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Research article

A quick method for electrical energy system load shedding based on equivalent areas

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Abstract

The main purpose of the paper is to present a fast load shedding scheme, based on the concept of equivalent areas in large power systems. Performing load shedding on such systems with several generators in each area by using the conventional method is consuming a large amount of time. The proposed method can significantly reduce energy not supplied and is absolutely affordable for not only energy producers, but also energy consumers. At first, the coherent generators in the network will be detected based on a generation acceleration technique. The coherent generators will be identified without performing transient stability studies or the comparison of rotor swing angles, and only will be detected by using Jacobian matrix elements of the linearized power system model. Each group of the coherent generators will be replaced by an equivalent generator to introduce a new reduced model. All analytical calculation and decision variable factors will be achieved centrally with mentioned model and the only signal sends to the network, is a load shedding command. UVLS technique will be applied to the load shedding scheme. In this method, the priority is to shed the busloads with the most amplitude of the voltage drop after disturbance, so the network voltage and frequency stability will be maintained. The scale of load shedding level is proportional to online mismatch power between generation and demand. Finally, a simulation of the standard 39-buses IEEE network will be carried out to prove the strategy's effectiveness.

Keywords: Power energy system, Coherency Load Shedding, UVLS, Frequency Stability.

1- Introduction

Along with the daily improvement of electrical power systems, many techniques have been introduced to speed up the network analysis & calculations. One of the conventional stability techniques is based on analyzing the coherent machines in the network using second-order equations of the classic model [1]. Stability analysis in the big power grid network works is always taking a large amount of time, the coherency technique can be used to reduce the model of the system. To reduce that time, power system mechanical equivalents are employed [2].

Under normal conditions, the total amount of production power and consumption in the network is the same, and this equality will change if any disturbance occurs. Any fault such as disconnection of heavy loads, disconnection of a vital line in the network, or tripping a generator may result in system unbalance. And following that, the system voltage and frequency will change and can cause to overload of other lines and trip the circuit breakers, or even cause systems collapse [3]. Voltage and frequency collapse caused several power system blackouts around the world, thus, voltage stability is one of the major concerns of power system operators. Various definitions have been introduced for voltage and frequency stability of power systems [4]. Therefore, under any sudden fast drop in the frequency, techniques like UFLS or UVLS must be used to prevent systems collapse. It has been proved that the UVLS can return the system stability. With this technique, a specific amount of load must be eliminated to regain the stability for the rest of the system and prevent the frequency to drop. The UVLS technique is mostly used for protection purposes and uses network frequency and its derivative to calculate the required amount of load, which must be eliminated from the network [5].

Based on the load shedding technique introduced by [4], the bus voltages, frequency, and its derivative must be sent to the central control station via WAMS, and after performing the specially programmed algorithm, it specifies load must be shed from the network and send it to the buses. The mentioned reference did not consider the signal delays and malfunctions. Therefore, here it is suggested to use an equivalent model for the system and the load shedding algorithm will use these virtual equivalent system parameters and just load shedding signals will be transmitted to the buses. Also, the equivalent model will be reduced with the coherency technique to increase the system response and send the load shedding signals faster.

In this paper, first, the coherent machines will be defined and the method of coherent machine group detection and modeling will be explained, and after that load, shedding algorithm will be introduced. As a result, the purposed technique will be simulated using a standard IEEE (New England) network with 39 buses and 10 machines to prove the presented theory. It has to be noted that in the recent decades, penetration of renewable energy sources in conventional power systems raises. One can ideate that this can challenge the proposed idea of this paper, but even in the worst case, it seems not to have a considerable portion of energy generation in the world [6].

