Optimal Reactive Power Dispatch for Voltage Instability Alleviation Using Evolutionary Programming Technique

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Abstract: - In the current power system planning and operation, a lot of concern has been shown in the security of the system and stability analysis. The load sharing or generation scheduling patterns have resulted in heavy flows which lead to greater losses; intimidate stability, security and eventually making certain generation patterns undesirable. With increased loading of existing power transmission systems, the voltage instability problem and voltage collapse have also become a major anxiety in power system planning and operation. Although voltage stability is more dependent on the reactive power sources or voltage profile in the system, it is also a function of real power flows. Voltage instability can be alleviated by performing reactive power dispatch in power transmission system. Reactive power dispatch problem embraced the voltage instability alleviation and minimisation of real power transmission losses while satisfying the equality and inequality constraints. This paper presents the optimal reactive power dispatch as a reactive power planning approach for alleviating voltage instability problem based on Evolutionary Programming (EP) optimisation technique. A line-based voltage stability index was chosen as the basis of the optimisation process, while voltage instability alleviation was chosen as the objective function. Extensive testing of EP was conducted and results are included to demonstrate the effectiveness of the proposed technique. From the study, it was revealed that the proposed EP optimisation technique has successfully alleviated the voltage instability condition and reduced the total loss, while improving the voltage in the system within minimal iteration number.

Key-Words: - Reactive power dispatch, Voltage instability alleviation, Evolutionary Programming, Objective function.

1 Introduction

Current scenario has witnessed a lot of voltage collapse incidents in many parts of the world. These were mainly caused by the stressed condition of power system network as well as unpredictable events such as contingencies caused by line or generator outages. This has also caused the power system network operates closed to its voltage stability limit. Lack in reactive power support has also contributed to the voltage instability problem. Hence, some measures should be taken in order to support for the reactive power loading along with enhancing the voltage stability condition of the system. Voltage stability study is a crucial aspect in the power system operation and planning. Reactive Power Planning embraced the reactive power dispatch, transformer tap changer setting and compensating capacitor placement. Reactive power dispatch dealt with the voltage instability alleviation through the reactive power to be injected to the generator buses, while the transformer tap changer setting altered the transmission system properties that could improve voltage stability in the system. On the other hand, the compensating capacitor placement technique is meant to improve the voltage profile at the local bus particularly in the radial distribution network. The use of FACTS devices technology has been known to extend the voltage stability margin as discussed by Messina *et al.* in [1]. This technique dealt with small-signal voltage stability, singular value decomposition (SVD) and modification of power system representation in order to come up with the remedial measures for voltage instability alleviation scheme. Among the dominant techniques in voltage stability enhancement are the static VAR compensator [2] and optimal reactive power dispatch [3-10]. In the radial distribution system, reactive power compensation was normally employed by placing shunt capacitor on the load bus to enhance the voltage at the local bus [11-13]. The implementation of voltage stability improvement involved the optimisation process to search for the optimal solution. This objective can be conducted using various optimisation techniques such as the simulated annealing (SA), Genetic Algorithm (GA) and Tabu Search (TS) as reported by Liu *et al.* [14]. The use of a stochastic optimisation technique in Evolutionary Programming (EP) is a remarkable technique to perform the similar task as reported by Lai *et al.* [15].

This paper presents the application of EP based optimisation technique to search for the most suitable amount of reactive power to be dispatched by the generators for alleviating the voltage instability condition in a power system. EP was known to be operating based on the natural generation involving initialisation, fitness calculation, statistical evaluation, mutation and selection. A line-based indicator called the *FVSI* [16] was utilised as the fitness function for the optimisation process. The technique was tested on the IEEE 30-bus Reliability Test System and the results indicated that EP optimisation technique with the proposed fitness function has able to alleviate the voltage instability problem while maintaining the voltage at an acceptable limit. Consequently, active power loss has also been reduced using this technique. The optimised reactive power obtained from the study could be utilised by the power system operators for the voltage instability alleviation scheme. The results also showed that the proposed technique can be implemented within minimal iteration number. The developed EP optimisation technique can be further utilised for other optimisation problems by modifying the objective function of the algorithm.

