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A New Frequency Response Estimation Method for High Wind Penetration

Considering Wind Turbine Frequency Support Functions

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Abstract: To achieve renewable energy targets, more Wind Turbine Generators (WTGs) are being integrated into many power networks around the world. However, unlike traditional synchronous generators, modern WTGs are driven by power electronic devices which provide almost zero inertia and frequency response to frequency related events such as generator tripping. Wind manufacturers and researchers have been working on synthetic WTG inertia support, which can better utilize the rotational nature of WTGs. However, synthetic inertia alone may be insufficient under certain circumstances to prevent automatic Under Frequency Load Shedding (UFLS) after generation tripping, which causes security concerns for network operation. Consequently, WTG Active Power Control (APC, similar to governor control) should be activated to improve network security. However, APC will costly reduce WTG output from the maximum power point and result in financial concerns. Therefore, when and how much APC service should be activated becomes an extremely important question, which has not been addressed in the literature. This paper develops a new method to quickly estimate frequency response caused by generator tripping so system operators can use this proposed method to continuously evaluate inertia and headroom

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competency and accordingly activate the amount of WTG inertia and APC required for reliable system operation.

Keywords: Frequency estimation, wind power, power system analysis computing.

1. Introduction

Wind penetration levels have recently increased significantly around the world. The installed wind capacity was around 24GW in 2001, but this figure has grown to 194GW in 2010 [1]. By the end of 2011 the possible maximum instantaneous wind penetration in some countries and regions has surged to a very high level – Ireland (108%), Iberian Peninsula (118%), Texas (41%), Western Denmark (196%) and South Australia (119%) [1-2]. With more and more non-synchronous generation (including photovoltaic power) in the existing power networks many independent system operators (ISOs) have recognized some important issues associated with such development and frequency response is one of these issues highlighted in their reports and studies [2-4].

Popular new wind technologies – Doubly Fed Induction Generator (DFIG) and Full Converter Generator (FCG) – do not generally provide inertia and governor support for network frequency response [5]. Moreover, historically Wind Turbine Generators (WTGs) have not been required to actively participate in frequency regulation [6-7]. Therefore, the existence of such non-synchronous generators displaces conventional synchronous machines and approximately 2/3 of the synchronous generators will be de-committed and 1/3 will be re-dispatched according to the Western Wind and Solar Integration Study (WWSIS) [8]. It is reported that the Eastern Interconnection of USA and Canada has shown a downward trend of inertia response over the last 15 years [9]. With potentially more non-synchronous generators to be integrated into the power grid, the total network inertia may

2

eventually drop to a critical level at which a generator trip event (statistically occurs several times every month for large networks [3, 10]) can make the network frequency decrease below the frequency limit consequently triggering automatic Under Frequency Load Shedding (UFLS) action and causing network stability and security concerns.

This frequency response issue has been identified by many ISOs around the world [3-4, 11-13] and industries and researchers have already developed some synthetic inertia control strategies for frequency support [14-18]. But WTG inertia alone can cause a second frequency nadir that may be worse than the first one [11], therefore the Active Power Control (APC, similar to governor control [17-18]) function is required for system security. The APC works by intentionally reducing the efficiency of WTGs (as known as de-loading) through pitch control, which means wind power is generated at a level which is less than the maximum so extra power can be produced during tripping events for frequency support. Clearly, APC for frequency response is a costly function, which will only be required during a circumstance of low inertia and governor reserve scenarios. Most likely the APC action for the frequency support purpose will only be needed collectively for a small fraction of period per year, thus the expensive APC should not be activated at all time. Therefore, the important questions are: How should the necessity of APC be recognized? When and how much APC should be activated? At the same time, how much synthetic inertia should be brought on-line? All these questions have not been addressed in the current literature.

In this paper a new method for frequency response estimation is proposed, in which both frequency and voltage dependence of the load has been modelled for achieving more accurate and realistic results. This method can incorporate both traditional synchronous

machines and modern WTGs with synthetic inertia and APC functions. Therefore, ISOs may utilize this new method to constantly assess the competency of system inertia and available fast ramp-up reserve (also known as headroom) and then the amount of WTG synthetic inertia and APC services can consequently be activated to ensure system security. This method can provide invaluable information to ISOs on frequency response performance and it can become a very useful tool for power network operation with high wind penetration.

2.   Studied Power Network and Frequency Operation Criteria

The studied network contains over 2000 buses and branches and more than 300 different generators with a total installed capacity of around 40,000MW. This network has been divided into 4 regions – Area A (Eastern part), Area B (mid Eastern part), Area C (mid Western part) and Area D (Western part). Some typical seasonal scenarios with loads ranging from 15,000MW (low demand) to 29,000MW (high demand) are studied with full dynamic models. This large network is modeled and simulated in PSS/E [19] (PSS/E has been widely used for power system analysis around the world).

As for frequency operational criteria, different ISOs have different UFLS thresholds and allowable frequency bands. They are summarized in Table 1 [3]. In this research, conservative criteria have been chosen based on Table 1, −1.6% for UFLS threshold and ±0.2% for the allowable band of normal operation. Further, both frequency and voltage dependence of the load should be considered for more accurate results. The frequency dependence – often expressed as a load frequency relief factor – is selected to be 1% of the load for every 1% frequency deviation according to [20]. As for voltage sensitivity, it normally depends on the studied network, and this will be addressed in the next section.