2- Machine Model

To perform power system stability analysis, the 4th order synchronous machine model (1) will be used and in each generator in the network, a power system stabilizer (PSS) has been used [7].

$$\begin{cases} \dfrac{d\delta}{dt} = \omega_b(\omega - 1) \\ \dfrac{d\omega}{dt} = \dfrac{(T_m - T_e - D(\omega - 1))}{2H} \\ \dfrac{dE'_q}{dt} = \dfrac{1}{T'_{d0}}\left[-E'_q + (\mathrm{x}_d - \mathrm{x}'_d)\mathrm{i}_d + E_{fd}\right] \\ \dfrac{dE'_d}{dt} = \dfrac{1}{T'_{q0}}\left[-E'_d - (\mathrm{x}_q - \mathrm{x}'_q)\mathrm{i}_q\right] \end{cases} \tag{1}$$

3- Coherent Machines

The coherency definition is one of the most important subjects to analyze the power system dynamics. Modeling the power system based on the coherency technique is having two-step. First, all coherent generators must be detected and after that for the next step, network reduction and equivalencing of the coherent groups with appropriate power generation and inertia and combination of the equivalent with the system retained. Therefore, the size of the equivalent network will be reduced significantly. The methods proposed in this paper for coherency identification and equivalencing are very efficient and less time-consuming than other methods [8-14].

Two generators will be considered coherent generator if their rotor angle differences in a specific period, is reliably constant. It can be explained that for a group of generators under a specific period if their rotor angle difference remains the same within the reliable limit, it is acceptable to call them coherent machines, or for I and j machines will have (2),

$$\left|\delta_{ij} - \delta_{ij}^{s}\right| \le \varepsilon \qquad 0 \langle t \langle t_s \tag{2}$$

Based on the method explained in [8], the coherent generators can be identified with linearized synchronous machine 2nd order equations, and only by using load flow information and the coherent machine matrix (ma) can be extracted.

Referring to [15] the coherency criterion is explained as the group of generators mechanical oscillating with the same angular speed, and with terminal voltages in a constant complex ratio.

A simple power network with three machines will be used to achieve the reduced equivalent network admittance matrix. If machine no.1 and 2 are coherent in the network, based on the [8], the coherent matrix (ma) will be as follow,

$$ma = \begin{bmatrix} 1 & 2 \\ 3 & 0 \end{bmatrix} \tag{3}$$

and based on the coherency technique,

$$\begin{cases} b = \dfrac{V_2}{V_1} \\ I_{e1} = I_1 + b^* I_2 \end{cases} \tag{4}$$

the node equations are,

$$\begin{cases} I_1 = y_{11}V_1 + y_{12}V_2 + y_{13}V_3 \\ I_2 = y_{21}V_1 + y_{22}V_2 + y_{23}V_3 \\ I_3 = y_{31}V_1 + y_{32}V_2 + y_{33}V_3 \end{cases} \tag{5}$$

using (4) and substituting V_2 into (5) and simplifying the equation,

$$\begin{cases} I_1 = (y_{11} + b \times y_{12} + b^* y_{21} + b^* b \times y_{22})V_1 \\ \qquad + (y_{13} + b^* \times y_{23})V_3 \\ I_3 = (y_{31} + b \times y_{32})V_1 + y_{33}V_3 \end{cases} \tag{6}$$

The node equations for the reduced model can be seen in (7) which compare to (6), the equivalent network can be extracted:

$$\begin{cases} I_{e1} = Y_{11}V_1 + Y_{12}V_2 \\ I_{e2} = Y_{21}V_1 + Y_{22}V_2 \end{cases} \tag{7}$$

$$\begin{cases} Y_{11} = y_{11} + b \times y_{12} + b^* y_{21} + b^* b \times y_{22} \\ Y_{12} = y_{13} + b^* \times y_{23} \\ Y_{21} = y_{31} + b \times y_{32} \qquad Y_{22} = y_{33} \end{cases} \tag{8}$$

Expanding the method and having a coherent machine group matrix (ma), the reduced model admittance matrix elements (mn) can be concluded by (9), in which ‘y’ is the reduced network admittance matrix and ‘c’ is the number of ‘ma’ matrix columns.

$$Y_{mn} = \sum_{j=1}^{c}\sum_{i=1}^{c}\left(\frac{V\,(\text{ma(m, j)})}{V\,(\text{ma(m,1)})}\right)^{*} \times \left(\frac{V\,(\text{ma(n, j)})}{V\,(\text{ma(n,1)})}\right) \times y\,(\text{ma(m, j)}, \text{ma}(n, \text{j})) \tag{9}$$