2 Problem Formulation

In optimal reactive power dispatch (RPD) scheme, the objective is to identify the optimal reactive power to be dispatched by the generators in the power system network to alleviate voltage instability condition. For alleviating the voltage instability problem in electric power system, an amount of reactive power is required to be injected by the generators in such a way that the reactively stressed condition can be compensated. Voltage instability alleviation has been identified as the objective for the optimisation process with a line-based voltage stability index termed as *FVSI* [16] being the fitness of the objective function. With this objective function total losses in the system are expected to reduce once the RPD has been performed. The results obtained from the optimisation process would be the amount of reactive powers required to be dispatched by the generators in the power system network in order to mitigate the voltage instability condition in the system.

2.1 Fitness Function

The fitness is the line-based voltage stability index derived in [16] termed as Fast Voltage Stability Index (*FVSI*). The mathematical equation for *FVSI* was formulated from a transmission line model. In general, the *FVSI* formulation connecting bus ‘i’ to bus ‘j’ can be given by:-

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^{\,2}X} \tag{1}$$

where:

Z = line impedance
X = line reactance
Q_j = reactive power at the receiving end
V_i = sending end voltage

FVSI values are ranging from 0.0000 to 1.0000. *FVSI* values for each line in the system will be computed to indicate the voltage stability condition of the respective line in the system. Based on the *FVSI* values computed in the system, voltage collapse can be accurately predicted by looking at the lines evaluated closed to 1.00. *FVSI* value has to be remained less than unity in order to maintain a stable system. The fitness was calculated by performing ac load flow programme in which the load flow programme was called repetitively into the EP main programme in order to compute the *FVSI* values and perform the optimisation process.

3 Algorithm for Evolutionary Programming Technique

Evolutionary Programming (EP) involves random number generation, statistical evaluation, fitness calculation, mutation, and finally the new generation resulted from the selection [15]. Initially, a series of random numbers have to be generated as the control variables. These random numbers will be assigned as the reactive power required to be dispatched by the generators for alleviating the voltage instability condition. Prior to the generation of random number, constraints must be defined so as to allow only the suitable candidates are generated. This will determine whether any constraint violations are experienced or not. Conventionally, twenty initial populations are required in order to search for the optimal solution. These populations are termed as parents. The populations those have satisfied all the predetermined constraints are stored in population pool prior to the starting of the optimisation process. Fitness values are then computed using these parents. The parents are mutated in order to produce offsprings. Using these offsprings, new fitness values are computed. The parents and offsprings are combined together making the total populations at this time is forty.

Selection is carried out in order to select twenty populations to be transcribed for the next generation. The process is repeated until the stopping criterion is satisfied. The overall EP processes are written in stages as follows:-

i. Set the RPD constraints, i.e. $FVSI \leq FVSI\_set$ and V_m(bus) $\geq V\_set$.
ii. Generate random number x_1, x_2, x_3, x_4 and x_5.
iii. Check for constraints violations. If constraints violated, go to step ii, otherwise go to step iv.
iv. Fill in population in pool.
v. If pool is not full, go to step ii, otherwise go to step vi.
vi. Determine x_min and x_max.
vii. Assign x_1, x_2, x_3, x_4 and x_5 to Q_{g2}, Q_{g5}, Q_{g8}, Q_{g11} and Q_{g13} in the system data.
viii. Calculate fitness by running load flow programme to evaluate *FVSI* values.
ix. Determine *FVSI_min*, *FVSI_max*, *FVSI_avg* and *FVSI_sum* (for statistical evaluation).
x. Mutate the parents i.e. x_1, x_2, x_3, x_4 and x_5 (generate offsprings).
xi. Recalculate fitness using the offsprings (Run load flow to re-evaluate *FVSI*).
xii. Combine parents and offsprings.
xiii. Perform selection by ranking process.
xiv. Transcribe new generations.
xv. If solution is not converged, repeat steps vi to xiv, otherwise go to step xvi.
xvi. Stop.

