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Real-time EMT Simulation Based Comparative Performance Analysis of Control Strategies for Wind Turbine Type 4 to Support Transient Stability

Stelios Papadakis[1], Arcadio Perilla[1], Jose Rueda Torres[1],
[1]Delft University of Technology, Delft, Netherlands
Corresponding author: J.L.RuedaTorres@tudelft.nl

Zameer Ahmad[1], Mart van der Meijden[1,2]
[1]Delft University of Technology, Delft, Netherlands
[2]TenneT TSO B.V, Arnhem, Netherlands

***Abstract*—Power System Stability is a major domain of renewed interest for electrical power system researchers worldwide. Among the different stability classification domains, large disturbance rotor angle (transient) stability studies are of high concern due to the decommissioning of conventional power plants which leads to a dramatic decrease of inertia and short-circuit capacity. In this paper, the superiority of a proposed Supplementary Damping Control (SDC) scheme, concerning with transient stability enhancement, is demonstrated against other existing controls, namely, a common form of low-voltage ride through (LVRT) controller with a post-fault ramp, and Voltage Dependent Active Power Injection (VDAPI) control strategy. Based on the analysis done with the modified IEEE 9 bus system with 52% and 75 % share of wind generation, it has been found that proposed SDC has quick damping of oscillations, and also causes a higher reduction of the magnitude of the first rotor angle swing, and has lesser impact on the overall system frequency performance. The controllers' performance against rotor angle stability threats is tested via EMT modelling and simulation with RSCAD software, which is a real-time digital simulation (RTDS) platform.**

***Index Terms*- Supplementary Damping Control (SDC), Transient Stability, Voltage Dependent Active Power Injection (VDAPI), EMT simulation, Wind Turbine Type 4, MIGRATE.**

I. INTRODUCTION

Traditionally, over the past years, mainly synchronous generators (SGs) were used to generate power. However, nowadays and in the future, several changes are expected in the electrical power systems. In particular, due to Kyoto protocol, a series of incentive programs have been set in order to encourage investors to associate with renewable energy sources (RES) **[1]**. These beneficiary policies, led the power system to undergo an evolutionary phase, since the traditional fossil-fuel plants are gradually decommissioned and at the same time share of RESs are increasing in the energy mix. Among the different renewable technologies, wind energy is rapidly increasing its share in the generation mix. The aforementioned ensue that the contemporary power systems present less inertia and reduced short-circuit current which can potentially lead to less controllability and inevitably to stability issues **[2]**.

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Control methods for transient stability enhancement can be classified into two categories: (i) addition of hardware components (e.g. FACTS devices **[3]**, fault current limiters **[4]**, dynamic breaking resistors **[5],** super-conducting magnetic energy storage devices **[6]**); and (ii) modification of outer control structure of the power electronic converters that interface the wind generator with the electrical power system.

The first category considers important capital investments and diminished reliability. Typical research efforts include addition of super conducting magnetic energy storage devices **[7],** or STATCOM devices **[8]** in parallel to wind generators (WGs) in order to smooth the power output oscillations of the wind generators.

Following the second category, controller modifications can concern the rotor side **[9]**, or the grid side voltage source converter (VSC) **[10]**. Nevertheless, there is lack of insight on the extent to which these modifications can be effective to enable higher share of power electronic interfaced generation. This paper addressed this gap by performing a comparative performance analysis with EMT modelling and simulation of Wind Turbine Type 4 and the electrical power system. This type of renewable generation is taken as a representative form of a fully decoupled renewable power plant. The focus is on modifications on the grid side converter. Hence, three current vector control based schemes of Wind Turbine Type 4 units: (i) a common form of LVRT control with a post-fault ramp in the active power injection, (ii) controller based on voltage dependent active power injection (VDAPI) strategy, and (iii) a proposed supplementary damping controller (SDC). The RSCAD software platform is utilized to execute EMT simulations in real time.

The remainder of the paper is organised as follows: Section II overviews the implantation aspects of the studied controllers. Section III presents and discusses the comparative analysis performed in RTDS. Finally, Section IV summarizes the concluding remarks.

II. IMPLEMENTATION OF CONTROLLERS UNDER STUDY

In this section, a brief introduction about three wind generator control strategies is provided. These strategies consist of outer loops that determine the set points of AC currents in the Point of Common Coupling (PCC) of the wind generator units, and the corresponding inner loops that receive the set points and compute the modulation signals in the valves of the converter that the controller belongs to. Fig. 1 illustrates the basic layout of the fully decoupled wind generator and the input signals in each one of the two converter controllers. Each converter controller is designed based on the synchronous rotating frame d-q analysis.