Based on (1) the model parameters are:

$$E'_{qe}, E'_{de}, \delta_e, x_{qe}, x_{de}, x'_{qe}, x'_{de}, \mathrm{E_{fde}}, H_e, T_{me}, T'_{qe}, T'_{de}$$

For example, parameters can be calculated as follow. Parameter E_i will be defined as below (10):

$$E_i = V_i + \mathrm{j x_{qi} I}_i \tag{10}$$

which the E_i vector is aligned with E'_q, therefore for machines no.1 and 2 we have:

$$\begin{cases} E_1 = V_1 + \mathrm{jx_{q1}I_1} \\ E_2 = V_2 + \mathrm{jx_{q2}I_2} \end{cases} \tag{11}$$

Multiply second equation E2 into b*xq1/xq2 and substituting V2 from (4) and add it with the first equation will result,

$$\frac{E_1 + b^* \frac{x_{q1}}{x_{q2}} E_2}{(1 + bb^* \frac{x_{q1}}{x_{q2}})} = V_1 + \mathrm{j} \frac{\mathrm{x_{q1}}}{(1 + bb^* \frac{x_{q1}}{x_{q2}})} (\mathrm{I_1} + b^* \, \mathrm{I_2}) \tag{12}$$

Compare with (10),

$$\begin{cases} E_{e1} = \dfrac{E_1 + b^* \frac{x_{q1}}{x_{q2}} E_2}{(1 + bb^* \frac{x_{q1}}{x_{q2}})} \qquad \delta_{e1} = \angle E_{e1} \\ x_{qe3} = \dfrac{\mathrm{x_{q3}}}{(1 + b_3 b_3^* \frac{x_{q3}}{x_{q5}})} \end{cases} \tag{13}$$

Using these techniques, it is possible to find the rest of the machine parameters, and by having a coherency matrix (ma) and expanding the equations we can reach (14) to (20).

$$\begin{cases} E_{ei} = \dfrac{\sum_j^c E\,(\text{ma(i,j)}) \frac{x_q\,(\text{ma(i,1)})}{\mathrm{x_q}\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*}{\sum_j^c \frac{x_q\,(\text{ma(i,1)})}{x_q\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})}) (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*} \\ \delta_{ei} = \angle E_{ei} \end{cases} \tag{14}$$

$$\begin{cases} x_{qei} = \dfrac{x_q\,(\text{ma(i,1)})}{\sum_j^c \frac{x_q\,(\text{ma(i,1)})}{x_q\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})}) (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*} \\ x_{dei} = \dfrac{x_d\,(\text{ma(i,1)})}{\sum_j^c \frac{x_d\,(\text{ma(i,1)})}{x_d\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})}) (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*} \end{cases} \tag{15}$$

$$\begin{cases} x'_{qei} = \dfrac{x'_q\,(\text{ma(i,1)})}{\sum_j^c \frac{x'_q\,(\text{ma(i,1)})}{x'_q\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})}) (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*} \\ x'_{dei} = \dfrac{x'_d\,(\text{ma(i,1)})}{\sum_j^c \frac{x'_d\,(\text{ma(i,1)})}{x'_d\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})}) (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*} \end{cases} \tag{16}$$

$$\begin{cases} E'_{ei} = \dfrac{\sum_j^c E'(\text{ma(i,j)}) \frac{x_q\,(\text{ma(i,1)})}{\mathrm{x_q}\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*}{\sum_j^c \frac{x_q\,(\text{ma(i,1)})}{x_q\,(\text{ma(i,j)})} (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})}) (\frac{V\,(\text{ma(i},j\text{))}}{V\,(\text{ma(i,1)})})^*} \\ E'_{qei} = \mathrm{Re}al\,(E'_{ei}\, \mathrm{e}^{j\,\delta_{ei}}) \\ E'_{dei} = \mathrm{Im}ag\,(E'_{ei}\, \mathrm{e}^{j\,\delta_{ei}}) \end{cases} \tag{17}$$

