Performance and dynamic response enhancement of PMSG based wind turbines employing
boost converter-diode rectifier as the machine-side converter

Amir Noori Khezrabad¹, Mohsen Rahimi*²

¹,² Department of Electrical and Computer Engineering, University of Kashan, Kashan, Iran
¹,² P. O. Box: 87317-53153, Phone: +9831 55913469, Mobile: 09127057737
Email: *mrahimi@kashanu.ac.ir

Abstract- Wind turbines (WTs) with Permanent magnet synchronous generator (PMSG) are mostly integrated in power systems as popular energy conversion systems. From the machine-side converter (MSC) structure point of view, there are two types of PMSG-WTs: PMSG-WT with voltage source converter (VSC) as the MSC, and PMSG-WT with boost converter-diode rectifier as the MSC. The focus in this paper is on the control modification and dynamic and transient behavior improvement of PMSG-WTs with boost converter-diode rectifier. In this way, inner control loop of the boost converter current and outer control loop of generator speed are developed and extracted. Next, the boost converter control loop is modified by adding two auxiliary control signals, known as auxiliary damping signal and auxiliary compensation signal. The auxiliary damping signal modifies the boost converter current and provides a damping torque for inhibition of WT torsional oscillations. On the other hand, the auxiliary compensation signal, as the second auxiliary signal, limits the dc-link overvoltage during the voltage dip and amends the WT low voltage ride through capability. By modifying the wind turbine control through second auxiliary signal, the size, cost and rated energy of the required dc chopper resistance decrease considerably.

Key words: PMSG based WT, boost converter, torsional oscillation, auxiliary control signals, dc-link voltage, low voltage ride through (LVRT), dc chopper

Nomenclature

| PMSG | Permanent magnet synchronous generator (PMSG) |
| WT | Wind turbine | DFIG | Doubly fed induction generator |
| MSC | Machine side converter | GSC | Grid side converter |
| v_{dq}, i_{dq}, \psi_{dq} | dq-components of the stator voltage, current and flux |
| R_s, L_s, X_s | PMSG stator resistance, synchronous inductance and reactance |
| \psi_{pm} | PMSG stator flux linkage due to rotor permanent magnet |
| T_g, \omega_g | Generator torque and rotational speed | \psi_e | Stator back-emf voltage |
| V_d | Diode rectifier output voltage | i_b | Boost converter current |
| L_b | Boost converter inductance | P_s | PMSG output active power |
| d | Duty cycle of the boost converter switch | V_{dc} | GSC dc link voltage |
\( \omega_i \) Closed loop bandwidth of the boost converter current

\( T_{i,\omega} \) Turbine torque and rotational speed \( T_{sh} \) Shaft torsional torque

\( H_n, H_f \) Inertia constants related to turbine and generator

1. Introduction

Variable speed wind turbines (VSWTs) as well known wind turbines types are mainly divided into two categories [1]: WTs with partially rated converters using DFIG and WTs with fully rated converters. Depending on the generator type, there are three classes of WTs with fully rated converters in the wind power industry: WTs with PMSG [2], WTs with wound rotor synchronous generator [3] and WTs with squirrel cage induction generator (SCIG) [4]. WTs with PMSG due to lower maintenance cost, simple structure, enhanced power factor and better maximum power capability are largely used in wind power systems [5-9]. WTs with PMSG are linked to the electric network through back-to-back VSCs, called machine-side converter (MSC) and grid-side converter (GSC). From the machine-side converter (MSC) structure point of view, there are two types of PMSG-WTs: PMSG-WT with voltage source converter (VSC) as the MSC [10], and PMSG-WT with boost converter-diode rectifier as the MSC [11]. Several research works have been done about the behavior analysis and control of PMSG-WTs employing VSC as the MSC. However, fewer publications have presented in-depth analytical studies regarding the PMSG-WTs employing boost converter-diode rectifier as the MSC. Figure 1 depicts the system under study in which a PMSG-WT linked to the grid through boost converter-diode rectifier and VSC.

This paper is a continuation of the previous paper by the authors [11], where the previous paper deals with the stability analysis in PMSG-WTs using boost converter-diode rectifier and examines the speed controller impact on the WT stability. However, the focus in this paper is on the control modification and dynamic and transient behavior improvement of PMSG-WTs with boost converter-diode rectifier.

