Multi- Level Optimization Strategy for Load Shedding with Tracing Capability Index

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Abstract*— Numerous stability indices have been developed to assess the voltage stability of power networks, since it is a powerful tool to identify the weakest bus and critical lines. To expand the knowledge of power tracing theory and its application into voltage stability assessment, this paper adopts the power tracing capable index into load shedding scheme. A modified novel line stability factor index with load tracing capability known as LQP_LT is used to classify the weak buses according to its priority rank for load shedding bus selection. IEEE 5 bus system is used to demonstrate the LQP_LT principles and concepts. The results obtained from the weak bus identifications is analyzed for load shedding optimization execution. Particle Swarm Optimization (PSO) is used for the optimization analysis in a multi- level approach and objective settings. The results obtained post- load shedding with the proposed method is found to be efficient for the implementation and execution of optimized amount and location selection for under voltage load shedding scheme.

***Index Terms*—*Reactive power tracing, voltage stability, load shedding*

I. INTRODUCTION

The non- linear nature of power system flow has caused the task of determining the power transfer from generators to loads or lines to be complex. Approximate models and tracing algorithms have been introduced in order to trace the power transfers between loads, generators and lines, with the real power tracing being the main commodity.

Nevertheless, reactive power in a system also plays a vital role to maintain the system stability and reliability. System operator need to make appropriate decision to implement the corrective and preventive actions during multi-contingency situations which can lead to voltage collapse occurrence. Many strategies are executed during the critical contingency situations with load shedding being the last resort for corrective action in order to stabilize a voltage collapse conditions [1]. Identification of the best location to perform load shedding in a critical power network is crucial since this will affect the system performance after improvement being done. The implementation of power tracing approach so far has been limited to the field of transmission service pricing. Due to the limited research done for reactive power tracing implementation in power system stability study, this paper presents a modified novel line stability factor index with load tracing capability known as LQP_LT, for the purpose of finding the appropriate locations in a power system network for any preventive and corrective actions [2].

The corrective action is implemented by restoring the system stability through load shedding. The minimization of sum of LQP_LT index and loss of active power at weak buses indicated by the power tracing capable index with the improvement of voltages at all buses are the objective functions for the study. The objective functions established were tested via nature inspired swarm intelligence technique known as PSO. Promising results achieved by performing the proposed multi- level optimization technique and stability of the test system was recovered post- load shedding subjected to the constraints set in the system.

II. MATHEMATICAL FORMULATION FOR LINE STABILITY FACTOR WITH LOAD TRACING (LQP_LT)

A. Mohamed et al. [3] had derived a line based stability factor, LQP based on the relationship of quadratic equation between two buses in a single transmission line. References [4-8] have utilized the LQP index and it is found to be suitable and comparable in terms of index performance with other stability indices in predicting the voltage collapse and voltage stability assessment. The LQP index of a line i-j can be represented as in Eq.1:

$$LQP = 4\left(\frac{X}{V_s^2}\right)\left(\frac{X}{V_s^2}P_s^2 + Q_r\right) \tag{1}$$

where X is the line reactance, Q_r is the reactive power flow at the receiving bus, V_s is the voltage on sending bus and P_s is the active power flow at the sending bus. Operating at secure and stable conditions requires the value of LQP index to be maintained less than unity.

A. LQP_LT Derivation

Load tracing is defined as a task to trace the powers contributed by an individual load. Utilizing [9], with appropriate modification performed for the purpose of reactive power flow derivation, the flow Q_{lm} on line l-m can be expressed as a summation of load components as in Eq.2:

$$Q_{lm} = Q_{lm}^{L1} + Q_{lm}^{L2} + Q_{lm}^{L3} + \cdots + Q_{lm}^{Ln} \qquad (2)$$

where n is the total number of loads in the network. The component of load defined as Q_{Li} on line *l-m* is expressed as a fraction x_{lm}^{i} of load Q_{Li} and written as follows:

$$Q_{lm}^{Li} = x_{lm}^{i} \cdot Q_{Li} \qquad (3)$$

thus, $Q_{lm} = \sum_{i=1}^{Ln} x_{lm}^{i} \cdot Q_{Li}$. (4)

