Understanding the Origin of SSR in Series-Compensated DFIG-Based Wind Farms: Analysis Techniques and Tuning

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ABSTRACT
This paper is dedicated to presenting control-tuning methodologies for the rotor-side converter (RSC) and grid-side converter (GSC) of series-compensated DFIG-based wind farms (WF) and to determining the origin of subsynchronous resonance (SSR). Unlike conventional approaches to re-tuning controller gains to achieve desirable performance, these methodologies only consider the mathematical models of the states variables to be controlled. A PI cascade topology is used to control the RSC and GSC. An inner loop is required for current control and an outer loop for voltage control. Special consideration is taken for tuning the RSC because this converter is coupled with the mechanical variables as mechanical rotor speed of the DFIG. Compared with standard tuning, a better system behavior during a resonance condition is achieved with the proposed tuning methodology. Regarding the analysis of the SSR origin, the modal impedance (MI) technique is used as a tool to study SSR issues; its advantages compared to the driving point impedance technique are highlighted. In this context, the small-signal-stability (SSS) analysis is performed to evaluate the overall system. With the combination of MI and SSS, the phenomena of induction generator effect, torque interaction, and torque amplification are analyzed. As a result, the modes involved in the SSR phenomenon are identified and a discrimination procedure is described to determine the origin of the SSR.

INDEX TERMS
Doubly fed induction generator (DFIG), subsynchronous resonance (SSR), eigenvalue analysis, oscillatory stability, power converter, wind farm, control tuning.

I. INTRODUCTION

According to Global Wind Energy Council (GWEC), wind energy is the most promising green power for bulk production due to it becomes more profitable each year and has an increasing global commitment to combat climate change [1]. The global trend in wind energy conversion systems (WECS) is the installation of series compensation in the transmission lines to increase the transmissible power capabilities of an existing transmission line. This solution is the most cost-effective to increase the power transfer capabilities [2]. In counterpart, series capacitors in transmission lines can bring some troubles related to sustained oscillations at frequencies below the system fundamental frequency; this phenomenon is called SSR, firstly described in [3]. SSR has been detected and documented in several WECS with catastrophic damages, as described in [4]–[6].

To tackle this issue, the state of the art shows solutions based on flexible AC transmission systems (FACTS). The use of FACTS of the series-connected controllers family as a thyristor-controlled series capacitor (TCSC) and GTO thyristor-controlled series capacitor (GCSC), where an auxiliary controller or the integration of a damping circuit on the existing topology are proposed in [7]–[9]; these two strategies of solution are the most common practice. Another solution is based on implementing an auxiliary control for the GSC controller (GSCC) or RSC controller (RSCC) of the DFIG [10]. In this regard, the installation of TCSC and fixed series compensation are the solutions offered by ABB for transmission systems improvement [11]. Other solutions
are based on static synchronous compensator (STATCOM), where a control strategy is proposed [12]–[14] or the implementation of a photovoltaic system as STATCOM for SSR alleviation in a steam turbine in a series compensated transmission line [15]. The less common proposed solution to mitigate SSR is based on unified power flow controller (UPFC) systems [16], [17]. Nevertheless, the connection of the FACTS to the network could increase the problems of SSR due to the standard tuning of its controllers, e.g., the TCSC can produce resonance by itself [18]. Additionally, the tuning methods of the RSCC and GSCC in DFIG-based WF are not widely reported [19]. The common practice in the tuning process is based on the methods for re-tuning the existing gains, as in [20] where the authors proposed a PI parameters optimization algorithm based on the small-signal model, eigenvalues, and participation factors to avoid the SSR. Similar work is presented in [14], where the authors proposed a method to adjust the gains using phase space reconstruction. However, the methods before mentioned can only be applied if the entire system to be re-tuned is able to be linearized. Since the DFIG-based WF is a critical active, in this paper methods already available are proposed to be used in Type 3 WECS with the additional merit of improving the back-to-back (BTB) performance for SSR. In this context, a methodology for tuning the BTB controllers is presented.

Once the controllers have been designed, several tools are used commonly to determine the whole system behavior and identify possible resonance issues. Among some tools are dynamic simulation, eigenvalue-based analysis, Bode diagrams, Nyquist diagrams, impedance analysis, or even analysis tools based on the equivalent circuit [21]–[23]. According to this, the importance of the analysis methods is addressed in [24], where a small-signal model approach is proposed to assess the low-frequency stability of the system. There are other analysis methods based on the impedance or admittance model, as [25] where the analyzed model can changes easily according to the presence of the number of distributed generators.

After the relevant topics have been identified, Figure 1 aims to describe the contribution areas to be developed in this paper. Figure 1 shows a graphic description of the interest topics under study pointed out in green boxes. Also, it is shown the general distribution of the problem due to the integration of series compensation and it is shown the relation of each topic.

According to the state of the art and considering Figure 1, the contribution of this paper is focused on two topics:

1) The control tuning process for each loop of the cascade topology is methodologically performed for the GSCC and RSCC; it is shown how to apply the tuning process in a BTB converter of a Type 3 WECS. The merit of this approach is that it only requires the linearization of those state variables to be controlled, instead of the linearization of the entire system as the proposed re-tuning techniques discussed above. The proposed tuning process implements five different approaches.

2) Modal impedance technique and equivalent circuit are tools used to detect the modes involved in the SSR and a procedure to determine the origin of the SSR is formulated. The features of modal impedance are studied in an environment of SSR.

