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*Published in:*
CIGRE Science & Engineering

*Publication date:*
2018

*Document Version*
Publisher's PDF, also known as Version of record

# Wind power support during overfrequency emergency events

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## Abstract:

This article concentrates on designing of frequency control and protection strategies for wind turbines during overfrequency emergencies. Critical overfrequency event on North-Eastern part of the UCTE network on 4th November 2006 is considered as a base case for investigation. A single bus power system model is developed to analyse the protection settings for this case and then to propose and discuss the design and recommendations for overfrequency control settings for wind turbines.

The results of the investigation show that modification of the protection settings alone may not be sufficient to prevent frequency instability especially when wind power penetration is high and system inertia is low. Robust overfrequency emergency control strategies from wind turbines can therefore be required. The article provides the design for control parameter settings for different degrees of wind power penetration. The performance of the proposed frequency control with the developed settings is validated by means of simulations with the large scale pan-European model.

## 1. Introduction

Wind energy will increasingly make larger contributions to electricity generation throughout the world. It is expected that wind energy will meet 15.7% and 28.5% of European electricity consumption in 2020 and 2030 respectively [2]. In order to operate power systems in a reliable, secured manner and with stable frequency, generation should always be able to match demand in the system. There are many uncertainties in the system, namely uncertainties due to outages, load, generation, weather etc. Generally, these uncertainties are handled with the help of operating power reserves. However, if the power reserves are not sufficient to contain a sudden severe frequency change, the system might be driven further from an alert state into an emergency situation activating defence plans [3, 4, 5, 6]. Emergency situation with respect to frequency can be of two types – underfrequency and overfrequency. This article deals with overfrequency emergency situation for a power system operating with high penetration of controllable wind power generation.

During overfrequency events power generating plants must reduce their active power outputs depending on their scheduled frequency response capabilities. These overfrequency control capabilities and overfrequency sensitive modes are defined in the ENTSO-E network code [7]. Transmission system operators (TSOs) in Europe design their overfrequency stability measures considering these requirements during the alert state after a contingency [8], [9]. If the power system remains insecure after implementing the required overfrequency control in the alert state, other measures, known as special protection schemes, are required to restore the network to a stable operating point in the emergency state [9]. Such protection schemes against overfrequency instability are traditionally implemented for conventional power plants (CPPs) and HVDC transmission links. The generator rejection schemes generally involve tripping of the CPP unit, especially for hydro-generators [10], while the flexible control capabilities of HVDC transmission links

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KEYWORDS
Defence plans, emergency control, frequency stability, overfrequency, wind power

can be exploited for fast power flow changes across the connected AC networks [11]. In the latter case, the DC power can be either ramped down or up (taking advantage of the short-term overload capability) to assist frequency stability.

Frequency support from wind turbines (WTs) are of particular interest during these emergency situations, especially if penetration of wind power is high in such operational hours. Although, considerable research has been performed with respect to WT support during underfrequency situations [12, 13], however, WTs and wind power plants (WPPs) have not been widely investigated in the literature, particularly with respect to overfrequency control and overfrequency protection.

In high wind power generation scenarios, CPPs may be operated closer to their minimum regulating level, and therefore they may have limited ramping down capabilities. Accordingly, some CPPs might be de-commissioned or offline in future (high wind) scenarios. In such situations, the rotational inertia of the network can become worryingly low since converter connected controllable wind turbines do not inherently add inertia to the system [14]-[16], which can be a challenge for the network following a large disturbance when the rate of change of frequency (RoCoF) is high, resulting in high peak frequencies (zeniths) during overfrequency events. This, in turn, can trigger the overfrequency protection systems of generating plants resulting in frequency instability and cascading disconnections in the emergency state. Such situations can be particularly critical in island power systems, where the number of online synchronous generators and the rotational inertia is naturally low. However, similar events can also occur in interconnected systems, as was the case experienced in 4th November 2006, when the Union for the Co-ordination of Transmission of Electricity (UCTE) network was split into three areas with the North-Eastern area experiencing an overfrequency situation [1], [8]. This situation can be considered as an important benchmark case for assessing the impact and opportunities for WTs in analysing their protection settings and frequency control parameters. It is worth noting the general difference between control and protection settings of WTs here. Protection is the open-loop triggering of functions that disconnect WTs from the grid, whereas control (here) means continuously acting, while closed-loop response to reduce power generation from WTs during over-frequencies maintaining connection of the WTs to the grid.

In this article, the protection settings and the overfrequency control mechanisms for converter connected WTs are investigated during the alert and emergency states of a large scale power system. Furthermore, different wind power penetration levels are considered, in order to recommend more robust protection settings and control parameters. The recommendations are proposed based on the North-Eastern part of the UCTE, and accordingly, they are validated through simulations of the PEGASE pan-European model [17]. The proposed recommendations can be considered by the TSOs for future transmission networks with high shares of wind power. In Section 2, a UCTE single-bus model, which is adapted from the PEGASE pan-European model, is developed and validated with frequency measurements from 4th November 2006. Accordingly, considering this benchmark case, modification of the WT protection settings is implemented as per existing ENTSO-E recommendations [7].