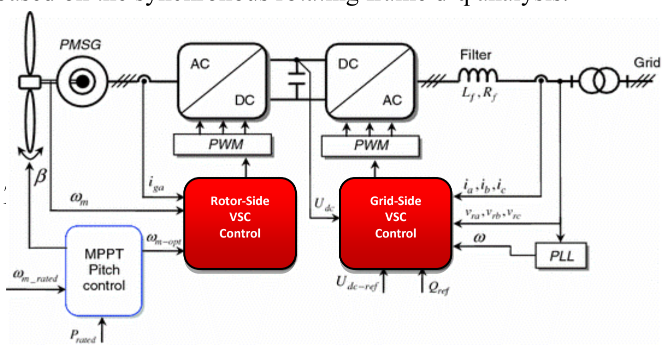

Figure 1. Full-scale power electronics wind generator unit and overall view of control schemes **[11]**

A. *Basic LVRT controller with a post-fault ramp*

This control entails prioritization of reactive current, during the fault, for voltage support and nullification of d-component current, for the facilitation of reactive power injection **[12], [13].** The dependence of the reactive current injection on the voltage deviation is reflected with a proportional gain, referred as “k-factor”. For instance, according to German standards, a k-factor of 2 can be used as a default case and the LVRT operation mode starts when the PCC voltage drops below 0.8 pu **[14]**. In the post-fault period, the active current increases exponentially towards its pre-disturbance value, whereas the reactive current immediately drops to zero. The active current recovery slope is being determined by the gain and time-constant of a first order transfer function. In the current study, 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. In Germany, the aforementioned recovery should have a rate at least 20% of the rated power per second **[14]**. The chosen parameters lead approximately to a 40% increment per second, so the control design comply with the grid codes.

In **[13],** it is stated that the rate of active power recovery after fault clearance must be high (e.g. >200 % per second) to ensure frequency stability and to avoid load shedding following short-circuits. However, a lower rate ramp is examined, due to the fact, that if in the post-fault period the active power injection of the Wind Turbine units, increases relatively slow, then to meet the load balance, the injection from the synchronous machines should be maintained in a high value. From the equation of motion of the synchronous machines, this behavior entails that the increased kinetic energy of the synchronous machines can be returned easier, so transient stability can theoretically be enhanced.

The block diagram of the outer active current control implemented in RSCAD software is illustrated in Fig. 2, in which two flags referred as “FRT_flag” and “Ramp_flag” are used to differentiate the three operational modes, according to Table I. The value 1 mans deactivated, whereas 0 means activated.

TABLE I. FLAG VALUES PER OPERATIONAL MODE

MODE	FRT FLAG VALUE	RAMP FLAG VALUE
Pre - Fault	1	1
Fault	0	1
Post - Fault	1	0

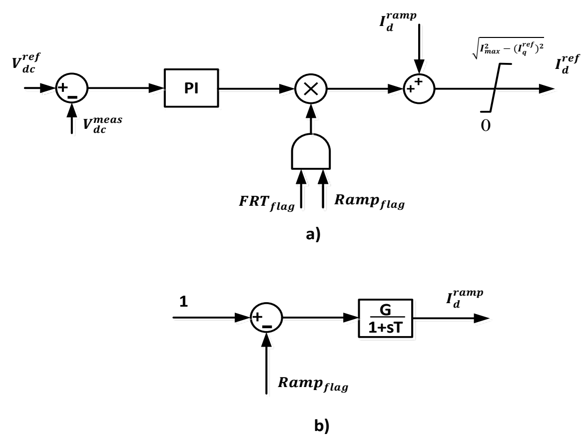

Figure 2. Basic LVRT control (a) i_d^{ref} computation, (b) ramping-up of i_d^{ref} (post-fault)

B. *Voltage Dependent Active Power Injection (VDAPI) controller*

The second controller concerns the ability of the wind generator to inject some active power during the fault.

During the fault, the active power of the synchronous generators drops a lot. If the active power of the wind generators also nullifies as in the first controller described previously, it is comprehensible that the imbalance between total generation and load will also be significant. This ensues, that the frequency deviates a lot from the nominal value. Since rotor angle of the machines and frequency are probably affected, this controller aimed not to nullify the I_d^{ref}, but to inject reduced (comparing to the pre-fault mode) active power. According to that approach, the active current reference as indicated in Fig. 2 is multiplied with the squared value of a factor F, which is dependent on the voltage measured value at the PCC of the wind generator. The controller is illustrated in Fig. 3, where I_d^{ref}, is computed from Fig. 2, in which however the “AND” logic gate in the multiplication point is neglected.

