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Frequency security constrained control of power electronic-based generation systems

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Abstract

Power grids with high integration of power electronic converters face new issues that have not existed before. The frequency in the power system is highly related to the inertia and the rotational speed of the operational synchronous machines. This is now changing, as the converter-based generation units are contributing increasingly to the balancing of active power in the modern power grid. Several frequency control designs for the power electronic-based generation units have been presented in the past. However, optimal control structures and settings are dependent on the current power grid parameters and operation. The converter-based units allow the transmission system operators to change their behaviour according to their grid requirements much more dynamical than ever before. The paper proposes a new analysis framework that can be utilized to find the best-suited control settings in converter-based units to enhance the system frequency reliability. The proposed framework is demonstrated in a study case by varying the settings of one frequency control scheme currently used in wind power plants in the Danish grid codes and validated on the IEEE 24-Bus reliability test system with additional wind power integration.

1 | INTRODUCTION

Large amounts of renewable power plants are installed in power grids all over the world [1]. The high amount of renewable power generation is now at a point where their power electronic converters define the behaviour of the power grid. Also, other converter-based units are getting connected to the grid, such as battery systems, flexible AC transmission systems (FACTS), and high voltage DC transmission units (HVDC). One of the challenges with this extensive usage of these units is the reduction of inertia in the power system. An active power imbalance between the generated power, P_{Gen} , and the demanded power of all loads in the grid, P_{Load} , causes a change in the system frequency following (1). The rated generator power S_B , and their time constant H are used to describe the system's frequency behaviour [2].

$$\dot{f} = (P_{Gen} - P_{Load}) \cdot \frac{f_{nom}}{2 \cdot S_B \cdot H}. \quad (1)$$

The reliability of the power system in all aspects is severely affected by the converter-based units. Nevertheless, the change in system frequency behaviour due to the proliferation of inertia-less units is a vast concern for transmission system operators (TSO) for the reliable operation of modern power grids [3–5].

Modern power system reliability can be divided into two main aspects, adequacy and security, as shown in Figure 1 [6]. The system adequacy describes the steady-state capability of the power system to operate. Parts of this can be the supply of system loads, even after the failure of any unit, and the system's capability to maintain a voltage at all buses within the allowed range.

The security of the system describes the dynamic capability of the system of withstanding a contingency. The analysis includes both the transient and static phases of the event. The TSO has to adjust the remedial actions depending on the grid conditions. These actions can be preventive (e.g. network topology changing, transformer tap changing, control changes) or corrective (e.g. load shedding, generator rejections). The steady-state

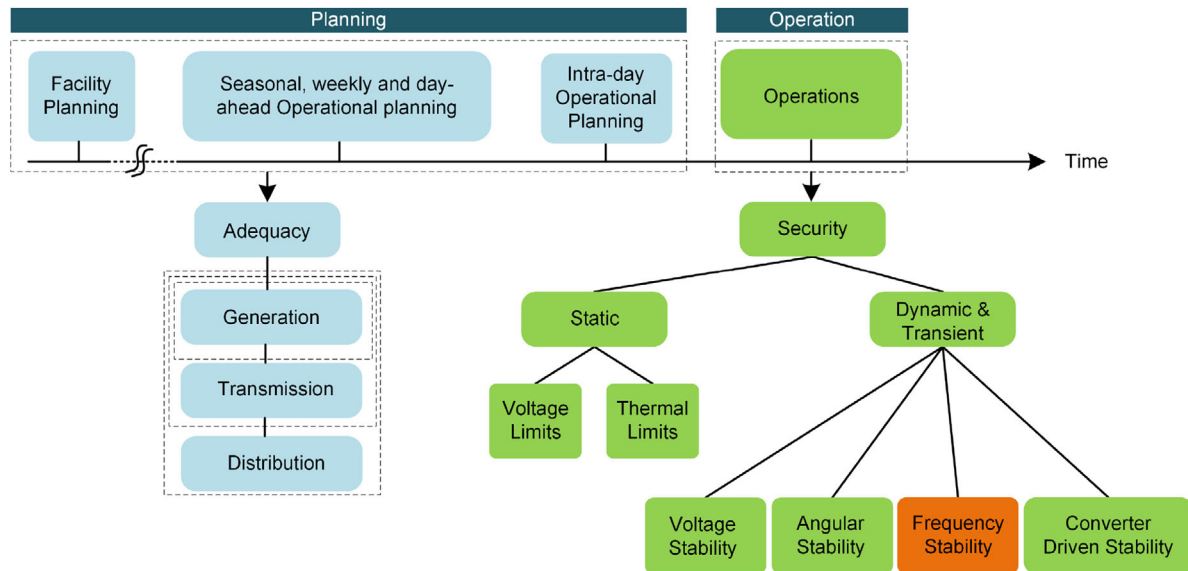


FIGURE 1 Reliability assessment overview in modern power systems [6]

voltage and thermal limits of the equipment are supposed not to deviate from the accepted operational limits. Otherwise, following events, like transmission line deactivation, can occur. The long term nature of these following events allows TSOs to perform corrective actions. The static assessment of system security is used to evaluate this kind of grid conditions. Transient and dynamic events, on the other hand, are too fast for operators to interfere with corrective actions. Nevertheless, TSOs estimate the state of the grid in steady state and the possible contingencies in these states. The operator ensures that enough reserves are available under all conditions by preventive actions. Hence, the operator has also to balance the benefits and the drawbacks of any used strategy. Every system operator has to consider the different aspects of voltage stability, angular stability, frequency stability, and converter-driven stability [6].

