A New Combined Index Applied for Anticipatory Load Shedding with Voltage Stability Consideration

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Received: July 2014 Revised: March 2015 Accepted: May 2015

ABSTRACT:
Under-voltage load shedding is an important measurement to maintain the voltage stability in power systems. In this paper, a new combined index is proposed for under-voltage load shedding. The proposed index is weighted combination of importance, sensitivity and value of loads. This is of paramount importance, since three vital factors such as importance of load, sensitivity of minimum eigenvalue of load flow Jacobian respect to load and the amount of loads are considered for optimal under-voltage load shedding. The algorithm accounts constraints not only in present operating condition but also for predicted next interval load. The proposed method is applied on IEEE 14-bus test system. This paper formulates the optimal under-voltage load shedding problem for power system as a Nonlinear Programming (NLP), and it solves the proposed problem using Generalized Algebraic Modeling Systems (GAMS) software package with CONOPT solver. Results have been compared with those researches based on sensitivity analysis. The results showed effectiveness of proposed index. This proposed index can be used in selecting candidate buses in different power system problems.

KEYWORD: New combined index, NLP approach, under-voltage load shedding.

1. INTRODUCTIN

With the expanding scale of the power grid and the development of power market, the system operation is running to its limit. In recent years, several worldwide voltage collapse accidents have forced the scholars from various countries focus on the severe social impact and economic losses caused by it. A quick and timely identification of the system's emergency state and take measures to prevent voltage collapse has important meaning. The voltage stability control measures are usually conservative and expensive, but automatic load shedding as an important measure for voltage stability is drawing more and more attention for its effectiveness and low costs.

The under-voltage load shedding problem optimization includes many methods. As reviewed in [1], the efficiency of the various voltage stability indices is studied in different cases. In the first case, under-voltage load shedding is simulated on electric power system consisting of an infinite-bus feeding a load through a large impedance line. Also, two other cases are simulated including a fixed capacitive impedance (representing a saturated SVC or similar) with 25 and 60 MVAr, both with a generator regulating the load bus voltage. An algorithm is described in [2] for load shedding under emergency condition to avoid the risk of voltage instability. For this purpose, the minimum eigenvalue of load flow Jacobian is selected as proximity indicator. The amount of load to be shed is decided so as to maintain a threshold value of indicator and all load bus voltages within limit. The sensitivity of indicator with load shedding has been utilized for problem formulation. Two fuzzy based load shedding algorithms that use a voltage stability indicator for averting voltage collapse are proposed in [3]. The first method identifies the most appropriate locations and uses an analytical procedure to compute the possible load shedding, while the second method predicts directly the amount of load to be shed at the critical buses. In [4], the problem of load shedding is addressed as an emergency means for avoiding occurrence of voltage instability in distribution and transmission power systems. Optimum locations of loads to be shed are found together with their optimum required quantities. Also, L-indicator index is used for this purpose with a modified new technique. A LP-based optimization load shedding algorithm is presented in [5] to improve the load margin. The objective function consists of minimizing the total system demand decrease. First order sensitivities of the load margin with respect to the load to be shed are considered. A preventive/corrective control model to prevent and correct the voltage instability is presented in [6], taking into account the load-shed dynamics. An OPF based model is proposed that provides an integrated framework to determine the optimal location, level, timing, and number of loads to be shed to maintain a pre-specified voltage stability margin. A design of load shedding against long-term voltage instability is proposed in [7]. It uses a set of distributed controllers, each monitoring a transmission voltage, controlling a group of loads, acting in closed-loop, and adjusting its action to the voltage evolution. Analytical description of the design of individual load-shedding schemes against voltage collapse in the Hellenic System is presented in [8]. The analysis and simulation results which validate the efficiency of these protection schemes are provided in [8]. Three adaptive combinational load shedding methods are proposed in [9] to improve the operation of the conventional under frequency load shedding scheme in order to enhance the power system stability following severe disturbances. The proposed methods use locally measured frequency and voltage signals to counteract such events. In the proposed algorithms, the load shedding is started from the locations which have higher voltage decay for longer period of time. The speed, location, and amount of load shedding are changed adaptively depending on the disturbance location, voltage status of the system, and the rate of frequency decline. An anticipatory load shedding methodology is presented in [10], which determines the optimum load shedding in selected buses under emergency based voltage stability. Accurate load shedding saves the loss of revenue to power utility in addition to avoiding voltage instability problem. The buses for load shedding have been selected based on the sensitivity of minimum eigenvalue of the load flow Jacobian with respect to load shed. An approach based on hybrid Particle Swarm-Based-Simulated Annealing Optimization technique (PSO-B-SA) is proposed for solving under-voltage load shedding (UVLS) problem in [11] as a most important tool for avoiding voltage instability. An optimal load-shedding algorithm is developed in [12] based on the concept of the static voltage stability margin and its sensitivity at the maximum loading point or the collapse point. A computationally simple algorithm is developed in [13] for studying the load shedding problem in emergencies where an ac power flow solution cannot be found for the stressed system. The proposed algorithm is divided into two sub-problems: restoring solvability sub-problem and improving the voltage stability margin sub-problem. In [14], a methodology is proposed to optimize the necessary load curtailments to restore the equilibrium of the operating point by accounting for operating and stability inequality constraints. A practical approach for determining the best location and the minimum amount of the load to be shed for the event-driven-based load shedding schemes is presented in [15]. In order to find the above key parameters; a non-linear optimization problem needs to be solved. In [16], an adaptive under-voltage load shedding scheme using the model predictive control is proposed to protect power system against voltage instability. The proposed scheme calculates the criticality of the system based on the measurements of voltage magnitudes and reactive power generations and then in case of voltage instability, a model predictive based step-sized load shedding scheme will be triggered. In [17], a method of under voltage load shedding in a power system incorporating the use of wind generators to maintain voltage stability following a severe disturbance is proposed. A technoeconomic multi-objective function is proposed in [18] to reveal an optimal load shedding scheme considering maximum social welfare. Particle swarm optimization is used to find an optimal load shedding scheme. In [19], a technique for locating the suitable load buses for the purpose of load shedding considering multi-contingencies is proposed considering stability index. Also, the amount of load power to be shed is determined via a modified version of fuzzy system.