$$\begin{cases} T'_{qei} = (\sum_j^c \dfrac{1}{T'_q(\text{ma(i,j)})})^{-1} \\ T'_{dei} = (\sum_j^c \dfrac{1}{T'_d\,(\text{ma(i,j)})})^{-1} \end{cases} \tag{18}$$

$$\begin{cases} v_{qei} = \mathrm{Re}al\,(\mathrm{V}_i\, e^{-j\,\delta_{ei}}) \\ i_{dei} = \mathrm{Im}ag\,(I_{ei}\, e^{-j\,\delta_{ei}}) \\ \mathrm{E_{fdei}} = v_{qei} - x_{dei}\, i_{dei} \end{cases} \tag{19}$$

$$\begin{cases} H_{ei} = \sum_j^c H\,(\text{ma(i, j)}) \\ T_{mei} = \sum_j^c T_m\,(\text{ma(i, j)}) \end{cases} \tag{20}$$

Now having all machine parameters, model initial values, and reduced network information, making a decision and send to the network are faster it is possible to check its positive effects on the system stability.

4- Load Shedding

Once the disturbance occurs, the dynamic frequency of all generators can be monitored via The AMS technique. Therefore, with knowledge of all machines' frequency deviation, any unbalance between produced power and consumed power can be found [4] and calculated numerically by (21).

$$\Delta P = \sum_{i=1}^{m} \Delta P_i = \sum_{i=1}^{m} (P_{mi} - P_{ei}) = \sum_{i=1}^{m} 2H_i \frac{df_i}{dt} = \xi \frac{df_c}{dt} \quad (21)$$

$$\frac{df_c}{dt} = \frac{\sum_{i=1}^{m} (\mathrm{H}_i \frac{df_i}{dt})}{\sum_{i=1}^{m} H_i} \quad (22)$$

First, the need to perform load shedding must be decided with a defined criterion and then using the UVLS load shedding technique, the network voltage and frequency stability will be maintained.

Having all bus voltages in the system at any moment is accessible for the control algorithm. Therefore, using the WAMS technique all bus voltage differences with references can be detected and it will be a reasonable scale to determine loads priority in which must be shed. And same priority will be used for load reclosing in the system.

Load shedding will be carried out on special loads in the system, in which the load with the most voltage drop will be removed first, till the total load shedding is bigger or equal ΔP . On the other hand:

$$\Delta P = \sum_{j=1}^{M} \Delta P_j \quad (23)$$

where M is the total amount of load which is shed or reclosing in the system, and ΔPj is the load to be shed with j[th] priority. In each step of load shedding, the ΔP must be calculated again and the new bus voltage values of the required amount of loads for load shedding must be concluded again. In this step, one load may have disconnected completely or partially, and it is not practical to eliminated a specific part of a load every time. Each buses are included some output feeders and one or more feeders can be disconnected from the system. In this paper, all buses considered to have four feeders and one or more feeders can be disconnected from the system in each step. [5] In Fig. (1) the load shedding flow chart is presented. df/dt & f of each generator and all bus voltages are derived from the WAMS, and using (21) and (22) the dfc/dt and ΔP can be calculated. At the next, step the need for load shedding is decided and by setting a marginal limit for dfc/dt, the fault will be detected and the control system will enter the load shedding algorithm. If dfc/dt is negative (ΔP<0) the load shedding program will be send a load shedding signal to the buses, and if dfc/dt is positive (ΔP>0) now the load shedding program will allow the load reclosed into the system and maintain the stability as well. So dfc/dt is an important scale for load shedding program and a limit for shedding or reclosing the load in the system must be defined, in which if dfc/dt < dfthmin its shedding time, and if dfc/dt > dfthmax it's the time for reclosing the loads to the system (dfthmin is negative value and dfthmax is a positive value).