4

Table 1. Frequency Response Standard within NERC [3]

Interconnection	UFLS Threshold Δf	Allowable Band Δf
East	−0.83%	±0.067%
West	−0.83%	±0.067%
Texas	−1.17%	±0.25%
Hydro Quebec	−2.50%	±0.067%

3. Proposed Method for Frequency Response Estimation

3.1 Proposed Method

To continuously evaluate the potential frequency nadir a much simpler model has to be developed rather than using a complete network model. This is due to the fact that the full model needs a huge amount of measured parameters before simulation such as machine outputs, load power values, tap changer positions, series/shunt compensation settings, and transmission line status and so on. Moreover, it takes a long time to properly validate power flow of a large network against the measurement and then it also requires quite some time to run the full model for all possible scenarios to obtain a value of the potentially lowest frequency nadir point.

3.1.1 Mathematical Model

A new method for frequency response estimation is proposed to solve the complication of using a full network model. This method is referenced to an average system frequency model established in [21] and this average model is modified and improved in this paper to estimate frequency nadir points. Considering all swing equations of online generators, the summation of all these equations becomes (1).

$$2 \cdot \frac{\sum_{i=1}^{n} H_i \cdot VA_i}{\sum_{i=1}^{n} VA_i} \cdot \frac{d \frac{\sum_{i=1}^{n} H_i \cdot VA_i \cdot f_{i_{pu}}}{\sum_{i=1}^{n} H_i \cdot VA_i}}{dt} = \frac{\sum_{i=1}^{n} P_{mi}}{\sum_{i=1}^{n} VA_i} - \frac{\sum_{i=1}^{n} P_{ei}}{\sum_{i=1}^{n} VA_i} \tag{1}$$

Where, H_i, VA_i, f_i, P_{mi} and P_{ei} are inertia (s), machine base (MVA), machine

frequency (pu), mechanical power (MW) and electrical power (MW) of the ith generator. For simplicity, Eq. (1) can also be expressed in a centre of inertia (COI) / centre of frequency (COF) [22] format as in (2).

$$2 \cdot COI \cdot \frac{dCOF}{dt} = P_{m\_total} - P_{e\_total} \qquad (2)$$

3.1.2 Model Modification and Improvement

Further to the average frequency model, active governor models are separated in this study from the non-governor models. This is to accurately present how frequency regulation works in reality. Moreover, the electrical power calculation has been greatly changed in this paper. Previously, the electrical power only relied on load frequency model, but this calculation may not be accurate enough. Because realistic system loads cannot purely be constant power with frequency dependence and based on observations they should also have voltage dependence. According to the advice from the local ISO, the constant current model was applied to real power load and the constant impedance model to reactive power load in the studied system.

Based on the results of Fig. 1, it is found that frequency disturbance (generation tripping) may also deeply affect network voltages [Fig. 1 (b)], which will consequently have a significant impact on the load [Fig. 1 (a)]. Therefore, this voltage effect should be considered in the calculation model. However, since voltage information is not available in the model according to (1) and (2), load (or electrical power) voltage dependence has to be estimated from frequency deviation, which is partially related to voltage variation during the tripping event. It should be noted that the voltage effect may not directly be factored into the load frequency relief relationship as the voltage effect on load may occur in a very different period after disturbance compared to the impact of system frequency [Fig. 1 (c)].
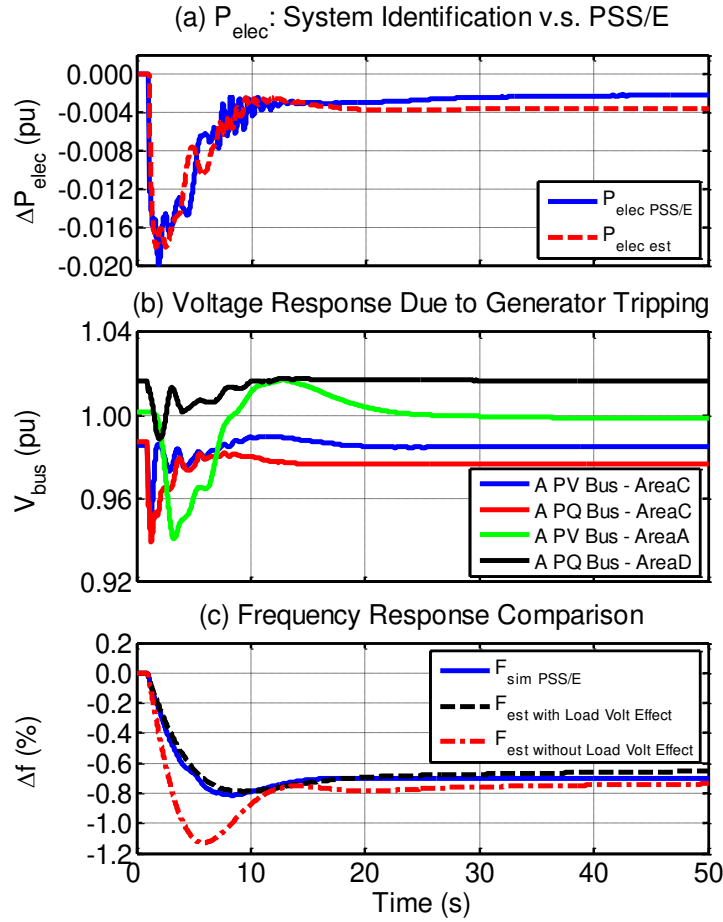
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Fig. 1. Overall voltage effect on electrical power during generation tripping

Based on (1) and (2), a method for frequency response estimation is proposed and illustrated in Fig. 2. The electrical power consists of a constant part, a frequency dependence part and a voltage dependence part. The constant part is the summation of all mechanical power before disturbance, so both load and line loss are considered and the system should initially be balanced. The frequency dependence part is built based on the load frequency relief factor, and this was addressed in the previous section. The voltage dependence part has to be constructed from frequency deviation. A transfer function (Estimator in Fig. 2) was estimated by system identification with the data from one instance of the full model simulation. For a certain scenario, after a generation trip in the full

network, the electrical power and rotor speed of all generators needs to be recorded and the COF and total electrical power are calculated as in (1). Then the estimator shown in Fig. 2 can be determined by system identification. It should be noted that none of load frequency dependence should be modelled during the system identification process to ensure only the voltage effect can be captured. After that the resulted values from the estimator are proportionally scaled if necessary based on the loading level of the scenario. Estimation of the load-voltage dependence is essential for a valid result. Fig. 1 (c) shows that if the estimation is conducted without considering this load-voltage dependence, the accuracy of result cannot be maintained. Validation of this approach will be conducted in the next section (Section 3.2), and the results show a reasonable match between the frequency response by the proposed estimation method and the frequency response by the full PSS/E simulation.

