Wind power plant grid-forming control and influences on the power train and power system oscillations

Farid K. Moghadam[1]* , Til Kristian Vrana[2]

[1]*Norwegian University of Science and Technology, Trondheim, Norway*
[2]*SINTEF Energy, Trondheim, Norway*
**E-mail: farid.k.moghadam@ntnu.no*

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Abstract

In future power systems, wind power plants are supposed to contribute in the voltage and frequency stability of the grid. For this purpose, the control strategy of the wind power-frequency converter system needs to change from grid-following to grid-forming control. In this paper, the influence of future wind power plants equipped with the grid-forming control strategy on the wind turbine itself and the power system oscillations is studied. For this purpose, the coupled model of wind power plant and a relatively realistic model of future power system is employed, which is able to capture the internal dynamics of wind turbine power train system and its dynamic interactions with the rest of power system. It is shown how wind power plant local- and inter-area oscillations can influence/be influenced by the power system if insufficient damping is presented by wind turbines' power train system. It is shown how the variation of demand in the power grid can consistently excite wind turbine local- and inter-area modes which can cause undamped oscillations in both wind turbine power train system and the rest of power system if insufficient damping is provided by the wind turbine power train system. A test case, using 1.5 MW NREL wind turbine drivetrain, is demonstrated.

1 Introduction

The European Commission proposed plan to meet the European Union (EU) aims to be climate-neutral by 2050 is to increase renewable energy from 32% to 40% by 2030, which will need 451 GW of wind power capacity by 2030, calling for 271 GW new installations. The latter calls for larger capacity of wind power plants which are supposed to be able to support the power system voltage and frequency stability by emulating a voltage source behavior.

When a wind farm equipped with grid forming control is connected to the power system, a coupled system-level frequency mode from the interaction between the grid impedance and the inertia of wind turbines appears. This inter-area mode along with the power train system torsional modes can be consistently excited due to inherently variable content of wind power generation and the variations of demand in the power system. The latter can cause additional vibrations of the wind turbine drivetrain components and oscillations in the generator induced voltage and generated power. The latter can result in the accelerated degradation of drivetrain, frequency converter and generator, and cause oscillations in the power injected to the grid which can reduce the grid power quality. Our simulations show that these wind farm-induced frequency modes can even cause undamped oscillations in wind farms and power system if insufficient damping is provided by the power train. Wind turbine power train system in our definition includes the whole power conversion system including back-to-back (BTB) frequency converter, generator, gearbox, shafts and main bearings and rotor, which have been taken into account in this work. The drivetrain system is also defined as the mechanical interface between rotor and generator including gearbox, shafts and main bearings.

The interactions of wind turbine power train and power grid are two sided. In grid feeding or grid following farms, the power train mechanical torsional vibrations can be transferred to the generator electromagnetic torque and then transfer to the farm output power and grid [1]. To mitigate this phenomenon, active damping is widely used. Active damping activities include but are not limited to using virtual inertia controller, oscillatory torque component compensation from generator reference torque, active line impedance control by using FACTS devices [2]. It is worth noting that the above approaches are effective in compensating the oscillations from the generated electrical power.

The effect of grid forming converters (GFCs) in improving the frequency stability of future low-inertia power systems is explained by the literature [3]. In GFC-based wind power plants, the interactions could also be from the other way around. It means that the power fluctuations at the power plant terminal can transmit to the power train system dynamics of each turbine, which can excite the drivetrain modes and increase the mechanical vibrations. The increased torsional vibrations are then transferred to the generator torque and power grid. The latter explains the increased coupling between the wind farms and power grid in grid forming wind farms.

Fischer *et al.* in [4] reports new oscillation modes in wind farms equipped with the grid forming control strategy based on virtual synchronous machine aimed at providing additional inertia in the power system. Authors perform an analytical modal analysis to specify the contribution of each subsystem in the oscillation modes. Authors in [5] report a new oscillation mode called grid control mode in grid forming wind turbines and discussed that this sub-synchronous mode can be close to turbine-generator torsional mode. Therefore there is a high possibility of sub-synchronous torsional interaction in the wind turbine equipped with grid forming control. The latter provides the possibility for the exchange of energy at this frequency to the power train. This exchange of energy results in torsional stress on the turbine generator shaft that can lead to accelerated fatigue damage and even the fracture of shaft in extreme conditions. The negative damping exhibited by induction generators-based power train technologies at sub-synchronous frequencies, *e.g.* in DFIG, can cause undamped oscillations in the torsional modes of power train systems [6]. The different operating modes of DFIG and the damping behavior of DFIG in different operating conditions and sub-synchronous frequencies are discussed in [6, 7]. In this generator, negative damping happens when the magnitude of equivalent rotor negative resistance exceeds the sum of the stator and grid resistances. DFIG is commercially available for the turbines as large as 6 MW, and is the drivetrain technology selected as the case study in this work. This generator technology has a direct coupling with the grid.

The explanation of coupling between wind turbine and grid dynamics in case of turbines being equipped with grid forming control strategy, the possibility of wind turbines local- and inter-area modes to be excited by the variation of demand in the power system and the resultant consequence on power system oscillations if sufficient measures are not taken into account are not adequately discussed in the literature. The motivation of this work is to find a better understanding about grid forming control operating mode and the consequence on the wind turbine's power train-grid coupled dynamics. Even during power system normal operations, any variations in demand and therefore wind generator electromagnetic torque can play the role as an impulse excitation which excites the drivetrain torsional mode. It is important that drivetrain presents enough damping for the first torsional mode when turbine is operating in grid forming mode. Due to the lower inertia of wind turbines compared to traditional synchronous generators (SGs), the influence of power system turbulences on individual turbines is not negligible when turbines are operating in grid forming control mode.

