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# Fuzzy-based frequency security evaluation of wind-integrated power systems

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**Abstract**

The transition to renewable energy-based power systems is fast progressing. One of the main challenges in keeping a power system with high operational reliability is to maintain the system frequency. As synchronous generator units are being replaced with power-electronic converters, the rotating mass and the system inertia are decreasing. Virtual synchronous machine (VSM) control is a modern control technique that aims to compensate for the reduction in inertia. The usage of power electronic-based converter units equipped with VSM control has to be managed and scheduled by system operators. An assessment of the operational frequency reliability is used to evaluate different service usages. A method is proposed that allows the comparison of different frequency management strategies. The proposed method uses fuzzy logic to evaluate the system risk for abnormal frequency and the system effort in the form of frequency control usage. This allows to quickly compare different frequency management strategies whilst keeping in mind many different reliability indices. The proposed method is validated with a modified IEEE Reliability Test System with integrated wind power capacity.

## 1 | INTRODUCTION

### 1.1 | Motivation and incitement

Modern power systems integrate more and more renewable generation units [1]. These use converters as the linking part between the renewable power source (solar or wind) and the power grid. The replacement of conventional, synchronous generation units with converters reduces the system inertia significantly during high renewable penetration phases. This weakens the system's capability of maintaining a normal frequency when contingencies occur, reducing the system operational reliability of the power grid. Transmission system operators (TSOs) have named reduced inertia the major concern for their operation in modern power grids [2, 3]. Severe frequency incidents are recorded and analysed by system operators to observe their grid operation and to improve the future handling of these incidents [4]. Modern frequency controls in wind power plants aim to contribute to the reliable system frequency. However, system operators have to evaluate when to utilise which additional frequency services. This is done by evaluating the power system's reliability with different frequency management strategies [5]. The evaluation of many different study cases is time consuming and requires considering many different factors on the system performance.

Figure 1 shows the power system's hierarchical levels, which are taken into account to assess the operational frequency security. The information and communication technologies layer describes the system operators' view of the system. The TSO evaluates the system and reacts with remedial actions when it is necessary to change the behaviour of the transmission network and the connected units at the plant level. These remedial system operator actions can be preventive or responsive. Responsive actions are, for example, the manual activation and deactivation of generation units. Preventive actions include power curtailment of renewable sources during steady-state operation to maintain the minimum inertia and change the set points and control strategies. In this work,

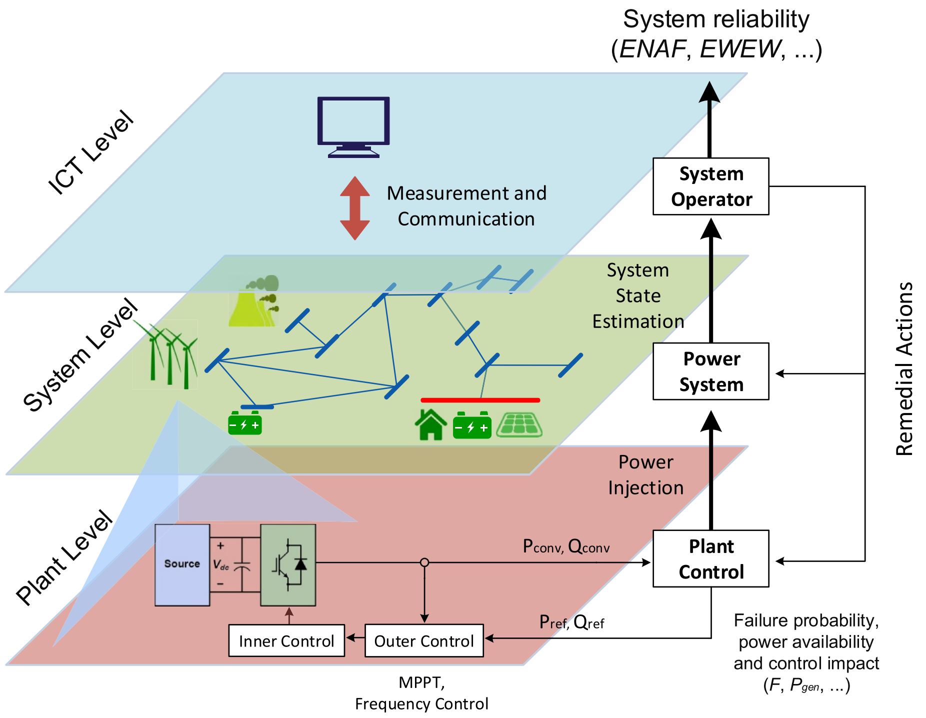


**FIGURE 1** Considered hierarchical levels for the system reliability assessment and the interactions between them [6]

the impact of strategies to order a virtual synchronous machine (VSM)-service by wind power plants is discussed. The main question is how a system operator can decide which frequency management strategy improves the system performance the best.

In conventional power systems, the amount of primary frequency reserves required is determined by the reference incident. This worst-case assumption for a system contingency varies for every synchronous area and is defined in the TSO policies [7]. However, modern power grids with converter-based units offer the system operators a much wider variety of frequency services and how and when to utilise them. These modern units are capable of implementing modern frequency controls that can be changed according to the system's needs, even during the operation.