Converter-based units allow a wide functionality in controlling the system voltage, as they are widely distributed, and they can inject controlled reactive power. The coordination of FACTS voltage controls for stable voltage control has been presented before [7], allowing a broader integration of these units in modern power grids. The proper local voltage control allows utilizing the faster control options that power electronic converters are capable of. In this field, converter-based units are advantageous to conventional solutions, such as the activation of mechanically switched capacitors (MSCs). The angular stability describes the maintenance of a safe angle deviation between all conventional units when severe voltage collapses occur [2]. Converter-based units can assist the grid during these events when using an assisting control method [8, 9].

This paper deals with frequency stability, assessing the impact and the possibilities of converter-based units in maintaining a stable system frequency during contingencies. TSOs can order the curtailment of generated powers by the renewable units in cases of high penetration levels, keeping a minimum number of

conventional units in operation, therefore conserving a minimum inertia level [10]. Also, the operators directly control the HVDC units, adapting their frequency behaviour to the system needs. The converter-based units, on the other side, are profiting from a reliable operation of the connected system as well. Wind power plants, as one of the main sources of renewable power generation, are capable of providing different frequency controls as their controls can be adapted to many requirements [11–13]. Grid codes are the way TSOs define the functions they demand from renewable generation units. It has been shown that wind, solar, and battery systems can provide a wide variety of services to assist the grid during frequency violation [14, 15]. Power electronic-based converters allow new flexibility with the usage of its controls that has not been seen before. It is now possible to activate and deactivate certain system services. TSO can also change the settings inside the frequency services to further adapt them to the system needs. These new options for remedial actions allow TSOs to shape these units' frequency behaviour to their needs, maintaining a high level of system reliability.

This relation between the system operator and the decentralized converter-based units are illustrated in Figure 2. The three considered levels are the plant level, the system level, and the information and communication technology (ICT) level. The system operator can interfere with the converter-based units in the plant level via communication links. These actions are changes in power reference values, control activation and deactivation commands, and set-point changes.

System operators face the challenge of incorporating the flexibility converter-based units offer. In conventional systems, only a few units with a large capacity are committing to the frequency control. In modern power grids, thousands of units are assisting in the system frequency control in parallel, such as wind power plants with their grid code requirements [14]. The change in power grids increases the complexity, and it requires

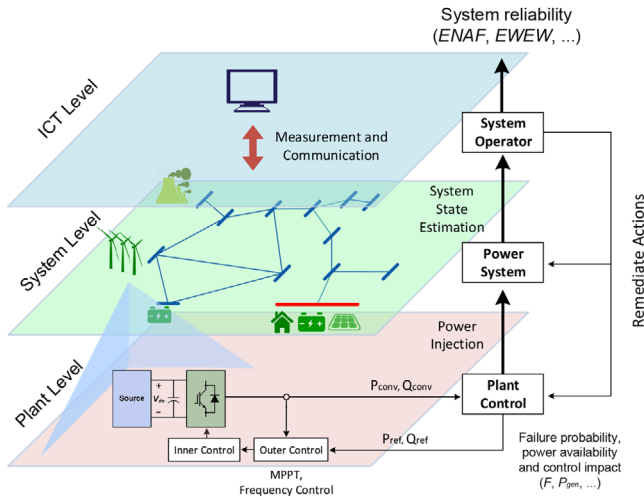


FIGURE 2 The interactions between ICT, system, and plant level in the power grid. TSOs change plant control through remedial actions to support overall system security

the consideration of many more possible system states, where the flexibility in the converter-based units has to be set in focus. When determining the reliability impact of frequency services, only a small number of variations is evaluated so far [16–18]. This, however, is going through a fundamental change with the increase in frequency control flexibility in modern power grids.

To overcome this, this paper proposes a framework that can incorporate changes in frequency control schemes and settings for the converter units. The proposed framework allows a comparison of the impact of operative actions on frequency security. The benefits of the tested control schemes and settings are compared with their negative consequences, such as the reduced power produced by the renewable units. The framework can assist TSOs during the design process to find practical guidelines for improving the frequency management.

2 | FREQUENCY-RELATED SECURITY ASSESSMENT

The procedure for a system frequency-related security analysis is shown in Figure 3. The system is described with the given load duration curve (LDC) and the other parameters

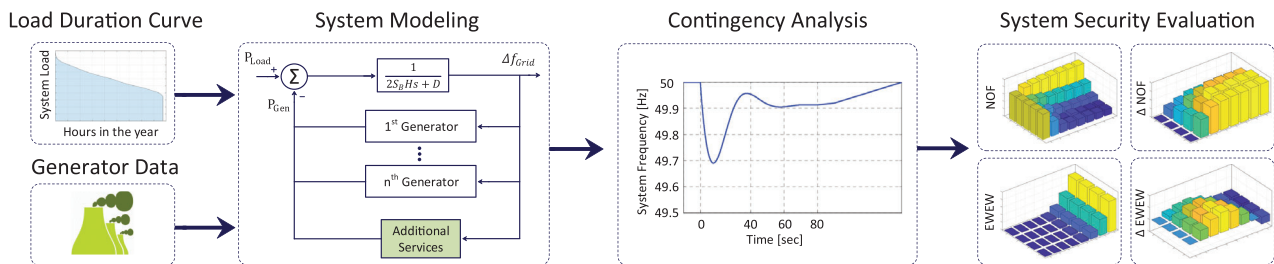


FIGURE 3 Conventional system frequency security assessment [19–21]

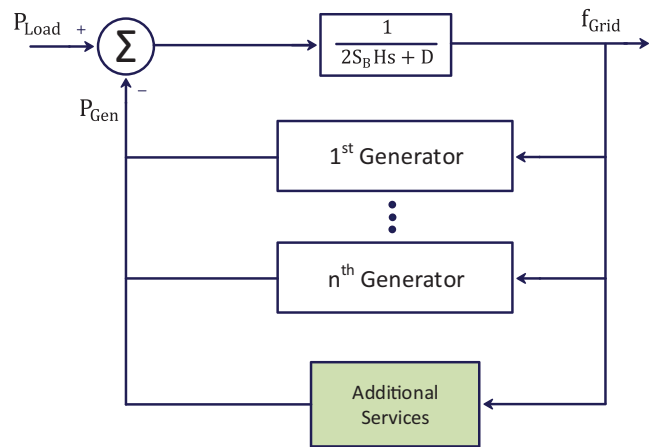


FIGURE 4 System simulation model, including primary and secondary frequency controls in the generation units, and additional services provided by converter-based units

that have to be considered, such as wind power distribution or solar irradiation characteristics. The conventional generation units and their frequency behaviour have to be included as well [19–21]. The system model can be done with different levels of accuracy. For frequency-related security analysis, a one-bus multi-machine model is often used [16]. Additional services, such as frequency control in wind power plants, are modelled as additional services. More detailed models are also possible, depending on whether the computational efforts are acceptable or not.

