Investigation of a new average value based load shedding concept to secure critical infrastructures in case of emergency

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***Abstract*— The increasing amount of renewable energy sources in distribution and transmission grids demands significant adjustments to secure stability of energy systems, for example in cases of emergency with under frequency below 49.8 Hz. One of the challenges is a high homogenous mixture of load and decentralist generation in the power system so that a selective identification of loads is not possible. This leads to the essential problems for the transmission system operator that if disturbances occur in the grid automatic under frequency load shedding (AUFLS) relays can disconnect renewable plants from the grid rather than of loads which decreases the probability of a successful remedial action. This paper gives an enlightening point of view by using a new load shedding concept in order to address the illustrated challenges. Especially the optimal distribution of relays in the control area according to the 5-step load shedding plan is focused in this investigation.**

***Keywords*— 5-step plan, frequency stability, load shedding, power system stability**

I. INTRODUCTION

Reliable energy supply is one of the main requirements of our society. Therefore, system operators have to secure stable operation of the electrical power system at any time. This paper deals with operation in critical situations, especially automatic under frequency load shedding in the electrical power system. The rising share of renewables in distribution and transmission grids in Germany demands significant adjustments to secure power system stability in dangerous situations with under frequency to prevent a black out. An important measure of last defense to avoid a blackout is the 5–step load shedding plan. Hence, the highest priority has the secure and reliable application of load shedding. The challenge under new conditions with high renewable energy feed in is to disconnect loads instead of renewable sources to stabilize the system frequency. The problem is that frequency measurement systems installed before the boom of distributed generation are not able to detect the load flow direction. This study introduces a new load shedding concept which considers the renewables and tries to answer the question if this new concept is more successful to distribute all required load shedding steps in a control area than the current available load shedding concept. According to the context “successful” means the highest probability to prevent further under frequency or a blackout (worst case) with the 5-step load shedding plan. The analyses presented in the following are based on vertical grid load data (one year) for 139 380 kV / 110 kV transformers from the transmission system operator 50Hertz transmission.

II. POWER SYSTEM STABILITY AND CRITICAL SITUATIONS

Power system stability is characterized by the ability of an electric power system to recover a state of operating equilibrium after a disturbance back to a given operating condition, such that the system remains intact. Power system stability is classified by three key factors. Rotor angle stability (synchronism of generators), voltage stability (steady voltage at all busses) and frequency stability.[1] The objective of the analyses was the frequency stability, which is characterized by balance between generated and consumed active power and losses. A disturbance in the power system e.g. load changes or generator outages leads to an unbalanced system (power imbalance) with change in frequency. Therefore the spinning reserve is an important property of the electric power system which is given by rotating masses of generators in the system and defined by the inertia constant J. The inertia of the rotating mass damps the frequency drop in the first seconds after disturbance until control reserves can be activated. Hence, the inertia constant defines the time of a system to react on changes in power balance and is a critical component of the system with increasing amount of renewables. Primary control reserves are dimensioned to stabilize the system in the range from 50.2 Hz to 49.8 Hz for disturbances up to 3000 MW in the interconnected European system. Secondary and tertiary control reserves are activated according to the German Transmission Code 2007 [2]. The control reserves are needed to compensate the active power mismatch.

The focus in this analysis was on the first frequency drop after disturbance which includes primary control with activation time of 30 seconds and some more primary control requirements that have been taken into account during this investigation [3]. In case of large disturbances with high frequency drops, the 5-step plan for load shedding is the last possible defense for a system operator to react in a critical situation with high active power imbalance (cf.).

TABLE I. 5-STEP PLAN TRANSMISSIONCODE 2007 [2]

Level	**Procedure**
Level 1: 49.8 Hz	alert at TSO
Level 2: 49.0 Hz	load shedding 10 %-15 %
Level 3: 48.7 Hz	additional 10 %-15 %
Level 4: 48.4 Hz	additional 15 %-20 %
Level 5: 47.5 Hz	generation separation

The load shedding plan is based on the procedure that the Transmission system operator (TSO) instructs all Distribution system operators (DSO) in its control area to set their automatic under-frequency relays to fulfill the 5-step plan. The calculation of the required value for load shedding in the TSO control area will be shown in the following section. Therefore the calculation is fundamental for application of load shedding and the reliable and secure prevention of under-frequency and a blackout (worst cast) in the power system.