The article is organised as follows. First the power system model with different wind power penetrations is briefly presented. In Section 3, overfrequency control for WTs is developed with modified protection settings. Based on the defined protection settings and control parameters, a sensitivity analysis is performed in Section 4 in order to recommend a droop value for various wind power penetration scenarios. Validation of the overfrequency protection settings and the proposed overfrequency control is presented in Section 5 by simulating the PEGASE pan-European model for the 4th November 2006 event. Finally, the conclusive remarks are reported, and the track for future work is briefly expressed.

## 2. Power system model with various wind power penetration levels

In order to investigate the impact and benefit of controlling the output of WTs, regarding frequency stability during overfrequency events, the North-Eastern area of the UCTE network disturbance on 4th

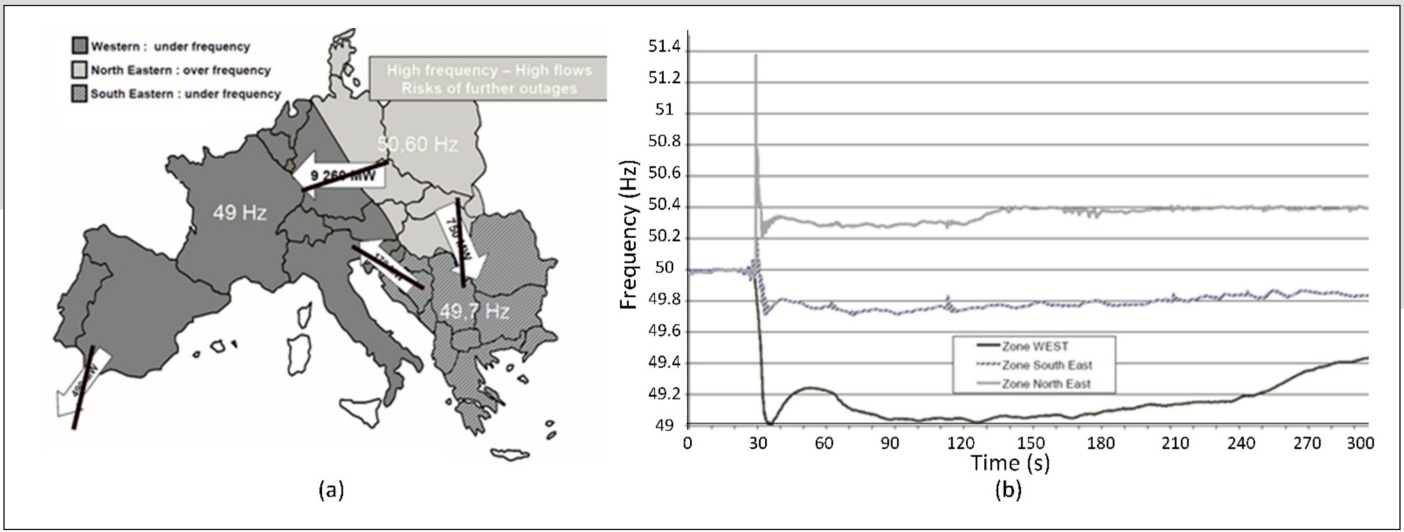


Figure 1. (a) Schematic map of UCTE network after the split into three areas and (b) Frequency response of the three areas [1]

November 2006 has been implemented using a single bus power system model. The single bus model is adapted from the PEGASE pan-European model [17], and the modifications introduced relate to the network split and modelling of the WTs. The recommendations on protection and control developed on single bus model is validated in detailed PEGASE pan-European model.

## 2.1. UCTE Disturbance on 4th November 2006

On 4th November 2006, the cascading events caused a large disturbance in the UCTE network and the overall network was split into three separate systems [1], as shown in Figure 1(a). After the split, the North-Eastern area (depicted by lightest grey in Figure 1(a)) had a generation surplus of more than 10 GW (i.e. around 17% of the total generation in this area) and therefore experienced an overfrequency situation. Figure 1b illustrates the frequency response recordings after the split in all the three areas.

After the split, the North-Eastern area had a wind power generation of more than 6 GW (10% of total generation) which started disconnecting at a frequency of around 51 Hz, according to [1]. The maximum transient frequency experienced by this isolated area went as high as 51.4 Hz. This transient peak could be a local frequency value observed resulting from measurement inaccuracies. Nevertheless, the frequency value rose as high as 50.78 Hz dynamically and shown afterwards in this article. The system frequency was lowered to 50.3 Hz through automatic pre-defined actions (primary control – standard and emergency range, activation of speed control of certain generating units) and automatic tripping of the generating units sensitive to high frequency value (mainly WPPs). Tripping of wind power generation with an estimated value of 6200 MW (approx. 5400 MW located in the North of Germany and 800 MW in Austria) played the crucial role in decreasing frequency during the first seconds of the disturbance. WPPs started reconnecting resulting in a further small increase in frequency at time=140 sec depicted in Figure 1(b). This situation was particularly concerning, since many of the conventional generators were already operating at their minimum output at this point and were unable to provide further frequency support (i.e. by lowering their power output). Through a co-ordinated manual control of CPPs (i.e. generator rescheduling, etc.) from all involved TSOs, the frequency was finally stabilized, being subsequently possible to reconnect the sub-systems together in more than half an hour [1].

## 2.2. Single-Bus Model of North-Eastern UCTE Area

As the emphasis in this article is mainly on wind turbines capabilities to support frequency stability during overfrequency events, only the frequency characteristic of the North-Eastern part of UCTE is modelled in this work, as this area was the only one experiencing overfrequency situation during the 4th November 2006 event. Also, this area had substantial proportion of installed wind power. This installed capacity is expected to increase further, mainly with the development of large offshore wind power plants in North Sea region. This provides further justification for the need of the studies provided in this article.

