Active Power Limiter for Static Synchronous Generators in Renewable Applications

Mostafa Abdollahi, *Student Member, IEEE*, Jose Ignacio Candela, *Member, IEEE*, Joan Rocabert, *Member, IEEE*, and Mohamed Atef Elsaharty, *Member, IEEE*

Abstract—Virtual Synchronous Generators (VSGs) are an interesting control approach for the connection of renewable energies to the electrical grid through power converters. These power devices have shown their ability to enable grid supportive services in terms of both voltage and frequency. The implementation form shown in the paper allows islanding as well as grid forming operation of the device. A challenging problem that arises is to make the grid supportive services compatible with the instantaneous power limits that renewable energies can provide. In this paper, an Active Power Limiter (APL) is proposed, designed and tested to manage output active power of power converters connected to a renewable source. The implementation of APL is tested on the Synchronous Power Controller (SPC) that emulates inertia and output admittance. The simulation and experimental results shown in the paper confirm that the proposed controller can efficiently control and limit the active power while still providing grid supportive services.

Index Terms—Active power limiter; power converters control; damping supporting; renewable generation units; synchronous power controller.

I. INTRODUCTION

IN the last few years there has been a great expansion of renewable energies all over the world, among which wind and photovoltaic energy stand out [1]. The integration of these new forms of generation into the electrical grid is proving to be a challenge for electrical Transmission System Operators (TSOs) and in the near future the likelihood of contribution of this type of generation will be even greater [2]. The grid interconnection of energy sources is mostly implemented through power electronic converters, typically working as Voltage Source Converters (VSCs) [3]. The connection of renewable source and VSC to the grid forms a Renewable Gen-

eration Unit (RGU) [4]. Typically, this type of generation units provide limited power or no support to the grid and are limited to supplying the grid with the all the active power available from the primary energy source [5]. These factors have forced TSOs to implement increasingly demanding grid codes for the connection of RGUs and sometimes to send set points that limit the output power of these plants [6]. One solution to this problem is the connection of RGUs to the grid emulating a VSG [7]. VSGs provide grid support through dynamic equivalency to the classic synchronous generators, allowing to provide wide grid support at both voltage and frequency level as well as phase stability level [8]. In current literature, among the different possible implementations of the VSG in a VSC, the SPC is one of attractive approaches [9]. On one hand, the SPC emulates mechanical characteristics with adjustable inertia and damping, and on the other hand it emulates electrical characteristics through a virtual output admittance. In addition, this implementation does not need a grid synchronization element like Phase Locked Loop (PLL) due to its ability to synchronize with the grid on the basis of power flow [10]. The implementation presented here automatically responds to grid frequency variations with changes in the active output power that is proportional to the emulated inertia [11]. Moreover, this type of implementation allows the RGU to operate in island mode, as long as the power demand is lower than the maximum power of the primary source [12].

An additional issue in connecting RGUs to the grid is that there are limits on the power that can be supplied, which cannot be exceeded even transitorily. There is a maximum power, P_{max} , which is determined by thermal limitations of the converter, but even more strictly by the power that the renewable resource can supply at any given time [13]. There is also a limitation on the minimum power, P_{min} , which is typically zero in the case of renewable energies [14]. Considering that a RGU can also consist of an energy storage system, for example to mitigate the variability of the renewable resource, the limits P_{max} and P_{min} can vary [15]. This variation depends on the state of charge of the energy storage and other factors allowing P_{min} to be equal but of opposite sign to P_{max} [16]. In renewable sources, such as photovoltaic, exceeding these maximum or minimum power limits can lead to very wide and rapid variations in the converter's DC bus voltage, leading

M. Abdollahi is with the Electrical Engineering Department, Technical University of Catalonia, Barcelona 08222, Spain, and also with the TRACTEBEL-ENGIE, Brussels 1000, Belgium (e-mail: mostafa.abdollahi@upc.edu, mostafa.bastaki@gmail.com).

J. I. Candela, and J. Rocabert are with the Electrical Engineering Department, Technical University of Catalonia, Barcelona 08222, Spain (e-mail: jose.ignacio.candela@upc.edu; joan.rocabert@upc.edu).

M. A. Elsaharty is with the Research Institute for Autonomous Systems, University of North Dakota, Grand Forks, 58202, North Dakota, USA (email: mohamed.elsaharty@und.edu).

Corresponding author is M. Abdollahi (mostafa.abdollahi@upc.edu).

to its disconnection [17].

Therefore, the RGUs based on VSG require a power limitation system that allows grid support as well as it needs to be compatible with the technical limits of the primary energy source. A saturation limiter for the reference output power is not sufficient since emulating inertia in a VSG causes a slow rate of response to power reference [18]. In such case as an example it has been proven that in PV systems the control of the converter was lost before the power was limited [19]. Based on these challenges, in continue of our previous works [20] and [21], this paper presents an APL that limits the RGU output power by providing two power control channels. The first channel would be activated in case of RGU arrives to the instantaneous power limits through the typical set point of the mechanical control of the VSG. Moreover, another control channel would be enabled that acts directly on the electrical part of the VSG, which presents a much faster response. Simultaneous operation of these two channels provides high performance of APL for active power control. The proposed system directly converts the reference power deviation into an angle deviation of the voltage of the VSG and leads to fast power limiting on favorable levels, as well as it enabling the power to be held within the desired limits while maintaining the required grid support as shown in the tests performed.