3.1.3 Discussion

This proposed method only needs real power outputs from all on-line generators and does not require other measurements and network load flow validation. Since normally only a fraction of all generators are participating for the service of fast frequency regulation and such service providers are relatively stable over a period of time, the estimation model in Fig. 2 is in a much simpler form than that of a full model, so the developed method is much faster and less complicated. This model however, does not consider small signal oscillation, line power transfer capability and voltage stability limit. Therefore, this method can estimate frequency response, but the estimation will not be 100 percent accurate. As for the final solution, full model verification in PSS/E is advised and the discretion of an experienced system operator is also extremely important for the ultimate decision.
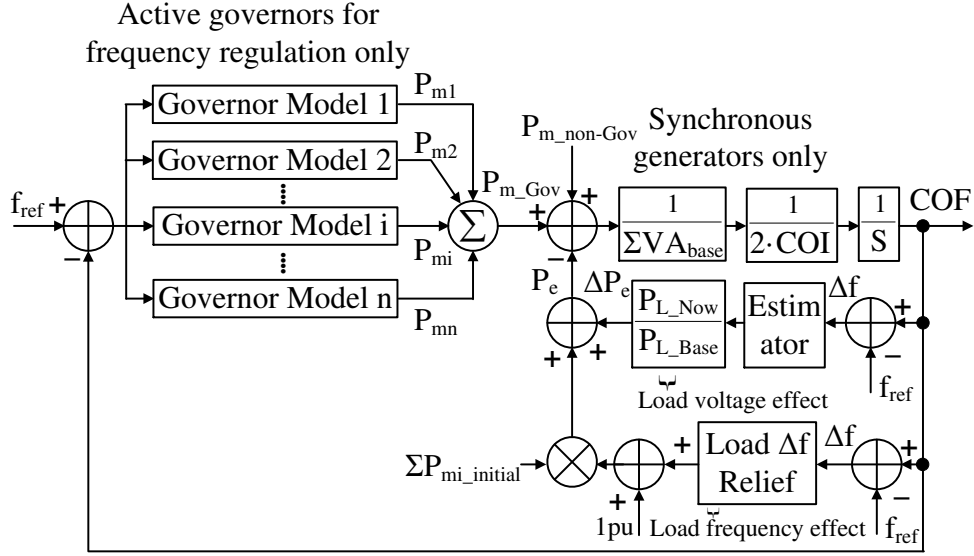
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Fig. 2. Proposed method for frequency response estimation

## 3.2 Frequency Response Comparison: Full Model versus Estimation

In this section, frequency response (due to generation tripping) estimated by the proposed method is validated with that of the full model simulation results from PSS/E. Verification is conducted under different tripping combinations – machine locations, number of generators, non-governor/governor units, power outputs and loading scenarios. The results are shown in Figs. 3 to 5.