Single-bus models are usually recommended by ENTSO-E for frequency stability studies for Continental European (CE) network [18]. Figure 2 depicts the implemented single-bus model of the North-Eastern area of the UCTE network, including models for:

- steam, nuclear, and hydro governor [17]
- active power control dynamics of the IEC Type 4A WT model [19]
- overfrequency and underfrequency protection settings of the CPPs and WTs
- emergency active power control of the HVDC links to the neighbouring synchronous area
- frequency dependent loads with 1%/Hz self-regulation

[20].

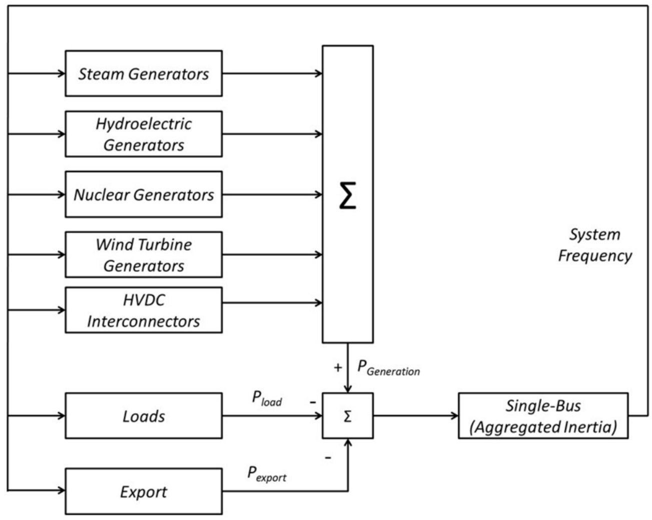


Figure 2. Single-bus power system model for the North-Eastern area of the UCTE

Limitation of the single-bus model is that voltage dependencies and network congestions can't be modelled. Voltage dependencies of the loads can be important in overfrequency situations as frequency emergencies can trigger voltage instabilities. However, these studies are not considered in this article.

The total scheduled generation output is approximately 52 GW and the total export from the North-Eastern area to other areas of UCTE is 10 GW. The contingency resulted due to the disconnection of this area from the UCTE network, has been thus modelled as a loss of the 10 GW export in the model, resulting in step increase of 10GW of excess generation. The governor controllers are modelled based on the EUROSTAG library for nuclear, steam and hydro power plants [21], while the WT models are implemented according to IEC 61400-27 [19]. In the UCTE report [1] , it is mentioned that during the split there were disconnections of other generations as well apart from wind power. Therefore, in order to match the frequency measurements from this report, disconnection of 2 GW of steam-based generation at 50.78 Hz is modelled and simulated. Multiple disconnections and reconnections of the WTs have been simulated, resulting in the net disconnection of around 2.25 GW of WTs during the 30 s after the split. All the events, connections/disconnections and dynamics implemented in this model are based on UCTE report [1] with a systematic approach. In Figure 3, the simulation result and the measurement data are compared for the first 30 s, given that the subsequent happenings of the event, until reconnection of the separated areas in UCTE network, are out of scope for this work.

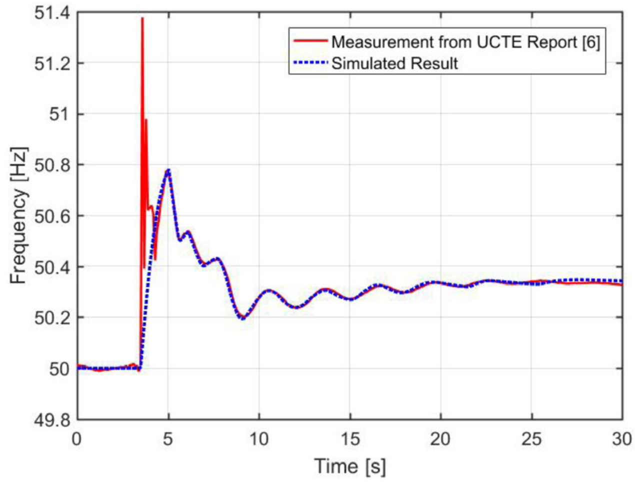


Figure 3. Measured and simulated frequency response for North-Eastern part of the UCTE.

As depicted in Figure 3, the simulated frequency using a single bus model matches well with the measurement data except during the initial transients. These transients in frequency measurements, which typically result from phase shifts or local frequency oscillations at the instance of the split, can't be reproduced by the single-bus model, as this only represents centroid frequency response and not the local frequency dynamics. Notice that after the initial transients, both the measured and the simulated frequency increase up to 50.78 Hz, which represents the centroid frequency of the system. There are several generation disconnections and reconnections occurring around this peak frequency (50.78 Hz) as seen by the sharp changes in frequency between 5 and 10 sec.

The comparison between the frequency measurement and the simulated frequency validates the single-bus model in respect to the overfrequency dynamics, and therefore this model can be conveniently used to investigate the design and the recommendations for the WT overfrequency control settings at different wind power penetration levels.