The present paper is an attempt to create an optimal under-voltage load-shedding scheme by presenting a new combined index based on importance, sensitivity and amount of loads. This is of paramount importance, since three vital factors such as importance of load, sensitivity of minimum eigenvalue of load flow Jacobian with respect to load and the amount of load are considered for optimal under-voltage load shedding.

For general optimization problems, one of the favorite choices is the general algebraic modeling system (GAMS) [20]. GAMS is a high-level modeling system for mathematical optimization problems. It consists of a proprietary language compiler and a variety of integrated high-performance solvers. GAMS is specifically designed for large and complex problems, and allows creating and maintaining models for a wide variety of applications and disciplines [20]. GAMS is able to formulate models in many different types of problem classes, such as linear programming (LP), nonlinear programming (NLP), mixed-integer linear programming (MILP), mixed-integer nonlinear programming (MINLP) and dynamic nonlinear programming (DNLP). It makes this framework as a problem-independent framework. Because of the changing in the objective function, by adding or deleting an item or variable, only the change of solver maybe necessary. For example, by adding an integer variable in NLP problem, it is necessary to change solver to another one that is capable to solve MINLP. Therefore, the objective function can be change easily according to decision makers and available planning options without worry of whole framework changing.

This paper proposes a novel method based on nonlinear programming approach which is capable of optimal load shedding to maintain voltage stability under critical conditions, which is a point worth mentioning in this paper. Thus, this paper formulate the optimal under-voltage load shedding problem for power system as a Nonlinear Programming (NLP), and solve them using Generalized Algebraic Modeling Systems (GAMS) software package [20] with CONOPT solver [21]. CONOPT has considerable build-in logic that selects a solution approach that seems to be best suited for the type of model at hand, and the approach is adjusted dynamically as information about the behavior of the model is collected and updated already supported by GAMS software.