The system simulation incorporates the different possible system states. Also, different load conditions are considered with their probabilities in the LDC. The conventional generation units are modelled with primary and secondary frequency controls, as described in [16]. The single-bus multi-machine model, as shown in Figure 4, has shown to be capable of analyzing the frequency behaviour, as generator-dependent time constants and non-linearities can be implemented, such as ramp rates and limitations.

As generator failures, the considered contingencies cause frequency excursions in the system, and it is followed by the control response to maintain the system frequency.

Following the reliability parameters presented in [16, 22–26], the abnormal frequency events are compared with different

TABLE 1 Reliability evaluation indexes used in the power system analysis [16]

Index	Unit	Full name
NOF		Exp. number of over-frequency events
NUF		Exp. number of under-frequency events
ENAF		Exp. number of abnormal frequency events
EOFD	min	Exp. over-frequency duration
UFD	min	Exp. under-frequency duration
AFD	min	Exp. abnormal frequency duration
EENS	MWh	Exp. energy not served to loads
EWEW	MWh	Exp. wind energy wasted
EWES	MWh	Exp. wind energy surplus supplied
IENS	MWh	Indirect energy not supplied
ECU	MWh	Unnecessary energy consumption

reliability indices. The reliability indices describe the number and duration of abnormal frequency in the power system. The power system's nominal frequency is 50 Hz in this analysis, with the abnormal frequency being counted at a frequency deviation of ± 0.5 Hz, as the control gets activated at a frequency deviation of ± 0.2 Hz.

Different indices can be used to describe the used energy for the frequency controls. The energies used for frequency regulation by the conventional generation units are taken as a metric. These are the not used wind energy due to output curtailment and the short-term surplus wind energy due to additional controls [16]. Moreover, the under-frequency load curtailment is taken into consideration, measuring the amount of not supplied load in the system due to severe under-frequency events. The indices are evaluated, taking the probabilities of system state and contingency into consideration. Often used indices for wind-integrated systems are listed in Table 1. For the system study performed in Section 4, the expected wind energy wasted, EWEW, and the number of severe under-frequency, NUF, are used to assess the system performance [16].

These indices represent the expected (Exp.) system behaviour with the given parameters. They are used to compare the given system's capability concerning its frequency behaviour and the spend and curtailed energy for maintaining it. It has to be noted that one cannot directly link the cost for primary or secondary reserves with these indices. The indices described above are only reflecting the energy used during an analyzed contingency.

3 | PROPOSED FREQUENCY-RELATED SECURITY OPTIMIZATION FRAMEWORK

As the possibilities for different controller schemes, settings, and scheduling increases severely with the extensive usage of renewable power generation units, the assessment has to be adapted to this. Changing the input to the assessment, how these units behave during the operation of the grid, has a severe

impact on the grid performance. System operators are in need of adapting their decision-making process to this change in the operation states. The aim is to reduce the frequency impact of the converter-based units while keeping the drawbacks as small as possible. Therefore, a framework for including multiple frequency managements and comparing their impact is proposed to find well-suited remedial actions for enhancing the frequency-related security. The proposed framework is shown in Figure 5.

The additional parts of the proposed framework are described in the following subsections.

3.1 | Design variations

The first addition to the standard assessment of the system security is the variance in the tested system. Different control strategies, settings, or scheduling can be used, affecting the system in operation. A variety of frequency managements is defined, which is then implemented in addition to the conventional power system. The system description includes the load variation and the information of the conventional generation units, under-frequency load shedding (UFLS) strategies, and primary and secondary frequency control settings. The system is simulated with all these defined variations. The study case in Section 4 varies one control parameter, resulting in a one-dimensional outcome. With more variations combined, the analysis can result in multi-dimensional outputs, where different variations are evaluated together. The possible variations can include control setting changes, different control schemes, and different activation strategies by TSOs.

The reliability indices, as assessment outcomes, are compared in the following step to determine the best-suited frequency management variation. This step is further illustrated in the system study in Section 4.

3.2 | Evaluation criteria

The second addition to the classical frequency-related security assessment is the choice of optimization strategy. The different indices that describe the abnormal frequency states and drawbacks in the frequency control processes have to be compared. Thus, multiple definitions are possible, such as the minimal needed energy used for reaching a certain frequency quality.