### 2.3. Impacts of Increasing Wind Power Penetration on power system behaviour

| Wind Power Penetration [%] | Steam | | Hydro | | Nuclear | | Wind | | Inertia Constant [MWs/MVA] |
|---|---|---|---|---|---|---|---|---|---|
| | Capacity [MW] | Set point [MW] | Capacity [MW] | Set point [MW] | Capacity [MW] | Set point [MW] | Capacity [MW] | Set point [MW] | |
| 10 | 46000 | 39100 | 6000 | 6000 | 10000 | 10000 | 6900 | 6900 | 5.17 |
| 20 | 46000 | 30500 | 6000 | 6000 | 10000 | 10000 | 15500 | 15500 | 5.15 |
| 30 | 46000 | 19430 | 6000 | 6000 | 10000 | 10000 | 26570 | 26570 | 5.14 |
| 40 | 46000 | 10800 | 6000 | 1870 | 10000 | 8000 | 41330 | 41330 | 5.12 |
| 50 | 29200 | 7440 | 6000 | 1200 | 10000 | 8000 | 45360 | 45360 | 3.61 |
| 60 | 16000 | 4800 | 6000 | 1200 | 10000 | 8000 | 48000 | 48000 | 2.41 |
| 70 | 5420 | 2690 | 6000 | 1200 | 10000 | 8000 | 50110 | 50110 | 1.46 |
| 80 | 3650 | 3000 | 2000 | 1200 | 7000 | 7000 | 50800 | 50800 | 0.9 |

Table I. Generation Scenarios for different degrees of wind power penetration

In order to understand the effects of increased wind power generation levels on the power system frequency stability during overfrequency emergency events, the developed single-bus model for the frequency characteristic of the North-Eastern part of UCTE is assumed as the base case.

The wind power penetration is defined in this work as the ratio of the wind power generation capacity to the total power generation capacity. According to this definition, the wind penetration level is (approximately) 10% in the base case.

Different wind power penetration levels from 10% to 80% have been further implemented, while keeping the system demand constant. Table I shows the different generation scenarios for different degrees of wind power penetration.

In order to study maximum support from wind power plants during overfrequency emergency, WTs are assumed to be operated at their maximum capacity without down-regulation and at rated power. Until the 40% level, online capacity from conventional generators remains unchanged, although their power set points are reduced towards their minimum output levels. At 40% wind power penetration, most of the CPPs are operated close to their minimum set points. Thereby, when the wind power penetration is increased beyond 40%, the online capacity from conventional generations needs to be reduced, and thereby reducing the rotational inertia of the system.

The inertia constant for different levels of wind power penetration is shown in Figure 4. It should be noticed that when the penetration rises above 40%, the inertia constant of the network starts to decrease getting below 1.5 s when the wind penetration is higher than 70%. It is worth mentioning that an alternative strategy to increase wind power penetration would be to keep some CPPs operating at their minimum set points while deregulating (curtailing) the WTs. Although such a strategy would not reduce the system inertia of the system, it is inherently expensive and has therefore not been considered in the present studies.

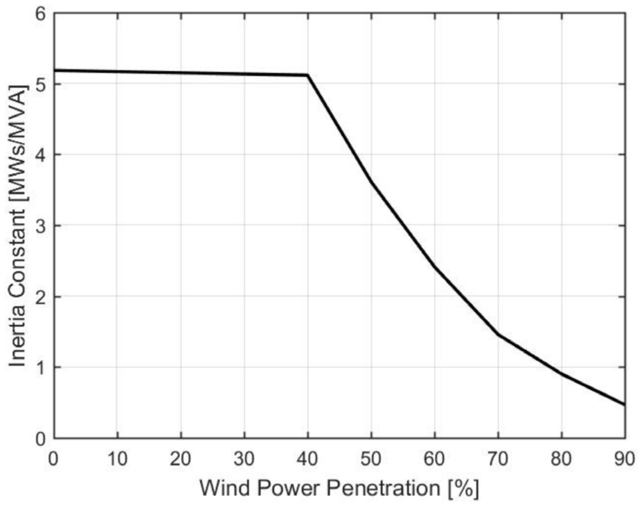


Figure 4. Wind Power Penetration vs. Inertia Constant in north-eastern area of UCTE.

A set of simulations with the aforementioned wind power penetration levels have been carried out assuming the same protection settings as on 4th November 2006 disturbance, which led to the disconnection and reconnection of the WTs in the North-Eastern part of the UCTE. Figure 5 illustrates the base case frequency response and the simulation results for different wind power penetrations higher than 10%. The overfrequency protection settings of WTs for the results shown in Figure 5 are derived from measurements and based on the protection settings for UCTE network on 4th November, 2006 and are not strictly conforming to the current required

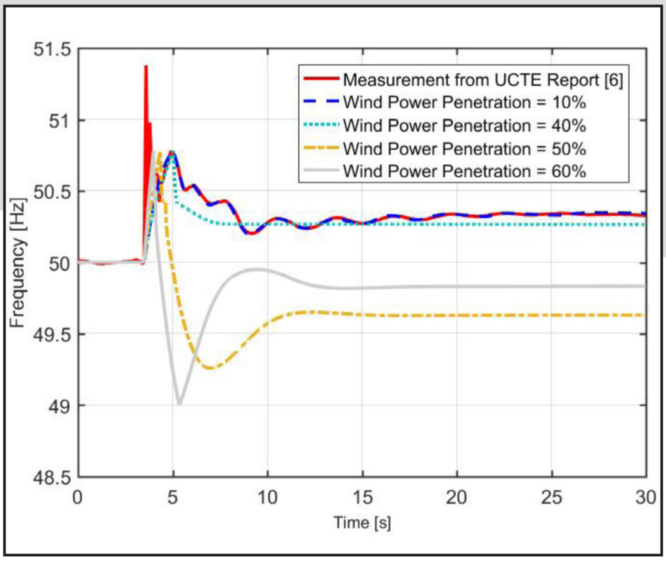


Figure 5. Simulated frequency response for various wind power penetrations with the same protection settings as 4th November 2006

