Optimal Load Shedding Based on Frequency, Voltage Sensitivities and AHP Algorithm

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Abstract. Voltage and frequency are the two important parameters affecting the maintenance of the power system stability. This paper presents the load shedding methodology based on frequency and voltage. The level of disturbance is estimated by using the rate of frequency change, and the location, number of loads shed at each bus has been determined based on the calculated voltage sensitivity at each bus in steady state. In the competitive electricity market, load shedding/not shedding Decision Support Systems are needed to find economical ways to serve critical loads with limited sources under various uncertainties. Decision - making is significantly affected by limited energy sources, generation cost, and network available transfer capacity. The load shedding program taking into account the importance and position of the load, investment rates per unit load, and the constraint conditions based on Analytic Hierarchy Process (AHP) algorithm to process when the system there are many different types of load.

Keywords: Load shedding, under frequency load shedding (UFLS), voltage sensitivities, Analytic Hierarchy Process (AHP), Linear Program.

1 Introduction

The two most important parameters to monitor are the system voltage and frequency. If the generators in the system are unable to supply the power needed, then the system frequency begins to decline, and when all the available controls cannot maintain stable frequency electrical systems, fired load will be used as a last resort to restore the limited frequency norms. The fired load optimization should consider the economic indicators and the importance of the load, and when all the available controls cannot maintain the stable frequency of electrical systems, load shedding will be used as a last resort to restore the limited frequency norms. The optimal load shedding should consider the economic indicators and the importance of the load.

Although there is some success, the load shedding the traditional load shedding based on under frequency or voltage relay have the following disadvantages: only consider the frequency reduction [2] or voltage in the power system, in this case the results are often less accurate, the mount of load is shed sometimes so large in a step, it causes excessive load shedding, the next planning does not have the flexibility to

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increase the number of load steps shed [3], [4]. To increase the efficiency of load shedding, some load shedding methods based on frequency or the rate of change of frequency (*df/dt*) [5], voltage, sensitivities QV at load bus. However, this case shows the processing speed algorithm is too slow [1].

The load shedding proposed algorithm below aims to optimize load shedding based on frequency, voltage sensitivities at the nodes, considering the importance of the load, the investment rate/unit load and constraint conditions to resolve the limitations of previous studies.

2 Approach Method

2.1 The Load Shedding Based on Frequency and Voltage Sensitivities

The proposed load shedding combined two parameters: frequency and voltage sensitivities at bus provide the mount and location of load to shed [1]. The first step is determination the equations of swing of the rotor:

$$\frac{2H_{eq}}{f_o}\frac{df_n}{dt} = P_{diff} = P_{mn} - P_{en} \tag{1}$$

Where: H_{eq} is the equivalent inertia constant of the generators; f_0 is the nominal frequency of the system; P_{diff} is the difference in the generated power and the load power; P_{mn} is the mechanical shaft power for n machines, P_e is the electrical power for n machines.

The next step calculates *dV/dt* value to determine the order of load shedding. Buses with large *dV/dt* biggest listed at the top of the list and then arranged in descending order. The equation for reactive power, active power, and voltage sensitivities is:

$$P_i = \sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \cos(\delta_{ij} - \theta_{ij}) \tag{2}$$

$$Q_i = \sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \sin(\delta_{ij} - \theta_{ij}) \tag{3}$$

$$\frac{dQ_i}{dV_i} = 2\left|V_{ii} Y_{ii}\right| \cos(\theta_{ii}) + \sum_{\substack{j=1 \\ j \# i}}^{n} \left|V_j Y_{ij}\right| \sin(\delta_{ij} - \theta_{ij}) \tag{4}$$

Where: P_i, Q_i are the powers incoming to the i^{th} node; V_i, V_j are the voltages at the i^{th} and j^{th} node; Y_{ij} is impedance matrix; δ_{ij} is the phase angle difference of the voltage at the i^{th} and j^{th}; θ_{ij} phase angle of line ij.

The sensitivities voltage of each bus and the load which is shed from a bus based on equation:

$$\frac{\frac{dV_i}{dQ_i}}{(\frac{dV_1}{dQ_1}+\frac{dV_2}{dQ_2}+....+\frac{dV_n}{dQ_n})} \tag{5}$$

$$S_i = \frac{\left(\frac{dV_i}{dQ_i}\right)}{\left[\sum_{i=1}^{n}\left(\frac{dV_i}{dQ_i}\right)\right]} P_{diff} \tag{6}$$

The algorithm load shedding flowchart is presented in Fig.1 [1].