The main focus of this paper is on the influence of wind turbine-grid coupling on the the increased power train components oscillations when turbine is equipped with grid forming control strategy and the consequence on power grid oscillations. These oscillation can contribute to power train system components fatigue damage as this system is responsible for 57% of turbine total failures and 65% of turbine total downtime [8]. The grid control mode resulted by the operation of wind farms in grid forming control is also explained. In this work, by providing a coupled wind turbine rotor, drivetrain, generator, power electronics converter and power system, it is shown how the interaction between the power train and grid in GFC-based wind farms can contribute to both power train and grid oscillations and even cause undamped oscillation and instability in the power train system. For this purpose, a new test system representing the future decentralized power systems with a considerable share of grid forming wind farms is defined. The dynamic interactions between different supplies in different configurations of power system, namely based on standalone wind farm, wind farm coupled with actual grid and without wind farm are studied. The combination of active and passive solutions to be implemented to wind turbine power train system to mitigate the observed oscillations, namely the compensation of the oscillatory component from the generator torque and additional passive mechanical damping in drivetrain are proposed as the solution to increase the the power train system damping at the new oscillation modes.

The main contributions of this paper are

- The fully coupled model of wind turbine, its power train system, and the power grid together with all the standard controllers is presented and used as the base model for analysis of wind turbine and grid coupled effects.
- A potentially destabilizing interaction of wind turbine local- and inter-area modes with power system when wind farm is equipped with grid forming controlling concept is revealed,
- The influence of wind turbine-grid interactions on increased oscillations in wind turbines' power train system, electric power injected by wind farm to the grid, and oscillations in the other sources in the grid is explained analytically and demonstrated by simulation studies,
- Possible solutions for attenuating oscillations induced by grid forming wind farms based on increasing power train system damping are proposed and tested.

2 System description and theories

In this section, the coupled power system and wind turbines model, the implemented control of wind turbine's GFC consisting of internal voltage and external droop control loops, the wind turbine power train system and resonance frequencies, different sources of power system sub-synchronous oscillations, and different active and passive techniques to damp/filter oscillations in power train system are discussed.

2.1 System description

To study the dynamics of a simplified low-inertia power system including the dynamic models of different power generation units and controllers Matlab/Simulink is used. A scaled-down low-inertia power system based on the combination of conventional SGs and GFC-based power generations which can represent the future power systems is the case study in this paper, where GFCs are controlled to support the frequency and voltage stability with respect to the variations in the grid. The configuration of the test system is shown in Fig. 1 (see Table 1 for the parameters). In the continued part, the main components of this model are explained.

Wind farm (DFIG wind turbines)					
$S = 50 \times 1.67$ MVA	$v = 575$ V	$H = 1.0$ s	$F = 60$ Hz	$poles = 6$	$d_p = 0.6$
SG (synchronous generator)					
$S = 100$ MVA	$v = 13.8$ kV	$H = 3.7$ s	$F = 60$ Hz	$\tau_g = 5$ s	$d_p = 1.3\%$
Other RES/ideal storage (Droop-controlled voltage source)					
$S = 83$ MVA	$v = 1$ kV	$F = 60$ Hz	$d_p = 0.6$		
T1 (LV/MV transformer D1-Yg)					
$P = 100$ MVA	$v = 575/25000$ V	$R_1 \approx 0\ \Omega$	$R_2 = 0.4\ \Omega$	$X_1 \approx 0\ \Omega$	$X_2 = 0.6\ \Omega$
T2 (LV/MV transformer D1-Yg)					
$P = 100$ MW	$v = 1/25$ kV	$R_1 \approx 0\ \Omega$	$R_2 = 0.4\ \Omega$	$X_1 \approx 0\ \Omega$	$X_2 = 0.6\ \Omega$
T3 (MV/MV transformer D1-Yg)					
$P = 100$ MW	$v = 13.8/25$ kV	$R_1 \approx 0\ \Omega$	$R_2 = 0.2\ \Omega$	$X_1 \approx 0\ \Omega$	$X_2 = 0.2\ \Omega$
L1 (power transmission line)					
$R = 1.3\ \Omega$	$X_L = 1.3\ \Omega$	$X_C = 20.8\ k\Omega$			
L2 (power transmission line)					
$R = 1.3\ \Omega$	$X_L = 1.3\ \Omega$	$X_C = 20.8\ k\Omega$			
L3 (power transmission line)					
$R = 0.1\ \Omega$	$X_L = 0.1\ \Omega$	$X_C = 208\ k\Omega$			
Load					
$P_{main} = 182.6$ MW	$P_{turb} = 33.2$ MW	$v = 25$ kV	$t_{turb} = 20$ s		

Table 1: Case study model and control parameters

- Wind farm: is consisting of 50 pitch controlled DFIG wind turbines with the nominal power of each 1.67 MVA. The wind turbine model contains the internal dynamics of DFIG, back to back (B2B) converter, drivetrain, turbine and standard controllers, which is built on Wind Farm - DFIG Detailed Model in Simulink with the parameters explained in [9] and adapted

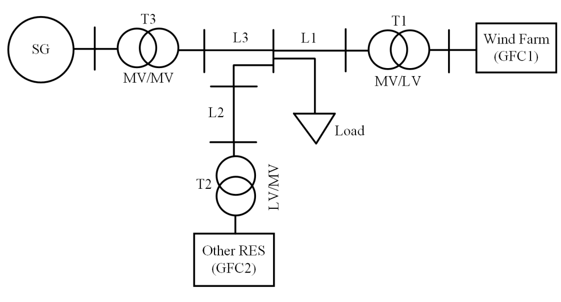


Fig. 1: Configuration of the studied test system.

for simulating a GFC-based wind farm by updating the generator controller based on grid forming voltage control concepts and power sharing droop control. For the average wind speed of 15 m/s which is the value assumed in this model, the turbine available power is 1 pu of its rated power, and the generator speed is 1.2 pu. The power train system parameters are updated based on 1.5 MW NREL wind turbine. The resultant model is able to capture the coupled dynamics of grid, power converter and controller, generator, drivetrain and turbine. An aggregate model consisting of 50 identical turbines is used, which does not limit seeing the grid and turbine dynamic interactions. The voltage, inertia, frequency, number of poles and droop gain of each DFIG generator are listed in Table 1.