3.1 Random Number Generation

Initialisation process in EP is required to generate the first populations termed as the parents. These populations were generated using the uniform distribution number. In this study, the random numbers will be assigned as the reactive power required to be dispatched by the generators in the system either to alleviate the voltage instability condition or to minimise the total loss in the system. The number of variables depends on the number of generator buses in a system excluding the slack bus. For the case of IEEE 30-bus system as the test specimen in this study; five variables namely x_1, x_2, x_3, x_4 and x_5 are assigned to represent the reactive power generated by the generators at buses 2, 5, 8, 11 and 13.

Technically, these variables will be assigned as the reactive load (Q_d) with negative sign. The negative sign implies the reactive power generator (or loaded negatively) for particular generator buses. The generator bus code should also be changed to load bus. Constraints must be set at the beginning so that the EP will only generate random numbers that satisfy some predetermined conditions. For alleviating voltage instability condition; the *FVSI* values computed in the objective function must be less than *FVSI_set*, while the bus voltage limit must be greater than *V_set* to ensure voltage profile is increased. *FVSI_set* and *V_set* are the *FVSI* and voltage values prior to the implementation of optimal RPD.

3.2 Mutation

Mutation is a process performed on the random number, x_i to produce offsprings. The mutation process is implemented based on the following equation:

$$x_{i+m,j} = x_{i,j} + N(0, \beta(x_{j\max} - x_{j\min})(\frac{f_i}{f_{\max}})) \qquad (2)$$

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_{jmax} = maximum random number for every variable
- x_{jmin} = minimum random number for every variable
- f_i = fitness for the i^{th} random number
- f_{max} = maximum fitness

The mutation scale, β determines the convergence speed during the optimisation. Large value of β causes slow convergence of the EP caused by large search step and vice versa.

3.3 Selection

The offsprings produced from the mutation process are combined with the parents to undergo a selection process in order to identify the candidates that have the chance to be transcribed into the next generation. This can be done using pair-wise comparison or priority ranking techniques. In this study, priority ranking technique was discovered as the most suitable selection technique considering the fast convergence process and accurate results. Since the objective of this study is to alleviate the voltage instability condition, therefore the population will be ranked in ascending order based on the minimum *FVSI* value. The first half population are taken as the new generation as proposed by Lai *et al.* in reference [15].

3.4 Stopping Criteria

The stopping criteria to achieve the optimal solution can be set based on the problem formulation. Since in this study, *FVSI* is ranging from 0.0000 to 1.0000, therefore the suitable stopping criteria is given in (3).

$$\max_{fitnesss} - \min_{fitness} \leq 0.0001 \tag{3}$$

If it is not reached, the process will repeat. For other optimisation problems that deal with higher fitness value, the stopping criteria can be set higher.

4 Results and Discussion

Reactive power dispatch (RPD) was implemented as the reactive power planning technique in order to alleviate the voltage instability condition in the system. The test was conducted on the IEEE 30-bus Reliability Test System with various loading conditions. The loading conditions were obtained by varying the reactive power loading of several load buses. But, only the results for reactive power loading variations at buses 14 and 26 are given in this paper to demonstrate the effectiveness of the technique. The reactive power loading at these buses were chosen one at a time. The RPD was performed with variation in loading conditions at these load buses so that the voltage profiles, *FVSI* trends and total loss variations can be monitored.

