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Hardware-in-the-loop based testing of wind turbine controllers for transient stability enhancement

Zameer Ahmad¹, Stelios Papadakis¹, Arcadio Perilla¹

¹Delft University of Technology, Delft, Netherlands

Corresponding author: J.L.RuedaTorres@tudelft.nl

Jose Rueda Torres¹, Mart van der Meijden^{1,2}

¹Delft University of Technology, Delft, Netherlands

²TenneT TSO B.V, Arnhem, Netherlands

Abstract—Traditionally, electrical power systems have been based on fossil-fuel fired generation plants to satisfy the load demand. However, due to environmental targets for significant CO2 reduction, a gradual decommission of the aforementioned plants is observed whereas renewable energy sources are gaining gradually increasing momentum, which entails radical changes in the dynamic behavior of electrical power systems. Among the existing renewable energy technologies, variable speed wind generators which utilize full-scale power electronics units, are a preferred technological solution to tackle the variability of renewable energy. Increasing renewable power generation caused a reduction of system inertia and short circuit capacity. This reduction challenges the rotor angle stability of remaining synchronous generators when large disturbance occur. This paper presents a study on modifications of the outer control loops of the grid side converter of wind generators type IV to limit the magnitude of the first rotor angle swing while increasing the overall damping performance of a power system. The study includes a comparison between three different wind generation controllers. Namely, a basic Low Voltage Right Through (LVRT) with a post-fault ramp in the active power injection strategy, a voltage dependent active power injection scheme and a Supplementary Damping control (SDC) method are examined and tested through a power hardware-in-the-loop (PHIL) based test bench. It has been found that SDC supports quick damping of oscillations and high reduction of magnitude of the first swing with respect to the other two control schemes.

Index Terms—Transient stability, full-scale power electronics wind generator units (type IV), voltage dependent active power injection (VD-API), supplementary damping control (SDC), Hardware-in-Loop testing (HIL), MIGRATE

I. INTRODUCTION

Electricity transmission networks of the future are expected to decrease their dependence of traditional fossil fuelled power plants by incorporating renewable energy sources. Based on this tendency, wind energy share is to be increased in the energy mix, which can potentially deteriorate power system's stability. The stability deterioration can be attributed to the reduced inertia and short circuit capacity that the power electronic interfaced wind generators introduce comparing to the ones associated to the synchronous generators [1]. This tendency arises new challenges related to power stability concepts, that are needed to be investigated and tackled.

The present paper focuses on the rotor angle stability aspects of power systems when described by high share of wind generation. In particular, it examines the synchronous generators' rotor responses when subjected under three phase fault conditions, therefore transient stability enhanced performance is the main objective.

In traditional power systems, dominated by conventional synchronous generators (SGs), the main tackling measures against rotor angle instabilities were Power System Stabilizers (PSS), attached in the voltage regulator controls of the SGs [2]. In a similar approach, over years, damping controllers were introduced in HVDC systems [3] and FACTS [4]. Therefore, the power electronics' flexibility can be also employed so as to design wind generator controllers capable to inject power in the main grid in a manner so as to dampen out the low frequency oscillations observed in the synchronous generator responses.

The aforementioned attribute of power electronic devices along with the significant improvements in digital communication networks and protocols over the past few years, enabled the control testing of wind generators' power electronic converters in laboratory conditions. Adopting the aforementioned methodology, named as Hardware-in-Loop testing, entails an accurate reproduction of the wind generators' actual operating responses, as a necessary step prior to the actual large scale commissioning of such converters' controls in existing power systems.

The sections of the paper are as follows. Section II, analyses the different wind generators employed for this study, namely a basic Low Voltage Right Through (LVRT) with a post-fault ramp in the active power injection strategy, a voltage dependent active power injection scheme and a Supplementary Damping control (SDC) method. Section III provides information about the power system benchmark that the wind generators are incorporated. Section IV illustrates the performance of the synchronous machines, when the aforementioned wind generators controllers are used, as obtained from Hardware-in-the-Loop (HIL) simulations. Last concluding remarks are given in Section V.

II. EXAMINED WIND GENERATION CONTROLS FOR TRANSIENT STABILITY STUDIES

This paper, analyses controls strategies as applied in fully decoupled wind generators (type IV), and different WGs' controllers' affection in the rotor angles of the synchronous machines. Type IV is taken as a representative generation technology, due to the advantages that this technology introduces, e.g. better Low Voltage Ride Through (LVRT) capabilities, full- speed ratio control, absence of gear-box e.t.c. Additionally, as to be presented, control modifications are performed in the grid side Voltage Source Converter (VSC), therefore the control strategies are not limited in WGs, but can be expanded in any source interfaced with a full-scale VSC.

