Activation Schemes for Synthetic Inertia Controller on Wind Turbines Based On Full Rated Converter

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Abstract—One of the challenges in future energy systems is the massive use of high power converters that decouple new energy sources from the AC power grid, disabling natural frequency response. This situation decreases the total system inertia affecting the ability of power system to overcome system frequency's disturbances. It has been established by the wind power industry a controller to enable inertial response on *wind turbines generators* (WTG) enabling the frequency response: Artificial, Emulated, Simulated, or Synthetic Inertia. However, there is a clear lack of knowledge about activation scheme used for these controllers and how they work in practical manner. This paper proposes two activation schemes for synthetic inertia controller on WTG based on *full rated power converters* (FRC): (i) under-frequency trigger and (ii) maximum-frequency gradient trigger. Simulations considering a test system are used for evaluation of the proposed activation schemes. The main contribution of this paper is the definition of two schemes to activate the synthetic inertia controller and the simulations results that demonstrate under-frequency trigger provides the best dynamic response in term of system frequency response.

Index Terms-- Frequency controller, frequency stability, power system, protection scheme, wind turbine generator.

I. INTRODUCTION

Future energy systems networks will be completely different to the power systems on nowadays [1], [2]. High and low power converters will be massively deployed in several areas on the electric network [3], [4], [5]: (i) renewable energy from highly variable generators connected over high 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, and (iii) Pan-European transmission network facilitating the massive 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. These high power converters typically tend to decouple energy sources from the pre-existent AC power systems [2, 5]. During a *system frequency disturbance* (SFD) the generation/demand power balance is lost, the system frequency will change at a rate initially determined by the *total system inertia* (H_T) [6]. However, future power systems will increase the installed power capacity (MVA) but the effective *system inertial response* will stay the same nowadays [2]. The result is deeper frequency excursions of system disturbances.

There are several good papers [7], [8], [9], and technical reports [10], [11], [12] dealing with theory [13], [14], [15], modelling [16] and simulation [8], [17] 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 [18], [19], [20]. Even some controls strategies have been proposed to mitigate the impact of reduced inertia [21]. However, there is lack of knowledge about control schemes used to activate the synthetic inertia.

This aim of this paper is to propose and evaluate activation schemes for synthetic inertia controller on WTG base full rated converters. The paper is organized as follows. Section II briefly describes the frequency response and indictors used to evaluate the system frequency response. Section III introduces the concept of synthetic inertia and presents *releasing "hidden" inertia* controller. Section III proposes three activation schemes for the synthetic inertia: (i) *Continuously Operating*, (ii) *Under-frequency Trigger* and (iii) *Maximum-Frequency Gradient Trigger*. Section V the results of simulations that assess the impact of the proposed activation schemes on the system frequency response and electro-mechanical variables on the WTG. The main contributions of this paper are: (a) three schemes to activate the synthetic inertia controller and (b) a preliminary assessment of these schemes. Simulations results on a test system demonstrates under-frequency trigger provide good dynamic response. Finally, the advantages/disadvantages of the activation schemes are discussed in Section VI.

II. System Frequency Response

The frequency (f in Hz) of a power system depends on real power balance: generation/demand. During normal operation, the system frequency (f_{sys}) 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 dispatch of *frequency response services*, under normal operation conditions the frequency is maintained at 50Hz±0.2Hz [22]. 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*.

The *frequency response* (*FR*) of a power system is evaluated considering three important indicators: ① *maximum frequency gradient* (*df/dt*) as observed by *Rate-Of-Change-Of-Frequency* (ROCOF) relays, ② *minimum frequency* or *nadir* (f_{min}) as observed by under-frequency relays and ③ *steady-state frequency error* (f_{ss}). The f_{min} and *df/dt* must be kept as small as possible to prevent relays from tripping. The *system frequency response* (SFR) indicators are defined on Figure 1.
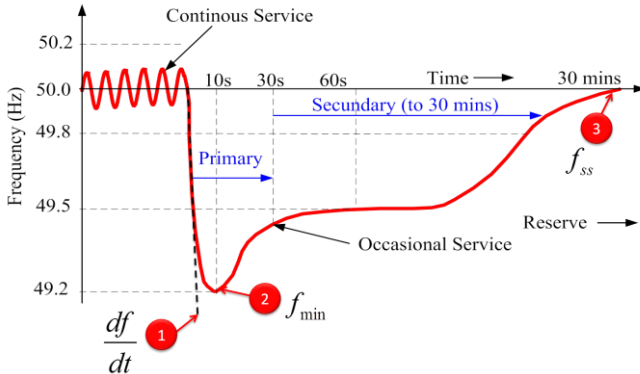

Figure 1.   Representative plot of System Frequency Response where main indicators are shown [5].

