Application of Input Shaping Method to Vibrations Damping in a Type-IV Wind Turbine Interfaced with a Grid-Forming Converter

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Abstract—Type-IV wind turbines can experience torsional vibrations in the drivetrain structure. This can lead to additional stress on turbine components and a quality reduction of the power delivered to the grid. The vibrations are mostly induced by fast variations of the electromagnetic torque depending on the control of a back-to-back converter. A number of studies have presented methods to mitigate the drivetrain vibrations. However, the research was dedicated to cases when the converter, interfacing a wind turbine to the grid, operates based on a grid-following control. A wind turbine can be also interfaced to a grid-forming converter. In this case, a back-to-back converter control creates a strong link between the electromagnetic torque and grid dynamics, so the abovementioned problem remains relevant. Therefore, this paper presents a solution to damp torsional vibrations in a Type-IV wind turbine, interfaced to the electrical grid with a voltage source converter based on a grid-forming control. The damping of the vibrations relies on the input shaping method. Simulation results prove the effectiveness of the method to damp drivetrain vibrations during grid frequency variations. In addition to that, damping impact on system behavior with respect to other parameters is analyzed and its mitigation is discussed.

Index Terms—Direct drive, grid-forming control, inertial response, input shaping, torsional vibrations, Type-IV wind turbine, vibrations damping, voltage source converter.

I. INTRODUCTION

TO support sustainable development and achieve carbon neutrality by 2050, EU countries subsidize the wind energy sector and simplify the permitting processes for wind farm construction [1]. The share of wind energy within Europe is planned to be around 350 GW by 2030 [2]. These intentions will result in the increased integration of wind installations in Europe. The most advanced installations are known as Type-IV wind turbines, which have so far been connected to the grid via grid-following converters requiring a phase-locked loop (PLL) for synchronization with the grid voltage [3]. Such a standard grid-following control of a conventional Type-IV wind turbine

allows the wind turbine to be fully decoupled from the grid dynamics, and the kinetic energy, stored in the rotating masses, is thus ‘hidden’ [4]. With the growing share of wind power plants being integrated to the power system, however, the total system inertia is reducing. Consequently, the rate-of-change of frequency in power systems increases and the level of frequency nadir reduces [5]. In order to prevent a further reduction of the overall system inertia, various solutions have been proposed in the literature in recent years to extract the ‘hidden’ kinetic energy from wind turbines interfaced with the electrical grid via grid-following converters [6], [7].

Future power systems are expected to operate with a prevailing ratio of power electronic (PE) converters and few to no synchronous machines (SM) [8]. In this scenario, the numerous PE converters relying on a grid-following control, by definition, will not be able to maintain system stability. Thus, the transition from a conventional power system to one dominated by PE converters implies moving converter control schemes away from grid-following to grid-forming solutions [9], [10]. Currently, the European Network of Transmission System Operators for Electricity (ENTSO-E) and its partners are developing grid codes which would take into account a substantial penetration of grid-forming converters [11].

Numerous ways have been presented over the past decade to implement such a grid-forming control (GFC). Many of the solutions emulate the classical swing equation [12]–[14]. The essential feature of a grid-forming converter is its ability to form and regulate a stable voltage and frequency at the converter terminals. Another feature is that a grid-forming converter can provide an inherent inertial response capability [15] and, in that sense, is able to become a stability source in power systems where PE converters prevail over conventional SMs [16].

The application of a grid forming control to a wind turbine has received some attention in the literature. Several publications, focused on applying GFC based on a virtual synchronous machine (VSM) to a Type-IV wind turbine, have shown such wind turbines operate stably in steady-state and after disturbances [6], [17], [18]. In these works, however, the wind turbine was analyzed with a one-mass drivetrain model and consequentially the models did not allow observing how an addition of a grid-forming control impacts on the wind turbine mechanical components. In [19], we introduced a two-mass drivetrain model and demonstrated the excitation of torsional vibrations within a drivetrain structure as a result.