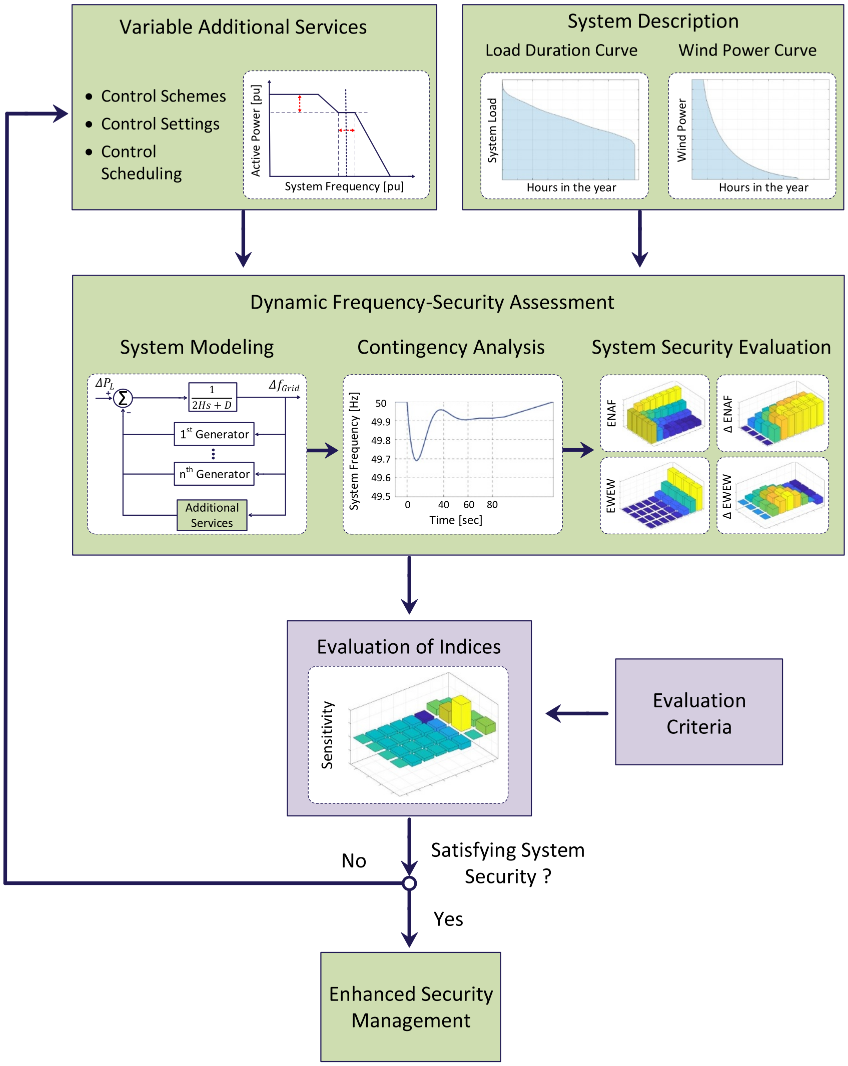
## 1.2 | Literature review

Modern controller designs in power electronic-based generation units aim to replace the conventional units and their system-supporting functions. These units already contribute during the system operation with assisting controls, as demanded by grid codes [8, 9]. These units stay in operation and inject reactive power during transient grid events, for example, when lightning strikes. Renewable units are required to curtail their power injection during events of over frequency [8, 9]. VSMs control converter-based units to mimic the synchronous machine's behaviour. This control structure is promising, as it allows the system operator to maintain an acceptable frequency deviation (NaDir) and limit the rate of change of frequency (RoCof). Recent overviews of VSMs and their frequency-supporting capabilities are given in [10–12]. Other, very similar controls are fuzzy-based VSM controls [13, 14], power-synchronisation controls [15, 16], and inertia emulating adaptations for microgrids [10, 17]. So far, VSM controls have been not used in many countries; only Hydro-Quebec demands inertia controls with 3.5 s time constant emulation during severe frequency deviations [18]. However, many system operators have discussed the need for converter-based units to provide frequency support by emulating the inertia of synchronous machines and these converter-based units may soon be a more general demand.

TSOs have to decide when to utilise the new frequency controls as services to improve their frequency controls. Thus, the power system reliability assessment compares multiple frequency management strategies to choose the most suitable one. The capability of converter-based units to change their frequency control schemes and the used settings vastly increases the number of operational options a TSO has to run the power system. A framework for enhancing the frequency management of modern power systems is given in Figure 2 [6].

The framework describes the different steps of the system reliability enhancement design process. Parts of the system data are fixed to describe the constant grid conditions for the assessment. Frequency management variations are then implemented to change the frequency controls by converter-based units. The dynamic frequency security assessment for all the considered variations is performed by modelling the different controls and system states, performing the contingency simulations and then calculating the reliability indices from the simulation results. Afterwards, the reliability indices

**FIGURE 2** Framework for enhancing frequency management; the evaluation is highlighted in violet [6]



have to be evaluated and compared based on the defined evaluation criteria. Several different indices are used to describe the system frequency performance and the utilised frequency controls [5, 19–23].

The high number of frequency control strategies tested leads to a high number of results that have to be evaluated and compared. TSOs have to determine which frequency control strategies match their reliability requirements best to adjust their grid-codes and frequency control usage throughout the power system's operation. However, the high number of possible frequency strategies and the high number of reliability indices that have to be evaluated for each run make this challenging. In this study, a fuzzy logic-based evaluation combines the different indices for a fast comparison of the frequency management strategies, assisting TSOs in their decision-making process.

Fuzzy logic is introduced to emulate language-based decision making [24, 25]. Until now, it has been used for the reliability assessment procedure, describing the probability of the system states to reduce the simulation burden during the assessment [26–29]. The fuzzy sets are thereby used to represent the system states' probability, such as load distribution or wind speed probability. In some works [26–28], this goes directly into the assessment method; in others, the fuzzy logic is utilised together with the Monte Carlo simulation to incorporate uncertainties in the system description [29].

### 1.3 | Contribution and organisation of the work

In this work, fuzzy sets are utilised in an entirely new way to describe the result of the reliability assessment. The usage of fuzzy logic for this task allows quickening the evaluation of different system management strategies while including the TSOs specific reliability aims. The fuzzy logic allows to combine the different calculated reliability indices for the system operation by assigning them into fuzzy membership, and combining these memberships to calculate the values describing the frequency reliability of the power system. This possibility of combining indices makes it possible to compare a high number of different frequency management strategies faster.

The main contributions of the proposed power system reliability evaluation method are as follows:

- Fast assessment of the power system reliability
- Consideration of all relevant reliability indices
- Evaluation can be adapted to the specific TSO requirements

The proposed evaluation method of system frequency management is presented in Section 2. A study case using the proposed method is described in Section 3 and the results are given in Section 4. Finally, the conclusions are drawn in Section 5.

## 2 | METHODS

The system reliability evaluation is based on the indices that are a result of the dynamic frequency security assessment. The frequency controls aim to reduce the number, duration, and negative effects of severe frequency disturbances. Well-designed frequency management strategies only utilise additional frequency control effectively, with well-chosen settings and only when it is required to keep the system operation economical.