These contributions permit to configure straightforwardly a proper solution for addressing the specific frequency components that originate the SSR. This paper is organized as follows: In Section II, the concerning models for analysis and the study system are described. In Section III, the background of the SSR issues is presented. The tuning process is addressed in Section IV. Dynamic simulations are performed in Section V. In Section VI the modal impedance analysis to identify the main modes of the system is applied and a phenomena discrimination procedure is presented. Conclusions are given in Section VII.

**FIGURE 1.** Graphic description of the contribution areas.

### II. MODELING OF DFIG-BASED WFS AND CONTROLS

This section is dedicated to the description of the dynamic equations considered for the analysis, as well as the general characteristics of the studied system. Due to the models involving WECS are well-reported, in this section the models are just briefly described. The wind, two-mass drive train, squirrel cage induction generator, and controllers models are included [26]–[28]. All the parameters and their nomenclature are shown in Appendix A.

#### A. SYSTEM DESCRIPTION

Based on [29], the schematic of a series compensated transmission line radially connected to a DFIG-based WF
is shown in Figure 2. In the analysis of WECS, instead of a group of wind generators, it is common to analyze an equivalent machine with its mechanical system and its power converter; in this paper, an equivalent of WECS is analyzed [30]. The studied power system is simulated using PSCAD/EMTDC and Matlab editor. PSCAD/EMTDC is analyzed [30]. The studied power system is simulated.

**B. SQUIRREL CAGE INDUCTION GENERATOR (SCIG)**

The dynamic model of the SCIG is shown in $dq$ frame, oriented along an arbitrary reference frame [26], [31], described as follow:

$$\begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{dq}}{dt} \\ \frac{di_{dr}}{dt} \\ \frac{di_{dq}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{\omega_b} & 0 & 0 & 0 \\ 0 & \frac{1}{L_m} & 0 & 0 \\ 0 & 0 & \frac{1}{L_m} & 0 \\ 0 & 0 & 0 & \frac{1}{L_r} \end{bmatrix}^{-1} \begin{bmatrix} v_{ds} - R_s i_{ds} - \omega_s \psi_{ds} \\ v_{dq} - R_s i_{dq} - \omega_s \psi_{dq} \\ v_{dr} - R_r i_{dr} + (\omega_s - \omega_r) \psi_{dr} \\ v_{dq} - R_r i_{dr} - (\omega_s - \omega_r) \psi_{dr} \end{bmatrix}$$

(1)

where $\omega_s$ is the rotatory reference frame (from the stator terminals), $\omega_b$ is the base speed, both in rad/s, $v$ is the stator or rotor voltage, $i$ is the stator or rotor current, $R$ is the stator or rotor resistance, $\psi$ is the stator or rotor flux, $\omega_r$ is the electrical rotor speed, with the subscripts $s$ and $r$ as the stator and rotor, the direct and quadrature axis as $d$ and $q$. The inductance matrix with $L_s = L_d + L_m$ and $L_r = L_q + L_m$, where $L_m$ is the mutual inductance, $L_d$ and $L_q$ are the rotor and stator leakage inductance, respectively. Except where is indicated, all in per-unit (p.u.).

**C. THE DC-LINK VOLTAGE**

The dc-link in the BTB converter of the DFIG is modeled according to Figure 3. The equation which describes the energy balance of the dc-link capacitor is expressed as follows:

$$C_{dc} \frac{dU_{dc}}{dt} = i_{dc}$$

(2)

where $U_{dc}$ is the dc-link voltage, the current through out the capacitor is $i_{dc} = i_{gdc} - i_{rdc}$, where $i_{gdc}$ is the DC current from the GSC, and $i_{rdc}$ is the DC current from de RSC.

**D. VOLTAGE-SOURCE CONVERTER (VSC)**

The VSC model is based on the average model described in [32]. The GSC circuit depicted in Figure 3 is used as a general study case.

In Figure 3, the phases are indicated by its subscript $a$, $b$, and $c$, the voltages are expressed in phase-ground value, $r_{sw}$ is the switch on-state resistance and includes losses of conduction. The bidirectional switching functions are identified by $S$ and $\bar{S}$ for each phase which can be either on or off (1 or 0, states of the switch), respectively [32].

**E. GRID-SIDE-CONVERTER CONTROLLER**

The GSCC is usually controlled by a vector-control scheme oriented along the stator voltage [26], [33]. The typical PI controllers are used for regulation dc-link voltage and reactive power; the reactive power control through GSC is out of the scope of this paper, then $i_{gq,ref} = 0$. The superscript $e$ in Figure 4 denotes the orientation of the reference frame. The stator-voltage-oriented reference frame allows the independent control of active and reactive power flowing from the stator side through the GSC to the dc-link.

According to Figure 3, the three-phase voltage balance across the inductance is:

$$v_{B1} = v_g + R_g i_g + \frac{L_g}{\omega_b} \frac{di_{g}}{dt}$$

(3)

where $R_g$ and $L_g$ are the GSC resistance and inductance, respectively. Using the Park Theory [34], equation (3) is
In steady state, $v_{qs} = R_i q_s + \omega_f \psi_{ds}$ and $v_{ds} = R_i d_s - \omega_f \psi_{qr}$ [34], and substituting $v_{qs}$ and $v_{ds}$ into (6), the voltage balance across the RSC and the rotor circuit of the SCIG in the stator-flux-oriented reference frame is:

$$
\begin{bmatrix}
\psi_{dS}^q \\
\psi_{qS}^q
\end{bmatrix} = R_f \begin{bmatrix}
\psi_{dS}^q \\
\psi_{qS}^q
\end{bmatrix} + \omega_{slip} \begin{bmatrix}
-\psi_{qS}^r \\
-\psi_{dS}^r
\end{bmatrix} + \frac{\alpha L_r}{\omega_b} d \begin{bmatrix}
\psi_{dS}^r \\
\psi_{qS}^r
\end{bmatrix}
$$

(7)

where $\omega_{slip} = \omega_s - \omega_r$ and $\alpha = 1 - T_m^2/L_m L_s$. Due to the stator-flux orientation, the next terms can be written as $\psi_{dS}^r = \frac{L_m}{L_r} \psi_s + \alpha L_r \psi_{qr}$, $\psi_{qS}^r = \alpha L_r \psi_{qr}$ and the electric torque as $T_e = -\frac{L_m}{L_r} \psi_s \psi_{qr}$ [35].

