IMPACT OF SYNTHETIC INERTIA FROM WIND POWER ON THE PROTECTION/CONTROL SCHEMES OF FUTURE POWER SYSTEMS: SIMULATION STUDY

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Abstract

Future power systems face several challenges; one of them is the use of high power converters that decouple new energy sources from the AC power grid. This decreases the total system inertia affecting its ability to overcome system frequency's disturbances. The wind power industry has created a controller to enable inertial response on wind turbines generators: Artificial, Emulated, Simulated, or Synthetic Inertial. This paper deals with issues related to the synthetic inertia of wind turbines based on full-converters and their effect on the frequency protection/control schemes during the recovery period after system frequency disturbances happen. The main contribution of this paper is to demonstrate (based on simulations) the recovery period of under-frequency transients on future power systems which integrate wind turbines with synthetic inertia capability not completely avoid worse scenarios in terms of under-frequency load shedding. The extra power delivered from a wind turbine during frequency disturbances can substantially reduce the rate of change of frequency providing time for the active governors to respond. However, synthetic inertia might not completely avoid under-frequency load shedding.

1 Introduction

Future power systems face several challenges: (i) the high penetration level of renewable energy from highly variable generators connected over power converters, (ii) several technologies for energy storage with very different time constants, some of them using power converters as an interface to the grid, (iii) A pan-European transmission network facilitating the integration of large-scale renewable energy sources and the balancing and transportation of electricity based on underwater *multi-terminal high voltage direct current* (MTDC) transmission. All of them have an element in common, high power converters that decouple the new energy sources from the pre-existent AC power systems. During a system frequency disturbance the generation/demand power balance is lost, the system frequency will change at a rate initially determined by the *total system inertia*. However, future power systems will increase the installed power capacity (MVA) but the effective system inertial response will stay the same nowadays, this is because the new generation units based on power converters creates a decoupling effect of the real inertia and the ac grid. The result is deeper frequency excursions of system disturbances. A considerable reduction in the ability to overcome system frequency's disturbances is expected, the inertia response may be decreased. The *inertial response* of the system might be negatively affected with devastating consequences for system security and reliability.

There are several good papers [1], [2], [3], and technical reports [4], [5], [6] dealing with theory [7], [8], [9], modelling [10] and simulation [2], [11] of inertial response of *wind turbine generators* (WTG) and some of them provide general ideas about possible impacts on power systems and there effects on transient under-frequency response [12], [13], [14]. Even some controls strategies have been proposed to mitigate the impact of reduced inertia [15]. However, there is lack of knowledge about the impact of inertial response of wind turbines on deterministic frequency protection/control schemes in future power systems.

This aim of this paper is presents the real impact of *synthetic inertia* on wind turbines based on full-converters and there effect on the frequency protection/control schemes during the recovery period after system frequency disturbances happen. The paper is organized as follows. Section 2 describes the frequency response on power system after a frequency disturbance. Section 3 presents the concept of synthetic inertia and show two approaches used on WT controller to create inertial responses. Section 4 address aspects related to protection/control schemes on power system and some potential challenges for futures networks. Section 5 the results of simulations that define the impact of synthetic inertia on the protection/control schemes over a test system. Finally, the advantages of this novel application are discussed in Section 5.

2 Frequency Response

The frequency of a power system depends on real power balance: generation-demand. In the normal operation of a power system, the frequency is regulated within strict limits by adjusting the electrical supply to meet the demand. Responsibility of frequency control is managed in United Kingdom by National Grid PLC, thought the procurement and despatch of *frequency response services*, under normal operation conditions the frequency is maintained at 50Hz±0.2Hz [16].

If the balance between generation-demand is not reached, the system frequency will change at a rate which is dependent upon the initial power mismatch and the *total system inertia*.

Large frequency disturbances, particularly trips of large generation plants, cause generation-demand unbalance that must be corrected by *frequency control loops*. These controllers are provided in order improve the *system frequency response* (SFR). The frequency controllers cover multiple time-frames: (i) *inertial response* also know as *fast primary response*, (ii) *governor response* also known as *slow primary response*, and (iii) *automatic generation control* (AGC). These controllers define the dynamic changes associated to *System Frequency Response* (SFR).