### 2.1 | Frequency reliability indices

The reliability indices are obtained by combining the results of the dynamic system simulations. Different system states, $N_i$, are determined, and $N_j$ contingencies are applied to evaluate the system frequency and the control performance. The results of the dynamic system simulation are evaluated in terms of abnormal frequency states, the curtailment of system loads, and the energy used for controlling the system frequency. A system reliability index is then calculated with an effect on the reliability index $Index_{i,j}$ during the system state $i$ and the contingency $j$, the probability of the respective system state $p_i$, and the probability for the simulated contingency $p_j$, as described in [5].

$$Index = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} Index_{i,j} \cdot p_i \cdot p_j \tag{1}$$

These indices are separated into two groups for evaluation. The first group describes the frequency quality as a measure of the system's risk of failing or operating in an abnormal state. It is determined by the abnormal frequency states due to contingencies during operation. The number and duration of abnormal frequencies are taken as indices that determine if the frequency controls are sufficient for the safe operation of the system or not. An abnormal system frequency is defined in this work as a frequency deviation of more than 0.2 Hz. System operators use this threshold in the synchronous area in central Europe [4]. The system's risk of failure is often described by the expected amount of energy not served to the loads (EENS) [30]. This energy is not served during severe frequency drops that result in the activation of under-frequency load shedding (UFLS) functions [31]. The less this index, the better the system frequency that is maintained by the generation controls. Other evaluated indices are the number and duration of abnormal frequency events throughout the operation [5]. The indices used in this study for describing the system risk are given in Table 1.

From these three indices, only EENS can be translated into a price for the grid operation. ENAF and EAFD, on the other hand, describe the resistance of the grid operating abnormally. This is not related to additional costs that have to be paid as compensation to the customers, as the supply of energy is still possible.

The second group of indices is used to describe the system effort by the frequency controls. Therefore, the energies are estimated, which are used by the frequency reserves (primary and secondary) and also the curtailed wind energy during operation (EWEW) [5]. In this work, a new index, EVSM, is introduced. This index describes the amount of VSM service ordered by the system operator throughout the operation. The EVSM index stands for the expected VSM service demanded. It measures how much the service is activated in the wind power plants but not its actual energy delivery during operation. It is used to compare the effectiveness of different scheduling strategies for activating this service. Table 2 shows the energy-related indices used in this study.

The reliability indices used describe the usage of frequency controls and can also be analysed with respect to their cost for TSOs. Then, either fixed prices for the controls or a bidding market has to be incorporated. The total money spent on the different controls can be calculated and used as a measure of the TSOs' effort towards frequency controls. The most reliable frequency management is then the one with the lowest cost. In this work, however, the focus is set to quantify other aims of the TSOs, such as renewable energy aims, to operate the power grids, which may counter the minimum cost evaluation.

**TABLE 1** Frequency reliability-related indices

| Index | Unit | Full name |
|---|---|---|
| ENAF | occur/year | Expected number of abnormal frequencies |
| EAFD | min/year | Expected abnormal frequency duration |
| EENS | GWh | Expected energy not served |

**TABLE 2** Frequency reliability-related indices

| Index | Unit | Full name |
|---|---|---|
| EVSM | GWh/year | Expected amount of VSM service provided |
| EWEW | GWh/year | Expected wind energy wasted |
| IENS | GWh/year | Indirect energy not supplied |
| ECU | GWh/year | Expected curtailed energy |

Abbreviation: VSM, virtual synchronous machine.

Therefore, the indices in Tables 1 and 2 are used in the proposed fuzzy-based evaluation to describe the system control effort and risk. The system's risk is an evaluation of the system's benefit when frequency controls are added. The effort-related indices are combined in the fuzzy-based evaluation to determine which frequency management uses the frequency controls the least. This is done with an aim to reduce the number of values that need to be compared.

## 2.2 | Fuzzy-based security evaluation

The fuzzy logic has been introduced to emulate language-based decision-making processes [24]. It is challenging for the TSOs to compare different strategies, as the given indices change when the remedial actions are varied. The evaluation step in Figure 2 is realised with the proposed fuzzy evaluation. Therefore, the reliability indices are combined in the two groups in Section 2.1 to better evaluate the balance between system risk and system effort. This is possible using fuzzy logic, as it allows multiple inputs. Fuzzy logic is based on three steps—fuzzyfication, interference and de-fuzzyfication, as shown in Figure 3.

### 2.2.1 | Fuzzyfication

The indices are normalised with a reference value to allow an easier comparison of variations in the system performance. In the present study, the reference value is given for the system reliability without the evaluated additional frequency services by the wind power plants. The reference index values for the case study can be seen in Tables 3 and 4 in the first row.

$$Index_{Normi} = \frac{Index_i}{Index_{Ref}} \tag{2}$$

In fuzzyfication, the indices are assigned to fuzzy sets, describing the index behaviour. The indices are thereby assigned to the sets not entirely but with a particular share, also called membership $M_{Index,Set}$. The assignment function of $M_{Index,Set}$ for the three sets used is shown in Figure 4. The indices are assigned to three sets (low, normal and high) with trapezoidal and triangle-shaped functions. An index assignment to the low set is described with the respective function, as in (3).

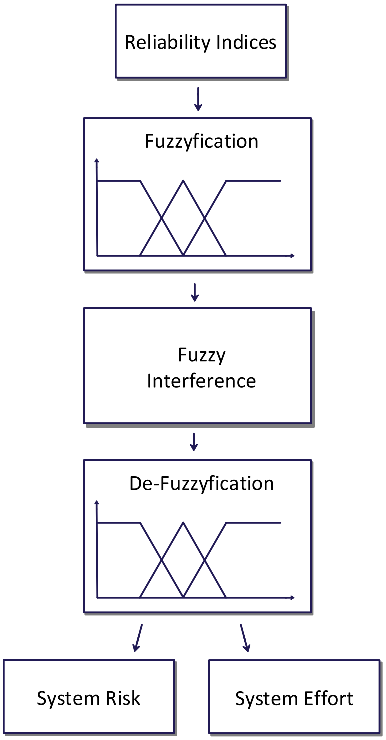


**FIGURE 3** Fuzzy logic used for the evaluation of system risk and system effort with the indices in Tables 1 and 2

**TABLE 3** Results of the system effort with SNSP-based scheduling

| $T_{SNSP}$ | EWEW GWh | EVSM GWh | ECU GWh | IENS GWh |
|---|---|---|---|---|
| 2 | 518.19 | 0 | 0.447 | 0.2629 |
| 2.2 | 516.57 | 16.63 | 0.425 | 0.2609 |
| 2.4 | 516.34 | 16.68 | 0.425 | 0.2607 |
| 2.6 | 516.03 | 16.81 | 0.423 | 0.2606 |
| 2.8 | 515.63 | 16.99 | 0.419 | 0.2604 |
| 3 | 515.27 | 17.16 | 0.417 | 0.2604 |
| 3.2 | 514.72 | 17.42 | 0.414 | 0.2604 |
| 3.4 | 512.89 | 17.68 | 0.409 | 0.2601 |
| 3.6 | 511.35 | 17.95 | 0.406 | 0.2599 |
| 3.8 | 510.61 | 18.13 | 0.404 | 0.2597 |
| 4 | 510.22 | 18.30 | 0.401 | 0.2597 |