According to equation (7) and the stator-flux oriented reference frame, the reference voltages with compensation terms described in dq-axis are:

$$
\begin{bmatrix}
\psi_{dS}^q & \psi_{qS}^q
\end{bmatrix} = \omega_{slip} \begin{bmatrix}
-\psi_{qS}^r & -\psi_{dS}^r
\end{bmatrix} + \begin{bmatrix}
\psi_{dS}^r & \psi_{qS}^r
\end{bmatrix}
$$

(8)

where voltages $\psi_{dS}^r$ and $\psi_{qS}^r$ are the rotor reference voltages, and $\psi_{dS}^r$ and $\psi_{qS}^r$ are the control signals.

If the infinite bus is assumed at stator terminals the calculation of the angle $\theta^\psi$ can be simplified [22], [26], [33], [35]. For the correct decoupling, in this paper, the reference frame angle is calculated using the stator-flux convention $\theta_{ph} = \text{atan}(\psi_{qs}/\psi_{ds})$, then:

$$
\theta^\psi = \theta_{ph} - \theta_r
$$

(9)

where $\theta_r$ is the rotor electrical angle of the induction machine. In some cases, a band-pass filter is applied to implement equation (9) avoiding the drift produced by low-frequency components in the stator voltage and current [33].

### III. BACKGROUND OF SUBSynchronous RESONANCE

The series compensation can improve the power transfer capabilities, but in some scenarios, it may lead to SSR phenomena [22], [36], [37]. The SSR is a condition in which a series compensated transmission line system significantly exchanges energy with a turbine-generator system at frequencies below the synchronous frequency [22]. Based on [21], [38]–[40], the following equation expresses the natural frequency of the electrical network.

$$
f_{er} = f_0 \frac{K_{cs} X_{line}}{X_{tot}}
$$

(10)

where $f_{er}$ is the natural frequency of the electrical system (in Hertz), $f_0$ is the nominal frequency of the system, $K_{cs}$ is the compensation level, $X_{line}$ is the transmission line reactance, $X_{tot}$ is the total inductive reactance seen from the infinite bus. SSR is classified into three phenomena, induction generator effect (IGE), torsional interaction (TI), and torque amplification (TA) [38]. IGE and TI produce self-excitation in the generator, and the third one produces, as its name says torque amplification.
A. INDUCTION GENERATOR EFFECT
IGE involves an electric machine with the network and it is purely an electrical phenomenon. Then, for induction machines, the slip at subsynchronous frequencies is described by [21]:

\[ S_{ssr} = \frac{f_{er} - f_r}{f_{er}} \]  \hspace{1cm} (11)

where \( f_r \) is the electrical frequency of the rotor. From the equivalent circuit of an induction machine, shown in Figure 16, the equivalent rotor resistance seen from the stator terminals at subsynchronous frequency is given by:

\[ R_{eq}^{ssr} = \frac{R_r}{S_{ssr}} \]  \hspace{1cm} (12)

where \( R_r \) is the rotor resistance. In the series compensated transmission line the inequality \( f_{er} < f_r \) is fulfilled (for SSR), \( S_{ssr} \) is negative, then \( R_{eq}^{ssr} \) is negative. If the magnitude of \( R_{eq} \) (seen from the stator terminals) exceeds the sum of the stator and network resistance, the system experiment negative damping at subsynchronous frequencies, and the IGE can be observed on the electrical system.

B. TORSIONAL INTERACTION
TI is the interaction between the turbine-generator mechanical system and a series-compensated electrical network. Small-signal disturbances in a power system result in simultaneous excitation of all-natural modes of the electrical and mechanical systems [38]. After the small disturbance, rotor torsional oscillation (at frequency \( f_n \)) rendering to the generator terminals produce stator voltage components at frequencies of:

\[ f_{en} = f_o \pm f_n \]  \hspace{1cm} (13)

When the frequency \( f_{en} \) is close to a natural frequency of the electrical system \( (f_n) \), the self-excitation phenomenon is produced by TI [21], [38].

C. TORQUE AMPLIFICATION
TA involves mechanical and electrical systems and occurs due to faults in the network or during switching operations. This results in system disturbances, which impose electromagnetic torques on generator rotors. Following a significant system disturbance in a series-compensated transmission system, the resulting electromagnetic torque oscillates at frequencies of [39], [40]:

\[ f_m = f_o \pm f_{er} \]  \hspace{1cm} (14)

where \( f_m \) is the induced subsynchronous and supersynchronous frequency in the generator. If \( f_m \) corresponds to a natural torsional vibration frequency \( (f_n) \) of the turbine-generator shaft system, the magnitude of the rotor oscillations are greatly amplified, then TA can be observed.

