Novel Analytical Method for Dynamic Design of Renewable SSG SPC Unit to Mitigate Low-Frequency Electromechanical Oscillations

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Abstract— Grid operators require grid connected Renewable Generation Units (RGUs) to provide specific dynamic features. Among those features, the RGUs must support the dynamic performance of the power grid as well as operate in such a way to ward off new issues in the power system. Recently, unfavorable oscillatory modes have appeared through the grid connection of RGUs due to their dynamic interaction with other classical components of the grid. Therefore, it is essential to develop a novel technique for the dynamic design of RGUs to mitigate such risky oscillations. In this paper, a novel analytical method is proposed for dynamic tuning of a Renewable Static Synchronous Generation unit controlled by SPC (RSSG-SPC). The proposed method is based on the mathematical analysis of the derivative function of general damping ratio formula. The analytical results establishes generalized solutions that cover all operation mode of the RSSG-SPC. Further on, the solutions are implemented into the dynamic model of the RSSG-SPC to obtain clear, accurate and trustable criteria for tuning of the virtual damping and virtual inertia. The dynamic tuning aims towards avoiding new oscillations in the system as well as to mitigate the natural oscillations of the power grid. The proposed approach was used for stability enhancement in high penetrated generation area as well as to support synchronization between interconnected areas in a two-area Kundur system. The proposed method was validated through modal analysis, time domain simulations as well as real-time evaluations which ensured that the proposed approach is a reliable technique for dynamic design of RSSG-SPCs.

Keywords— Control design; dynamic interaction; low-frequency oscillations; oscillation damping; power system stability; synchronous power controller.

I. INTRODUCTION

High power RGUs have a remarkable role in the power grid from the technical and economic points of view [1],[2]. From the dynamic performance point of view, the lack of damping and inertia in RGUs caused a negative impact in the dynamic characteristics of the power grid [3]–[5]. So, several recent new control technologies have tried to overcome these dynamic challenges [6],[7].

However, the evolution of sustained oscillatory modes between the modernized sections and classic parts of the power system, is a new dynamic challenge for grid operators. Recently, such undesirable oscillations were observed in different range of frequencies over the grid connection of large wind farms and VSC-HVDC systems [8]–[10]. The interactions between DFIG controllers and wind turbines with the grid can cause voltage/current harmonics oscillations in the 10 Hz range [11].

VSC-HVDC systems can cause sustained sub-synchronous oscillations (20-30 Hz) with the inductive parts of the transmission system when the converters have capacitive impedance or negative resistance characteristics [12],[13]. Moreover, gradually increasing medium frequency oscillations (250-350 Hz) appears through the impedance intersections between the generation units and grid in VSC-HVDC systems [14]–[16]. Furthermore, very high frequency oscillations (1000-1200 Hz) observed in VSC-HVDC systems during the transition from grid-connection operation mode to stand-alone operation mode [17]. This can be observed as well in conjunction with VSC-HVDC systems connected to weak grid or are connect to grid through the long distance transmission system [18].

Several recent research [19]–[24] have shown that the detection and mitigation of such oscillations is a difficult and complex challenge. In most cases, an extra control layer is designed to mitigate these kinds of the oscillations. However, having these extra damping control loops reduces the efficiency of the overall system as well as affects the dynamics of the control system [22]. It is a known fact that the risk of such oscillations increases when the system lacks damping or inertia in the frequency range of these sustained oscillations. Therefore, finding a novel method for tuning control parameters of a voltage source converter (VSC) to provide sufficient

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damping and inertia effects for these different range of the oscillations, is an essential task that needs more efforts.

Synchronous power controller (SPC) is one of the modern control technologies proposed for RGUs [25]. What makes the SPC stand out is that it provides grid synchronization process without the use of a phase-locked loop [26]. Moreover, SPC is equipped with virtual damping and inertia layers that applies flexible dynamics to RGUs [27],[28]. Several research has validated that the SPC fortifies the power grid with high control flexibility [29],[30].

Among the applications of the SPC discussed in literature, a RSSG-SPC based unit has been discussed in [27]. With the expansion of required services from RGUs, RSSG-SPC based units needs to satisfy the grid operator's expectations of dynamic flexibility. However, several challenges constrict the path to such goals. The main challenges to fulfill these goals depends upon the optimum design of dynamic parameters of the RSSG-SPC. Moreover, this is accompanied by the challenge of tuning such parameters to handle the dynamic interaction of the RSSG-SPC with other classic generation units or RGUs inside a local generation area. Furthermore, future research needs to focus on the higher level control interplay between high penetration RSSG-SPCs with other neighborhood areas. This is required to maintain the overall required performance criteria, as well as to avoid creating new sustained oscillations in the power grid.

In this paper, a new method is presented aiming to dynamic design of the RSSG-SPC. The method is based on the in-depth analysis of the derivative function of general damping ratio formula. The methods aims to mitigate electromechanical oscillations in the power grid through transferring available maximum damping ratio to an electromechanical oscillatory mode. The extracted mathematical equations are implemented for both one-dimension (only D or M) and two-dimension (D and M) dynamic design of RSSG-SPC. Moreover, these equations are applicable in stand-alone operation mode as well as grid connection operation mode of RSSG-SPC. Based on the mathematical model and the analysis results, an optimal design methodology is derived for the virtual inertia (M) and damping (D) of the RSSG-SPC. Further on, these equations were validated based on Kundur two-area system to investigate the RSSG-SPC capability to mitigate the local and interarea oscillations on interconnected areas by supporting phase angle stability. This analysis was performed based upon modal analysis, time-domain simulations and real-time test which presented the improvements in several performance criterias.

This paper is organized as follows: in Section II, the main strategy and advantage of the proposed method are summarized. Then, in Section III, a brief review is presented on the dynamics of active power in RSSG-SPC. In Section IV, firstly the main dynamic equations of the grid connection mode of RSSG-SPC are extracted. Further on, details of the novel method is explained in this section where the new equations are obtained for optimal design of virtual inertia (M) and damping (D) of the RSSG-SPC based on the proposed method. Section V presents the modal analysis, time-domain simulation and

real-time tests of the designed RSSG-SPC installed in a two-area system. Finally, conclusions are summarized in Section VI.

II. MAIN STRATEGY AND ADVANTAGE OF THE PROPOSED METHOD

In this work, using partial derivative method, the derivative equation ($\partial^2 \xi_m$) of the general damping ratio formula (ξ_m) is obtained for a complex oscillatory mode ($\lambda_m = -a_m \pm b_m i$). The $\partial^2 \xi_m$ is expanded based on the real and imaginary coefficients of λ_m (a_m, b_m). Then the general solutions (roots) of the $\partial^2 \xi_m$ are extracted based on the (a_m, b_m). Afterwards, general solutions are categorized to summarize the required settings for the maximization of ξ_m . It is shown that the roots of $\partial^2 \xi_m$ can have two types of the general solutions (*Solu (I)* and *Solu (II)*). Then general condition of each solution is illustrated based on the (a_m, b_m). In this case, it is possible to accurately control both damping and oscillation frequency of the λ_m .