- SG: it is a large synchronous generator which is directly connected to the power system without any interface. It models the traditional power generation based on SGs without power electronic interfaces with the grid. The governor and turbine dynamics are included. The SG model has eight state variables and contains the field and rotor damper windings dynamics [10]. The nominal power, voltage, inertia, frequency of generator, the turbine time constant and and the droop setting are listed in Table 1.
- Other RES/ideal storage: is modelling a grid forming-based power generation unit equipped with droop control without modelling the internal dynamics. It can represent an ideal storage device, which is required in microgrids based on the requirements provided by IEEE 1547 standard, or any other renewable energy source (RES) such as photovoltaic (PV) which its internal dynamics is not modelled/focused in this study. This generation unit is represented by RES in the rest of paper.
- Transmission lines: are modelled with pi-sections. The lines parameters per unit of length are selected based on the voltage level and the equivalent positive sequence values are listed in Table 1.
- Load: is modelled resistive and spatially concentrated. It has two components, the constant and disturbance components. The disturbance component is 20% of the constant load.

The schematic of the coupled wind farm and power system model is illustrated in Fig. 1. For the sake of simplicity, model details such as shunts are not shown in this figure. In this model, the wind farm, traditional SG and the droop-controlled voltage source are equipped with grid forming control strategy and cooperate to supply a shared load. The wind farm GFCs cooperate with the other power generation units in the power system to support a large load disturbance in the grid while maintaining the voltage and frequency in the predefined range in the grid.

The electromechanical dynamics can be captured by using the electromechanical model of power system, which are of interest in this work assuming slow variations of the frequency in the system. In such a dynamic analysis, the generators frequencies, the buses voltages and the generators internal voltages are estimated by integrating, linearizing and solving the set of differential-algebraic equations (DAEs) describing the power system as [11]

$$\dot{\boldsymbol{x}}(t) = f(\boldsymbol{x}(t), \boldsymbol{y}(t)), \tag{1a}$$

$$g(\boldsymbol{x}(t), \boldsymbol{y}(t)) = \boldsymbol{0}, \tag{1b}$$

$$\boldsymbol{x}(t) = \boldsymbol{x_0}, \tag{1c}$$

where $\boldsymbol{x}$ is the state variables vector, *e.g.*, the phase angle of voltage sources, and $\boldsymbol{y}$ is the algebraic variables vector, *e.g.*, nodal voltage amplitude and phase angles. The droop control equations are the algebraic equations which are combined with internal voltage and current control loops realization and influence the internal dynamics of the voltage sources.

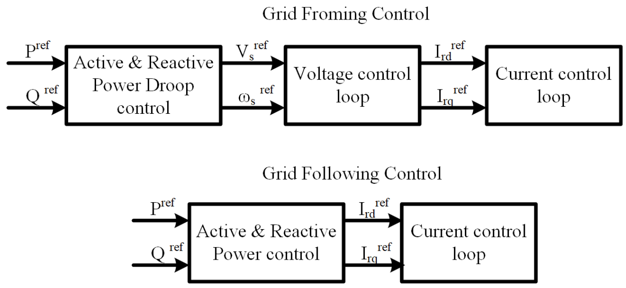


Fig. 2: Grid forming vs. grid feeding control.

Since the interactions between wind power plant and power system in grid forming control mode are of the main focus, more details about the implemented controllers and power train system of the wind power plant are provided in the continued part.

2.2 *Wind power plant grid forming control*

The concept behind grid forming droop control compared to grid following power control is demonstrated in the flowchart in Fig. 2. In the following, the low-level voltage and high-level droop control as the complementary concepts implemented in applied grid forming control strategy are explained.

2.2.1 Low-level voltage control: Grid support is a common feature in converter-based power generations which includes the increase or decrease of real and/or reactive power production required to maintain the voltage amplitude and frequency within a predefined range. In grid forming, the inverter control structure directly incorporates voltage tracker/regulator and its frequency is self-generated so that it does not rely on an external voltage source

The control requirements for these actions depend on the internal dynamics of power production unit, the topology of the power system, the electrical distance between loads and generation units, and the loading on the transmission or distribution system [12]. Different grid forming control concepts are presented in [3]. The most common grid forming control design by using droop-based voltage and frequency control is employed here. The implementation of droop-controlled GFC for DFIG is presented by [13]. The control concept based on stator voltage oriented rotating reference frame according to [13] is employed for the realization of voltage controller in grid forming controlling strategy for DFIG. The main difference in realization of voltage control concept compared to the conventional current control loop is in the additional voltage control loop and the calculation of reference angle for the rotating reference frame as shown in the block diagram in Fig. 3. In this figure, RSC stands for the rotor-side and GSC stands for the grid-side converters. As it can be seen, the grid forming control is implemented by modifying the rotor-side converter controller. However it also influences the grid-side control since this control strategy uses an internal frequency reference calculated by the grid forming controller to obtain the stator and rotor voltages angles instead of using phase-locked loop (PLL).

2.2.2 High-level power sharing droop control: Block diagram of active and reactive power sharing droop control applied to DFIG and RES are shown in Fig. 4a. The reference values of stator voltage frequency ω_s^{ref} and amplitude V_{sd}^{ref} calculated from the

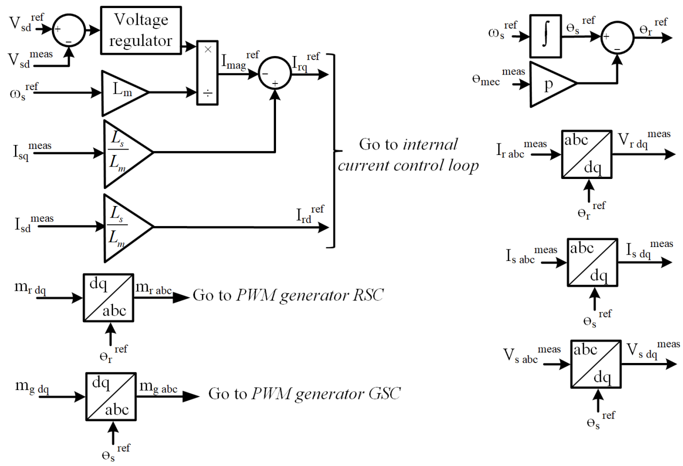
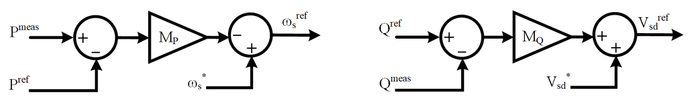
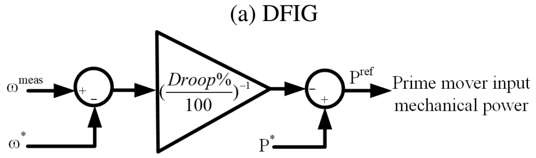


Fig. 3: Realization of voltage control in grid forming strategy.



