ASSESSMENT AND ENHANCEMENT OF A FULL-SCALE PMSG-BASED WIND POWER GENERATOR PERFORMANCE UNDER FAULTS

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Abstract: A full-scale permanent-magnet synchronous generator (PMSG)-based wind turbine with dc-link voltage control via the machine-side converter has the potential to provide inherent low-voltage ride-through (LVRT) performance without additional hardware components. However, several important performance aspects related to this topology are not addressed in this literature. This paper investigates the impacts of the LVRT control on the stability and risk of resonance, successful operation, and fatigue in a full-scale PMSG-based wind power generation system. An analytical model, considering the double-mass nature of the turbine/ generator and typical LVRT requirements, is developed, validated, and used to characterize the dynamic performance of the wind generation system under LVRT control and practical generator characteristics. To enhance the operation and reduce the fatigue under LVRT control, two solutions, based on active damping control and dc-link voltage bandwidth retuning, are proposed, analyzed, and compared. The detailed nonlinear time-domain simulation results validate the accuracy of the developed model and analytical results.

1. INTRODUCTION

Wind turbines technology has become very advanced So that wind power is considered as a major green source In modern power systems. Therefore, the penetration level of Wind power generation is increasing rapidly with no signs of Slowing down [1]–[3].While the classical issues of wind power, Such as extracting the maximum available wind power, have Been solved, the increased penetration level of wind power is Creating new problems for power systems. Incorporating wind Power generators in frequency regulation and low-voltage ride thorough (LVRT) are among these serious issues. Frequency Regulation has gained significant attention in the literature in Recent years [4]–[6], and grid codes for LVRT have been standardized And implemented in several countries [7].

Generally, LVRT standards emphasize the need to keep a wind power generator connected to the grid and to improve the voltage profile during low-voltage transients. Reference [8] shows that all the generators in a wind farm are not required to provide LVRT capability; however, this reference does not question the need to implement LVRT implementation in wind power generators. The performance of a doubly-fed induction generator (DFIG), as the most popular type of wind generator, has been extensively studied under LVRT [9]. Although the crowbar method is widely utilized in DFIGs, it is characterized by the loss of control and the waste of energy [10]. As an alternative, the demagnetizing control method has been proposed; however, it has not been widely adopted due to its complexity.

All these difficulties, besides some other problems, such as reliability, losses, and the cost of slip rings and gearboxes, reduce the advantages of DFIGs and result in an increasing trend toward using direct-drive permanent-magnet synchronous generators (PMSG) with full-scale back-to-back converters. The objectives of these studies were to not only enhance the dc-link voltage dynamics during faults, but also to improve different aspects of the grid voltage even under asymmetric faults. The results of these studies are promising and present the PMSG as a generator with an inherent LVRT capability without the need for any additional components. In other words, adopting a realistic double-mass model for a PMSG-based wind turbine is necessary because using the single-mass model can lead to an incorrect and deceptive assessment of LVRT operation.

On the other hand, utilizing the rotating masses in a PMSG for storing the excessive energy during the fault will expose its shaft to the power system transients. Considering the softness of a direct-drive PMSG shaft, the LVRT control scheme may increase the fatigue and speed up the aging of the wind generator. Recently, it has been found that wind generators suffer from faster aging than expected, mainly because of mechanical fatigue. Although addressing the fatigue caused by wind speed variation has gained significant attention, the impact of faults on the LVRT-capable PMSG fatigue is not addressed in the current literature. It has been shown that these faults can increase the stresses and wear out the generator faster.

To characterize the pros and cons of the LVRT-capable control method, detailed modelling and thorough analysis are needed. This paper investigates the impacts of the LVRT

control on the stability of wind power generator and the risk of resonance in its mechanical drive, successful operation during faults, and fatigue in a full-scale PMSG-based wind power generation system. An analytical model considering the double-mass nature of the turbine/generator and typical LVRT requirements is developed, validated, and used to characterize the dynamic performance of the wind generation system under LVRT control and practical generator characteristics. The model can also be effectively used to tune and optimize the control parameters in the generator system. To enhance the operation and reduce the fatigue under LVRT control, two solutions, based on active damping control and dc-link voltage control bandwidth re-tuning, are proposed and compared.

This paper is organized as follows. The modelling is presented in Section II. Detailed analysis and mitigation methods are discussed in the next section. Time-domain simulation results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. MODELING

Fig. 1 shows a PMSG-based wind power generator. Classically, the grid-side converter (GSC) is utilized to regulate the dc-link voltage whereas the wind-generator-side converter (WSC) extracts the maximum available power. During a fault, the GSC loses its capability to inject or sink active power, partially or completely; thus, a voltage violation may occur in the dc-link voltage.

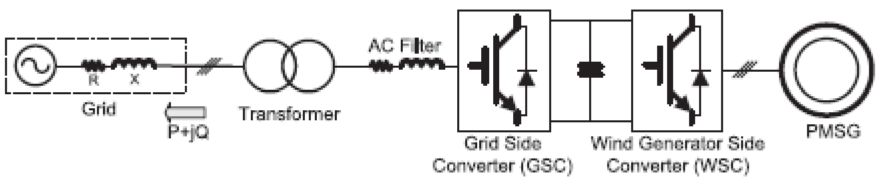


Fig:1. PMSG-based grid-connected wind power generator

In this paper, the performance of an LVRT-capable PMSG-based wind generator in which the control functions of the WSC and GSC are permanently switched is analyzed. It is easy to show that no major difference exists in the behavior of a PMSG-based wind generator under normal operating conditions with the dc-link voltage regulated by either the GSC or the WSC.