The VDAPI control is applied in the Spanish transmission system **[15]**, whereas as stated in **[16],** a reduction in the active reference current is needed, due to the increment of the installed wind capacity. This increased wind capacity adversely impacts the voltage at the PCC.

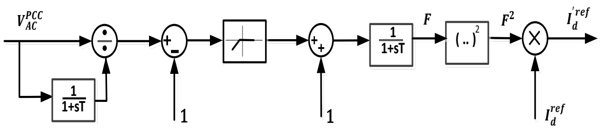

Figure 3. VDAPI control Scheme for i_d^{ref} computation

C. Supplementary Damping Controller (SDC)

The third controller is related to supplementary Damping Control (SDC) branch that is connected to the P-control loop of the Wind Generator.

In principle, the SDC, implemented in the form of a power system stabilizer, can be added either into the active power (P)-loop controller of the wind generator (affecting the d- reference current) or in the reactive power (Q)-loop controller (affecting the q- reference current). Nevertheless, it was decided to add SDC into the P-loop controller due to two reasons. The first one is associated with the electromechanical oscillations that lead to transient instability. These oscillations are caused by a mismatch (according to the dynamics described by the swing equation of each synchronous machine) between the electrical power and the mechanical power of the synchronous generators being in service in a power system. Thus, controlling the active power of the wind generators, will affect directly the active power of the synchronous generators connected to the system. The second reason is related to the location of the wind generators with respect to the location of the synchronous generators. According to **[17]**, the wind generators that are connected electrically close to synchronous generators will tend to have a stronger influence on the active power transfer from the synchronous generators if the wind generators have the supplementary damping control superimposed on the P-loop controller. In the power system examined in this report, the Wind Generators are closely connected to the Synchronous Generators.

Fig. 4 shows the proposed SDC structure, enclosed in the red layout when superimposed on the output of the active power (P)-loop controller of the wind generator. As shown, the damping controller has the simple form of a washout filter, whereas the input is the rotor angle difference between synchronous generators connected to the power system. Unlike typical damping controllers attached to synchronous generators, the lead-lag compensation has not been considered, because a small phase lag between the modulated current reference in the d-axis and the active power output of the grid side converter is assumed. Furthermore, as stated in **[18]**, "The active power should be modulated in phase with the speed of the machine". The blue layout in Fig. 4 is not implemented, but facilitates the explanation of the previous notion as following. The rotor angle constitutes the integral of the rotor speed, and has a phase shift of -90 degrees with respect to the rotor speed. In addition, it is taken into account that the washout filter is a high pass filter, and introduces a phase shift of 90 degrees. Hence, no phase compensation is needed when rotor angle is taken as input in the stabilizing control. The following parameters (G=10, T=0.1s) are used in the simulations, explained in following section.

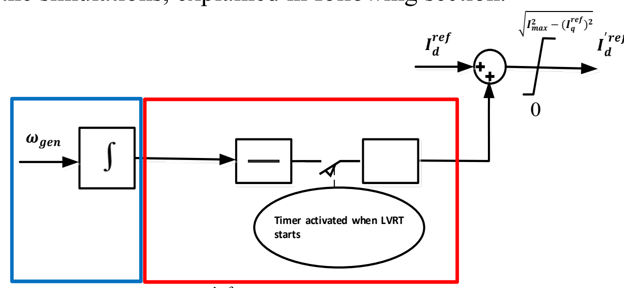

Figure 4. $i_d^{'ref}$ computation in SDC control scheme

In Fig. 4, the implemented SDC is enclosed in the red layout. The blue layout is for the reader's insight regarding the absence of phase compensation in the controller as described in the previous paragraph. A timer has been added in order to deactivate the damping controller when desired. This time period may be between 10-15 s, which is usually the transient stability time frame period, however, in order to prevent unwanted noise or high frequency oscillations, the deactivation time of the SDC loop, can be set around 5 seconds after the LVRT mechanism is triggered.