Recently the Grid Voltage Modulated Direct Power Control (GVM-DPC) presented in [22]. The GVM-DPC controls active power directly ignoring the Phase Locked Loop (PLL) and Park transformation, which is similar to SPC technique. Compared to the conventional vector current control (VCC), the GVM-DPC has better transient response due to the exclusion of the PLL since it exhibits slow dynamics [23],[24]. Moreover, as discussed in [25], the GVM-DPC has been developed by implementing the voltage modulated approach and feedback linearization to have linear performance. Therefore, the GVM-DPC overcomes the disadvantage of conventional Direct Power Control (DPC) method and achieves better steady-state performance. Furthermore, GVM-DPC has been applied in the inner control loops such as dc-link [26]. However, the GVM-DPC has no virtual damping and virtual inertia capabilities, which are the essential features of the SPC [9]. As mentioned in [22], the key point of the GVD-DPC is that it converts the real nonlinear system to a linear system which can provide several possibilities to design controllers. Similarly, the SPC uses the second order system to provide a simple mechanism with lower computational burden and simple design methods. The Virtual Synchronous Reference Frame (VSRR) based DPC is another efficient power control method [27]. In this method, virtual phase angle is used instead of voltage phase angle which also eliminates the necessity of a PLL. However, the SPC extracts the power angle directly form the calculated power, so the grid synchronization of the SPC is easier, faster, and more efficient compared to the VSRR. The VSRR has shown good performance in unbalanced grid voltage and harmonically distorted voltage conditions [28],[29], similarly, these features were validated with the SPC technique [10].

In this paper, the power angle would be controlled directly by the APL-SPC. This is the key difference between the APL-

SPC as compared to the GVM-DPC and VSRR. So, the APL-SPC gives a damped and fast transient process. Moreover, as explained in [11], the Renewable Static Synchronous Generator controlled by SPC (RSSG-SPC) is equipped with internal current controllers thus APL-SPC directly controls the current and provides high-quality performances. This high-quality performance is essential for industrial applications as well as grid integration of power converters to participate in ancillary grid services [30]. The rest of the paper is organized as follows. In Section II, structure and operational mechanism of APL are discussed. In this section, the performance of APL is analyzed deeply, aiming to control the active power during steady state condition and transient intervals. The APL design is discussed in Section III, stability analysis of APL for RSSG-SPC is summarized in Section IV, and APL performance has been checked in Section V. Section VI is assigned for the application of APL where RSSG-SPC is installed in Kundur system. Section VII evaluates the performance of APL through a real-time test using a 21-kVA power laboratory platform. Finally, conclusions are summarized in Section VIII.

II. ACTIVE POWER CONTROL ON RSSG-SPC: PROPOSED ACTIVE POWER LIMITER

The power converters of RSSG-SPC can control energy extracted from renewable energy sources. The primary source of energy can be wind turbines, solar panels, or even energy storage system as depicted in Fig. 1. The control strategy in RSSG-SPC for management of active and reactive power is discussed in [11]. The mechanism of active power control in RSSG-SPC is presented in Fig. 2. In this case, RSSG-SPC synchronizes with the external power grid without using phased locked loop (PLL) system. Also, the primary control of active power is achieved through an Electromechanical Model (EM). Furthermore, the RSSG-SPC contributes in frequency regulation process through the power-frequency droop system (P-f droop).

Fig. 1. Grid connection of RSSG-SPC

Fig. 2. Active power control process in RSSG-SPC

As shown in Fig. 2, virtual damping (D) and virtual inertia (H) provide primary dynamics of output active power (P_{SSG}) in Fig.1. These important dynamic parameters (D, H) have essential role in the grid connection of RSSG-SPC. The tuning

method of these parameters is deeply discussed in [11], aiming to proper management of RSSG-SPC. The set points of maximum and minimum power borders (P_{min} , P_{max}), as well as the measured active power (P_{meas}) are input of the APL block. The APL affects the EM through two stages. Firstly, phase angle corrective signal ($\Delta\theta_{Limiter}$) directly manages main reference of phase angle (θ_{ref}), thus it rapidly contributes in the control of transient condition of P_{SSG} . Then, active power corrective signal ($\Delta P_{Limiter}$) modifies reference of power (P_{ref}^*) whereupon the steady-state condition of P_{SSG} will be managed. Moreover, the P-f droop system adds a supplementary corrective active power signal (ΔP_{droop}) to the P_{ref}^* after defining the frequency error (Δf) from measured frequency (f_{meas}) and frequency reference (f_{ref}^*) according to the droop characteristic (R_f).