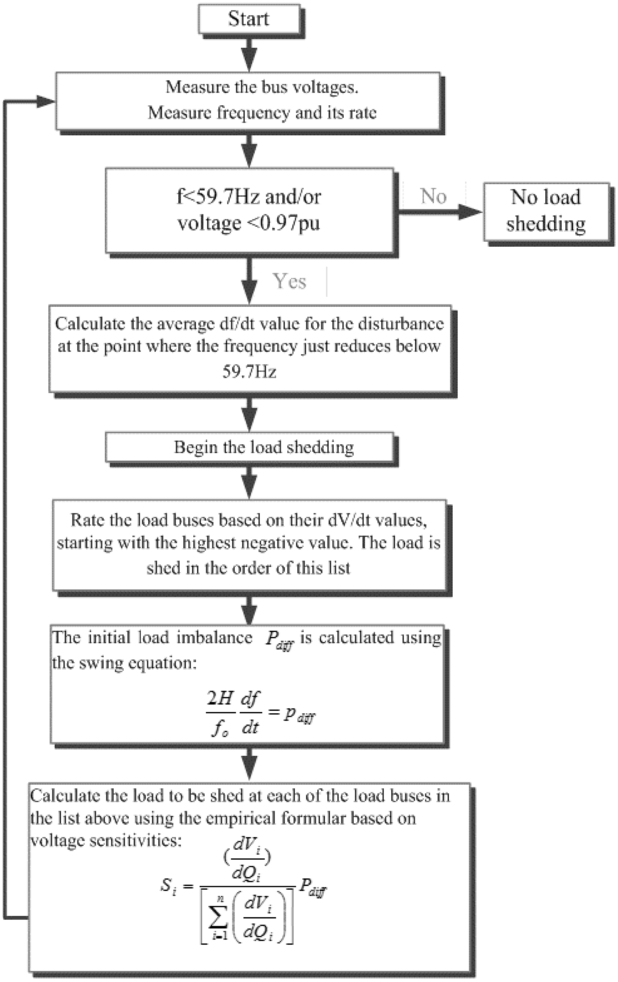

Fig. 1. Flowchart algorithm load shedding based on frequency and voltage sensitivities

2.2 Load Shedding Consider the Importance of the Load Based on AHP Algorithm

The load shedding program combinations of parameters: The importance of load, the investment rate/unit load, the load changes on time of day, the constraint conditions of power, thereby making the decision variables and calculates the maximum benefit achieved through the objective function.

1) Objective Function

$$\text{Max } H_i = \sum_{j=1}^{ND(K)} w_{ij} v_{ij} x_{ij} \tag{7}$$

Where: $x_{ij}$is decision variable (it equals 0 or 1) on load bus j at the i^{th}time stage; ND(k) is total number of load sites in load center k; $w_{ij}$is load priority to indicate the importance of the j^{th} load site of the i^{th}time stage; $v_{ij}$the investment rate/unit load (or compensation cost/kW power failure) on load j_{th} at the i_{th} time stage ($/kW or $/MW); H objective function.

2) Analytic Hierarchy Process (AHP) Algorithm

Step 1: The hierarchical network model

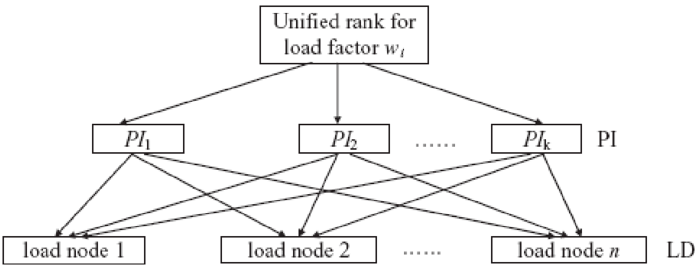

Fig. 2. Hierarchical network model

Analytical Hierarchy Process (AHP) is a method for ranking decision alternatives and selecting the best one when the decision maker has multiple criteria [6].

Step 2: Building judgment matrix A-PI and A-LD reflects the relative importance of load centers and loads in each of load center. The value of elements in the judgment matrix reflects the user's knowledge about the relative importance between every pair of factors. The judgment matrix A - PI can be written as follows:

$$A - PI = \begin{bmatrix} w_{K1}/w_{K1} & w_{K1}/w_{K2} & \cdots & w_{K1}/w_{Kn} \\ w_{K2}/w_{K1} & w_{K2}/w_{K2} & \cdots & w_{K2}/w_{Dn} \\ \vdots & & & \vdots \\ w_{Kn}/w_{K1} & w_{Kn}/w_{K2} & \cdots & w_{Kn}/w_{Kn} \end{bmatrix} \tag{8}$$

Where: w_{ki} is the importance of the i^{th} load center, this value is unknown; w_{ki} / w_{kj} which is the element of judgment matrix A - PI, represents the relative importance of the i^{th} load center compared with the j^{th} load center. The value of w_{ki} / w_{kj} can also be obtained according to the experience of electrical engineers or system operators using some ratio "1-9" scale methods.