This process will continue till produced power becomes in balance with consumed power in the system, and at this moment df_c/dt will be in the acceptable range and system frequency stability has been

achieved The dfthmin & dfthmax limit has strong influences on the system final frequency and speed of damping, therefore proper attention must be considered while choosing the limits.
A constant delay block (0.2 sec) had been added to the flow chart due to transmission devices & circuit breakers' natural delay

5-Fast Load Shedding
In load shedding algorithm all decision making parameters such as bus voltages, frequency and machines frequency derivation must be send to the control station via WAMS and after performing the algorithm, the load shedding signals must be send back to the system. This technique is having a delay and may result total breakdown of the system or instability in the primary cycles.

The suggested block diagram is present in Fig. 2. This technique will use the network load flow information and extracts the reduced model for the network. After that, it will perform load shedding algorithm on the reduced model and send the necessary signals to the main network. Above technique is much faster in decision making process, as a lot of unnecessary signals are eliminated.

6-Simulation
Standard IEEE (New England) test system with 39 buses and 10 machines had been used for simulation in most of the papers. To test the system and analyzing the results, three phase earth fault sets near to bus no. 28 at t = 0.1 sec for 100ms period of times, which indicates overload for the system and line 28-29 will be disconnected. The 4th order synchronous machine equations had been used, and all loads are modeled by constant admittance in the simulation.

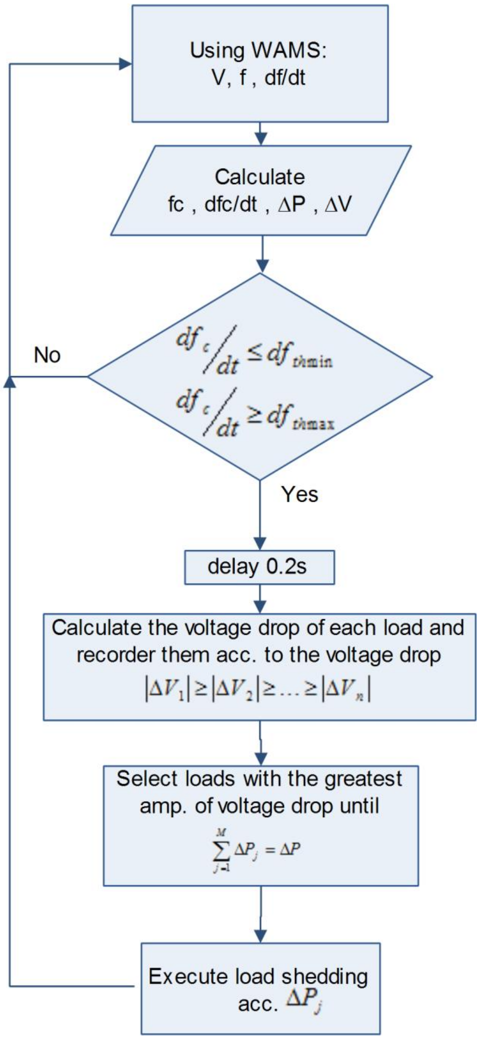

Fig.1 The UVLS load shedding technique flow chart [5].

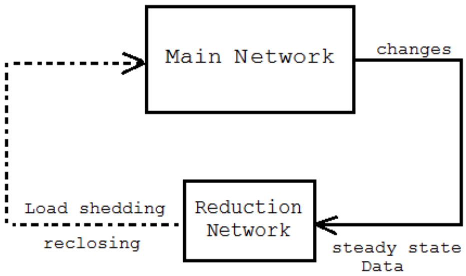

Fig.2 Fast load shedding block diagram

It is obvious from Fig. 4, first the generators rotor angle and frequency increases, and after tripping the generator no.9 and unbalancy between loads and generated power occurs, all rotor angles start to fall together. Therefore, the network still is stable for rotor angles, but the damped frequency is below the network nominal frequency.