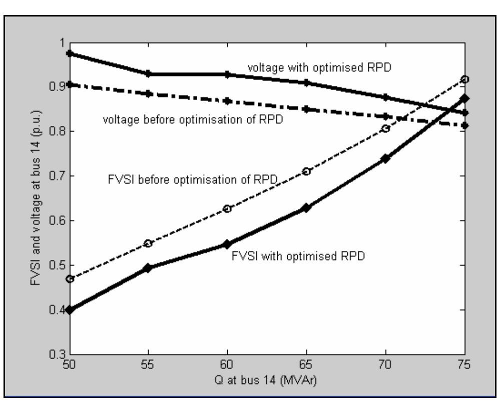
4.1 Optimal RPD with Bus 14 Loaded

The load at bus 14 was gradually increased up to a point closed to the voltage stability limit. This is to obtain the maximum point for stability beyond which voltage instability will be experienced. The results for RPD performed on the system when bus 14 was reactively loaded are tabulated in Table 1. All the *FVSI* values after the implementation of RPD are smaller before its implementation, which implies that the voltage instability condition has been alleviated or voltage stability condition has been improved. Voltage profile of the system is also improved and total losses are minimised as a result of the implementation of RPD.

It can be seen that at Q_{d14} = 75 MVAr, the implementation of RPD has alleviated the voltage instability condition of the system indicated by the reduction in *FVSI* value from 0.9164 to 0.8745. This has also reduced the total loss from 27.90 MW to 13.11 MW. Subsequently, the voltage is improved from 0.8132 p.u. to 0.8409 p.u.. This is achieved within 882.49 seconds in 5 evolutions. The values for Q_{g2}, Q_{g5}, Q_{g8}, Q_{g11} and Q_{g13} identified by the EP as shown in the table are the optimised reactive power to be dispatched by the generators in order to alleviate the voltage instability condition of the system. The trends for *FVSI*, total losses and voltage with respect to reactive load variation at bus 14 are illustrated in Figure 1. From Figure 1(a), the implementation of RPD has able to improve the voltage profile for every increment in the reactive power loading at bus 14. Similarly, the *FVSI* values are reduced accordingly with the implementation of RPD in the system indicating voltage instability mitigation. It is also observed that, the implementation of RPD has reduced the total losses in the system as shown in Figure 1(b).

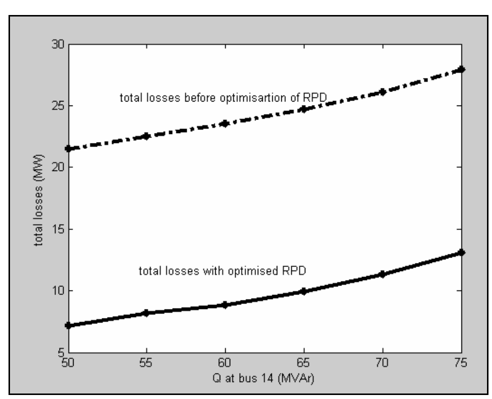
Table 1
Results for RPD when bus 14 was reactively loaded

Loading Condition (MVAr)	Analysis	*FVSI*	Total loss (MW)	Evo no	Comp time (sec)	Q_{g2} MVAr	Q_{g5} MVAr	Q_{g8} MVAr	Q_{g11} MVAr	Q_{g13} MVAr	V_m (p.u.)
Q_{d14} = 70	pre-RPD	0.8060	26.08			51.27	31.58	60.39	24.86	41.90	0.8336
	post-RPD	0.7386	11.31	5	208.69	44.99	33.56	57.56	23.38	22.12	0.8764
Q_{d14} = 75	pre-RPD	0.9164	27.90			21.47	38.53	69.64	23.1	47.90	0.8132
	post-RPD	0.8745	13.11	5	882.49	38.80	36.89	58.97	23.50	21.98	0.8409



FVSI and voltage profiles as Q at bus 14 was increased: before and after optimal RPD

Figure 1 (a)



Losses variations when bus 14 was loaded: before and after the optimal RPD

Figure 1 (b)