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The appearance of these vibrations in a GFC-based wind turbine was showed to be linked to a rapid variation of the electromagnetic torque, which can be caused by grid frequency variations. These torsional vibrations are scaling up the risk of increasing the mechanical stress on turbine components. Generally, for wind turbines connected to the grid via a grid-following converter, these vibrations are actively damped through the control actions of the machine-side converter [20], [21]. In [22] we proposed that vibrations damping can be also implemented for a wind turbine interfaced to a grid-forming converter. The results from [22] demonstrated that the presented damping method based on a high-pass filter could not completely suppress mechanical vibrations. In this paper, a solution based on an input shaping method is provided in order to entirely suppress the unwanted mechanical oscillations. Furthermore, the analysis is carried out on how the proposed damping impacts other system quantities and how the compensation of this impact may induce a possible negative effect on the performance of a GFC and especially on the frequency support.

The paper is organized as follows. Section II presents the description of the considered system and its model. Section III explains the GFC relying on the VSM principle and introduces the modifications in the control structure of a back-to-back converter required to integrate the GFC scheme. Section III-C demonstrates how a rapid change of the electromagnetic torque excites torsional vibrations in the two-mass drivetrain model. In order to mitigate the induced vibrations, the input shaping is presented and implemented in the system model in Section IV. In Section IV-C, the influence of the input shaping on the system dynamics is discussed.

II. MODELING AND CONTROL OF THE WIND TURBINE INTERFACED TO A GRID-FORMING CONVERTER

The system under study includes a wind turbine, a direct drivetrain, a permanent-magnet synchronous generator (PMSG), a back-to-back converter comprised of a machine-side converter (MSC), a DC bus, a grid-side converter (GSC) and the controls.

A. Model description

A detailed model of the system is presented in Fig. 1, where p_{msc}^* and p_{gsc}^* are the instantaneous values of the active power reference for the MSC and GSC, p_{pcc} is the instantaneous active power measured at PCC, p_{dc}^* is the power reference from the DC bus voltage control, $\hat{\omega}_g$ is the grid frequency estimated with PLL, θ_g is the grid voltage angle, L_f , R_f and L_t , R_t are the filter and grid equivalent inductances and resistances, respectively. AC grid frequency dynamics are taken into account by a simplified model of a SM, representing the governor, prime mover modeled as a lead-lag filter and mechanical dynamics by means of an equivalent inertia.

B. Wind turbine

1) *Turbine aerodynamics*: the mechanical power, $P_{m,wt}$, captured by a wind turbine is found as:

$$P_{m,wt} = 0.5\rho AC_p(\lambda, \beta)v_{wind}^3, \quad (1)$$

where ρ is the air density, A is an area swept by the wind turbine rotor, C_p is the power coefficient, λ is the tip-speed ratio, β is the pitch angle, v_{wind} is the wind speed.

2) *Drivetrain*: the direct drive configuration can be analyzed with a one- or two-mass model. The use of a one-mass model can represent the general behavior of a drivetrain through:

$$2(H_t + H_g)\frac{d\omega_{gen}}{dt} = T_m - T_{em}, \quad (2)$$

where T_m , T_{em} are mechanical and electromagnetic torques, H_t , H_g are inertia constants, ω_{gen} is the rotational speed on the generator side. When a more detailed assessment of the impact of drivetrain mechanical dynamics is required, the two-mass model allows assessing the impact of these wind turbine dynamics on the grid response and vice versa. The model includes turbine and generator masses with a flexible shaft in between. The length of a shaft in a direct-drive PMSG-based wind turbine is relatively short, so its stiffness is typically high. Depending on the mechanical parameters, the natural frequency of such a drivetrain can be up to 10 Hz [23].

The two-mass model is described by:

$$2H_t\frac{d\omega_t}{dt} = T_m - k_s\theta - d_s\dot{\theta}, \quad (3)$$

$$2H_g\frac{d\omega_{gen}}{dt} = k_s\theta + d_s\dot{\theta} - T_{em}, \quad (4)$$

$$\frac{dT_{sh}}{dt} = k_s\dot{\theta} + d_s\ddot{\theta}, \quad (5)$$

where $\theta = \int(\omega_t - \omega_{gen})$ is the shaft displacement, T_{sh} is the shaft torque, k_s , d_s are the stiffness and damping coefficient of the shaft, and ω_t is the rotational speed on the turbine side.

