Design of a New Under Frequency Load Shedding Algorithm Using EMD and FSD Methods

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Abstract—In this paper a new under frequency load shedding algorithm is introduced and simulated on the IEEE 39-Bus test system. Using multiple load estimators and arranging busbar techniques reduces the probability of over or under shedding during the process. Selecting the optimum place for load shedding can have an impact on the frequency at steady state. The main advantages and disadvantages of conventional, new schemes and the proposed algorithm have also been discussed throughout the paper.

Keywords—Underfrequency load shedding, estimate magnitude of disturbance (EMD), frequency seconds deravitive (FSD), load shedding

1. INTRODUCTION

Early power grids were built at small levels, distributed and in close range to each other. Therefore maintaining and controlling of them was simple. Over the years as the demand for suitable electric energy increased power grids became larger, interconnected and more complex than ever, requiring complicated controlling and protection systems to maintain the stability of the power grid. As the dependency to a reliable power source increases the goal to operate the power grid stability of the power grid. As the dependency to a reliable power source increases the goal to operate the power grid

Conventional load shedding algorithms used parameters such as frequency and loading factor (L) to determine suitable amount of load to be shed [15-16]. In [17] a load shedding method is introduced using Estimating Magnitude of Disturbance (EMD) as load estimator and the voltage stability VQ margin as the arranging parameter. In some of the literatures the lowest economic loss and social impact has been selected as the prioritization method for arranging busbars [18]. Implementation of this method would require a wide study in different loads in the region and their economic loss due to sudden shedding. The presented algorithm in [19] has focused on the minimum frequency threshold and number of steps required for optimum load shedding. The regression tree is a new method introduced in [20] which the minimum frequency is predicted after a generation outage to calculate the necessary load shedding amount. In another approach, the Kalman filter is used [21] to estimate the frequency and its rate of change using voltage samples of the power grid. Also, in an approach which is presented in [22], a new load shedding scheme is introduced by considering the load frequency characteristics. Moreover, under frequency load shedding methods have been demonstrated with self-healing capabilities in [23]. This algorithm has been tested on a 179-bus test system with 20 generation machines, which activates after a sudden lack of generation and divides the power grid into some small controllable islands and since these islands have a much smaller inertia constant reviving system frequency will be much easier. Several solutions have been introduced to the disturbance estimator problems using artificial neural networks [24], fuzzy logic [25] and genetic algorithm [26].

The design of a UFLS scheme begins by answering the questions of “how much?”, “where?”, “when?” and “is it enough?”. The main goal of this paper is to introduce a new under frequency load shedding algorithm combining the effectiveness of previous schemes and eliminating their main disadvantages. The proposed scheme uses multiple imbalance estimation and busbar arranging methods, which each estimation technique is activated depending on the fault influence over the power system frequency. Determining the initiation frequency and selecting the optimum busbar position for disconnecting loads have been tested and compared through several fault conditions. The final program was simulated and tested through the IEEE NewEngland 39-Bus system using DIgSILENT Power factory and MATLAB as data acquisition and processing units.

The rest of paper is organized as follows. In Section II the definition and characteristics of special protection schemes (SPS) followed by the main requirements for communications and UFLS programing is discussed. The UFLS scheme is proposed in Section III by describing the main estimating and arranging methods. Specification and features of IEEE New England 39-Bus is defined in Section IV. Simulation results containing the comparison of load shedding amount based on
frequency initiation and busbar arranging method are presented in Section V and finally the conclusion is presented in Section VI.

II. SPECIAL PROTECTION SCHEMES (SPS)

System protection schemes are a wide range of protection strategies designed and implemented to detect uncommon and irregular conditions, causing unusual stress to the power system [17]. The most common protection schemes used are under voltage and under frequency load sheddings. Preliminary work on the load shedding scheme started in 1950’s [16]. Following the 1965 Northeast blackout, application of under frequency load shedding became accepted utility practice. As power systems have matured, however, voltage problems are often likelier than islanding with a large generation-load imbalance [27]. Under voltage load shedding is a partial solution to voltage stability challenges analogous to the use of under frequency load shedding in other circumstances.

Typically, load shedding protects the power system against excessive frequency or voltage decline by attempting to balance real and reactive power supply and demand in the system. Common disturbances that can cause this condition to occur include faults, loss of generation, switching errors, lightning strikes, etc [28]. There has been three approaches to the load shedding algorithms, namely; Traditional, Semi-adaptive and Adaptive Under Frequency Load Shedding.