In summary, the frequency response curves estimated by the proposed method are reasonably close to those simulated by the full PSS/E model, in terms of frequency nadir time and magnitude. Many more frequency responses have randomly been conducted under different scenarios in this study and all of them have shown a close agreement with those of the full model simulation. For system evaluation purposes (e.g. frequency response), network operators need a tool for network performance analysis which should be as accurate as PSS/E with a faster and simpler process. The developed new method will fulfil such requirement. This is also the reason of comparing the results of the proposed method
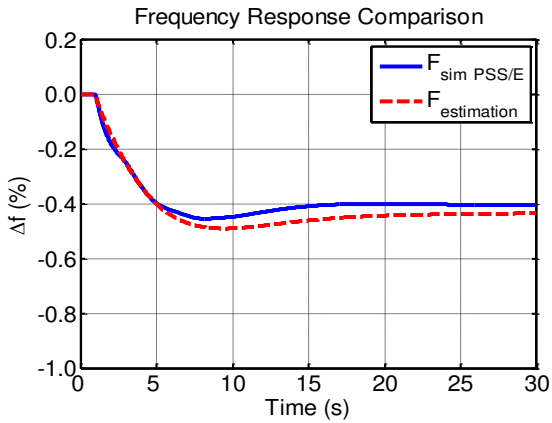
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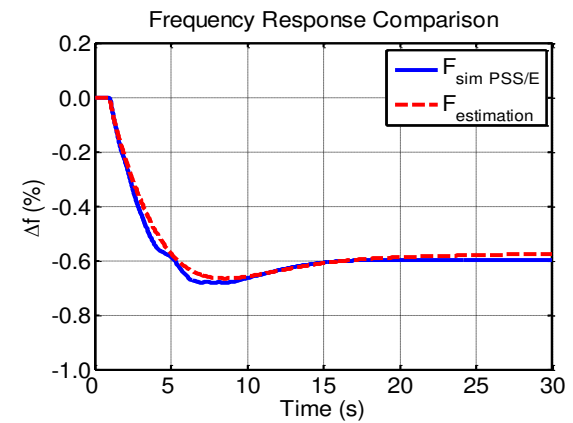with those of the full PSS/E model.
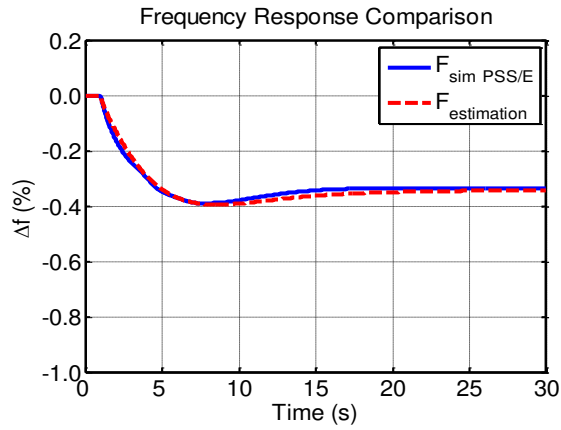
(a) 1 non-gov unit trip (654MW) in Area B
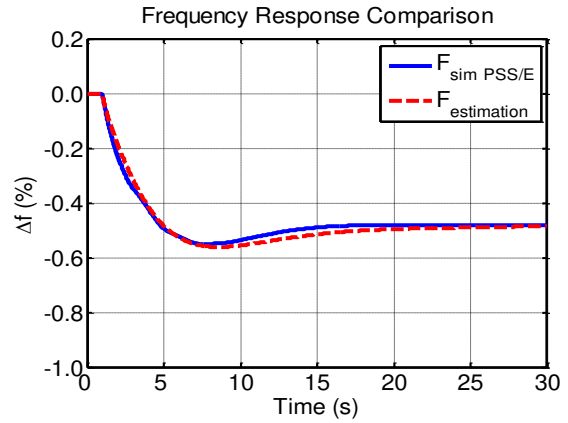
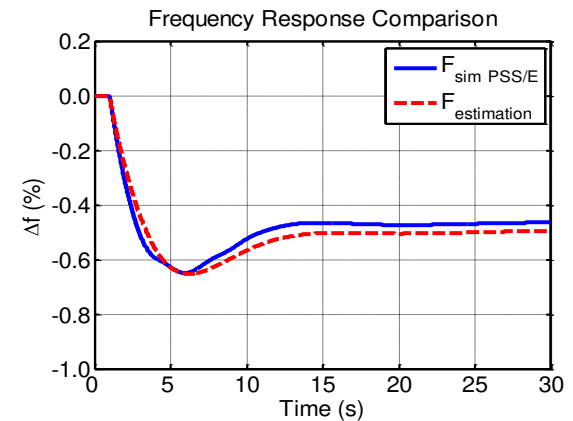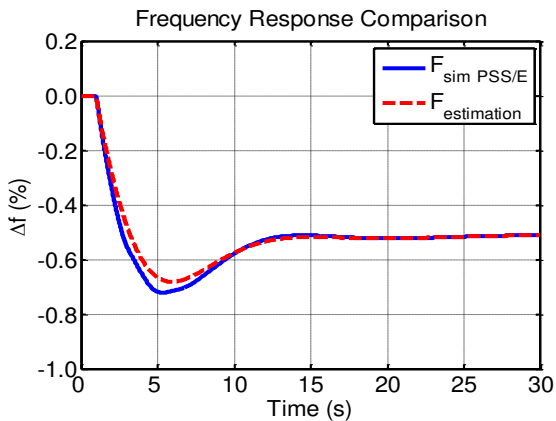(b) 2 non-gov units trip (928MW) in Area B

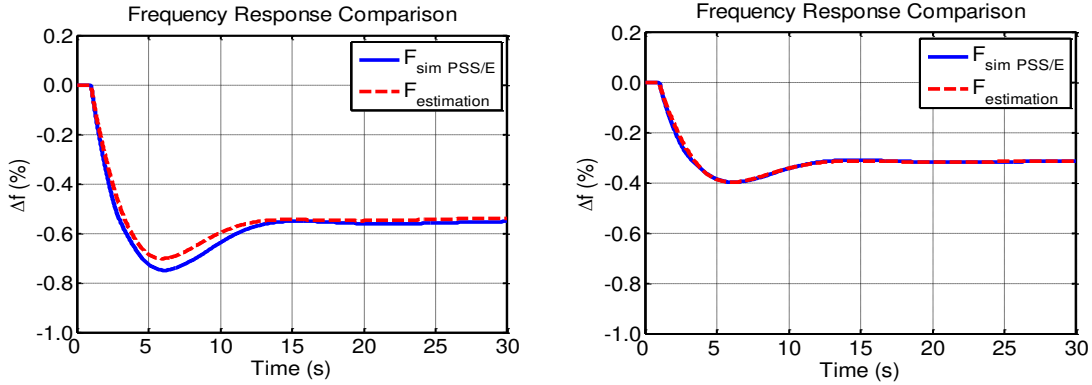(c) 3 gov units trip (725MW) in Area A

(d) 3 non-gov units trip (1100MW) in Area C

Fig. 3. Winter high scenarios

(a) 2 non-gov trip (935MW) in Area B   (b) 2 gov and 2 non-gov trip (863MW) in Area C

Fig. 4. Summer low scenarios

(a) 2 non-gov units trip (877MW) in Area B   (b) 2 gov units trip (490MW) in Area B

Fig. 5. Winter low scenarios

3.3 Extension of the Proposed Method: WTG with Inertia and APC

In this section, the proposed method will be extended to accommodate modern WTGs with frequency support functions – Inertia and APC. The well accepted GE WTG model equipped with WindInertia and APC (with the recommended parameters adopted) [18] is implemented in this study. Its control scheme is shown in Fig. 6 [18].