There are some papers [11-21] in literatures regarding different aspects of PMSG-WTs employing boost converter-diode rectifier. Ref. [11] first deals with the modeling and control of PMSG-WT and then examines the effect of speed controller on the stability of WT by modal and small signal stability analyses. In [12-14], sensorless operation of small PMSG-WTs with diode rectifier in the maximum power mode is discussed. In [12], relation between the current and voltage at the dc-side and at the maximum power mode is extracted, and then WT is controlled for operation in the maximum power mode. Ref. [15] presents a maximum power mode algorithm, known as incremental conductance algorithm, for small PMSG WT supplying a dc load.
Ref. [16] employs sliding mode control technique and Refs. [17-18] use model predictive control approach for the control of PMSG-WT with boost converter-diode rectifier. In [19], an active power conditioner based on low power wind system is presented in which a boost converter fed from a PMSG is used for battery charging. Refs. [20-21] deal with the operation of PMSG-WT with boost converter-diode rectifier and energy storage system in stand alone applications. Also, in [22], a sensorless control approach is presented for improvement of maximum power mode operation in PMSG-WT supplying a dc load via diode rectifier and boost converter.

In this paper, indeed, the boost converter control is modified in order to improve the damping of torsional oscillations under wind speed variations and limit the dc link overvoltage at voltage dip conditions.

In comparison with conventional power plants, the shaft stiffness coefficient in wind turbines is relatively low [23], that may result in torsional vibrations under wind speed variations or grid fault conditions. Torsional vibrations appeared on the shaft torsional torque may result in fatigue and stress on the drive train system. Usually a two mass model is used for describing the drive train system in wind turbine dynamic studies.

Use of additional mechanical components mounted on the drive train is a method for damping improvement of torsional oscillations. However, it is expensive and requires additional space on the shaft. Using the ability of blade pitching and adjusting the WT mechanical torque by the pitch control system is an approach for suppressing the drive train oscillations in PMSG based WT. However, this method reduces the WT output and requires system pitch with faster dynamics. Several papers enhance the damping of torsional vibrations by modifying the MSC control system and via the generator speed feedback [24-29]. The mentioned approaches mainly do based on the generator speed feedback with employing the band pass or high pass filters. However, the capability of these approaches are highly dependent on the band/high pass filter parameters and may be failed under uncertainty of the drive train system. There are also several papers proposing other control approaches for damping of torsional oscillations in wind turbines. Ref. [30] proposes a damping and stiffness compensation control method to suppress the torsional vibration based on roots locus and bode graph. In [31], an adaptive fuzzy logic control based structure is proposed for damping of torsional vibrations. In Ref. [32], a damping approach for damping of torsional oscillations is proposed doing based on feedback of the generator/turbine speed and shaft twist angle and employing band pass and notch filters. Ref. [33] deals with damping of torsional oscillations in wind turbines by employing the $H_{\infty}$ controller.

Further, there are some improved control approaches omitting band/high pass filter that have been proposed for PMSG WT employing VSC as the MSC [34-36]. However, there are less analytical works regarding the WT control
modification for improvement of torsional oscillations damping and limiting the dc link overvoltage under transient and dynamic conditions in PMSG WTs assisted with diode rectifier-boost converter.

The main outlines of this are as follows. This research first presents the control structure of PMSG-WTs assisted with boost converter-diode rectifier, in which the boost converter is used for the control of the generator speed in the maximum operation mode and the GSC is used for setting the dc-link to a constant value. In this way, the relation between the mean values of the boost converter current and q-component stator current is extracted, and after that the PMSG torque is expressed in terms of the boost-converter current. Then control loops of the generator speed and boost converter current are extracted. Next, as the main contribution, the boost converter control loop is modified by adding two auxiliary control signals, known as auxiliary damping signal and auxiliary compensation signal. The auxiliary damping signal, by the feedback of the generator and turbine speeds, modifies the boost converter current and consequently the PMSG torque, and provides a damping torque for inhibition of WT torsional oscillations. On the other hand, the second auxiliary signal, known as auxiliary compensation signal, by the feedback of the dc-link voltage, limits the dc link overvoltage during the voltage dips and enhances the WT LVRT ability. By modifying the wind turbine control through second auxiliary signal, the size, cost and rated energy of the required dc chopper decrease considerably. At the end, the WT performance with the modified control structure is studied and simulation results are presented.

2. PMSG modeling

Figure 1 shows a grid connected WT in which a surface mounted PMSG is connected to the grid via diode rectifier-boost converter and GSC.

For a surface mounted PMSG, the stator voltages/fluxes in the rotating dq reference frame with angular speed of \( \omega_r \), are given by [10]:

\[
\begin{align*}
  v_{sdq} &= R_s i_{sdq} + j \omega_r \psi_{sdq} + \frac{d\psi_{sdq}}{dt} \\
  \psi_{sd} &= L_s i_{sd} + \psi_{pm} \\
  \psi_{sq} &= L_s i_{sq}
\end{align*}
\]  

(1)

(2)

where \( \psi \), \( v \) and \( i \) denote the flux, voltage and current, and subscript \( s \) stands for the stator variables. \( L_s \) and \( R_s \) are the synchronous inductance and stator resistance, respectively. \( \psi_{pm} \) is the stator flux linkage due to rotor permanent
magnet, and $\omega_r$ is the rotor electrical speed. At steady state conditions, $\omega_r$ is equal to the stator frequency, $\omega_s$.