(a) DFIG



(b) SG

Fig. 4: Realization of droop control.

droop control go to the internal voltage control loop as shown in Fig. 3. M_P and M_Q are the active and reactive powers droop gains, respectively. It is worth noting that the inverse droop as a part of SG governor function is applied to the conventional SG model as shown in Fig. 4b, where ω^{meas} and ω^* are the actual and reference turbine speeds, respectively.

2.3 Wind turbine power train model and frequency modes

Power train system consists of back-to-back (BTB) frequency converter, generator, gearbox, shafts and main bearings and rotor. A relatively high-fidelity sixth-order state-space model of DFIG and the full-switched model of 3-phase pulse width modulation (PWM) frequency converter are engaged to study the dynamic interactions between the power train system's drivetrain and power system.

The general form of the lumped-parameter torsional model of drivetrain with n degrees of freedom in the time domain is defined by [14]

$$\mathbf{J}\ddot{\boldsymbol{\theta}}(t) + \mathbf{C}\dot{\boldsymbol{\theta}}(t) + \mathbf{K}\boldsymbol{\theta}(t) = \mathbf{q}(t), \tag{2}$$

where $\mathbf{J}$, $\mathbf{C}$ and $\mathbf{K}$ are the moment of inertia, damping and stiffness matrices with the size $n \times n$. $\boldsymbol{\theta}$ and $\mathbf{q}$ are the response and load vectors with the size $n \times 1$, where each element of these two vectors represent a time series. 2-DOF torsional model is used which is able to capture the dynamics of the drivetrain 1^{st} torsional mode. In such a model, the gearbox is modelled with the gear ratio, two moment of inertia parameters of generator and rotor-hub assembly, and the equivalent stiffness of the connecting links to the gearbox are modelled. The 1^{st} torsional frequency by using such a model is calculated by [15]

$$f_1^{tor} = \frac{1}{2\pi}\sqrt{\frac{k_{eq}}{J_{eq}}}, k_{eq} = \frac{\alpha_1^2\alpha_2^2\alpha_3^2 k_r k_{gen}}{k_r + \alpha_1^2\alpha_2^2\alpha_3^2 k_{gen}}, J_{eq} = \frac{\alpha_1^2\alpha_2^2\alpha_3^2 J_r J_{gen}}{J_r + \alpha_1^2\alpha_2^2\alpha_3^2 J_{gen}}, \tag{3}$$

where k_{eq} is the equivalent shaft stiffness from the rotor side, J_r and J_{gen} are the moment of inertia of rotor and generator, k_r and k_{gen} are the shaft stiffness of rotor and generator, and α_1, α_2 and α_3 are the inverse of the gear-ratios of 1^{st}, 2^{nd} and 3^{rd} stages of gearbox. By taking into account the material damping of rotor and generator shafts, the 1^{st} damped natural frequency will be [16]

$$f_d = \zeta^i f_n + j f_n\sqrt{1-(\zeta)^2}, \tag{4}$$

where ζ is the damping coefficient related to the 1^{st} mode ($\zeta = \frac{d_a}{d_c}$, $d_c = 2\sqrt{k_{eq}J_{eq}}$, where d_c and and d_a are the equivalent critical and actual damping, respectively). The parameters of 2-DOF model of 1.5 MW NREL power train system applied to Simulink model are listed in Table 2.

Parameter	Value
$Rated\ power\ (MW)$	1.5
$Rated\ rotor\ speed\ (rpm)$	18.4
$k_{eq}\ from\ low-speed\ side\ (N.m/rad)$	$1.6E+08$
$d_c\ from\ low-speed\ side\ (N.m.s/rad)$	$2.1E+07$
$J_r\ (kg.m^2)$	$4,085,000$
$J_{gen}\ (kg.m^2)$	132
$Gearbox\ ratio\ G/R$	78.3
$1^{st}\ undamped\ torsional\ natural\ frequency\ (Hz)$	2.4

Table 2: Drivetrain specification [17]

2.4 Power system and wind farm oscillations in grid forming operating mode

As discussed earlier, power train system oscillations can transfer to the power system if adequate damping and filtering activities is not employed. Dynamic variations in the power system due to different sources such as supply-demand mismatch and grid faults can also excite the power train modes. In the following, different sources of power train and power system oscillations and power train-power system coupled modes are discussed.

2.4.1 Power system oscillations: Power system is a complex dynamical system and its oscillations are complex and not straightforward to analyze [18]. Power system oscillations can be due to both local- and inter-area oscillations [19]. Sub-synchronous oscillations in power systems caused by grid-following wind farms based on both synchronous and induction generators and the route cause analysis methods are discussed in [20]. In the following, the different possible sources of local- and inter-area oscillations appeared by the interaction of GFC-based wind farms with power system are discussed.