III. REACTION ON CRITICAL SITUATIONS WITH A NEW LOAD SHEDDING CONCEPT

The calculation of load shedding for each level of the load shedding plan is based on the transformer individual reference value ($P_{\text{Reference}}$). The currently applied concept to determine the reference value is called annual peak load concept (JHL) and takes the day (1/4 h-values) with the highest system load into account [4]. Within the given database the highest system load (reference) was identified by the highest vertical system load (13th February 17:45-18:00) and afterwards identified for each transformer for this point of time. For this point of time 16 out of 139 transformers show a negative active power value, which represents a power flow from DSO to TSO. These transformers cannot be used for load shedding calculation because the reference values have to be positive. Furthermore, these 16 transformers represent the upcoming challenge of homogenous mixture of load and generation in the distribution grid making it almost impossible to solely shed loads but shed a small amount of generation as well. Even at the day with highest vertical load, there is an energy surplus at some points in the grid.

According to the high installed capacity of renewable generators and the associated high fluctuating supply reasoned by daily, seasonal and meteorological fluctuations a new load shedding concept is required. This new concept should ensure that mostly load will be disconnected from the grid instead of generation in case of large disturbances. The massive consequence of generation disconnection is a rising frequency droop which should not be a case in this emergency plan. Based on the illustrated problem the technical note from FNN recommends a new concept by taking the annual average load into account [4]. Therefore the new load shedding concept is based on average values to reduce the possibility of generation shedding. The reference values are calculated individually for each transformer by division of the power measurement values into similar blocks of 12 months. Thereafter follows the calculation of the average value for each month and the identification of the maximum average value over the year such that the average value concept (JM) is a maximum monthly average value concept. This calculation represents a worst case regarding the month with the highest load. By analyzing all 139 transformers, 23 reference values are negative. The average values show a more reliable detection of transformers with high probability generation shedding. Following the transformer reference values for the average value concept are lined up from the smallest to the greatest value and illustrated in Figure 1 (red). Each associated transformer reference value for the annual peak load concept (blue) is also shown in Figure 1. The result by comparison of the two concepts is that the average deviation between the reference values are 31 MW and the JHL- concept span a total larger area.

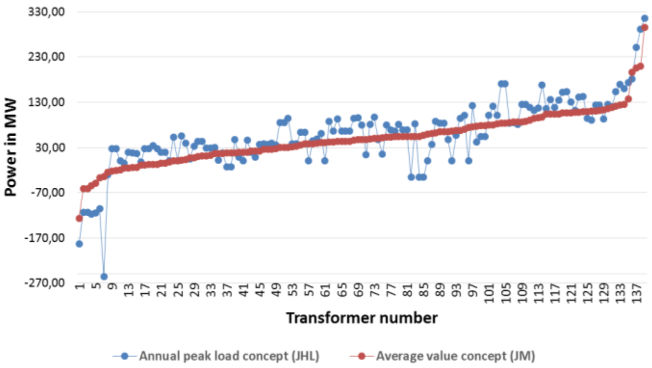

Figure 1. Comparison of reference values (JHL and JM) for load shedding at each transformer, lined up from the smallest to the greatest reference value based on average value concept

After defining all reference values for both concepts it is possible to calculate the load shedding for each load shedding level. A simplified assumption during the investigation is a continuous load shedding of about $r = 10\,\%$ in each load shedding level of the 5-step plan. Equation 1 shows how to calculate the load shedding for the annual peak load concept ($P_{\text{load shedding, JHL}}(\text{Level})$). This can be applied similarly for the average value concept.

$$P_{\text{load shedding, JHL}}(\text{Level 1}) = P_{\text{Reference, JHL}} \cdot r \qquad (1)$$