Another design goal is to find the highest efficiency between system benefits and the required drawbacks. Then, one can use a sensitivity analysis of the indices of interest. The change of the reliability indices for a given variation of input is given in (2). The reference value to compare with is the one where the control is deactivated.

$$\Delta Index_i = Index_i - Index_0. \quad (2)$$

The change of an index value is an indication of how much the operational actions affect the system security. It allows

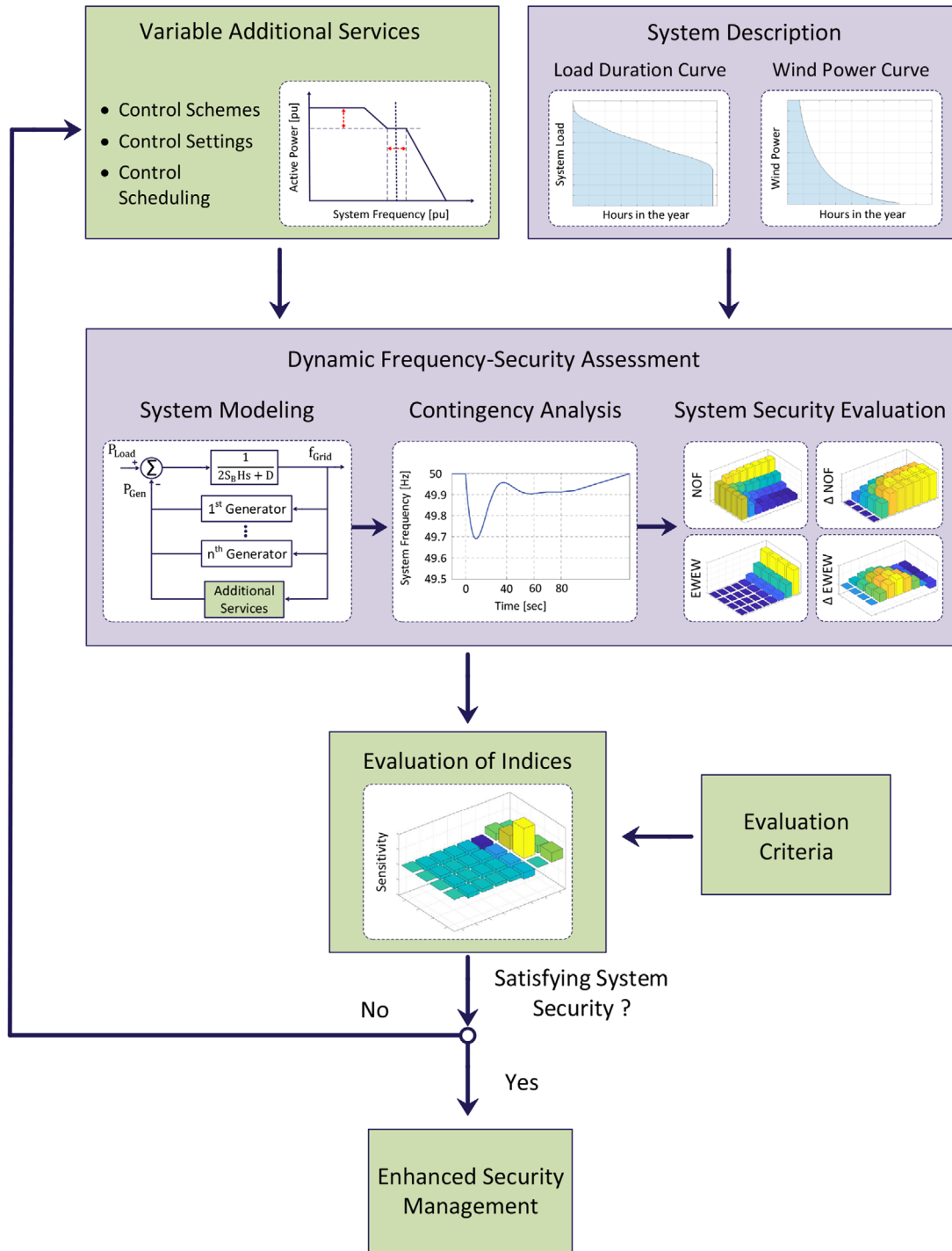


FIGURE 5 Frequency-related security framework, to enhance system security management in modern power systems. The proposed steps for improving the security management are indicated in green

seeing the effect of different controller settings or varying shares of converter-based penetration level. The relative change of a given index, described in (3), can be used to quantify the improvement due to the tested control.

$$\Delta Index_{Rel} = \frac{\Delta Index_i}{Index_0}. \quad (3)$$

The relative change of index value allows the combination of different frequency quality measures such as ENAF and EAFD to find the best-suited operational strategies for the given grid requirements. The relative frequency quality change is combined with other reliability indices of interest. The aim is to achieve an optimal system performance and to incorporate the system efforts for this improvement. As described in

[16, 23], the energy used for the frequency control in the different participating units is an essential factor when assessing the system performance and economics. The analysis allows a fast way of balancing the benefits and drawbacks of the applied system changes. For this analysis, the change in EWEW from the reference outcome is taken to determine the not produced power of the wind power plants as the control effort. The combination of benefits and costs is given with the sensitivity index given in (4).

$$S_{Freq,Index} = \frac{\Delta Index_{Quality}}{\Delta Index_{Drawback}}. \quad (4)$$

Other relevant indices can be the number of certain events, such as the number of occurring system splits or the activation of different functions. The evaluated indices are based on the TSO design choice, determining which effect in the power grid is aimed to be optimized.

3.3 | Design evaluation

In the last step, the optimization strategy is used to assess the system variations of interest. The strategy best suited for the TSO is determined, allowing an enhanced system performance. The outcome of the assessment can also be obtained by an iterative process. The iterations can include different frequency management choices, like control schemes, settings, and scheduling of usage. The evaluation step is the point where the proposed framework is changing from a descriptive process to a design tool, so operators can clearly see trends in their system reliability and the drawbacks of achieving it. Further changes, adapting to smaller system variations, can be incorporated.

The proposed framework is used on a test case in the following section, illustrating the proposed additional steps to the conventional system assessment. With this, TSOs can better plan the remedial action needed to manage modern power system security.