2.4.2 Local-area oscillations: Wind turbine generator electromagnetic torque oscillations can happen due to tower, blades and drivetrain torsional dynamics which are coupled with the generator torque through eq. (2). These oscillations are considered as local-area oscillations. In traditional SGs, the drivetrain systems rotate in synchronous speed. In wind turbines, the consistent variations of rotational speed which acts as impact, the drivetrain modes are frequently excited, which causes the generator torque and drivetrain torsional vibrational response oscillate with the system frequencies. The latter can be problematic if adequate damping or filtering is not applied. If the source of oscillation is drivetrain resonances, dependent on the size of turbine, the frequency will change. For the multi-megawatt scale wind turbines, the range of structural induced excitation frequencies and drivetrain first resonance frequency are in the range of fraction of hertz up to few hertz. As a rule of thumb, the value of these excitation frequencies reduce as the size of turbine increases, but it also depends on the design. Drivetrain faults in gears and bearings, generator cogging effect, distortion of sinusoidal distribution of generator air-gap flux density due to saturation and nonuniform air-gap thickness, and current ripple resulting from PWM are the other sources of electromagnetic torque oscillation, which can cause harmonics in range of fraction of hertz up to few thousands of hertz. Active damping by adding virtual damping in the torque control for the low-frequency oscillations (such as oscillations at drivetrain and tower side-side frequency modes) and shunt capacitive passive filtering for high frequencies (such as PWM switching frequency) are common approaches to mitigate these oscillations.

DFIG electromagnetic torque can be described as a function of stator fluxes (ψ_{ds} and ψ_{qs}) and currents (I_{ds} and I_{qs}) by [21]
$Te = \psi_{ds} \times I_{qs} + \psi_{qs} \times I_{ds}$.

Therefore the torque is linked with the stator currents and therefore grid dynamics, which shows that the power system oscillations can be another source of electromagnetic torque distortion. This may not be the case for wind generators with a full converter as the interface with the grid, because it is believed that GSC decouples the generator from the sub-synchronous network resonances. However, even in full converter-based wind generators, the generator dynamics seem to be coupled with the grid dynamics through the voltage control loop which gets feedback from the grid voltage. Therefore commenting on the coupling between wind generators and power system in case of using full-converters needs further investigation.

2.4.3 Inter-area oscillations: As discussed earlier, grid control mode appears when wind farms operate in grid forming mode, which is in inter-area oscillations. The latter is a coupled mode between the wind turbine-generator equivalent inertia and the short circuit ratio (SCR) at the wind power plant's point of common coupling (PCC). To find this frequency mode, the per-unit form of swing equation which reflects the coupling between grid impedance and turbine-generator dynamics is employed as

$$J_{eq}\frac{d^2\delta}{dt^2} + k_{eq}\delta \approx \frac{\delta}{X}, \tag{5}$$

where J_{eq} is the equivalent moment of inertia of the turbine generator and X_{eq} is the Thévenin equivalent reactance at PCC, both in per-unit. It is worth noting that eq. 5 is based on the approximation that the resistance of a transmission line (R) is small compared to its reactance (X), which is applied to the range $1 << X/R << \infty$. The lower is this ratio, the higher is the error. In the test system used in this paper, this ratio is closer to one so the estimation based on this equation may not be accurate.

The eigenvalues of the characteristic equation of eq. 5 provide a good estimation of grid control frequency mode which can be approximated by

$$f^{Grid-control} \approx \frac{1}{2\pi}\sqrt{\frac{1}{J_{eq}X_{eq}}}, \tag{6}$$

which is linked to the short circuit ratio at the turbine terminal, $SCR = \frac{1}{X_{eq}}$. The weaker the grid, the lower the SCR at wind farm PCC and therefore the lower the value of grid control frequency. $f^{Grid-control}$ is the grid control frequency mode in Hz. The local- and inter-area modes of other power plants and SGs-wind power plants coupled/inter-area modes can also be other source of oscillation which can transfer to GFC-based wind farms. The control is the other source which can introduce new oscillation modes and modify the existing modes. The standard controllers are employed in the simulated generation units.

In this work, it is shown by the coupled simulation models containing the internal dynamics of wind farms, conventional SGs and other converter based RES and standard controllers, how wind farms in grid forming mode can cause both local- and inter-area oscillations. The described frequency modes can be excited by power system disturbances or wind turbine-generator angular velocity variations. Loss of generation units, line switching, load switching, capacitor switching and transmission system faults are examples of disturbances that occur frequently in any power system.

2.5 Power train system resonance load mitigation

Different techniques can be applied for resonance load mitigation in drivetrain which can subsequently reduce the power system local-area oscillations. Active damping, by compensating the oscillatory component from the generator reference torque is usually included in the wind turbines standard torque control, which is also implemented in this research. The block diagram representing the functionality of active damping feed forward is shown in Fig. 5. The 2^{nd} order filter provides 90^0 phase shift at its cutoff frequency required to convert velocity to the equivalent torque. k_{dmp} is the active damper gain which is selected with respect to the actual and critical damping of the drivetrain at the 1^{st} torsional frequency to provide additional damping at this frequency and improving the generator inertial response.

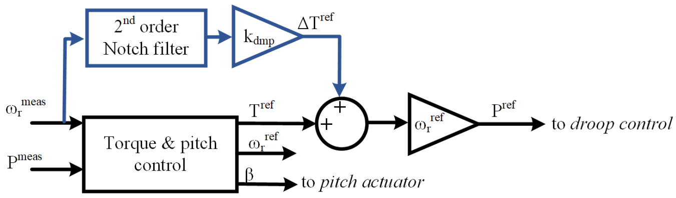


Fig. 5: Block diagram of active damper feed forward.

The aforedescribed approach tries to compensate the oscillation from generator torque but it does not influence the drivetrain system dynamical properties. The compensation of the oscillatory component from load based on eq. (2) can change the amplitude of oscillation at the oscillation frequency.

The second approach is able to modify the system parameters and dynamic properties including damping. This approach can add to drivetrain actual damping and increasing the damping coefficient by using additional passive mechanical vibration dampers. Coulomb or squeeze film-type rotary dampers [22], non-contact magnetic eddy current rotary dampers which dissipate energy through induced eddy-currents generated in a small disk mounted to the shaft [23], torsional tuned mass dampers [24] and magnetorheological elastomer (MRE) torsional vibration absorbers [25] are some examples of the physical systems which can be used to damp/isolate the vibrations. Stiffness and damping properties of hydraulic/elastic/hydro-elastic coupling have also the potential to change both the system frequency and amplitude of response at the system frequency.