IV. MODELLING AND DYNAMIC ANALYSIS

The evaluation of the new load shedding concept requires not only a static data analysis of the reference values. This investigation used a dynamic model to evaluate the concept by applying load shedding with consideration of primary control, power system parameters (inertia constant (H) and self-regulation of load (D)) and the resulting frequency deviation. The model is based on the power balance model (2) [5, 6]. This equation directly shows the relationship between power imbalance and following frequency deviation Δf. Power change is represented by the delta of generation ($\Delta P_{\mathrm{Gen}}(t)$) and the delta of load ($\Delta P_{\mathrm{Load}}(t)$). The disturbance ($P_{\mathrm{Dist}}$) is not directly considered in the equation but is assumed to be part of the load change. The right side of the equation represents key parameters of a power system with inertia constant, self-regulation of load and the resulting frequency deviation in case of power imbalance.

$$\Delta P_{\mathrm{Gen}}(t) - \Delta P_{\mathrm{Load}}(t) = 2 \cdot H \cdot \mathrm{d}\,\Delta f(t)/\mathrm{d}t + D \cdot \Delta f(t) \qquad (2)$$

Following equation 2 the power system was modelled with generation, load, inertia constant, self-regulation of load and the measured frequency deviation. Hence, additional system components were configured and implemented in the model. This considers the primary control with typical configuration according to the ENTSO-E OH [3] and given parameters by 50Hertz transmission. Furthermore the disturbance represented by additional load, the 5-step load shedding plan as well as generation separation at 47.5 Hz where integrated in the electric power system model. Figure 2 displays a simplification of the described model. Afterwards the model was implemented in MATLAB/Simulink©.

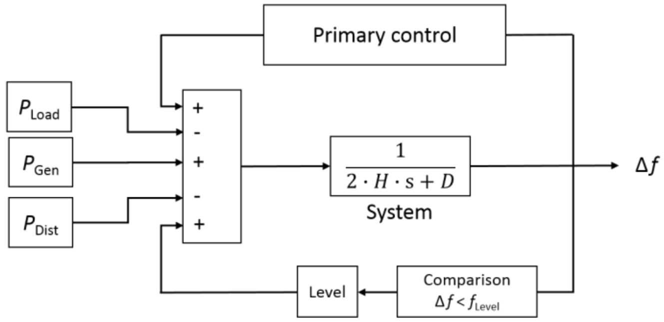

Figure 3. Dynamic system model for load shedding analysis

After implementation of all components in the dynamic model the system has to be proofed. Especially the primary control is an important point during the investigation of load shedding. To validate the model the primary control has to be operational according to the primary control requirements of the ENTSO-E OH [2]. For a disturbance in the amount of the primary control the frequency curve has to fulfill some defined points like a maximum dynamic frequency deviation of about - 800 mHz and the primary control have to bring back the frequency to the static frequency deviation of -180 mHz under consideration of self-regulation of load. Figure 3 represents the associated curves for the validation of the used model with full activation of primary control under steady state generation and load as well as a disturbance with the amount of the primary control reserve. The model performance (blue curve) shows nearly the required behavior according to the ENTSO-E OH (red curve). Only a slight overshoot in the return of the frequency at 60 second is not satisfied.

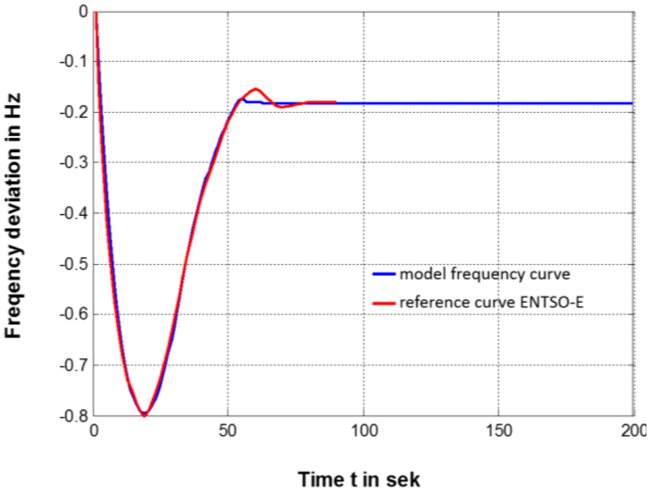

Figure 2. Model validation with primary control performance

The operation of the dynamic analyses follow the main objective to vary the load shedding for each level of the load shedding plan at a given state of the power system. A given state means a fixed load and generation and a fixed value of disturbance according to the load shedding level which should be analyzed. Therefore, disturbance and primary control were calculated for each transformer to have a fixed individual state of the power system and to have an independent investigation for the transformers. The gain of load shedding variation was to calculate the probability of a successful load shedding, e.g. not too much and not too little load shedding. For example a load shedding in level 2 is successful if the static frequency after disturbance lies in the range of 50 Hz ± 200 mHz and load shedding level 3 was not activated. This investigation was done for each transformer and each load shedding level.