The judgment matrix A-LD:

$$A - LD = \begin{bmatrix} w_{D1}/w_{D1} & w_{D1}/w_{D2} \; ..... \; w_{D1}/w_{Dn} \\ w_{D2}/w_{D1} & w_{D2}/w_{D2} \; ..... \; w_{D2}/w_{Dn} \\ . & . \\ . & . \\ . & . \\ w_{Dn}/w_{D1} & w_{Dn}/w_{D2} \; ..... \; w_{Dn}/w_{Dn} \end{bmatrix} \tag{9}$$

Where: w_{Di} is the importance of i^{th} load, this value is unknown; w_{Di}/w_{Dj} which is the element of the judgment matrix A-LD, represents the relative importance of the i^{th} load compared with the j^{th} load. The value of w_{Di}/w_{Dj} can be obtained according to the experience of electrical engineers or system operators using some ratio "0-9" scale methods.

It is very difficult to compute exactly the weight factor of each load. The reason is that the relative importance of these loads is not the same, which is related to the power market operation conditions. According to the principle of AHP, the weight factor s of the loads can be determined through the ranking computation of a judgment matrix, which reflects the judgment and comparison of a series of pair of factors.

The unified weight factor of the load w_{ij} can be obtained from the following equation:

$$w_{ij} = w_{kj} \text{ x } w_{Di} \qquad D_i \in K_j \tag{10}$$

Where: $D_i \in K_j$ means load D_i is located in load center K_j.

After calculation of the critical load factors and load centers, plans to load shedding optimization and achieve maximum benefits are calculated through the approach proposed.

Step 3: Calculate the maximal eigenvalues and the corresponding eigenvector of the judgment matrix.

Step 4: Hierarchy ranking and consistency check of results.

3 Calculation, Experiments, the Simulation on System

3.1 In Case of Study Load Shedding Based on Frequency and Voltage Sensitivities

Experiments on typical systems IEEE with f= 60Hz include 37 buses 9 generators. Consider the case of loss of a generator at bus 4, simulate with POWERWORLD software and observe getting results when applying the program conventional load shedding and proposed load shedding program. Using the equations of swing of the rotor, calculates as reduction of about 185MW. Results frequency graph when does not load shedding is shown in Fig. 3.

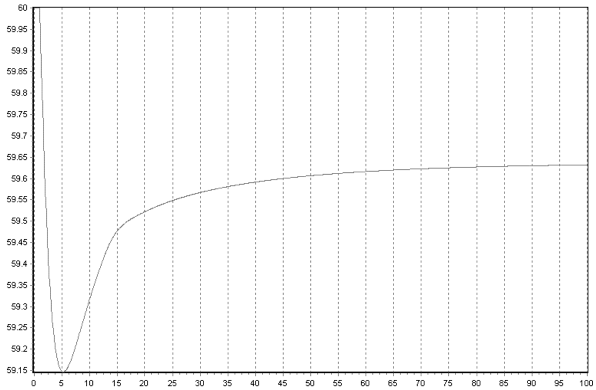

Fig. 3. Frequency system in case of failure at the generator bus 4

When no load shed, value frequency reduced 59.6 Hz is lower than the standard limit requirement. Therefore, should have solutions to restore system frequency back to the permitted limit value. The value of at the load buses are calculated and arranged in order beginning with the largest negative value. Load will be shed by order of the list presented in Table 1 and increased of 0.05s to avoid sudden loss of load. The increase in the number of load steps and load shedding in small steps avoid shedding too much load.

Table 1. The order of arrange in dv/dt at the bus

Bus	The order	dV/dt	Bus	The order	dV/dt
4	1	-0.04125	8	14	-0.01933
30	2	-0.03828	9	15	-0.01900
32	3	-0.03628	10	16	-0.01825
34	4	-0.03485	16	17	-0.01755
35	5	-0.03450	11	18	-0.01750
3	6	-0.03200	13	19	-0.01750
2	7	-0.02975	22	20	-0.01725
25	8	-0.02650	15	21	-0.01625
6	9	-0.02600	14	22	-0.01575
7	10	-0.02575	19	23	-0.01475
36	11	-0.02450	23	24	-0.01475
5	12	-0.02250	12	25	-0.01325
37	13	-0.02177	12	25	-0.01325

Shed power value at each bus will be based on its voltage sensitivities. The value of was calculated separately for each load bus at the operation steady state. The values of are applied to the voltage sensitivities formula to be calculate how much load will be shed at each bus. Frequency graph after applying load shed program is shown in Fig.4. The obtained results, the frequency before using the load shedding program is

59.6 Hz, after application proposed load shedding program, the frequency has improved to a stable value near 60 Hz (59.995 Hz) in 32s.