Further on, it is shown that *Solu (I)* belongs to the situation that λ_m will arrive to over-damped situation. So, *Solu (I)* describes the situations that ξ_m will take the absolute maximum value ($\xi_m = 1$). Then, it is illustrated that *Solu (I)* is applicable for the operation of a RSSG-SPC in the power system where a RSSG-SPC is connected to a stiff-grid as well as stand-alone operation mode. In these operation modes of RSSG-SPC, the most observed oscillation in the system is the internal dynamic mode of the RSSG-SPC which can be suppressed completely using *Solu (I)*. The clear equations for tuning of the D, M in these situations are discussed deeply in [31],[32] as well as shortly reviewed in this work.

Solu (II) defines the situations that λ_m will not take the zero frequency oscillations ($b_m \neq 0$). So, in this case λ_m will always remain in the under-damped situation. Thus, *Solu (II)* gives a relative maximum damping ratio for a sustained oscillatory mode λ_m ($\xi_m < 1$). In reality in the power system, this sustained oscillatory mode (λ_m) represents a common mode between the several participators such as reviewed in Section I.

The main focus of this work is on *Solu (II)* and its application for RSSG-SPC tuning. The oscillatory mode λ_m is considered to be the common mode between the RSSG-SPC and other classic SG in the external grid. So, *Solu (II)* gives the direct and simple technique to tune D and M aiming to mitigate the oscillations caused by the selected λ_m . As *Solu (II)* represents the condition to obtain possible maximum damping ratio for λ_m , this work confirmed that *Solu (II)* is a simple and sufficient tuning method for RSSG-SPC to reduce the risk of oscillatory modes in a power grid.

In summary, from the application point of view, the proposed method has several key advantages:

- 1) The proposed method is a mathematical approach, so solutions are accurate and trustable results where the simulation and real time evaluation approved it. The proposed method gives the basic solutions for dynamic tuning of the RSSG-SPC and covers all RSSG-SPC's operation modes. Also the

proposed methods can be expanded for other synchronous machine emulation techniques reviewed in [6],[7].

2) The method gives clear equations (*Solu (I)*) for internal dynamic design of the RSSG-SPC. *Solu (I)* clarifies the limitation borders of the dynamic tuning of the RSSG-SPC. This advantage is an essential capability for local operator to select a stable operating point for the RSSG-SPC.

3) The method can accurately target the specific oscillatory mode (λ_m) to mitigate it. So, just by measuring the voltage/current harmonics or power oscillations in the PCC and defining the frequency of the most observed oscillatory mode (λ_m), a RSSG-SPC can be easily tuned using the proposed method and equations. The targeted modes can have very low or very high frequency. So, the method gives adaptable solutions for several kind of applications in the power system.

4) In this work, mostly the mathematical background and concept of the method is explained. Then, the performance of the method is evaluated to suppress very low frequency oscillations (0.5-2.00Hz). According the simplicity of the SPC technique and the high clarity of the proposed method, there is a possibility to expand this method for multimodal oscillations. For example this can cover sub-synchronous, synchronous, and super-synchronous oscillations simultaneously. In this case, multi-electromechanical blocks need to be implemented in parallel inside of the RSSG-SPC control system. Then, each block needs to be tuned using *Solu (II)* to damp the specific oscillatory mode (specific λ_m). In this case, each sub-block provides possible maximum damping ratio to the specific frequency of the oscillation.

III. SPC BASED RSSG

The general configuration of a RSSG-SPC unit is presented in Fig. 1. As mentioned in our previous works [27], [28], the power converters of this RGU provides the required dynamic flexibility based on the electromechanical emulation of a conventional synchronous generators.

Fig. 1. Configuration of a Renewable Static Synchronous Generation unit controlled by SPC

Fig. 2. Equivalent dynamic active power loop for the study of phase oscillations

Through the implementation of a SPC in the RSSG in Fig.1, the equivalent dynamic active power loop of the unit is

represented in Fig. 2. The Fig. 2 will be explained more in deep in the next section (Section IV.A).

The dynamic flexibility of the RSSG-SPC is represented in the controllable two degrees of freedom of virtual damping (D_{SSG}) and virtual inertia (M_{SSG}). Moreover, synchronization with the external grid and primary active power control are achieved based on this electromechanical model. Participation of RSSG-SPC in power sharing between generation units as well as coordination with neighboring units can be achievable by adding extra control layers. One example of such loop can be the power-frequency droop such that the RSSG-SPC would support frequency recovery of the grid by participating in the secondary control of active power [31-33].

Such dynamic capability is promising in the sense that a RSSG-SPC can be designed and tuned dynamically to satisfy different goals of the grid operator. One of these goals can be supporting of power angle stability in grid by providing supplementary damping in generation areas and/or on interarea tie lines.

IV. DYNAMIC DESIGN OF RSSG-SPC

In this section, the proposed method for design of internal dynamic parameters of a RSSG-SPC will be presented with an aim to maximize damping effect on the grid. The internal dynamic behavior of a RSSG-SPC is deeply analyzed through the power loop and the main equation to present a viable tuning methodology.

A. Dynamic Analysis of Power Loop (Damping Analysis)

There are two main goals of interest in the analysis of the active power loop: a) Determination of the border of Critically-Damped condition ($\xi_{\lambda_{SSG}} = 1$) inside of RSSG-SPC. This means, the analysis should reveal the specific critical value of virtual damping (D_{SSG}^{Ovr}) after which the RSSG-SPC cannot sufficiently interact with the external grid to damp oscillations in the external grid. At such value, the RSSG-SPC has internally reached over-damped region ($\xi_{\lambda_{SSG}} > 1$) and RSSG-SPC has no adequate internal dynamic flexibility as result of big damping tuning. Thus the value of D_{SSG}^{Ovr} dictates the maximum tunable virtual damping and it should not be crossed. b) The second goal in the analysis is based on determination of the proper zone of damping where the RSSG-SPC can have enough dynamic interaction with the grid. This condition means RSSG-SPC has an internal oscillatory mode and the critically-damped border are not crossed. In other words, the RSSG-SPC is in the under-damped situation ($\xi_{\lambda_{SSG}} < 1$) therefore the tunable virtual damping would have a value of D_{SSG}^{Und} .