The primary structure of APL is proposed in [20]. The main motivation of an APL aims towards expansion of RGUs considering the limitation of active power. In fact, APL is proposed for increased compatibility of SPC technique with realistic renewable energy sources. The enhanced structure of APL is presented in Fig. 3. This improved mechanism has decreased transient tension in the control of active power, as well as it has faster and smoother dynamics.

Fig. 3. Proposed active power limiter (APL)

The APL presented in Fig.3 has two parallel corridors to limit the active power in both Up and Down borders. The Up-Border are related to the positive power error ($\Delta P_{SSG}^{(+)}$) intervals and this corridor is active where the power measured is higher than the maximum limit ($P_{meas} > P_{max}$). The $\Delta P_{SSG}^{(+)}$ passes through a PI controller equipped with an anti-windup system. Then, the error signal will be checked within the range of the power converter nominal rate ($0/+S_{Nom}$). Finally, the corrective signal of Up-Border corridor will be generated. Considering the operation of the saturation block ($0/+S_{Nom}$), this corridor creates an output signal while the $\Delta P_{SSG}^{(+)}$ is positive. This means that this corridor has no output once the power error (ΔP_{SSG}) reached zero or a negative value. The same mechanism is used for down-border corridor aiming to generate the corrective signal while the P_{meas} is less than P_{min} . In this case, the corridor will be activated where the $\Delta P_{SSG}^{(-)}$ is less than zero. In other words, this corridor doesn't create any corrective signal where the power error (ΔP_{SSG}) is zero or positive. Finally, at the output of both corridors, the final corrective signal will be sent to the EM block through two links. As previously mentioned, these two links

operate to control the transient situation through the washout dynamic coefficient (K_{ff}) as well as the steady-state condition of P_{SSG} . The mathematical expression of the APL operation can be formulated as in (1) and (2).

$$\Delta P_{Limiter} = \dots \begin{cases} (P_{meas} - P_{max}) \cdot \left(K_p + \frac{K_i}{s}\right); \Delta P_{SSG} > 0 \\ (P_{meas} - P_{min}) \cdot \left(K_p + \frac{K_i}{s}\right); \Delta P_{SSG} < 0 \end{cases} \quad (1)$$

$$\begin{cases} \Delta\theta_{Limiter} = K_{ff} \cdot \Delta P_{Limiter} \\ K_{ff} = \frac{X}{EU \cos(\theta_o)} \cdot \left(\frac{s}{s + \omega_c}\right) \end{cases} \quad (2)$$

Equation (1) describes the characteristics of each corridor where the dynamics of each one is manageable by tuning the PI controller parameters (K_p, K_i). Also, Equation (2) shows conversion of the power correction signal ($\Delta P_{Limiter}$) to the phase correction signal ($\Delta\theta_{Limiter}$). With a well-tuned PI controller and well-designed feed forward washout dynamic coefficient factor (K_{ff}), the corrective signals will be sent to the several parts of the EM block simultaneously and coordinately. According to (1) and (2), the APL affects the steady state dynamics of P_{SSG} by controlling $\Delta P_{Limiter}$. Therefore, the APL contributes in steady state condition of P_{SSG} based on tuning of (K_p, K_i). Moreover, the (K_p, K_i) and the washout dynamic coefficient (K_{ff}), define the contribution of APL in the transient state of P_{SSG} . From the stability point of view, the dynamics of the washout must be close to dynamics of EM block to achieve smooth and fast control of P_{SSG} in the grid connection of RSSG-SPC. The design analysis of APL is discussed in Section III.

III. STEP BY STEP DESIGN OF ACTIVE POWER LIMITER

The simplified block diagram of the open-loop system of SPC beside of the APL (APL+SPC) is presented in Fig. 4. It is assumed that the APL is activated for P_{max} . In Fig. 4, G_1 presents the electromechanical model, G_2 obtains the external grid effects, G_3 presents the external part of the APL (PI controller), and G_4 clarifies the internal system of APL (washout block).

Fig. 4. Simplified model of RSSG-SPC equipped with APL

Using Fig. 4, this section will summarize the main steps in the design of an APL for RSSG-SPC system installation. STEP (I) discusses the design of the electromechanical model (SPC loop), while STEP (II) and STEP (III) discuss the design of the APL loop.

STEP (I): Stable Design of the Electromechanical Model

A detailed method for the stable design of the electromechanical model was presented in [31]. Moreover, the designed parameters of RSSG-SPC for application in the Kundur system, which is applied in this study and in [32], was presented in [33]. These methodologies were utilized to acquire a stable design of the electromechanical model. The dynamic response of a RSSG-SPC must be evaluated while it is connected to the grid and APL is switched off. The goal is to evaluate the RSSG-SPC dynamic performance considering the dynamics of the grid (especially grid reactance X_{Grid}^{PCC}). Later, these dynamics would be used to tune the internal system of the APL (G_4). The step response of the designed RSSG-SPC for installation on the Kundur system (as presented in Section VI) can be calculated using the step response of the SPC loop presented in Fig. 4 taking in to account the effect of G_1 and G_2 .