The configuration of type IV wind generators interfaced with the back-to- back VSCs (i.e. rotor side & grid side converter), as long as their typical control layouts, are depicted in Figure 1.

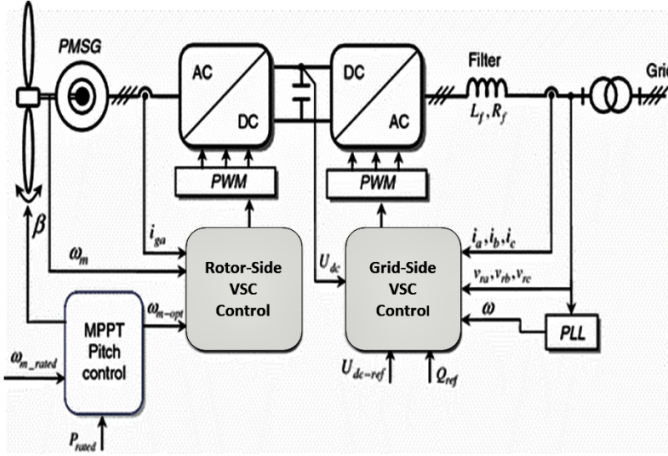


Fig. 1. Wind generator type IV configuration and basic VSC controllers' layout

The examined grid-connected VSC schemes are presented in this section, and their common attribute is that they are described by current vector controllers schemes, and in particular they adhere to voltage oriented control (VOC) strategies. This scheme is based on transformation between the abc stationary reference frame and dq synchronous frame where all the variables are of DC components in steady state. This facilitates the design and control of the inverter [5]. The rotor side VSC converter, also based on vector current controllers, aims to Maximum Power of Point Tracking purposes using Unity Power Factor (UPF) control [5]. Controllers' modifications of rotor side VSCs, for transient stability enhancement are out of scope of this study. The following subsections present a brief overview for the examined control schemes and how the outer current controllers, which define the current set-points, can be modified accordingly.

A. Basic LVRT controller with a post-fault ramp

Similar to voltage regulators (i.e. AVR) applied in conventional synchronous generator plants, a reactive current

injection from a wind generator point of common coupling (PCC), as performed under the frame of Low Voltage Ride Through (LVRT) strategy, can not only support the voltage levels in the given power system, but also improve the transient stability of the integrated synchronous generators [6], [7].

The magnitude of the reactive short circuit current should be provided to the grid as a function of the rms voltage deviation at the grid connection point. The slope of the curve is a variable which the relevant TSO needs to specify and it is referred as 'k' gain or "k-factor". According to German standards, a k-factor of 2 can be used as a default case [8], [9]. The provision of reactive power is implemented when the voltage drops below a specific threshold point (e.g. dead-band of 10-20%) [10], and needs to be provided in a predefined by the relevant TSO rise time. Normal values of this rise time would be less than 20ms, which are typical time constants of the power electronic valves.

With the VOC scheme, the three-phase line currents in the abc stationary frame are transformed to the two-phase currents in the dq synchronous frame, which are the active and reactive components of the three-phase line currents, respectively. The independent control of the aforementioned d and q current components provides an effective means for the independent control of system active and reactive power respectively. Therefore according to the previous analysis, during the fault, reactive power is prioritized, whereas the active power which is proportional to the d current component is nullified, so as to comply to the magnitude limit dictated by the converter rating (e.g. 1.1 pu). Over-sizing the converters, could be not cost-effective and additionally can cause an unstable wind generator behavior [11].

Apart from the injection of reactive power during the fault-period, an additional measure to enhance transient stability is to gradually increase the active power injection towards its pre-default value, with a specific slope. As tested in HVDC systems [6], this active power-recovery rate has an important influence on the ac system's transient stability when relatively small systems with a low short-circuit power are considered. In Germany, the aforementioned recovery should have a rate at least 20% of the rated power per second [9]. Maintaining this slope relatively low, entails that the active power injection from the WGs remains low after the fault period, therefore the synchronous generators tend to maintain their active power injection in high levels, thus from their equation of motion they tend to decelerate more. This ensues that they are able to damp out their oscillations more effectively.