**TABLE 4** Results of the system risk with SNSP-based scheduling

| $T_{SNSP}$ | EENS GWh | ENAF occur | EAFD min |
|---|---|---|---|
| No VSM | 6.234 | 39.67 | 55.21 |
| 50% | 5.902 | 37.56 | 54.37 |
| 48% | 5.887 | 37.49 | 54.10 |
| 46% | 5.883 | 37.42 | 54.08 |
| 44% | 5.879 | 37.36 | 54.06 |
| 42% | 5.875 | 37.29 | 54.04 |
| 40% | 5.870 | 37.16 | 54.04 |
| 38% | 5.866 | 37.03 | 54.03 |
| 36% | 5.862 | 36.89 | 53.97 |
| 34% | 5.860 | 36.83 | 53.89 |
| 32% | 5.858 | 36.76 | 53.82 |
| 30% | 5.856 | 36.69 | 53.80 |

Abbreviation: VSM, virtual synchronous machine.

$$M_{Index,Low} = f_{Low}(Index_{Ref}) \tag{3}$$

The example in Figure 4 assigns a relative index value of 93%, with 30% to the normal set and with 70% to the low set.

The three frequency-related indices are combined with different levels of importance. The proposed evaluation uses two different levels of importance, reduced priority and increased priority. This allows a fast weighting of the indices by the system operator. In the case study, the amount of load curtailment is considered with increased priority, whereas the number and duration of abnormal frequency events are considered with reduced priority. Afterwards, the set values of the two priorities are combined with their averaged memberships. As a result, six sets are assigned with different shares, reduced and increased priority with each of the three sets low, normal and high.

### 2.2.2 | Fuzzy-interference

The fuzzy sets are, in this step, combined based on their memberships. The sets for the reduced priority indices and the increased priority indices are used to achieve the set values for the five sets used to describe the system risk and effort values. The five sets are very low, low, normal, high, and very high. These five sets' assignment is described with the relationships in Table 5 by multiplying the low priority and high priority set memberships.

As an example, the membership for very low system risk is determined by the combined memberships of EENS, ENAF and EAFD as follows:

$$M_{RiskVeryLow} = M_{EENSLow} \frac{M_{ENAFLow} + M_{EAFDLow}}{2} \tag{4}$$

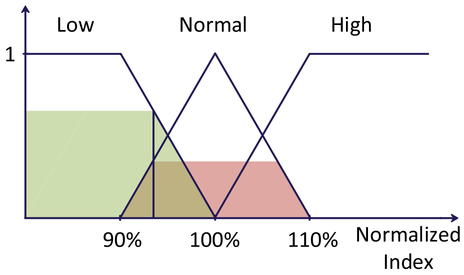


**FIGURE 4** Fuzzy sets, describing the membership functions of the system reliability indices

**TABLE 5** Interference matrix used to combine multiple input indices

| | | Increased priority | | |
|---|---|---|---|---|
| | | Low | Normal | High |
| Reduced priority | Low | Very low | Low | High |
| | Normal | Low | Normal | High |
| | High | Low | High | Very high |

First, output sets are assigned to multiple combinations. Then, the respective membership products are summed up. The five sets are used in the de-fuzzyfication step for the two values, risk and effort.

### 2.2.3 | Defuzzyfication

The five output fuzzy sets achieved in the interference are translated back into a single value in the third and last step, the de-fuzzyfication steep. In this step, the sets are assigned to discrete values representing the state of the system. Hereby, the five sets are summed up with their memberships. This summation is done with the mean weighted value, determined with the membership values of the corresponding sets, as shown in (5).

$$\begin{aligned} Risk = {} & 0 \cdot M_{RiskVeryLow} + 0.5 \cdot M_{RiskLow} \\ & + 1 \cdot M_{RiskNormal} + 2 \cdot M_{RiskHigh} \\ & + 5 \cdot M_{RiskVeryHigh} \end{aligned} \tag{5}$$

Figure 5 shows an example where the risk sets very low, low, normal, and high are assigned with a membership value. The outcome of the evaluation is thereby given as the summation of the share of the set with its assigned value. This means the outcome of the system risk and the system effort, respectively, can vary between 0 and 5. A risk value of 0 indicates that all three frequency-related indices are entirely assigned to the low set, meaning the risk in the system is severely reduced compared to the reference case. A risk value of 5 indicates an assignment of these three indices to the high set. So the system frequency is worse than in the reference case.

The same relationship exists for the effort of the system in maintaining the system frequency. A value of zero means that all the determined energies have been significantly reduced, meaning they are assigned to the low set. A system effort of five, on the other hand, means that the frequency controls are utilised more often and more severely.

## 3 | CASE STUDY

The proposed evaluation method of multiple reliability assessments is tested on an IEEE Reliability Test System (RTS) with 1000 MW additional wind power plants. The system is described in detail in [32, 33]. The integration of VSM services,

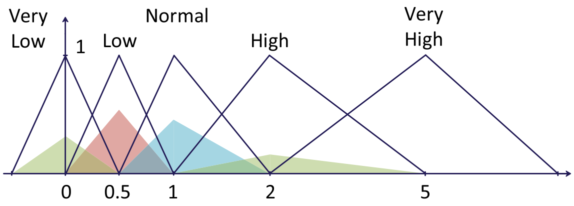


**FIGURE 5** Fuzzy sets used to calculate the outcome of the evaluation

provided by the wind power plants, into the system aims to support the remaining synchronous machines to keep the frequency-related indices within an acceptable range.

The main power system information is given in Section 3.1, together with the additional wind power plant information. The additional VSM service from the wind power plants and the utilised scheduling scheme for the service are described in Section 3.3.

### 3.1 | Power system modelling

The dynamic generator data used to simulate the system frequency during contingencies are given in [33]. The system is represented as a one-bus system with multiple generation units [19]. The unit commitment order of the conventional generators first activates the generators with higher time constants and activates the smaller units only if needed. This results in highest system inertia for any given load and wind power injection condition and more severe contingencies in case of large generation unit failures. Primary and secondary frequency controls are implemented in dedicated conventional generation units, as described in [5].

The system load is represented by the hourly peak load, resulting in the load duration curve (LDC). The data for the LDC is given in [32] and shown in Figure 6. For the IEEE RTS, the maximum hourly peak load is 2850 MW. Fifty discrete load steps are used for the initial conditions of the dynamic system simulation.