Further, the generator torque in a surface mounted PMSG can be given as:

$$ T_e = \frac{3}{2} n_p \left( \psi_{pm} i_q \right) $$

where $n_p$ is the number of generator pole pairs. By setting the stator flux derivative to zero in (1) and using (2), the PMSG steady state model is achieved as given in (4).

$$ v_{sdq} = R_s i_{sdq} + j X_s i_{sdq} + j \omega_s \psi_{pm} $$

where $j \omega_s \psi_{pm}$ in (4) is internal back-emf voltage induced in the stator.

From (4), the equivalent circuit of each PMSG phase at steady state conditions is obtained as depicted in Fig. 2, where $X_s$ and $R_s$ are the stator synchronous reactance and resistance, respectively.

The direction of the stator current in Fig. 2 is considered into the stator winding. $E_g$ in Fig. 2 is the back-emf voltage induced in the stator and is given by $E_g = j \omega_s \psi_{pm}$.

If the inductor $L_b$ related to the boost converter is selected sufficiently large, the boost converter works at the continuous conduction mode (CCM). The boost converter current $i_b$, see Fig. 1, in the CCM is continuous modeled as a dc current source at the output of the diode rectifier, as depicted in Fig. 3:

In Fig. 3, $E_{ag}$, $E_{bg}$ and $E_{cg}$ are the three phase back-emf voltages, $V_d$ is the rectifier output voltage, and $i_b$ is the boost converter current. The stator resistance is small compared to $X_s$, and thus in Fig. 3, $R_s$ is neglected to simplify the analysis. According to [37], the rectifier average output voltage can be given as:

$$ V_d = \frac{3\sqrt{3}}{\pi} |E_g| - \frac{3}{\pi} X_s i_b $$

where $|E_g| = \omega_s \psi_{pm}$ is the stator back-emf voltage. In (5), the second term, $(3/\pi)X_s i_b$, is the average output voltage drop of the rectifier caused due to presence of synchronous reactance $X_s$. It is noted that the current commutation in the diode rectifier, due to reactance $X_s$, is not instantaneous resulting in rectifier output voltage drop.

2.1 PMSG torque representation as a function of boost converter current

According to (4) and Fig. 2 and by neglecting the stator resistance, the PMSG output active power can be given by
\[ P_s = -\frac{3}{2} \alpha \psi_{pm} i_{sq} \]  

(6)

Due to nonlinear nature of the diode rectifier, higher harmonics appear on the three-phase stator currents. In the synchronous reference frame, the stator currents with the fundamental frequency appear as dc components and other harmonics as ac ripples with frequency of \( 6 \omega_0 \) (\( \omega_0 \) is the fundamental frequency). The active power related to higher current harmonics is negligible, and thus power transfer in (6) is done by the fundamental component of the stator current and consequently by the average component of the q-axis stator current, \( \bar{i}_{sq} \). Hence, the average output active power of the PMSG is given by

\[ \bar{P}_s = -\frac{3}{2} |E_s| \bar{i}_{sq} = -\frac{3}{2} \alpha \psi_{pm} \bar{i}_{sq} \]  

(7)

where the superscript \( \bar{\cdot} \) in (7) stands for average value. According to Fig. 3, the diode rectifier output power is given as \( P_d = v_d i_b \). Hence, by neglecting the rectifier losses, the PMSG average output power and the rectifier output power are identical, and thus according to (5) and (7), it is concluded that

\[ -\frac{3}{2} |E_s| \bar{i}_{sq} = \left( \frac{3\sqrt{3}}{\pi} |E_s| - \frac{3}{\pi} X_s i_b \right) i_b \]  

(8)

From (8), the relationship between the boost converter current \( i_b \) and \( \bar{i}_{sq} \) is obtained. Using (8), \( i_b \) can be given as:

\[ i_b = \frac{3\sqrt{3}}{\pi} \frac{|E_s| \pm \sqrt{(27/\pi^2)}|E_s|^2 - (18/\pi)|E_s| X_s \bar{i}_{sq}}{(6/\pi)X_s} = \frac{3\sqrt{3}}{\pi} \frac{|E_s| \pm \sqrt{(27/\pi^2)}|E_s|^2 - (12/\pi)X_s \bar{P}_s}{(6/\pi)X_s} \]  

(9)