The calculation of the probability for a successful load shedding is firstly based on the variation of load shedding. The value of load shedding is for example about 10 MW in load shedding level 1 for a reference value of 100 MW. Then the variation of load shedding level 1 could have been in the range from 7 MW to 14 MW. Furthermore, based on this given power value range the probability was calculated using the transformer individual statistic power value distribution of one year, such that the probability for successful load shedding is for the given example about 43 % in level 1

V. RESULTS

The results of the investigation compare the current load shedding concept (JHL) with the new concept by evaluating the probability of a successful load shedding in each load shedding level for 139 transformers. After determining the probabilities it was possible to detect the level with the highest probability at each transformer. An example is given in the following Figure 4 where the probabilities for a successful load shedding are represented for each level at a transformer. The main focus by analyzing this example is on load shedding level 1 because both concepts show the highest probability in this level. Regardless of the current or new concept it will be optimal to use this transformer with a probability over 50 % for load shedding level 1 so that the relay can be configured with this setting. This procedure was done for each transformer as explained in the example.

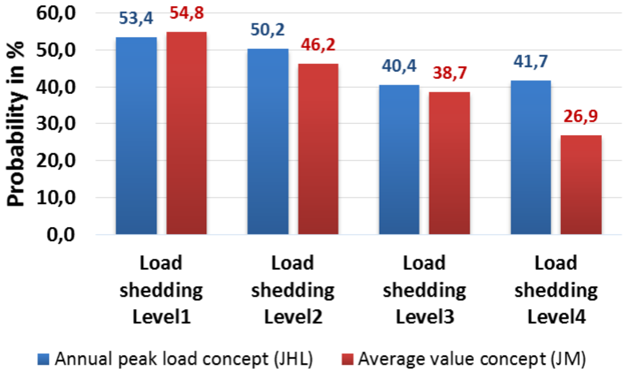

Figure 4. Example transformer 1, probabilities for a successful load shedding at each load shedding level for both concepts

A. *Optimal distribution of load shedding levels*

The objective for the TSO is now to have a steady contribution of transformers that have the highest probability for a successful load shedding over all load shedding levels. For example 30 transformers have the highest probability in level 1, 30 in level 2 etc. This distribution will secure the most effective and reliable emergency plan. But the results show a different distribution (Figure 5). Transformers with a negative reference value were not considered as explained in section III. Both concepts show that most transformers offer the highest probability for a successful load shedding in level 1. 73 transformers for the annual peak load concept and 87 transformers for average value concept and far less transformers in the other load shedding levels except level 4 for the JHL-concept (38 transformers). The maximum 13 transformers (JM-concept) respectively 9 transformers (JHL-concept) in the other levels represent not an optimal distribution for the realization of the 5-step plan in the TSO control area. But it can be shown that there is a small but not significant advantage for the currently applied JHL-concept. It is remarkable that most transformers have the highest probability at level 1. That indicates that vertical power values are mostly in lower area which leads to the point that a high percentage of the load in the 50Hertz control area is supplied by renewable generation. This results in the situation that if a clear peak load cannot be identified anymore it is inevitable to use the average value concept.

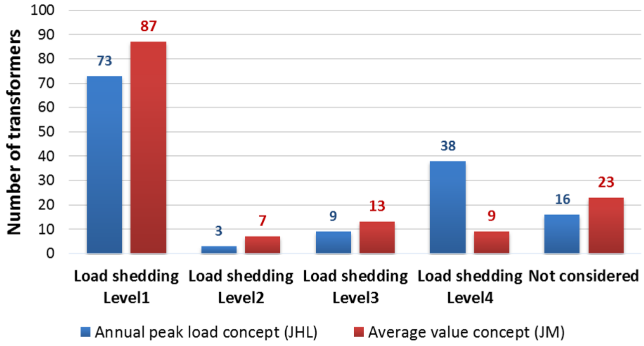

Figure 5. Distribution of transformers within load shedding levels for annual peak load concept and average value concept

