Evolutionary Optimization Technique for Optimal Placement of a Shunt FACTS Controller in a Java-Bali 24-bus Indonesian System

T.Naveen Kumar, Dr.P.Santosh Kumar Patra

Assistant Professor in EEE Department, St. Martin's Engineering College (Autonomous), Secunderabad-500100, INDIA

Principal and Professor in CSE Department, St. Martin's Engineering College (Autonomous), Secunderabad-500100, INDIA

***Abstract*—One type of Evolutionary Optimization Technique namely Particle Swarm Optimization (PSO) have been proposed in this paper to obtain the optimal placement a Shunt Flexible AC Transmission System (FACTS) Controller i.e. Static VAr Compensator (SVC) in the network. An Optimal Power Flow (OPF) problem with mixed integer programming has been formulated for simultaneously optimizing multi-objectives optimization problem viz., enhancing the power system loadability, minimizing the active power loss of transmission line, and by considering installation cost of the controller whereas maintaining the system security and stability margins, e.g., small signal stability, fast voltage stability index, and line stability factor in their acceptable margins. The effectiveness of the proposed methodology has been investigated on a practical Java-Bali 24-bus Indonesia system. Results demonstrate that the static and dynamic performances of the power system can be effectively enhanced by the optimal allocation of the SVC in the network.**

Keywords— Optimal placement; PSO; SVC; system loadability; system security and stability margins.

I. Introduction

In recent decade, the actual power systems are facing new challenges due to deregulation and restructuring of the electricity market. It has become imperative to better utilize the existing power networks to increase capacities by installing FACTS controllers [1]. The variables and parameter of the transmission line, which include line reactance, voltage magnitude, and phase angle are able to be controlled using FACTS controllers in a fast and effective way [2].

The benefits derived from FACTS include improvement of the stability of power system networks, such as the small signal stability, transient stability, and thus enhance system reliability. However, controlling power flows is the main function of FACTS [3],[4]. Maximal system loadability can also be obtained with the optimal location and parameter setting of FACTS controllers [5],[6]. The maximum benefit of the FACTS controllers depends greatly on how these controllers are allocated in the power system: namely, on their location and settings [7].

From the previous works [8],[7],[9],[10],[11], it can be concluded that most the problem of optimal location of FACTS controllers using the evolutionary optimization algorithm is generally formulated as a mono-objective optimization problem. Unfortunately, the formulation of FACTS location problem as a mono-objective optimization is not quite practical. While, planners the power systems aim to take advantage of FACTS controllers considering several objectives at the same time. However, the dynamic performance base on small signal stability, fast voltage stability index (FVSI), and line stability factor (LQP), and their impact on the optimal placement of SVC by considering installation cost of the SVC are not wholly considered yet.

In this paper, an algorithm of the optimal placement of one type of shunt FACTS controllers, SVC, is suggested as a multi-objective problem to maximize system loadability within system security and stability margin i.e., small signal stability, voltage stability index, and line stability factor. By means of optimal placement of the SVC, the active power losses of the transmission system and installation costs of the controller are minimize as well, whereas the system loadability of the transmission lines is maximized. In realizing the proposed objectives, the suitable location of the SVC and its rated values must be determined simultaneously. In doing so, the PSO technique is used.

II. SVC Modelling

In this paper, the SVC is modeled as an ideal reactive power injection at bus *i* [4].:

$$\Delta Q_i = Q_{SVC} \tag{1}$$

The model is completed by the algebraic equation expressing the reactive power injected at the SVC node [3], [12]:

$$Q_{\mathrm{SVC}} = b_{SVC} V^2 \tag{2}$$

where, V and b_{SVC} are the voltage magnitude of bus at which the component are connected and total reactance of the controller, respectively.

III. Problem Formulation

The objective functions taken into account in this paper are expounded in detail in below.

A. Maximize the System Loadability (max. SL)

$$\text{Maximize } F_1(\mathbf{x},\mathbf{u}) = \{\lambda_1\} \quad (3)$$

$$\text{Subject to } VL = \sum_{i=1}^{N_l} OLL_i \times \sum_{j=1}^{N_b} BVV_j \quad (4)$$

where VL is the thermal and bus violation limit factor, OLL_i and BVV_j represent the overloaded line factor and branch the bus voltage violation factor, respectively; N_l and N_b are the total numbers of transmission lines and buses, respectively. In addition λ_1 is a load parameter of the system, which intends to locate the maximum sum of power that the network is able to supply within the system security margin [13], [14].

B. Minimization of Active Power Loss (min. P_{loss}) of the transmission lines

This objective is to minimize the active power losses (P_{loss}) in the transmission lines and which can be expressed as:

$$F_2(\mathbf{x},\mathbf{u}) = \sum_{k=1}^{N_l} g_k \left[V_i^2 + V_i^2 - 2V_iV_j \cos t(\delta_i - \delta_j)\right] \quad (5)$$

where, N_l is the number of transmission lines; g_k is the conductance of the k^{th} line; $V_i\angle\delta_i$ and $V_j\angle\delta_j$ are the voltages at the end buses-i and j of the k^{th} line, respectively.

C. Minimize the installation cost (min. C) of SVC

Based on the Siemens AG Database [5],[7] the cost function for the FACTS controller is developed. The cost function for SVC is:

$$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38 \quad (6)$$

where; C_{SVC} is in US$/kVAR and S is the operating range of the FACTS controller in MVAR.

$$S = |Q_2| - |Q_1| \quad (7)$$

where, Q_2 is the reactive power flow in the line after installing FACTS controller in MVAR and Q_1 is the reactive power flow in the line before installing the SVC in MVAR.