1) *Determination of D_{SSG}^{Ovr}* : The Fig. 2 shows the equivalent power loop model of the system presented in Fig. 1. The Fig. 2 looks to consider the oscillatory modes of the external grid into dynamic loops of RSSG-SPC. In such method, the grid oscillatory modes is modeled as grid phase (power angle) oscillations at PCC ($\Delta\theta_{grid}$). Thus, the effect of the RSSG-SPC on the dynamic of the grid mode would be achieved using Fig. 2. As observed in Fig. 2, to simplify the modelling approach of the external grid, we can assume that the grid phase θ_{grid} has

oscillation and it acts as the input of the dynamic model of RSSG-SPC. Moreover, P_{SSG} is the output power of the dynamic model that we want to control which aims to have the specific frequency of internal oscillation in RSSG-SPC (ω_{ssg}^{os}). Referring to Fig. 2, we can extract transfer function from grid phase oscillation $\Delta\theta_{grid}$ to RSSG-SPC output power oscillation ΔP_{SSG} , as expressed in (1) to (3).

$$\frac{\Delta P_{SSG}}{\Delta\theta_{grid}} = -\frac{G_1}{1 + G_1 G_2 G_3} \quad (1)$$

$$\Delta = \frac{\Delta_{num}}{\Delta_{den}} = 1 + P_s \cdot \left(\frac{\omega_o}{s}\right) \left(\frac{1}{M_{ssg}s + D_{ssg}}\right) = 0 \quad (2)$$

$$\lambda_{SSG} = \frac{-D_{ssg} \pm \sqrt{D_{ssg}^2 - 4M_{ssg}P_s\omega_o}}{2M_{ssg}} \quad (3)$$

$$P_s = \frac{E_{ssg}E_{grid}}{X_{tie}} \cos\delta_o \quad (4)$$

The transfer function of closed loop system can be extracted as in (1). Therefore, the characteristic equation (CE) of the system can be represented as in (2). The roots of (2), will define the modes of the RSSG-SPC power loop and can be calculated from (3) where P_s is synchronization power which is obtained from (4).

Since all the parameters of the system are purely real, therefore oscillatory modes in RSSG-SPC would rely on (5) as a condition in the radical expression of the modes calculated by (3). After some mathematical simplification, (6) will give us the value D_{ssg}^{Ovr} for damping in RSSG-SPC, which is the border between over-damped modes and oscillatory modes condition in RSSG-SPC model. The value obtained for D_{ssg}^{Ovr} in (6), is the critical damping value for the local modes inside of a RSSG-SPC when it is connected to an external grid.

$$D_{ssg}^2 - 4M_{ssg}P_s\omega_o < 0 \quad (5)$$

$$D_{ssg}^{Ovr} = |D_{ssg}| = +\sqrt{4M_{ssg}P_s\omega_o} \quad (6)$$

This value is dependent upon the moment of inertia in the RSSG-SPC (M_{ssg}), synchronization power (P_s), and the nominal frequency of the system (ω_o). The P_s reflects the effect of the voltage condition in RSSG-SPC and grid side (E_{ssg}, E_{grid}); as well as the effect of interconnected reactance between RSSG-SPC and grid (X_{tie}).

2) *Determination of D_{ssg}^{Und}* : The condition stated in (5) should be satisfied for the oscillatory modes of the RSSG-SPC. This means performance range as expressed in (7) is the area that RSSG-SPC has under-damped oscillatory modes and there is the possibility to have proper dynamic interaction with the grid.

$$0 < D_{ssg}^{Und} < +\sqrt{4M_{ssg}P_s\omega_o} \quad (7)$$

In this condition, the expression inside of the root in (3) has a negative value. Therefore (3) can be rewritten to describe the

oscillatory mode of RSSG-SPC (λ_{SSG}^{os}) as shown in (8) or (9), where ω_{ssg}^{os} shows the frequency of oscillation inside of the RSSG-SPC power loop.

$$\lambda_{SSG} = \lambda_{SSG}^{os} = -\frac{D_{ssg}}{2M_{ssg}} \pm \left(\frac{\sqrt{4M_{ssg}P_s\omega_o - D_{ssg}^2}}{2M_{ssg}}\right)i \quad (8)$$

$$\lambda_{SSG}^{os} = -\frac{D_{ssg}}{2M_{ssg}} \pm \omega_{ssg}^{os}i \quad (9)$$

If the external grid has an oscillatory mode in PCC (λ_{grid}^{os}) with the frequency equal to ω_{grid}^{os} , it can be expressed as in (10); where all damping effects of the grid are ignored. Aiming towards modelling the grid connection of RSSG-SPC, (11) should be satisfied to model the grid synchronization of the RSSG-SPC.

$$\lambda_{grid}^{os} = 0 \pm \omega_{grid}^{os}i \quad (10)$$

$$\omega_{grid}^{os} = \omega_{SSG}^{os} = \left(\frac{\sqrt{4M_{ssg}P_s\omega_o - D_{ssg}^2}}{2M_{ssg}}\right) \quad (11)$$

Solving (11) for D_{ssg} will give us (12).

$$D_{ssg} = \sqrt{4M_{ssg}P_s\omega_o - (2M_{ssg}\omega_{grid}^{os})^2} \quad (12)$$

The solution of (11) for D_{ssg} yields (12), in which it can be observed that each of damping and inertia of RSSG-SPC are dependent on one another. This means that for a specific value of inertia M_{ssg} in typical range, we can define the damping D_{ssg} to satisfy (11). So, in summary, the (12) defines the required damping setting for tuning in RSSG-SPC where the RSSG-SPC connected to the external grid, as well as RSSG-SPC has the same oscillation frequency with the external grid.

B. Optimal Dynamic Tuning of RSSG-SPC

In this section, based on the dynamic analysis performed in the previous section as well as by using zeta maximization condition, we will describe the procedure for tuning both dynamic parameters in RSSG-SPC (M_{ssg}, D_{ssg}). The main goal is to have maximum damping effect of RSSG-SPC on the grid oscillatory modes, while the RSSG-SPC has proper and flexible interaction with the grid.

1) *Damping Ratio Maximization (Prove of the Proposed Method)*: As mentioned in Section III.A.2 (see (8)), the RSSG-SPC will give us a flexible dynamic mode which can be expressed in general form as in (13) and (14). The mode λ_m with both variable real and imaginary parts (a_m, b_m) is the general format of an electromechanical oscillatory mode. In this oscillatory mode, θ_m and ξ_m are the angle and damping ratio, respectively. Therefore, it can be observed that $\xi_m = F(a_m, b_m)$ is a two-variable function based on the (a_m, b_m). To explain the critical points that cause significant changes in ξ_m , it is required to make the partial derivative of ξ_m with respect to (a_m, b_m) as well as to study the locus of roots of the derivative function ($\partial^2 \xi_m$). The partial derivative of the ξ_m with respect to (a_m, b_m) can be obtained as illustrated in (15) to (17). Equation (17) explains the general function of the $\partial^2 \xi_m$

$$\begin{cases} \lambda_m = -a_m \pm b_m i \\ \theta_m = \tan^{-1}\left(\frac{b_m}{a_m}\right) \end{cases} \quad (13)$$