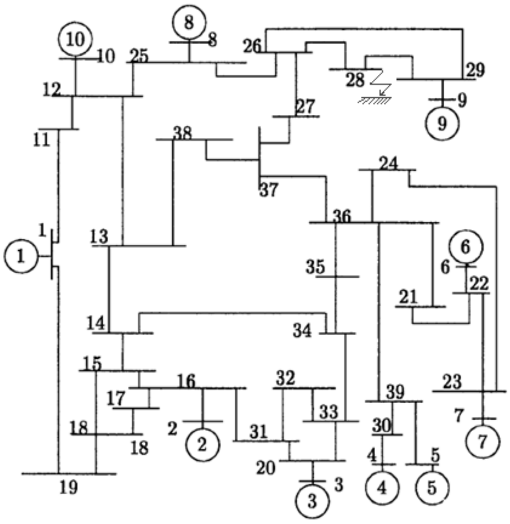

Fig.3 *IEEE 39-bus system (New England)*

The coherent machine matrix (ma) can be found through the coherency algorithm,

$$ma=\{1,(2,3),(4,5)(6,7)(8,10),9\} \quad (24)$$

Based on (ma), network Y_{bus} and machine parameters can be extracted from (18) to (24). And the following result can be derived from the fast load shedding algorithm.

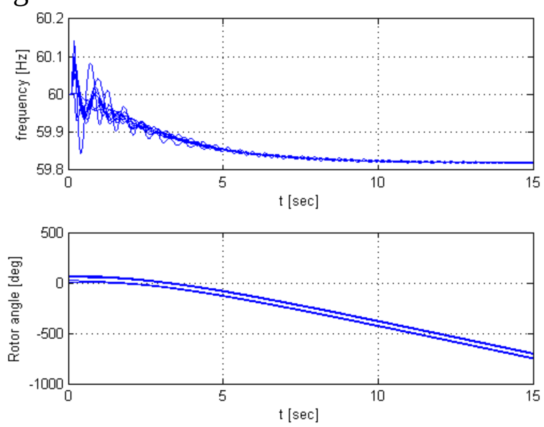

Fig.4 Rotor angle and frequency of all generators

Fig. 5 presents all machines rotor angles and frequency after load shedding. Fig. 6 shows the time and amount of disconnected loads in per-unit and percentage. As it can be seen, the rotor angle stability has been maintained and network frequency will have returned back to its nominal value while balance occurs between power production and consumption. In Fig. 7 the bus voltage amplitudes is presented after performing the suggested load shedding technique. It can be noted that with UVLS load shedding technique, the voltage stability in the network has been maintained satisfactory and buses voltage amplitudes has returned back to their nominal values.

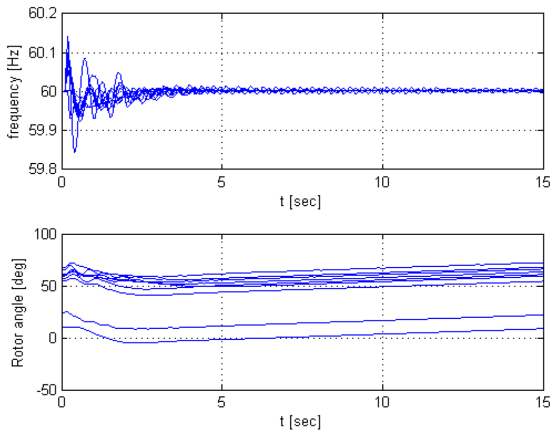

Fig. 5 Rotor angle and frequency of all generators UVLS algorithm

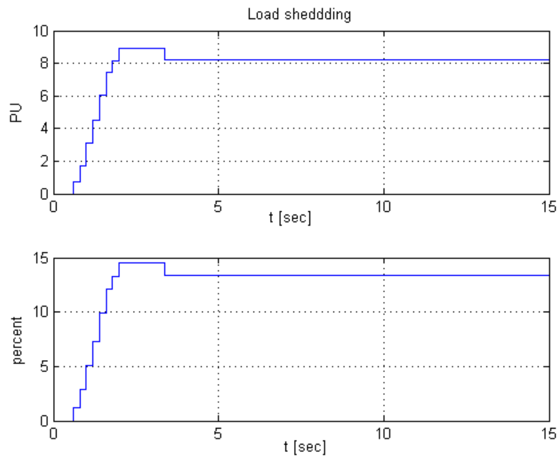

Fig. 6 Amount of loads which is shed or reclosed

7-Conclusion

In the purposed technique, to gain more practical result due inherent damping of the machines, using 2nd order synchronous machine equation is not possible, therefore

4th order equation has been used.