3) *Generator*: The mechanical power from a wind turbine is converted to electrical power by a PMSG, whose electrical behavior is described in a rotating d-q frame by:

$$\frac{di_{sd}}{dt} = \frac{1}{L_s}(v_{sd} - R_s i_{sd} + L_s \omega_{elec} i_{sq}), \quad (6)$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_s}(v_{sq} - R_s i_{sq} - L_s \omega_{elec} i_{sd} - \psi_m \omega_{elec}), \quad (7)$$

$$T_{em} = \frac{3}{2}\psi_m \omega_{elec} i_{sq}, \quad (8)$$

where i_{sd} , i_{sq} and v_{sd} , v_{sq} are the d-q stator currents and voltages, R_s , L_s are the stator resistance and inductance, $\omega_{elec} = p\omega_{gen}$ is the electrical generator speed, p is the number of pole pairs, and ψ_m is the flux linkage produced by a permanent magnet.

The control of the PMSG can be performed with the field-oriented current control, such that the dq-axis voltage references can be expressed as [24]:

$$v_{sd}^* = (K_p + \frac{K_i}{s})(i_{sd}^* - i_{sd}) - L_s \omega_{elec} i_{sq}, \quad (9)$$

$$v_{sq}^* = (K_p + \frac{K_i}{s})(i_{sq}^* - i_{sq}) + L_s \omega_{elec} i_{sd} + \psi_m \omega_{elec}. \quad (10)$$

Fig. 1. System model.

4) *MPPT*: while a wind turbine operates at the partial load, the extracted active power follows the optimal power curve:

$$P_{wt}^*(\omega_{gen}) = \frac{1}{2} \rho A C_{p,opt} \left(\frac{\omega_{gen} R_{wt}}{\lambda_{opt}} \right)^3. \quad (11)$$

5) *Pitch control*: the pitch angle is controlled with a gain-scheduling technique compensating the variations of the aerodynamic characteristics of a turbine. The pitch control is shown in Fig. 2.

Fig. 2. Pitch control.

III. CONTROL STRATEGY SELECTION FOR A BACK-TO-BACK CONVERTER WITH GRID-FORMING CAPABILITIES

This section introduces the back-to-back control configuration required to integrate the GFC, so that a Type-IV wind turbine equipped with this converter could supply the optimal power in steady state and react to the grid frequency variations by providing an inertial response.

A. Grid-forming control

As mentioned in the introduction, the important features a GFC can bring to the converter operation are the control of the magnitude and phase of the output voltage and the provision of an inertial response. These functions can be obtained with a VSM-based GFC emulating the classical swing equation [13]. Its per-unit expression is given in (12) and the dynamics implementation is shown in Fig. 3.

$$2H_{vsc} \frac{d\omega_m}{dt} = p_{gsc}^* - p_{pcc} - K_{vsc}(-\hat{\omega}_g + \omega_m), \quad (12)$$

where H_{vsc} and K_{vsc} are the inertia constant and damping coefficient, ω_m is the converter frequency.

Fig. 3. Grid-forming control.

Based on the control scheme in Fig. 3, in steady state, $\omega_m = \hat{\omega}_g$, and $p_{pcc} = p_{gsc}^*$. During a frequency transient, $\omega_m \neq \hat{\omega}_g$, and $p_{pcc} \neq p_{gsc}^*$. This is due to the inertial effect of a GFC.

Hence, it is not possible to have an accurate power control during this kind of transient. As explained later on, this has an important consequence for the DC bus voltage control.