IV. CONTROL TUNING
This paper aims to make straightforward the analysis providing a complete tuning procedure for back-to-back converters of DFIG-systems. Hence, in this section, the controller tuning methods for VSC-HVDC systems [41], as well other extra methods, are proposed to be used in VSC of DFIG-based WFs.

A. TUNING OF GRID-SIDE-CONVERTER CONTROLLER
The aim of the GSCC topology is to control the dc-link voltage through the \( d \) component, while \( q \) component is zero \((\epsilon_{qg.ref} = 0)\).

![FIGURE 6. GSCC block diagram for the inner current controller.]

1) INNER CURRENT CONTROLLER
Considering the structural similitude, the tuning criterion of a VSC-HVDC system is used for the VSC of DFIG-based WF. The inner current controller is tuned based on the modulus optimum tuning criterion described in [42], the transfer functions required for the inner current controller block diagram are shown in Figure 6, where the PI controller, PWM time delay approximation, and the plant are considered. The time delay in the control process associated with the PWM and the digital implementation can be neglected if the rate of change of the controller signal is slower than the PWM commutation and sampled period. Developing the tuning criterion given in [42], \( T_a = 1/(2f_m) \), substituting (5) in (4), and the following transfer function can be obtained applying the Laplace transform:

\[ \frac{I_{ig}^e}{V_{ig}} = \frac{1}{R_g \tau_{ig}s + 1} \]  \hspace{1cm} (15)

where \( x = d, q \) and \( \tau_{ig} = \frac{L_g}{\omega_{0} R_g} \).

It can be observed in Figure 6 that if \( T_{iq} = \tau_{ig} \), the zero-pole cancellation is achieved. Then, the reduced transfer function in open loop and closed-loop of Figure 6 are, respectively:

\[ G_{ig,OL} = \frac{K_{Pig}}{R_g \tau_{ig} T_a s^2 + \tau_{ig} R_g s + K_{Pig}} \]  \hspace{1cm} (16)

\[ G_{ig,CL} = \frac{K_{Pig}}{R_g \tau_{ig} T_a s^2 + \tau_{ig} R_g s + K_{Pig}} \]  \hspace{1cm} (17)

Equation (17) can be rewritten as a second-order transfer function in the following form:

\[ G_{ig,CL} = \frac{K_{Pig}}{s^2 + \frac{1}{T_a s} + \frac{K_{Pig}}{R_g \tau_{ig} T_a}} \]  \hspace{1cm} (18)
According to (18), the undamped natural frequency is \( \omega_n^2 = \frac{K_{pg}}{\tau_{ig}T_a} \) and the damping factor is \( \xi = \frac{1}{2} \sqrt{\frac{\tau_{ig}R_g}{K_{pg}T_a}} \). Evaluating the condition \( |G_{ig,CL}| = 1 \) in equation (17) the proportional gain can be found as follows:

\[
K_{Pig} = \frac{\tau_{ig}R_g}{2T_a} \tag{19}
\]

The open-loop Bode diagram of (16) is shown in Figure 7. It can be seen that the phase margin corresponds to 65° with a frequency of 4,550 rad/s and the gain margin is infinite, then the system is stable.

The outer controller requires the current-controller transfer function, in this regard, a simplification of (18) for zero-pole cancellation is developed. Substituting (19) in (18) yields

\[
G_{ig,CL1} \approx G_{ig,CL2} = \frac{1}{T_{eq}s + 1} \tag{20}
\]

The open-loop transfer function of the GSCC outer controller without the feed-forward and disturbance input is given by:

\[
G_{udc,OL} = K_{pudc} \left( \frac{T_{indc}s + 1}{T_{indc}s} \right) \left( \frac{1}{T_{eq}s + 1} \right) \left( \frac{V^e_{dg,0}}{U_{dc,ref}} \right) \left( \frac{\omega_b}{C_{dc}s} \right) \tag{23}
\]

The Nyquist criteria of stability are

\[
|G_{udc,OL}(j\omega)| = 1 \quad \angle G_{udc,OL}(j\omega) = -180^\circ + \Phi_M \tag{25}
\]

The open-loop transfer function of the GSCC outer controller without the feed-forward and disturbance input is given by:

\[
\frac{C_{dc}dU_{dc}}{\omega_b} \frac{df_{dg}}{dt} = \frac{V^e_{dg}f_{dg}}{U_{dc,ref}} - i_{ndc} \tag{21}
\]

Equation (21) is a nonlinear equation; to perform a linear stability analysis, (21) is linearized around the steady-state, where the equilibrium values are \( U_{dc,ref}, V^e_{dg,0}, \) and \( f_{dg,0} \). The inputs of interest are \( f_{dg} \) and \( i_{ndc} \), and the linearized equation can be simplified according to [42], as follows:

\[
\frac{C_{dc}dU_{dc}}{\omega_b} \frac{df_{dg}}{dt} = \frac{V^e_{dg,0}}{U_{dc,ref}} \Delta f_{dg} - \Delta i_{ndc} \tag{22}
\]

where \( \Delta i_{ndc} \) is a disturbance signal. The Laplace transform is applied to equation (22); the term \( \Delta \) is omitted to simplify the block diagram. The reference [42] shows the implementation of feed-forward term, in this investigation, the feed-forward term is not included due to its steady-state dynamic is close to zero; the block diagram is shown in Figure 8.

FIGURE 7. Open-loop Bode plot of inner current controller.

2) OUTER CONTROLLER

The outer controller for the GSC block diagram is made up of the PI controller (Figure 4), the closed-loop transfer function of the inner current controller (equation (20)), and the transfer function of the plant of the dc-link for the BTB topology.