Comparison the case load shedding is not order sorted value, load is shed in this order: load smallest value shed before increasing order. The frequency after the load shedding is shown in Fig.4. The value frequency recovery is 59.87 Hz, and recovery time to the frequency stability is 50 seconds.

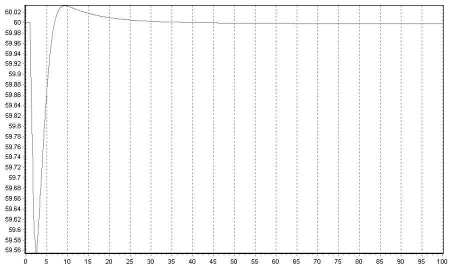

Fig. 4. Freq. of system after using load shedding based on freq. and voltage sensitivities

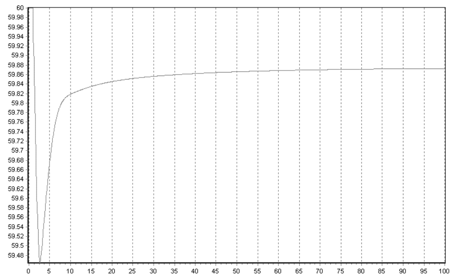

Fig. 5. Frequency of system after applying the load shedding no order *dV/dt*

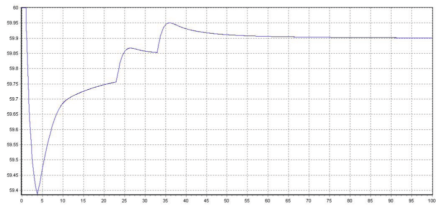

Fig. 6. Freq. of system after application load shedding by steps the decline of freq

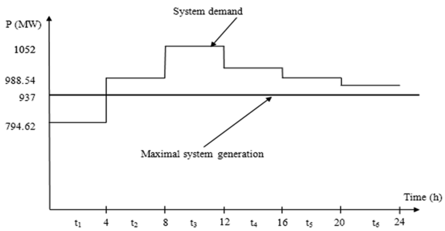

Fig. 7. Maximum system generation and load demands

Comparison with the case load shedding by steps based on the decline of frequency [3], the frequency of systems is shown in Fig. 6. In conclusion, the program loads shedding based on frequency and voltage sensitivities has faster recovery time, power load shedding less than traditional methods.

3.2 Load Shedding Consider the Importance of the Load Based on AHP Algorithm

The case study considered the 37 bus 9 generators system. The total generation power of source and load demand in the stages is shown in Fig.7.

At first, the judgment matrices A-LD and A-PI. After calculating the value of the weight factors of each unit load at each time stage can be calculated from AHP method, ranking the unit load in order of descending priority is presented in Table 2. Load has weight factor W_{ij} lager is more important.

Table 2. Reduced ranking weight factors W_{ij} computed by AHP

Load center	Weighting Factor W_{kj} (A-PI)	Load Node	vij ($/kW)	Weighting Factor W_{di} (A-LD)	Unified WeightingFactor W_{ij}
CK1	0.49421	PD5	300	0.09518	0.047039008
CK1	0.49421	PD7	300	0.07729	0.038197193
CK1	0.49421	PD6	300	0.06821	0.033709162
CK1	0.49421	PD4	280	0.06306	0.031163832
CK1	0.49421	PD2	280	0.06165	0.030469937
CK1	0.49421	PD8	280	0.05830	0.028811996
CK1	0.49421	PD9	280	0.05180	0.025600079
CK1	0.49421	PD3	300	0.04724	0.023347549
CK3	0.25112	PD22	220	0.04180	0.010496781
CK3	0.25112	PD16	220	0.02940	0.007381787
CK3	0.25112	PD15	280	0.02608	0.006548176
CK3	0.25112	PD19	245	0.02410	0.006050998
CK2	0.11346	PD10	245	0.04994	0.005665628
CK2	0.11346	PD13	280	0.04936	0.005600806
CK4	0.14122	PD25	300	0.03434	0.004848719
CK3	0.25112	PD23	280	0.01822	0.004576043
CK4	0.14122	PD35	245	0.02566	0.003623070
CK4	0.14122	PD32	220	0.02524	0.003564782
CK4	0.14122	PD36	300	0.02524	0.003564782
CK4	0.14122	PD34	220	0.02094	0.002957412
CK4	0.14122	PD37	220	0.02069	0.002922123
CK4	0.14122	PD30	220	0.01980	0.002796493
CK2	0.11346	PD11	280	0.02357	0.002674183
CK2	0.11346	PD14	220	0.02234	0.002534066
CK2	0.11346	PD12	300	0.02055	0.002331816