B. DC bus voltage control

As seen in Fig. 1, the stability of the DC bus voltage and the whole system depends on the balance of power between both sides of the DC bus capacitor. At one side, the current $i_{dc,msc}$ depends on the power p_{msc} , flowing from the generator (13). At the other side - $i_{dc,gsc}$ depends on the power p_{gsc} , exchanged with the AC side (14).

$$p_{msc} = \sum_{i=a}^c i_{s,i} v_{s,i} = i_{dc,msc} u_{dc}, \quad (13)$$

$$p_{gsc} = \sum_{i=a}^c i_{g,i} v_{g,i} = i_{dc,gsc} u_{dc}. \quad (14)$$

Thus, both converters have to be controlled in a proper way to maintain a stable operation. There are two strategies conceivable to control the DC bus voltage:

1) *Strategy 1*: The DC bus voltage is controlled by the GSC, while the power flowing into the converters is controlled by the MSC: $p_{msc}^* = p_{wt}^*$ and $p_{gsc}^* = p_{dc}^*$;

2) *Strategy 2*: The DC bus voltage is controlled by the MSC, while the power transmitted to the grid is controlled by the GSC: $p_{msc}^* = p_{dc}^*$, $p_{gsc}^* = p_{wt}^*$.

In present day the grid-following control, strategy 1, is typically implemented since it seems more intuitive to control the power of the converter connected to the PMSG. However, strategy 2 is more interesting if the provision of grid-forming functionalities is required. Indeed, as explained in Section III.A, during a frequency variation, the measured active power is not equal to the control reference. In other words, the active power is not controlled well. In case this power is also used to control the DC bus voltage, this may have a large adverse consequence on the DC bus stability. This is the reason why in this study, the DC bus voltage is controlled with the MSC. This issue was also described in [6], [17] and the second strategy has been successfully implemented and tested in [19].

C. Results on the inertial response provision

The system model presented in Fig. 1 is simulated with a second control strategy using MATLAB Simulink. The parameters of the model and its controllers are given in Table I - III. The main event is the connection of a 1-MW load to the grid. Since the grid is modeled with a simplified synchronous machine, this event implies a frequency change. The latter induces a fast power variation in the converter because of its GFC with inertial effect. The wind turbine drivetrain is modeled with a two-mass model in order to demonstrate the torsional vibrations being excited within the drivetrain.

The results describing the inertial response from a 5 MW Type IV wind turbine are presented in Fig. 4(a)-(b). In steady state, the power supplied to the grid is based on the MPPT. After a load connection to the grid bus, the GFC commands the GSC to transmit the additional active power to the PCC. At this moment, the DC-bus voltage starts reducing. To keep it constant, the DC-bus voltage controller rapidly increases the electromagnetic torque through the increase of the q-axis current reference. The increase of the electromagnetic torque leads to a slowdown of the turbine as it is depicted in Fig. 4(a)-(b). It means that the kinetic energy stored in the rotating masses is being extracted. As soon as the inertial response is finished, the wind turbine recovers the kinetic energy until the speed returns to the optimal operating point. These results highlight the low-frequency vibrations appearing on the mechanical side due to the fast variation of the electromagnetic torque.

IV. DRIVETRAIN VIBRATIONS DAMPING

To mitigate or completely remove torsional vibrations, various methods exist in literature for grid-following wind turbines where power and electromagnetic torque are fully regulated at MSC [20], [21]. The general idea behind these damping

Fig. 4. Inertial response from a Type IV wind turbine with grid-forming VSC, a) torques, b) rotational speed on turbine and generator sides.

techniques is to modify the electromagnetic torque reference with a filtered oscillation component of the mechanical speed. The idea of torque reference modification has been verified for a grid-forming wind turbine. In [22], the damping has been integrated in the control configuration of a back-to-back converter with a GFC by using a high-pass filter. However, the results showed that the residual vibrations are still present in the system. Therefore, to improve the effectiveness of damping and analyze its influence on system behavior, another approach is proposed in this paper. It implies the implementation of the input shaping (IS) method presented in [25], [26].

A. Description of the input shaping method

The principle of the IS is to modify a controlled reference signal by a convolution with a sequence of impulses. It is usually implemented with finite impulse response filters. One type of these filters is known as a zero-vibration (ZV) filter allowing to achieve zero level of residual vibrations [27]. A 2-pulse ZV filter can be expressed with a transfer function:

$$IS(s) = A_1 e^{-t_1(\xi\omega_n + j\omega_d)} + A_2 e^{-t_2(\xi\omega_n + j\omega_d)}, \quad (15)$$

where A_i is the amplitude of i-th pulse, t_i is the time shift between i-1 and i-th pulse, ξ , ω_n , ω_d are damping coefficient, natural frequency and damped natural frequency of the drivetrain oscillatory modes, respectively.