Deriving linearized models for a wind power generator is crucial to analyze the generator dynamic performance during LVRT and to coordinate different controllers. Under LVRT, a wind generator will be subjected to different operating conditions and huge changes; therefore, utilizing one linearized model does not seem reasonable. Instead, three models are adopted in this paper. The first model characterizes the wind power generator dynamics in the pre-fault condition. In this case, the model input is the wind speed. The second model considers the generator dynamics in the "during fault" period, where the generator output power is dictated by the power system conditions instead of extracting the maximum available wind power. The third model characterizes the wind power generator dynamics after fault clearance when the generator has complete control over its output power. The wind power generator dynamics, which is moved from its steady-state mode during the fault, tries to restore the pre-fault condition. Here, the system is responding mainly to its initial states rather than any external forces. This initial state is, in fact, the final state obtained from the "during fault" model. Each of these modes and the corresponding linearised models will be discussed in the following sections.

A. Pre-Fault:

This state can be identified as a normal operating condition, but it has a significant common feature with the "during fault" period.

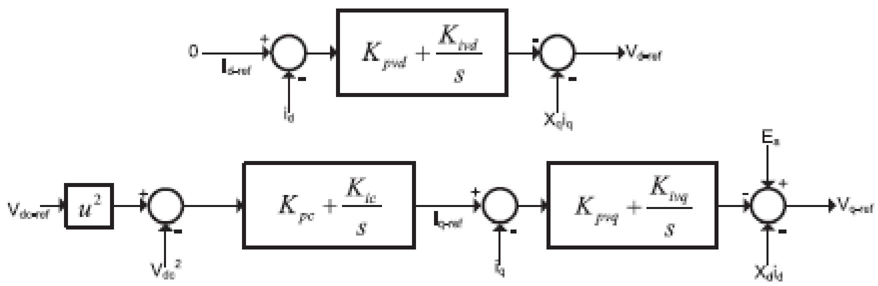


Fig:2. Block diagram of the WSC controller.

In fact, when the WSC controls the dc-link voltage, the WSC and consequently the generator, in both normal and fault conditions, work similarly to regulate the dc-link. The GSC performance during a fault may yield different dynamics and disturbances imposed on the dc-link.

To facilitate the close control of a PMSG, a field-oriented control system implemented in the *d*-*q* reference frame is usually employed. This frame associates the *q*-axis current *iq* with the active power production, whereas the reactive power is dependent on the *d*-axis current component, *id* , which is usually regulated to zero.

iq−ref = (V 2ref − V 2DC)(Kpc + Kics).................. (1)

iq =1/(τis + 1)*iq−ref ....(2)

The reference current is compared to the actual value and fed to a PI current controller as depicted in Fig.2. In most cases, the current dynamics, the relation between the actual and desired *q*-axis currents can be approximated by (2), where τi is the closed-loop current control time-constant [28]. This current is related to the electromagnetic torque by (3), where *Tg* , *P*, and λm are the electromagnetic torque, pole-pair number, and the electromagnetic flux constant of a PMSG, respectively:

$$Tg = 3/4P\lambda m\ iq \ldots\ldots(3)$$

$$Pgen = Tg\omega g \ldots\ldots(4)$$

On the one hand, the electromagnetic torque impacts the dclink voltage via the generator electric output power *P*gen, as given by (4), where ωg is the rotational speed of the generator. Equation (5) relates the PMSG output power and GSC output power, *P*grid to the dc-link voltage, where *C* and *P*nom represent the dc-link capacitance and nominal power. *P*gen and *P*grid here are in per unit whereas the other parameters have their well known SI units (Watt, Farad, and Voltage).

$$Pnom(Pgen - Pgrid) = CddtV\ 2DC\ldots\ldots (5)$$

On the other hand, *Tg* is an important variable in the mechanical part of the generator as shown by (6)–(8), where *H*, *T*, *Ks* , *D*, θ, and ω represent the inertia constant, torque, shaft stiffness, damping factor, shaft angle and rotating speed, respectively; and

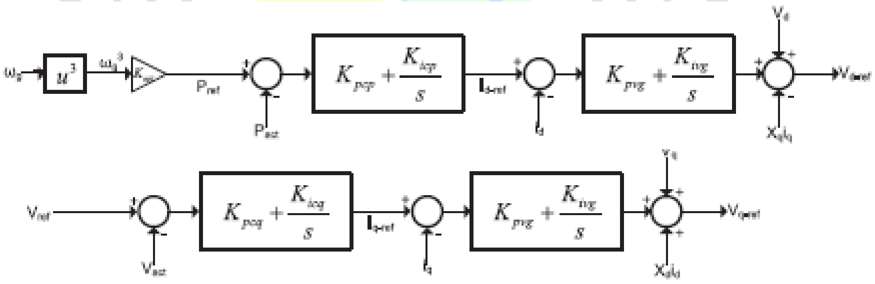


Fig. 3. Block diagram of the GSC controller.