4 | SYSTEM STUDY

The framework is applied in a modified IEEE reliability test system (IEEE RTS) [27, 28]. The aim is to use frequency control in wind power plants to improve the system's frequency quality. The conventional parts of the system are described in detail in [28]. This power system is well established for different types of reliability analysis, from security to adequacy assessment [29]. For the study, an increasing number of installed wind turbines are considered to determine the change in operative actions. Wind power generation is chosen as it is the main contributor to renewable generation in many countries. Nevertheless, the framework can also be applied to other converter-based units with frequency control capabilities. The integration of wind turbines into the IEEE RTS and the respective reliability impact has been analyzed before, like in [16, 30]. In [16], they focus on the frequency-related security due to the power electronic-based

TABLE 2 Generator data [28]

Rated power [MW]	Number of units	MTTF [h]	MTTR [h]	H [s]	Ramp rate [MW/hr]
12	5	2940	60	2.5	60
20	4	450	50	3.0	80
50	6	1960	20	3.5	30
76	4	1960	40	4.0	304
100	3	1200	50	4.3	300
155	4	960	40	4.8	620
197	3	950	50	5.0	591
350	1	1150	100	5.5	350
400	2	1100	150	6.0	800

units, but without additional frequency support functionalities in the respective units. The software MATLAB Simulink is used to simulate the system behaviour during the contingencies.

4.1 | Conventional system components

The conventional generation units in the IEEE RTS have a total capacity of 3405 MW. Each generator has a certain probability of a failure per year, as given in [28]. The dynamic generator parameters are shown in Table 2 with the mean time to failure (MTTF) and the mean time to repair (MTTR). The dynamic generator data describes the frequency behaviour and the probability of the units for failing during operation.

The unit commitment order of the conventional generators under different system states is determined in a heuristical manner. The strategy includes the units with the highest time constant first, only activating the smaller units if needed. This results in a relatively high system inertia in the power system for any given load and wind situation. The generation units, which are committed to frequency control, can provide primary and secondary control, as discussed in [16]. There, the ramp rate restrictions for secondary control are considered.

The system load is not constant during the operation throughout the year. The system load can be represented by the hourly peak load, resulting in LDC. In the IEEE RTS, the peak load throughout the year is 2850 MW, the LDC is given in [27].

The UFLS follows the ENTSO-E guidelines [31]. It is used as a protective function to stabilize the system frequency after a severe generation outage [31]. The UFLS is the last option for the power system operation, keeping the remaining parts of the loads still supplied. The UFLS scheme is fixed in this analysis, as it is implemented in the protection relays, and is not changed dynamically during operation.

4.2 | Modelling wind power plants

Wind power plants are additionally included in the IEEE RTS. The number of connected turbines is increased in this study

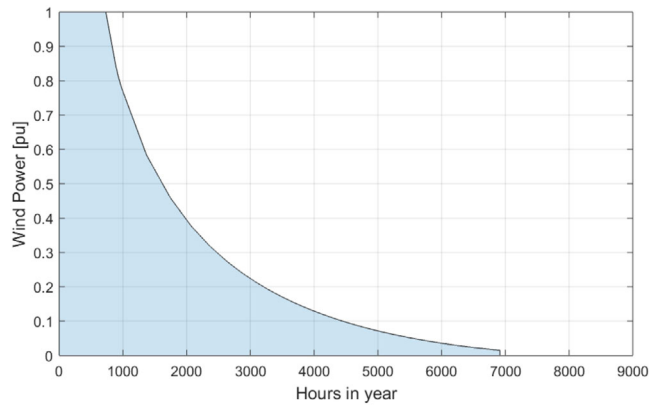


FIGURE 6 Wind power duration curve, giving a capacity factor of 28.5%

to see the effect on the system reliability throughout different wind power penetration levels into the system. The rated power of installed wind power plants is increased from zero up to 1000 MW. The actual wind power injected into the power system is determined by the current wind speed and the design of the turbines. The rated wind turbine power is 5 MW. The cut-in, the rated, and the cut-out wind speed are 3, 11.4, and 25 m/s, as suggested in [32]. The produced wind power during every hour of a year can be combined to a wind power duration curve, as shown in Figure 6. In the performed analysis, the wind turbines operate with 2500 full load hours, with a capacity factor of 28.5% in a year [33].

The rated power of the wind turbines is varied in its share related to the peak load in a year to see the effect of the control parameters when more wind power plants are added to the system. The injection of wind power throughout the operation is curtailed above the maximum allowed penetration level of 70%. The wind power plant deloading is realized as proposed in [34]. The rotor speed depends on the current wind situation and the amount of demanded power curtailment per turbine. The wind power curtailment is set in place to keep a minimum number of conventional units in operation, preserving minimum system inertia at all times.

The applied frequency control in this work is the 'frequency control' scheme, described in the Danish grid code [14], as illustrated in Figure 7. It provides a high degree of flexibility, as many parameters (P_{Delta} , $Droop_1$, $Droop_2$, $f_{deadband}$) can be changed during the operation to adapt to the future grid needs. It can be realized in wind power plants without additional battery systems. The control scheme is included in all simulated wind power plants.

The setting in the control scheme that is varied in the assessment is P_{Delta} , which is the curtailed wind power in steady state. It is increased linearly from zero up to 0.2 pu, severely deloading the wind power plants during operation, as described in [34]. The frequency control in the performed study is only activated by the TSO when the wind power plants currently inject more power than 50% of the actual system load. Otherwise, P_{Delta} is set to zero, resulting in over-frequency wind power curtailment, as it is mandatory in the Danish grid code for wind power plants. When power is curtailed during steady-state operation, the full