The step response of the closed SPC loop is presented in Fig. 5, where $H = 2.94s$, $D = 0.157pu$, and $P_s = 1.20pu$. In the SPC loop, P_s is the synchronization power with an external system and it can be calculated using (3); where E is the internal electromagnetic force, U is the voltage of the grid, θ_o is the initial phase angle, X_v is the reactance of virtual admittance tunned in SPC dynamic loop, X_{Grid}^{PCC} is the grid reactance in point of common coupling (PCC), and X is the total reactance. Considering $E = U = 1pu$, $\theta_o = 0^\circ$, $X = X_v + X_{Grid}^{PCC} = 0.3 + 0.5336 = 0.8336pu$, the settling time of SPC loop is $T_{step}^{SPC} \approx 700ms$ as can be seen in Fig. 5. This settling time is acceptable for grid code compliance and stable connection of the RSSG-SPC to the Kundur system [32],[33].

Fig. 5. Step response of the SPC loop ($D = 0.157pu$, $H = 2.94s$, $P_s = 1.20pu$)

$$P_s \approx \left(\frac{EU}{X_v + X_{Grid}^{PCC}} \right) \cos \theta_o \quad (3)$$

The SPC is essentially a second-order system with the main dynamic performance parameters D and H . Once, these parameters are determined using the methodologies discussed earlier, the only parameter that can alter this second-order system is the X_{Grid}^{PCC} . However, having the stable tuning of (D, H), the overall closed loop transfer function of SPC will be stable for any value of X_{Grid}^{PCC} , since it is a transference of a stable second-order system.

STEP (II): Internal Design of APL (Washout Controller G_4):

The internal system of the APL contains a washout block with the dynamic coefficient K_{ff} . This block controls the power angle as illustrated in Fig. 3. The dynamic response of washout

(G_4) must be matched to the dynamics of the electromechanical model (SPC dynamic loop) in grid-connected situation. This is essential for coordinated control of transient response and steady-state response of the RSSG-SPC equipped with APL. If the SPC dynamic loop has a settling time T_{step}^{SPC} , then the aim would be to have the same dynamic response in APL to control the angle. The washout constant time (T_c) must also be equal to the dynamic response of SPC loop, this means $T_c = T_{step}^{SPC} \approx 700ms$. Moreover, It must be noted that in (2), K_{ff} must be calculated where the X accounting the total reactance observed from the APL point of view, this means $X = X_v + X_{Grid}^{PCC}$.

STEP (III): External Design of APL (PI Controllers G_3):

The external system of the APL consist of two pairs of PI controllers (G_3) those are responsible of tuning the exchanged RSSG-SPC power at the maximum and minimum borders. The essential points that must be considered in the tuning of K_p and K_i are as follows: i) the dynamic response of the PI controllers must be adequately fast in relation to the dynamic response of the electromechanical model, ii) having sufficient coordination between the designed D (tuned in SETP (I)) and gain K_i , while considering the overshoot in the active power signals must be limited on the 5%, and iii) the anti-windup resets the integrators after each operation of the PI controller. Therefore, in order to achieve coordinated set and reset process of the integrator, the anti-windup feedback gain (K_t) must be equal to the integrator gain ($K_t = K_i = 1/T_i$) where T_i is the integrator time constant.

IV. STABILITY ANALYSIS OF RSSG-SPC WITH APL (APL+SPC)

As mentioned in Section III, the detailed design of the SPC dynamic loop was discussed in [32] and [33]. Using the results of these references ($D = 0.157pu$, $H = 2.94s$), the combination of G_1 and G_2 will result in the second-order system in Fig. 4. The step response of the SPC dynamic loop was presented in Fig. 5 that confirms the stable performance of the SPC loop. Moreover, considering the model presented in Fig. 4, the open-loop transfer function of APL+SPC system from P_{max} to P_{elec} can be expressed by (4).

$$TF_{Open}^{APL+SPC} = G_3 G_1 G_2 + G_3 G_4 G_2 \quad (4)$$

Fig. 6. Bode plot of open-loop model of APL+SPC system

The bode plot shown in Fig.6 illustrates the frequency response of the APL+SPC open-loop system for $K_p = 0.1$ and $K_i = 10$. Fig. 6 shows that APL+SPC has stable modes with sufficient damping ratios. Moreover, having this tuning for K_p and K_i , the system would be stable with sufficient damping

ratios and safety margins as well as sufficient stability margins within the electromechanical oscillations frequency boundary (0.1Hz to 2Hz). This can be observed from the resulting gain margin that *APL+SPC* is stable for electromechanical frequencies with gain margin $GM = -24\text{dB}$ where the $Phase < -180^\circ$, and minimum phase margin $PM = 44^\circ$ for frequencies higher than 1.12Hz. Therefore, the stable design of the *APL+SPC* system can be achieved through a step by step methodology with the stability criteria and grid connectivity in considerations.