subscripts *B*, 0, *t*, and *g* denote the base, initial, turbine, and generator, respectively. Obviously, the initial values of the torques and speeds of the generator and turbine are the same

$$\dot{\omega}\ t = 1/2Ht*(Tt - Ks\theta - Dt\omega t) \ldots\ldots(6)$$
$$\dot{\theta} = \omega B\ (\omega t - \omega g) \ldots\ldots(7)$$
$$\dot{\omega}\ g = 1/2Hg(Ks\theta - Tg - Dg\omega g). \ldots\ldots(8)$$

The wind turbine performance can be described by (9), where ρ is the air density; *CP* is the power coefficient of the wind turbine; λ is the tip ratio; θ is the pitch angle; *Ar* is the effective area covered by the turbine blades; β is the pitch angle; *vw* is the wind speed; and *Pm* is the mechanical input power and is equal to the product of Tt and ωt , Pm = 0.5ρCP (λ, β)Ar v3w = Ttωt ....(9)

*P*grid−ref = *K*OPT*ω*3 *g* .... (10)

In normal operating conditions, the reference grid-power is set to extract the maximum available power, as Fig.3 shows. Reference [29] shows that if the pitch angle is constantly kept at zero, this optimum power can be expressed by (10) in which *K*OPT is a constant. The GSC controller is fast enough to assume that the actual amount of *P*grid is equal to its reference value [6].

In a double-mass mechanical system, resonance is possible; therefore, an active damping controller can be used to suppress resonance without the physical losses associated with a passive damping solution. To complete the model, a typical active damping controller is augmented in the system dynamics. Basically, it is a band-pass filter aiming to increase the damping of the natural resonance frequency, *ω*ad, of the generator. This damping can be discarded simply by assigning *Dv* , the active damping gain, to zero. In (11), *V*nom is the nominal dc-link voltage. The application of the active damping in both normal and fault situation will be discussed later to construct the final model, the system dynamics need to be linearized;

$$V_{\mathrm{ref}}^2 = V_{\mathrm{nom}}^2 + \frac{D_v}{\tau_{\mathrm{ad}}s+1}\cdot\frac{2\xi_{\mathrm{ad}}\omega_{\mathrm{ad}}s}{s^2+2\xi_{\mathrm{ad}}\omega_{\mathrm{ad}}s+\omega_{\mathrm{ad}}^2}\omega_g. \quad (11)$$

however due to lack of space, this step is not detailed here except when it has resulted in introducing new states or parameters such as (12)–(15), where Δ*φ*1 , Δ*φ*2 , Δ*φ*3 andΔ*φ*4 are introduced to realize (11) and (1). The change in the mechanical input power, Δ*Pm,* in general is a function of the pitch angle, rotor rotational speed and wind speed. However, the pitch angle is usually zero, and because of the maximum power point tracking (MPPT), *dPm/dωt* = 0. Therefore, the mechanical power can be expressed as a single-variable function of the wind speed as in (16). The linearization point in the modelling is the system's equilibrium point, which is a function of wind speed.

Δ˙φ1 =(−2ξadωad – 1)/τadΔφ1 – (ω2adτad + 2ξadωad)τad Δφ2− ω2adτadΔφ3 +Δωg.......(12)

Δ˙*φ*2 = Δ*φ*1 ....(13)

Δ˙*φ*3 = Δ*φ*2............................ (14)

Δ˙*φ*4 = Δ*v*2 ref − Δ*v*2 dc ....(15)

A = ∂ΔPm∂Δvw= 0.5ρAr (3CP V 2w0V 3w0 ∂ΔCP /∂Δλ. ∂Δλ/∂Δvw)....................(16)

Equation (17) at bottom of the page represents the complete linear model. In this small-signal model, the equilibrium point is the origin.

B. During Fault:

During the fault, a model modification is needed, due mainly to the inability of a wind power generator to inject the available wind power to the system. This requirement means that for a slow recovery (e.g., up to

900 ms), no active power can be injected into the system, and even after that occurs, the active power injection should be increased gradually to respect the grid codes and converter rating, as shown by

Pgrid =_S2conv − Q2grid ....(17)

Therefore, the main difference here is the grid power, which can no longer be described by (10).

C. After Fault Clearance:

After the time instant denoted by $t*$ in Fig. 6, the GSC returns to its previous control, introduced in (10), trying to restore its initial pre-fault operating point. It means that (17) is once more valid to describe the system; however, it is not in its equilibrium point anymore. This initial point could be easily extracted from the previous part. In other words, the final states of the fault part could be used as initial values for this mode. To simplify the model, the wind speed changes could be ignored here. Then this mode could be understood as an initial value response.

D. Model Verification:

To validate the proposed model, a typical 2.0 MVA PMSG based wind turbine is simulated for detailed time-domain simulation studies.

The proposed model and the time-domain simulation model have the same parameters and are excited by a three-phase solid fault occurring at the point of common coupling

III. DOUBLE-MASS PMSG AND LVRT

The detailed state-space model allows (1) studying the stability and characterizing the performance of the system under fault conditions, (2) observing different states and parameters, (3) tuning and coordinating the generator system control parameters, and (4) testing the performance of the new controllers needed to improve the generator stability and performance under faults. The analysis and solutions presented in this section illustrate the usefulness of using the proposed analytical model.