The remained of this paper is organized as follows: Section 2 presents the new combined index. The problem formulation for under-voltage load shedding is introduced in Section 3 based on proposed index. Section 4 is devoted to the simulation and application results of the proposed index on a case study. Finally, conclusions and contribution of the paper are presented in Section 5.

2. NEW COMBINED INDEX

The pervious works are using the sensitivity of minimum eigenvalue of load flow Jacobian with respect to system loads such as [10] and [14] for under voltage load shedding. The amount of selected load buses by sensitivity analyze may be low. Then, in severe disturbance, the voltage stability may not be satisfied by shedding of the selected loads. In these cases, the algorithm must select other load buses. In other words, the amount of load is affected on selecting of load buses for under voltage load shedding. In addition, some loads such as heavy industrial loads and military loads are very important. These loads should not be shed if it is possible. Then, in this paper a new combined index is proposed for this aim.

The proposed combined index is defined based on a linear combination of sensitivity of minimum eigenvalue of load flow Jacobian with respect to system loads, amount and cost of loads. Therefore, the new combined index is calculated based on:

$$index(i) = w_1 . \frac{\partial \lambda}{\partial P_i} + w_2 . P_i + w_3 . C_i \quad (1)$$

This equation contain three terms. The first term demonstrates sensitivity of minimum eigenvalue of load flow Jacobian with respect to system loads. This terms is explained in many researches such as [10] and [14] in details. The second part of equation (1) is defined as the effect of amount of loads on ranking of buses to load shedding candidate. The third term illustrates the importance of load.

In the proposed index, w_1 and w_2 are positive coefficients and w_3 is negative coefficient. Then, the load buses with higher sensitivity, higher amount and lower importance (the curtailment cost is minimum) are selected to load shedding candidate for voltage stability. This new index is calculated for all of load buses of the power system. These buses are ranked based on this index. The buses with higher indexes are selected for load shedding. It should be mentioned, the decision maker selects amount of w_1 and w_2 and w_3 coefficients considering contingency and power system network.

3. PROBLEM FORMULATION

The proposed index is calculated for all of load buses. Then these buses are ranked based on the index. Finally, the buses with higher indexes are candidates for load shedding.

Therefore, the objective function is the total shedding loads at candidate buses considering rank of load buses based on proposed index:

$$J = \sum_{i=1}^{NLS} ls_i \quad (2)$$

Where, ls_i is the shedded load of bus i and NLS is the set of candidate load buses for load shedding. This objective function is minimized subject to the following constraints:

3.1. Power flow constraints

The power flow constraints should be considered under current operating condition as well as next predicted loading condition accounting load shed:

$$P_{Gi}^0 - P_{Di}^0 + \Delta P_{Di} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \cos(\delta_{ij} + \delta_j - \delta_i) \quad (3)$$

$$Q_{Gi}^0 - Q_{Di}^0 + \Delta Q_{Di} = -\sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \sin(\delta_{ij} + \delta_j - \delta_i) \quad (4)$$

$$P_{Gi}^C - P_{Di}^C + \Delta P_{Di} = \sum_{j=1}^{N} |V_i^C||V_j^C||Y_{ij}| \cos(\delta_{ij} + \delta_j^C - \delta_i^C) \quad (5)$$

$$Q_{Gi}^C - Q_{Di}^C + \Delta Q_{Di} = -\sum_{j=1}^{N} |V_i^C||V_j^C||Y_{ij}| \sin(\delta_{ij} + \delta_j^C - \delta_i^C) \quad (6)$$