V. CASE STUDY DESIGN AND PERFORMANCES OF APL+SPC

Following the step by step stable design of *APL+SPC*, the case study design and performance of *APL+SPC* is explained in this section. The operation of Up-border corridor coordinated with Down-border corridor in a well-tuned APL results to a proper control of the active power as illustrated in Fig. 7 to Fig. 10. These figures describe how the APL handles active power in the control system (see Fig. 2), where the specific data are reported in Table I. As shown in Fig. 7, the P_{SSG} crosses both of the minimum and maximum borders when the APL is deactivated. In this situation, there are steady state errors for both positive and negative power errors ($\Delta P_{SSG}^{(-)}$, $\Delta P_{SSG}^{(+)}$). Also, there is a significant overshoot/undershoot during transient intervals. The details of these errors are represented in Fig. 8 where power error is negative ($\Delta P_{SSG}^{(-)}$).

Fig. 7. Crossing active power boundaries (APL-OFF)

Fig. 8. Transients and steady state condition of step-down power change (APL-OFF)

With the APL activated, Fig. 9 shows the action of the power blocking process. As illustrated in Fig. 9, the damped blocking of power over both borders (P_{min} , P_{max}) is achieved with proper dynamics. The APL affects both transients and steady-state conditions in both situations ($\Delta P_{SSG}^{(-)}$, $\Delta P_{SSG}^{(+)}$). The effect of the power blocking on P_{min} is shown in Fig. 10. This shows that power is accurately blocked at the minimum border during the

steady state condition. Comparing Fig. 8 and Fig. 10, they clearly show the beneficial APL's effects in both transient and steady state conditions. Moreover, $\Delta\theta_{Limiter}$ reduces the undershoot during the first transient cycle. Also, it is clear that $\Delta P_{Limiter}$ controls P_{SSG} on the P_{min} border by forcing $\Delta P_{SSG}^{(-)}$ to zero in a quick yet damped dynamic approach.

Table I. Specific data of RSSG-SPC and APL

RSSG-SPC		
H	Virtual inertia	2.94 s
D	Virtual damping	0.157 pu
R_v	Resistance of virtual admittance	0.1 pu
X_v	Reactance of virtual admittance	0.3 pu
R_f	P-F droop characteristics	5 %
ω_o	Nominal angular frequency	377 rad/s
APL		
K_p	Proportional gain of PI controller	0.1
K_i	Integrator gain of PI controller	10
K_t	Feedback gain of Anti-windup	10
E	Internal electromagnetic force	1 pu
U	Voltage of grid	1 pu
θ_o	Initial phase angle	0°
X	Total reactance ($X_{SSG} + X_{Grid}^2$)	0.8336 pu
ω_c	Frequency of washout block $\omega_c = 1/T_c$, $T_c = 700\text{ms}$	1.4 rad/s

Fig. 9. Blocking on power boundaries by activation of power limiter (APL-ON)

Fig. 10. Limiter effects on transients and steady state condition of step-down power change (APL-ON)

VI. TEST OF APL IN GRID APPLICATION OF RSSG-SPC

Kundur's two area system was selected to assess the performance of APL in the grid connection of RSSG-SPC. SG_2 in the Kundur Base System (KBS) was replaced with a RSSG-SPC considering the same power capacity, as depicted in Fig. 11 and Fig. 12.

Fig. 11. Base model of two area generation system (KBS)

Fig. 12. RSSG-SPC installed in Area (I)

Moreover, all the Power System Stabilizers (PSS) were deactivated in all classic units on both cases of the grid model. Deactivation of the PSS enables an accurate evaluation of the advantages of SPC mechanisms as well as to investigate APL effectiveness. The small damping coefficient ($K_d = 0.01$) was tuned for all SGs aiming to have a flat initial operation point in the time domain signals. The EM and the APL were tuned according to the discussions explained in Section III.

The sequenced step changes in the active power reference in Bus_2 are considered as the operation scenario. The same scenario is applied to all cases of the grid model as $\Delta P_{Bus2}^{t=25s} = -100MW$, $\Delta P_{Bus2}^{t=40s} = 0MW$, $\Delta P_{Bus2}^{t=50s} = +100MW$. The limiter is tuned with $P_{min} = 0.795pu$ and $P_{max} = 0.875pu$. These settings are selected taking into account the power flow tuning required to achieve safe and stable operation of Kundur model [34]. The essential signals for revealing the performance improvement were plotted for three different cases of the Kundur system including: (a) KBS, (b) Kundur system in the presence of the RSSG-SPC with the APL deactivated (APL-OFF), and (c) Kundur system in the presence of the RSSG-SPC with APL activated (APL-ON). Time domain signals covers the analysis on the active powers and frequencies of the system which are presented in Fig. 13 to Fig. 21.