A. Successful LVRT Operation:

A conventional PMSG-based wind generator usually has no active or passive damping mechanism In fact, the active damping introduced in (11) is one of the solutions discussed to solve this problem. In normal situations where the GSC and WSC active powers are equal, the generator torque is equal to$K$OPTω2 g . Therefore, the MPPT produces a stabilizing torque in the generator, and no additional remedy is necessary. For this reason, active damping is not usually employed in conventional wind generators; however, this reason is not clearly discussed in the literature.

1) Problem Description:

The positive *dTg/dωg* condition can totally change if a fault occurs. Although the WSC can still regulate the dc-link, the risk of instability in the mechanical system of the generator exists. Whereas the system in the normal (*pre-fault*) condition is reasonably damped, the faulty ("*During fault*") system is vulnerable to resonance. Using the pre-fault model for the post-fault situation implies that the system stability before a fault guarantees the stability after the fault clearance. Thus, regardless of the conditions that the generator experiences during the fault, the generator will be restored to its pre-fault status if it were a stable point. However, the situation is much more complicated. In reality, some relays will disconnect the generator if the observed parameters (e.g., generator speed, dc-link voltage, etc.) violate their allowed range. Not only stability, but also the system limitations should not be violated. The system designer must check the limit violation as well.

The limited time of the fault does not allow the unstable modes to generate severe unstable responses; however, these models may lead to a violation of the limits of the dc-link voltage or generator rotating speed.

The soft shaft of the mechanical system does not permit equal involvement of both rotating masses in storing energy. The generator rotating mass, which is more controllable, stores a larger portion of excessive energy than what is stored in a system with a stiff shaft, or equivalently, with a single-mass model. However, this mass is usually much lighter than the turbine mass. A single-mass (or a stiff shaft) model predicts equal changes in the angular speeds of the masses, and consequently, division of the excessive energy between them will be based on their inertia. The energy stored in a rotating mass is a function of the square of its angular speed, *ω*, and its inertia *H*. This disproportion increases the chance of very high generator speeds.

In high wind speeds, a change in the generator rotating speed equal to or greater than 20% can trigger the over-speed relay. In other words, a generator with a soft shaft or a light rotating mass (while the turbine and, consequently, the total rotating masses are heavy enough) cannot override the fault. Therefore, the utilization of a single-mass model of the turbine generator does not facilitate accurate LVRT study, and can lead to deceiving LVRT capability results. This important finding is missing in the current literature supporting the LVRT control method for PMSG-based wind generators.

2). Remedy:

To stabilize the system during the fault and control the states, the dc-link voltage control bandwidth, as one of the already available control levers, can be used. The dc-link voltage control bandwidth *f*dc can be calculated, as given by (20), by assuming a fast current controller, i.e., a small enough *τi*. The *K*ic parameters can be adopted to control *f*dc,

$$f_{\rm dc} = \frac{1}{2\pi}\sqrt{\frac{3P\lambda_m}{2}P_{\rm nom}\omega_{r0}K_{\rm ic}/C}. \quad ....(18)$$

A smaller bandwidth means that the controller is slower, and a wind generator is not responding to changes rapidly. In other words, now the dc-link should play the role of a buffer that does not allow the generator to be exposed to fast changes. In this case, fault transients will be suppressed by the dc-link slow dynamics instead of being directly imposed on the rotating masses of the generator. This major role of the dc-link in stabilizing the system under faults is in contrast with the philosophy of LVRT in a PMSG-based wind generator, in which the rotating mass of the generator is preferred over the dc-link to store the excessive energy. First, the differences in the changes in the speeds of the turbine and generator rotating-masses seem significant. More importantly, this figure shows that to reduce the maximum generator speed considerably, a relatively low dc-link bandwidth is needed. However, this enhancement in the generator speed will be gained at the cost of undesired large dc-link fluctuations.

On the one hand, during a fault, the system becomes temporarily unstable, and there is no control of the energy management between sources. On the other hand, the dc-link voltage

Control bandwidth cannot solve the problem. Active damping may be proper solution.faulty situations. Even in the normal condition, the stability is significantly improved.

B. Fatigue Analyses:

Researchers understood the importance of fatigue analysis of power generators a relatively long time ago. In the literature, fatigue is associated with the notion of stress. When the stress is higher than a certain limit, the shaft material will go through the plastic strain region. In this region, the shaft material deforms irreversibly, and this non reversible deformation can be interpreted as fatigue.

On the other hand, this result also implies that under that at a certain stress limit, the shaft remains in the elastic stress region, and the machine experiences no faster aging. A machine in this condition has not yet reached its fatigue limit, which describes the maximum stress that does not result in any fatigue.

Though the shaft stress is a linear function of the shaft torque, the relation of fatigue and the shaft torque is much more complicated. The relation of stress and strain makes hysteresis cycles, and to calculate the impact of stress on the fatigue, the maximum stress, average stress and number of each cycle during a relatively long time should be calculated. The method used is highly nonlinear, cumulative, and complicated. Recently, a new study presented a method for estimating the fatigue in wind turbines. After some further calculation, it can be formulated as Obviously, the fatigue estimation, F, is a function of the shaft torque and its derivative.

$$\_ = aT\text{shaft} + g\,\dot{T}\text{shaft} \text{ .... } (21)$$

The positive parameters a and g are calculated online, and, because of the cumulative nature of fatigue, they vary over time. On the one hand, the shaft torque and its derivative can be used as indices for the fatigue investigations. On the other hand, limiting the mechanical tensions can prevent them from adding to the generator fatigue. Thus, the shaft torque and its derivative can be gauged and controlled to restrict the shaft fatigue.