3.2. Voltage stability margin constraints

To ensure the voltage stability, the loading margin is considered as a soft constraint in the proposed problem as following:

$$P_{Gi}^{0} - (1+\lambda_{\min})(P_{Di}^{0} - \Delta P_{Di}) = \sum_{j=1}^{N} |V_i^C||V_j^C||Y_{ij}|\cos(\delta_{ij} + \delta_j^C - \delta_i^C) \quad (7)$$

$$Q_{Gi}^{0} - (1+\lambda_{\min})(Q_{Di}^{0} - \Delta Q_{Di}) = \sum_{j=1}^{N} |V_i^C||V_j^C||Y_{ij}|\cos(\delta_{ij} + \delta_j^C - \delta_i^C) \quad (8)$$

$$\lambda_{\min} \geq \lambda_{\min}^{th} \quad (9)$$

3.3. Technical constraints of generators

Active and reactive power generation constraint under base case condition as well as at next predicted loading condition accounting load shed should be satisfied as:

$$\underline{P}_{Gi} \leq P_{Gi}^{0} \leq \overline{P}_{Gi}$$
$$\underline{P}_{Gi} \leq P_{Gi}^{C} \leq \overline{P}_{Gi} \quad (10)$$

$$\underline{Q}_{Gi} \leq Q_{Gi}^{0} \leq \overline{Q}_{Gi}$$
$$\underline{Q}_{Gi} \leq Q_{Gi}^{C} \leq \overline{Q}_{Gi} \quad (11)$$

3.4. Voltage limit constraints

Inequality constraints on bus voltages should be satisfied in the predefined limits as following:

$$\underline{V}_i \leq V_i^0 \leq \overline{V_i}$$
$$\underline{V}_i \leq V_i^p \leq \overline{V_i} \quad (12)$$

3.4. Load shedding constraints

Shedding load of each bus is limited as following:

$$\underline{ls}_i \leq ls_i^0 \leq \overline{ls_i} \quad (13)$$

Where ls_i is the amount of total load shed and $\overline{ls_i}$ and $\underline{ls}_i$ denote maximum and minimum permissible load shed at i^{th} bus, respectively. In fact permissible load shedding is a fraction of total load at selected bus.

It is stressed that load shedding is performed at current loading condition. Further, constraints as in Equations (10)-(12) are ascertained by performing load flow solution at current operating condition (after load shedding) and predicted load condition (accounting load shed).

4. CASE STUDY

The new combined index has been implemented on under-voltage load shedding problem in IEEE 14-bus system. For this purpose, the system has been stressed by uniform loading such that the proximity indicator has been reduced to very small value and there is severe violation of bus voltages.

4.1. 14-bus test system data

Figure 1 shows IEEE 14-bus standard test system. This system consists of three generator buses and eleven load buses. The desired range of load bus voltage is 0.95 *pu*–1.05 *pu*. Table 1 shows the line data of this system. Also, the bus data is presented in Table 2. From operational experience of the system, the threshold value of proximity indicator is selected as $\lambda_{\min} \geq 0.4$.

In order to clearly illustrate the effectiveness of the proposed index, two cases are compared: (I) Under-voltage load shedding considering sensitivity analysis, (II) Under-voltage load shedding considering the proposed index.

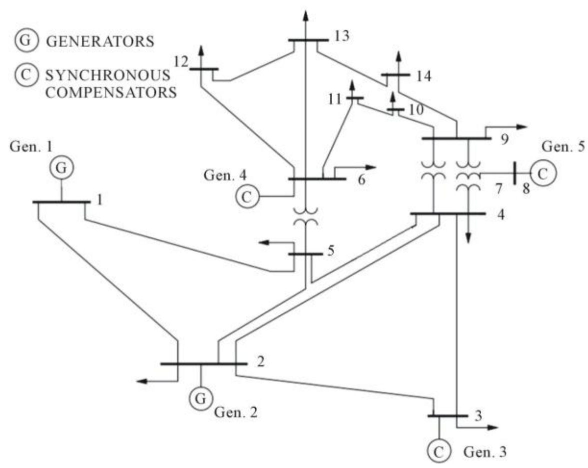

Fig. 1. IEEE 14-bus standard test system

4.1.1. Under-voltage load shedding considering sensitivity analysis

Load bus ranking according sensitivity of minimum eigenvalue of load flow Jacobian with respect to system load for 14-bus system is presented in [14]. Load buses which have highest sensitivities are selected for load shedding. The selected buses are 14, 13, 12, 11 and 10 [14].