During a system frequency disturbance, the inertial response dominates initial frequency changes then the combination of system inertia and governors response dictate the extreme value of frequency (maximum or minimum). Later, the governor response and load response dominate the frequency mismatch between the system frequency and *statutory value* until AGC takes over. Tertiary frequency control is additional and slower compared to previous two controllers. The task of tertiary control depends on the organizational structure of a given power system and the role that power plant plays in the structure [17]. Primary response is provided locally at *device level*, Secondary response is mainly *area-wide* inside an administrative area, and tertiary response is a *global* concept for interconnected systems.

Frequency response provided by WTG's is different to traditional generation systems. Modern variable speed WTG does not naturally contribute to system inertial and does not contribute to the governor response without incurring significant operational cost penalties.

3 Synthetic Inertia

The *total system inertia* of a traditional power system comprises of the combined inertia of most of the spinning generation and load connected to the power system. The contribution of the system inertia to a single load or generator depend on changes in the system frequency and causes change in its rotational speed hence, a change its *kinetic energy*.

The power associated with this change in kinetic energy is fed or taken from the power system and is known as the *inertial response*. During a system frequency event the total system inertia response of all electrical machines connected to the system is the main factor that determines the initial *rate of frequency change* (ROCOF).

Modern WTGs use power electronics converters to enable variable speed operation in order to capture wind energy over a wide range of speeds. However, these converters isolate the rotational speed from the system frequency so WTG based on back-to-back AC/DC/AC converters offer no *natural* response to system frequency [3], [10].

Author has included the adjective "*natural*" on the previous sentence because some manufacturers have started to integrate controllers on modern WTG's in order to provide inertial response (and governor response on some cases) for large, short-duration frequency deviations.

The Wind turbine industry has created several names for this control system that enable inertial responses on a WTG: *Artificial, Emulated, Simulated,* or *Synthetic Inertial*. Examples of synthetic inertia controlled commercially available for WTG are: General Electric WindINERTIA™ [18], [19], ENERCON® Inertia Emulation [20].

The objective of the synthetic inertia control is extracting the stored inertial energy from the moving part on WTGs. The idea is to produce incremental energy similar to that provided by a synchronous generator with real inertia. This is a local and automatic controller at wind turbine level which has a response in the same time-frame as primary controllers (<30s). Synthetic inertia controllers are based on two different approaches: (a) *Releasing "hidden" inertia* and (b) *Reserve capacity in pitch*.

2.1 Releasing the "Hidden" Inertia

Releasing the "hidden" inertia concept allows a controller to the take the kinetic energy from a wind turbine (WT) rotating mass. Significant energy is stored on a WTG, electrical generator operating at high speed has a large amount kinetic energy stored in rotor of generator, but majority of that kinetic energy is in rotor bales. A WT using *permanent magnet synchronous generator* (PMSG) on a direct-drive concept has less kinetic energy stored due to the lower rotational speed. Table 1 shows typical values of 3MW modern variable speed WTG.

Drive train Concept	*Generator Type*	*Rated Speed [rpm]*	*Generator rotor inertia [Kg/m^2]*
Double fed 3-stage gear	Wound rotor asynchronous 6-pole	1200	250
Low Speed Full converter (LSFC) Direct drive	Permanent magnet, multi pole	14	40,500
Medium Speed full Converter (MSFC) 2-stage gear	Permanent magnet 14-pole	400	510
High Speed Full Converter (HSFC) 3-stage gear	Permanent Magnet 6-pole	1600	115

Table 1: Typical data for a 3MW WTG.

