Assessment of Maximum Loadability Point for Static Voltage Stability Studies Using Evolutionary Programming

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Abstract: - This paper presents a critical evaluation of maximum loadability point identification in a power system network. The study involved maximum loadability identification on individual load bus and simultaneous increase at several load buses. This is to identify the strength of the system when single load increase was performed to the system as compared to multi-load increase. To obtain the optimum load values prior to voltage instability occurrence; Evolutionary Programming (EP) technique is introduced as the optimization technique. Results obtained from the studies revealed that the implementation of EP in identifying the optimal point of single maximum loadability and also for the several load increase are very accurate indicated by *FVSI* close to 0.95 as the reference ceiling value. It was also discovered that, the maximum loadability point of a single load is higher as compared to load simultaneous load increase at several load buses. This due to the fact that, the system can sustain higher load if only one load is subjected to loading variation, while considering other load buses maintained at the base case condition. The proposed EP technique was validated on the IEEE Reliability Test System and promising results were produced. Comparative studies performed with respect to artificial immune system (AIS) and automatic voltage stability analysis (AVSA) had revealed that EP outperformed both techniques in terms of accuracy and computation times.

Key-Words: - Voltage Stability, Maximum Loadability, Evolutionary Programming, Artificial Immune System.

1 Introduction

The fast growth in power system grid could result in the increase of power system plant to cope with the high demand. This has caused the power system to be more complex in the future. Power systems are becoming heavily stressed due to the difficulty in constructing new transmission systems as well as the complexity of building new generating plants near the load centres. Most of the load demand is in form of reactive power effect such as heavy machines confining windings, transformers and other elements rather than the real power effect.

There have been a number of incidents in the past few years which were diagnosed as voltage instability problem due to the increase in loading and decrement of stability margin. The stability margin can be defined as the distance between the base loading of the system and the maximum loading limit of the system. The contingencies occur in the system would lead to the decrease in stability margin and the system approaches a very critical stage, which may lead the system to a total collapse. Various techniques were reported in the literature to identify and estimate the maximum loadability [1-5] to indicate its importance in power system studies.

One of the conventional techniques is the repetitive power flow in which load was increased in steps until load flow diverges [6,7]. At this point, it was assumed that the system is at its maximum loading point prior to the system collapse. The inaccuracy in determining the maximum loadability point through the conventional technique has been identified as the setback of the technique.

This technique estimates the maximum loadability through the implementation of automatic voltage stability assessment in estimating the maximum. Previous work on determining maximum loadability was proposed by I. Musirin *et al.* [8] using an index termed as Fast Voltage Stability Index (*FVSI*). This index is based on the evaluation of transmission line indices interconnected among buses in the system. Determination of point of collapse (POC) in the load flow studies can also be conducted using automatic voltage stability assessment (AVSA) as reported in [9]. However, this technique has the demerit in terms of inaccuracy of the collapse point. The implementation of optimization process could help identifying the accurate point of collapse.

One of the popular techniques and fast search techniques is by using the Artificial Intelligence (AI) optimization techniques. Musirin *et al.* [8] developed a new algorithm to execute the Evolutionary Programming (EP) based optimization technique for estimating maximum loadability or critical loading condition in power system for one load bus. Other optimization techniques which can also perform similar task are linear programming, Genetic Algorithm, quadratic programming, ant colony optimization (ACO) [10] and artificial immune system (AIS) [11].

This paper presents the application of EP technique for searching single and multi-load optimal points critical loading condition utilizing a pre-developed voltage stability index as the measuring instrument. In this study, optimization engines for identifying single point maximum loadability and load increase at several buses were developed separately. This technique can assist the power system operators to plan and study the system capability in terms of incremental of loads in simultaneously. Comparative studies were performed with respect to Artificial Immune System (AIS), AVSA. Results had indicated the merit of the proposed technique.

2 Voltage Stability Assessment

Voltage stability is defined as the ability of a system to maintain its equilibrium condition when it is subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage [4]. The main factor which has profoundly caused instability condition is the constraint in reactive power support. Voltage stability problems normally occur in heavily stressed systems. While the disturbance leading to voltage collapse may be initiated by various causes, the underlying problem is an inherent weakness in the power system.