A conventional generator continues to extract the maximum available energy from wind regardless of faults, and all tensions should be handled by the dc-link capacitor and GSC. Therefore, the LVRT control method eliminates the need for new components to dissipate the excessive energy during the fault, but this method can increase the aging of the generator. The mechanical stress can be reduced via active damping control or dc-link voltage control bandwidth re-tuning, but at the cost of higher stress on the dc-link capacitors. This mechanical stress issue, associated solutions, and trade-offs are not addressed in the literature.

However, even the active damping method yields high oscillations in the dc-link voltage for an acceptable reduction mechanical tension. Considering that the dc-link capacitors are the weakest components in power converters, a system designer can be faced with a strong trade-off. On the one hand, with either no or a small amount of active damping, the dc-link capacitor does not experience any serious overvoltage, but the turbine-generator shaft wears out more quickly.

On the other hand, the active damping controller can reduce or eliminate the mechanical stresses at the cost of wearing out the dc-link capacitor. Such issues can limit the effectiveness and adoption of the LVRT-capable control method for PMSGs. To increase the breadth of the analysis, two aspects need to be analyzed.

a) Impact of Fault Duration:

In a fast recovery, the fault clears relatively quickly. This situation is desirable; however, the fault clearance acts as another disturbance stimulating the resonance of the mechanical system again. The clearance disturbance might add to the previous disturbance, the fault itself, which created mechanical oscillations in the first place. These initial oscillations are not usually completely damped before the fault clearance. On the contrary, in the slow recovery situation, the mechanical system has more time to be damped before the second disturbance, or the fault clearance. First, without any active damping (which yields the minimum Vdc, max), the mechanical stresses are almost the same. Therefore, even in a slow recovery, the mechanical system is exposed to high stresses and wearing out. However, much less energy is needed from the dc link to suppress these tensions in this case. On the other hand, these reductions are swiftly saturated, and for a slight further reduction in the shaft torque or its derivative, a considerably higher contribution from the dc-link becomes necessary. Even in a slow recovery, huge mechanical stresses are imposed on the shaft, and their mitigation results in compromising the dc-link performance and stress levels.

b) Impact of Unsymmetrical faults

Unsymmetrical faults are not usually as severe as symmetric three-phase-to-ground faults (at the same location), but they occur more frequently in typical power systems. Because of the accumulative nature of fatigue, they can play an important role in wearing out the generator.

In other words, asymmetric faults neither increase the fatigue of the mechanical system nor result in over speeding of rotating masses that may threaten successful LVRT. This analysis also shows that the LVRT-capable PMSG is not inherently capable of reducing electrical tensions imposed on the dc-link during asymmetric faults. However, some, usually relatively complicated, methods allow mitigating the unbalanced fault tensions on the dc-link.

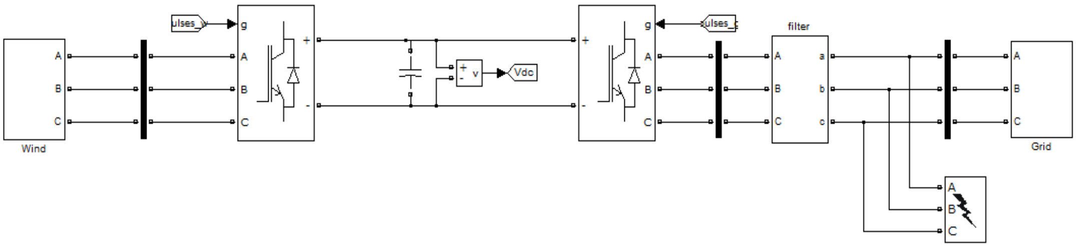


Fig.4. Simulation modelling of proposed system

IV. TIME-DOMAIN SIMULATION RESULTS

To verify the theoretical analysis in the previous sections, time-domain simulations based on the detailed nonlinear model of a typical Ontario, Canada-based system, shown in Fig.4, are employed. The wind generator converters controllers are depicted in Figs.3A PMSG is employed in a distributed generation unit 1 (DG1). The droop and excitation system models are also included. Typical distribution system lines, with low X/R ratio (X/R = 2), are modelled as lumped R–L elements, and the loads are represented by parallel R–L elements. The disturbance used for studying this system is a three phase to-ground fault that occurs at bus #4 at t = 35 s in most the cases. Such a severe fault close to the wind generator allows for observing the worst-case scenario. The Matlab/Simulink package is employed for simulation studies.