The block diagram of the outer active current control is depicted in Figure 1. As seen, two flags named as "FRT_flag" and "Ramp_flag" are used to differentiate the controller logics in the different time frames, i.e. pre-fault, during fault and post-fault conditions. In the pre-fault conditions, both flags have unity values, during the fault "FRT_flag" has zero value, whereas in the post-fault period "Ramp_flag" has zero value. The active current recovery slope is regulated by adjusting the gain and time-constant of a first order transfer function. For the simulations performed, a transfer function with unity gain and

a time constant of 0.5 seconds is selected. Additionally, the duration of the ramp is set at 0.6 seconds. The aforementioned parameters' selection, corresponds to a 40% increment per second of the wind generator rated power.

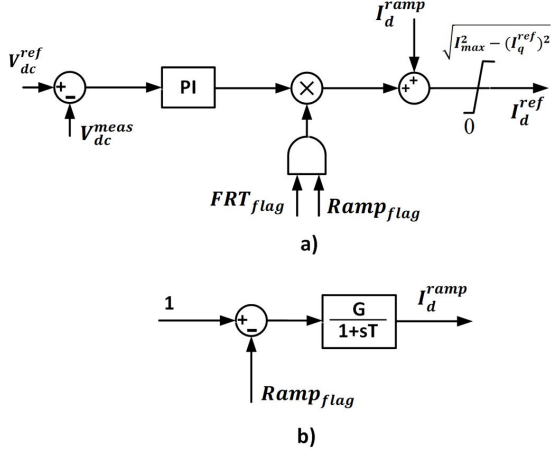


Fig. 2. BASIC LVRT control (a) idref computation, (b) ramping-up of idref (post-fault)

B. Voltage Dependent Active Power Injection (VDAP) controller

The nullification of the wind generators' active power during the fault period, can potentially create significant frequency dips, due to the active power imbalances between generation and demand. This frequency deviation, can potentially be reflected to the SGs' rotor angles due to the integral relationship between frequency or SGs' speeds and their rotor angles. Therefore, a second controller is tested, which considers an injection of a reduced active power, with respect to the pre-fault injection. The active power injection during the fault and post-fault period are being determined on the voltage level of the PCC, as seen in Figure 3. This is a control scheme that several system operators perform, among them the Spanish ones [12].

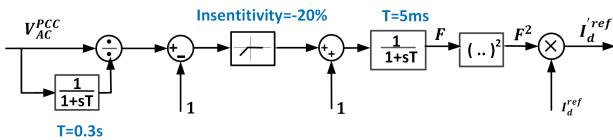


Fig. 3. VDAP control: idref computation

C. Supplementary Damping Controller (SDC)

As depicted in Figure 4, the active power loop control model of Figure 2 is modified, in a manner so as a structure, resembling to Power System Stabilizers applied to synchronous machines, to be integrated. The supplementary controller is added in the WG's active power loop, since transient stability is quantified by the deviation of the mechanical power applied in the shaft of the SGs from their active power injections.

Different input signals can be fed in the damping controllers, whereas the eigenstructure of the system can be utilized and mode of observability index can be exploited [13], to find the best input signal for the controllers. However, the computational effort for this approach is high therefore this paper considers as the rotor angle difference between synchronous generators located in different sites, a promising signal for rotor angle damping aims. The effectiveness of this signal selection can be explained as follows. Apart from being a remote signal which tackles low frequency oscillations in a more efficient way [14] and being a signal which is directly involved to the equation of motion of the SGs, it can also lead to a neglect of a phase compensation unit, in contrast to the conventional PSS units applied to SGs. As [15] mentions, "The active power should be modulated in phase with the speed of the machine" to tackle low frequency oscillations excited between synchronous generators. Additionally the rotor angle constitutes the integral of the rotor speed, and has a phase shift of -90° with respect to the rotor speed. In addition, it is taken into account that the employed washout filter is a high pass filter, and introduces a phase shift of 90° for the low frequencies of interest. Therefore, from the aforementioned it becomes clear that any additional block for phase compensation is not needed, and this facilitates the SDC parameters' tuning. In Figure 4, the integral block logic, is fictional, and is employed for a corroboration of the previously described analysis. The optimal tuning of the washout filter is out of scope of the current paper. Based on sensitivity analysis, it is found that, for the power system described in the following section, a selection of $G=10$ [p.u] and $T=0.1$ [s], leads to a satisfactory rotor angle damping.