The limitation of under-voltage load shedding considering sensitivity analysis is shown by two scenarios as following:

Scenario1- Uniform loading of the system up to 35% greater than normal loading and the optimization algorithm sheds loads until $\lambda_{\min} \geq 0.4$.

Scenario2- Uniform loading of the system up to 120% greater than normal loading and the optimization algorithm sheds loads until $\lambda_{\min} \geq 0.4$.

The results of scenario 1 are shown in Table 3. This table shows effectiveness of under-voltage load shedding considering sensitivity analysis. Also, objective function is % 11.8 of total load.

The results of optimal load shedding in scenario 2 are shown in Table 4. According to Table 4, the optimal load shedding based on sensitivity analysis is inefficient with 5 selected buses. The algorithm shed load from 3, 6 and 9 load buses in addition to five selected buses. It was observed that the load is shed based on sensitivity analysis and amount of loads. Therefore, the amount of load is important, too.

Table 1. Line data

Line No.	Bus No. From	Bus No. To	Resistance (pu)	Reactance (pu)	Susceptance (pu)	Tap	Flow Limit (pu)
1	1	2	0.01938	0.05917	0.0264	1.0	0.92
2	1	8	0.05403	0.22304	0.0246	1.0	0.55
3	2	3	0.04699	0.19790	0.0219	1.0	0.41
4	2	6	0.05811	0.17632	0.0187	1.0	0.70
5	2	8	0.05695	0.17388	0.0170	1.0	0.50
6	6	3	0.06701	0.17103	0.0173	1.0	0.04
7	8	6	0.01335	0.04211	0.0064	1.0	0.42
8	6	7	0.00000	0.20912	0.0000	1.0	0.42
9	6	9	0.00000	0.55628	0.0000	1.0	0.20
10	8	4	0.00000	0.25202	0.0000	1.0	0.52
11	4	11	0.09498	0.19890	0.0000	1.0	0.09
12	4	12	0.12291	0.25581	0.0000	1.0	0.10
13	4	13	0.06613	0.13027	0.0000	1.0	0.20
14	7	5	0.00000	0.17615	0.0000	1.0	0.01
15	7	9	0.00000	0.08450	0.0000	1.0	0.42
16	9	10	0.03181	0.08450	0.0000	1.0	0.08
17	9	14	0.12711	0.27038	0.0000	1.0	0.12
18	11	10	0.08205	0.19207	0.0000	1.0	0.05
19	12	13	0.22092	0.19988	0.0000	1.0	0.025
20	13	14	0.17093	0.34802	0.0000	1.0	0.08

Table 2. Bus Data

Bus No.	*Real Load (pu)*	*Reactive Load (pu)*
1	0.0000	0.0000
2	0.2170	0.1270
3	0.9420	0.1900
4	0.1120	0.0750
5	0.0000	0.0000
6	0.4780	0.0390
7	0.0000	0.0000
8	0.0760	0.0180
9	0.2950	0.1660
10	0.0900	0.0580
11	0.0350	0.0180
12	0.0610	0.0160
13	0.1350	0.0580
14	0.0580	0.0580

Table 3. The results of scenario 1

Bus number	*Amount of load shedding*
10	0.044
11	0.038
12	0.066
13	0.146
14	0.063

Table 4. The results of scenario 2

Bus number	*Amount of load shedding*
3	0.931
6	0.475
9	0.387
10	0.158
11	0.062
12	0.107
13	0.238
14	0.102

Table 5. The rank of load buses based on the proposed index

Rank number	*Load bus*	*index*
1	3	0.4244
2	9	0.2219
3	6	0.2106
4	13	0.1631
5	14	0.1590
6	10	0.1433
7	4	0.1382
8	12	0.1188
9	11	0.1141
10	2	0.1006
11	8	0.0492