An auxiliary equation is required to obtain the transfer function of the plant. According to the orientation of the reference frame, the active power in bus B1 can be calculated as \( P_{gsc} = V^e_{dg}f_{dg} \), the power in the DC side of the GSC is calculated as \( P_{gdc} = U_{dc}f_{gdc} \), and the power balance in the AC and DC side meets the following condition \( P_{gsc} = P_{gdc} \). According to the above, the equation (2) can be written as follows:

\[
\frac{C_{dc}dU_{dc}}{\omega_b} = \frac{V^e_{dg}}{U_{dc,ref}} f_{dg} - i_{ndc} \tag{21}
\]
where $\Phi_M$ is the phase margin. Then, the angle condition from the open loop of the outer controller is:

$$\angle G_{\text{adc,OL}}(j\omega) = -180^\circ + \tan^{-1}(\omega T_{\text{adc}}) - \tan^{-1}(\omega T_{\text{eq}}) = 180^\circ + \phi$$

The angle $\phi$ is positive for all the values of $\omega$. Differentiation of this angle with respect to $\omega$ can give the maximum value of phase margin. The value of $T_{\text{adc}}$ should be designed to be small, especially when $\phi$ approaches $\Phi_M$, otherwise, the response to the disturbance becomes slow. In this sense, the maximization condition $\frac{d\phi}{d\omega} = 0$, the angle is maximum when $\omega_d = \frac{1}{\sqrt{T_{\text{adc}} T_{\text{eq}}}}$. Hence the phase margin is:

$$\Phi_M = \tan^{-1}\left(\frac{T_{\text{adc}}}{T_{\text{eq}}} - \tan\left(\frac{T_{\text{eq}}}{T_{\text{adc}}}\right)\right)$$

(29)

This condition gives the tuning criterion for the time constant of the controller as:

$$T_{\text{adc}} = T_{\text{eq}} \left(\frac{1 + \sin \Phi_M}{1 - \sin \Phi_M}\right)$$

(30)

The resulting open-loop frequency characteristic will have a maximum phase of $\Phi_M$ at the crossover frequency of $\omega_d$, symmetric about $\frac{1}{T_{\text{adc}}}$ and $\frac{1}{T_{\text{eq}}}$. Then, by the symmetric property, it can also write:

$$T_{\text{adc}} = a^2 T_{\text{eq}}$$

(31)

where $a$ is the symmetrical distance between $1/T_{\text{adc}}$ to $\omega_d$, and $1/T_{\text{eq}}$ to $\omega_d$. Now, from the magnitude condition, the tuning for the gain of controllers can be found as follows:

$$|G_{\text{adc,OL}}(j\omega)| = \frac{K_{\text{adc}}K_{Pudc}}{\omega_d^2 T_{\text{adc}} T_{\text{eq}}} \sqrt{\left(\frac{\omega_d T_{\text{adc}}}{\omega_d T_{\text{eq}}}\right)^2 + 1} = 1$$

(32)

Then, the proportional gain is obtained as follows:

$$K_{Pudc} = \frac{T_{\text{eq}}}{K_{\text{adc}}} \frac{T_{\text{eq}}}{\sqrt{T_{\text{adc}} T_{\text{eq}}}}$$

(33)

Figure 9 shows the frequency response of the open-loop transfer function of Figure 8. The system is stable because the phase margin is about $71^\circ$ with a frequency of 830 rad/s and the gain margin is infinite.

Finally, the time response of the inner current controller and the outer controller for the GSCC due to the input of the unit step function is depicted in Figure 10. It can be observed the fast response of the inner current controller in comparison with the outer controller.

**B. TUNING OF ROTOR-SIDE-CONVERTER CONTROLLER**

In this section, the tuning process is analyzed to control the rotor speed and the voltage of the stator terminals of the induction machine. The tuning process for the RSCC can be done by applying the same technique as the above. However, in this section, one extra procedure is performed for tuning the inner current and outer controller.
unit, is described by:

$$
\frac{I_{xr}}{I_{xr,ref}} = G_{ir,CL} = \left(\begin{array}{c}
\frac{1}{K_{ir} s + 1}
\end{array}\right)
$$

(35)

The time constant can be defined as $\tau_{ir} = R_p / K_{ir}$. The rotor time constant for RSC can be assumed to be 0.1 seconds. On the other hand, due to the zero/pole cancellation, the proportional gain, per unit, is described by:

$$
K_{pir} = \frac{\alpha L_r}{\omega_b R_p} K_{ir}
$$

(36)

The time constant $\tau_{ir}$ can be selected according to the system requirements, as well as, the $d$ and $q$ components can be tuned independently or using the technique that best fits the requirements.

2) OUTER CONTROLLER

The outer controller of the RSC controls the rotor speed and the stator terminal voltage of the induction machine. In this section, two criteria for tuning the outer controller for the RSC are presented. The rotor speed is tuned according to the step response criterion and the stator-terminals voltage is tuned with the pole location criterion.

Step Response for Rotor Speed (Outer Loop): In spite of the drawbacks of the method [45], [46], this method can be used for tuning the RSCC. The challenges associated to obtain a transfer function of the RSC can be overcome with this method.

The methodology to tune the RSCC is focused on the S-shape reaction curve [45],[46]. Without rotor controller (the RSCC in open-loop) and if the initial condition of rotor speed is zero, the rotor speed response will resemble an S-shape. The parameters $K$, $T$, and $L$ are measured from the S-shaped response shown in Figure 12. According to Table 1, the gains for PI control are computed.