$$\xi_m = F(a_m, b_m) = \frac{1}{\sqrt{1 + \frac{b_m^2}{a_m^2}}} \quad (14)$$

$$\frac{\partial \xi_m}{\partial \theta_m} = \frac{\partial^2 \xi_m}{\partial b_m \partial a_m} = \frac{\partial}{\partial b_m} \left(\frac{\partial \xi_m}{\partial a_m} \right) \quad (15)$$

$$\frac{\partial^2 \xi_m}{\partial b_m \partial a_m} = \frac{\partial}{\partial b_m} \left(\frac{b_m^2}{a_m^3 \left(1 + \frac{b_m^2}{a_m^2} \right)^{\frac{3}{2}}} \right) \quad (16)$$

$$\begin{aligned} \frac{\partial \xi_m}{\partial \theta_m} &= \frac{\partial^2 \xi_m}{\partial b_m \partial a_m} = \\ &= -\frac{3b_m^3}{a_m^5 \left(1 + \frac{b_m^2}{a_m^2} \right)^{\frac{5}{2}}} + \frac{2b_m}{a_m^3 \left(1 + \frac{b_m^2}{a_m^2} \right)^{\frac{3}{2}}} \end{aligned} \quad (17)$$

for an oscillatory mode (λ_m).

Further simplification can be applied to (17) to the form shown in (18) and (19). Further on, to obtain the required condition of maximum damping ratio (ξ_m^{max}), the derivative function should be considered equal to zero as in (20). Based on (21), the denominator of $\partial^2 \xi_m$ (f_{den}) is always positive and with a nonzero value for all modes outside of the center of the coordinate system ($a_m, b_m \neq 0$). However, the numerator of $\partial^2 \xi_m$ (f_{num}) has different conditions based on different values of b_m . Finally, f_{num} defines the roots of $\partial^2 \xi_m$, which has two general solutions as illustrated in (22) and (23).

$$\frac{\partial^2 \xi_m}{\partial b_m \partial a_m} = -\frac{3b_m^3}{(a_m^2 + b_m^2)^{\frac{5}{2}}} + \frac{2b_m}{(a_m^2 + b_m^2)^{\frac{3}{2}}} \quad (18)$$

$$\frac{\partial^2 \xi_m}{\partial b_m \partial a_m} = \frac{+2b_m a_m^2 - b_m^3}{(a_m^2 + b_m^2)^{\frac{5}{2}}} \quad (19)$$

$$\xi_m^{max} \rightarrow \frac{\partial \xi_m}{\partial \theta_m} = \frac{\partial^2 \xi_m}{\partial b_m \partial a_m} = \frac{f_{num}}{f_{den}} = 0 \quad (20)$$

$$\begin{cases} f_{den} = (a_m^2 + b_m^2)^{\frac{5}{2}} > 0, & a_m, b_m \neq 0 \\ f_{num} = +2b_m a_m^2 - b_m^3, & \forall a_m, b_m \end{cases} \quad (21)$$

As explained in the set (22), *Solu (I)* is linked to the condition that the frequency of λ_m becomes zero ($b_m = 0$). This condition is an Over-Damped condition of λ_m

$$\begin{cases} f_{num} = 0 \Rightarrow \text{Solu (I):} \\ \text{if } b_m = 0 \text{ then } a_m = a_m, \forall a_m \\ (b_m = 0, a_m = a_m) \\ \lambda_m = -a_m \\ \xi_m = 1 \rightarrow \text{Over-Damped} \end{cases} \quad (22)$$

$$\begin{cases} f_{num} = 0 \Rightarrow \text{Solu (II):} \\ \text{if } b_m \neq 0 \text{ then } +2a_m^2 - b_m^2 = 0 \\ |a_m| = \left| \pm \frac{\sqrt{2}}{2} b_m \right|, \forall a_m, b_m \\ \left(b_m \neq 0, |a_m| = \left| \pm \frac{\sqrt{2}}{2} b_m \right| \right) \\ \lambda_m = -a_m \pm b_m i = -\frac{\sqrt{2}}{2} b_m \pm b_m i \\ \xi_m = \frac{\sqrt{3}}{3} = 0.577 \approx 0.60 \text{ Under-Damped} \end{cases} \quad (23)$$

($\lambda_m = -a_m$). This case is applicable for situations that λ_m can reach to zero in the frequency of oscillations. This situation will happen when λ_m is under high control of the RSSG-SPC or λ_m is considered to be the internal mode of the RSSG-SPC ($\lambda_{SSG} = \lambda_m$) [27],[31]. This case will happen in Stand-Alone operation of the RSSG-SPC or on the connection of the RSSG-SPC to an external grid with stiff dynamics as depicted in Fig. 3a and Fig. 3b.

Fig. 3. Application of solutions in grid connection of RSSG-SPC: a) connection to a stiff bus; b) Stand-Alone operation of RSSG-SPC; c) Connection to power grid with oscillatory modes $\lambda_{SSG}^{os} = \lambda_{grid}^{os} = \lambda_{SSG}^{grid}$.

On the other hand, as shown in (23), *Solu (II)* is related to the conditions that the frequency of λ_m cannot be zero ($b_m \neq$

0). This solution will give us the Under-Damped condition of λ_m as well as the extremum value of ξ_m which in this scenario is $\xi_m \approx 0.60$. This solution is applicable for the grid connection of the RSSG-SPC, where λ_m is under control of the several participators and the frequency of λ_m on PCC cannot be completely zero through the exclusive support of RSSG-SPC (see Fig. 3c).

The locus of the *Solu (I)* and *Solu (II)* are depicted on Fig. 4 for variable a_m , where *Solu (II)* is studied for $b_m = b_o = 1$. As shown in Fig.4, $\xi_m \approx 0.60$ gives a satisfactory result for the roots of $\partial^2 \xi_m$. Moreover, based on the condition of $\partial^2 \xi_m$, there are four Zones (A to D) to tuning a_m . In Zone A, $\partial^2 \xi_m$ holds a negative value. Tuning a_m in Zone B would achieve zero or near zero values of $\partial^2 \xi_m$. For higher value of a_m in Zone C, $\partial^2 \xi_m$ will be positive and further on $\partial^2 \xi_m$ will converge to zero in Zone D.

The general pattern of the root-locus of the internal dynamics of the RSSG-SPC (λ_{SSG}) in Stand-Alone Operation was discussed in [27],[31], so in this study we will ignore further discussion about it due to the limited number of pages. Moreover, based on our previous research published in [27] and [32],[33], it can be confirmed that the general pattern of the control of modes in grid connection of a RSSG-SPC is as depicted in Fig. 5. As illustrated in Fig.5 it can be seen that by increasing D_{SSG} , the controlled mode by the RSSG-SPC (λ_{SSG}^{grid}) has a curved shape but other common modes (λ_{com}) have a more flat shape.

Fig. 4. Locus of general solutions of the derivative of damping ratio

Fig. 5. Definition of operating zones for tuning of D_{SSG} in grid connection of RSSG-SPC.