From (9), there is a real solution for \( i_b \) if the following constraint is satisfied:

\[ |E_s| \geq \frac{2}{3} \sqrt{\pi X_s \bar{P}_s} \]  

(10)

Figure 4 shows the average values of the q-component stator current \( \bar{i}_{sq} \) and boost converter current \( i_b \) in response to the wind speed change from 6 to 12 m/s for the study system with parameters of Appendix A. According to Fig. 4, for different wind speeds, the values of \( |\bar{i}_{sq}| \) and \( i_b \) are relatively identical, and thus for a wide operating range, we can write \( |\bar{i}_{sq}| = i_b \). Hence, according to (3), the PMSG torque as a function of \( i_b \) may be approximated by

\[ T_e = -\frac{3}{2} n_p \left( \psi_{pm} i_b \right) \]  

(11)

3- Average dynamic model and control of the combined system
For the controller design and dynamic performance analysis of the PMSG-WT, it is required to find the PMSG model from the rectifier output point of view. Considering Fig. 1 and according to [38], the PMSG and diode-rectifier can be modeled with an appropriate equivalent dc circuit at the dc-side, as depicted in Fig. 5.

where $u_{dc} = \left(3\sqrt[3]{3}/\pi\right)E_{pm}$, $R = 2R_s + (3/\pi)X_s$ and $L = 2L_s$. Also, $R_b$ and $L_b$ are the resistance and inductance of the boost converter inductor, $v_{dc}$ is the voltage of the dc-link capacitor, and $v_d$ is the output dc voltage of the diode rectifier. According to Fig. 4, the rectifier output current can be controlled by changing the duty cycle, $d$, of the switch SW. Assuming the CCM operation for the boost converter, there are two states: the first state corresponding to when the SW is on and the second one associated to when the switch SW is off. The average model of the PMSG-rectifier-boost converter can be extracted, as depicted in Fig. 6.

Considering Fig. 6, the average representation of the boost converter dynamics over a switching period can be given as

$$u_{dc} = (R + R_b)i_b + (L + L_b)\frac{di_b}{dt} + v_{dc}(1-d) \quad (12)$$

where $d$ stands for the duty cycle of the switch, SW. Assuming $d = D + \Delta d$, $i_{dc} = i_{dc} + \Delta i_{dc}$, $u_d = U_d + \Delta u_d$, and $v_d = V_d + \Delta v_d$, where $\Delta$ denotes the small signal variation, and the capital letter represents the variables at operating point. Considering (12), the small signal from of the boost converter dynamics is obtained as

$$\left(L + L_b\right)\frac{d\Delta i_{dc}}{dt} + (R + R_b)\Delta i_{dc} = \Delta V_{dc} - \Delta v_{dc}(1-D) + \Delta u_{dc} \quad (13)$$

According to (13) and by employing the PI controller, $PL_{fb}(s) = k_p + k_i/s$, the following boost converter current control loop, depicted in Fig. 7, is achieved, where $d$ as the control signal adjusts $i_b$ to the reference value.

In Fig. 7, by using the pole-zero cancellation method, it is concluded that $k_p/k_i = (R + R_b)/(L + L_b)$. Hence, by selecting $k_p = \alpha_1(L + L_b)$, the transfer function from $i_{b-ref}$ to $i_b$ will be

$$\frac{i_b(s)}{i_{b-ref}(s)} = \frac{\alpha_1}{s + \alpha_1} \quad (14)$$

where $\alpha_1$ is the closed loop bandwidth of the boost converter current control loop, $\alpha_1 = k_p/(L + L_b)$. Considering (11), there is a direct relation between the generator torque $T_e$ and boost converter current $i_b$. Hence, the reference current $i_{b-ref}$ in Fig. 7 is assigned by the outer speed controller.
3.1 Speed control loop of PMSG

In this section, the PMSG speed is controlled in the maximum power mode via the boost converter current control. The two-mass representation is usually used for modeling the WT drive train, and is given by

\[ 2H_g \frac{d \omega_{e-pu}}{dt} = T_{e-pu} + T_{sh-pu} \]  \hspace{1cm} (15)

\[ \frac{d \theta_{sh}}{dt} = \omega_h (\omega_{t-pu} - \omega_{e-pu}) \]  \hspace{1cm} (16)

\[ 2H_t \frac{d \omega_{t-pu}}{dt} = T_{t-pu} - T_{sh-pu} \]  \hspace{1cm} (17)

\[ T_{sh-pu} = k_s \theta_{sh} + D_{sh} (\omega_{t-pu} - \omega_{e-pu}) \]  \hspace{1cm} (18)