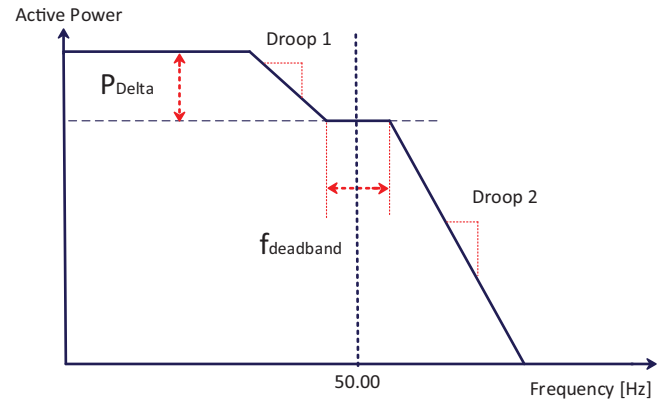


FIGURE 7 Danish grid code requirement regarding the frequency response of wind power plants [14]

wind power is injected into the grid at a fixed frequency value of 49.2 Hz. The used frequency control aims to reduce the risk of UFLS. The dead-band value is fixed at 0.2 Hz, specified in the Danish grid code as the standard value. Full power curtailment is performed at a frequency of 52 Hz, protecting the system from over-frequency deactivation of equipment. The values for $Droop_1$ and $Droop_2$ are adjusted during this analysis, as P_{Delta} is varied and the frequency set-points for zero and full power curtailment are fixed. The frequency control is implemented in the wind power plant controller, receiving the controller setting from the TSO.

4.3 | Results of the study case

The IEEE RTS with the different capacities of installed wind power and the changed controller settings is simulated. The system frequency is highly affected by the additional frequency control in the wind power plants. In the shown contingency in Figure 8, a 100 MW generator failed, causing a severe frequency drop in the system. The installed amount of wind power in the system is 1000 MW. Due to the control settings, the wind power reserve allows for a power increase during the frequency drop.

The simulation results in Figure 8 shows one system state, where the power curtailment P_{Delta} is set to 0.2 pu. The curtailed power offers then frequency control options during under-frequency contingencies. In the shown contingency, the frequency control is able to prevent a severe frequency drop below 49.5 Hz. This reduces the expected number of severe frequency events and therefore enhancing the frequency quality during operation. The reduction of wind power in steady state causes a slightly higher system inertia, as more generation units have to be activated to supply the system load. In the shown result, this increased inertia is only marginal so that the rate of change of frequency is not severely affected.

The frequency-related security assessment results with all possible system states and contingencies allow an estimation of the system security during the grid operation of 1 year. The results of the assessment are illustrated in the following figures. The expected number of under-frequency drops below 49.5 Hz,

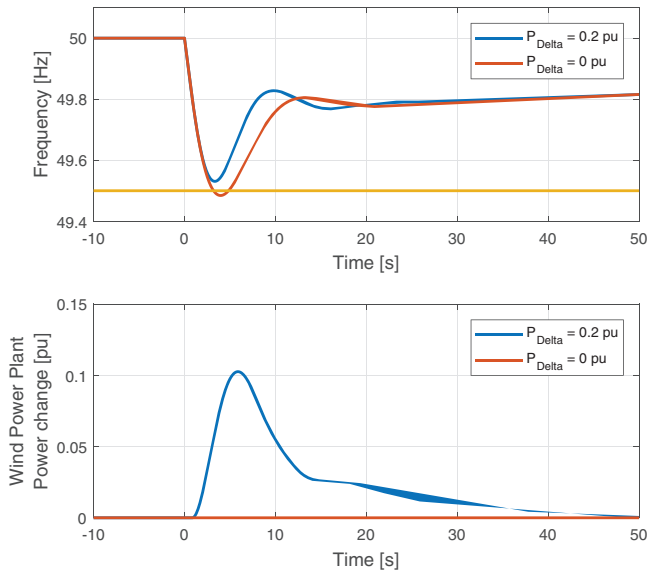


FIGURE 8 System frequency and wind power during a 100 MW generator failure with changed frequency control behaviour. The threshold for severe under-frequency occurrence is shown in yellow

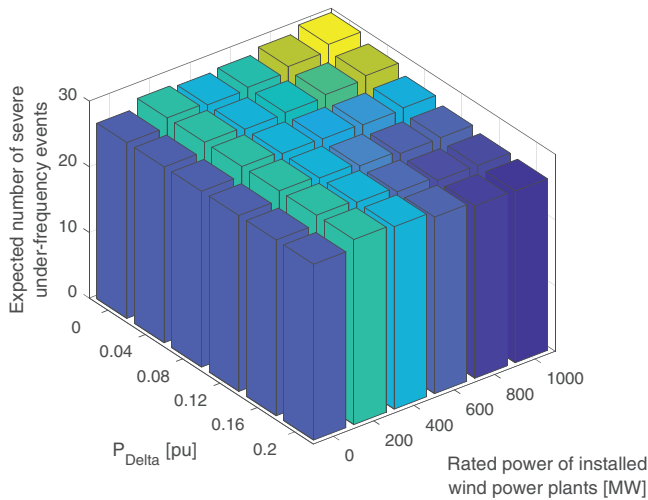


FIGURE 9 Expected number of severe under-frequency events, dependent on the control setting P_{Delta}

ENUF, is shown in Figure 9. The results are shown for the used values of P_{Delta} , which are varied in the analysis.

The change in the NUF events is twofold. The usage of wind power plants reduces the number of running conventional units, resulting in a reduction of inertia during high renewable power injection phases. Counteracting is the reduction of potential contingencies, as the generation units are less likely to be in operation during wind power injection. Therefore, the expected NUF events are not rising severely.

The influence of the used 'frequency control' in the wind turbines can be seen by calculating the change relative to the deactivated control, as described in Section 3.2. The improvement in the NUF events is shown in Figure 10.