Indepth analysis of both Fig. 4 and Fig. 5 confirms that the locus of the *Solu (II)* can clearly explain mathematically the condition of λ_{SSG}^{grid} in all Zones A to D. Especially for Zone B, from one side this zone is in the neighborhood of the root of $\partial^2 \xi_m$ for an oscillatory mode ($\lambda_m = -\frac{\sqrt{2}}{2} b_m \pm b_m i$) (see Fig.

4), and from another side this zone is in the neighborhood of the corner point that will happen for this oscillatory mode in root-locus graph (see Fig. 5). Therefore, it can be concluded that Zone B is an important area for tuning D_{SSG} in the grid connection of RSSG-SPC which can be obtained through the study of the solution of $\partial^2 \xi_m$. In other words, the conditions governing *Solu (II)* that is expressed in (23), will give us the clear index for dynamic tuning of the RSSG-SPC aim to achieve an optimal solution of ξ_m .

Activation both of (D_{SSG}, M_{SSG}) in RSSG-SPC is equivalent to having the variables (a_m, b_m) in λ_m . In this condition, the dynamic surface of the ξ_m is as depicted in Fig. 6. As observed in Fig. 6, *Solu (I)* is the flat peak of this surface, while *Solu (II)* is located on the slope areas of the ξ_m surface in Fig. 6. This dynamic surface will give us a global basic view for dynamic tuning of the RSSG-SPC.

Fig. 6. Meaning and application of solutions from ξ_m point of view.

A specific case of the zeta surface for the internal dynamics of the RSSG-SPC ($\xi_{\lambda_{SSG}}$), based on (1) to (9), is depicted in Fig. 7, where $\omega_o = 377 \text{ rad}$, $X_{SSG} = 0.30 \text{ pu}$, $X_{grid} = 0.3842 \text{ pu}$, $X_{tie} = X_{grid} + X_{SSG}$, $E_{grid} = 1 \text{ pu}$, $E_{SSG} = 1 \text{ pu}$, $\delta_o = 0^\circ$. As it can be observed that the general pattern of Fig. 6 appears in Fig. 7 and it includes a flat roof bedside of the sloped areas. In the next part (Section III.B.2&3) we will see that based on the *Solu (II)* and applying its condition (23) to the internal mode of the RSSG-SPC, we can select an optimal dynamic tuning on the hillside of $\xi_{\lambda_{SSG}}$ surface for grid connection of the RSSG-SPC.

Fig. 7. Tuning of the internal dynamic of RSSG-SPC for grid connection

2) *Optimal Value for D_{SSG}* : Section III.B.1 (see (23)) explained the link between real and imaginary part of an oscillatory mode for having extremum damping ratio in the general case, as well as (8) described the general form of oscillatory modes in the RSSG-SPC connected to the grid. So, applying condition of *Solu (II)* (set (23)) into (8), achieves

maximum damping ratio condition (ξ_m^{max}) for oscillatory modes (λ_m) as described in (24). Solving (24) for D_{ssg} will result in (25).

$$\begin{cases} \lambda_{ssg}^{os} = -\frac{D_{ssg}}{2M_{ssg}} \pm \left(\frac{\sqrt{4M_{ssg}P_s\omega_o - D_{ssg}^2}}{2M_{ssg}} \right) i \\ |a_m| = \left| \pm \frac{\sqrt{2}}{2} b_m \right| \end{cases} \quad (24)$$

$$D_{ssg} = D_{ssg}^{\xi_m^{max}} = \sqrt{\frac{4M_{ssg}P_s\omega_o}{3}} \quad (25)$$

Equation (25) will achieve a damping value that satisfies the maximum damping ratio ξ_m^{max} when the RSSG-SPC and external grid are connecting together and they are oscillating by a dynamic common mode ($\lambda_{ssg}^{os} = \lambda_{grid}^{os} = \lambda_{ssg}^{grid}$). From grid point of view, $D_{ssg}^{\xi_m^{max}}$ is the optimal value where RSSG-SPC has proper dynamic interaction with the grid, as well as RSSG-SPC, is transferring possible maximum damping ratio (ξ_m^{max}) to this common oscillatory mode. As we will see later, this oscillatory mode can be local mode in a generation area.

3) *Optimal Value for M_{ssg}* : If we assume that RSSG-SPC is connected to the grid and both of them participate in common mode ($\lambda_{ssg}^{os} = \lambda_{grid}^{os} = \lambda_{ssg}^{grid}$). Meanwhile, the main goal is set to acquire maximum damping effect (ξ_m^{max}) on the common oscillatory mode, then we can write a set of the equation as below by using (11) and (25).

$$\begin{cases} \omega_{ssg}^{os} = \omega_{grid}^{os} = \left(\frac{\sqrt{4M_{ssg}P_s\omega_o - D_{ssg}^2}}{2M_{ssg}} \right) \end{cases} \quad (26)$$

$$\begin{cases} D_{ssg} = D_{ssg}^{\xi_m^{max}} = \sqrt{\frac{4M_{ssg}P_s\omega_o}{3}} \end{cases} \quad (27)$$

Substituting (27) into (26), then solving (26) for M_{ssg} will give us (28). Upon simplification of (28) will result in (29), where P_s is synchronization power and it can be calculated by (4).

$$\omega_{ssg}^{os} = \omega_{grid}^{os} = \left(\frac{\sqrt{4M_{ssg}P_s\omega_o - \left(\sqrt{\frac{4M_{ssg}P_s\omega_o}{3}} \right)^2}}{2M_{ssg}} \right) \quad (28)$$

$$M_{ssg} = M_{ssg}^{\xi_m^{max}} = \frac{2P_s\omega_o}{3(\omega_{grid}^{os})^2} \quad (29)$$

Equation (29) will give us the proper value for tuning the moment of inertia in RSSG-SPC to have maximum damping effect on the common oscillatory mode ($\lambda_{ssg}^{os} = \lambda_{grid}^{os} = \lambda_{ssg}^{grid}$). So we can call this specific value of the moment of inertia as

($M_{ssg}^{\xi_m^{max}}$), which is required for transferring maximum damping to the oscillations of λ_{ssg}^{grid} in the system depicted in Fig. 3c.

V. RSSG-SPC IN TWO AREA SYSTEM

To justify and validate the proposed method, a RSSG-SPC was designed and tuned for a Kundur two area system [34]. Furthermore, results of modal analysis (which was extracted based on the dynamic modeling method discussed in [27]) is presented for both Base Grid Model (BGM) and grid model in presence of RSSG-SPC (marked as *SSG*). Later on, time domain analysis was performed which was executed through Simulink environment and compared for both cases to validate modal analysis outcomes. Finally, a real time test was executed to validate all of the former evaluations.