Releasing the "hidden" inertia control loop increases electric power output during the initial stages of a significant downward frequency event. The active power (inertial power, ΔP) of the control is achieved by:

$$\Delta P = 2H \times f_{sys} \times \frac{df_{sys}}{dt} \qquad (1)$$

where H express the synthetic inertia (sec) and f_{sys} system frequency (p.u). Implementation of releasing hidden inertia controllers is depicted on Figure 1. The WT can quickly store and release a large amount of kinetic energy in the rotating masses because of the power electronic converter, due to a large amount of inertia and wide rotational speed. However, discharge of energy to the grid is only for a short period available (<30s) and *recovery* of WT power is supplied by the grid (unless the wind speed increases favorably!!!).

Slowing the wind turbine reduces aerodynamic lift and security limitations must be considered to avoid a stall. Inertial power must respect WTG components rating like mechanical loading as well as converter and generator electrical rating [9]. For large under-frequency events, the inertial control feature temporarily increases the power output of the wind turbine by about 5% to 10% of its rated power, for several seconds. ENERCON® emulated inertia increases the power output about 4% to 10% of rated power for 10s [8].

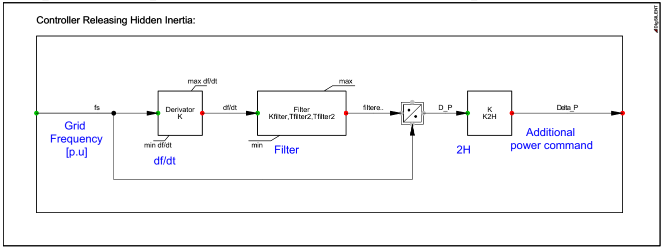

Figure 1: Releasing Hidden Inertia Controller.

2.2 Reserve Capacity in Pitch

Traditional variable speed WTs are designed to always operate at the *maximum power point tracking* (MPPT) so they have no power reserve to support frequency control in there steady state. Reserve capacity in pitch concept coerces a wind standby power by maintaining reserve capacity in pitch [9], [21]. A *de-loading controller* enable the WT to operate over de-loading curves instead of MPPT and saves the available power as reserve by using a *pitch controller* (pitching) or increasing the rotational speed from the MPPT value (over-speeding).

Frequency support using this controller is already discussed in details in several publications [2], [9], [18], [22], even EirGrid, the transmission system operator of the Republic of Ireland, already estipulate a scheme with this controller [23]. One negative consequence of this controller is WTs have to be operated at a considerably lower power output that otherwise possible for a given wind speed, as a consequence, less power generation is achieved and the wind is not fully utilized. A monetary compensation scheme for the wind farm owners can be created to resolve this situation. An additional grid frequency control loop in the pitch angle controller is required and it must be carefully designed in order to meet mechanical loads on the pitch drive. This approach involves some well-know consequences and requirements, as consequence, it is not considered in this paper.

4 Protection/Control Schemes

When a severe frequency disturbance occurs, e.g. loss of a station (all generating units), loss of a major load centre, or loss of AC or DC interconnection, *emergency control measures* may be required to maintain frequency stability. These control measures may include: tripping of generators, fast generation reduction, HVDC power transfer control, load shedding, controlled opening of interconnection to neighbouring systems to prevent spreading of frequency problems and *controlled islanding* of local system into separate areas with matching generation and load.

Under-frequency load shedding (UFLS) is the most widely used protection against *frequency collapse*. Typically, load is shed based on a local frequency measurement in several steps of 5-20 % (of the total feeder load) each. Automatic load shedding is implemented using *underfrequency relays*. Typical threshold values are 48-48.5 Hz for a 50 Hz system.

The main draw back of these schemes is their delayed response since they must wait for the frequency to decline before taking action. A great proportion of inertia is expected to be decoupled to the system frequency in future power systems. As consequence a larger frequency drop is expected in future networks, as consequence deterministic frequency protection/control schemes must be re-thought. Synthetic Inertial response from wind turbines can increase system security and aid large scale systems to overcome system frequency disturbances, however, control interactions can create disastrous situations.

5 Simulation and Results

This section presents simulations and results over a Test System representative of a future network. All models where developed by the author using information publically available and personal assumptions where they are necessary. DigSILENT® PowerFactory™ [24] is used for time-domain simulations and *DIgSILENT Simulation Language* (DSL) is used for dynamic modelling. All simulations are performed using a personal computer based on Intel®, Core™ i7 CPU 2.0GHz, 8 GB RAM with Windows 7 Home Edition 64-bit operating system.