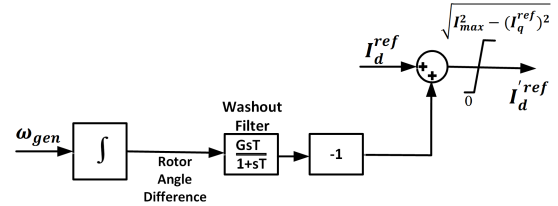


Fig. 4. SDC control: idref computation

III. POWER SYSTEM DESCRIPTION

The controllers are evaluated by using a modified IEEE 9 bus benchmark system.

The system is adjusted to encounter a 52% power share from fully decoupled wind generation. The location of the wind plants and synchronous generators is highlighted in Figure 5. For the RMS simulations, simple steam turbine governors (standard model: TGOV1 [16]) and AVR's IEEE DC1 (standard model: avr_IEEEEX1 [17]) of synchronous generators are employed. Additionally Power System Stabilizers are neglected.

The load flow results which correspond to the 52% wind generator share are additionally depicted in Table I. The loads' specifications are as follows: LA=125+j50 [MVA], LB=90+j30 [MVA], LC=100+j35 [MVA].

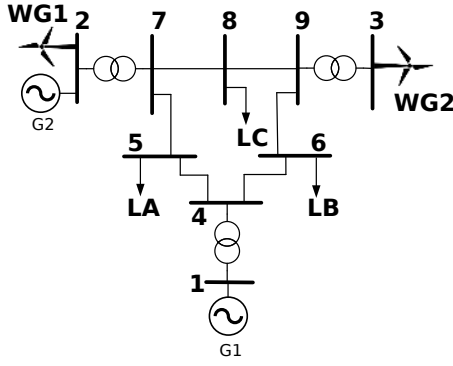


Fig. 5. IEEE 9 Bus power system with 52% WG share

TABLE I
POWER FLOW RESULTS

	G1	G2	WG1	WG2
P [MW]	73.02	81.5	81.5	85
Q [MVAR]	36.05	-4.6	0	0

IV. REAL-TIME DIGITAL SIMULATION RESULTS VALIDATED THROUGH HARDWARE-IN-LOOP (HIL)

The aforementioned wind generator controllers, as well as the benchmark power system, are built in an EMT simulation platform, and in particular employing a powerful tool provided by Real Time Digital Simulator (RTDS) Technologies Inc. The Simulator, requires parallel processing, in order to compute the system's state during the time step that is chosen. Significantly small time steps in the range of $1.4\mu s$ - $3.75\mu s$ enable the performance of dynamic studies for monitoring and control purposes. Additionally, RTDS can also be used for closed loop testing (HIL/SIL), which is essential for components' testing and control in the real world.

Hardware-in-the-Loop (HIL) simulations offer a cost-effective and safe method to test physical devices under real-time operating conditions. Real-time HIL simulation is the standard for developing and testing the most complex control, protection and monitoring systems. Testing of control systems has traditionally been carried out directly on physical equipment (i.e. plant) in the field, on the full system or on a power taster in a lab. While offering testing fidelity, this practice can be very expensive, inefficient and potentially unsafe. In this study, a HIL test set-up has been developed to validate the control strategies for the mitigation of transient stability threats.

A HIL test set-up has been developed in the intelligent electric power grid group (IEPG), TU Delft, as seen in Figure 6. The test setup composed of NovaCor real-time digital simulator, real-time target (RTT), grid emulator (combined front-end and a voltage source converter) and a dc-ac converter (device under test). The different options for mitigation of transient stability threats, such as the use of basic LVRT controller, voltage-dependent active power reduction controller, and the proposed SDC strategies have been discussed in detail

in Section II. In order to validate these control strategies in HIL, a test set up has been prepared, as depicted in Figure 6. The steps adopted for testing of control methods for mitigation of transient stability threats by support from wind turbine grid-side converter are as follows.

- 1) The EMT model of modified IEEE 9 bus as shown in Figure 3, is compiled and running on RTDS NovaCor.
- 2) The voltage and frequency of the simulation network are sent from RTDS to real time target (RTT) to reproduce the voltage and frequency at the output terminals of the device under test (DUT) (i.e. grid side VSC of WG1) by a grid emulator.
- 3) As RTT and RTDS both are running in real time, control strategies for mitigation of transient stability threats can be implemented either in RSCAD or Matlab software. The control strategies for mitigation of transient stability threats basic LVRT controller, voltage-dependent active power reduction, and proposed SDC generate current references for active and reactive power generation. Depending on the value of the current reference, DUT which is emulating the grid side converter of wind turbine type IV injects active and reactive power into the grid.
- 4) Finally, the active and reactive output power of the DUT are injected into the grid running on RTDS.