The challenge is to accommodate the WTG model, which does not act like a synchronous machine, into the proposed model that is based on an average synchronous machine model shown in (1) and Fig. 2. Since (1) is only for synchronous machines the existence of WTGs should not affect COI and power base in the proposed model. Therefore, the idea is to add the WTG model by considering its real power contribution during frequency response. WTGs normally behave as negative loads and they only actively participate in frequency regulation during disturbances by providing extra real power. Thus only the additional power from WTGs will be counted for mechanical power contribution

11

in the proposed model and normally WTGs should have no impact on the model. The extended estimation model is illustrated in Fig. 7. This model extension will be further verified in the next section.
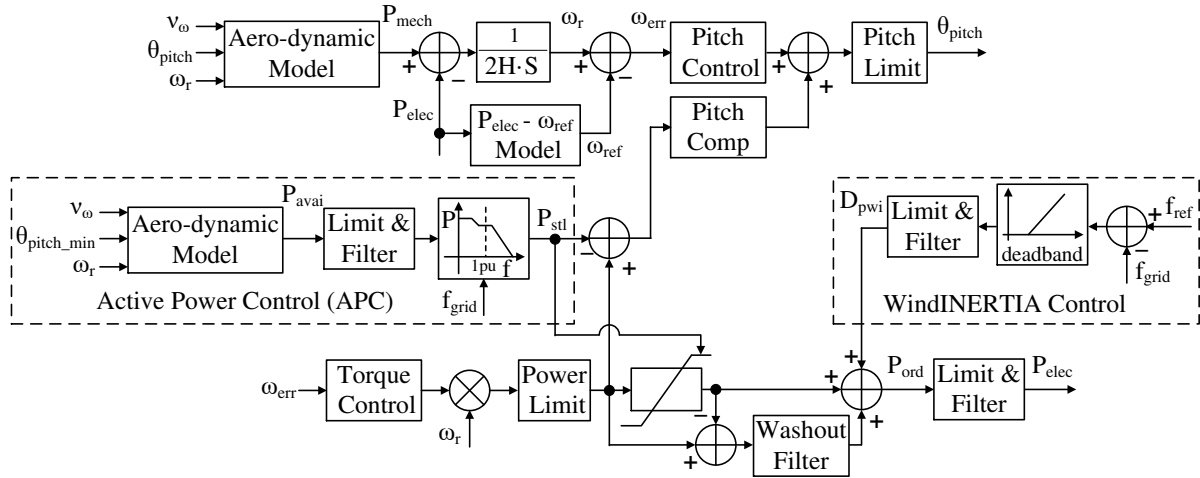

Fig. 6. GE WTG model with inertia and APC functions [18]

4. Justification of Activating Wind Generator Frequency Control Functions

This section will present the reasons why WindInertia alone may not be sufficient under certain circumstances; therefore costly APC has to be activated.

4.1 Wind Generator – Inertia Support Only

Due to relatively low WTG penetration in the studied network, currently there is no concern on UFLS caused by generation tripping. This can also be observed from the frequency response conducted in Section 3 and the frequency excursion magnitudes were not even close to −1.6% (UFLS threshold). If the normal operational frequency band (±0.2%) is taken into account, the concerning frequency deviation should be around 1.4%. Realistically, a certain safety margin should be applied. However, frequency response is still not a critical issue under current conditions of the network.
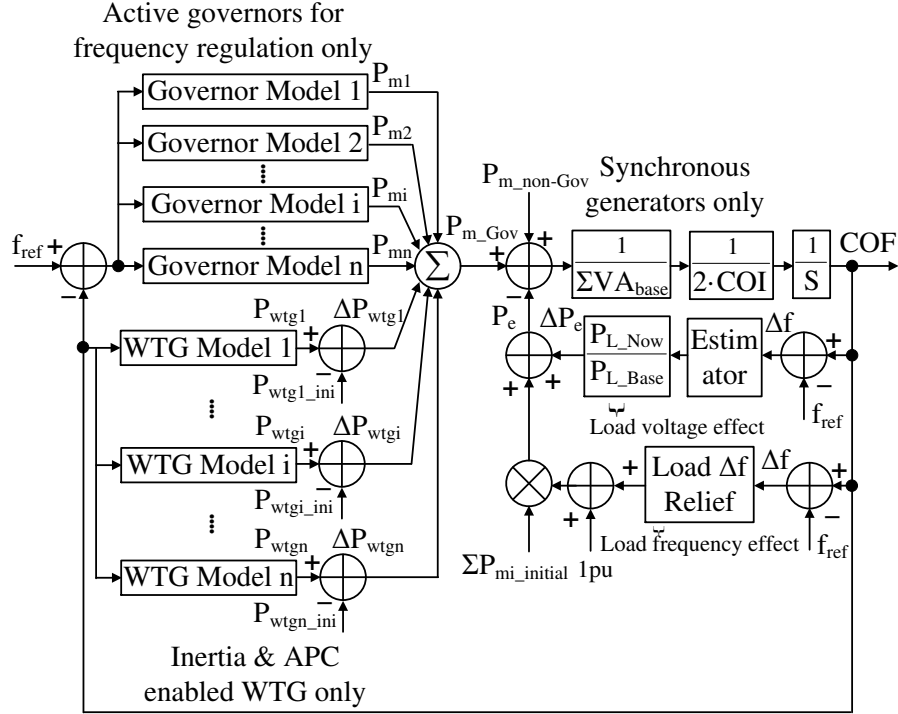
Fig. 7. Proposed method with WTG frequency control functions