3 Results and discussions

The three following simulation scenarios are designed to show the influence of GFC-based wind farm on the power system and wind turbine power train system oscillations:

- Standalone wind farm equipped with grid forming control supply a load,
- In absence of wind farms, where conventional SG and RESs other than wind farm contribute to supply a shared load,
- Fully-coupled model consisting of GFC-based wind farm, conventional SG and other RESs (as shown in Fig. 1) cooperate to supply a shared load.

In all these scenarios, load disturbance occurs at $t = 20$ s when the demand of active power increases by 20%, and the values of constant and disturbance load is adjusted based on the available power generated. The different test scenarios and the related results are elaborated hereunder.

3.1 Standalone wind farm

The main goal in this test scenario is to evaluate the performance of designed voltage control. In this test scenario, the converters of wind turbines inject a fraction of available power to grid, and power reference is adjusted as per requirement. The details of derated power control strategy is provided in [26]. The performance of DFIG frequency converter operating in grid forming mode in maintaining voltage in terminal when demand is changing is shown in figures 6a-6d (standalone wind farm). As it can be seen, the controller is able to maintain the voltage amplitude and frequency in PCC in the defined range by providing adequate active and reactive power support. In other words, the internal voltage controller is able to follow the changes in the reference voltage frequency and amplitude imposed by droop characteristics for different load conditions. The variation of reactive power is due to the coupling between active and reactive powers in the power system with inductive-resistive links. The performance of DC-link voltage control is also shown in Fig. 6e, which shows the proper operation of implemented GSC controller.

In the results demonstrated in Fig. 6, additional passive and active damping are added to the drivetrain system and torque controller, respectively. The default value of drivetrain damping in NREL 1.5 MW drivetrain provides the damping coefficient $\zeta << 1$. In case of not employing additional mechanical damping in the drivetrain and deactivating active damping, DFIG active power injected to the grid, drivetrain loads and responses, and power converter electrical parameters are shown in Fig. 7, which all oscillate with the same oscillation frequencies and show that if insufficient damping is present in the system, instability may occur. To investigate more about the frequencies of oscillations, as example, the power spectral density (PSD) of P^{DFIG} and T_e^{DFIG} are shown in figures 7a and 7b. As it can be seen, active power injected to grid is oscillating with two main frequency components $f = 2.4$ Hz and $f = 0.13$ Hz. Employing the approximated eqs 6 and 3 shows that these two harmonics are the 1^{st} drivetrain torsional (drivetrain mode) and the grid control (drivetrain-grid coupled mode) natural frequencies, respectively. It is worth noting that in wind farm standalone operation, SCR at PCC is the inverse of the algebraic summation of the impedances of $L1$ and $T1$ in per-unit. Simulink does not have modal analysis module which makes it difficult to find the source of inter-area oscillations, *e.g.* grid control mode. However, drivetrain natural frequency is a local mode. To ensure that the source of this frequency oscillation is the drivetrain dynamics, Simulink control system designer tool is used which helps find the transfer function/state-space representation between the selected input and output signals to look at the internal dynamics of that specific part of model. To look at the internal dynamics of drivetrain, the transfer function between input torque and generator speed is obtained and the associated bode diagram is shown in Fig.

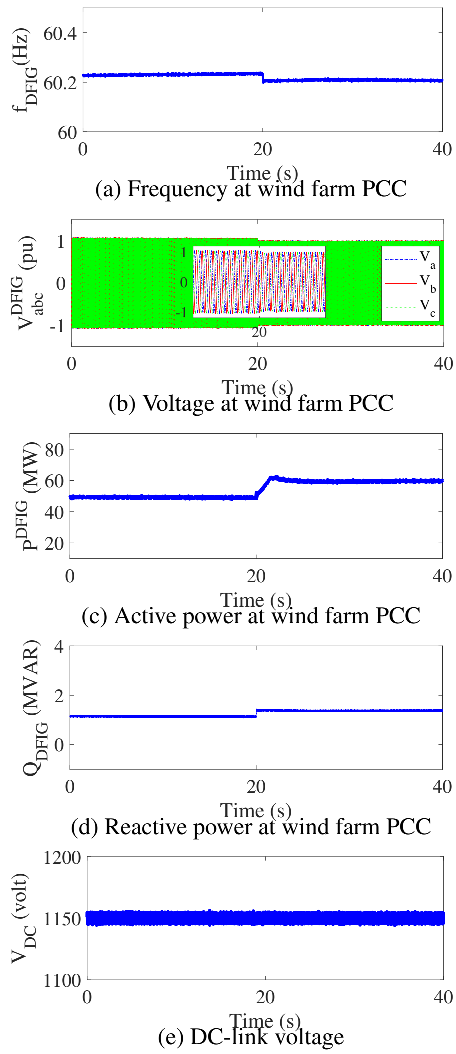
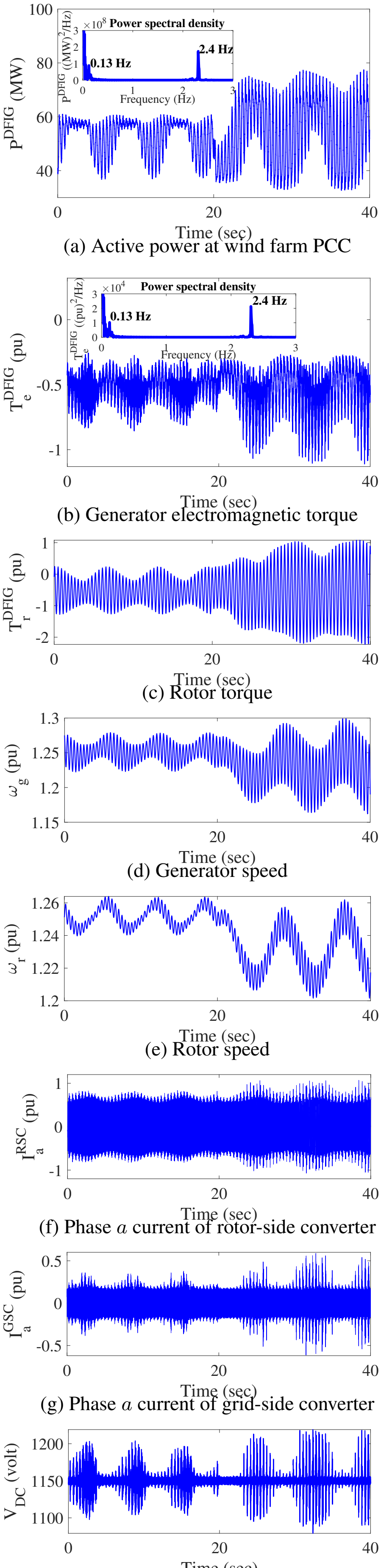


Fig. 6: Wind farm standalone operation (with power train additional damping).