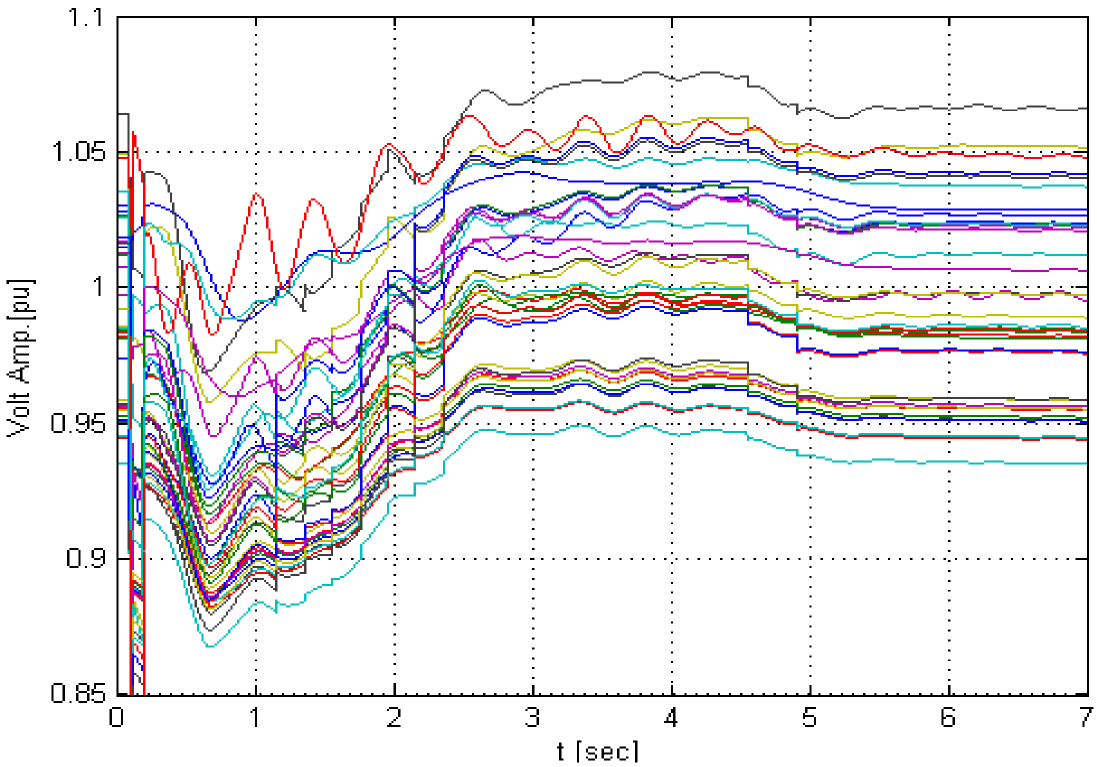

Fig. 7 Voltage of all buses by Executing UVLS load shedding

In most of the past published papers related to the coherent machines, the 2nd order form had been used, while in this paper by expanding the technique, the 4th order equations for synchronous coherent machines has been achieved. In coherent machine detection process, instead of analyzing and comparison between machine rotor angles, without carrying the system stability calculations, the coherent machine groups are defined and coherent generators can be detected just by load flow calculations and using classic linearized Jacobian matrix.

In conventional load shedding techniques, it is needed to send all system parameters derived via WAMS to the control station, and the required signals will return back to the system. In this purposed technique, by removed the received signals and model the system into smaller network, the decision for any change in the system can be made faster and causes the system frequency to return to its nominal frequency. Using UVLS technique causes to maintain the voltage stability and force the bus voltages to return back to their initial values.

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