A. Modal Analysis

1) *Base Grid Model (BGM)*: For a clearer realization of the dynamic conditions of the BGM (see Fig. 8a), some primary assumption was considered in its dynamic modelling. Firstly, all machine inertias are equal to the value presented in main reference [34], but all damping providers such as Power System Stabilizers (PSS) were deactivated in all Classic Generation Units (CGU). Therefore, in the BGM, a small damping

Fig. 8. Base grid model: (a) Schematic of grid; and (b) Participation factor of states in dynamic modes

Table I. Condition of oscillatory modes in base grid model (BGM).

λ	Eige	$f(\text{Hz})$	ξ	Dominant States	Description
$\lambda_{1,2}$	-3.4898 -0.1489	—	1.0000	—	—
$\lambda_{3,4}$	$\pm 2.8128i$ -0.1453	0.4477	0.0529	$\Delta\delta_{1:4}, \Delta\omega_{1:4}$	Interarea
$\lambda_{5,6}$	$\pm 7.1776i$ -0.1523	1.1423	0.0202	$\Delta\delta_{1:2}, \Delta\omega_{1:2}$	Local (I)
$\lambda_{7,8}$	$\pm 7.3653i$	1.1722	0.0207	$\Delta\delta_{3:4}, \Delta\omega_{3:4}$	Local (II)

coefficient ($K_d = 0.01pu$) was tuned in all machines. This primary assumption will help us to have a clear view of all electromechanical modes in each area. Moreover, observation of the effects of RSSG-SPC in such modes will be easier.

The small signal model of a BGM was obtained and its equivalent oscillatory modes as reported in Table I. Moreover, normalized Participation Factor Matrix (PFM) of all generation units in all oscillatory modes were calculated and plotted in Fig. 8b. As it can be observed from Fig.8b, there are three pair of oscillatory modes. Mode $\lambda_{3,4}$ with oscillation frequency around 0.5Hz and 5% damping ratio is an interarea mode. Modes $\lambda_{5,6}$ and $\lambda_{7,8}$ with almost 1Hz frequency and 2% damping ratio are local modes of Area (I) and Area (II), respectively.

2) *Grid in Presence of RSSG-SPC*: a RSSG-SPC was designed and tuned for installation in Area (II) in parallel of SG_4 in order to investigate the effect of RSSG-SPC as a small generation unit in both local and interarea modes. The RSSG-SPC was tuned based on the optimal dynamic design process presented in Section III. In this case of the design, the primary oscillatory mode of BGM at Bus 4 ($\lambda_{7,8}$ in Table I) was accounted for in calculations i.e. $\omega_{grid}^{os} = \omega_{\lambda_{7,8}}^{os}$. The values $D_{ssg}^{\xi_{max}} = D_{ssg}^{opt} = 0.187pu$ and $M_{ssg}^{\xi_{max}} = M_{ssg}^{opt} = 6.797s$ are the optimal dynamic tuning for RSSG-SPC when it is installed in Bus 5 as depicted in Fig. 9a. As discussed before, we expect that the RSSG-SPC applies maximum damping on external grid mode appearing from the installation point of view. Moreover, based on (6), $D_{ssg}^{ovr} = 0.49pu$ is the maximum setting limit of damping in RSSG-SPC upon installation in the presented location. In order to validate the optimal tuning of RSSG-SPC, a detailed modal analysis of grid in presence of RSSG-SPC was extracted when the moment of inertia was fixed at M_{ssg}^{opt} and damping of RSSG-SPC (D_{ssg}) was variable. The condition of all modes and PFM, where damping was tuned on two different values $D_{ssg}^{Low} = 0.01pu$, $D_{ssg}^{opt} = 0.187pu$, were obtained and reported in Table II to Table III and Fig. 9 to Fig. 11, respectively.

The condition of modes and PFM of generation units for $D_{ssg} = D_{ssg}^{Low}$ and $M_{ssg} = M_{ssg}^{opt}$ are shown in Fig. 9 and Table II. In this case, it can be considered as the primary case in the presence of RSSG-SPC where there is one interarea mode ($\lambda_{3,4}$), one local mode in Area (I) ($\lambda_{5,6}$) and two local modes in Area (II) ($\lambda_{7,8}$, $\lambda_{9,10}$). Comparison between the condition of interarea mode ($\lambda_{3,4}$) in BGM (Table I) and current case (Table II) shows that the RSSG-SPC will participate in the interarea mode such as other generation units; although based on the PFM of this case (see Fig. 9b) RSSG-SPC's factor is almost half of the share of $SG_{3,4}$. Local mode in Area (I) ($\lambda_{5,6}$) is still affected only by $SG_{1,2}$ (see Fig. 9b), so we don't expect to see any change in the condition of this mode when compared with BGM case. But in Area (II), based on Fig. 9b, two main changes occur after the installation of RSSG-SPC. Firstly, the RSSG-SPC participates in the old local mode of this area ($\lambda_{7,8}$), but the participation factor of RSSG-SPC is much less than $SG_{3,4}$. Secondly, a new local mode ($\lambda_{9,10}$) in Area (II) appears in presence of RSSG-SPC.

Fig. 9. RSSG-SPC in Area (II): (a) Schematic of grid; and (b) Participation factor of states in dynamic modes for D_{ssg}^{Low} .

Table II. Condition of oscillatory modes for small damping in RSSG-SPC (D_{ssg}^{Low}).

λ	Eige	$f(Hz)$	ξ	Dominant States	Description
$\lambda_{1,2}$	-2.9284 -0.1616	—	1.0000	—	—
$\lambda_{3,4}$	$\pm 2.8168i$ -0.1464	0.4483	0.0573	$\Delta\delta_{1:SSG}, \Delta\omega_{1:SSG}$	Interarea
$\lambda_{5,6}$	$\pm 7.1732i$ -0.1568	1.1417	0.0204	$\Delta\delta_{1:2}, \Delta\omega_{1:2}$	Local (I)
$\lambda_{7,8}$	$\pm 7.2820i$ -0.2490	1.1590	0.0215	$\Delta\delta_{3,4}, \Delta\omega_{3,4}$	Local (II)
$\lambda_{9,10}$	$\pm 9.9927i$	1.5904	0.0249	$\Delta\delta_{4:SSG}, \Delta\omega_{4:SSG}$	Local (II)

According to the Fig. 9b, the RSSG-SPC and SG_4 are the main participants in this new mode and SG_3 has a small contribution on it, which can be negligible.

Furthermore, for the analysis of variable damping of RSSG-SPC, The D_{ssg} was increased from D_{ssg}^{Low} to D_{ssg}^{ovr} while keeping $M_{ssg} = M_{ssg}^{opt} = 6.797s$ fixed. Root-Locus graph and supplementary damping ratio provided by RSSG-SPC for grid modes are presented in Fig. 10. As illustrated in Fig. 10, RSSG-SPC has been able to move ($\lambda_{9,10}$) to more stable zones, as well as ($\lambda_{3,4}$) as the interarea mode has gained significant damping. But the other two pair modes, ($\lambda_{7,8}$ and $\lambda_{5,6}$) where the RSSG-SPC has not a significant factor in them, didn't have any noticeable change. The general pattern of $\lambda_{9,10}$ placement is a curved shape and after passing the peak of ($\xi_{\lambda_{9,10}}$) at specific value of D_{ssg} , then $\lambda_{9,10}$ will return to zones close to $j\omega$ axes.