5.1 Test System

The test network used for simulation in this study it is given in Figure 2. This system consists of 8-generator, 8-bus, 7-load, and 22-transmission lines. It is a hypothetical simplification of a large 400 kV transmission system, it has been divided in seven areas: Top-Right, Top-left, Upper-Tail, Tail-Right, Lowest-Tail, Middle and Core+Tail. The generator G4(a) represents the aggregation of a large number of generators and it is selected as a reference. The system has a total generation of 100.736 GW and a total load of 96.75GW.

Figure 2 shows the load flows for case base, there is a power flow of about 15 GW from the Top to Tail, particularly from Upper-Tail and Tail-Right and Core-Tail. Tail is an area rich on generation and Core-Tail is a load-rich area. Dynamic models for governor and *automatic voltage controller* (AVR) are provided to this test model.

Figure 3 and 4, show the general steam turbine used as governor for all synchronous power plants and a version on IEEE Type I excitation system [25] is used as AVR. For the system demand of 100 GW, equivalent system inertia of 7.2 MWs/MVA is assumed by the author for the synchronous power plants (no wind). Demand is considered 100% dynamic with a time constant of 0.1s and frequency dependence of active power is included.

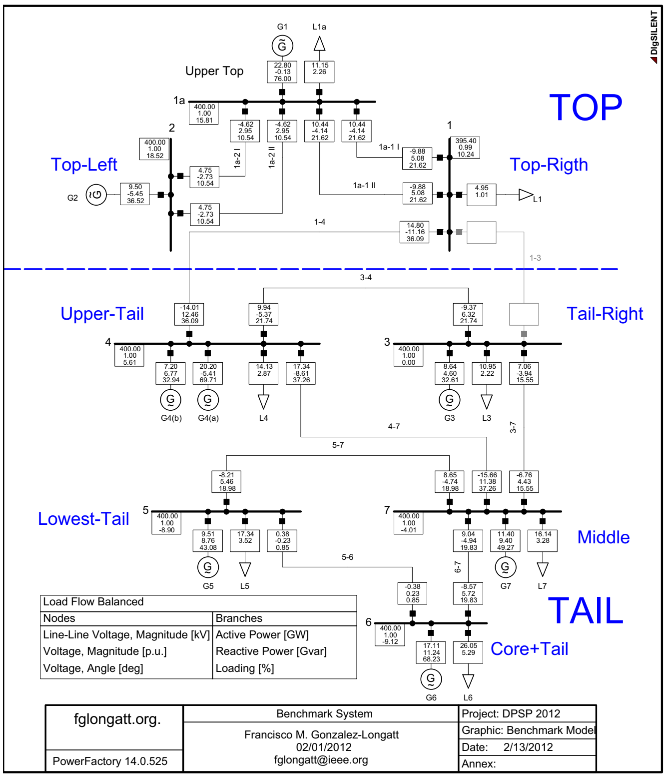

Figure 2: Test System: Case Base.

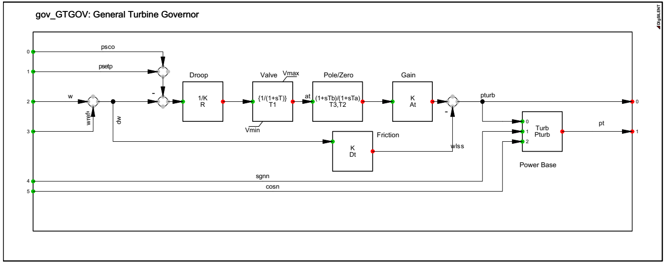

Figure 3: Model of General Turbine Governor.

