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Load Shedding Based on Sensitivity Index to Avoid Voltage Collapse

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***Abstract*: The occurrence of a large disturbance in a power system can lead to a decline in the system frequency and bus voltages due to a real and reactive power deficiency or due to the formation of islands with generation–load imbalance. Load shedding is a last line of control action that can prevent a blackout in the power system by relieving the overload in some parts of the system. This paper describes a new algorithm for load sheding under emergency condition to avoid risk of voltage instability. For this purpose minimum eigen value of load flow Jacobian has been selected as proximity indicator, which is obtained using continuation power flow methodology. The amount of load to be shed is decided by sensitivity index so as to maintain a threshold value of proximity indicator and all load bus voltages within limit. Sensitivity of indicator with respect to load (real & reactive power) to be shed has been used to rank the load buses and, simultaneously minimize the computation time and amount of load to be shed. Higher order load buses are selected for load sheding to avoid voltage collapse problem in stipulated time to maintain the reliability of the supply system. Developed algorithm has been implemented on a IEEE 14-bus system, 20-line test system.**

***Keywords*: Load shedding, voltage instability, minimum eigenvalue, sensitivity index and continuation power flow.**

1. Introduction

Usually the power system operates in a correctively secure state till all operating constraints are satisfied. In the case of contingency or increased load condition, system falls into non correctable emergency [1, 2, 3]. This may arise due to (i) Sudden loss of generation/increase in load which will result in decrease infrequency (ii) Outage of one or more transmission line thus reducing network (iii) Over loading of the transmission line. Thus heavy loading may lead to voltage instabilities or collapses or in the extreme to complete black outs. **At** first a gradual voltage drop in one or several consumer regions may lead to increased reactive losses in the system and push transformer taps towards maximum values. Some generators or compensators can reach their limits of reactive power. Then voltage drops rapidly and it may drop so far as to cut off generating units and lines one after the other thus causing a complete collapse of the system. Thus a common limiting factor for power transmission is the risk of voltage instability in recent years. One technique of avoiding voltage instability is to shed some consumer's loads in Order to draw the operating point away from the critical voltage value[4].Voltage collapse can be avoided by taking urgent measures such as (i) decreasing voltage set point. (ii) blocking on load tap changers. (iii) appropriate load shedding on consumer network. Under voltage load shedding scheme is normally the primary choice for most of the utilities due to its simplicity. Load bus voltage level alone is not a good indicator to assess the security of the operating conditions, especially when the shunt compensation and/or some other voltage control devices are heavily used in the modern power systems. Moreover, the load shedding amount is difficult to be minimised only based on the voltage levels at some particular buses. In order to optimise the load shedding schemes, several methods which are aimed at minimising the load shedding amount have been proposed in recent years [4-7]. The sensitivities of the load-ability margin and the sensitivities of voltage with respect to the load parameters are often used to determine the optimum load locations. By using the sensitivities information, an optimization problem is usually formed and the minimum load shedding amount is determined by solving it. Load shedding amount which is computed based on the sensitivities obtained before the load shedding is applied [8-11].

This paper proposes a method for determining the amount of the load to be shed in order to avoid risk of voltage instability. The method defines clearly the bus where load shedding should make. Minimum eigen value has been used as indicator. A threshold value of this indicator can be assumed for a specific system. Emergency load shedding is required if this value falls below the threshold value. In practice at collapse point the minimum eigen value is very small [12-14]. Sensitivity relations have been derived between indicator changes and load shed at a bus. Buses having large sensitivities are selected for load shedding. A relation between voltage stability indicator and load power to be shed is developed. Using the relation the amount of load to be shed is determined. Operating constraints on the load to be shed have been accounted. Due to operating constraints there is a maximum limit to the load that can be shed at the selected buses to ensure a minimum service. The proposed method is valid for any system of any size at any loading conditions.