To ensure boundary of system in reliability and security; the incremental loads have to be monitored closely. The loads can be increased individually and also simultaneously for several chosen loads. Maximum loadability is one aspect which determines the load limit of a system prior to system instability. The determination of maximum loadability of one load or several chosen loads can be assessed by voltage stability analysis. This will require optimization technique to search the optimal point which may require an indicator. In this study a line-based voltage stability index termed as Fast Voltage Stability Index (*FVSI*) is utilized as the indicator. The mathematical formulation for *FVSI* is given as shown below.

$$FVSI_{ij} = \frac{4Z_{ij}^2 Q_j}{V_i^2 X_{ij}} \qquad (1)$$

where Z_{ij} = line impedance

X_{ij} = line reactance

V_{ij} = voltage at the sending end

Q_j = reactive power at the receiving end

FVSI was developed by Musirin *et. al.* [8], which could determine the voltage stability condition of all lines in a power system. This index has a range between 0 at no load and 1.0 at instability condition. To indicate voltage instability of the whole system, the maximum *FVSI* value for the system is indicative enough to imply the situation.

3 Algorithm for Maximum Loading Identification

Identification of load flow analysis is used for searching the maximum loadability point of a particular load bus and also to compute the values of *FVSI*. The following procedures were implemented to identify the maximum loadability point in power system:

i. Choose load bus for the test.
ii. Run voltage stability analysis.
iii. Evaluate the *FVSI* values for all lines in the system using the load flow solution.
iv. Monitor the highest *FVSI* value for the system.
v. If maximum *FVSI* is less than 0.95; increase the load at the selected bus and go to step (ii), otherwise go to (iv).
vi. Record the loading conditions of the chosen load bus.
vii. For other load buses, repeat steps (i) to (vi). These are the maximum permissible load at the

buses increased concurrently prior to system instability.

The steps described above are the conventional techniques which are computationally burdensome since heuristic technique is involved. In order to reduce the computation burden and to achieve more accurate results, optimization technique could be an effective technique. In this study Evolutionary Programming (EP) is proposed to alleviate the setback of the existing technique.

4 Evolutionary Programming

Evolutionary Programming (EP) is a stochastic optimization technique based on the natural generation. It was invented by D. Fogel in 1962 and further extended for the optimization process by Burgin [12]. The process involves random number generation at the initialization, followed by statistical evaluation, fitness calculation, mutation and finally the new generation created as a result of the selection [13,14]. The generated random numbers represent the parameters which will responsible for the optimization of the fitness.

4.1 Evolutionary Programming Algorithm

The optimization process implemented using EP can be represented in the following steps:-

i. Initialization (Generate random numbers).
ii. First fitness calculation.
iii. Mutation.
iv. Second fitness calculation.
v. Combination.
vi. Selection/tournament.
vii. Next generation definition.
viii. If solution converges, stop; otherwise go to step (ii).

4.2 Random Number Generation

In EP, initialization process was conducted by generating a series of random number using a uniform distribution number generator. The random numbers represent the reactive power loading at the chosen load buses for estimating the maximum loadability. The number of variables depends on the number of buses chosen for the simultaneous load increase. Since the objective of adopting EP is to estimate the maximum loadability using accelerated search technique, therefore the parameters would be only the reactive power on the chosen loads. Some constraints must be set at the beginning so that the EP will only generate random numbers that satisfy some pre-determined constraint. For the purpose of maximum loadability estimation, only one constraint was identified i.e., the calculated *FVSI* must be less than 0.95 and it is termed as *FVSI*_set.

4.3 Fitness Calculation and Statistical Evaluation

In this study *FVSI* is taken as the fitness equation, which needs to be maximized and it was calculated by conducting the ac load flow program. It was done by calling the load flow program into the EP main program. Thus in this problem, the objective function was not going to be a single mathematical equation but rather a subroutine which is executed accordingly in the EP main program.

4.4 Mutation

Mutation was performed on the generated random numbers, x_i to produce the offsprings. The mutation process was implemented based on the following equation:

$$x_{i+m,j} = x_{i,j} + N(0,\gamma^2) \tag{2}$$

$$\gamma^2 = \beta(x_{j\max} - x_{j\min})(\frac{f_i}{f_{\max}}) \tag{3}$$

where:

$x_{i+m,j}$ =mutated parents (offspring)

x_{ij} = parents

N= Gaussian random variable with mean μ and variance γ^2

β = mutation scale, $0 < \beta < 1$

$x_{j\max}$ = maximum random number for every variable

$x_{j\min}$ = minimum random number for every variable

f_i = fitness for the i^{th} random number

$f_{\max}$ = maximum fitness

The mutation scale, β could be manually adjusted in order to achieve better convergence [14, 15].

4.5 Selection

The offsprings produced from the mutation process were combined with the parents to undergo a selection process in order to identify the candidates to be transcribed into next generation. In this study, elitism technique was performed to select the candidates to be transcribed for the next generation.