![FIGURE 12. Rotor speed of the induction machine, without rotor control.](image)

The results for $T_{fs}$ and $K_{pfs}$ are shown in Table 1, where $R = K / T$. Despite this methodology has been used over many years, it has not been used for tuning the RSCC.

Pole Location for Stator Terminals Voltage (Outer Loop): The RMS voltage of stator terminals can approximate to $v_{ds}$, namely $v_{ds} \approx U_s$. In steady-state an expression can be synthesized from the induction model of the rotor current in equation (6). According to the same criterion explained in Section IV-A2, the linearized equation which relates the input with the output without the disturbance and feed-forward terms is written as follows:

$$
\frac{\Delta V_{ds}}{\Delta I_{fr}} = \frac{\frac{L_r^2 L_s \alpha^2}{\omega_b L_r L_s \alpha R_p} + \frac{L_r^2 L_s \alpha^2}{\omega_b L_r L_s \alpha R_p} + \frac{L_s^2 L_r \alpha^2}{\omega_b L_r L_s \alpha R_p} + \frac{L_s^2 L_r \alpha^2}{\omega_b L_r L_s \alpha R_p}}{-\omega_b L_m L_r \alpha} + K_{fus} + K_{fus}
$$

(37)

The block diagram for the outer controller of stator terminal voltage is shown in Figure 13.

![FIGURE 13. RSCC block diagram for outer controller.](image)

The closed-loop transfer function of Figure 13 can be reduced to a first-order system, as it is shown in the equation (40), as shown at the bottom of the page. Then, the constraints are set to assure the localization of the pole at the left-side of the $s$-plane. In this sense, the proportional and integral gains are computed according equations (38) and (39); its values are $K_{fus} > 18.2351$ and $K_{pfs} > 0.0112$.

$$
K_{fus} > \frac{\omega_b L_m L_r \alpha}{L_s^2 L_r \alpha^2 + \omega_b L_r L_s \alpha R_p}
$$

(38)

$$
K_{pfs} > \frac{\omega_b L_m L_r \alpha}{L_s^2 L_r \alpha^2 + \omega_b L_r L_s \alpha R_p}
$$

(39)

V. DYNAMIC PERFORMANCE OF THE SYSTEM

The complete system shown in Figure 2 is studied. PSCAD is used to validate the dynamic model programmed in ODES. Besides, the proposed methodology to calculate the gains of the GSCC and RSCC is compared against the ones reported in the literature; this comparison is conducted with quasi-stationary changes in the series compensation (capacitance $C_{cs}$) to produce SSR.

Figure 14 shows the component $d$ of the stator and rotor currents. The system is simulated, and a transient is set at 1 second, it can be observed that the dynamic responses overlap each other, which validates the ODES.

| Controller | $K_{pfs}$ | $T_{fs}$ | $T_{pfs}$ |
|------------|----------|---------|---------|
| Formulation | $0.9/RL$ | $1.0/0.3$ | $0$ |
| Value      | 3.4538   | 1.6667  | 0       |
Table 2 shows the gains calculated through the proposed tuning methodology and the gains recommended in the literature. The reference [47] recommends control parameters values for wind turbines between 1.67 MVA to 4.0 MVA. Using this recommendation and the parameters described in the model of the type-III wind turbine analyzed in [48], [49], the simulation is performed.

The evaluation of the system performance with these two sets of gains is conducted by simulating the system with series compensation of 10% as an initial condition, when the system reaches the steady-state at 100 seconds, the series compensation is changed to 70%, and then to 71% at 105 seconds. These compensation levels are selected to excite the SSR event.

- According to these results, the mitigation of the SSR can be achieved by re-tuning the gains of the RSCC and GSCC. In this sense, if the solution to mitigate SSR is based on the implementation of a FACTS, the origin of the SSR must be understood to propose a targeted solution or equipment.

VI. UNDERSTANDING SUBSYNCHRONOUS RESONANCE

In this section, an approach is proposed to understand the causes of how a series-compensated transmission line can produce SSR in DFIG-based WF. Through an analytical procedure, and according to the definition of IGE, TI, and TA, the behavior observed in the simulation is compared with the definitions to know which of them are the causes of SSR. In this regard, the steady-state equivalent circuit is shown in Figure 16, based on it, modal impedance (MI) [50] and driving point impedance (DPI) [51] are computed for SSR characterization. Then, the eigenproperties are assessed as the eigenvalue of the entire system.

A. STEADY-STATE ANALYSIS TOOLS

To apply a proper solution for SSR issues, it is required to discriminate the phenomena mentioned in the previous section and it can be done by, firstly, the use of a steady-state circuit. Figure 16 shows the equivalent circuit of the induction machine with the series-compensated transmission line (equivalent circuit of Figure 2).

\[ X_{lr} \text{ and } X_{ls} \text{ are the rotor and stator leakage reactance; } R_s \text{ is the stator resistance; } X_m \text{ is the mutual reactance; } V_r \text{ is the rotor voltage; } R_g \text{ and } X_g \text{ are the resistance and reactance of GSC; the total resistance of the system is } R_{tot} = R_{line} + R_T; \text{ the total reactance of the system is } X_{tot} = X_{line} + X_T; \text{ the series compensation is } X_{cs} = K_{cs}X_{line}. \]

The main task of the investigation is to seek out the resonance frequency because of the series compensation, as the first instance, it can be done by equation (10), which will give a small deviation due to, this equation does not consider the reactance of the parallel branches. But this equation gives a close approximation of the SSR frequency.