Considering the rapid development of wind farms around the world, frequency response may become a serious problem in future. In this research, 7,800MW of non-synchronous generation has been integrated into the studied network to displace synchronous machines in Winter Low Load scenario (15,970MW demand), which represents 48.8% penetration. If none of the WTG frequency control functions are activated, frequency can drop by 1.6% after a trip of generation (877MW) as illustrated in Fig. 8. This is much more than the concerning level of 1.4% so it is very likely to trigger UFLS. This result can successfully be estimated using the proposed method. Since the whole network inertia is lower than expected, WTG inertia support should be initiated. It should be noted that in this paper the WindInertia and APC (de-loading) functions are activated only if wind speed of a wind farm is high enough (alternatively only if the ratio of WTG generation to its rating is high enough). Otherwise, WTG is prone to stall, and its inertia cannot be

13

utilized. In other word, the responsibility of a wind farm for frequency support should be aligned with its power generation.
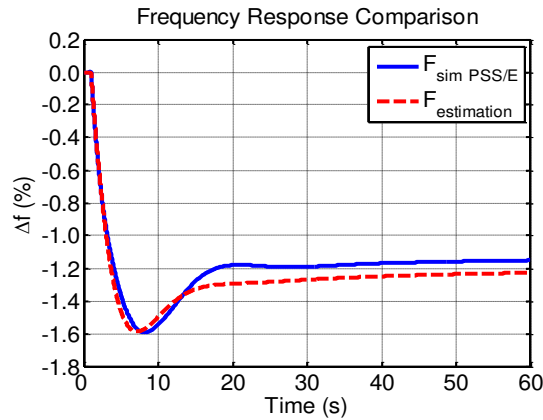

Fig. 8. Winter low – 48.8% WTG: 877MW trip in Area B

If the WTGs with 917MW power generation are called for inertia support, frequency response will certainly be improved as depicted in Fig. 9 (a) where the frequency deviation is 1.48% compared with 1.6% in Fig. 8. However, this does not bring the system above the critical level – 1.4%. More inertia support is required. It can be noted that the estimated frequency response starts to show a second frequency nadir. This is mainly due to the way of simulating electrical power changes in the proposed model. It is inevitable that the estimated electrical power will have small difference to that of the full model, so sometimes mechanical power is very close to electrical power at the first frequency nadir but just cannot catch up with electrical power [Fig. 9 (b)]. As a result, the estimated frequency curve has some difference from the full model simulation. However, as shown later in the section this small mismatch does not have much impact on the decisions to be made based on the estimation.
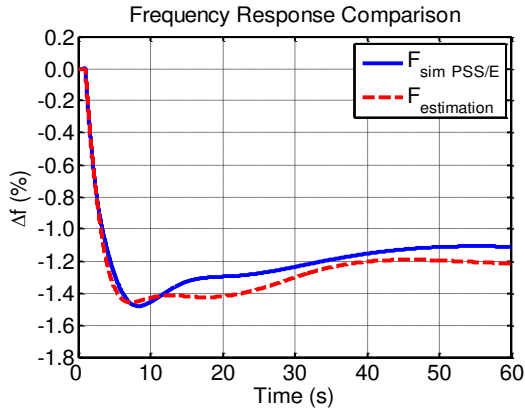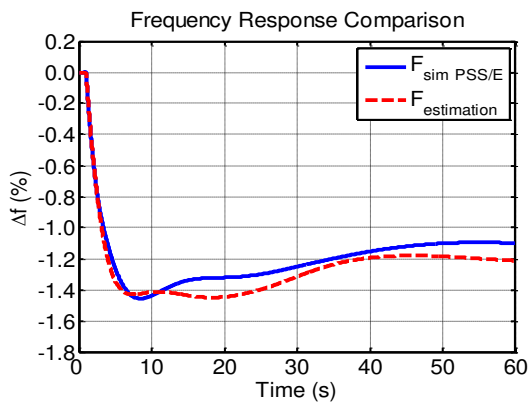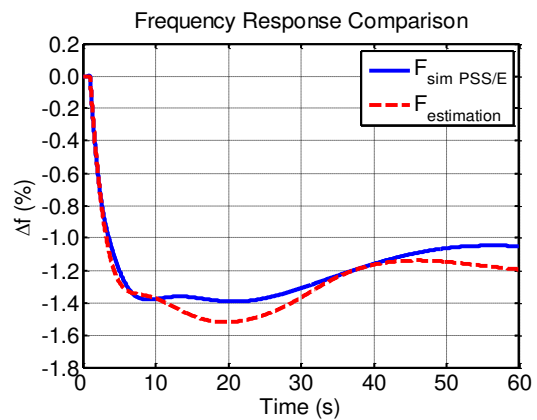
(a) 917MW WTG with Inertia control
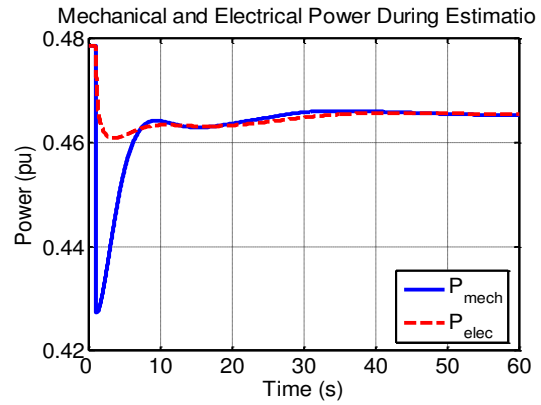
(b) P_mech and P_elec in proposed model

Fig. 9. Winter low scenario (48.8% WTG) – a fraction of WTG with Inertia control

As activating WindInertia control of 917MW WTGs is not enough to mitigate the frequency response concern, more wind farms are requested to participate in WindInertia control. However, no matter how many wind farms actively contribute to the inertia pool, the frequency deviation cannot be brought to a level, which provides a decent margin above 1.4%. Some examples of this process have been demonstrated in Fig. 10. It is worth noticing that if too much WindInertia has been committed to frequency support the first nadir point may be increased to a healthy magnitude, but the second nadir may still be very close to the critical level – 1.4% as shown in Fig. 10 (b).