5 Results and Discussion

In this study, maximum loadability estimation was conducted considering single load and multi-load bus increment. In realizing the effectiveness of the proposed technique, a reliability test system namely the IEEE 30-bus system was used as the test specimen.

5.1 Optimization of Maximum Loadability

Maximum loadability of load buses is identified by increasing the reactive power loading at particular load with the *FVSI* value set as 0.95. *FVSI* value at 0.95 is chosen as the maximum limit to imply the cut off point prior to voltage collapse occurrence. This is due to the fact that any lines connected to the system will collapse when *FVSI* is reaching 1.0. This limit is specified in order to search the Q_{max} before system loses its stability.

5.2 Maximum Loadability at Single Load

One load bus was chosen at a time randomly for this analysis. In this case, four load buses namely buses 4, 14, 16 and 24 were chosen for the test. However, only results for buses 4 and 14 are given in this paper. EP was implemented to search the maximum loadability, Q_{max} for all these load buses one at a time. Prior to this implementations automatic voltage stability analysis was conducted to monitor the voltage and *FVSI* profile with respect to the variation in reactive power loading. In this study, it is obvious that only reactive power loading was varied instead of the active/real power. This is due to the fact that, active power is not significant in affecting the voltage stability. This statement can also be referred to several previous works in [7, 9, 16-17].

Fig. 1 illustrates the effect of reactive power loading variation to voltage and *FVSI* profiles. From the figure, it is observed that the voltage increases accordingly as reactive power loading at bus 4 increase. The minimum voltage; i.e 0.80097 p.u is resulted when the load is subjected to 380 Mvar prior to the divergence of load flow. Therefore this value is identified as the maximum loadability for bus 4 with its corresponding *FVSI* of 0.92694. It is also observed that the *FVSI* value increases accordingly as Q increases. At the minimum voltage level, the computed *FVSI* value is closed to 0.95. This is the maximum *FVSI* value before

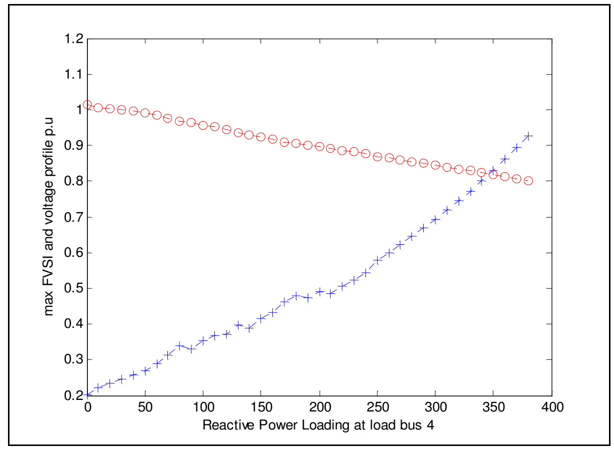

Fig. 1: Max *FVSI* and Voltage profile in p.u versus reactive power varies at bus 4

system started to lose its stability.

5.3 Simultaneous Load Increase

In this study, simultaneous load increase at several load buses was also conducted. Voltage and *FVSI* profiles were also monitored during this process. The results for the voltage profile at buses 4, 14 and 24, when reactive powers at these buses were increased are depicted in Fig. 2. The maximum *FVSI* value stopped at 0.92779 p.u with the respective Q_{max} of each bus equals to 70 Mvar. From the figure, it is also observed that the Q value for each bus is 70 Mvar. This implies that simultaneous load increase has caused a low reactive power loading at the corresponding buses.

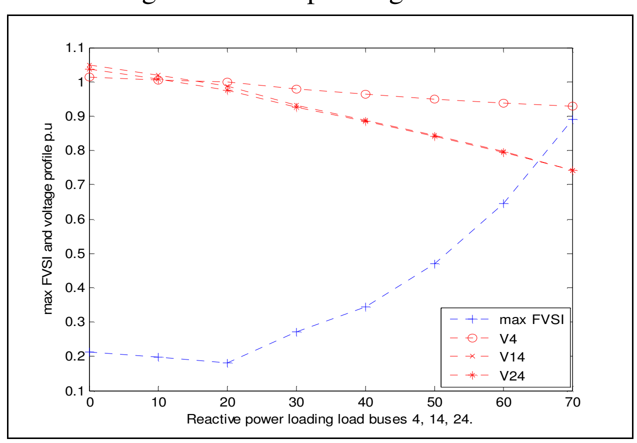

Fig. 2: Max *FVSI* and Voltage profile in p.u versus reactive power varies at bus 4, 14 and 24

5.4 EP Implementation for Maximum Loadability Identification

Table 1 tabulates the maximum loadability values for single load increase at buses 4, 14, 16 and 24. From the table, it is observed that the maximum loadability value for bus 4 identified using EP is 386.5 Mvar with *FVSI* value of 0.94945, which has been achieved in 76.781 seconds. On the other hand, the maximum loadability value for bus 14 identified using EP is 76.341 Mvar with *FVSI* value of 0.94178, which has been achieved in 99.281 seconds. From the results it is shown that EP managed to search the closest point to 0.95.