Applying the above concept into LQP_LT of line *l-m* for summation of individual load components, gives Eq. (5):

$$LQP\_LT_{lm} = LQP_{lm}^{L1} + LQP_{lm}^{L2} + LQP_{lm}^{L3} + \cdots + LQP_{lm}^{Ln} \qquad (5)$$

or can be written also as:

$$LQP\_LT_{lm} = 4\left(\frac{X}{V_s^2}\left[\sum_{i=1}^{Ln} Q_{r,lm}^{i}\right] + \frac{XP_s^2}{V_s^2}\right). \qquad (6)$$

III. IEEE 5 Bus System as Test System

From the above derivation, the receiving end reactive power fraction is traced using the downstream algorithm [10] and the inverse distribution matrix is calculated for the IEEE 5 bus test system. The receiving end reactive power fraction which was found by the inverse distribution matrix will actually determine the reactive power share or extraction of each load into the lines. It is important to note that the share of load in a line flow in this method is always positive thus enable the LQP_LT index tracing to be simulated effectively. The IEEE 5 Bus system for base case with modified π equivalent model is shown in Figure 1.

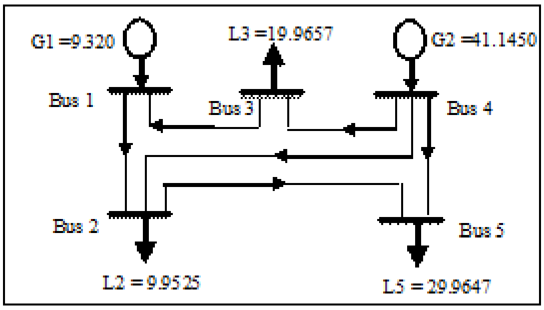

Fig. 1. IEEE 5 bus system with modified π equivalent model.

IV. Under Voltage Load Shedding Optimization Using PSO

Particle swarm optimization is an evolutionary computation method introduced in 1995 [11]. PSO optimizes a problem by having a population of candidate solutions, called as particles, and moving these particles around in the search-space according to simple mathematical formulation over the particle's position and velocity. Each particle's movement is influenced by its local best known position but, is also guided toward the best known positions in the search-space, which are updated as better positions found by other particles. This is expected to move the swarm toward the best solutions.

The implementation of PSO for load shedding is done by the formation of multi- objectives function shown in Eq. 7:

$$f = \min\left(\sum LQP_{LT}, \sum_{i=1}^{n} (Pshed_i + Qshed_i)\right) \qquad (7)$$

The objective function above is programmed as bi- level programming whereby the first problem are constrained to be the optimal solution of the lower- level problem. To obtain a feasible solution for the bi- level optimization function defined, the following constraints were established.

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

$$Q_{Gi}^{0} - Q_{Di}^{0} + \Delta Q_{Di} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\sin(\delta_{ij} + \delta_j - \delta_i) \qquad (9)$$

$$\frac{\Delta P_{Di}}{\Delta P_{Di}^{0}} = \frac{\Delta Q_{Di}}{\Delta Q_{Di}^{0}} \qquad \textit{fixed power factor} \qquad (10)$$

$$V_{i,lower} \le V_i \le V_{i,upper} \qquad (11)$$

Parameters P_{Di} and Q_{Di} terms refer to the real and reactive load demands on bus i. Index "0" refers to parameters at initial stage. The control variables that leads to an optimal solution are ΔP_{Di} and ΔQ_{Di}. The operational constraint which is the system voltage is defined as:

$$0.75 \le V_i \le 1.05. \qquad (12)$$

With the above formulas, the PSO algorithm is programmed to deliver precise, robust and simplified optimization solution.

V. Simulation Results

The proposed methodology of under voltage load shedding is implemented for base case and heavy loading conditions.