FR provided by WTG's is very different to traditional generation systems [2], [4]. 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.

III. Synthetic Inertia

Modern WTGs use power electronics converters to enable variable speed operation in order to capture wind energy over a wide range of speeds. However, power converter isolates 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 [9], [16]. The WT industry has created several controllers for modern WTG's in order to provide inertial response (and governor response on some cases) for large frequency deviation for, short-duration: *Artificial, Emulated, Simulated,* or *Synthetic Inertial*.

Examples of synthetic inertia controlled commercially available for WTG are: General Electric WindINERTIA™ [23], [24], ENERCON® Inertia Emulation [25].

The objective of the synthetic inertia control is "*to extract the stored inertial energy from the moving part on WTGs*" [26]. There are several versions of synthetic inertia controllers; however they can be classified in two main approaches: (a) *Releasing "hidden" inertia* and (b) *Reserve capacity in pitch*. In this paper the hidden inertia approach is considered and it is named synthetic inertia from here.

Synthetic inertia concept allows a controller to the take the kinetic energy from a WT rotating mass. This controller is well-explained in several publications [8], [13], [27]. It is control loop that 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:

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

where H_{syn} express the synthetic inertia (sec) and f_{sys} system frequency (p.u). Implementation of synthetic inertia controller is depicted on Figure 2.
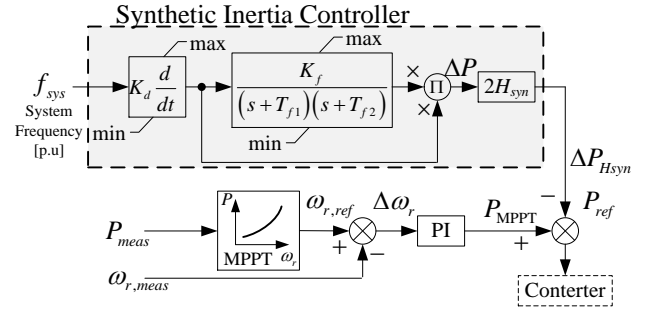

Figure 2.   Representative diagram of Maximum Power point Tracking controller and Synthetic Inertia Controller (shadowed) [1].

Several publications relate the main aspects about synthetic inertia [28], [26]; however, there is not a paper that formally discusses the trigger mechanism to activate the synthetic inertia controller. Three activation schemes are presented and discussed in this paper:

A. Scheme I: Continuously Operating

This is the approach assumed in several publications [15], [7], however is unrealistic. Many publications assume there is not a triggering mechanism for the synthetic inertia controller, in fact, it means the inertia controller receives continuously a system frequency measurement (f_{meas}) signal from the AC system and it is used to derivate the inertial power (*ΔP*) using (1) –see Figure 2. This is an unrealistic control scheme because kinetic energy is taken from rotating mass continuously and wind turbine is not allow the recover its kinetic inertia in typical normal operation. However, this scheme is included in this paper only for comparison purposes.

B. Scheme II: Under-frequency Trigger

This activation scheme uses a *trigger controller* that produces a *trigger signal* (*ts*) based on a comparator. The controller compares the system frequency measurement (f_{meas}) with a *frequency threshold* (f_{act}), the output signal is generated to activate the synthetic inertia controller if system frequency measured is below the *action frequency* (f_{act}). The activation function of this controller is as follow:

$$\text{Trigger Signal:} \begin{cases} ts = 0 & f_{meas} \geq f_{act} \\ ts = 1 & f_{meas} < f_{act} \end{cases} \tag{2}$$

C. Scheme III: Maximum-Frequency Gradient Trigger

This activation scheme uses a controller that is similar to the typical logic control observed in ROCOF relays. It measures the frequency and calculates *df/dt,* once the rate of change of frequency exceeds the pre-determined setting (df/dt_{act}), a trip signal is initiated. The activation function of the maximum-frequency gradient trigger for synthetic inertia is defined by:

$$\text{Trigger Signal:} \begin{cases} ts = 0 & \left| \dfrac{df_{meas}}{dt} \right| < \left(\dfrac{df}{dt} \right)_{act} \\ ts = 1 & \left| \dfrac{df_{meas}}{dt} \right| \geq \left(\dfrac{df}{dt} \right)_{act} \end{cases} \tag{3}$$

The df/dt_{act} is threshold that activates the synthetic inertia controller. This approach has been used for years on ROCOF relays and it is used on [29] to activate the synthetic inertia, there is not discussion about its implication on that reference.