In the two-mass model, a spring and damper as the flexible shaft model is considered between the turbine low speed mass and generator high speed mass. The superscript \( pu \) in (15)-(18) and Fig. 8 stands for per unit (pu), and \( \omega_{t-pu} \) and \( \omega_{e-pu} \) are the speeds of the turbine and generator (in pu), \( \theta_{sh} \) is the angle of the shaft twist (in rad), \( H_g \) and \( H_t \) are the generator and turbine inertia constants (in sec), respectively, \( k_s \) is the shaft stiffness (in pu/elec. rad), \( D_{sh} \) is the damping coefficient of the shaft (in pu), \( T_{e-pu} \) and \( T_{t-pu} \) are the generator and turbine torques, respectively, (in pu), and \( T_{sh-pu} \) is the shaft torque, (in pu). Figure 8 shows the speed control loop of the PMSG-WT.

The term \( \omega_h / (s + \omega_h) \) in Fig. 8 corresponds to the boost converter current control loop, and thus the boost converter reference current is obtained from the outer speed controller.

4- Wind turbine performance improvement through control system modification

In this section, performance of the WT is enhanced by modifying the WT control system. The modified control system, in turn, improves damping of torsional oscillations appeared on the shaft torsional torque, and limits the dc-link voltage variations under transient conditions. The above mentioned improvements are realized by adding auxiliary control signals and updating the boost converter current reference, as will be shown in Sections 4.1 and 4.2.

4-1 Damping of shaft torsional torque oscillations

Considering (15)-(18), the shaft torsional torque dynamics, in terms of \( T_{e-pu} \) and \( T_{t-pu} \), may be given as

\[ \frac{d^2 T_{sh-pu}}{dt^2} + \frac{D_{eq}}{2H_{eq}} \frac{dT_{sh-pu}}{dt} + k_s \frac{\omega_h}{2H_{eq}} T_{sh-pu} = \frac{k_s \omega_h}{2} \left( \frac{\bar{T}_t}{H_t} - \bar{T}_e \right) + \frac{D_{eq}}{2} \frac{d}{dt} \left( \frac{\bar{T}_t}{H_t} - \frac{\bar{T}_e}{H_g} \right) \]  \hspace{1cm} (19)
where \( H_{eq} = \frac{H_0 H_1}{H_0 + H_1} \) and symbol \(-\) denotes the small variation around the operating point. According to (19), the shaft torsional torque natural frequency, \( \omega_n \), and damping ratio, \( \xi \), are obtained as: \( \omega_n = \sqrt{\frac{k_s \omega_b}{2H_{eq}}} \) and \( \xi = \frac{D_{tg}}{2} \sqrt{\frac{1}{k_s \omega_b \frac{1}{2H_{eq}}}} \). In WT, \( D_{tg} \) as the shaft damping coefficient is relatively small resulting in the low value of damping ratio \( \xi \). Considering (19), if the PMSG torque \( T_e \) and accordingly the boost converter current \( i_b \) contains a component proportional to \( d\dot{T}_{sh-pu}/dt \), the damping of shaft torsional oscillations can be actively increased. According to (16) and (18), \( d\dot{T}_{sh-pu}/dt \) can be given as

\[
\frac{d\dot{T}_{sh-pu}}{dt} = k_s \omega_b (\ddot{\omega}_{t-pu} - \ddot{\omega}_{t-pu}) + D_{tg} \frac{d}{dt} (\ddot{\omega}_{t-pu} - \ddot{\omega}_{t-pu})
\]

(20)

By neglecting \( D_{tg} \), (20) can be approximated by

\[
\frac{d\dot{T}_{sh-pu}}{dt} = k_s \omega_b (\ddot{\omega}_{t-pu} - \ddot{\omega}_{t-pu})
\]

(21)

Hence, from (21), for damping enhancement of shaft torsional oscillations, it is required that the electromagnetic torque \( T_e \) and thus the boost converter current \( i_b \) has a component proportional to \( (\omega_t - \omega_s) \). For realizing this, the reference of the boost converter current is modified by adding an auxiliary damping signal \( i_{b1-aux} \) as shown in Fig. 9. Figure 9(a) shows the modified boost converter current control loop, including the auxiliary damping signal \( i_{b1-aux} \). Also, Fig. 9(b) shows the closed loop generator speed control system with the auxiliary damping signal. Hence, when torsional oscillations appear on the generator speed, the auxiliary signal \( i_{b1-aux} \), with the same frequency of torsional oscillations, is generated and thus a damping torque reducing the shaft torque oscillations is generated.