Ranking of all loads in the order of priority for each time stage and rule - based system decides the commitment or load shedding. This priority rank considers does not involve the constraints of power balance and reserve requirements when increase or decrease the load. So the final results are obtained through the combination between AHP and rule - based constraints checking. The calculation results are presented in Table 3. By the table, the decision variable xij = 1 means that this load is committed at the time stage t, and xij = 0 means that this load is shed at the time stage t.

The conventional load shedding LP method does not consider the importance of the loads as well as their relationship with each other load sites. The result comparison shows that the load shedding based on AHP is more optimal. It not only benefits the maximum load capacity of not less than layoffs, but also attention to the importance and location of the load.

Table 3. Comparison load shedding at the stages based on AHP (1) and LP (2)

LOAD SITE	STAGE T1		STAGE T2		STAGE T3		STAGE T4		STAGE T5		STAGE T6	
Methods	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
PD2	1	1	1	0	1	0	1	0	1	0	1	0
PD3	1	1	1	1	1	0	1	0	1	1	1	1
PD4	1	1	1	1	1	1	1	1	1	1	1	1
PD5	1	1	1	1	1	1	1	1	1	1	1	1
PD6	1	1	1	1	1	1	1	1	1	1	1	1
PD7	1	1	1	1	1	1	1	1	1	1	1	1
PD8	1	1	1	1	1	1	1	1	1	1	1	1
PD9	1	1	1	1	1	1	1	1	1	1	1	1
PD10	1	1	1	1	1	1	1	1	1	1	1	1
PD11	1	1	1	1	1	1	1	1	1	1	1	1
PD12	1	1	1	1	1	1	1	1	1	1	1	1
PD13	1	1	1	1	0	1	1	1	1	1	1	1
PD14	1	1	0	0	1	0	0	0	0	0	0	0
PD15	1	1	1	1	1	1	1	1	1	1	1	1
PD16	1	1	1	1	1	0	1	1	1	1	1	1
PD19	1	1	1	1	1	1	1	1	1	1	1	1
PD22	1	1	1	1	1	0	1	1	1	1	1	1
PD23	1	1	1	1	1	1	1	1	1	1	1	1
PD25	1	1	1	1	1	1	1	1	1	1	1	1
PD30	1	1	1	1	1	1	1	1	1	1	0	1
PD32	1	1	1	1	1	1	0	1	1	1	1	1
PD34	1	1	0	0	1	1	0	1	1	0	1	1
PD35	1	1	1	1	1	1	1	1	1	1	1	1
PD36	1	1	1	1	0	1	1	1	1	1	1	1
PD37	1	1	0	0	1	0	1	0	0	0	1	0

Table 4. Summary results compare between method conventional load shedding LP and AHP

Methods	Time stage	Max system generation (MW)	System demands (MW)	Total load shedding (MW)	Objective H_i	Benefit $\sum V_{ij}P_{ij}$ $(x10^3)\$$
AHP	t_1	937	794.62	0.00	94.78	213658
LP		937	794.62	0.00		213658
AHP	t_2	937	988.54	51.54	92.93	254655
LP		937	988.54	67.28		250246
AHP	t_3	937	1052	115.10	92.74	255142
LP		937	1052	116.20		254974
AHP	t_4	937	1000	63.31	92.79	255205
LP		937	1000	65.86		252308

Table 4. (*continued*)

AHP	t_5	937	988.54	51.54	93.58	254655
LP		937	988.54	67.28		250246
AHP	t_6	937	977.13	42.25	93.61	253639
LP		937	977.13	47.87		251467

4 Conclusion

The load shedding based on frequency and voltage sensitivities with frequency recovery time faster than traditional methods. However, this method isn't to mention the economic criteria and apply for emergency situations such as the loss of a generator or the loss of transmission lines.

Using the program loads shedding based on AHP algorithm considering load shedding problem considering the importance of the load, the investment rate/unit load, the load changes according to time of day and the constraint conditions allow load shedding is less than traditional methods and maximize the objective function.

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