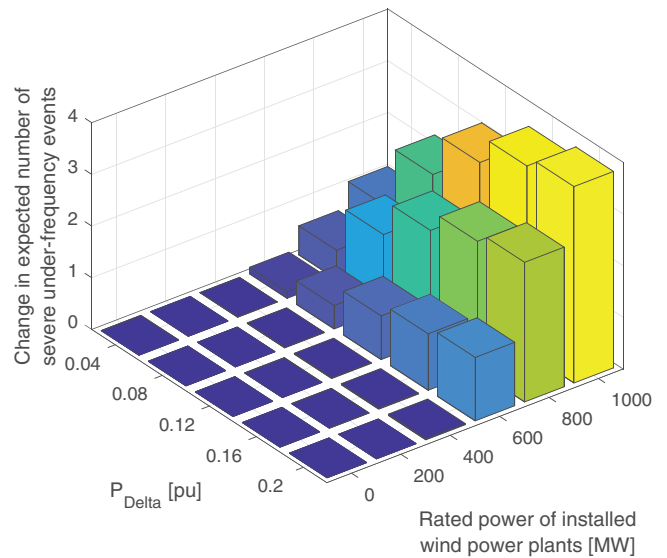


FIGURE 10 Change in severe abnormal frequency occurrences during the operation. Wind power penetration level and control value are varied. Positive values indicate a reduction in abnormal frequency states

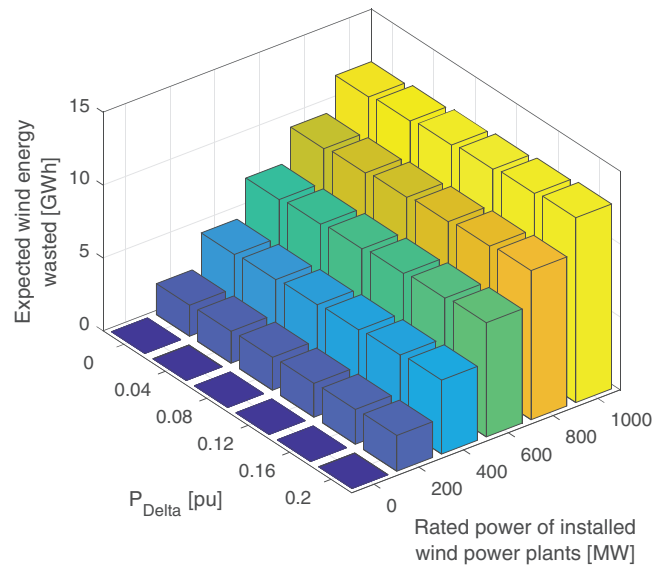


FIGURE 11 Expected wind energy wasted for the tested system conditions. Wind power penetration level and control value are varied

With rising wind power and increasing P_{Delta} , the values of the reduction due to the steady-state power curtailment is shown in Figure 10. The positive control impact is dependent on the system and frequency control settings. Nevertheless, the control has a positive effect on the frequency quality under various system conditions.

Hence, the 'frequency control' also has drawbacks that have to be considered for reliable frequency management. The EWEW is shown in Figure 11 for the different determined study cases. It is affected by the remedial actions of the TSO. These are the tested frequency control and the curtailment of

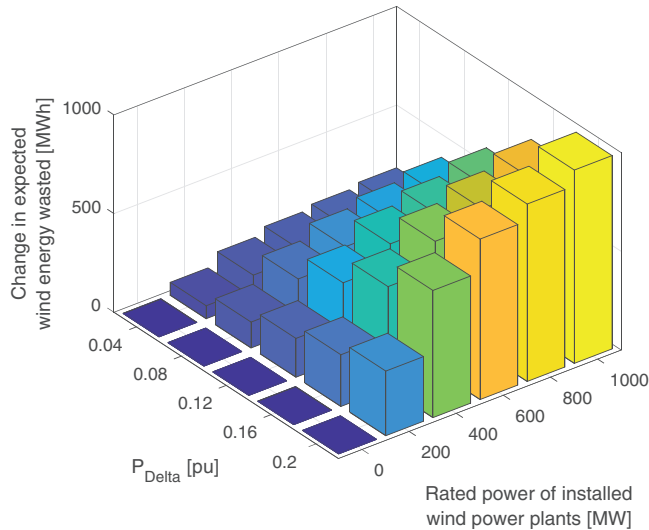


FIGURE 12 Change in the expected wind power wasted during operation. Wind power penetration level and control value are varied

wind power when the available injection is higher than the allowed share of the system load.

The results show that the EWEW increases severely with more wind power plants installed in the grid, but only slightly with the additional frequency control. The deviation caused by the 'frequency control' is determined by a change in EWEW for each assessed P_{Delta} setting for the different wind power levels, which is illustrated in Figure 12. This change due to remedial has to be balanced with the frequency quality gain, allowing for a reliable system operation.

The EWEW increases with the amount of installed wind power plants and curtailed wind energy in steady state. The most reliable setting is determined in the following section by two different approaches to illustrate the capability of the framework to adapt to the TSO demands. One optimization strategy determines the wasted wind energy that is needed to restore the frequency quality that the system has without wind integration. The other one determines the most efficient ratio of wind energy curtailment with the enhancement in frequency quality.

4.4 | Improved system security management

Two strategies are used to determine the remedial actions best suited for enhancing security management.