Table 1: Maximum Loadability using EP

Bus no	Q_{max} (Mvar)	*FVSI*	Computation time (sec)
4	386.5	0.94945	76.781
14	76.341	0.94178	99.281

Table 2: Several Load Increase Using EP

Combination	Bus no	Q_{values}	*FVSI*	Computation time (sec)
1	4	79.767	0.9424	49.531
	14	71.656		
	24	68.47		
2	4	77.032	0.94948	175.859
	16	63.92		
	24	95.308		

On the other hand Table 2 tabulates the results for simultaneous load increase at several chosen load buses. From the table, it is observed that the Q_{max} for buses 4, 14 and 24 increased simultaneously is 79.767 Mvar, 71.656 Mvar and 68.47 Mvar respectively.

The corresponding *FVSI* value is 0.9424. This is achieved within 49.531 seconds in the second combination; reactive power loading at buses 4, 16 and 24 were increased simultaneously. The result is 77.032 Mvar, 63.92 Mvar, 95.308 Mvar for buses 4,16 and 24 respectively with *FVSI* value of 0.94948. This is achieved within 175.859 seconds.

Table 3 tabulates the comparative studies for maximum loadability identified using EP, AVSA and AIS. From the table it is observed that for bus 4; EP managed to search Q_{max} up to 386.5 Mvar, while AIS result is 385.51 Mvar and AVSA result is 380 Mvar. This implies that EP outperformed AIS and AVSA in terms of accuracy. Results for other load buses can be obtained from the same table.

Table 4 tabulates the comparative studies for simultaneous load increase at several load buses using EP, AIS and AVSA. From the table it is observed that when reactive load at buses 4, 14 and 24 was increased simultaneously, EP technique managed to search up to 79.07 Mvar, 71.656 Mvar and 68.47 Mvar respectively with *FVSI* value of 0.9424. On the other hand, AIS only managed to search for 59.779 Mvar, 73.009 Mvar and 36.318 Mvar with corresponding *FVSI* value of 0.93595. AVSA technique gives Q_{max} value of 70 Mvar at all the buses with its corresponding *FVSI* value of 0.89013. This shows the high accuracy achieved using EP over AIS and AVSA. Similar phenomenon can be observed from the same table for other load combinations.

6 Conclusion

Maximum loadability identification for single and multi load using Evolutionary Programming (EP) has been presented. In this study EP, was used as the optimization technique to optimize the exact reactive

Table 3: Results for Comparative Studies for Single Load Q_{max} (Mvar)

Bus no	EP			AVSA			AIS		
	Qmax (Mvar)	*FVSI*	Comp Time (sec)	Qmax (Mvar)	*FVSI*	Comp Time (sec)	Qmax (Mvar)	*FVSI*	Comp Time (sec)
4	386.5	0.94945	76.781	380	0.92694	5.234	385.51	0.94596	142.25
14	76.341	0.94178	99.281	70	0.80306	0.766	76.127	0.9369	283.562

Table 4: Results for Comparative Studies for Multiple Load

Combination	Bus no	EP			AVSA			AIS		
		Reactive power loading	*FVSI*	Comp time (seconds)	Reactive power loading	*FVSI*	Comp time (seconds)	Reactive power loading	*FVSI*	Comp time (seconds)
1st combination	4	79.767	0.9424	49.531	70	0.89013	0.875	59.779	0.93595	161.078
	14	71.656						73.009		
	24	68.47						36.318		
2nd combination	4	77.032	0.94948	175.859	80	0.73502	0.938	88.237	0.93076	330.625
	16	63.92						94.888		
	24	95.308						85.358		

power loading values increased in several loads chosen randomly one at a time and several load simultaneously. In this study, EP technique was developed considering the optimized maximum loadability in particular loads as the objective function. Results obtained from the study utilizing EP were compared with the results using AIS and AVSA. It was also found that EP outperformed AIS and AVSA in terms of accuracy on the maximum optimum loadability values and computation time. It can be concluded that EP technique is a better optimization technique as compared to AIS in searching the optimum value of reactive power loading at a single or multi-load. The developed EP engine could be beneficial for solving other optimization problems.

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