B. *Loss of probability at switching the load shedding level*

The fact that it is not possible to realize an optimal distribution no matter which load shedding concept is applied, results in the finding that it is necessary to know the amount of loss of probability to switch from the level with the highest successful probability to the second best. This approach should ensure that all load shedding levels are available with the highest reliability and probability in the control area. This is explained first using the example of transformer 1 (cf. Figure 4). By regarding level 1 with 53.4 % probability for a successful load shedding (JHL-concept) a switch to the second best level will result in losing 3.2 % of probability. This is a relative small loss in comparison to the JM-concept with a loss of 8.2 % by switching to the second highest probability. In this example it might be better for the system operator to apply the annual peak load concept. Figure 6 presents results for all transformers and both concepts categorized in 2 % steps.

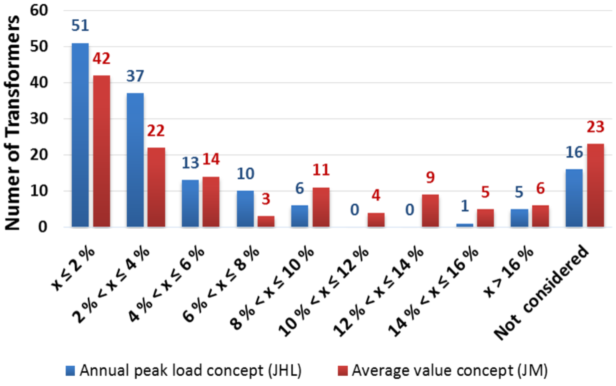

Figure 6. Difference in probability for successful load shedding from best load shedding level to second best load shedding level. Comparison of the concepts in categories and number of transformers.

The first two categories in the illustration show that usage of the level with the second highest probability, which leads to a loss of probability of maximum 4 %. There is a high benefit by applying the JHL-concept because most of all transformers (88) are located in this area. In comparison to this, the average value concept has a smaller number of transformers (64) in the categories with loss of probability of maximum 4 % by changing to the second best load shedding level. Furthermore, the following categories with a very high gradient greater than 4 % by switching the load shedding level should not be considered to secure the functionality of the 5-step plan. As presented in the diagram the other half of the analyzed transformers is located in an area where a change of the level leads to a significant loss of probability for a successful load shedding (JM-concept). Summarizing this part of the results it is shown that the annual peak load concept has an advantage to realize the most optimal equally distribution of the transformers in the control area to ensure the 5-step plan. But the given results impressively present that the new load shedding concept is not much worse and is an option to react on the challenges in the power system.

VI. SUMMARY

Security and stability of the electrical power systems are indispensable even for the emergency situation and have to be realized by the system operator. This investigation analyzed especially the case of high disturbance with following under-frequency under consideration of new challenges with rising renewable energy supply. This case requires the application of the 5-step load shedding plan. Therefore the analyses compared the current load shedding concept based on annual peak load with a new average value concept which should take the rising renewable energy supply into account. The study includes the development of a dynamic model, based on the power balance model, which represents the 50Hertz Transmission control area with primary control and load settings. The model fulfils the primary control constraints of the ENTSO-E OH as well as other technical constraints. The main objective of this paper focusses on the probability for a successful load shedding at each transformer (139 transformers) as a result of load shedding variation under defined conditions. The probabilities enable the identification and evaluation of an optimal load shedding level with the highest probability. Hence, the distribution of optimal load shedding levels in the control area show a significant number of optimal transformers in level 1, regardless of the concept. Furthermore the results present that a change in load shedding level is combined with loss of probability for successful load shedding. Finally this study can show that the introduction of the new load shedding is a beneficiary approach to manage the new system challenges. This new concept gives the system operator the possibility to react on the high penetration of DG sources and prevent blackouts.

This investigation shows the results for the TSO point of view. But to get a more detailed evaluation of the new concept it is necessary to continue this investigation for DSO grid area. Furthermore the results can change by regarding a different scenario year, so that it can be useful to repeat this study for a different year.

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