A. Base Case Analysis

Power flow simulations were carried out using Matlab for the base case. The tracing of reactive power for base case and the LQP_LT index calculation was performed using a generalized tracing algorithm. The LQP_LT index is computed from the reactive power fraction contribution from the individual load to each transmission lines. The computed index is shown in Table I. Table II show the ranking of the sum of LQP_LT index computed for all the loads. Figure 2 show the index contribution of each to all the lines. It can be seen that load 5 requires more reactive power flow in the line 4 to 5. These are followed by load bus 2 in line 4 to 2 and finally load bus 3 in line 4 to 3. The voltages for base case are found to be stable and stay within the stable regions as defined in the constraints setting with the lowest at bus 5 with 0.9400 p.u.

TABLE I. LQP_LT COMPUTED FOR ALL LINES BY INDIVIDUAL LOAD FRACTION

From Bus	To Bus	Load 2	Load 3	Load 5	LQT_LTsum
		LQP_LT			
1	2	0.022224	0.010309	0.027402	0.059935
3	1	0.023807	0.008613	0.030408	0.062828
4	2	0.037125	0.001214	0.052728	0.091068
2	5	0.011616	0.011616	0.083704	0.106936
4	3	0.002474	0.024572	0.003283	0.030329
4	5	0.019457	0.019457	0.170061	0.208975
Highest		0.037125	0.024572	0.170061	0.560070
Rank		2	3	1	

TABLE II. SUM OF LQP_LT RANKING FROM HIGHEST TO LOWEST

From Bus	From Bus	Ranked LQP_LT sum
4	5	0.20897
2	5	0.10694
4	2	0.09107
3	1	0.06283
1	2	0.05993
4	3	0.03033

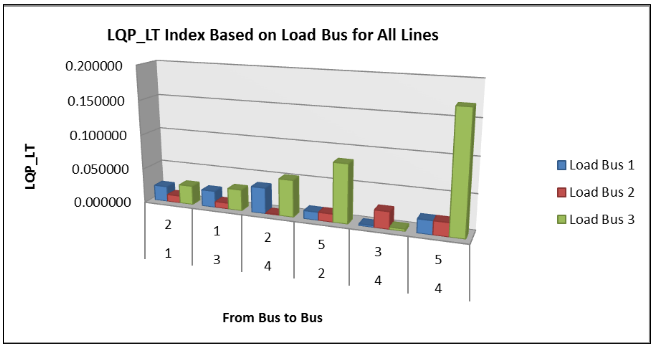

Fig. 2. Distribution of LQP_LT index for all lines based on individual loads for base case

B. Heavy Loadings

With the lowest voltage limit for system recovery set as 0.75, the system load is increased to a load factor of 2.2, with the system remain at constant power factor. The voltage versus bus for the 5 bus system is shown in Figure 3.

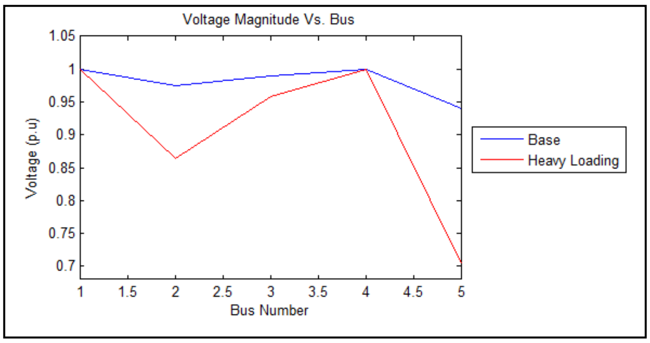

Fig. 3. IEEE 5 bus system with modified π equivalent model.

The individual computed LQP_LT index for all lines due to the loads is tabulated in Table III. Load at bus 5 has turn out to be the foremost contributor for the high congestion level of the system. However, the sum of LQP_LT index for the lines shows that line from bus 3 to 1 has the highest value of the index among all. It can be justified that the total sum index value is insufficient to decide on the priority ranking bus selection for the load shed. Thus, the most suitable bus for load shedding should be done in priority list of load bus 5 followed by load bus 2, and finally load bus 3.