The active power of the generation units are compared in Fig. 13 to Fig. 18. As illustrated in Fig. 13, the power signals in KBS contain low-frequency oscillations. The frequency of these oscillations is around 0.50Hz and 1.20Hz [32]. These basic oscillations are clearly visible in Fig. 14 which represents the zoomed preview of Fig. 13. As mentioned before, all PSS were deactivated in the classic generation units, thus the basic oscillations of the KBS appear in the power signals. Fig. 15 shows the power signal of the Kundur system in the presence of the RSSG-SPC while the APL was deactivated. This figure confirms that a well-designed RSSG-SPC can remove and damp most part of these basic oscillations. Fig. 15 is zoomed and presented in Fig. 16 which shows that local oscillation were

damped in the installed area (Area I). Furthermore, the propagation of this oscillation is significantly prevented from the neighborhood area (Area II).

Fig. 13. Power oscillations in KBS

Fig. 14. Oscillations in generation units of KBS

Fig. 15. Support damping by RSSG-SPC (APL-OFF)

Fig. 16. Stiff bus in Area (I) (APL-OFF)

Fig. 17 and Fig. 18 show the power signals of the Kundur system in the presence of RSSG-SPC when APL was activated. These plots confirm that the advantages of RSSG-SPC were not altered by the activation of APL. In other words, the RSSG-SPC's power (P_{SSG}) was blocked on both borders as well as the RSSG-SPC provided supplementary damping for the grid oscillations. This is the sign of high adaptivity of APL's structure with the mechanism of SPC technology. Activating APL, the power-sharing between the generation units changes as a result of the power-frequency droop system. This change in power-sharing is visible by comparing Fig. 16 with Fig. 18.

Fig. 17. Support damping by RSSG-SPC (APL-ON)

Fig. 18. Keeping stiff bus in Area (I) (APL-ON)

Fig. 19. Frequency condition in KBS

Fig. 20. Support COI in presence of RSSG-SPC (APL-OFF)

Fig. 21. Support COI in presence of RSSG-SPC (APL-ON)

Another advantage of SPC and APL can be evaluated by considering the frequency of the generation unit which are illustrated in Fig. 19 to Fig. 21. In the KBS model in Fig. 19 SGs don't share enough inertia in the entire system as a result of the lack of damping in SGs ($K_d = 0.01$). Thus, there is a high

Rate of Change of Frequency (ROCOF) in KBS. Moreover, a low value of Frequency Nadir (FN) appears in each generation unit as well as the Center of Inertia (COI) has very weak dynamics in the entire KBS. On the contrary, Fig. 20 shows that these important indices were significantly improved in the presence of the RSSG-SPC. As shown in Fig. 20, the ROCOF is dropped, the FN achieves higher value, and the COI has the stiff and flat dynamics. The system frequency is plotted in Fig. 21 when the APL is activated. As illustrated in Fig. 21, the RSSG-SPC still dispatches the virtual inertia through the grid. Moreover, with the control of powers in borders, the frequency coupling between units is still strong as well as the COI has solid dynamics.

Fig. 22. Surplus damping in tie line power (APL-OFF)

Fig. 23. Surplus damping in tie line power (APL-ON)

Fig. 22 and Fig. 23 show the damping of the interarea oscillations in presence of RSSG-SPC. These signals confirm that a well-designed RSSG-SPC contribute in suppressing interarea modes as deeply discussed in [32]. Activating APL creates limiting boundaries on sending power from Area (I) to Area (II), thus the interarea power (P_{A1toA2}) has tided steady state changes compared to when the APL was deactivated. Moreover, when the APL is ON, P_{A1toA2} has fewer oscillations range in the first variation cycles compared to the case of APL-OFF. So, in the case of APL-ON, the interarea vibration is less than the case of APL-OFF as a result of the blocking RSSG-SPC's power in P_{min} and P_{max} .

VII. REAL TIME LABORATORY TEST

A laboratory platform shown in Fig. 24, was utilized to evaluate the performance of APL in the real-time environment. The specific data of the external grid, experimental platform and emulated RSSG-SPC are reported in Table II. The current closed-loop strategy was implemented in the platform as illustrated in Fig. 25 aiming to emulate the grid connection of RSSG-SPC. In the left side of platform, the set of OPAL-RT and PCU 21kVA power amplifier emulate the characteristics of

external power grid. The Kundur model was modeled in OPAL-RT, then the electrical characteristics of Bus_2 were transferred to the power amplifier through the command signal (V_{com}). Thus, the PCC emulates the Bus_2 in proper scaled voltage and sufficient power level. In the right side of platform, the set of the 32kW REGATRON dc power supply, 5kVA power converter and LCL filter emulate the performance of RSSG-SPC. The SPC equipped with APL and programmed in dSPACE 1103 were installed on the power converter.