After crossing corner part in Fig. 10a, for large D_{ssg} ($D_{ssg}^{ovr} \approx 0.50$), the mode ($\lambda_{9,10}$) is pushed back to position with small stability margin. In depth view of Fig. 10b shows us the increase in ($\xi_{\lambda_{9,10}}$) will continue until a maximum value as the peak of damping ratio for this controlled mode will happen

Fig. 10. Effect of RSSG-SPC dynamic flexibility in grid modes: a) Poles trajectory shapes and damping critical borders, and b) Supplementary damping provided by RSSG-SPC in grid modes.

Fig. 11. Participation factor of states in dynamic modes for D_{SSG}^{Opt} .

Table III. Condition of oscillatory modes for optimal damping in RSSG-SPC (D_{SSG}^{Opt}).

λ	Eige	$f(\text{Hz})$	ξ	Dominant States	Descri
$\lambda_{1,2}$	-3.8753	—	1.0000	—	—
$\lambda_{3,4}$	-0.6849 $\pm 2.7963i$	0.4451	0.2379	$\Delta\delta_{1:SSG}, \Delta\omega_{1:SSG}$	Interarea
$\lambda_{5,6}$	-0.1473 $\pm 7.1797i$	1.1427	0.0205	$\Delta\delta_{1:2}, \Delta\omega_{1:2}$	Local(I)
$\lambda_{7,8}$	-0.2645 $\pm 7.3954i$	1.1770	0.0357	$\Delta\delta_{3:4}, \Delta\omega_{3:4}$	Local(II)
$\lambda_{9,10}$	-3.9168 $\pm 7.9307i$	1.2622	0.4428	$\Delta\delta_{3,4,SSG}, \Delta\omega_{3,4,SSG}$	Local(II)

in $(0.20 < D_{SSG} < 0.22)$. Following the process in Fig. 10a confirms that $(0.20 < D_{SSG} < 0.22)$ is the threshold of corner point for $\lambda_{9,10}$. The quantity of D_{SSG} in this threshold area is very close to the optimal value of D_{SSG} ($D_{SSG}^{\xi_{max}} = D_{SSG}^{Opt} = 0.187pu$) which is calculated from (25). Arriving to maximum

value of $\xi_{\lambda_{9,10}} = \xi_{max} = 0.443pu$ in $(0.20 < D_{SSG} < 0.22)$ reveals that RSSG-SPC can transfer maximum damping to the targeted modes at the installed area by proper tuning of the internal dynamic parameters. This discussion confirms that optimal value (D_{SSG}^{Opt}) can be calculated directly and correctly based on the new developed equations in Section III. Table III and Fig. 11 describe status of modes where $D_{SSG} = D_{SSG}^{Opt} = 0.187pu$. Comparison between PFM of D_{SSG}^{Opt} and D_{SSG}^{Low} (see Fig. 11 and Fig. 9b) confirms that the RSSG-SPC has the significant factor in $(\lambda_{9,10})$ and has a bigger share than $SG_{3:4}$. This clarifies that extra damping provided for $(\lambda_{9,10})$ is just as a result of tuning of D_{SSG} in RSSG-SPC.

B. Time Domain Analysis

In this section, both BGM (labeled as *NoSSG*) and grid in presence of RSSG-SPC (labeled as *SSG*) were modelled in details under Simulink to investigate all mathematical equations and modal analysis results in time domain. All generation units in both cases were equipped with 5% power-frequency droop system. Dynamic tuning of RSSG-SPC was obtained by the equation of optimal tuning and validated by modal analysis as discussed in the previous sections. All damping adjustments in CGU were set to a low level ($K_d = 0.01pu$) for both cases of grid modeling to achieve similar conditions to the previous modal analysis. Outage of 130MW load from the base load of Bus 9 (Area II) at $t = 30s$ was applied as an operation scenario for both cases.

In the BGM (*NoSSG*), initial operating point was tuned as discussed in [34], as shown in Fig. 12a1 and Fig. 12b1 there is a stable initial operating point for BGM. After applying the operation scenario, this scenario is a local disturbance from the $SG_{3:4}$ point of view, so the most obvious oscillations appeared in $P_{SG3:4}$ and $W_{SG3:4}$ having a frequency around 1Hz that remained in the system for more than 20 seconds. The tie line power was supporting the supply shortage of Area (II), so the half hertz oscillation in P_{A1toA2} (see Fig. 12e) was mixed with local oscillation inside of Area (II). Therefore, most of signals in Area (II) had a combination of local and interarea frequencies as shown in Fig. 12a1 and Fig. 12b1. On the other hand, the disturbance was an incident far away from Area (I) and transmitted thorough the tie line, so it is an interarea event for Area (I). Therefore, similar to the swings in tie line power, all oscillations in Area (I) have only frequency close to interarea mode with small damping ratio.

A 200MW RSSG-SPC, controlled in P-V mode and equipped with 5% power-frequency droop system was connected to Bus 5. The RSSG-SPC was tuned to provide $P_{SSG}^o = 120MW$, $Q_{SSG}^o = 8Mvar$ as shown in Fig. 12d. The same scenario was applied for the grid in presence of RSSG-SPC and the main signals are shown in Fig. 12a2 and Fig. 12b2. A global view on these signals for $t > 30s$ confirms that most of the oscillations in both Area (I) and Area (II) were damped as well as magnitude of few primary oscillations were reduced in presence of RSSG-SPC. Based on a preliminary view of such results, it can be concluded that most of the outcomes from the modal analysis were validated.

Fig. 12. Response of grid to step change in active load: (a1) Active powers in BGM; (a2) Active powers in presence of RSSG-SPC; (d) Active and reactive power of RSSG-SPC; (b1) Frequency oscillation in BGM; (b2) Frequency oscillation in presence of RSSG-SPC; (e) Interarea active power.

Aiming for a deeper view of the effects of RSSG-SPC on the whole system, the installation area's influence can be analyzed by taking into consideration the active powers in this area. As shown in Fig. 12d at the first cycle of oscillation ($30 < \Delta t_1 < 31.5s$) where the RSSG-SPC has no serious interaction with the grid, the interarea mode and both local modes of Area (II) were visible in the local active powers (see $P_{SG3:4}^{SSG}$ in Fig. 12a2 at Δt_1). Slight reduction in ΔP_{A1toA2}^{SSG} at first cycle (around $20MW$ in Fig. 12e) was also the result of this low initial interaction of RSSG-SPC. But in the second swing at ($31.5 < \Delta t_2 < 33s$) where the RSSG-SPC has highest interaction ($\Delta P_{SSG} = 40:45MW$), the frequency of ΔP_{SSG} was close to $f_{\lambda_{9,10}} = 1.26Hz$ in Table III in this interval. This confirms that $\lambda_{9,10}$ is subjected by this big interaction of RSSG-SPC, therefore this local mode of Area (II) was strongly damped. Finally, at the end of Δt_2 , $\lambda_{9,10}$ disappeared from $P_{SG3:4}^{SSG}$ (see Fig. 12a2) as well as its expansion in the tie line has been prevented (see Fig. 12e). This is the main reason that P_{A1toA2}^{SSG} oscillations in Area (I) were severely damped after $t = 33s$.