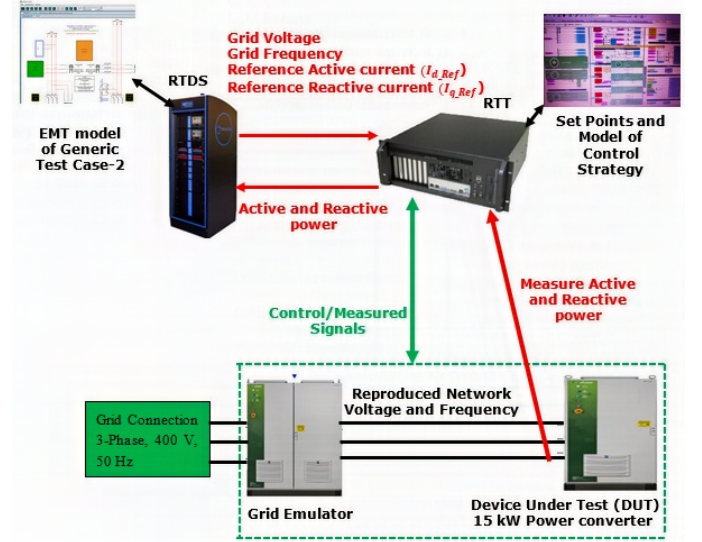


Fig. 6. HIL test bench for validation of control strategies under study for mitigation of transient stability threats

The control strategies for mitigation of transient stability threats have been tested under the following conditions: (a) The developed modified IEEE 9 bus has 52% share of wind power generation, (b) Device under test is emulated the grid side converter of the wind turbine connected at bus 7 and (c) 3-phase short circuit fault at bus 8 for 6 cycles.

Figure 7 to Figure 9 show the active and reactive power injection by grid side converter of the RTDS simulation model and DUT (real converter) due to the control strategies for

mitigation of transient stability threats such as basic LVRT controller, voltage-dependent active power reduction and proposed SDC respectively. It can be seen that the dynamics of active and reactive output power of DUT or real converter is the same as the simulation results. As it can be also observed, the converter is not islanded during a fault. It is injecting active and reactive power according to the control strategies. Hence, these control strategies and converter are suitable for mitigation of transient stability threats. Figure 10 shows rotor angle deviation of the synchronous machine G2 with respect to the angle of the slack machine G1, during and after the fault period. It can be seen that the synchronous machines have not lost synchronism in all three control strategies for mitigation of transient stability threats under study at 52% share of power electronics-based generation, whereas the rotor angle oscillations amplitude and settling time are different. The proposed SDC strategy is capable of damping out the rotor due to an anti-phase injection of active power with respect to the active power injection of the nearby synchronous machine.

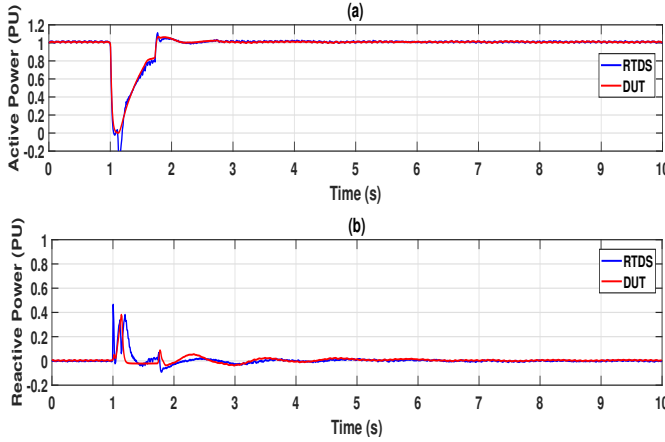


Fig. 7. HIL test bench for validation of basic LVRT control strategy as employed for mitigation of transient stability threats

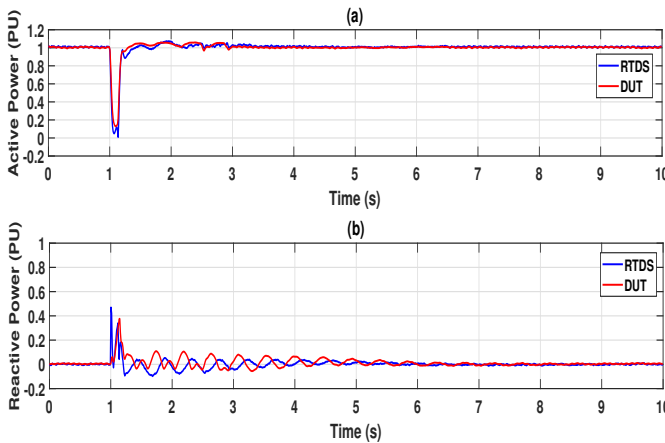


Fig. 8. HIL test bench for validation of VDAPI control strategy as employed for mitigation of transient stability threats