Table 6. The results of load shedding based on the proposed index

Bus number	*Amount of load shedding*
3	1.519
6	0.771
9	0.476
13	0.218
14	0.093

4.1.2. Under-voltage load shedding using the proposed new combined index

Considering limitation of under-voltage load shedding based on sensitivity analysis, the new combined index has been defined as the combination of sensitivity analysis, amount and importance of loads in section 2. In this case w_1, w_2 and w_3 are set to be 0.4, 0.4 and -0.2, respectively by decision maker. Also, the curtailment cost of loads is assumed to be same. This combined index is calculated for ranking load buses of IEEE 14 bus test system and the results are shown in Table 5. According to this table, the five selected buses for load shedding are 3, 6, 9, 13 and 14.

The results of optimal load shedding based on the proposed index are shown in Table 6 for scenario 2. Considering table 6, the load shedding algorithm shed load from load buses of 3, 6, 9, 13 and 14. These buses are selected based on proposed index. This table shows the effectiveness of under-voltage load shedding based on the proposed index.

5. CONCLUSION

In this paper, optimal under-voltage load-shedding problem was solved based on proposed combined index. The old index was based on sensitivity of minimum eigenvalue of load flow Jacobian with respect to load whereas the proposed index uses the addition factors such as importance of load and value of load. This index was calculated for all of load buses of the power system in order to rank them. The buses with higher indexes are selected for load shedding. In order to clearly illustrate the effect of the proposed index in IEEE 14-bus system, two cases are considered, namely: (I) Under-voltage load shedding considering sensitivity analysis, (II) Under-voltage load shedding considering proposed new combined index. Finally, the under-voltage load shedding based on proposed index is compared with traditional sensitivity analysis. The comparison results showed the effectiveness of proposed index to achieve optimal load shedding for stable voltage in power system. In future works, the proposed index can be useful in reaching the desired result, faster.

Nomenclature

w_1, w_2, w_3	important coefficients of combined index
$\frac{\partial \lambda}{\partial P_i}$	sensitivity of minimum eigenvalue of load flow Jacobian with respect to *i*th load
P_i	active power of *i*th bus
C_i	curtailment cost of *i*th load bus
ls_i	the load shedding of bus i
NLS	set of the candidate load buses for load shedding
P_{Gi}^0	active power output of *i*th generator under current operating condition
P_{Di}^0	active power of *i*th bus under current operating condition
ΔP_{Di}	the amount of active load shedding at *i*th bus
V_i	voltage of *i*th bus
δ_i	angle of *i*th bus voltage
Y_{ij}	admittance line between *i*th bus and *j*th bus
δ_{ij}	angle of admittance line between *i*th bus and *j*th bus
Q_{Gi}^0	reactive power output of *i*th generator under current operating condition
Q_{Di}^0	reactive power of *i*th bus under current operating condition
ΔQ_{Di}	the amount of reactive load shedding at *i*th bus
P_{Gi}^C	active power output of *i*th generator under next predicted loading condition
P_{Di}^C	active power of *i*th bus under next predicted loading condition
V_i^C	the amount of active load shedding at *i*th bus under next predicted loading condition
δ_i^C	voltage of *i*th bus under next predicted loading condition
Q_{Gi}^C	reactive power output of *i*th generator under next predicted loading condition
Q_{Di}^C	reactive power of *i*th bus under next predicted loading condition
$\lambda_{\min}$	minimum eigenvalue of load flow Jacobian of power system
$\lambda_{\min}^{th}$	threshold of minimum eigenvalue of load flow Jacobian of power system
$\underline{P}_{Gi}$	minimum active output power of *i*th generator
$\overline{P}_{Gi}$	maximum active output power of *i*th generator
$\underline{Q}_{Gi}$	minimum reactive output power of *i*th generator
$\overline{Q}_{Gi}$	maximum reactive output power of *i*th generator
$\underline{V}_i$	minimum of voltage of *i*th bus
$\overline{V}_i$	maximum of voltage of *i*th bus
$\underline{ls}_i$	minimum load shedding of bus i
$\overline{ls}_i$	maximum load shedding of bus i
ls_i^0	load shedding of bus i

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