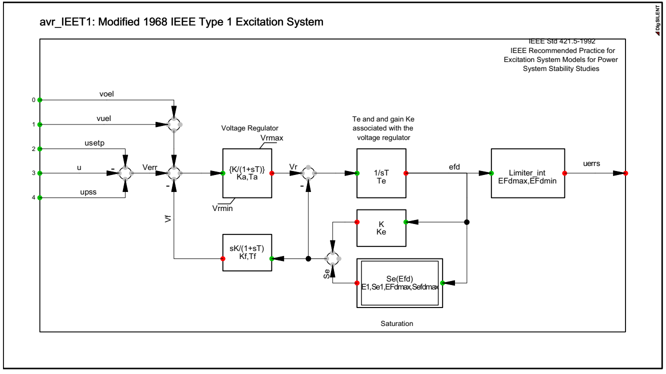

Figure 4: Model of General AVR.

5.2. Frequency Response Assumptions

In this paper, the operational-control criteria used for system frequency analysis is based a specific criteria defined by the author, it is mainly a personal version of the GB *Security and Quality of Supply Standards* (GB SQSS). The following assumptions are used in this paper: (i) the *level of infrequency loss of power infeed* is set-up to 1.800 GW, and frequency response must avoid a deviation of the system frequency outside statutory limits: range 49.8 Hz to 50.2Hz for more than 5 cycles, (ii) the *level of normal loss of power infeed* is set-up to 1.35 GW, frequency response to avoid a deviation in the system frequency by more than 0.2Hz, (iii) the system frequency could rise to 52 Hz or fall to 47 Hz in exceptional circumstances. If system frequency is over 52.0 Hz, over-frequency relays will trip generators, (iv) frequency control devices (or a speed governor) are set up to operate with an *overall speed Droop of 4%* (GB SQSS establishes between 3 and 5%). In this paper, UFLS is set to start at 49.8Hz and the plan consists of six load shedding steps of unequal size with the total amount of load shed of 0.25 p.u [26]. A delay for each load shedding step is 0.1 s (5 cycles). Figure 5 shows specific under-frequency relay model developed and used in this paper.

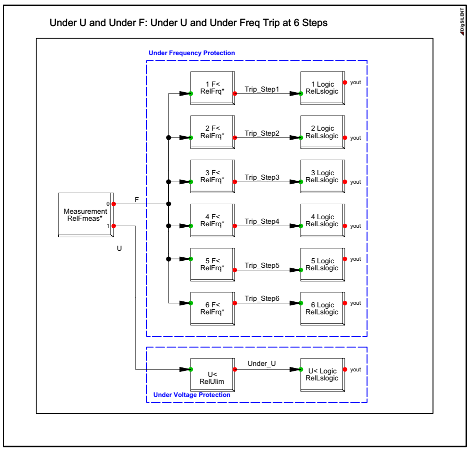

Figure 5: Under-frequency Relay Model including 6-step load shedding.

5.3 Wind Turbine Model

Figure 6 depict the general structure of a variable-speed wind turbine with a direct-drive permanent magnet synchronous generator (PMSG) and Figure 6 shows the model for the wind turbines created using DSL. Figure 7 show the models used for a back-to-back converter, details of each model are taken from: [27], [28], [29]. The parameters used for these models are escalated to simulate an equivalent 5 MW wind turbine.

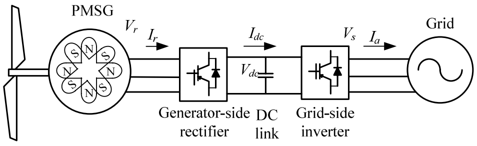

Figure 6: General structure of a variable-speed wind turbine with a direct-drive synchronous generator with full-scale frequency converter.

5.4 Results and Discussion

The impact of a synthetic inertia is being quantitatively analysed through time-domain simulations. This is a multi-machine system as consequence, the author uses the *concept of frequency of inertia centre* (f_c) to analyse changes in system frequency. A loss infeed is used as system frequency disturbance; it consists of tripping at $t = 1.0$s of one generating unit connected to Upper-Tail area at 1s (generator

G4(b) on Figure 2). The case base consists of just synchronous generators (no wind) which feed system demand. The author assumes four generators providing a governor frequency response and three conventional generators (G2, G5, and G7) will be operating without active governors (e.g., nuclear power stations) or at maximum power (e.g., valves wide open). Several levels of loss of power infeed from 0.3 to 3.2 GW are simulated and *rate of change of frequency* (ROCOF) is plotted on Figure 8. The ROCOF and the minimum frequency (*nadir*) increases as the level of loss of power infeed increase.