DPI can be evaluated with the complete steady-state circuit. One common procedure is based on the injection of a voltage or current at several frequencies in a concerning bus to know the impedance response at a specific frequency [50]. Another method is to obtain an analytic expression of the equivalent impedance in each bus, due to the small size of the equivalent circuit, an analytic expression of the impedance at...
bus 3 (bus of the series compensation) is obtained as follows:

$$Z_{bus3} = \frac{Z_{eq3}Z_{cs}}{Z_{eq3} + Z_{cs}}$$ (41)

with $Z_{cs} = -jX_{cs}$, $Z_{eq3} = (Z_{eq1} + jX_{ls})Z_{cp}/(Z_{eq1} + jX_{ls} + Z_{cp} + X_{tot}$, $Z_{eq1} = (jX_{lr})(jX_{tm})/(jX_{lr} + jX_{tm})$, and $Z_{cp} = (jX_{g})(-jX_{c})/jX_{g} - jX_{c}$; the term $X_{c}$ as the filter reactance. The resistances are neglected to observe only the effect of the reactances.

MI is commonly used for resonance analysis above the synchronous frequency [50]. In this research, MI is used for SSR analysis in DFIG-based WFs. The main benefit of this technique is the discrimination of several sources of resonance, as explained in [50]; further simulations show that the discrimination property is preserved for SSR cases.

FIGURE 17. Natural frequency and induced frequency versus series compensation level of equation (10), DPI and MI.

Figure 17 shows the natural frequency of the network $(f_{er})$ and the induced frequency $(f_m)$ versus series compensation for equation (10), DPI, and MI. The green line (dash line) shows the behavior for the DPI and MI, the results applying the equation (10) are shown in the blue line (solid line). According to equation (10), $f_{er} = 42.9$ Hz in consequence $f_{m} = 17.1$ Hz. But, according DPI and MI, $f_{er} = 16.51$ Hz in consequence $f_{m} = 43.49$ Hz. The data interpretation, in this case, shows that DPI and MI deliver similar results, while the error can be larger using equation (10); this is confirmed by modal analysis.

FIGURE 18. Impedance versus frequency of DPI and MI from bus 3 at different frequency ranges.

The main difference concerning DPI and MI is depicted in Figure 18, where the equivalent impedance from bus 3 versus frequency is shown. The blue line (solid line) represents the DPI and the green line (dash line) represents the MI. The figure is split in two, for subsynchronous and supersynchronous frequency levels. The peak in the range of subsynchronous frequency can be matched with the frequency of $f_{er} = 16.51$ on Figure 17, which represents the resonance frequency of the electrical network, in consequence, the peak shown in the subsynchronous range in Figure 18 is due to the series compensation. Because there are only two capacitors in the equivalent circuit, the peak in the range of supersynchronous frequency is due to the passive filter at 1437 Hz.

MI technique shows only one peak corresponding to the effect of the series capacitor, while DPI shows the effect of the two capacitors. As a result, in a complex system where several series-compensated transmission lines are installed, the use of MI as an analysis technique will allow discriminating the effect of each series-capacitor in the system.

B. SMALL-SIGNAL STABILITY ANALYSIS

Small-signal stability (SSS) is widely used for stability studies [24], [34]. In this section, the linearization of the complete system, as well as the eigenvalue and eigenvectors are calculated by means of the fsolve function of Matlab. The identification of each mode is described with the MI technique and the eigenvalue analysis.

The identification of the modes is done with the aid of the MI technique, as following. Using the MI technique and equation (14) the induced subsynchronous and supersynchronous frequencies $(f_m)$ are computed as shown in Figure 19.

FIGURE 19. Induced frequency versus compensation level calculated using MI.

According to the modal analysis, Figure 20 shows the main modes at their respective frequency versus compensation level. First, in Figure 20 the induced modes can be identified due to their frequency behavior through the compensation level is similar to the Figure 19. Besides, the mode due to the filter in Figure 20 can be identified due to its frequency behavior is close to the supersynchronous frequency computed by MI technique and shown in Figure 18; the resonance frequency of the electrical system due to the filter is 1438.5 Hz, according to modal analysis.

The shaft train model is based on the two-mass model, the torsional mode is one and its frequency can be calculated in the steady-state condition as follows [37]:

$$\omega_n = \sqrt{\frac{K_{tg}(H_g + H_{wt})\omega_{mb}}{2H_gH_{wt}}}$$ (42)

According to equation (42), the mechanical mode is identified in Figure 20. The supersynchronous modes are not shown in this analysis due to they are not involved in SSR, but those can be associated with the controllers.

The SSR definition [38] indicates that if two modes (electromechanical and electrical) are close enough, the system can oscillate indefinitely. In this regard, as the compensation level increases, the subsynchronous induced mode is getting close with the electromechanical mode, producing the resonance zone. According to Figure 20, the subsynchronous
induced mode at compensation level of 71% shows a frequency of 43.56 Hz, while the electromechanical mode at the same compensation level shows a frequency of 41.56 Hz, the difference of 2 Hz is called frequency gap of SSR; a frequency gap of SSR equal or lower than 2 Hz produce SSR.

It can be observed that the induced component \( f_{\text{m}} \) for the MI technique is 43.49 Hz, which is too close to the computed ones using modal analysis with a frequency of 43.56 Hz. The conclusion is that the MI technique can be used to calculate the SSR frequency for the case when a disturbance induces a frequency to the generator; which corresponds to the TA phenomena.

Figure 21 shows the same modes as above, in this case, the real part of the modes is shown. The resonance zone is shown after the series compensation of 70% and the real part of the electromechanical mode changes to positive in \( K = 71\% \), which makes the system unstable.