TABLE III. SUM OF LQP_LT RANKING FOR HEAVY LOADING

From Bus	To Bus	Load 2	Load 3	Load 5	LQT_LTsum
		LQP_LT			
1	2	0.250900	0.229900	0.247200	0.728000
3	1	0.500900	0.497300	0.500300	1.498500
4	2	0.173400	0.020400	0.146700	0.340500
2	5	0.291400	0.291400	0.450500	1.033300
4	3	0.001200	0.072700	0.001100	0.075100
4	5	0.123200	0.123200	0.749600	0.996000
Highest		0.500900	0.497300	0.749600	4.671400
Rank		2	3	1	

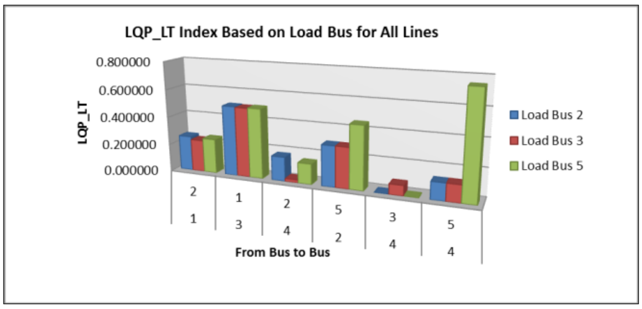

Fig. 4. Distribution of LQP_LT index for all lines based on individual loads for heavy loading case

TABLE IV. SUM OF LQP_LT RANKING FROM HIGHEST TO LOWEST FOR HEAVY LOADING

From Bus	From Bus	Ranked LQP_LT sum
3	1	1.49850
2	5	1.03330
4	5	0.99600
1	2	0.72800
4	2	0.34050
4	3	0.07510

Figure 4 shows the distribution of index computed with respect to the reactive power fraction contribution on all the lines due to load. Table IV shows the ranking results for the total LQP_LT computed.

C. Optimization of the Amount of Load Shed

The optimal load shedding in the selected weak buses aims to enhance the voltage stability at all buses and minimize the deduction of active and reactive load. At the situation of heavy loading, the total system generations was recorded at 495 MW and 174MVAR. The heavy loading with multiplication factor of 2.2 make the total demand of active and reactive power at all buses to be higher than the maximum generation capacity of the system. The total demand is recorded at 540MW and 180MVAR. Load shed at the weak buses was performed to minimize the active and reactive by setting the upper value and lower value of the control variable limits. The upper limit is set to be the highest value of the total demand that makes the system to be at verge of collapse point, which is 540MW and 180MVAR. The lower limit is taken as 5-10% less than the upper limit. The lower limit setting is in line with the standard set by IEEE Standard 18-2002 [12] and is taken at 10% for the study. Table V shows the upper and lower setting limits.

TABLE V. CONTROL VARIABLE LIMITS FOR OPTIMUM LOAD SHED AMOUNT

Load Bus	Pmax_load	Qmax_load	Pmin (Lower Limit)	Qmin (Lower Limit)
2	150	30	135	27
3	180	60	162	54
5	210	90	189	81
Total	540	180	486	162

Figure 5 show the mean populations and the best fitness value obtained at the starting of the optimization stage while Figure 6 shows the mean population and best fitness value achieved as the solution converge to the final global optimum solution. The optimized amount of load to shed at every bus is shown in Table VI. The summation of LQP_LT index has decreased to 3.5915 as indicated in Table VII. This index value is obtained with the lowest system voltage at the weakest load bus 5 recovered to 0.753 p.u. Table VIII shows the stages of voltage improvisation achieved in the optimization process. The best fitness value for active and reactive power convergence is found to be at 1.4899 and 1.0545 respectively.

With the achievement of all the results, it is also observed that the total remaining load after load shed implementation is 493.3625MW and 166.5554MVAR. This amount is just as close as to the maximum generation capacity of the whole system which is 495 MW and 174MVAR.