UFLS is implemented to determine the amount of load not supplied. This is the last option for the system operation during frequency drop contingencies. With the controlled load deactivation still, the remaining parts of the system can be supplied. The UFLS scheme is fixed in this analysis, and so it is not changed during the operation of the grid. The UFLS scheme used follows the guidelines of the ENTSO-E [31].

The additional 1000 MW wind power plants included in the test system are described in detail in Section 3.2.

### 3.2 | Wind power plant modelling

Wind power plants are additionally included in the IEEE RTS to analyse their impact on the frequency quality. The wind power plants included in the analysis have a total rated power of 1000 MW. Two hundred wind turbines are included in the IEEE RTS with a rated wind turbine power of 5 MW. The current power injection of the wind power plants depends on the wind speed distribution and the design and control of the turbines. The wind speed probability follows the Gaussian distribution, a commonly used method for modelling wind power throughout the yearly operation [34]. The cut-in, the rated, and the cut-out wind speed are 3, 11 and 25 m/s. The details of the turbine modelling are described in [35]. The wind power produced in every hour of a year can be combined in a wind power duration curve. The wind power plants and the wind speed distribution are designed to have 4000 full-load hours [36], representing offshore wind conditions.

### 3.3 | VSM service by wind power plants

Additional frequency controls in wind power plants are designed to improve the system frequency reliability in power electronic converter-based generation units. Wind power plants are also, within certain limits, capable of performing VSM services. However, when additional active power is supplied to the grid, the wind turbines slow down and have to be recovered after the disturbance is cleared. The VSM control is described in Section 3.3.1, whereas the two scheduling schemes compared are described in Section 3.3.2.

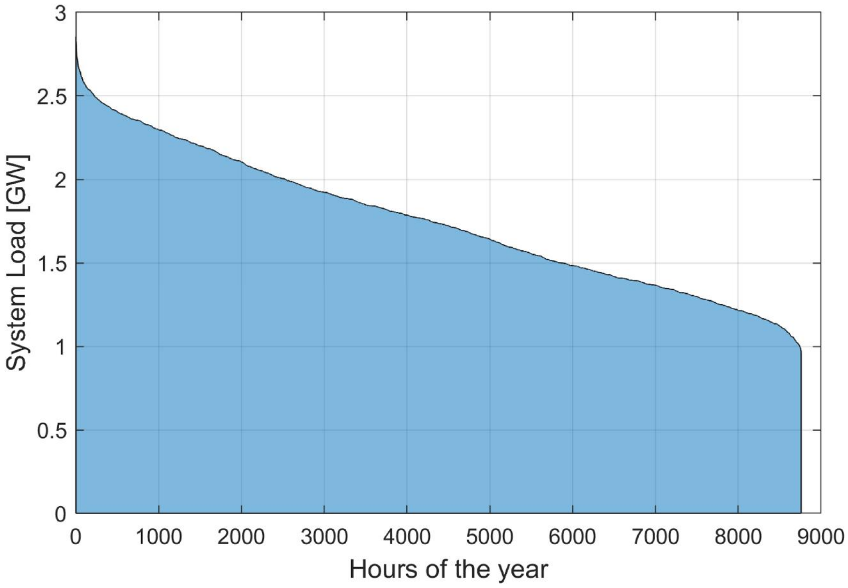


**FIGURE 6** Load duration curve in the IEEE Reliability Test System; data given in [32]

### 3.3.1 | VSM control in the wind power plants

Wind power plants in operation have a certain amount of kinetic energy available in the rotating blade, gear and generator, allowing the short-term power output to increase by reducing the rotational speed of the turbine. It has been shown that wind power plants are capable of delivering this kind of active power service [37–39].

Until now, converter-based units have been current controlled, meaning they synchronised with the grid voltage and then injected current into the grid. VSM control is severely changing the way converters behave. The active and reactive power flows of VSM-controlled machines are directly dependent on the changing grid conditions. Reactive power loops change the magnitude of the converter output voltage, whereas the active power control is responsible for the voltage angle, emulating the inertia from machines. Different ways of VSM implementations are possible. In practice, however, inner current controls are still responsible for the equipment protection and for backup purposes during grid faults, together with a phase-locked loop for grid synchronisation [12]. The virtual inertia and power control block is responsible for the frequency-dependent converter's behaviour. This control block is shown in Figure 7. Two timeframes are given in this control block, the inertia-emulating part and the steady-state droop-based control actions.

It can be seen in Figure 7 that the measured active power flow $P$ into the grid is compared to the reference value $P^*$. Any deviation causes a change in the internal rotational speed value and, therefore, the angle of the output voltage and, with this, the amount of active power produced. The internal frequency is also used in a loop so that the converter operates with a droop characteristic, being defined with the control value $k_d$. This allows for finding a stable operating point after disturbances occur in systems with multiple machines. $T_a$ is the time constant that represents the time constant of the synchronous machine. The emulated time constant $T_a$ is set to 5 s and the damping $k_d$ is set to 50, as used in [40]. The possible active power change due to the enabled VSM service in the wind power plants is set to 0.2 pu. The VSM service is, when activated, used at 20% of the wind power plants, as all the wind power plants may not be equipped with the control option of the VSM service.

This study evaluates the active power delivery as a system service and does not give design proposals for the internal controls, such as the synchronisation, current and voltage controls. When the system operator orders the service during operation, the wind power plants can deliver more active power for a short duration during frequency drops. During an increasing system frequency, the wind turbines curtail their power output, balancing the system's active power. The power reduction can be realised for a long duration without damaging the equipment.

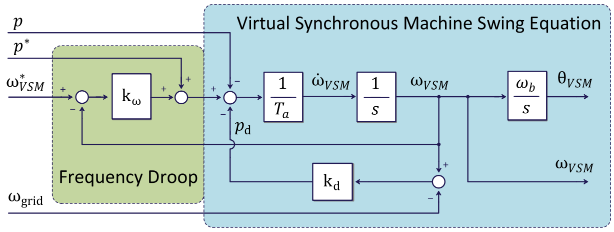


**FIGURE 7** Virtual inertia control block of a wind turbine [12]

### 3.3.2 | VSM scheduling strategies

The VSM functionality is a system service ordered by the system operator. This service is scheduled to be utilised only when needed by the system during weak grid conditions. With the scheduling scheme, the TSO can decide when to activate this service and when it is not needed. For this, the system operators have to estimate the state of the power grid, the amount of system load, the number of conventional generation units in operation, and the current number of converter-based generation. The decision is based on the scheduling strategy, which considers the acquired information. Service activation is then distributed via communication links to the system equipment, changing the operating states.