A. Shaft Stiffness

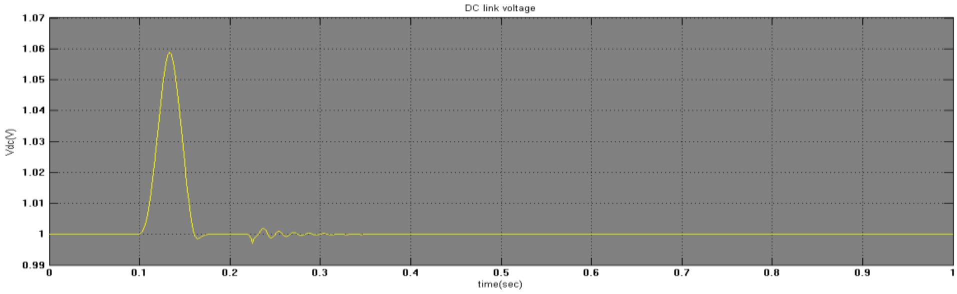
The shaft stiffness and weight ratio of the rotating masses are changed to examine the analytical results. The results are shown in Fig.5. While these changes do not impact the dc-link voltage, the generator rotating mass can experience a 30% over speed. Meanwhile, the turbine rotating speed does not exceed 1.18 per unit. The results, once more, show that the utilization of the single-mass model can lead to misleading results.

B. DC-Link Controller Bandwidth

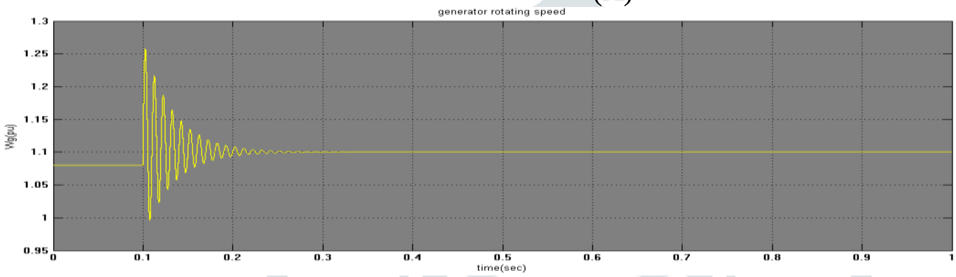
A fast recovery scenario is also tested; the results are shown in Fig.6. As predicted by the theoretical analysis, a lower dc-link voltage control bandwidth reduces the amplitude of oscillations on the rotating masses speeds at the cost of larger changes in the dc-link voltage. The figure also depicts the mechanical tensions and how using the dc-link as a buffer can save the generator shaft from higher stresses. Although the stress on the mechanical system of the generator is reduced, the capacitor will wear out faster.

C. Active Damping

Fig.7 shows the generator performance when the active damping is applied in the slow voltage recovery case. Again,



(A)



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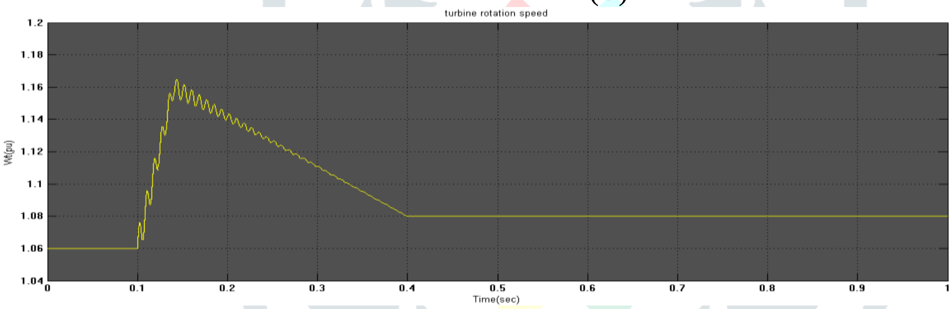
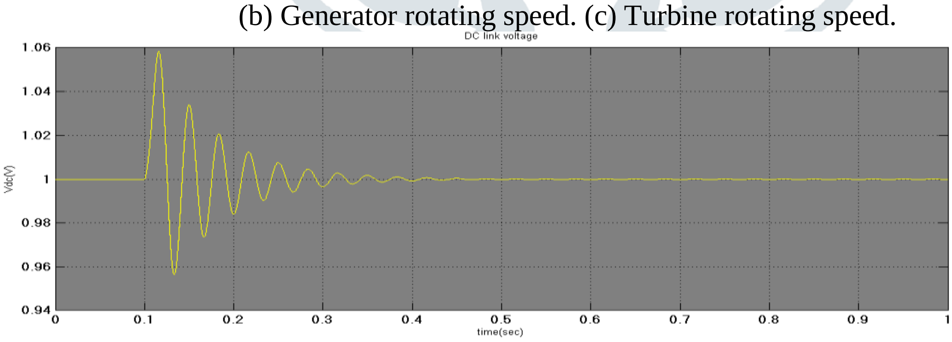
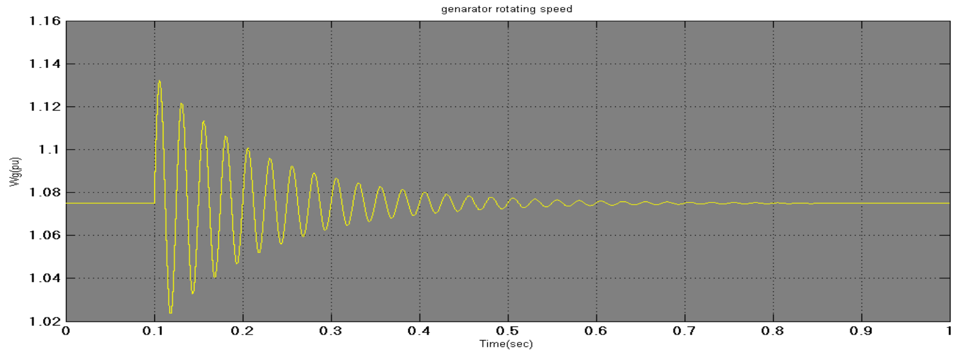


Fig.5. Impact of doubly-mass model specifications when a slow recovery occurs after fault: (a) DC-link voltage. (b) Generator rotating speed. (c) Turbine rotating speed.