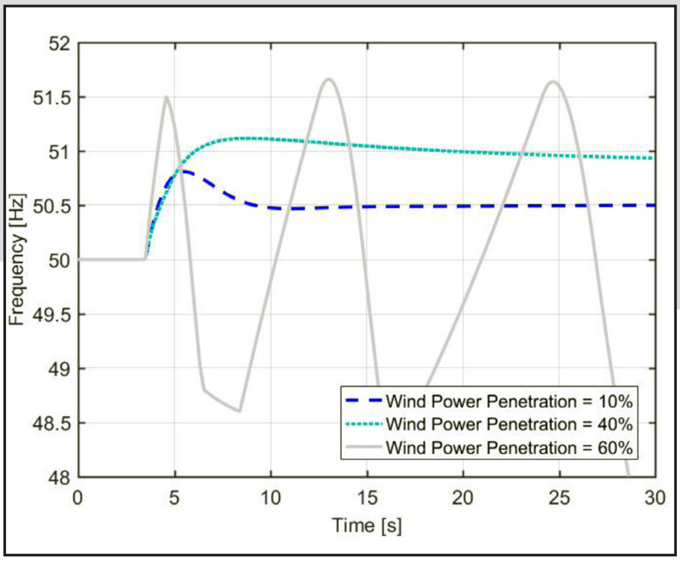


Figure 6. Frequency response for various wind power levels with modified protection settings according to [7]

settings from the ENTSO-E network code [7]. It can be seen in Figure 5 that sharp changes in frequencies due to undesired disconnection and reconnection of WTs can cause large (upward and downward) frequency excursions and thus frequency instability. It is observed that until 40% wind power penetration, disconnection of WTs is capable of mitigating the overfrequency. Notice in Figure 5 that for wind power penetration of 50% the RoCoF is bigger than 40% penetration, and this is due to the fact that in this case the inertia of the system is much lower (i.e. 3.61 s instead of 5.12 s) due to displacement of CPPs. Disconnection of WTs may not be sufficient to prevent instability in such scenarios when system inertia is low. Accordingly, sudden disconnection of a large volume of WTs in the low inertia system causes the frequency to fall to 49.26 Hz. Although the system stabilises at 49.63 Hz, the frequency response is poor and on the verge of load shedding. It is also worth mentioning that when the wind power penetration is 60%, the large disturbance cause frequency excursion with even higher RoCoF, as the system inertial constant is even lower, i.e. only 2.41 s. In such system, sudden disconnection of a large volume of WTs causes the frequency to reach 49 Hz, and thereby initiating load shedding and emphasizing the ineffectiveness of the existing overfrequency protection settings. It becomes therefore evident that the protection settings of the WTs need to be modified in order to handle overfrequency disturbances at times of high penetration of wind power. The over-frequency protection for this exercise is a single trigger frequency and delay (if any). This work ignores the staggering of trip thresholds and/or delays. Design and effects of staggering of trip thresholds and/or delays should be studied in details in future works to understand whether it can help in preventing frequency instabilities in future power systems with high penetration of wind power.

In this work, the focus has been on implementation of load shedding scheme according to the recommendations given by ENTSO-E [8]. However, smart load shedding schemes [5] could be developed for future power systems which distinguish between underfrequency (insufficient generation) and overfrequency (excess generation) events. A set of simulations have been performed with the protection settings modified according to the current grid code requirements for various wind power levels. In current ENTSO-E network grid code, all generators are required to remain connected for overfrequency up to 51.5 Hz for at least 30 minutes. The simulation results for the frequency responses are shown in Figure 6. It is clearly seen that the overfrequency peak value becomes higher as the penetration level increases. Notice that when the wind power penetration is 60%, the peak frequency reaches 51.5 Hz, and thereby potentially triggering the protection relay of the generators rendering the network unstable. This implies that modification of the protection settings alone can't prevent frequency instability, especially with high shares of wind power. Accordingly, at wind power penetrations of 10% and 40% the initial RoCoF is identical due to same amount of spinning synchronous generation while, at 60% wind power penetration level the RoCoF is higher due to the reduced online inertia.

It is thus clear that modification of the overfrequency protection settings of 51.5 Hz for all units alone is insufficient to prevent frequency instability, and that overfrequency control support from WTs becomes an obvious need/option, especially at wind power penetration higher than 60%.

## 3. Overfrequency control of wind turbines

The ENTSO-E network code [7] defines the operational limit for the overfrequency withstand capability and also the design specifications for the overfrequency control, described as the limited overfrequency sensitive mode for all the generators. When operating in this mode, generators shall be capable of activating a frequency response above a frequency threshold with a droop setting specified by the relevant TSOs. The frequency threshold is defined between 50.2 Hz and 50.5 Hz. In addition, the range for the droop value is between 2% and 12%. Considering all these design specifications, the overfrequency control structure for WTs, depicted in Figure 7, is developed in order to support frequency stability. It is worth mentioning that the overfrequency control of WT depend on a set of parameters like activation delay, droop settings and ramping rate.