8, which proves that the frequency $f = 2.4$ Hz is a drivetrain eigenvalue and initiated from the drivetrain dynamics. The Fig. 7a shows how this oscillation can transfer to the grid through the active power. The figures 7b-7e show how these two excited modes can influence the drivetrain loads (generator electromagnetic and rotor torque) and responses (generator and rotor angular velocity). It can be seen that the grid control mode which has a low-frequency nature is transferred to the load and response of wind turbine drivetrain and rotor. This oscillation frequency is in the range of drivetrain low-speed shaft frequency, and close to the range of 1^{st} tower side-to-side and blade's edgewise natural frequency, which can be problematic if sufficient damping is not provided by the drivetrain. To show the influence of these excited modes on the oscillations of electrical characteristics of frequency converter components, oscillations of collector currents of IGBTs in RSC and GSC converters (which has direct connection with power loss and thermal stress in switch) and the voltage of DC-link capacitors are shown in figures 7f-7h. Our simulations show that by the increase of damping ratio from 5 to 15% (the increase of shaft actual damping of wind turbine drivetrain threefold), the amplitude of the aforedescribed undamped oscillation converges to 0. Due to consistent variation of demand in the grid, even the damped oscillations in long-term can accelerate the fatigue damage of power train system components.

Our observations show that the active damping presented in Fig. 5 does not significantly influence the drivetrain vibrations,



(a) Active power at wind farm PCC

(b) Generator electromagnetic torque

(c) Rotor torque

(d) Generator speed

(e) Rotor speed

(f) Phase a current of rotor-side converter

(g) Phase a current of grid-side converter

(h) DC-link voltage

Fig. 7: Wind farm standalone operation (no additional damping).

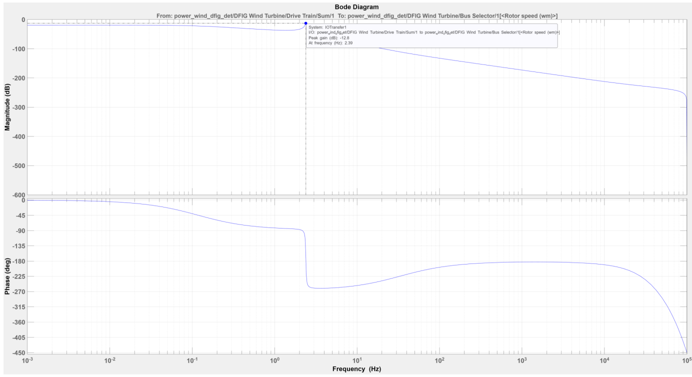


Fig. 8: Bode diagram of power train transfer function.

but it can mitigate the amplitude of oscillations in electromagnetic torque and the power injected to the grid power. The aforedescribed low damped case is an exaggerated case which may not never happen in reality but was chosen to show the dynamic interaction between drivetrain, frequency converter and grid dynamics in case of wind farm being equipped with grid forming control strategy. Any variation in power demand or angular velocity of drivetrain can excite the drivetrain and grid control mode which can considerably influence the fatigue damage of drivetrain, frequency converter and reduce the grid power quality if sufficient damping for these two frequency modes is not presented by wind turbine power train system.

3.2 Conventional SG and RES in absence of wind farm

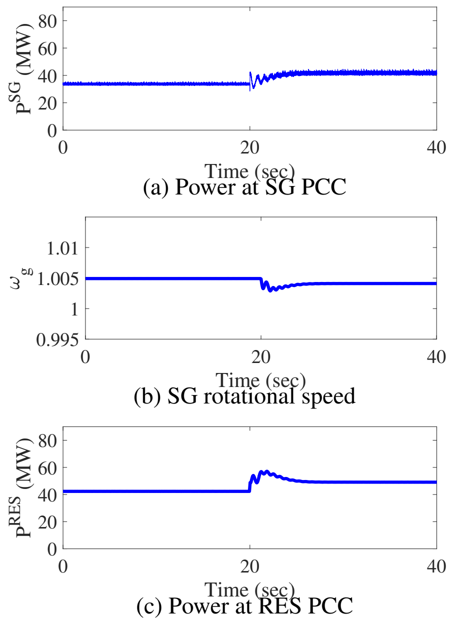
In this case study, conventional SG and RES, both operate as voltage sources and cooperate to supply a shared load. The performance of active power sharing droop control of SG and RES in distributing the disturbance load between SG and RES is shown in figures 9a and 9c. The contribution of each generation unit in responding to the load disturbance can be determined by the predefined droop control gains. As it can be seen in Fig. 9, the two frequency modes observed in wind farm standalone operation are not seen in this case study neither in the active power injected by SG and RES to the grid nor in SG rotational speed which represents the SG turbine internal dynamics. The latter confirms that those modes are related to wind farm operation.

The grid control frequency mode can be similarly defined as the resonance frequency between the inertia of conventional SG and the Thévenin impedance seen at SG terminal. Due to the higher inertia of SG, this frequency mode has a lower value than the wind turbines' grid control mode. Detection of such low-frequency oscillations in the interconnected power system requires advanced algorithms which is beyond the scope of this paper [27].