IV. SIMULATIONS AND RESULTS

This section presents simulations and results over a *Test System*. An equivalent synchronous generator (GS) and loads are used as representative equivalent model of a traditional power system and a small transmission system is included considering two voltage levels –see Figure 3. VSWT using an *Electrically Excited synchronous generator* (EESG), Type 4-C, is used on the simulation for demonstrative purposes. The output of the generator is passed through the full rated power converter to the grid. In this paper, an equivalent model of a cluster of 30×4.5MW direct-drive EESG is considered (similar characteristic of the Enercon E-112). Figure 4 depicts the general structure of a VSWT the model for the direct-drive EESG. This model uses a back-to-back converter, details of all models used can be found on [30], [31], [32]. The parameters used for these models are escalated to simulate an equivalent 4.5 MW wind turbine. DIgSILENT® PowerFactory™ [33] is used for time-domain simulations and *DIgSILENT Simulation Language* (DSL) is used for dynamic modelling [34]. Figure 5, 6, and 7 show the DSL models created for the activation schemes considered in this paper.
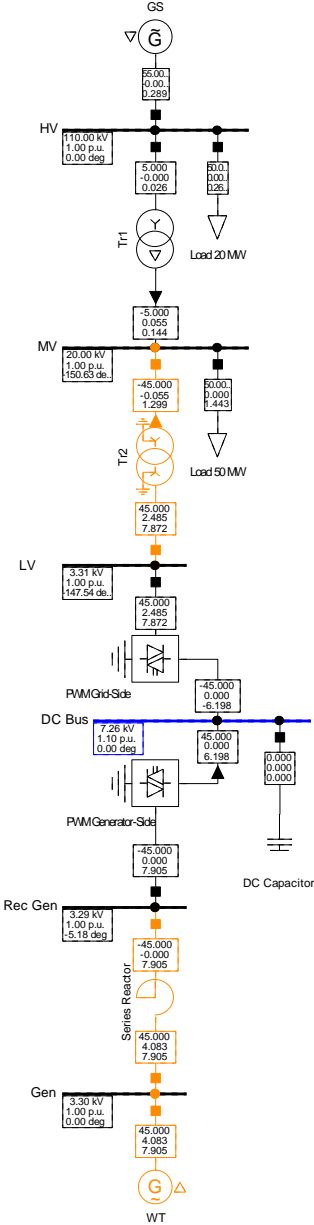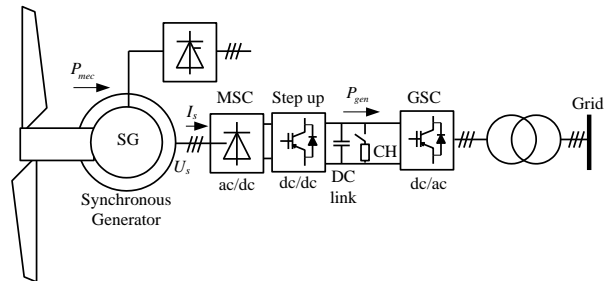

Figure 3. Test System.

Figure 4. General structure of a variable-speed wind turbine with a direct-drive synchronous generator with full-scale frequency converter.
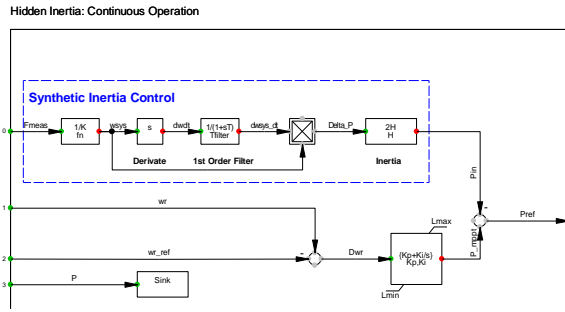
Figure 5.   DSL Model *Scheme I*: Synthetic Inertia Controller using Continuous Operation Scheme for triggering.
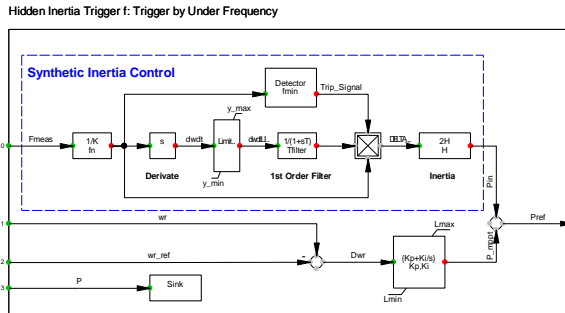

