s_1 &= \frac{d_2}{a_2} \\
    d_1 &= a_0s_1 + b_0r_1 \rightarrow r_1 &= \frac{d_1 - a_0s_1}{b_0} \\
    d_1 &= b_0r_0 \rightarrow r_0 &= \frac{d_1}{b_0} \\
    T &= r_0
\end{align*}
$$

(23)

V. CASE STUDIES

To examine the effectiveness of the proposed STATCOM controller, the system in Fig. 3 was simulated using Matlab®/Simpower and the results are presented. The system parameters used in the simulation are listed in Table I. The residual magnetism in the machine is taken into account in the simulation process without which it is not possible for the generator to self-excite. Initial voltage in the capacitor is also considered. The results obtained for different considerations are as follows.

A. Excitation with and without saturation

![Fig. 6. Simulation of the SEIG with/without saturation](image)

If the magnetizing inductance is considered as constant and equal to its value in the unsaturated state, the magnetization characteristic then has no saturation bend and there is no intersection with the external characteristic of the capacitor so that the stator variables evolve into the infinite as shown in Fig.6.

To take account of the saturation of the magnetic circuit of the machine, the magnetization curve is necessary; it is generally obtained by experimentation and approximated by a polynomial interpolation. Fig. 7 illustrates the case when the system is started from zero speed. The SEIG is excited with capacitance value $C=270\mu F$ and value of rotor speed $\omega_r = 314 \text{ rad/s}$ the generated voltage and current attain their steady state values of $220 \text{ Volts}$ and $19 \text{ A}$ in $0.8$ sec, respectively.

![Fig. 7. Simulation of the SEIG with $C_{ex} = 270\mu F$ with saturation](image)

B. Variation of load resistance in steps

In this case, the rotor of the induction machine is driven at $1500 \text{ r/min}$ while $C_{ex} = 270\mu F$. The load $R$ is applied to evaluate the performance of the proposed control strategy of the STATCOM. The load resistance is varied in steps.

1) Variations of load without loop control

The load variation range should be small compared with the regulated system to avoid the demagnetization of the SEIG.

![Fig. 8. Effect of load variation on the voltage and frequency](image)

As shown in Fig. 8 the magnitude of the voltage and frequency increases as the load is increased and decreases with the load.

2) Load variation with voltage & frequency control

To test this case, simulation results are shown in Fig. 9. It shows that the STATCOM has very fast dynamic responses. In addition, we observe that the variation of STATCOM current is
also proportional to load changes. For the powers, we note that the variation of $P_s$ is related to the regulation of the frequency and the variation of $Q_s$ is for the voltage regulation. Initially, the system voltage is at its nominal value, $P_s$ and $Q_s$ for (VSI) must be zero, as there is no need for regulation. At time $t = 2 s$ we can see that if the frequency decreases the VSI must provide $P_s$ and if it increases then the VSI must absorb $P_s$. Similarly, if the voltage amplitude decreases the VSI should provide $Q_s$ and vice versa, which keeps the reactive power constant.

![Fig. 9. Performance characteristics of the SEIG-STATCOM with load variation.](image1)

C. Voltage control under wind speed variation

In this case, the rotor of the induction machine is driven by speed steps while $C_{ex} = 270 \mu F$.

1) Variation of speed without control

At $t = 2 s$, the rotor speed rises from $315 \text{ rad/s}$ to $320 \text{ rad/s}$ and down to $310 \text{ rad/s}$ at $t = 5 s$, while the consumer load remains at $R = 1 \text{ K}\Omega$, as shown in Fig. 10. The magnitude of the voltage and frequency increases when the speed is increased and decreases when the speed is decreased.

![Fig. 10. Effect of wind speed variation on the voltage and frequency](image2)

2) Variation of speed with voltage and frequency control

As in the previous case, the voltage and frequency are controlled efficiently (Fig. 11). After transient periods, both the voltage magnitude and frequency return to their rated values as a result of the variation of the reactive power or active power dealt by the compensator. The STATCOM increases the output currents after the wind speed changes but the load voltage and frequency remain constant.

![Fig. 11. Effect of wind speed variation on the voltage and frequency](image3)
effective for the regulation of the voltage and frequency when the wind speed varies.

![Graph showing performance characteristics of SEIG-STATCOM with wind speed variations.](image)

VI. CONCLUSION

This paper has presented the control of the induction generator using a STATCOM for improving the performance without mechanical turbine control. The control scheme of STATCOM with independent control of its active and reactive powers is proposed. This control can be successfully employed for frequency and voltage magnitude regulation under varying wind speed and load conditions. The results demonstrate that RST controller presents the best performance and the feed forward control enhances the transient response and decoupling of direct and quadrature currents. This work presents some encouraging results that have been determined for the SEIG variable load/ wind speed. The proposed scheme has been verified by simulations results and shows good performance.

APPENDIX

<table>
<thead>
<tr>
<th>Symbol</th>
<th>PARAMETER</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_m )</td>
<td>Rated power of the SEIG</td>
<td>3.5 kW</td>
</tr>
<tr>
<td>( V_n )</td>
<td>Rated voltage of the SEIG</td>
<td>220/380 V</td>
</tr>
<tr>
<td>( I_n )</td>
<td>Rated current of the SEIG</td>
<td>14/8 A</td>
</tr>
<tr>
<td>( R_s )</td>
<td>Stator resistance</td>
<td>0.76 Ω</td>
</tr>
<tr>
<td>( R_r )</td>
<td>Rotor resistance</td>
<td>0.74 Ω</td>
</tr>
<tr>
<td>( L_{is} )</td>
<td>Stator Leakage inductance</td>
<td>0.003 H</td>
</tr>
<tr>
<td>( L_{ir} )</td>
<td>Rotor Leakage inductance</td>
<td>0.003 H</td>
</tr>
<tr>
<td>( L_m )</td>
<td>Magnetization inductance</td>
<td>0.074 H</td>
</tr>
<tr>
<td>( P )</td>
<td>Pole pair number</td>
<td>2</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>( L_m )</td>
<td>Magnetizing Inductance</td>
<td>( L_m = 0.63 \tan^{-1}(0.15 L_m)/I_m )</td>
</tr>
</tbody>
</table>

\([V],[I],[R],[L]\) and \([G]\) are defined below:

\[
L = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & I_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}; \quad G = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -L_m & 0 & 0 & -L_r \\ 0 & 0 & 0 & 0 \end{bmatrix};
\]

\[
[R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_d & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_p \end{bmatrix}; \quad [V] = \begin{bmatrix} V_{ds} & V_{qr} & V_{dr} & V_{qr} \end{bmatrix}^T;
\]

\[
[I] = \begin{bmatrix} I_d & I_q & I_d & I_q \end{bmatrix}; \quad L_s = L_{ig} + I_m; \quad L_r = L_{ir} + L_m
\]

REFERENCES