2. Sensitivity derivation of indicator with respect to load shed at buses

An estimate of absolute sensitivity of minimum Eigen value with respect to real and reactive power changes at bus can be written as follows[3]-

$$\frac{\partial\lambda_{min}}{\partial P_i} = a_{i,} \qquad \frac{\partial\lambda_{min}}{\partial Q_i} = b_{i,}$$

$$\Delta\lambda_{min} = a_i.\Delta P_i + b_i.\Delta Q_i \qquad (1)$$

Since when load shed takes place at a bus, then ΔQ_i bears a fixed ratio ΔP_i with (decided by power factor at that bus) as follows:

$$\Delta Q_i = \beta_i.\Delta P_i \qquad (2)$$

$$\Delta\lambda_{min} = (a_i + \beta_i.b_i).\Delta P_i \qquad (3)$$

$$\Delta\lambda_{min} = S_i.\Delta P_i \qquad (4)$$

where,

$S_i = a_i + \beta_i.b_i$

$\beta_i = \tan\phi_i$

$\phi_{i=}$Power factor angle at i-th load bus

$\lambda_{min=}$Minimum eigenvalue of load flow Jacobian

Expression for $a_r$can be written as follow

$$a_r = \frac{\partial\lambda_{min}}{\partial P_r} = \sum_{ij}\frac{\partial\lambda_{min}}{\partial H_{ij}}\frac{\partial H_{ij}}{\partial P_r} + \sum_{ij}\frac{\partial\lambda_{min}}{\partial N_{ij}}\frac{\partial N_{ij}}{\partial P_r} + \sum_{ij}\frac{\partial\lambda_{min}}{\partial M_{ij}}\frac{\partial M_{ij}}{\partial P_r} + \sum_{ij}\frac{\partial\lambda_{min}}{\partial L_{ij}}\frac{\partial L_{ij}}{\partial P_r} \qquad (5)$$

$$b_r = \frac{\partial\lambda_{min}}{\partial Q_r} = \sum_{ij}\frac{\partial\lambda_{min}}{\partial H_{ij}}\frac{\partial H_{ij}}{\partial Q_r} + \sum_{ij}\frac{\partial\lambda_{min}}{\partial N_{ij}}\frac{\partial N_{ij}}{\partial Q_r} + \sum_{ij}\frac{\partial\lambda_{min}}{\partial M_{ij}}\frac{\partial M_{ij}}{\partial Q_r} + \sum_{ij}\frac{\partial\lambda_{min}}{\partial L_{ij}}\frac{\partial L_{ij}}{\partial Q_r} \qquad (6)$$

where H_{ij} ,N_{ij} , M_{ij}, L_{ij} the elements of sub jacobian matrix of the load flow.

3. Formulation of load-shed optimization problem

It is understood that load shedding should take place at minimum number of buses. These buses should be selected and then upper limits of load shed (LS) must be decided from operating constraint view point. Buses are selected, which are having highest sensitivity in descending order of change in minimum eigenvalue with respect to load shed. Once the buses are selected for load shedding the following objective function is minimized.

$$J = \Delta P^T . \Delta P$$

where, ΔP is a vector of bus power shed at the pre-selected buses. The above objective function is minimized subject to the desired change in minimum eigenvalue due to load shedding at pre-selected buses.
Subjected to following inequality constraints:

$$\text{Vn} \geq \text{Vmin}$$

where, 'n' lies in the set of buses where still voltage magnitudes are less than specified value.

4. Algorithm for determining Load to be shed on load- buses

The step by step procedure of load shedding algorithm is given as follows-

Step-1: Carry out load flow by Newton Raphson Method using following algorithm and compute λ_{min}
i) Choose the initial values of the voltage magnitudes $|V|^{(0)}$of all *np* load buses and $n - 1$ angles $\delta^{(0)}$ *of* the voltages of all the buses except the slack bus.

$$J \begin{bmatrix} \Delta\delta \\ \vdots \\ \Delta\delta_n \\ \frac{\Delta|V_2|}{|V_2|} \\ \vdots \\ \frac{\Delta|V_{1+n_0}|}{|V_{1+n_0}|} \end{bmatrix} = \begin{bmatrix} P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_{1+n_0} \end{bmatrix}$$

ii) Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ *to* calculate a total $n - 1$ number of injected real power $Pcalc^{(0)}$andequal number of real power mismatch $\Delta P^{(0)}$.