III. REAL-TIME DIGITAL SIMULATION RESULTS

The IEEE 9-bus system, which is used to assess the large-disturbance rotor angle, is depicted in Fig. 5. Two wind share levels are examined; 52% and 75%. The transition from the low to the high wind share configuration is performed in such way so as the SGs' pre-disturbance loading is the same in the two topologies, for a fair comparison, so as more reliable results to be deduced. Fig. 5 illustrates the modified IEEE 9 Bus system, in which the integration of the plants (synchronous or wind based) for each wind share case scenario is depicted in Table II. Table II, additionally depicts the load flow results for each case. The examined contingency concerns a three phase fault of impedance 0.2 Ohms, applied at Bus 8, with 120 ms Fault Clearing Time (FCT). For each wind share scenario loads remain constant: i.e. LA=125+j50 [MVA], LB=90+j30 [MVA], LC=100+j35 [MVA].

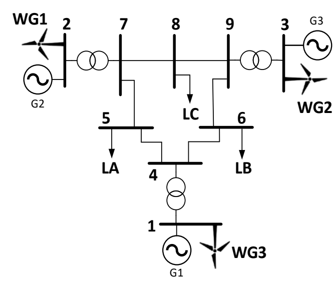

Figure 5. IEEE 9 Bus system with integrated wind plant Type 4

TABLE II. LOAD FLOW RESULTS

Plant	Only SGs		52 % WG		75% WG	
	P[MW]	Q[MVar]	P[MW]	Q[MVar]	P[MW]	Q[MVar]
G1	73.06	36.11	73.02	36.02	35.3	20.4
G2	163.08	-9.1	81.5	-4.6	40.75	-2.6
G3	85.03	-4.943	-	-	-	-
WG1	-	-	81.5	0	124.9	0
WG2	-	-	85	0	83.6	0
WG3	-	-	-	-	38.7	0

A. 52% WG Share- Responses

The currents and their correlation with the powers are presented in Fig. 6, for the previously described control strategies.

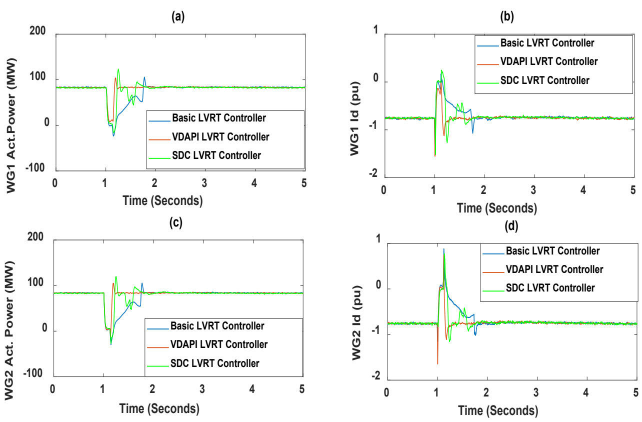

Figure 6. 52% WG share a) & b) WG1 active power and active current, c) & d) WG2 active power and active current

In Fig. 7, it is shown that electromechanical oscillations are evident, when only SGs are connected, or when VDAPI or basic LVRT WGs are used. With the SDCs employed, the oscillations are damped out quickly.

In Fig. 8, when SGs are only connected, the frequency increases due to the higher active power synchronous generation than demand. (Load C due to the fault at bus 8 drops to zero.) In the basic LVRT WGs case, the total generation drops faster than the load, as a result frequency decreases significantly. With the VDAPI, since the WGs continue injecting some active power during the fault, the frequency decreases less. Last, SDC equipped WGs are also improving the frequency response as a consequence of the rotor angle improvement. Moreover, the high inertia of the system when only SGs are connected is clear, from the lagging characteristic comparing to the WG connected cases. SDC equipped WGs is the only measure that improves rotor angle responses, as derived also from Fig. 8.

B. 75% WG Share- Responses

For a higher share of wind power generation, the system is stable only when the SDC is implemented, for a three-phase fault at Bus 8 with FCT at 120ms as shown in Fig. 9.

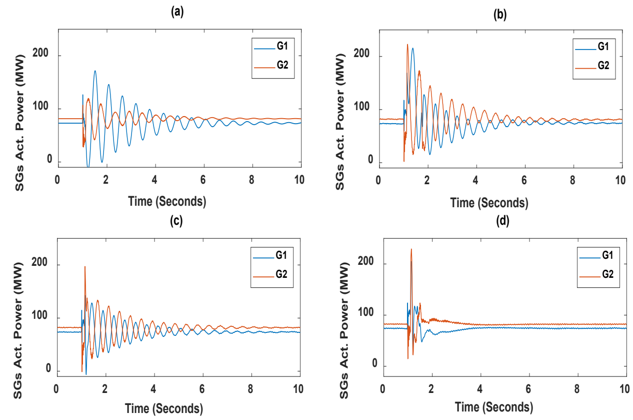

Figure 7. Active Power from SGs due to a Fault at Bus 8- 6 cycles: a) only SGs connected, b) Basic LVRT controller applied in WGs, c) VDAPI LVRT controller applied in WGs, d) SDC LVRT controller applied in WGs