Comparison of frequencies in Fig. 12b1 and Fig. 12b2 will better reveal the effect of RSSG-SPC dynamics with the grid. Having long lasting frequency variation with big magnitude deviations in BGM (see $W_{SG1:4}$ in Fig. 12b1), then removing these oscillations in less than 5 seconds by RSSG-SPC (see $W_{SG1:SSG}^{SSG}$ in Fig. 12b2), shows the clearly that the RSSG-SPC supports the dynamics of the grid. Deeper analysis of these signals shows that the BGM had big Rate of Change of Frequency (ROCOF) and the grid operation was oscillatory around a weaker Center of Inertia (COI) due to the small damping in all CGUs. But in the compensated system (see Fig. 12b2) the variation of frequencies were reduced significantly at second swing (Δt_2) which was a result of the big interaction of RSSG-SPC as discussed earlier. This means now there is stronger frequency interconnectivity between generation units as compared to the BGM. Therefore we can conclude that the phase coupling between the two areas is rigid. In much simpler terms, the present system COI has stiffer dynamics in presence

of RSSG-SPC which is confirming the higher synchronism coefficient between interconnected areas.

C. Real Time Validation

To validate the theoretical method and Simulink analysis, a laboratory platform was under tested as shown in Fig. 15 and details are reported in Table IV. The grid was modeled in details by ARTEMIS toolbox and implemented in OPAL-RT5600 as a Real Time Digital Simulator. Electrical signals of Bus 5 was sent as command from OPAL to PUISSANCE PCU 21kVA power amplifier. The power amplifier was connected to a 5kVA Voltage Source Converter (VSC) developed by Sistemas Eléctricos de Energía Renovable research group at Universidad Politécnica de Cataluña. The VSC was controlled based on SPC technique using dSPACE 1103. A 32kW REGATRON power supply supports converter as dc source. BGM as well as compensated grid were tested for same scenario such as Simulink analysis section. For each case, three group of signals were captured as shown in Fig.13 which included: a) variation of all frequencies around the COI ($\Delta \omega_{1:SSG} = \omega_{1:SSG} - COI$) and active power of generation units ($P_{1:SSG}$), b) Tie line power (P_{A1toA2}) and load powers in Bus 9 (P_{LB9} , Q_{LB9}), c) Voltage in both side of tie line (V_{B7} , V_{B9}) and reactive power of generation units ($Q_{1:SSG}$). By comparing Fig. 13 with Fig. 12 it can be observed that the results of real time test show that analysis and discussion in theoretical and Simulink parts are identical for both BGM and grid in presence of RSSG-SPC.

Moreover, the dynamics of active and reactive interaction between RSSG-SPC and the grid were validated as shown in Fig. 14. In Fig.14, the RSSG-SPC was reacting rapidly to most phase oscillations in PCC on the proper dynamic bandwidth based on the flexible dynamics provided by the well-tuned SPC. This capability clearly appeared in P_{SSG} (see Fig. 14a) where the frequency of ΔP_{SSG} in each swing was compatible with PCC requirements. Furthermore, although the reaction level of RSSG-SPC even in the biggest case ($\Delta P_{SSG} = 45MW$) is very small compared to the nominal generation capacity installed in this area ($\Delta P_{SSG}/1800MW = 2.5\%$). However, this reaction has been done in the large level of virtual damping as compared

Fig. 13. Real time validation results: (a1) Frequency deviation around COI and active powers in BGM; (a2) Frequency deviation around COI and active powers in compensated grid; (b1) Interarea and load power in BGM; (b2) Interarea and load power in compensated grid; (c1) Voltage in both sides of tie line and reactive power of generation units in BGM; (c2) Voltage in both sides of tie line and reactive power of generation units in compensated grid.

Fig. 14. Dynamic interaction between RSSG-SPC and grid: (a) Active interaction with other generation units; (b) Reactive interaction with other generation units.

to damping of CGUs ($D_{ssg}^{opt}/K_d = 1870\%$). So, the RSSG-SPC with low temporary participation in power sharing and big damping capability will act as a strong damper for active power which damps both local and interarea oscillations.

VI. CONCLUSION

This paper proposed a new solution for regulation of main dynamic parameters in RSSG-SPC to mitigate sustained oscillatory modes in the power grid. Through deep mathematical analysis on the derivative function of the damping ratio formula as well as on the dynamic model of a RSSG-SPC connected to the grid, the clear indices were extracted for regulation of virtual damping and inertia in order to achieve maximum damping effect on local modes and support damping on interarea modes. State space model of multi-area system in presence of RSSG-SPC was extracted then analyzed the electromechanical modes for variable virtual damping in RSSG-SPC. The analysis confirmed that the

proposed analytical method has defined correctly the critical borders of dynamic parameters. Study on the participation factor matrix as well as root-locus index showed that the dynamic tuning of RSSG-SPC has a vital effect on the suppressing the oscillatory modes as well as on the stability enhancement of the power grid through a RSSG-SPC. Time domain results and real time test validated that based on the high dynamic flexibility in a SPC, the RSSG-SPC can react to the range of electromechanical oscillations in the grid and damp them significantly. In fact, after proper dynamic tuning through the proposed method, the RSSG-SPC creates a stiff bus in the generation area and has reduced frequency variations as well as provided a solid center of inertia for the whole of the grid. In this way, both local and interarea oscillatory modes have been mitigated significantly. Finally, it can be concluded that by having efficient control technology as well as well-designed dynamic parameters using trustable methods, the RSSG-SPC can act as a strong power damper and can satisfy operator's

requirements in regards to stability enhancement of the power grid.

Table IV. Platform and power grid specific data.

Section	Details
Power Grid	KUNDUR two area system [34]
	$5kVA, V_{ac} = 400V, V_{dc} = 600V, 10kHz$
Power Converter & Emulated RSSG-SPC	$M_{ssg} = M_{ssg}^{\xi_{max}} = M_{ssg}^{opt} = 6.797s,$ $D_{ssg} = D_{ssg}^{\xi_{max}} = D_{ssg}^{opt} = 0.187pu,$ $R_v = 0.1pu, X_v = 0.3pu, X_{grid}^{Bus 5} = 0.3842pu$ Emulated RSSG-SPC in OPAL-RT: 200MVA, 20kV, 60Hz

Fig. 15. Laboratory platform for real time test

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