The system frequency is the only parameter used in the Traditional Load Shedding schemes. After the frequency drops to a certain amount, a predefined amount of load will be disconnected through several steps from the power system. Preliminary and final steps usually include smaller portions of loads to be shed. Even though the implementations of these schemes were fairly simple but the possibility to shed insufficient or excessive load is very high and this is considered as the main disadvantage. Semi-adaptive schemes on the other hand, take the frequencies rate of change into account to shed an amount of load adequate to the disturbance. Although this approach helps to distinguish between small and large disturbances but the main disadvantage of over or under shedding makes it unsuitable in most cases. Adaptive load shedding is the most complete algorithm among other designs. This scheme uses the frequency and its rate of change not only to determine the magnitude of disturbance but also to determine the optimum place for shedding this overload, eliminating any chance of over or under shedding in case of system disturbances. The main disadvantages of this algorithm were the complexity of implementation and the lack of high speed communication networks.

Special Protection Schemes (SPS) can also be categorized under “Response-based/Event-based” or “Centralized/Local” schemes [29-30]. In response-based schemes, response of the system to disturbances is used to make decisions. Input signal of the system may be voltage, frequency, etc. However, in event-based protection schemes decision is based on the state of specific elements in the system such as important transmission lines or generators which is transmitted to control center via a communication link [17].

III. DESIGN OF A NEW UFLS ALGORITHM

As mentioned in previous sections the under frequency load shedding scheme is the systems final getaway plan or in other words, the last resort against cascading faults resulting in power system blackouts in scenarios which a large portion of generation is lost due to generator trip or disconnection of transmission lines. The frequency will drop dangerously if the reserve power or other protection schemes fail to maintain power system stability. The decline in frequency depends on various parameters, such as system inertia, fault duration, magnitude of disturbance, and position on the grid.

The proposed method in this paper uses two disturbance estimators known as Estimation of Magnitude of Disturbance (EMD) and Frequency Second Derivative (FSD), three arranging busbar methods and a simple relation to divide the imbalance calculated by the estimators between the busbars selected with higher priority. As such the main parts of the algorithm can be explained in the following subsections:

A. Estimating Magnitude of Disturbance (EMD)

For faults or disturbances relatively small compared to total generation, the proposed scheme uses the EMD method which is based on the generator swing equation. Equation (1) shows the linearized form of this equation for the ith Generator:

\[
\frac{2H_i}{f_n} \frac{df_i}{dt} = p_{m_i} - p_{e_i} = p_{dist}, \quad i = 1,2,3,...,N
\]

where \( p_{m_i} \) represents the mechanical power input by the turbine in pu, \( p_{e_i} \) is the electric power usage output in pu, \( p_{dist} \) the total imbalance in pu, \( H_i \) is the inertia constant of the \( i \)th generator in seconds, \( f_i \) is the frequency and \( f_n \) is the rated value in Hz. By summing (1) for the overall \( N \) generators the following expression for the total imbalance between generation and load forms:

\[
P_{dist} = \sum_{i=1}^{N} p_{dist_{i}} = \left( \frac{2}{f_n} \right) \sum_{i=1}^{N} H_i \frac{df_i}{dt} = \alpha \frac{df_n}{dt}
\]

Since the frequency of equivalent inertia center, \( f_c \) and constant \( \alpha \) can be calculated in advanced they can be treated as known parameters of the equation. They are defined as below:

\[
f_c = \sum_{i=1}^{N} f_i \left/ \sum_{i=1}^{N} H_i \right.
\]

and

\[
\alpha = 2 \sum_{i=1}^{N} H_i \left/ f_n \right.
\]

A negative value of \( df/dt \) will imply that the electric power usage seen from the machines point of view is greater than the mechanical power input of the turbine. In other words an overload will occur, resulting in the reduction of system frequency. Because of the turbine, generator and other control elements of system dynamics, the presented statements are only valid momentarily after fault occurrence [3].