(a) 1138MW WTG with Inertia control

(b) 1871MW WTG with Inertia control

Fig. 10. Winter low scenario (48.8% WTG) – a fraction of WTG with Inertia control

The reasons for this phenomenon lie in the fundamental difference between a conventional synchronous machine and a modern WTG. To better explain this issue, a simple GE test network with two 333.3MW synchronous generators and one 100.5MW wind farm is simulated [18] and the results are shown in Fig. 11. During frequency response, because of the governor droop function the frequency level after disturbance will be lower than the pre-disturbance level. According to (3), a traditional synchronous machine will release more kinetic energy than that it will absorb, which positively contributes to frequency response. However, a WTG works on a different principle. Unlike a synchronous machine, the rotor speed of a WTG needs to be recovered after the first inertia contribution, and this will temporarily decrease WTG power output. Thus, a second nadir may appear if too much WindInertia has been activated. Overall, during the whole process a WTG will not inject extra energy into the grid as a synchronous machine. If the WTG rotor speed is not recovered, WTG may still not put additional energy into the network. Because a lower rotor speed can reduce WTG tip speed ratio and consequently power efficiency, WTG generation will drop.

$$E_{release} = \frac{1}{2} \cdot J \cdot \omega_{m\_before}^2 - \frac{1}{2} \cdot J \cdot \omega_{m\_after}^2 \qquad (3)$$
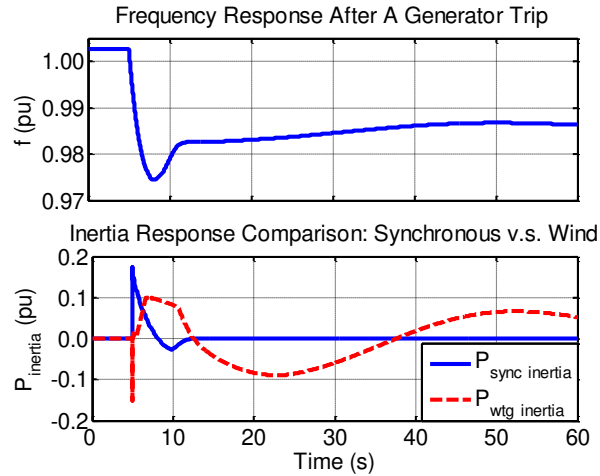
Fig. 11. Inertia response comparison: synchronous machine v.s. WTG

4.2   Wind Generators – Active Power Control Requirement

As shown in Section 4.1, although WindInertia control does not involve much cost, WindInertia alone may not be sufficient to bring inertia and headroom of a system into a safe level. Then the APC function should be activated to ensure the network is competent for a major tripping event. This is a much quicker responsive function than the traditional governor, so it should be more effective for frequency control. Fig. 12 demonstrates if the APC reduces wind farm output to 90-98% of the available power, the frequency nadir will be improved and left with a certain margin to the limit of UFLS. Although APC is costly, APC service is absolutely necessary for maintaining network security in this situation. For the APC settings from 90 to 98%, 1.3-1.35% frequency deviations can be observed in Fig. 12 (b), which provides a margin of 0.1-0.05% from the UFLS limit. Whether this margin is acceptable or not in reality is up to the judgment of the involved ISO.

It can be seen from Fig. 12 that frequency response improves with more APC commitment from the wind farms, and with less APC contribution (98% APC case) frequency deviation can become larger and the second nadir can become closer to the first

nadir. However, if 0.05% frequency margin is acceptable according to the local ISO, 98%

APC setting will certainly be much more economical than 90-95% APC setting during

operation. Therefore, it is important to evaluate the optimal amount of APC contribution

based on both frequency response security and APC commitment cost. However, this task

is beyond the scope of the current paper, and it needs to be further investigated in the future

research. It should be pointed out that Fig. 12 only shows one possible solution and it may

not be an optimal solution. The reduction of wind power due to the APC control was

mainly covered by the existing online synchronous generators without quick governor

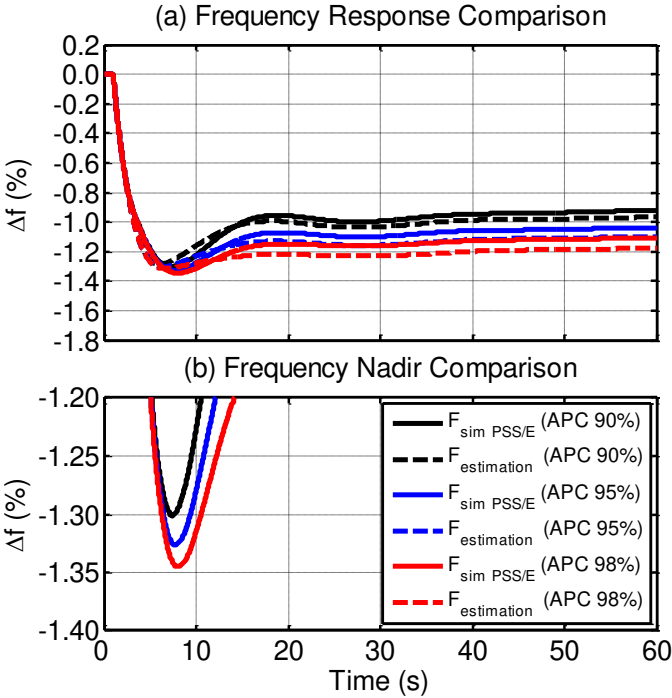services, so the total system headroom was not much affected.