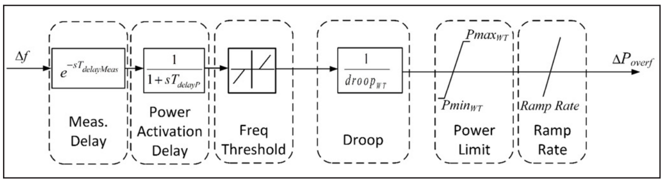


Figure 7. Overfrequency control structure of WT

The input to the overfrequency control is the frequency deviation (Δf), while the output is the active power deviation (ΔPoverf) which is in added to the active power set point of WT model [19]. As can be seen in Figure 7, the total delay is composed of a measurement delay (TdelayMeas) and a power activation delay (TdelayP). The values of the parameters for the overfrequency control depicted in Figure 7, are given in Table II.

Table II. Parameters for WT overfrequency control

| Parameters | Values |
|---|---|
| $T_{delayMeas}$ | 100 ms |
| $P_{maxWT}$ | 0.9 p.u. |
| $P_{minWT}$ | 0 p.u. |
| frequency threshold | ±0.2 Hz |
| $T_{delayP}$ | 0.5 s |
| *ramp rate* | ±0.1 pu/s |
| $droop_{wind}$ | 2-12% |

## 4. Overfrequency control recommendations for various wind power penetration levels

A set of sensitivity studies for the impacts of various wind power penetration levels has been performed incorporating the developed WT overfrequency control into the WT model in the single-bus power system model depicted in Figure 2. The sensitivities of interdependencies between ramp rate, activation delay and droop settings are studied in details in [23]. In these studies, a ramp rate of 0.1 p.u./s [22] is considered with an activation delay of 0.5 s and a droop parameter (droop_wind) which is varied between 2% and 10%. Figure 8 shows the simulation results of the sensitivity analysis for the10%, 40%, 60% and 70% wind power penetration levels, respectively, with and without overfrequency control support from WTs.

Figure 8a depicts the frequency response for 10% wind power penetration for different values of the droop parameter. Notice that for this low wind power penetration, there is no considerable improvement in the frequency response with the overfrequency control support from WTs compared to the case without any support from WTs. However, this is not the case for an increased wind power penetration of 40%, , when, as depicted in Figure 8b, the overfrequency control support has a considerable impact, namely an improvement in the steady state frequency of at least 500 mHz depending on the value of the droop parameter. Figure 8d depicts the 40% case, when the CPPs are operating closer to lower active power limits. Notice that in this case, as CPPs are not able to reduce their output, the steady-state frequency is higher than that for 10% case. It is clear here the beneficial impact of the overfrequency control from WTs. As expected, the lower the droop parameter, the better the frequency response becomes. A droop parameter of 2% can be thus recommended for the considered conditions.

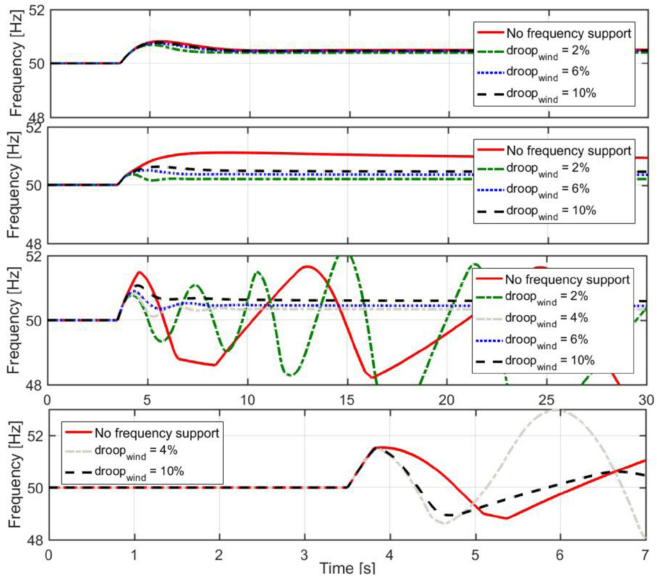


Fig. 8. Sensitivity analysis of WT droop parameter with various wind power penetration levels, (a) 10% penetration (b) 40% penetration (c) 60% penetration (d) 70% penetration.

When the wind power penetration is increased beyond 40%, the online inertia of the system starts decreasing, as previously indicated in Figure 4. Figure 8c illustrates how the network, due to a low inertia, becomes unstable at 60% wind power penetration when there is no frequency support from WTs. It is further noticed that for this high wind power penetration, the network can become unstable even with overfrequency control support from WTs for a low value of 2% for the droop parameter, having a reduced damping and attenuation It is however noticeable that, the network is stable for frequency support from WTs with a droop parameter of 4-10%. A droop setting of 4% is therefore recommended for a wind power penetration level of 60%. Figure 8d indicates that, when the wind power is increased further to 70%, the online rotational inertia of the network is so low that overfrequency support from WTs at any droop setting (2%-12%) is insufficient to prevent any frequency instability.