B. Frequency Second Derivative (FSD)

According to gathered data from past blackouts, small faults can lead to cascading events disconnecting a large amount of generation from load. Since the response of power system frequency is mainly unknown, the proposed algorithm uses the frequency second derivative to predict the total imbalance throughout the grid. Fig. 1 shows the possible different impacts of disturbances on the frequency and its first and second derivative.
It can be seen that the power system response through the frequency and its rate of change are highly unpredictable. On the other hand the frequency second derivative shows promising results. Since the overall behavior of this parameter does not change significantly, it can be used as basis to predict the minimum frequency reached. The main goal of this method is based on finding a suitable mathematical expression describing the frequency second derivative response. By calculating this equation and using numeric integration, the minimum frequency can be estimated. In this paper a new RBF fitting method is used to estimate the overall characteristics of the frequency second derivative. The following equation shows the general form of this equation:

\[
\hat{f}(x) = \sum_{j=1}^{M} \alpha_j \sum_{i=1}^{N} \phi_j(\|x - x_i\|)
\]

\(\hat{f}(x)\) represents the selected function for estimating the frequency second derivative. Also, \(\phi(x)\) is known as the base function which can be different depending on the data set available, \(\alpha_j\) is a numerical constant, \(x_j\) is the \(j^{th}\) data and the distance between \(x\) and \(x_j\) through space or surface is shown by \(\|x - x_j\|\). The frequency second derivative form Fig. 1 can be described as an exponential behavior throughout the data set. Therefore, the Gaussian base function is used for the purpose of this paper. After calculating the estimated function and using numeric integration the mathematical representation for system frequency will form. Finding the minimum of this function will show the lowest frequency predicted to reach.

By expanding (5) and using the second derivative data gathered from different buses we have:

\[
\begin{bmatrix}
\phi(\|x_1 - x_1\|) & \phi(\|x_1 - x_2\|) & \cdots & \phi(\|x_1 - x_N\|) & \alpha_1 \\
\phi(\|x_2 - x_1\|) & \phi(\|x_2 - x_2\|) & \cdots & \phi(\|x_2 - x_N\|) & \alpha_2 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\phi(\|x_N - x_1\|) & \phi(\|x_N - x_2\|) & \cdots & \phi(\|x_N - x_N\|) & \alpha_N
\end{bmatrix}
\begin{bmatrix}
f(x_1) \\
f(x_2) \\
\vdots \\
f(x_N)
\end{bmatrix}
= 
\begin{bmatrix}
f(x_N) \\
f(x_{N-1}) \\
\vdots \\
f(x_1)
\end{bmatrix}
\]

(6)

The element of the \(i^{th}\) row and \(j^{th}\) column represents the value of the Gaussian expression at \(\|x_i - x_j\|\). It can be seen that the coefficient matrix is diagonally symmetric, thus using this method will increase calculation speed due to the transform of the equations to simple linear systems.

A simple relation between the minimum frequency estimated and the total load to be shed from the power system must form. A linear curve is selected over other possible curves, whereas it has been shown that different slopes do not much affect the total load-shedding amount [14]. Fig. 2 shows the total amount of load to be shed in respect to the minimum frequency calculated using FSD for a 60Hz system.

After determining the amount of load to be shed either with EMD or FSD, the question of “where is the optimum position to disconnect this load?” comes to mind. In the proposed algorithm three arranging busbar methods are introduced and programmed. The busbars are arranged using 1. \(\text{df/dt}\) and \(\text{dv/dt}\), 2. Magnitude of \(V\) and \(\text{df/dt}\) and 3. Electric distance:

1. In the first approach the program sorts the busbars in two separate single column matrices using their rate of change in frequency and voltage, therefore the busbars with higher sensitivity will be ranked higher. A high change of rate would imply that the fault has a higher impact on the selected busbar. The program then adds the position of busbars from each matrix. The busbar with the lowest sum will represent the highest sensitivity to frequency and voltage among others.

2. To arrange the busbars using their voltage magnitude and rate of change in frequency the program divides the busbars in separate matrixes with voltage ranges of (0.85-0.9), (0.9-0.95), (0.95-1) and greater than 1 pu. Afterwards the busbars are sorted by \(\text{df/dt}\) in each matrix separately. The final arrangement will be created by attaching each matrix to the beginning of the next range starting from the lowest voltage. Since motorized loads will stall under voltage magnitude of 0.8 pu, they have the highest priority.

3. Electric distance is the third criteria for arranging busbars. This method uses the \(Z_{bus}\) matrix as the basis of calculating and defining busbars nearest to fault. First the algorithm removes busbars with no loads or loads marked as vital; afterwards the remaining busbars are sorted according to the \(Z_{bus}\) matrix. The closer the load or busbar is to the fault, the higher the sensitivity of that busbar will be.