Fig. 24. Laboratory platform for real time test

Fig. 25. Schematic of the implementation technique

Table II. Data of Grid, Experimental Platform and Emulated RSSG-SPC

Grid		
KUNDUR two area system [34]		
Experimental Platform		
S_N	Rated apparent power	5 kVA
V_{ac}	Phase to phase grid voltage	400 V
V_{dc}	DC-link voltage	600 V
$L_{T(abc)}$	Coupling transformer (3-phase)	2 mH
$L_{f(abc)}$	Filter inductor (3-phase)	6 mH
$C_{f(abc)}$	Filter capacitor (3-phase)	5 μ F
$R_{d(abc)}$	Damping resistor (3-phase)	1.8 m Ω
f_{sw}	Converter switching frequency	10 kHz
Emulated RSSG-SPC in OPAL-RT		
S_b	Base power	900 MVA
V_{ll}	Nominal line to line voltage	20 kV
f_n	Nominal frequency	60 Hz

The electrical interaction between the power converter and power amplifier were transferred into the OPAL-RT model through the current feedback. Then, this interaction was modeled as a dependent current source in Bus_2 using the scaled down gain. The three sets of the real-time signals were captured for several cases of grid model (KBS model, grid model with RSSG-SPC APL-OFF, and the grid model with RSSG-SPC

APL-ON). The signals are presented in Fig. 26(a1) to Fig. 26(c1) and each set includes: (a) frequency deviation of the generation units around the COI ($\Delta\omega_{SG1:4} = \omega_{SG1:4} - COI$), (b) the active power of each generation units ($P_{SG1:4}$), and (c) interarea active power (P_{A1toA2}). For each case, the significant signals for performance measurement linked to the APL and RSSG-SPC are zoomed in Fig. 27(a1) to Fig. 27(c1).

Fig. 26. Real time validation results: (a1) Frequency deviation around COI, Active power of generation units and Interarea power in KBS; (b1) Frequency deviation around COI, Active power of generation units and Interarea power in compensated grid APL-OFF; (c1) Frequency deviation around COI, Active power of generation units and Interarea power in compensated grid APL-ON.

The global view in Fig. 26(a1) to Fig. 26(c1) confirms the weak dynamics of the KBS which is visible in the active power and frequency. Moreover, it validates that the RSSG-SPC is capable of damping the entire system. Furthermore, it can be seen that the RSSG-SPC reinforced the dynamics of the COI and reduced the variations of the frequency. Therefore, it can be concluded that all the analysis mentioned in the previous sections were validated. Comparing Fig. 27(a1) with Fig. 27(c1) clearly shows APL's effectiveness in the system. These plots confirm the proposed APL's structure has been reliable and provided efficient power control in the limiting borders. In Fig. 27(c1), the APL was in ON state and the SPC still damped the oscillations and supported the inertia of the system. Keeping these advantages of the SPC in presence of the APL, proves the high adaptability of APL with SPC mechanism. Moreover, the blocking process of active power on both borders was executed with noticeable performance. Thus, the APL operates linearly

and in a reliable manner over both borders and this is the key advantage of APL in the grid connection of the RGUs. Fig. 28 shows the initial moments of the power blocking process with Fig. 28(a) revealing the P_{SSG} crossed the P_{min} border in 125ms.

Fig. 27. Real time validation results: (a1) Frequency deviation around COI and active power of SG_2 in KBS; (b1) Frequency deviation around COI and active power of RSSG-SPC where APL-OFF; (c1) Frequency deviation around COI and active power of RSSG-SPC where APL-ON.

Later on, P_{SSG} was returned to the P_{min} border in 340ms and P_{SSG} maintained the appropriate range due to the action of the APL. Finally, P_{SSG} was blocked on the P_{min} border in 495ms after arriving to the appropriate range. In Fig. 28(b), P_{SSG} passed the P_{max} border in 160ms during the scenario. Then later on it returned to the P_{max} border over the 300ms by the APL action. The returning time to P_{min} and P_{max} borders (340ms, 300ms) clarifies the APL speed performance. The small difference between these required times is due to several reasons. Having a difference in power errors before blocking power ($\Delta P_{SSG}^{min} = P_{SSG} - P_{min} = 833 - 795 = 38\text{mpu}$, $\Delta P_{SSG}^{max} = P_{max} - P_{SSG} = 875.7 - 827.3 = 48.4\text{mpu}$) is the main reason. Furthermore, the different time needed to control power flow on the new operating point can be another reason, where the droop system also contributes. Moreover, in the first case P_{A1toA2} was reduced but in the second case P_{A1toA2} was increased (see Fig. 26(c1), so the power flow pattern for the RSSG-SPC's contribution in power and frequency support would be different in each case and it needs different settling time to reach new operation point. However, as shown in Fig. 28, the power blocking process is performed in a damped

manner, reasonable speed, and with smooth dynamic over the both power borders. Also, the APL doesn't make any electrical or dynamic tensions in the system on both cases. So, it can be stated that the proposed APL's structure is a grid-friendly design for the RGUs.