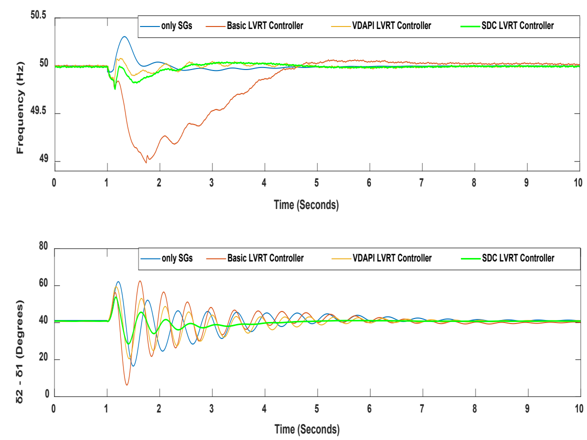

Figure 8. 52% WG share Frequency & Rotor angle responses

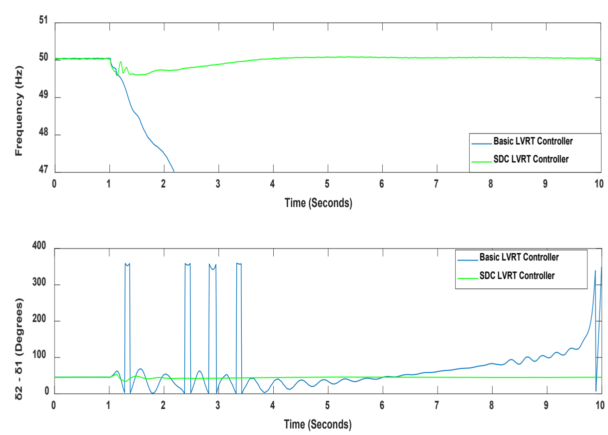

Figure 9. Frequency & Rotor angle responses with 75% WG share

IV. CONCLUSIONS AND DISCUSSION

The main conclusions derived from the analysis performed using EMT simulations for testing of different Wind Turbine Type 4 controller's regarding their capabilities to support power system transient stability are presented and discussed as follows.

i) The rotor angle deviation between two synchronous generators in the power system is a suitable input of the damping controller. Since, it is directly related to the transient stability performance of a power system. Additionally, if this input is used in the damping controller, no lead-lag compensation needs to be integrated. Lastly, this input signal, is concerned as a remote input. Since the inter-area low frequency modes are excited between machines in different areas, retrieving signals as inputs that are associated with machines located relatively far, will introduce better damping. The implications of latency delays in the controller is an open-research topic.

ii) As seen in Fig. 4, the action of the SDC control lays on the following: when the speed of the SG tends to increase, then the WG decreases its active power injection in an anti-phase manner, therefore, the difference of the mechanical and electrical torque of the synchronous unit decreases and damping torque component is enhanced.

iii) Basic LVRT controller has the worst frequency behaviour due to the big imbalance between generation and demand. Since no damping enhancement controller is applied and the inertia of the system is smaller, rotor angle response is deteriorated comparing to the only SGs situation.

iv) Utilizing the VDAPI controller, the frequency response is improved, since the imbalance between consumption and generation is decreased. The rotor angle first swing is worse comparing to the basic LVRT scheme, due to the fact that during the fault, the SGs are injecting less power comparing to the first case in which the WGs do not inject any active power. The damping torque is not differentiated that much between the two aforementioned strategies.

v) SDC controller can improve both frequency and rotor angle response comparing to the case in which only LVRT control strategy is used during the fault period. For higher wind share (75%) it was proven that only this control strategy is capable to avoid transient stability for a considerable FCT of 120ms. Moreover, the first swing contribution is the same as in the basic LVRT controller, due to the fact that they incur the same equivalent impedance as seen from the synchronous unit terminals. This means that both two schemes nullify the active current of the wind generators during the fault.

Hence, the derived SDC is a suitable candidate for the mitigation measure of transient stability issue of power grids that target to significantly increase the share of power electronic interfaced generators.

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