An additional control action to emulate the inertia contributions to the system is therefore required from WTs. One possible control method can be the synthetic [7] or virtual inertia [24]. According to [7], the synthetic inertia is the capability provided by WTs to represent the effect of inertia of a synchronous power generating module to a prescribed level of performance. Such synthetic inertial support from WTs is a relevant option when the online system inertia is low and the wind power penetration is high.

In this work, the synthetic inertial support from WTs is modelled as described in [24]. As shown in Figure 9a, the synthetic inertia contribution from WTs is incorporated in parallel with the droop-based frequency support model of WTs.

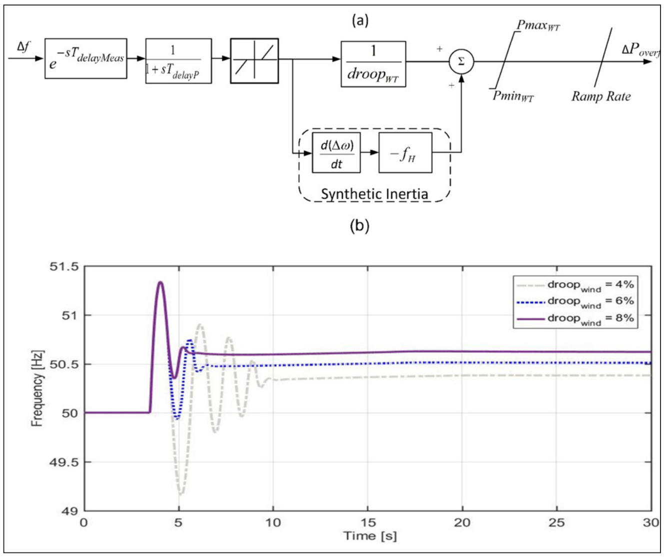


Figure 9. (a) Synthetic inertial support incorporated within overfrequency control of WTs, and (b) Frequency response at 70% wind power level with synthetic inertial support.

As illustrated in Figure 8d, at 70% wind power penetration (without considering synthetic inertia), the system becomes unstable regardless of the droop setting, due to high frequency oscillations. The beneficial impact of the synthetic inertia support from WTs is depicted in Figure 9b, where it can be seen that the frequency is stabilised even for lower values of the droop settings, i.e. 6% or 8%, respectively. It should be noticed that the steady-state frequency is improved with the more responsive 6% droop settings and therefore this value is the recommended WT droop settings at 70% wind penetration.

From the above studies, it is clear that improper settings for overfrequency control of WTs can invoke frequency instability and this issue becomes more prominent at high wind power penetration levels. It is worth concluding that low droop settings for WT generators are viable choice in high inertia systems with low wind penetration, while high droop settings may be suitable for low inertia systems with high wind penetration.

# 5. Validation of proposed

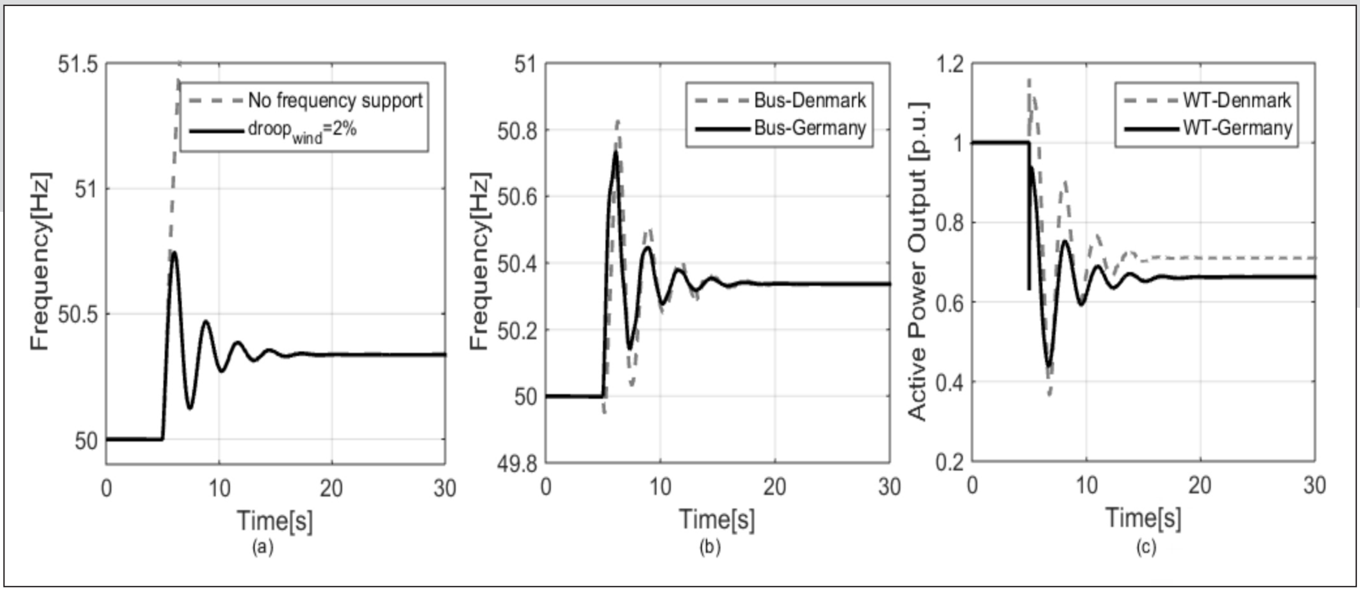


Figure 10. (a) Centroid frequency response of North-Eastern Area in PEGASE pan-European Model with and without frequency support from WTS (b) local frequencies observed in Denmark and Germany (c) wind turbine outputs of 2 WTs in Denmark and Germany

## recommendations on a large-scale power system model

In Section 4, the recommendations for the frequency control of WTs have been defined based on studies on a single-bus power system model, where network constraints such as bus voltage magnitudes, line limits, network protection are not considered. The performance of the frequency control of WTs with the recommended settings, proposed in Section 4, is now further validated by means of a representative large-scale power system model of the European Transmission Network, known as PEGASE pan-European EHV network [17].