Fig. 28. Soft damped transients during the blocking process: a) Threshold of power blocking in P_{min} ; b) Threshold of power blocking in P_{max} .

Comparison between results presented in Fig. 26 to Fig. 28 and the results presented in [22]-[25] confirms that the SPC loop equipped with the virtual inertia, virtual damping and anti-windup PI controllers within the APL are able to support the RSSG-SPC to have fast power reference tracking and smooth power blocking capability. Based on the results obtained in [22]-[25], the GVM-DPC has small overshoot but with a nonlinear performance in transient response. However, the GVM-DPC has robust properties in steady-state conditions with the drawback of being a much more complex system to design as compared to the APL+SPC.

VIII. CONCLUSION

In this work, a novel power limitation system was proposed for renewable energy-based generation equipment that is interconnected to grid through VSG. The implementation of the limiter was performed in a SPC which is a type of VSG that enables a very wide support to the grid, both in voltage and frequency. The proposed limiter allows combining the provided grid support through virtual inertia or virtual admittance with the active power limitations that can be provided from a renewable energy source. The proposed limiter has two channels of action, a fast channel which acts directly on the voltage angle and another slow channel which allows to reach desired steady state through its action on the inertia by varying the power set point. In addition, it has been confirmed that the advantages of the SPC for the grid, such as providing virtual inertia and supplementary damping to the grid, has been maintained while the APL was activated. Simulations and experimental results validated the advantage of the proposed

solution as a power limiting element applicable also to other VSGs.

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Mostafa Abdollahi (S'18) received the B.Sc. degree in electrical engineering from Power & Water University of Applied Science and Technology, Shiraz, Iran, and the M.Sc. degree in power system engineering from University of Isfahan, Isfahan, Iran, in 2007 and 2011, respectively. He joined the Faculty of Electrical Engineering at Azad University (IAU), Hormozgan, Iran, in 2009. He was the lecturer in Power & Energy Systems in IAU, then he was the Head of Electrical Engineering Department, Head of Education & Student Office and Head of Research and Technology Office, respectively. Also, he worked as Project Manager and Research Assistance in cooperative projects with Esfahan Regional Electric Company, Hormozgan Electrical Distribution Company, and Amirkabir University of Technology from 2012 to 2015. He joined to Research Center on Renewable Electrical Energy Systems (SEER) at the Universitat Politècnica de Catalunya (UPC), Spain as a Ph.D. student in 2015. He worked on projects supported by the European Commission and the Spanish Ministry of Science and Technology for improving the stability of the transmission systems. From 2018 to 2019, he was a Research Assistant at the University of Florence (UNIFI) and ENEGAN Company, Tuscany, Italy. He worked on Smart Energy Management System for Smart Renewable Clients (E-CUBE). Currently, he is a Power System Consultant at TRACTEBEL-ENGIE, Brussels, Belgium since 2019. He is Ph.D. student in Electric Energy Systems at UPC and his research interests include Grid Integration of Renewables, Design & Control of Power Converters (Renewables, FACTS), Smart Grids, and Power System Stability.

Jose Ignacio Candela (S'99–M'04) received the B.S. and M.S. degrees in industrial engineering and the Ph.D. degree in electrical engineering from the Technical University of Catalunya (UPC), Barcelona, Spain, in 1987, 2000, and 2009, respectively. In 1990, he became an Assistant Professor with UPC, where he later advanced to Associate Professor in 1993. Currently, he is part of the research group on Renewable Electrical Energy Systems, Department of Electrical Engineering. He has authored or coauthored more than 30 published technical papers, and holds several patents. His current research interests include power conditioning, integration of distributed energy systems, and the control of grid connected power converters.

Dr. Candela is a member of the IEEE Power Electronics Society, the IEEE Industrial Electronics Society, and the IEEE Industry Application Society.

Joan Rocabert (S'08–M'11) received the M.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Catalonia, Barcelona, Spain, in 2003 and 2010, respectively. From 2004 to 2008, he was a Research Assistant with the Department of Electronic Engineering, Technical University of Catalonia, where, he has been a Researcher and an Assistant Professor with the Department of Electrical Engineering since 2008. His current research interests include power electronics, photovoltaics, wind energy

systems, and microgrids.

Mohamed Atef Elsaharty (S'12, M'13) received the B.Sc. and M.Sc. degrees in electrical and control engineering from Arab Academy for Science, Technology, & Maritime Transport (AASTMT), Alexandria, Egypt, in 2009 and 2012, respectively. He received his Ph.D. degree in Electric Energy Systems from the Technical University of Catalonia (UPC), Barcelona, Spain in 2018. Currently, he is a Post Doctorate Research Fellow at the Research Institute for Autonomous Systems, University of North Dakota since 2019. His research interests include power

electronics converters, power transformers, renewable energy systems and autonomous systems. Dr. Elsaharty is a member of IEEE Power Electronics Society, IEEE Industrial Electronics Society, IEEE Power & Energy Society, and IEEE Industry Applications Society.