4-2 Restriction of dc-link voltage variations at transient states

In PMSG based WTs, during the grid fault and voltage dip, the output power injected to the grid drops down, and thus the dc-link voltage may go over the allowable range and damage the dc-link capacitor. To limit the dc-link voltage variation under grid fault conditions, we can modify the boost converter current \( i_{b-ref} \) by adding an auxiliary signal \( i_{b2-aux} \), as shown in Fig. 10. Figure 10(a) depicts the modified boost converter current control loop comprising the auxiliary compensation signal \( i_{b2-aux} \) alleviating the dc-link voltage overvoltage below \( 1.1V_{dc-ref} \) during the grid voltage
dips. Also, Fig. 10(b) shows the closed loop generator speed control system with the second auxiliary compensation signal $i_{\text{br2-\text{aux}}}$. In Fig. 10, the compensation gain $K_{2-\text{aux}}$ converts the dc-link voltage variations to an auxiliary compensation signal, reducing the dc-link voltage change under grid voltage dip.

5- Simulation studies

In this section the simulation results for the study system are presented. The study system is in accordance with Fig. 1, in which, a grid connected PMSG WT is connected to a 20 kV grid (with short circuit power of 20 MVA) via diode rectifier-boost converter, GSC, related 690 v/20 kV transformer and 1 Km transmission line. The system under study parameters are given in Table 1 at Appendix. Simulations results are done in Matlab-Simulink environment with sampling period of $10 \mu\text{sec}$ (sampling frequency of 100 kHz).

Figure 11 depicts the d and q components of the stator current and boost converter current for the wind speeds of 10 and 12 m/sec. As explained before, due to presence of the full bridge rectifier operating in CCM mode, the three phase stator currents comprise the fundamental frequency and harmonic components. Hence, as depicted in Fig. 11(a) and (b), $i_{sd}$ and $i_{sq}$ are not constant and contain ac harmonic ripples. The mean value of $i_{sq}$ is responsible for energy conversion and generator speed control. Considering Fig. 11(b), the average values of $i_{sq}$ for wind speeds of 10 and 12 m/sec are 2010 A and 2550 A. Also, according to Fig. 11(c), the average values of the boost converter current $i_{b}$ at the wind speeds of 10 and 12 m/sec are 2000 A and 2550 A, which are approximately identical to the average values of $i_{sq}$.

Fig. 12 shows time responses of the GSC three phase AC currents and GSC active and reactive powers injected to the grid at the wind speed of 12 m/sec. It is clear that at $V_w=12$ m/sec, the amplitude of the GSC currents is 0.98 pu, the active power is $P_g=0.98$ pu, and since the GSC is controlled at unity power factor, the injected reactive power to the grid is equal to zero $Q_g=0$. Also, Fig. 13 shows GSC phase $a$ current and corresponding FFT analysis. According to FFT analysis of Fig. 13, the THD of the GSC current is 1.64%, and the magnitude of the highest harmonic relative to fundamental component is 0.8%. Table 2 shows current distortion limits for systems rated 120 V through 69 kV according to IEEE standard-519. In the study system, the grid short circuit power at the connection point of the wind turbine to the grid is more than 100 MVA, and since the wind turbine rated power is 2 MW, the short circuit ratio of the grid at the connection point of the wind turbine is more than 50. According to Table 2, the allowable value of the THD current at $I_g/I_L>50$ is 12% and thus the WT THD current meets the IEEE standard-519.
Figure 14 shows responses of the generator speed and shaft torsional torque for the step change of the wind speed from 10 m/sec to 12 m/sec. In Fig. 14, damping action of the control system with the proposed auxiliary damping signal is compared with the capability of the one without the auxiliary damping signal. According to Fig. 14, after the wind speed step change, torsional oscillations appear on the $T_{sh}$ and $\omega_r$, where in the case with the auxiliary damping signal, these oscillations are damped faster.

In the following (in Fig. 15), performance of the proposed damping approach of Fig. 9 is compared with that of the damping approach based on the generator speed feedback. Considering Fig. 15, it is clear that the proposed active damping approach is more effective than the approach based on the generator speed feedback in damping of torsional oscillations.

Figure 16 shows time response of the dc-link voltage once a 70% voltage dip with duration of 100 msec is imposed on the grid. In Fig. 16, effectiveness of the control system with the proposed auxiliary compensation signal (proposed in Section 4.2) is compared with the capability of the one without the auxiliary compensation signal. It is noted that the dc-link voltage under normal steady state conditions is 1100 v. According to Fig. 16, once the voltage dip is imposed on the grid, the output active power injected to the grid by the grid side converter drops down resulting in overvoltage in the dc-link voltage. According to Fig. 16, in the case without the auxiliary compensation signal, the dc-link voltage reaches the large value of 2200 v damaging the dc-link capacitor. In the other case with the auxiliary compensation signal, the power imported to the dc-link from the stator is reduced and thus the peak of the dc-link voltage is limited to 1350 v after occurring the voltage dip. Hence, by using the proposed method in Fig. 10, the change of the dc-link voltage due to voltage dip decreases considerably. This, in turn, enhances the LVRT behavior of the turbine-generator.