Figure 6.   DSL Model *Scheme II*: Synthetic Inertia Controller using under-frequency trigger.
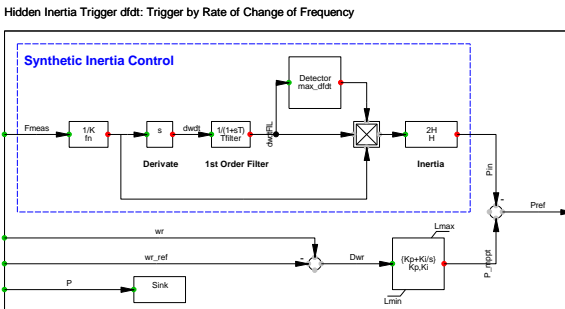

Figure 7.   DSL Model *Scheme III*: Synthetic Inertia Controller considering a ROCOF trigger.

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. The system frequency disturbance consists of the sudden load increase (ΔP_L).

Plots of electromechanical variables on the traditional power system (equivalent synchronous generator -GS) side and wind farm side are shown on Figure 7 and 8 respectively. The activation scheme based on continuously merriment signal (*Scheme I*) is the only scheme that includes a negligible time delay on the activation of synthetic inertia, it is an expected result because the control scheme is acting continuously to any frequency change. The small time delay found on the response is provided by the first order filter used to remove the noise amplification on the derivate of the measured frequency.

Activation *Scheme II* and *III* require activation condition must be satisfied before activate the synthetic inertia

controller, and it depends on the whole system frequency response where the characteristics of the traditional power system (equivalent synchronous generator) has impact on the dynamic performance.
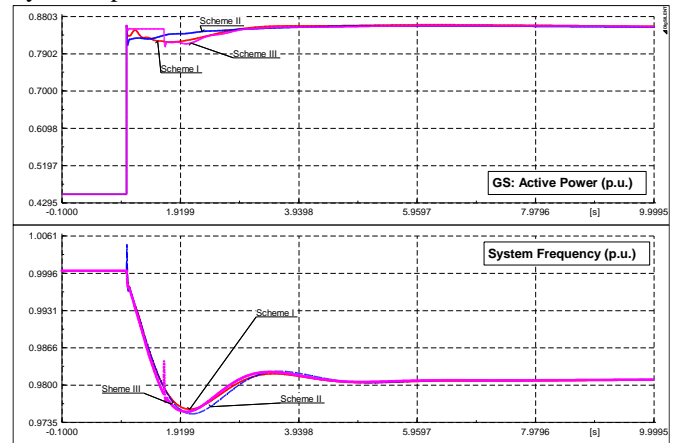

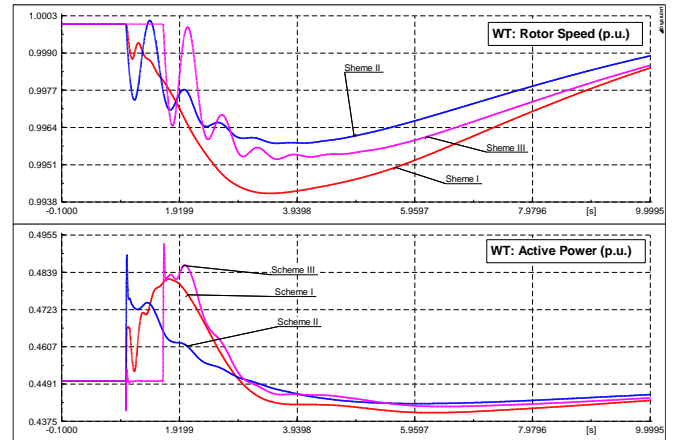Figure 8.   Grid Side: Simulation Results