Fig. 5. System model with the indicated position of the damping block.

Two requirements for a ZV filter have to be complied [25]:

$$0 \leq t_1 < t_{i+1}, \quad (16)$$

$$\sum_{i=1}^n A_i = 1. \quad (17)$$

B. ZV filter setting

In order to design a filter with satisfactory performance, it is important to properly determine the drivetrain oscillatory modes which are to be damped. This can be done by deriving a transfer function for the drivetrain and a state-space model of the entire system. Once the drivetrain modes are found, the filter settings can be calculated by following the step-by-step methodology proposed in [26]. For this article, a 2-pulse ZV filter is chosen and the steps to design it are as follows:

- 1) Knowing that the distance between the impulses has to be the same, the time shift for each impulse can be determined as:

$$t_1 = 0, t_2 = t_1 + T_d, \quad (18)$$

where $T_d = \frac{\pi}{\omega_d}$ is the damped period of the drivetrain oscillatory modes.

- 2) Pulses amplitude A_1 and A_2 are then found as:

$$A_1 = \frac{\bar{a}_1}{k}, A_2 = \frac{\bar{a}_2}{k}, \quad (19)$$

where $k = \bar{a}_1 + \bar{a}_2$, $\bar{a}_1 = a_1$, $\bar{a}_2 = a_2 e^{-\xi \omega_n t_2}$

Coefficients a_1 and a_2 can be optimally determined based on the generalized parameters derived in [26] with respect to the filter type.

C. Results on the application of a ZV filter

Taking into account that the second strategy is chosen to control the Type-IV wind turbine with a GFC, a ZV filter has to be applied in series between the DC bus voltage and current controller of the MSC, as shown in Fig. 5. To verify the performance of the designed ZV filter, the results of simulating the inertial response from a Type-IV wind turbine are obtained for two cases. For the first case, a drivetrain is considered with the parameters as given in Table II, and the natural frequency of drivetrain vibrations is around 2.5 Hz. In the second case, in order to prove the robustness of the proposed damping, the drivetrain frequency is changed to 2 Hz and 3 Hz by modifying the shaft stiffness to 182 pu and 408 pu, respectively. The parameters of a ZV filter are given in Table III. The term $\Delta p = k(p_{damp}^* - p_{msc}^*)$ added to the reference of the GFC is not considered ($k = 0$), and will be discussed in Section IV-D.

- 1) Drivetrain natural frequency equal to 2.5 Hz

It can clearly be seen from Fig. 6(a)–(e), that the application of a ZV filter allows reducing the drivetrain vibrations. In Fig. 6(c), for the case of the included damping, the electromagnetic torque increase is separated into initial and delayed components. It implies that the vibrations induced by the initial component are then counteracted by a delayed one. In Fig. 6(d)–(e), the mechanical speed on the turbine side as well as on the generator side has almost no oscillations compared to the results when the damping is not applied. However, due to the delayed component of the electromagnetic torque, the initial DC bus voltage reduction and its sequential increase are more significant as shown in Fig. 6(b). In Fig. 6(a), it is shown that the inclusion of a ZV filter makes it possible to almost entirely dispose of the active power oscillations propagated to the grid side. Hence, the major and the only drawback of using the damping with the IS method is in the DC-bus voltage oscillations, whose severity is determined by the nominal DC-bus voltage, the size of DC bus capacitor and

Fig. 6. Results on damping for case 1, a) active power, b) DC-bus voltage, c) torque, (d)-(e) rotating speed on the turbine and generator sides.

Fig. 7. Results on damping for case 2, (a)-(b) rotating speed on the turbine and generator sides.

Fig. 8. Results on damping for case 1 with added Δp term, a) grid frequency; b) active power, c) DC-bus voltage, d) electromagnetic torque.

operational voltage limits.

2) Drivetrain natural frequency variation from 2 to 3 Hz

For this case the parameters of the ZV filter remain unchanged. The results in Fig. 7(a)-(b), show that the ZV filter still mitigates the mechanical vibrations even if the drivetrain natural frequency moves from the one the filter is designed for. Since the filter is not perfectly tuned, there are residual vibrations that are still small compared to the case without damping which is depicted with a dark red curve. Therefore, it could be pointed out that the considered filter is resilient to eventual fluctuations of the drivetrain oscillation modes.