(A)



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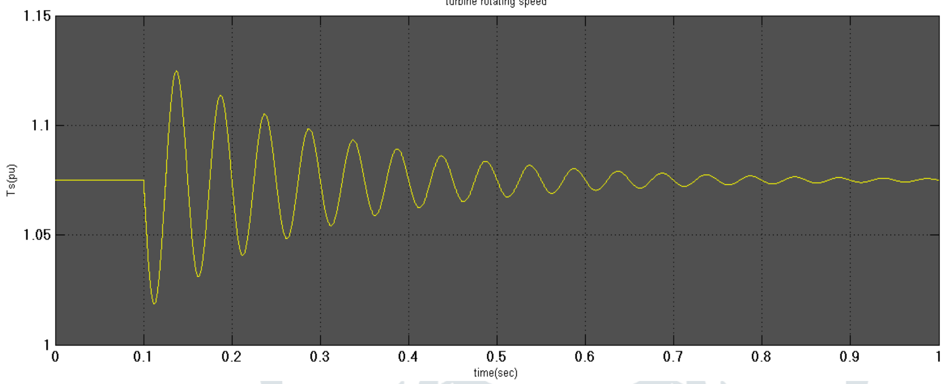


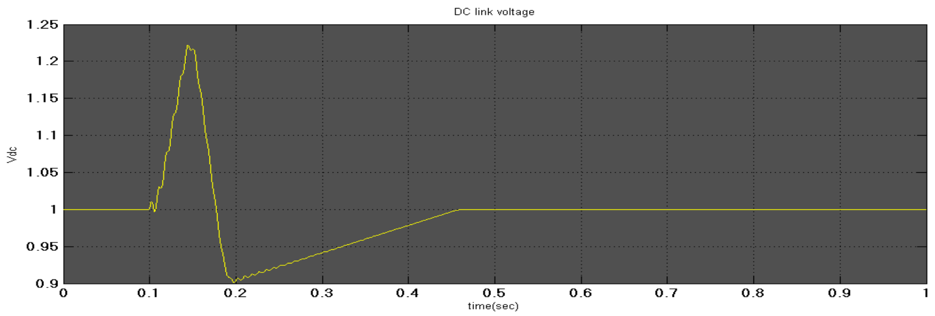
(C)

Fig:6. Impact of dc-link controller bandwidth when a fast recovery occurs after fault. (a) DC-link voltage. (b) Generator rotating speed. (c) Torque of shaft

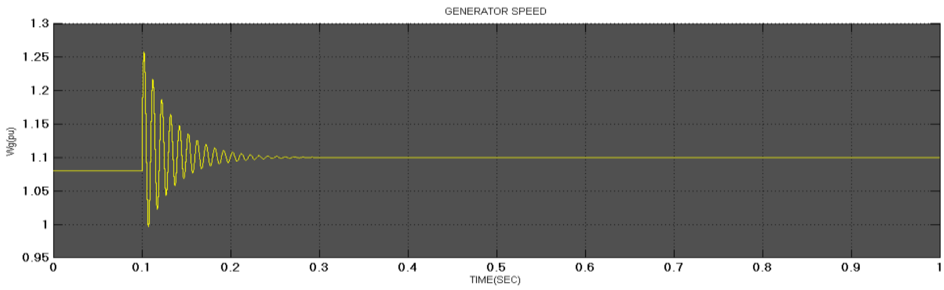
time-domain simulations confirm the theoretical findings, where the active damping method reduces the fluctuations in the generator rotating mass speed at the cost of higher deviations in the dc-link voltage. Fig.6(b) reveals that at a wind speed of 12 m/s, the generator rotating speed can exceed 1.20 p.u., which is close to the over-speed threshold of wind turbines. The active damping method yields a successful LVRT and reduces the mechanical stresses on the turbine shaft, as predicted by the analysis (see Fig.6(c)).

D. Asymmetric Fault

Fig.8. shows the wind power generator performance when a single-phase fault occurs at the generator terminals. Obviously, with a 1.20 p.u. thermal limit of the power converter, the healthy phases are capable of injecting the active power of the faulted phase.