The first analysed scheduling scheme evaluates the SNSP, the system non-synchronous penetration. With higher penetration of converters, this value is increased throughout the operation. However, it is not a direct measure of the remaining system inertia. It only depends on the share of converter-based injection and not on the total value of remaining synchronous generation units. It is given, as described in (6). The SNSP for the given IEEE RTS with the additional wind power plants is given in Figure 8.

The scheduling scheme is illustrated in Figure 9. The scheduling strategy activates the VSM service by the wind power plants whenever the actual SNSP is above a pre-defined threshold $T_{SNSP}$. The value of $T_{SNSP}$ is varied in this analysis from 50% to 30% to compare the different settings according to their impact on the system reliability. The wind power is always curtailed so that it never exceeds a penetration level of 50%; so the service is first activated at this threshold. Reducing the threshold activates the service at lower penetration levels; so the service is used more often during the operation.

The second strategy for utilising the VSM service is based on the remaining total system inertia (TSI). When the TSI is below a certain threshold $T_{TSi}$, the system frequency is at a greater danger of being in an abnormal state and the VSM service is demanded. The TSI is defined by the conventional synchronous generation units in the system.

$$TSI = \sum_{i=1}^{N_i} SB_i \cdot H_i \tag{6}$$

The TSI of the IEEE RTS system without and with the 1000 MW wind power installed is shown in Figure 10.

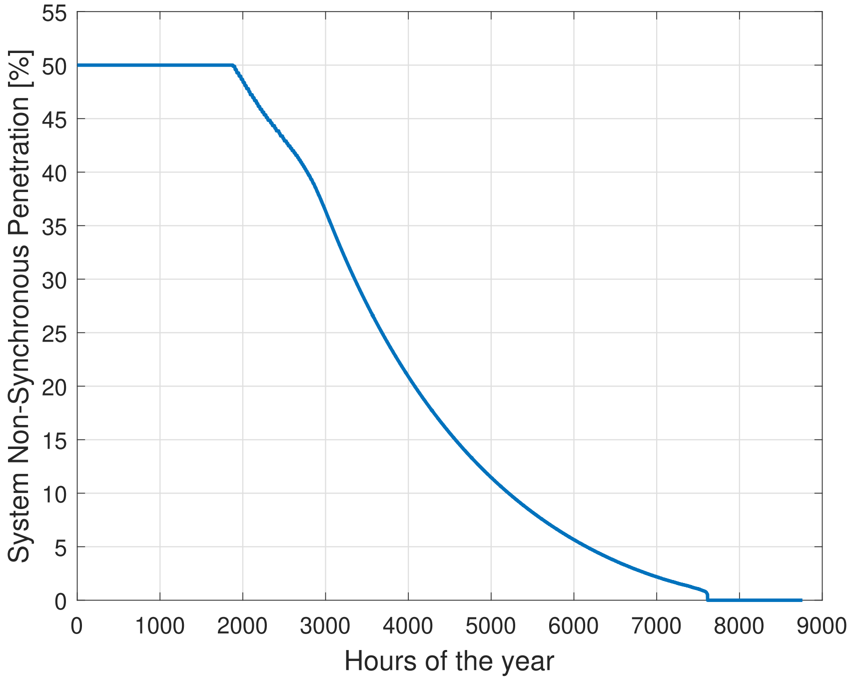


**FIGURE 8** SNSP of the IEEE RTS system with 1000 MW wind power installed. RTS, Reliability Test System

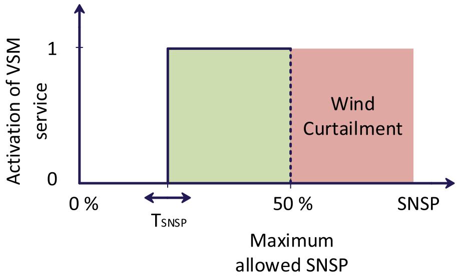


**FIGURE 9** Proposed VSM scheduling scheme based on the SNSP, with the variable $T_{SNSP}$ being changed during the reliability assessment. VSM, virtual synchronous machine

$T_{TSi}$, the threshold for demanding the VSM service, is varied in this analysis from 2 to 4 GWs to determine the most reliable setting for frequency management.

## 3.4 | Fuzzy-based evaluation in the case study

The fuzzy-based evaluation is adapted in the power system analysed and the frequency management strategies used. The fuzzy sets for the given case study allow for comparing the system frequency performance and load curtailment enhancement. The three indices for the system risk description (EENS, ENAF and EAFD) are fully assigned to the low set when their values are reduced by 10%; they are assigned as high when their values increased more than 10%. In between these values are the sets also assigned to the normal set, following the scheme in Figure 4.

The effort-related index EVSM changes severely for the different scheduling strategies and settings used. The assignment is normal at zero VSM service usage. It is fully assigned to the high set when it is at 36 GWh. This is the amount of VSM service that will be demanded when the service is ordered full time. It depends on the power system's behaviour and has to be adapted when the VSM usage, control settings, and scheduling strategy are varied. EWEW, IENS and ECU are assigned to the low set when reduced by 10%. They are fully assigned as high when increased by 10%.

The interference matrix used in the case study is shown in Table 5. The interference is not dependent on the case study, as the membership assignment of the fuzzy sets themselves are adapted to the specific case study.

The de-fuzzyfication is performed as described in Section 2.2.3. The five sets, very low, low, normal, high and very high, are assigned with values 0, 0.5, 1, 2 and 5, respectively. This is done to increase the effect of indices rising more than the reduction of indices due to frequency management changes. In the test case shown, this would mean an increase in system risk if the ENAF rises by 10% and the EAFD drops in the same case by 10%. Other strategies for the evaluation can also be chosen, such as a balanced rise to reduction ratio.

The resulting frequency reliability of the above described case study is described in Sections 4.1 and 4.2. The fuzzy-based evaluation for the case study is described in Section 3.4.

## 4 | RESULTS

This section describes the reliability analysis in the case study described. The results of the two activation schemes for the additional frequency control are described first. Then, the proposed fuzzy logic is utilised to determine which schemes are well suited for use in the power system analysed.