This model is representative for the CE network, incorporating 16578 buses, 3240 generators, 14044 lines, 9654 transformers, and a total load of 400 GW. The model is implemented in Eurostag software. The implementation of the 4th November 2006 event is carried out by using a slightly modified disturbance, since there is incomplete public information about the disconnection and reconnection of WTs. Furthermore, as the PEGASE pan-European network is anonymised, the split is realized as the disconnection of the Danish and German networks from the rest of the CE network. This assumption is considered feasible and valid for demonstrating the impact of high levels of wind power penetration and the necessity for overfrequency control from WTs, according to [17]. In this context, two simulated areas are experiencing a frequency response - i.e. overfrequency in North-Eastern Area comprising of Germany and Denmark while underfrequency in rest of the CE. Overfrequency emergency control is included for the WTs in North-Eastern area. The results are presented in Figure 10 for wind power penetration levels of 40% and value of 2% for the droop setting of the frequency control of WT.

Figure 10a demonstrates the local frequency whereas 10b depicts the local frequencies at 2 different buses in Denmark and Germany. Centroid frequency can be seen as the average of all the local frequencies for all the buses and therefore the local oscillations in the buses are filtered out in centroid frequency response. Figure 10a shows the centroid frequency response with and without support from WTs for the North-Eastern area of PEGASE network. The system becomes unstable without the support from the WTs while the peak frequency is contained within 50.75 Hz when overfrequency emergency control from WTs is activated. Observe that the local frequencies of Figure 10b varies from each other and with the centroid frequency. Remark that single bus model only provides the centroid frequency and therefore the local phenomenon are not observed in this model. Figure 10c shows the wind power output of 2 WTs in Denmark and Germany. Overfrequency control from WTs are based on the local frequency measurement from the buses where the WTs are connected. Since, the local frequency observed by the WTs are different, the power outputs of the WTs also vary from each other.

## 6. Conclusion

The emphasis in this article has been on the design and recommendations for frequency control and protection strategies for converter connected WTs which have a crucial role during overfrequency emergencies especially in power systems with high wind power penetration and reduced inertia. The 4th November 2006 situation, when the UCTE network was split into three areas, has been considered as a base case for the present investigation, with special focus on the North-Eastern part of the UCTE experiencing an overfrequency situation which provoked a cascade of unintentional disconnections and reconnections of the WTs with high risk for frequency instability.

The studies for overfrequency protection settings and control strategies for WTs have been performed in the first step using a single bus power system model for the North-Eastern part of the UCTE to simulate the 4th November 2006 situation. The performance of the proposed frequency control with the derived settings has been validated by means of simulations with the large scale PEGASE pan-European model with various levels of wind power penetration.

The results of the investigation have shown that modification of the protection settings implemented according to ENTSO-E network code requirements may not be sufficient alone to prevent frequency instability especially when wind power penetration is high and system inertia is low. One way to overcome this challenge is to use frequency control capabilities of wind turbines.

The article describes the design for such overfrequency control support from wind turbines based on intensive open loop studies of the frequency control capabilities of wind turbines, where the impact on system frequency response of different control parameter settings (i.e. activation delays, droops, ramp rates) are analysed.

Investigations show that higher the ramp rate, more is the frequency support from WTs, and that the ramp rate plays more vital role than droop and activation delay values in terms of frequency support. Moreover, low droop settings may be viable at low wind power penetrations (i.e. high inertia system), while high droop settings may be useful for high wind power penetration (i.e. low inertia system) scenarios, as expected. It is observed in the studied model that for wind power penetration levels less than 40%, the overfrequency droop setting should be 2%. Additionally, for wind power penetration between 40% and 60%, the overfrequency droop setting should be 4%, while for wind power penetration levels beyond 60%, a droop-based overfrequency controller is insufficient alone to prevent frequency instability. This is due to the low rotational inertia of the network, and with the current and traditional network code requirements the frequency instability can be imminent. In such cases, synthetic inertial support from WTs can be beneficial and by including such support into a droop-based overfrequency controller, WTs can be helpful in stabilizing the network with high shares of wind power during severe disturbances.

For future investigations, frequency measurement dynamics and accuracy can be considered in the simulations. Additionally, in order to make the simulation scenarios more realistic, the estimation accuracy of the frequency measurements can be analysed together with the wind power variations. In the studies performed in this article, droop settings are assumed symmetrical both for overfrequency and underfrequency regions. Impact of asymmetrical droop settings for WTs for overfrequency and underfrequency can therefore be investigated in future. It should also be noted that the studies presented in this article are initial steps for designing the protection and control strategies for WTs in overfrequency emergency situations and this work can be used for further creative, economic and robust control design to address this problem.

## 7. Acknowledgments

This work was supported by the European Commission through the European FP7 project iTesla under the grant agreement n° 283012.

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