3.3 Fully-coupled model consisting of wind farm, SG and RES

In the last case study, the fully coupled model of power system including wind farm, conventional SG and RES, all behaving as voltage sources is employed, as shown in Fig. 1. To simulate a realistic scenario, active damping is activated but additional physical damping is not introduced to the wind turbine power train model.

The performance of active power sharing droop control of the three different power generation units based on their predefined droop control settings in responding to the variation of demand in the power system is shown in figures 10a-10c. Figures 10a-10f show how the wind farm-induced oscillation $f = 2.4$ Hz can be transmitted to the active power and internal dynamics of the other



(a) Power at SG PCC

(b) SG rotational speed

(c) Power at RES PCC

Fig. 9: Operation of conventional SG and RES in absence of wind farm.

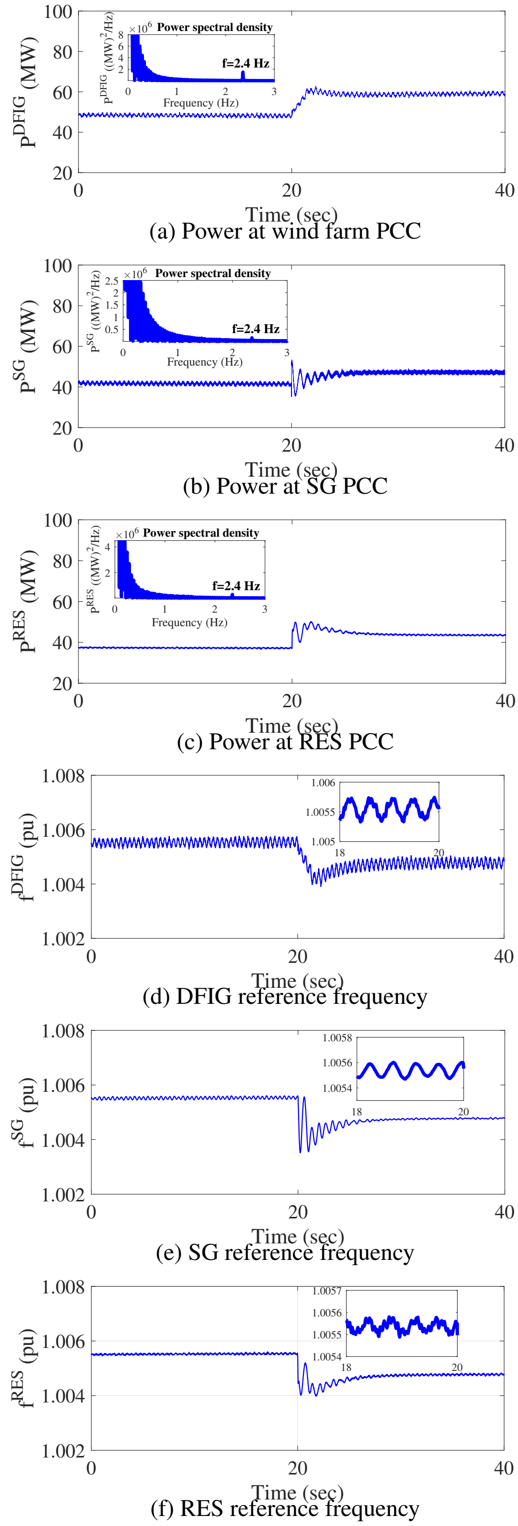
power generation sources, *i.e.* SG and RES, which also leverage the grid forming concept. The internal frequencies of DFIG, SG and RES shown in figures 10d-10f demonstrate the oscillatory component 2.4 Hz, which proves that this wind farm local-area oscillation is transmitted from DFIG to SG and RES internal dynamics. The latter shows the high coupling between the internal dynamics of different power generation units which use grid forming concept. The latter can increase the fatigue damage of power train system of the other grid forming power generation units. To mitigate the effects of grid forming wind farms on conventional SG turbine-generator dynamics, damper windings (which absorbs the energy of oscillations) and proper tuning of automatic voltage regulator can play a role.

In this work, we focused on 1^{st} torsional mode of wind turbine's power train system as a local-area mode which can transfer to the electric power injected to the grid and to the internal dynamics of other power generation units in the grid. However, the results of this study can be extended to other sources of local-area oscillations such as the harmonics induced by the wind turbine's power train system defects which can similarly transmit to the grid in case of wind farm grid forming operation.

Due to the slight increase of Thévenin impedance at wind farm PCC in case of fully-coupled model, the value of wind turbines' grid control mode is expected to reduce compared to standalone operation. The results related to fully-coupled analysis shown in Fig. 10 do not show the grid control frequency mode which was showing in wind farm standalone operation (see Fig. 7). It can be deduced from the results that when the farm is connected to the power system, the damping of this oscillation mode is increased. Therefore, this inter-area frequency mode does not seem to significantly influence the power system, though this mode is power system topology-dependent.

4 Concluding remarks

This research was aimed at showing how the operation of wind farm in grid forming can influence both wind turbines internal dynamics and the rest of power system. It was shown that how the wind turbine local- and inter-area modes can be excited by variations in the grid in case of operation in grid forming mode, how it can increase the oscillations in the power train system of



(a) Power at wind farm PCC

(b) Power at SG PCC

(c) Power at RES PCC

(d) DFIG reference frequency

(e) SG reference frequency

(f) RES reference frequency

Fig. 10: Operation of fully-coupled model consisting of wind farm, SG and RES (no additional damping).

wind turbines, how it can influence the wind turbines generated power injected to the grid and affect grid power quality, and how those wind farm-induced oscillations can spread in the power system and transmit to the internal dynamics of the other voltage sources in the grid. Solutions based on employing additional damping to the wind turbine power train system were proposed and tested. The simulation results showed that the new dynamics are not critical, given that the wind turbine power train presents sufficient damping. Future work will be devoted on investigating the influence of power system faults on the wind turbines' power train system dynamics and estimating the relative change of fatigue damage in this system when operating in grid forming mode. Performing a similar study for wind generators with full converter is also considered as a future work.

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