4.2 Optimal RPD with Bus 26 Loaded

To realise the effectiveness of the proposed technique, similar test was performed to the system when bus 26 was subjected to reactive load variation. The load at bus 26 was gradually increased up to a point closed to the voltage stability limit. The results for RPD performed on the system when bus 26 was reactively loaded are tabulated in Table 2. From the table, similar observation is discovered as that for bus 14. All the *FVSI* values after the implementation of RPD are smaller before its implementation, which implies that the voltage instability condition has been alleviated. Voltage profile of the system is also improved and total losses are minimised as a result of the implementation of RPD. It can be seen that at Q_{d26} = 32 MVAr, the implementation of RPD has alleviated the voltage instability condition indicated by the reduction in *FVSI* value from 0.9799 to 0.8047. At the same time, the total loss is reduced from 28.94 MW to 11.26 MW. The voltage is increased from 0.6358 p.u. to 0.7594 p.u.. This is achieved within 67.25 seconds in 6 evolutions. The values for Q_{g2}, Q_{g5}, Q_{g8}, Q_{g11} and Q_{g13} identified by the EP as shown in the table are the optimised reactive power to be generated by the generators in order to alleviate the voltage instability condition of the system.

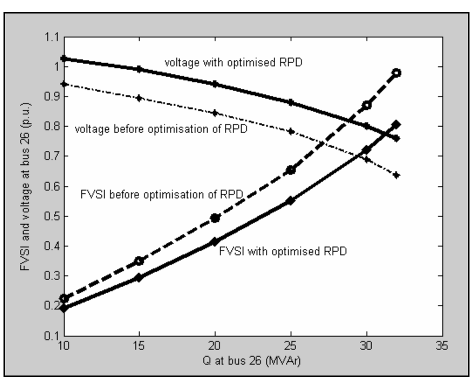
The trends for *FVSI*, total losses and voltage with respect to reactive load variation at bus 26 are illustrated in Figure 2. From Figure 2(a), the implementation of RPD has able to improve the voltage profile for every increment in the reactive power loading at bus 26. Similarly, the *FVSI* values are reduced accordingly with the implementation of RPD in the system indicating voltage instability alleviation. It is also observed that, the implementation of RPD has minimised the total losses as shown in Figure 2(b).

5 Conclusion

Optimal reactive power dispatch for voltage instability alleviation based on Evolutionary Programming (EP) technique was presented. EP was employed as the optimisation approach in determining the optimum values for the control variables in the optimal RPD. Results showed that the optimal RPD using the EP has alleviated the voltage instability and improved the voltage profile while at the same time minimising the total transmission loss in the system. The results obtained from the optimal RPD indicate the reactive power to be dispatched by the generators in order to alleviate the voltage

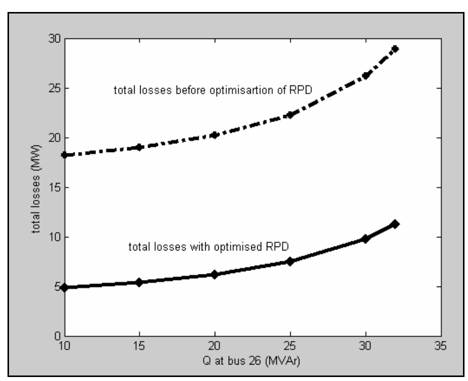
Table 2
Results for RPD when bus 26 was reactively loaded

Loading Condition (MVAr)	Analysis	*FVSI*	Total loss (MW)	Evo no	Comp Time (sec)	Q_{g2} MVAr	Q_{g5} MVAr	Q_{g8} MVAr	Q_{g11} MVAr	Q_{g13} MVAr	V_m (p.u.)
Q_{d26} = 30	pre-RPD	0.8698	26.20			36.68	39.04	50.14	21.69	22.29	0.6878
	post-RPD	0.7209	9.82	5	43.39	33.04	17.22	42.36	21.93	18.52	0.8003
Q_{d26} = 32	pre-RPD	0.9799	28.94			38.34	39.61	54.05	22.76	23.69	0.6358
	post-RPD	0.8047	11.26	6	67.25	33.04	17.22	42.36	21.93	18.52	0.7594



FVSI and voltage profiles as Q at bus 26 was increased: before and after optimal RPD

Figure 2(a)



Total losses when bus 26 loaded: before and after optimal RPD

Figure 2(b)

instability condition in the test system. Consequently, the developed EP optimisation technique can be further explored for solving other optimisation problems.

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