Figure 17 shows the time responses of the system under both wind speed variations and grid voltage dip, with and without proposed compensation approaches. In the case with proposed compensation approaches, both auxiliary signals of Figs. 9 and 10 are applied to the boost converter control in order to damp torsional oscillations and limit the dc link over voltage. According to Fig. 17, it is clear that with the proposed compensation approaches, torsional oscillations are well damped and dc link over voltage is limited below the threshold value.

Figure 18 shows the the dc link voltage under 70% single phase voltage dip. According to Fig. 18, the proposed compensation signal of Fig. 10 limits the dc link voltage below 1300 volt.

In the following to limit the dc-link voltage below the threshold value, a dc-chopper with dump resistor is employed in the dc-link part, as depicted in Fig. 19. The threshold value of the dc-link voltage is considered 1.15 times the reference
of the dc link voltage, i.e. $1.15 \times 1100 = 1210$ v. Figure 20(a) shows the dc-link voltage in the case without the auxiliary compensation signal, with and without the dc-chopper. It is clear that without the auxiliary compensation signal and dc chopper, the dc link voltage during the fault reaches the high value of 2300 v. In this case, by using the dc chopper, the dc link voltage is limited to 1265 by dissipating energy on the chopper resistance. Also, Fig. 20(b) shows the dc-link voltage in the case with the auxiliary compensation signal, with and without the dc-chopper. It is clear that in this case the dc link voltage is limited to a large extent by the auxiliary damping signal, and the dc chopper limits the dc link voltage slightly.

Also, Fig. 21 shows the dc chopper current for the cases with and without the auxiliary compensation signal. According to Fig. 21, in the case without the auxiliary compensation signal, the dc chopper current during the fault is 1175 A, the dump resistor is 1.1 ohm and 170.9 kj energy is dissipated on the dc chopper resistance during the fault. On the other hand, in the case with the auxiliary compensation signal, the dc chopper current during the fault is 350 A, the dump resistor is 3.5 ohm and 55.4 kj energy is dissipated on the dc chopper resistance during the fault. Hence, in the case with the auxiliary compensation signal, the energy dissipated on the dc chopper is much lower than the one in the case without the auxiliary compensation signal. Therefore, by using the auxiliary compensation approach, the size of the dc chopper and the energy dissipated on the dump resistor decreases significantly.

6. Conclusion

This paper enhances dynamic performance of the grid connected PMSG-WT employing boost converter-diode rectifier as the machine side converter. In this way, the boost converter control is modified in order to improve the damping of torsional oscillations and limit the dc link overvoltage at voltage dip conditions. According to the obtained results, after the wind speed step change, torsional oscillations appear on the responses of shaft torsional torque and generator speed, where in the case with the auxiliary damping signal, these oscillations are damped faster. It is shown that by using the auxiliary compensation signal, the change of the dc-link voltage due to voltage dip decreases considerably, and thus the LVRT capability of the WT is improved significantly. Further, it is shown that in the case with the auxiliary compensation signal, the energy dissipated on the dc chopper is much lower than the one in the case without the auxiliary compensation signal. Therefore, by modifying the boost converter control and adding the auxiliary control signals, the size of the dc chopper and the energy dissipated on the dump resistor decreases significantly.
Appendix
Parameters of the 2 MW, 690 V, 50 Hz, PMSG-WT are given below in Table 1.

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Amir Noori Khezrabad received his B.Sc. degree in Electrical Power Engineering in 2014 from Shahid Beheshti University (SBU), Shahid Abbaspour School of Technology, Tehran, Iran. He obtained the M.Sc. degree in Electrical Power Engineering from University of Kashan, Kashan, Iran in 2017. Currently he is with Tehran Regional Electric Company (TREC). His current research interests include renewable energy systems and power system studies.

Mohsen Rahimi received his B.Sc. degree in Electrical Engineering in 2001 from Isfahan University of Technology, Isfahan, Iran. He obtained both his M.Sc. and Ph.D. degrees in Electrical Engineering from Sharif University of Technology (SUT), Tehran, Iran, in 2003 and 2011, respectively. He joined the Department of Electrical and Computer Engineering at University of Kashan, Kashan, Iran, as an Assistant Professor, in 2011. Currently, he is an Associate Professor at University of Kashan, and his major research interests include modeling and control of renewable energy sources, wind turbines and microgrids.
Figures captions:

Fig. 1 PMSG-WT linked to the grid via boost converter-diode rectifier and GSC
Fig. 2 Equivalent circuit for one phase of PMSG
Fig. 3 Equivalent circuit of the PMSG, diode rectifier and boost converter at the CCM at Steady state condition
Fig. 4 Average values of the boost converter current and q-component stator current at different wind speeds for the study system
Fig. 5 Simplified model of the PMSG-diode rectifier connected to the boost converter
Fig. 6 Boost converter average model in CCM mode
Fig. 7 Boost converter current control loop
Fig. 8 Speed control loop of the PMSG-WT
Fig. 9 Modified PMSG control system for damping of torsional oscillations, (a) boost converter inner current control loop, (b) generator speed outer control loop
Fig. 10 Modified PMSG control system for limiting the dc-link voltage variations, (a) boost converter inner current control loop, (b) generator speed outer control loop
Fig. 11 System time responses for the wind speeds of 10 and 12 m/sec, (a) d-component stator current, (b) q-component stator current, (c) boost converter current, (d) mean values of dq axes stator current
Fig. 12 GSC time responses at the wind speed of 12 m/sec, (a) GSC three phase AC currents, (b) GSC active and reactive power injected to the grid
Fig. 13 GSC phase a current and FFT analysis with THD of 1.64%
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Fig. 16 DC-link voltage with and without the auxiliary compensation signal under 70% grid voltage dip
Fig. 17 Time responses of the system under both wind speed variations and grid volatge dip, with and without proposed compensation approaches, (a) shaft torsional torque, (b) generator speed
Fig. 18 DC-link voltage with and without the auxiliary compensation signal under 70% single phase voltage dip
Fig. 19 PMSG with dc-chopper protection
Fig. 20 DC-link voltage with and without dc-chopper protection, under 70% grid voltage dip, (a) without the auxiliary compensation signal, (b) with the auxiliary compensation signal

Fig. 21 DC chopper current with and without auxiliary damping

**Tables captions:**

Table 1 System under study parameters

Table 2 Current distortion limits for systems rated 120 V through 69 kV according to IEEE standard-519
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![Diagram](image1)

Fig. 20 DC-link voltage with and without dc-chopper protection, under 70% grid voltage dip, (a) without the auxiliary compensation signal, (b) with the auxiliary compensation signal

![Graph](image2)
Fig. 21 DC chopper current with and without auxiliary damping
Table 1 System under study parameters

| Component                  | Parameter          | Value         |
|----------------------------|--------------------|---------------|
| PMSG WT parameters         | Rated Power        | 2 MW          |
|                            | Rated stator voltage | 690 v        |
|                            | Rated Frequency    | 50 Hz         |
|                            | Number of pole pairs | 4            |
|                            | \( \psi_{pm} \)    | 0.95 pu       |
|                            | \( R_s \)          | 0.0087 pu     |
|                            | \( L_s = L_d = L_q \) | 0.14 pu      |
|                            | \( H_g, H_s \)     | 0.6 sec, 4 sec|
|                            | \( D_{tg} \)       | 1 pu          |
|                            | \( k_s \)          | 0.6 pu/elec rad |

| WT transformer parameters 690 v/20 kV | \( X_{trans} \) | 0.1 pu       |

| Boost converter parameters | \( R_b, L_p \) | 5 \( \Omega \), 2.5 mH |

| GSC parameters | DC link voltage \( V_{dc} \) | 1100 v |
|                | DC link capacitor \( C_{dc} \)  | 50 mF  |
|                | GSC output LC filter \( L_f, C_f \) | 0.15 pu, 0.07 pu |

Table 2 Current distortion limits for systems rated 120 V through 69 kV according to IEEE standard-519

| Maximum harmonic current distortion in percent of \( I_L \) | Individual harmonic order |
|-----------------------------------------------------------|---------------------------|
| \( I_w \) : Maximum short circuit current at PCC          | \( I_L \) : Maximum demand load current (fundamental frequency component) at the PCC under normal operating conditions |
| \( I_w/I_L \)                                              | 3 \( \leq h < 11 \)    | 11 \( \leq h < 17 \) | 17 \( \leq h < 23 \) | 23 \( \leq h < 35 \) | 35 \( \leq h \leq 50 \) | THD |
| <20                                                       | 4                        | 2                        | 1.5                        | 0.6                        | 0.3                        | 5               |
| 20<50                                                     | 7                        | 3.5                       | 2.5                       | 1                          | 0.5                        | 8               |
| 50<100                                                    | 10                       | 4.5                       | 4                         | 1.5                        | 0.7                        | 12              |
| 100<1000                                                  | 12                       | 5.5                       | 5                         | 2                          | 1                          | 15              |
| >1000                                                     | 15                       | 7                         | 6                         | 2.5                        | 1.4                        | 20              |

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