Fig. 12. Winter low – 48.8% WTG: 1871MW WTG – a fraction of WTG with both WindInertia and APC (90-98% for frequency=1pu)

The estimated frequency response is very close to that of the full model simulation

as illustrated in Fig. 12. This once again validates the proposed method. As for the

electrical power issue mentioned in the last section, it becomes clear at this stage that this small estimation error will not have much effect on the decision making process. Because the objective is to avoid second frequency nadir and to leave a reasonable margin to the critical level (1.4%). Once the estimated frequency response starts to show the trace of the second nadir, measurement should be taken to resolve it. As the proposed method can be executed very fast, it can complete estimation for different combinations within a short time. Once a reasonable solution of APC is found, the proposed method should be able to predict the frequency response with a decent level of accuracy as shown in Fig. 12. It should be noted that the solution in this section demonstrated how the proposed model can be utilized for fast evaluation of frequency performance, and further research is needed to develop a strategy that can determine the required amount of WindInertia and APC participation in frequency response for network security using the developed method.

5. Discussion on Model Sensitivity of System Parameters

The developed model in Fig. 7 requires many parameters, and it may be more sensitive to some parameters than the others. In general, ISOs can acquire very accurate models of both traditional generators and WTGs, and their power generation information can be obtained every couple of seconds through supervisory control and data acquisition (SCADA) system. Therefore, fairly accurate values of many parameters are readily available, and discussions on model sensitivity will focus on the system parameters that are not measured or available and may vary during operation. On this ground, system center of inertia, WindInertia gain and load frequency relief factor are selected to analyze model sensitivity. Fig. 13 shows their impacts on frequency response.

It can be observed that system center of inertia does not have significant influence

on frequency response [Fig. 13 (a)], but the WindInertia gain that controls the wind inertia response magnitude has a reasonable impact on frequency nadir [Fig. 13 (b)]. In contrast, the load frequency relief factor may considerably affect frequency response [Fig. 13 (c)]. This implies that if the ISO uses an optimistic load frequency relief factor (a higher value, e.g. 1.6%, but in reality it is 1% instead), frequency deviation will be wrongly estimated to a relatively lower level. As a result, wind frequency support may be regarded as unnecessary; however, this may be really needed in reality.
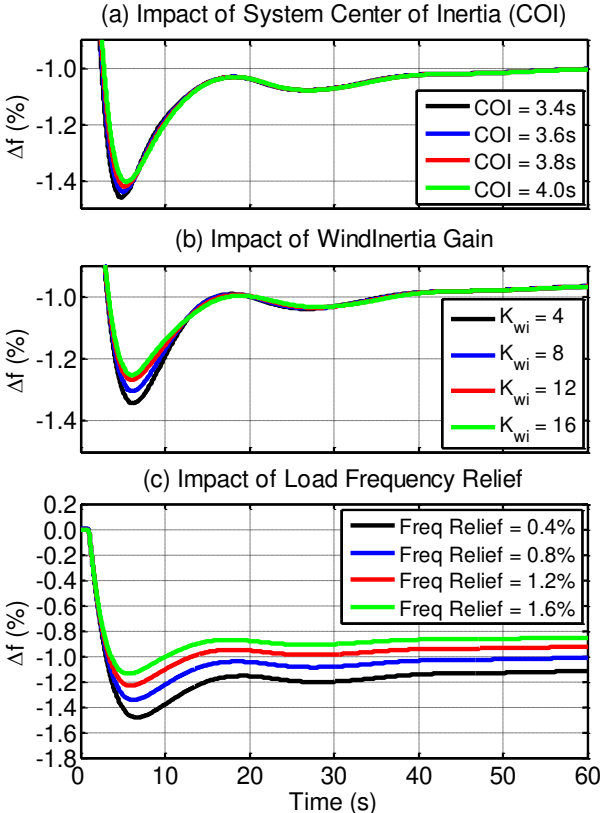

Fig. 13. Impacts of system center of inertia, WindInertia gain and load frequency relief factor on frequency response

6. Conclusions

This paper proposes a new method for estimating power system frequency response due to generation tripping. This method can include both conventional synchronous

machines and modern WTGs with frequency support functions – WindInertia control and APC. Moreover, both frequency and voltage dependence of the load has been successfully incorporated into the established model. A new load-voltage dependence model has been developed, and it has shown that this model is vital for the accuracy of frequency response estimation. The simulation results have shown excellent performance of the proposed method. It requires fewer parameters from the system, runs much faster in simulation and has an acceptable level of accuracy.

Increase of non-synchronous generation has displaced many traditional synchronous machines and this trend has raised concern on inertia and headroom competency of power networks. In the future, with a high level of non-synchronous penetration a common generator tripping may push grid frequency to drop below the limit causing UFLS, which significantly affects power system security. This situation should quickly be identified and WTG inertia support should be initiated. However, under certain conditions WindInertia alone cannot provide frequency support to a satisfactory level, so the costly APC function should be activated for system security. The proposed method can quickly provide the ISOs with invaluable information, such as whether the system is at a risk of UFLS, so the ISOs can accordingly take actions to resolve the risk. If the developed model is incorporated into the program of the ISO network, it will be extremely helpful to quickly estimate the amount of WindInertia and APC required for maintaining frequency response to an acceptable level. Future work will focus on how to systematically determine the optimal WTG inertia and APC support using the proposed method.

7. Acknowledgment

support through a Linkage Project.

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