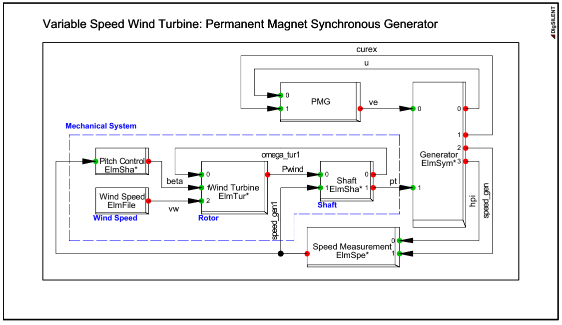

Figure 6: General structure of the model for a variable-speed wind turbine.

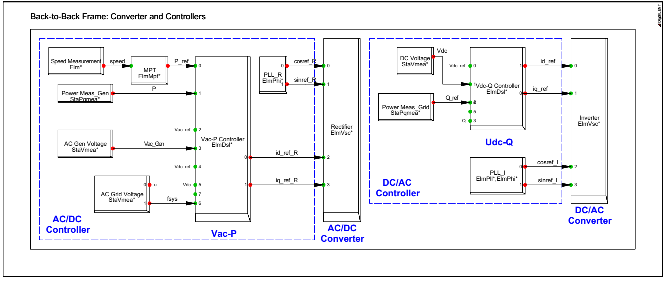

Figure 7: General structure of the model for back-to-back converter.

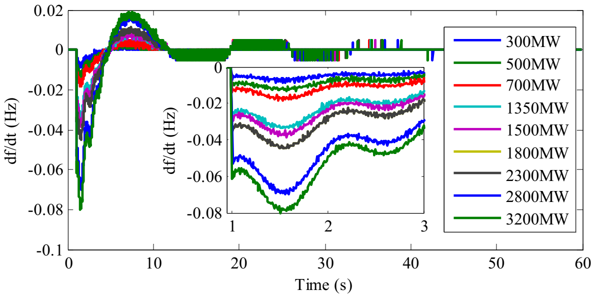

Figure 8: Under-frequency Relay Model including 6-step load shedding.

The author used an exceptional loss of power infeed to trigger a substantial frequency excursion in the Test System; this system frequency disturbance activates the UFLS. This exceptional loss risk deviates system frequency more than 741 mHz and persist for more than 5 cycles (see Figure 9 and Case I Figure 10). Several UFLS schemes on demand side of Tail area are tested, loads: L4, L5, L6, L7 (see Figure 2), results of system frequency and ROCOF are shown on Figure 10 (load shedding Case I: 0 GW, II: 2.8260GW, III: 6.2940 GW, IV: 5.7520GW, V: 7.3660GW). A cluster of wind farms is connected on bus 3 at the Tail-Right area and is generating 30 GW and the control loop for releasing "hidden" inertia of $H = 3.75$s is included. Benefits of the integration of this wind farm include the reduction of power flows between Top and Tail areas but an increase of 164 mHz in the minimum frequency during at exceptional loss of the power infeed.

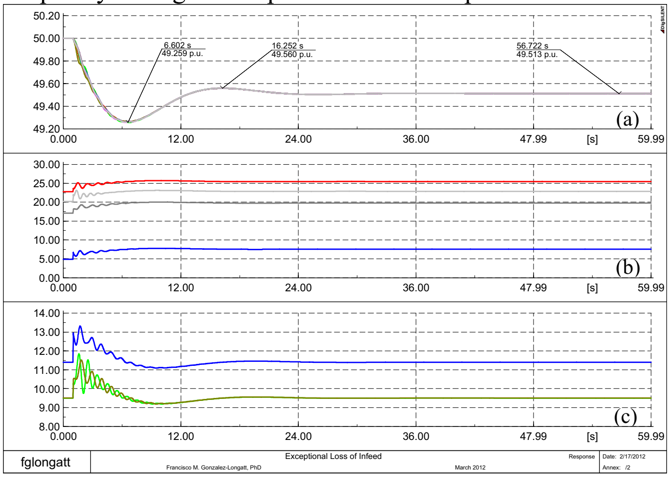

Figure 9: System Frequency response to an exceptional loss of generation infeed (a) Frequency, Generation active power in GW (b) with and (c) without frequency response.