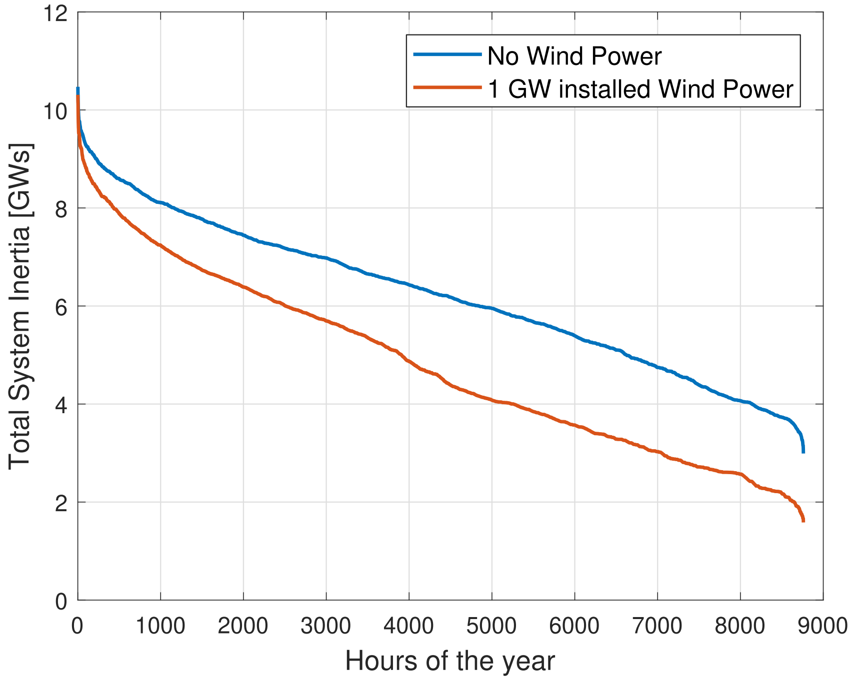


**FIGURE 10** TSI of the IEEE RTS system without and with 1000 MW wind power installed. RTS, Reliability Test System; TSI, total system inertia

## 4.1 | Reliability with TSI-based scheduling

The system reliability is influenced by the value set for the scheduling scheme $T_{TSI}$. The risk-based indices of the system are shown in Table 6. The results show how a higher threshold value changes the VSM service usage, influencing EENS, ENAF and EAFD.

The results in Table 6 are illustrated in Figure 11. The indices are changed with the different TSI values that are used for the VSM service's activation.

The system efforts used for the different frequency management strategies are shown in Table 7, with the indices EWEW, EVSM, ECU and IENS. Other indices can help determine the optimal frequency management strategy when utilising different frequency control schemes.

It can be seen that changing the scheduling strategy has an influence on all the frequency control-related indices determined in the study. A comparison of the frequency performance and the control effort is further shown in Section 4.3. The proposed evaluation method is used to determine which scheduling strategy is better suited for reliable frequency management.

## 4.2 | Reliability with SNSP-based scheduling

In this section, the system reliability is evaluated using an SNSP-based scheduling strategy. The threshold for activating the VSM service $T_{SNSP}$ is varied to determine its influence on the system frequency reliability. The risk-related indices are shown in Table 4.

**TABLE 6** Results of the system risk with TSI-based scheduling

| $T_{TSI}$ GWs | EENS GWh | ENAF occur | EAFD min |
|---|---|---|---|
| No VSM | 6.234 | 39.67 | 55.2 |
| 2 | 6.194 | 39.31 | 54.78 |
| 2.2 | 6.156 | 39.17 | 54.72 |
| 2.4 | 6.122 | 39.04 | 54.63 |
| 2.6 | 6.088 | 38.91 | 54.58 |
| 2.8 | 6.032 | 38.67 | 54.54 |
| 3 | 5.971 | 38.45 | 54.50 |
| 3.2 | 5.923 | 38.29 | 54.46 |
| 3.4 | 5.896 | 38.25 | 54.42 |
| 3.6 | 5.882 | 38.10 | 54.38 |
| 3.8 | 5.879 | 37.67 | 54.27 |
| 4 | 5.874 | 37.46 | 54.12 |

Abbreviations: TSI, total system inertia; VSM, virtual synchronous machine.

The effort of the system with SNSP-based scheduling is shown in Table 3. $T_{SNSP}$ is varied to determine its influence on the frequency control effort by the system.

As different indices describe the system reliability for the management strategies tested, it is difficult to assess which one is suitable for TSO needs. This is also the case for other studies, which analyse different levels of wind power integration [5, 41, 42] or the effect of different amounts of frequency control reserves in the power grid [19, 20].

The effort has to be compared with the system's frequency behaviour, described in Table 4. The proposed fuzzy-based

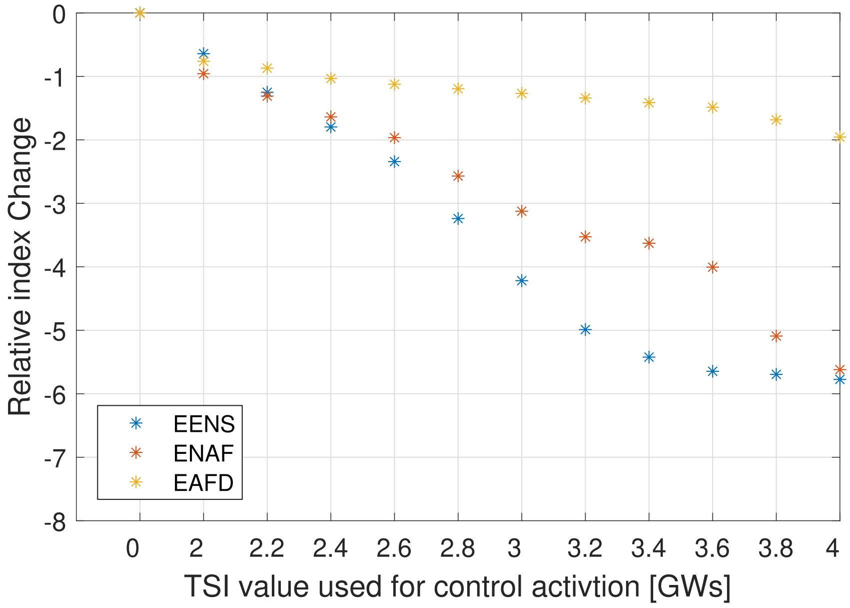


**FIGURE 11** Frequency-related reliability index changes dependent on the TSI value chosen for the VSM-service activation. TSI, total system inertia; VSM, virtual synchronous machine