Calculate voltage stability indicator for all load buses

iii) Use the estimated $|V|^{(0)}$ and $\delta^{(0)}$ *to* formulate the Jacobian matrix $J^{(0}$.
iv) Solve for $\delta^{(0)}$and $\Delta|V|^{(0)} \div |V|^{(0)}$

v) Obtain the updates from

$$\delta^{(1)} = \delta^{(0)} + \Delta\delta^{(0)}$$
$$|V|^{(1)} = |V|^{(0)} \left[1 + \frac{\Delta|V|^{(0)}}{|V|^{(0)}}\right]$$

vi) Check if all the mismatches are below a small number.
Terminate the process if yes. Otherwise go back to step-1 to start the next iteration with the updates given by (v).

Step2: Calculate voltage stability indicator for all load buses.

Step 3: Calculate the required load to be shed using eq. (3).
Step 4: Remove this load and go to step (1)

5. Results and Discussions

The developed algorithm has been implemented on IEEE 14-bus, 20-line test system. The acceptable range as per IEEE standard, of voltages on generator bus: 0.95-1.10pu, load buses voltage: 0.95-1.05pu, Shunt compensation on load buses: 0.0000 - 0.055pu, settings of Taps on OLTC: 0.9 -1.1. For this purpose system has been stressed by uniform loading where all type of rescheduling are exhausted and the value of proximity indicator has been reduced to very small value and system is at the verge of violation of inequality constraints. To save the system load shedding was carried out on predicted buses as per developed algorithm based on sensitivity Index. Amount of load has also been calculated in single step due closed form relationship. Load sheding recommended is 0 – 80% of the load bus capability, which violates operating constraints.

Under stressed condition minimum eigen value = 0.19

Threshold value of proximity indicator = 0.4

After Load sheding minimum eigen value = 0.42

Bus no.	Base case		Best solution based load shedding	
	Load (pu)	Voltage (pu)	Load (pu)	Voltage (pu)
1	0.0000	1.0929	0.0000	1.0929
2	0.5154	1.0379	0.5154	1.0379
3	1.9699	1.0323	1.9699	1.0323
4	0.2763	0.8722	0.2763	1.0224
5	0.0000	0.8389	0.0000	0.9843
6	0.9831	0.9289	0.9831	1.0134
7	0.0000	0.8389	0.0000	0.9843
8	0.1601	0.9262	0.1601	1.0058
9	0.6939	0.808	0.6939	0.9744
10	0.2195	0.7994	0.2195	0.9719
11	0.0806	0.8262	0.0806	0.9894
12	0.1292	0.8412	0.1292	1.0031
13	0.3012	0.8235	0.3012	0.9972
14	0.1681	0.7804	0.1681	0.9691

6. Conclusion

This paper proposes a load shedding scheme for providing voltage stability. The overall load shedding scheme is divided into two sub-problems: selection of load buses and determine amount of load to be shed. The decomposition of the overall problem into different sub-problems minimizes the risk of failure in obtaining the solution, and allows the operator to choose an appropriate number of buses to obtain a good sub optimal solution quickly. Moreover, the decomposition can give the reasons that lead to unfeasible power flow solution or insufficient VSM. The test results on 14- bus systems show that the load shedding method can be obtained to restore power flow solvability in a computationally efficient manner and the number of control actions calculated using the proposed method is less than solving a single optimization problem directly, although the solution cannot be guaranteed to be the global optimum of the problem, it is a local optimum satisfactory enough in practice.

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