(A)



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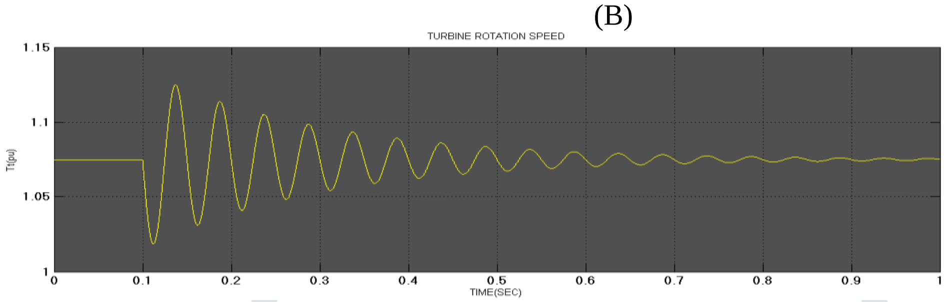
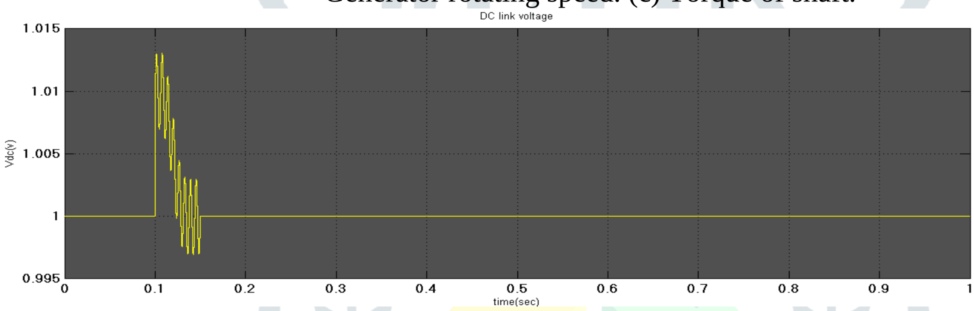
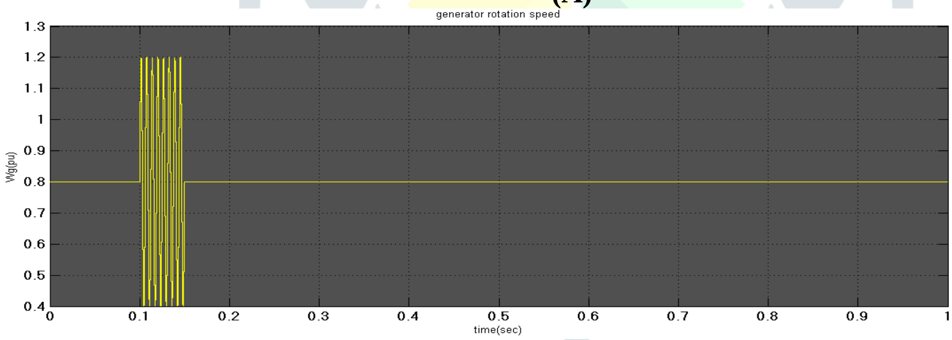


(C)

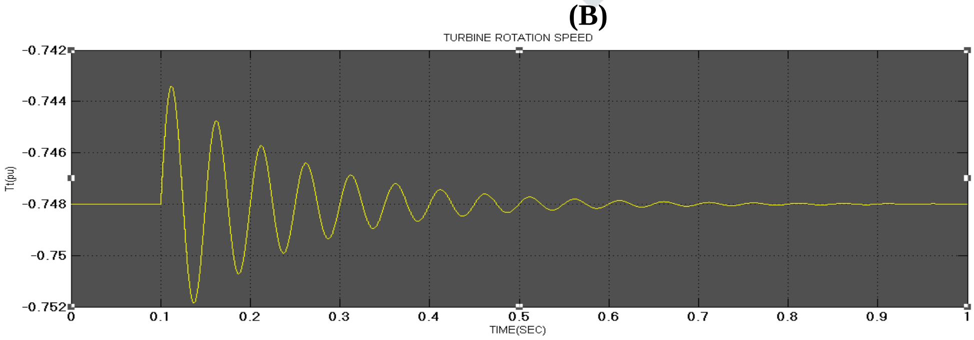
Fig.7. Impact of the active damping when a slow recovery happens after fault; (a) DC-link voltage. (b) Generator rotating speed. (c) Torque of shaft.



(A)



(B)



(c)

Fig.8. Impact of a single-phase fault that occurs at the generator terminal: (a) Output power of wind generator. (b) DC-link voltage. (c) Torque of shaft.

In such a case, the average power remains constant, but the second-order harmonic appears on the generator output active power, *Pwind*. However, these oscillations do not yield observable oscillations on the shaft torque and its derivative. Only negligible fluctuations, because of the transients associated with the fault and its clearance, are observed. Instead, the dc-link voltage fluctuates because of the asymmetrical fault.

V. CONCLUSION

The modelling and analysis of a direct-drive PMSG-based wind power generator during fault and post-fault conditions were presented in this paper. An analytical multi-mode model, considering the double-mass nature of the turbine/generator and typical LVRT requirements was developed and validated against the detailed nonlinear time-domain simulation results. The model was successfully used to conduct a detailed analysis to characterize the generator performance under LVRT control, and to tune the control system parameters. The analysis showed the following. 1) Using the rotating masses for storing the excessive energy during the fault can lead to over-speeding the generator. 2) An LVRT-capable PMSG can be subjected to mechanical stresses and, accordingly, faster aging, due to electrical system faults. 3) The use of the active damping method reduces the mechanical tensions at the cost of increasing the electrical stress on the dc-link capacitor. 4) The use of the dc-link voltage control bandwidth retuning reduces the mechanical stresses; however, it yields a higher electrical stress on the dc-link capacitor as compared to the active damping methods. The detailed time-domain simulation results validated the analytical results and discussions.

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