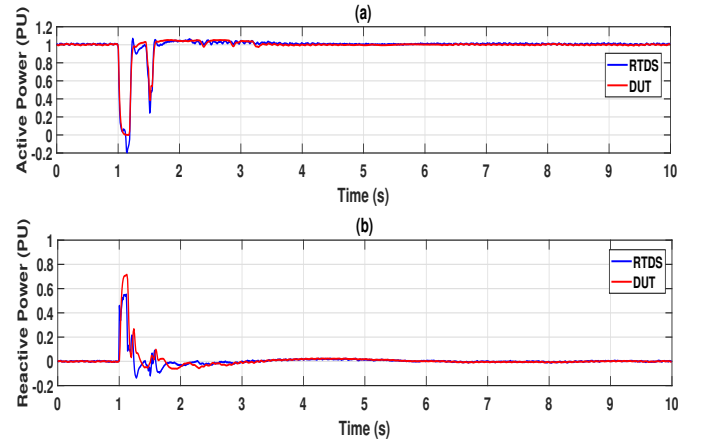


Fig. 9. HIL test bench for validation of SDC control strategy as employed for mitigation of transient stability threats

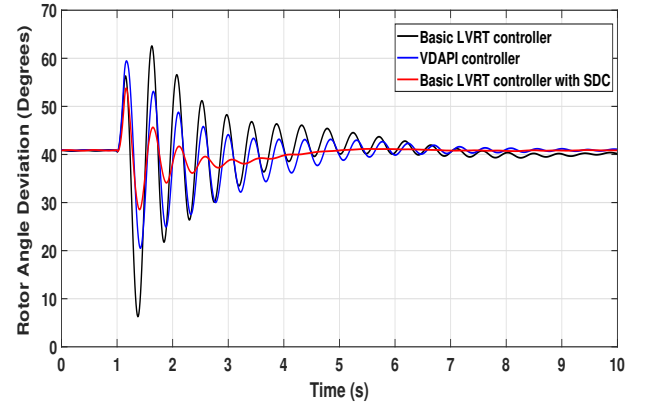


Fig. 10. HIL test bench for validation of control strategies under study for mitigation of transient stability threats

V. CONCLUSIONS

In this study, EMT simulations and a HIL test set-up (i.e. the grid side converter of wind generator type IV used as device under test – DUT) are presented and discussed for transient stability enhancement aims. Analysis is conducted by considering the EMT model of the modified IEEE 9 bus, implemented in RTDS, with a 52% wind generation share. Three control strategies are tested and implemented in the wind generators: a basic LVRT controller with a post-fault ramp in the active power injection, a voltage dependent active power injection (VDAPI), and a supplementary damping control (SDC) method. Figures 7-9 indicate the good accuracy of the EMT simulations with respect to the HIL testing which reflects reality better. As seen in Figure 10, the SDC controller when applied in the active power loop and when the input signal is the rotor angle difference between the two SGs that participate in the inter-area oscillations, is the most effective strategy considering the rotor angle excursions damping.

The SDC controller is an effective way to mitigate the rotor angle oscillations for the following reason. Assuming that the

synchronous generator and the wind generator, equipped with SDC, are located in the same electrical area and that the synchronous generator oscillates against other area(s) of the power system, then, during the fault, due to the action of the proposed supplementary damping controller, when the rotor angle difference increases, the wind generator will decrease the active power production (c.f Figure 4). This entails that the synchronous generator needs to increase the active power injection to feed the load, thus from its swing equation, the speed acceleration will decrease and a damping is introduced. The opposite phenomena are arising when the rotor angle difference of the SGs decreases in the post-fault period; the active power injection of the WGs decreases, therefore the active power injection from the SGs increases trying to meet the demand. From the SGs' equation of motion, this entails smaller deviation between electrical power and mechanical power thus higher rotor angle deceleration.

Moreover, since the WGs, when employing either basic LVRT strategy or SDC, are having the same active power injection during the fault, it is expected that the first swing stability is to be similar. With the VDAPI scheme, the first swing is deteriorated, due to the injection of active power from the wind generator plants during the fault, which ensues a higher initial acceleration in the SG's rotor.

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