**TABLE 7** Results of the system effort with TSI-based scheduling

| $T_{TSI}$ GWs | EWEW GWh | EVSM GWh | ECU GWh | IENS GWh |
|---|---|---|---|---|
| No VSM | 518.19 | 0 | 0.447 | 0.2629 |
| 2 | 517.63 | 4.23 | 0.442 | 0.2621 |
| 2.2 | 517.41 | 6.73 | 0.438 | 0.2619 |
| 2.4 | 517.07 | 7.18 | 0.434 | 0.2619 |
| 2.6 | 516.87 | 8.91 | 0.433 | 0.2617 |
| 2.8 | 516.41 | 10.30 | 0.430 | 0.2614 |
| 3 | 515.90 | 11.59 | 0.428 | 0.2611 |
| 3.2 | 515.24 | 13.25 | 0.423 | 0.2609 |
| 3.4 | 514.48 | 15.93 | 0.418 | 0.2608 |
| 3.6 | 513.76 | 17.27 | 0.416 | 0.2606 |
| 3.8 | 513.32 | 19.89 | 0.414 | 0.2603 |
| 4 | 513.17 | 21.32 | 0.412 | 0.2601 |

Abbreviations: TSI, total system inertia; VSM, virtual synchronous machine.

evaluation method aims to allow this to happen. The adaptation of the fuzzy evaluation for the case study is shown in Section 3.4. The system effort and system risk calculated are then compared in Section 4.3.

## 4.3 | Comparison of the scheduling strategies

The reliability indices shown in Sections 4.1 and 4.2 are difficult to compare. Multiple indices have to be assessed to find the most reliable frequency management strategy. The proposed fuzzy-based evaluation determines the risk and effort values of the respective scheduling settings and strategies. The results of both the strategies in the case study evaluated with the utilised frequency management strategies are shown in Figure 12.

It can be seen that both the strategies reduce the system risk by increasing the frequency management effort. The reduction in risk indicates that the additional frequency control reduces the amount of load curtailment and the abnormal frequency states and duration. However, the SNSP-based scheduling strategy more effectively reduces the system risk without increasing the effort excessively. This indicates that the SNSP-based scheduling activates the VSM service more effectively in grid conditions. It is more useful for frequency management in the power system and wind condition evaluated.

On the other hand, the TSI-based scheduling scheme allows for a more gradient change in the system frequency management. This can be explained by comparing Figures 8 and 10. An increase in the threshold of the TSI-based scheduling causes a slow increase in the VSM service usage. In contrast, the SNSP-based scheduling is initially activated during larger shares of the system operation at the initial usage stage when SNSP is 50%.

The fuzzy-based evaluation also allows to determine the trend within the scheduling schemes. The TSI-based frequency control activation shows that the rise in effort does not linearly decrease the system sisk. There is a change in controller usage effectiveness, when the activation threshold is above 3 GWs. This indicates that the wind power plant service is then demanded more often in cases where no actual frequency improvements are made, causing higher prices for the customers without further beneficial system reliability. This behaviour can not directly be seen, when comparing the indices in Tables 6 and 7.

Comparing the different scheduling strategies allows TSOs to decide fast which frequency management strategies are worth investigating closer.

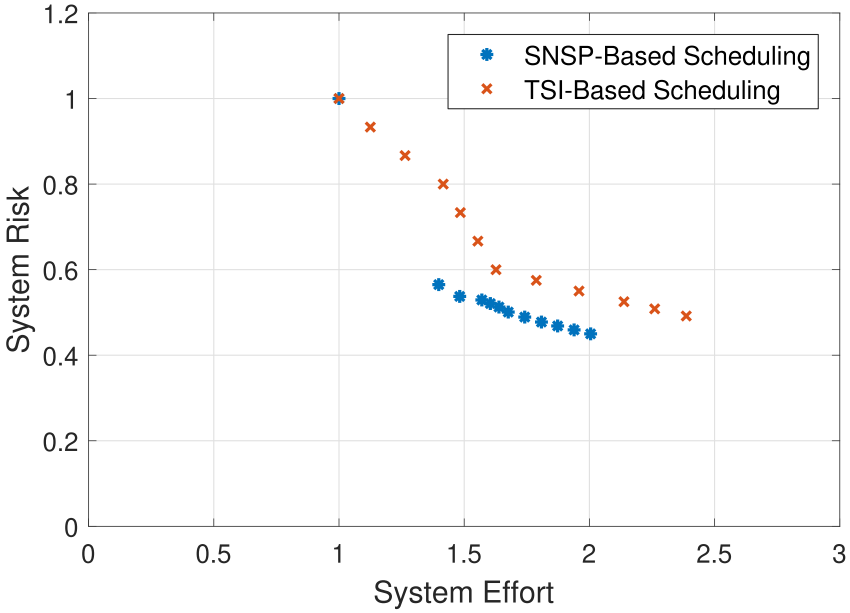


**FIGURE 12** Results of the reliability evaluation, allowing for comparison of different frequency management strategies

## 5 | CONCLUSION

A new evaluation method for power system frequency assessment is proposed in this work. It utilises fuzzy logic to combine multiple different reliability indices to only two values, the system risk and the system effort. These two values allow a quick comparison of different frequency management strategies by the system operator. This allows finding the most reliable operational strategy for power systems with a high penetration of converter-based generation units.

A comparison of two scheduling strategies with changing settings for the VSM service by wind power plants has been evaluated in this study. It shows which strategy allows a more effective VSM service usage, concerning frequency management. The different schemes activate the service based on two criteria: the remaining system inertia and the actual non-synchronous penetration level. Therefore, the VSM service can be utilised more effectively, and weaker grid conditions can be controlled in a more reliable way. The proposed fuzzy-based evaluation allows adapting to operator preferences quickly by assigning the indices with different priorities. Under different grid conditions, the evaluation can be adapted very quickly by changing the shape of the fuzzy memberships in the fuzzyfication step.

The proposed method also allows to describe the trends within the scheduling schemes, as shown with the decreasing effectiveness of the additional frequency controls when utilised in grid conditions with sufficient remaining inertia.

The computational effort of the proposed evaluation is neglectable to the computational burden of the dynamic system simulation that is required to calculate the reliability indices. Therefore, the proposed method can be used as an additional tool to find frequency management strategies with low potential for improving the power system reliability.

The proposed method is used to compare different scheduling strategies, as done in the study case. At the same time, it can also be utilised to compare different control structures, control settings and service scheduling. The frequency management design for improved frequency reliability allows for a wider integration of renewable-based generation units into the system, while maintaining high operational frequency reliability. Solar systems, HVDC and battery systems can also provide frequency services to the system. Their effect on the system reliability has to be determined to guarantee the best system performance with the least frequency control effort.

Further research should aim to utilise more advanced fuzzy-set shapes during fuzzyfication. Different interference strategies can also be utilised and their ability to detect optimal frequency management strategies can be compared.

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