Figure 9.   Wind Farm Side: Simulation Results

Simulation results show the under-frequency trigger activation (*Scheme II*) produces the second faster *activation time* ($t_a\sim$2msec) after the frequency disturbance detection (f_{act} = 0.998 p.u.). The activation time for maximum-frequency gradient trigger is the longest ($t_a\sim$450msec), it is because the df/dt depends on the total system inertia and for the tests system considered this value is extremely highly compared with the system inertia provided by the controller (H_{sys} = 0.25 sec). Details about activation time and inertial power (ΔP) contribution are shown on Figure 10. Inertial power provided by the activation Scheme III is the largest and it is intrinsically related with the threshold df/dt_{act}. The initial peak of inertia power after the activation process is large in all cases and it is caused by the df/dt, however, *Scheme II* exhibit a larger peak than *Scheme I*. This initial peak indicates a quick response on releasing large amount of kinetic energy in the rotating masses on the WT caused by the power electronic converter. However, discharge of energy to the grid is only for a short period available, and potential dangerous consequences on the mechanical par must be
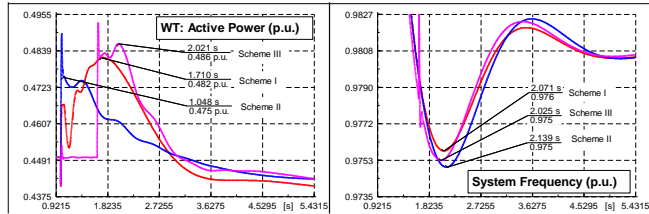
seriously evaluated.

Figure 10. Details of wind farm active power production and system frequency.

The effect of the activation scheme on the rate-of-change-of-frequency and frequency nadir (f_{min}) is very important on the system frequency stability. The positive effect of all schemes is shown on Figure 11. The synthetic inertia modifies the df/dt, however, activation *Scheme I* causes the slower change ($f_{min}\sim0.976$p.u @ 2.071sec) and *Scheme II* and *Scheme III* produces almost the same change on f_{min} but *Scheme III* reach the frequency nadir first ($t_{min}=2.025$sec) compared with *Scheme II* ($t_{min}=2.139$ sec).
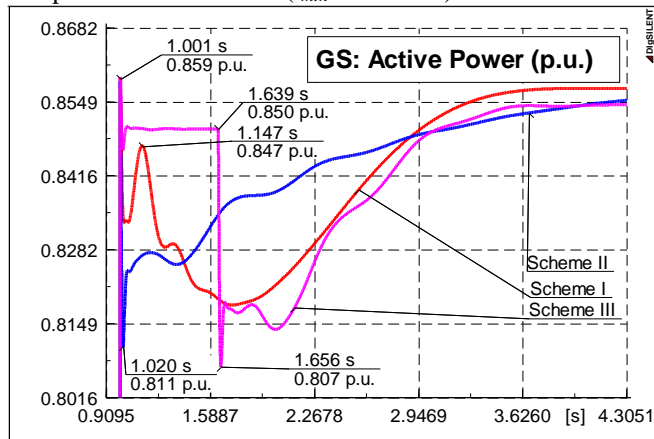

Figure 11. Details of frequency response of the traditional power system side considering the activation schemes.

An important aspect about the impact of activation schemes is the power production of the traditional synchronous generator. The long activation time on the synthetic inertia controller caused by the *Scheme III* imply traditional generator must quickly react to cope with the system frequency disturbance, that situation makes this activation scheme unpractical in a future electricity network with low inertia. *Scheme II* produce a fast response and initially reduce the active power solicitation form the traditional generator, however, *Scheme II* provide the best performance in term of release the requirements of active power from the traditional generators.

V. CONCLUSION

This paper proposes three activation schemes for synthetic inertia controller on WTG based on full rated power converters: (i) continuously operating triggering, (ii) under-frequency trigger and (iii) maximum-frequency gradient trigger. Time-domain simulations over a simple test system

are used to evaluate the system frequency response considering the activations schemes proposed. The main contribution of this paper is the three schemes to activate the synthetic inertia controller and its assessment. Results demonstrate an outstanding system frequency response when the synthetic inertia is activated using the under-frequency trigger. However, further evaluations are required. The author is proposing the under-frequency trigger and maximum-frequency gradient trigger as main activation scheme considering the inertia values on the system to be used.

VI. REFERENCES

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