![Fig.1. Impact of disturbance on frequency and its first and second derivative](image)

![Fig.2. Determining total shedding amount from minimum frequency estimation](image)

Depending on the amount of imbalance estimated in the previous section, the number of selected busbars varies to carry of the load shedding process. Table I shows the proposed selection of busbars by this algorithm:

Table I. Number of busbar selected in different disturbance estimations
Estimated Disturbance | Number of Busbars Selected
---|---
Lower than 60MW | 1
60MW – 300MW | 3
300MW – 600MW | 5
Higher than 600MW | 7

After determining the imbalance throughout the grid and the optimum position to shed this load from, a relation must be determined to determine each of the high ranked busbars share. In this algorithm, equation (7) is assigned for carrying out this goal:

\[
\Delta P_i = \frac{dp_i}{dv_i} \times \Delta V_i \times P_{dist} \tag{7}
\]

In which \(\frac{dp_i}{dv_i}\) is defined as

\[
\frac{dp_i}{dv_i} = \sum V_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{8}
\]

where \(\delta_i\) and \(\delta_j\) are the voltage angles of busses i and j, \(V_{ij}\) is the admittance magnitude for the connecting line between the i and j busbars and \(\theta_{ij}\) is the respected angle. \(P_{dist}\) represents the load imbalance calculated in each cycle of the program (if more than one cycle is required) and \(\Delta P_i\) is the amount of load assigned to be shed from the i\(^{th}\) busbar selected from the arranged matrix.

C. Proposed Method Flowchart

The majority of the process is discussed in this section. Since mentioned before an UFLS algorithm should be complete and consider as much scenarios as possible. A complete cycle of the proposed algorithm is shown in Fig. 3. As shown, by monitoring the frequency (\(f\)) and the rate of change of frequency (\(df/dt\)), the scheme activates when the frequency exceeds either one of thresholds of \(f_{th1}\) or \(f_{th2}\). If frequency increases a certain level a signal of over generation will be send to control turbine input power, in other cases when frequency drops below \(f_{th2}\) (frequency initiation), it would indicate that the spinning reserve and other controlling schemes failed to control the generation outage and the UFLS procedure begins. After considering the rate of change of frequency at fault time, the program will decide if whether Method I or Method II is necessary for estimating the total imbalance in the power grid.

The importance of considering motorized and vital loads can be seen in both estimation methods. In the proposed scheme shown in Fig. 3, if the frequency rate of change remains negative after shedding loads from either methods, the algorithm will send a signal to begin islanding procedure to break the grid into smaller and more controllable systems. In each island depending on them being either “Generation Rich” or “Load Rich”, appropriate actions will take place. Since the majority and behavior of frequency after islanding is unknown, the proposed method for UFLS in each island is FSD.

IV. IEEE 39-Bus New England

The IEEE 39-Bus New England System was first introduced by Prof. Gerry Heydt from Perdue University [32]. It shows the structure of the 1960 New England power grid, which only contains distribution voltage level. The main property of this system is the availability of the generator dynamic information. Since the generators are the key elements in all dynamic studies, the complexity of the dynamic study is determined by the number of generators. This test power system consists of 10 synchronous machines, 6250 MW active power and 1390MVar reactive power usage, 46 transmission lines, 12 transformers which 10 of them are Generator Step-Up (GSU) transformers. Fig. 4 shows the single line diagram of the New England 39-Bus power system.

V. Simulation Results

Simulations on different scenarios have been done on the 39-Bus New England power system. In this section we examine and compare the main aspects and advantages of the proposed method. Three scenarios have been selected as follow:
- Loss of G10 (250 MW)
- Loss of G06 (650 MW)
- Cascading effect of losing G07 and G02 (1230 MW)

The following parameters are analyzed throughout the simulation:

1. Frequency initiation impact on calculating the total imbalance
2. Accuracy of the FSD method using RBF fitting
3. Impact of different arranging methods on the steady state frequency

![Image of IEEE 39-Bus New England test system](image)

Fig. 4. IEEE 39-Bus New England test system [33]

A. Loss of G10 (250MW)

By losing G10 either to generator trip or disconnection on the outgoing feeders, 4% of total active power will be lost. After the frequency drops below 57.5 Hz the imbalance estimation procedure starts. Since the disturbance does not create a large \( \frac{df}{dt} \), the program automatically selects the EMD method to calculate the total imbalance. Table II shows the result for running the EMD method:

<table>
<thead>
<tr>
<th>Arranging Criteria</th>
<th>Load to be shed</th>
<th>Selected bus No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{df}{dt} ) and ( \frac{dv}{dt} )</td>
<td>39.1 MW</td>
<td>No. 25</td>
</tr>
<tr>
<td>( \frac{dv}{dt} ) and ( \frac{df}{dt} )</td>
<td>39.1 MW</td>
<td>No. 1</td>
</tr>
</tbody>
</table>

Even though the simulation has been done for the arrangements by electric distances, the results were mostly not converged, because the test system does not have enough line connections to increase the probability of having multiple disconnection busbar options at fault presence using this method. Electric distance can prove to be suitable for large and highly intertwined systems. Fig.5 shows the impact of the generator outage and the response after disconnecting the estimated load to be shed. By activating the FSD method manually and processing the gathered data, the minimum frequency estimated will result in 59.2229 Hz which compared to the actual minimum frequency (59.47 Hz) from Fig. 5 shows promising results.

B. Loss of G06 (650MW)

By disconnecting generator No. 06, 10.4% of total system generation is lost. Table III shows the total amount of load imbalance in respect to the frequency initiation. As seen from the table, the higher the frequency initiation is selected the more significant the rate of change in frequency would be and therefore the program would require shedding more loads to maintain the stability of the power grid. Fig. 6 shows the result of implementing the estimated imbalance. Even though a large portion of load is being shed for the frequency initiation of 59.5 Hz, but the frequency will still remain under the threshold value. After a small delay for gathering new data the program will disconnect a second amount of load to meet with the stability conditions.

C. Cascading effect of losing G07 and 02

After the disconnection of Generator No. 02, Generator No. 07 will face an overload and will trip shortly after. By losing these two generators 19.68% of total generations are disconnected. The imbalance estimator shows a load shedding of 584 MW in first and 188 MW in second steps.

Table III. Comparison of different frequency initiations on total load shedding estimation

<table>
<thead>
<tr>
<th>Arranging Method I (( \frac{df}{dt} ) and ( \frac{dv}{dt} ))</th>
<th>Initiation Frequency</th>
<th>Execution Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.5 Hz</td>
<td>239.1 MW</td>
<td>-</td>
</tr>
<tr>
<td>58.5 Hz</td>
<td>322.5 MW</td>
<td>-</td>
</tr>
<tr>
<td>59.5 Hz</td>
<td>392.8 MW</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Arranging Method II (( \frac{dv}{dt} ) and ( \frac{df}{dt} ))</th>
<th>Initiation Frequency</th>
<th>Execution Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.5 Hz</td>
<td>239.1 MW</td>
<td>-</td>
</tr>
<tr>
<td>58.5 Hz</td>
<td>322.5 MW</td>
<td>-</td>
</tr>
<tr>
<td>59.5 Hz</td>
<td>392.8 MW</td>
<td>60 MW</td>
</tr>
</tbody>
</table>

![Image of Frequency response](image)

Fig. 5. Frequency response of power system to the lack of generation of 250MW and frequency initiation of 59.5 Hz

![Image of Frequency responses](image)

Fig. 6. Comparing frequency responses due to 650MW generation outage in different frequency initiations

![Image of Frequency steady state](image)

Fig. 7. Comparing frequency steady state by using different arranging busbar methods
shed was the same, the steady state frequency is different. Choosing the rate of change in frequency and voltage has proven to show a better effect.

VI. CONCLUSION

In this paper a new adaptive Under Frequency Load Shedding scheme has been introduced for protection against cascading and catastrophic faults using two imbalance estimators (EMD & FSD) and three arranging busbar methods. Each method is activated automatically depending on the impact of disturbance over the system frequency ($\frac{df}{dt}$). The final program was tested offline on the IEEE New England system, comparing the results in three different scenarios. The effects of different initiation frequencies have been discussed and judging by the results, 57.5 Hz would indicate the optimum frequency to begin UFLS procedure since it would require much less load to be shed and create a suitable time delay for the algorithm to gather and process data. Using two disturbance estimators (EMD and FSD) reduces the probability of over or under shedding of loads. FSD has shown promising results in predicting minimum frequency and estimating the system overloading conditions. Also, by comparing results from different busbar arrangements, sorting them by rate of change of frequency and the magnitude of voltage has proven to have a better response among others since the frequency steady state has shown to be higher.

REFERENCES