D. Impact of vibrations damping on other system quantities

As it is indicated in the previous subsection, the application of a ZV filter allows suppressing the torsional vibrations on the mechanical side. However, the oscillations of the DC bus voltage become more pronounced. To mitigate this effect, the power reference for the GFC is modified by incorporating a term $\Delta p = k(p_{damp}^* - p_{msc}^*)$ as depicted in Fig. 5 in order to share the damping effect on both converters. The simulation results, obtained for the same event, as previously, are showcased in Fig. 8. The simulations are performed for $k = 0, 1, 2$. From Fig. 8(c), it is seen that the DC bus voltage management has been improved. When increasing the coefficient k , the maximum voltage deviation decreases. However, this has a negative impact on an inertial effect of the

GFC since it alleviates the peak of the power injected to the grid during the inertial response, Fig. 8(b). As it can be seen in Fig. 8(a), this impact is negligible for the grid frequency behavior. Considering the wind turbine generator, the sharing of the damping effect slightly influences the electromagnetic torque as depicted in Fig. 8(d). It re-introduces some few low-frequency oscillations to the DC bus and the grid side. Nevertheless, compared to the case without damping in Fig. 6(a)-(c), these oscillations are only present in the initial phase of a transient period.

V. CONCLUSION

An integration of a grid-forming control into a back-to-back converter control of a Type-IV wind turbine requires to change the responsibilities between the machine- and grid-side converter. This modification links the electromagnetic torque of a wind turbine generator with grid dynamics. As a consequence, the excitation of drivetrain modes during transient events leads to the appearance of torsional vibrations propagating to the AC side as low-frequency oscillations.

The proposed damping method implemented with an inclusion of a ZV filter resulted in a positive impact on the damping of the drivetrain vibrations as the oscillations amplitude can be significantly reduced even if the shaft stiffness deviates from the values a filter is designed for. The only drawback of the applied damping method noted from the results is the increased amplitude of DC bus voltage fluctuations because the MSC is

now simultaneously responsible for two functions: vibrations damping and DC bus voltage regulation.

To decrease these fluctuations, a deterioration of the GFC performance achieved by sharing the damping effect between both converters has been proposed. It slightly affects the inertial response provided from the GSC, while there is no significant impact on the grid frequency. Whatever a decision from a trade-off is made between inertial response provision and DC voltage regulation performance, the efficiency of vibrations damping remains almost unchanged.

TABLE I. Parameters of the grid

Parameter	Value
S_g, U_g, SCR	5 MW, 690 V, 5
R_g, L_g, R_f, L_f	0.02 pu, 0.2 pu, 0.005 pu, 0.15 pu
T_N, T_D, R_s, H_{eq}	1, 6, 4 %, 5 s

TABLE II. Parameters of wind turbine and generator

Parameter	Value
$P_{wt}, \omega_{t,nom}$	5 MW, 1.27 rad/s
$R_{wt}, \lambda_{opt}, C_{p,opt}$	63 m, 7, 0.44
k_s, d_s, H_t	280 pu, 1 pu, 1.93 s
$P_{gen}, U_s, \omega_{elec}, H_g$	5 MW, 690 V, 61 rad/s, 0.8 s
R_s, L_s, ψ_m	2.45 mΩ, 4 mH, 5.84 Wb

TABLE III. Parameters of controllers

Parameter	Value
$H_{vsc}, K_{vsc}, R_v, \omega_f$	3.5 s, 233 pu, 0.09 pu, 60 rad/s
$\tau_{pll}, \xi_{pll}, K_{p,pll}, K_{i,pll}$	10 ms, 0.707, 1.9, 0.0033
$\tau_{dc}, \xi_{dc}, K_{p,dc}, K_{i,dc}$	2 s, 0.707, 0.18, 0.19
$\tau_{pitch}, \xi_{pitch}, K_{p,pitch}, K_{i,pitch}$	4 s, 0.707, (gain scheduling)

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