4.4.1 | Optimizing for restoring frequency quality

The first strategy assesses the needed amount of wasted wind energy to achieve the same frequency quality the system has without wind power penetration. The change in frequency-related security can be determined by comparing the results shown in Figures 9 and 11. It can be seen that the additional frequency control service with 600 MW and lower are not capable of restoring the number of severe abnormal frequency events (26.8 occurrences per year) that the grid had before installing

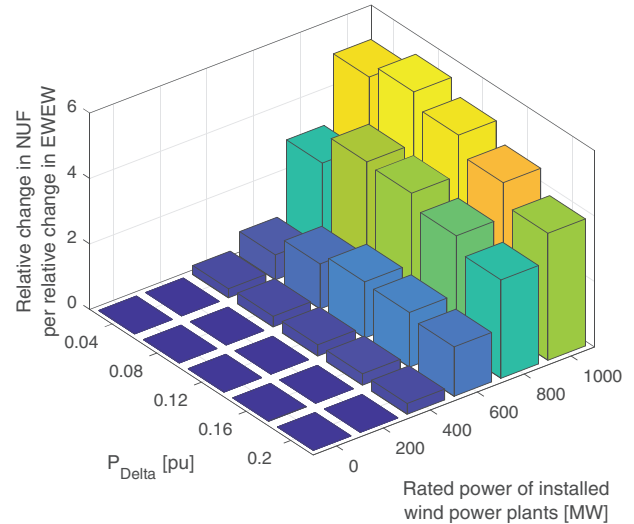


FIGURE 13 Ratio between change of the number of abnormal frequency conditions to the change in the expected wind power wasted during operation, depending on the amount of installed wind power plants and on the set wind power curtailment during operation

the wind turbines. With 800 MW installed wind power plants, this index can be achieved with a setting of 0.16 pu. The expected wasted wind energy is then 9.88 GWh per year. With the full 1000 MW installed rated wind power, the abnormal frequency states can be reduced to the original value with P_{Delta} set to 0.12 pu and 12.5 GWh wasted wind energy per year. The proposed assessment allows determining this quickly, giving a secure frequency management.

4.4.2 | Optimizing for effective wind energy usage

When the optimization strategy's goal is to determine the most efficient balance between frequency quality increase and wasted wind energy, one has to compare the relative changes the control variation causes. The control value, where the highest benefit in system quality is gained compared to the wasted wind energy, can be easily determined for the different wind integration levels. The relationship is shown in Figure 13.

In the shown case study, a P_{Delta} value of 0.08 pu is the most effective at a wind power penetration of 800 and 1000 MW, whereas it is more effective to use a power curtailment of 0.12 pu when wind power plants with a rated power of 600 MW are installed. The most effective setting at lower penetration levels can be found at 0.16 pu. Other combinations of indices used for the evaluation of the system performance can be chosen as well. The used evaluation strategy depends on the TSO and the specific grid requirements.

5 | DISCUSSION

The proposed framework for enhancing the system's operational reliability can be used, as described in Section 4.4.2,

to optimize the frequency controls in the evaluated power system. The framework is assisting TSOs when all steps are designed carefully to represent their system behaviour accurately.

As the first step, the variations in frequency management are defined. The frequency control scheme used in the shown study in the installed wind power plants is based on the 'frequency control' required in the Danish grid code [14]. The evaluated control scheme curtails the injected wind power during steady state to have reserve power available during under-frequency events. The frequency control is droop based, so it causes an active power change proportional to the frequency change.

The power system modelling incorporates all generation units with their dynamics and frequency controls. The wind power plants are modeled to represent their behaviour during the frequency events. With the proposed framework, it is also possible to implement demand-side controls balancing the system load throughout the operation. Other load-shedding strategies are also a research target to assist for the reliable frequency management.

With the variations defined and the modelling done, the third step of the proposed framework is executed doing contingency analysis with the calculation of the reliability indices. The assessment has to be done for all the defined variations to determine the system performance of one year.

The performed study shows how TSOs can compare the total amount of wind power curtailment in one year of operation with the resulting improvement in frequency quality. The evaluation criteria is to find the curtailment setting, which allows for the best ratio of increased wind power wasted to the reduction in abnormal frequency occurrence. In the shown case, the most effective amount of curtailment is 16% at an installed wind power of 400 MW or less in the IEEE RTS. With 600 MW installed wind power, this changes to 12% curtailment. And even down to 8% curtailment at 800 MW or more wind power being installed. The example case shows how TSOs have to adapt their frequency management when installing more wind power in the power grid.

However, the proposed framework allows TSOs to include their grid-specific evaluation criteria used to determine which frequency management fits the best to their requirements. Other evaluations may be more appropriate for the usage in real power grids. Often, TSOs have a maximal number of abnormal frequency states as a defined threshold that is not allowed to be violated. Then, the evaluation may consider the minimum EWEW to achieve this target.

The feedback loop in the final step allows changing the variations further if the achieved results are not satisfying. Then different settings or different frequency managements can be evaluated. Further assessment can include different settings, but also the decision-making which is leading to service activation. So the service can be demanded at different conditions than shown in the case study. Then, the service usage may be more effective in regards to the evaluation criteria. This allows TSOs to find the most reliable frequency management for the requirements of the power grid operation.

6 | CONCLUSION

The proliferation of power electronic-based generation units makes the coordination of frequency controls a more demanding task for system operators. Nevertheless, power converter-based units provide an unused degree of flexibility in frequency controls. The proposed framework for frequency security optimization in highly converter-integrated power grids allows system operators to determine optimal strategies in the usage of these units. The framework adds different steps to the assessment process, beginning at the variable system input to choose the optimization strategy. A strict procedure is proposed, which still keeps the assessment open to the requirements of the analyzed power grid. The combination of fixed and variable system parameters allows a fast assessment of the reliability of different scenarios. The costs and the benefits of the different scenarios can be evaluated and combined to estimate the control options best suited for the given system demand.

The different steps in the proposed framework can be adapted to any grid that faces a high integration of converter-based units, allowing the operator to choose their remedial actions to manage the system's frequency-related security. Different power sources, such as photovoltaic, wind, and battery systems, can be included in the analysis, and HVDC transmission systems. For this, the possible variations increase even more, as frequency controls can be realized in all connected equipment. Other indices have to be respected in this condition, representing, for example, the not utilized solar energy or the amount of battery system usages.

In the study case, the power reduction in steady state for a given frequency controller settings of a wind-integrated power system is shown. The test case shows that converter-based units can contribute, at least partially, to improve the frequency quality. The proposed framework can be combined with more advanced ways of optimizing the control, such as more iterative steps to enhance the system frequency management further.

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