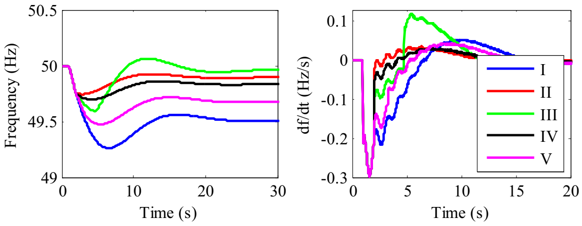

Figure 10: System Frequency and ROCOF considering different UFLS schemes: Base Case

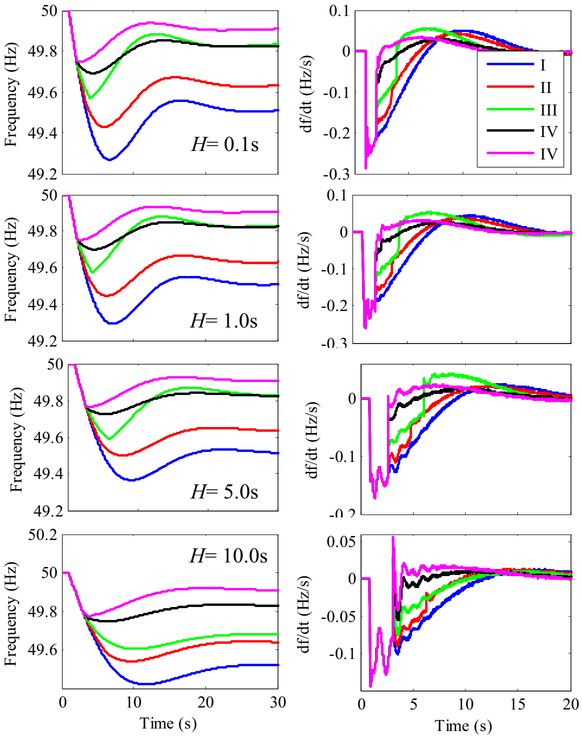

Figure 11: System Frequency and ROCOF considering different UFLS schemes: Wind Integration.

The inertial control has a substantial impact on system performance. The short term impact is delivery of extra power from WT with substantially reduces the ROCOF, allowing time for the active governors to respond (see Figure 11). Increasing the capability of WT to release of hidden inertia helps to delay the UFLS. However, the frequency response provided by synthetic inertia might not completely avoid UFLS. Reducing the amount of synthetic inertia reduces the recovery effect but frequency support provided by wind turbines is reduced as well. Results demonstrate UFLS helps to reduce the negative recovery effect caused by synthetic inertia and increase security level during extreme loss power infeed.

4 Conclusions

This paper is presents simulations results that provide ideas about the potential impact of *synthetic inertia* on wind turbines based on full-converter on the under-frequency protection/control schemes during the recovery period after system frequency disturbance happen. The substantial impact of synthetic inertia is on system inertial response: (a) the extra power delivered from WT can substantially reduces the ROCOF (b) it provides time for the active governors to respond, however a coordination between controllers looks desirable (c) increasing synthetic inertia helps to delay the UFLS (d) synthetic inertia might not completely avoid UFLS, (e) UFLS helps to reduce the negative recovery effect caused by synthetic inertia. The main contribution of this paper is to demonstrate (based on simulations) recovery period of under-frequency transient on future power systems that integrate synthetic inertia capability not completely avoid worse scenarios in terms of UFLS.

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