C. DISCRIMINATION PROCEDURE AND RESULTS

The procedure to discriminate the phenomena that can produce SSR is described as follows:

1) Implement the modal impedance technique presented in Section VI-A.
2) Perform the small-signal-stability analysis presented in Section VI-B.
3) By using the results of the small-signal analysis, determine the frequencies associated with these eigenvalues. Compare these frequencies with those obtained in step 1. The matching frequencies will be the interest frequencies related to the SSR.
4) If \( R_{\text{eq}}^{\text{SSR}} < R_{\text{tot}} \) is fulfilled IGE is discriminated. SSS analysis is not required.
5) If the frequency \( f_{\text{en}} \) (13) rendered to the network is not close to the frequency \( f_{\text{er}} \) (10), TI is discriminated.
6) If an induced current component in the generator of frequency \( f_{\text{m}} \) (14) is not close to any frequency associated with the turbine-generator modes, TA is discriminated.

In this research, IGE is discriminated due to the condition \( R_{\text{eq}}^{\text{SSR}} < R_{\text{tot}} \) is fulfilled, otherwise, MI technique would show a zero crossing in the impedance versus frequency plot, as Figure 18. TI is discriminated due to the frequency of the voltage component rendered to the system in the condition of SSR (compensation of 71%), according equations (13) and (42), is \( f_{\text{en}} = 58.23 \) Hz, which is not close to the subsynchronous frequency \( f_{\text{er}} = 16.51 \) Hz in the electrical system, shown in Figure 17, green-dash line.

The precise interpretation of the analysis indicates that, due to series compensation of 71%, current components of frequency around \( f_{\text{en}} = 43.56 \) Hz (according to Figure 20) are induced in the generator which is close to the electromechanical mode, in this case with a frequency of 41.56 Hz, which match with the definition of TA, therefore SSR arises in the transmission system.

According to the criteria of phenomena discrimination performed in this research, in a complex system with several sources of resonance (as capacitors in series or parallel), it is possible to know precisely the buses that are prone to producing SSR.

VII. CONCLUSION

DFIG-based wind farms are prone to subsynchronous resonance under the series-compensated condition. The proposed

| Symbol | Description | Value |
|--------|-------------|-------|
| \( V_p \) | Single machine | 1.667 MVA |
| \( V_{st} \) | Stator Voltage (L-L rms) | 575 V |
| \( f_s \) | Nominal frequency | 60 Hz |
| \( \omega_b \) | Base frequency | \( 2\pi f_s \) |
| \( \omega_{\text{Mech}} \) | Base mechanical frequency | 125.66 rad/s |
| \( \omega_m \) | Mechanical rotor speed | 1.02 |
| \( U_{dc} \) | DC-link voltage | 1.15 kV |
| \( C_{dc} \) | DC-link capacitance | 10 mF |
| \( f_{\text{en}} \) | Commutation frequency | 4980 Hz |
| \( R_{\text{r}} \) | Radius | 37.5 m |
| \( C_p \) | Power coefficient | from [28] |
| \( V_w \) | Wind speed | 15 m/s |
| \( \beta \) | Pitch angle | 3.07° |
| \( N_p \) | Gearbox ratio | 1 |
| \( P_{\text{pol}} \) | Pole-pair number | 3 |
| \( f_r \) | Rotor electrical frequency | 1.02 |
| \( H_{\text{r}} \) | Turbine inertia constant | 4.32 s |
| \( H_{\text{g}} \) | Generator inertia constant | 0.685 s |
| \( K_{\text{g}} \) | Shaft stiffness | 1.11 |
| \( L_{\text{d}} \) | Shaft mutual damping | 1.5 |
| \( L_{\text{t}} \) | Stator leakage inductance | 0.018 |
| \( L_{\text{o}} \) | Rotor leakage inductance | 0.016 |
| \( L_m \) | Mutual inductance | 2.9 |
| \( R_s \) | Stator resistance | 0.023 |
| \( R_r \) | Rotor Resistance | 0.016 |
| \( F \) | Generator mechanical damping | 0.01 |
| \( f_{\text{nom}} \) | VSC switch on-state resistance | 0.001 \( \Omega \) |
| \( R_T \) | Transformer equivalent resistance | 0.001 |
| \( L_T \) | Transformer equivalent inductance | 0.005/3 |
| \( R_{L1} \) | Transmission line equivalent resistance | 0.02573 |
| \( L_{L1} \) | Transmission line equivalent inductance | 0.01972 |
| \( R_{L2} \) | Transmission line equivalent resistance | 0.001 |
| \( L_{L2} \) | Transmission line equivalent inductance | 0.006 |
| \( I_{L1} \) | GSC inductance | 0.3 |
| \( R_e \) | GSC resistance | 0.003 |

*Except where indicated, parameters are in per-unit system.*
methodology facilitates generating a transfer function for the state variables that relate the mechanical to the electrical part. Also, this proposed tuning methodology reduces the risk of SSR and enhances the stability of the system under an increase in series compensation.

Modal impedance is a useful technique to determine the capacitor involved in SSR issues; even if several capacitors are connected in the system, modal impedance can discriminate them, while the steady-state circuit of the induction generator with the series-compensated transmission line can be used to evaluate the origin of SSR. When the properties of modal impedance are used together with small-signal-stability analysis, the modes that directly intervene in the process of SSR are identified. Besides, the determination of the origin of SSR can be done by the proposed discrimination procedure, the benchmark addressed in this research shows that the torque amplification is the origin of undamped oscillation.

APPENDIX A

PARAMETERS AND NOMENCLATURE

Shown in the previous page.

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