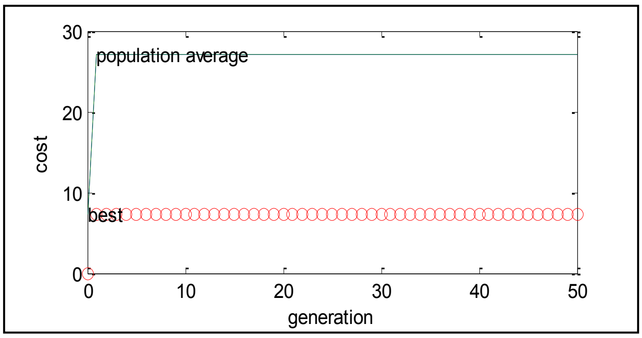

Fig. 5. Mean population and fitness value versus iteration at initial optimization

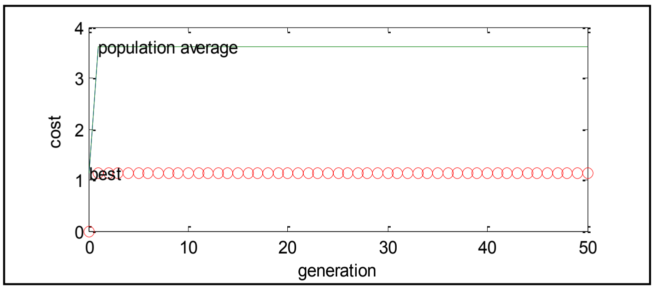

Fig. 6. Mean population and fitness value versus iteration at final optimization

TABLE VI. THE VALUE OF REMAINING LOAD AFTER OPTIMIZATION

Load Bus	Pmax_load	Qmax_load	Pmin	Qmin	Popt 10	Qopt 10
2	150	30	135	27	137.25727	28.0573
3	180	60	162	54	165.06401	55.169
5	210	90	189	81	191.04124	83.3291
Total	540	180	486	162	1.4899	1.0545

TABLE VII. MINIMIZATION OF TOTAL LQP_LT

Optimization Stages		Stage 1	Stage 2	Final Stage
FROM BUS	*TO BUS*	*LQP_LT*	*LQP_LT*	*LQP_LT*
1	2	0.6819	0.6467	0.5503
3	1	1.3621	1.2866	1.0813
4	2	0.3322	0.3235	0.3132
2	5	0.9653	0.8897	0.7519
4	3	0.0738	0.0723	0.0692
4	5	0.9634	0.9157	0.8256
Total		**4.3787**	**4.1345**	**3.5915**

TABLE VIII. MINIMIZATION OF VOLTAGE VALUES AT ALL BUSES

Optimization Stages	**Initial**	**1**	**2**	**9**	**10**
Bus No. and Voltage	***Voltage (p.u)***	***Voltage (p.u)***	***Voltage (p.u)***	***Voltage (p.u)***	***Voltage (p.u)***
1	1.00000	1.00000	1.00000	1.00000	1.00000
2	0.86400	0.87	0.877	0.889	0.89
3	0.95900	0.961	0.962	0.964	0.965
4	1.00000	1.00000	1.00000	1.00000	1.00000
5	0.70400	0.715	0.731	0.746	**0.753**

VI. CONCLUSIONS

To summarize, a new approach of multi-level optimization for under voltage load shedding has been recommended. The method implements line stability factor, LQP_LT which has the ability to trace the stressed lines contributed by individual load in a system. Enabling the priority ranking list based on the traced LQP_LT, system operator can perform an accurate selection of critical load bus prior to performing any corrective action against voltage instability condition. Based on the results obtained, it can be validated that LQP_LT is efficient and reliable to identify the weak points in any contingency conditions. The optimization results obtained on the amount of load to shed via PSO algorithm has provided the best global minimum solution to recover the system from stressed conditions and improve the overall system voltage stability. The PSO algorithm is found to be effective and robust in providing the optimum solution. Finally, this study has established the capability and implementation of power tracing techniques to be applied for under voltage load shedding scheme.

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