D. Power System Stability Constraints

- *Small signal stability*

The eigenvalue stability analysis is incorporated in the constraint by the equation in PSAT [12].

$$E_i(F_x, F_y, G_y, G_x) = 0 \quad (8)$$

The eigenvalue based stability assures grid stability under various levels of system loadability.

- *Fast voltage stability index*

Fast Voltage Stability Index (*FVSI*) proposed by Musirin [15] is utilized in this paper to assure the safe bus loading. The *FVSI* is the device used to indicate the voltage stability condition formulated based on a line or a bus as defined by

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \quad (9)$$

where, Z is the line impedance, X is the line reactance, Q_j is the reactive power at the receiving end, and V_i is the sending and voltage. *FVSI* index incorporation in the controller assures that no bus will collapse due to overloading.

Line stability factor

System stability index is also assured by Line Stability Factor (*LQP*) proposed by A Mohamed *et al* [16]. The formulation begins with the power equation in a power system and is expressed as

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \quad (10)$$

where, X is the line reactance, V_i is the sending end voltage, P_i is the sending end real power, and Q_j is the receiving end reactive power. The *LQP* must be kept less than 1.00 to maintain a stable system. *LQP* assure the controller that no line is over loaded under any grid condition.

IV. METHODOLOGY DEVELOPMENT

A. Overview of PSO

In a PSO system [17], [18], each particle in search space is defined by the following elements [19]: x_i^k is the value of particle i at generation k. The update of particle i in the search space is defined by (11); p_{best} is the best value found by the particle i until generation k; v_i^{k+1} is the velocity of particle i at generation k. The update of velocity during the search procedure is presented by (12); g_{best} is the best particle found in the group until generation k

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (11)$$

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand_1 \times \left(p_{best_i} - x_i^k\right) + c_2 \times rand_2 \times \left(g_{best} - x_i^k\right) \quad (12)$$

where,
ω: weighting function,
c_j : weighting factor,
$rand_i$: random number between 0 and 1,
p_{best}: p_{best} of particle i,
g_{best}: g_{best} of the group.
The following weighting function is usually utilized [18]:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter \quad (13)$$

where: ω_{max}, ω_{min}, $iter_{max}$ are the initial weight, final weight, and the maximum iteration number, respectively.

B. Calculation of Fitness Function

The optimization problem for the best promising placement of the SVC controller is changed into an unconstrained optimization problem using a penalty factor

(PF) as given in (14). This becomes the fitness function in (FF) the PSO technique.

$$\text{Fitness function } = \mu_1 F_1 - \mu_2 F_2 - \mu_3 F_3 + PF \times |VL - 1| \qquad (14)$$

From (14) it can be seen that there are four terms to the equation where the first term corresponds to Max SL of the SVC controller formulated by (3), whereas the second and the third ones correspond to Min P_{loss} of transmission system and Min C of the controllers represented by (5) and (6) repectively. The last term relates to a constraints violation that is multiplied by a PF to calculate the fitness function given by (14) for each particle. Constant μ_i is the weighting coefficient which is used to adjust the slope of the PSO. For each particle, the line and the bus data is updated according to the SVC controller's setting and location and the current SL of the system. The NRPF method is performed to gauge the voltage at each bus and line flow. Using these results, the value of VL for each particle is attained by using (4) and the FF of each particle is calculated by using (14). The particle that gives the maximum value for the fitness function in the population is considered as g_{best} particle.

The new velocity and the new position of each particle are calculated using (12) and (11), respectively. The procedures are repeated until the maximum number of iterations is reached then the value of VL and all stability constrains as shown in (8), (9) and (10) for the g_{best} particle is tested. If the value is equal to 1, then using that g_{best} particle, the current value of SL can be met out without violating line flow, bus voltage limit constraints, and all stability constrains within limits as well. In addition, the g_{best} particle is saved together with its SL, P_{loss} and C_{svc}. The SL for each load buses are then increased again when the PSO algorithm is run. If the value of VL for the g_{best} particle is not equal to 1 then the g_{best} particle is unable to meet out the current SL and the g_{best} particle with VL = 1, obtained in the previous run, is considered as the best optimal setting. The SL corresponding to that g_{best} particle is considered as the maximum SL.

V. SIMULATION AND DISCUSSION

To validate the results obtained, a simulation study have been conducted to maximize system loadability (Max SL), to minimize the active power loss (Min P_{loss}) of transmission line and to minimize installation cost (Min C) of a SVC controller by optimal allocation of the SVC controller for the practical utility systems. With the aim of providing more real aspect, the proposed method has been applied on the practical Indonesia Java-Bali 24-bus system [20] which its single line diagram is depicted in Fig. 1. The data of the system are taken from the Indonesia Government Electrical Company and which has 8 generators and 49 lines. The total active and reactive load of the system is 10570.87 MW and 4549.23 MVAR, respectively.

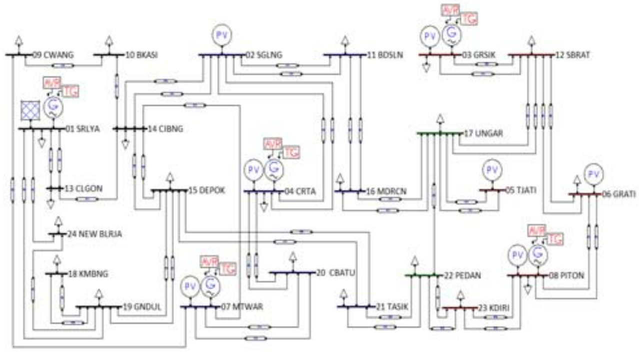

Fig. 1 Single line diagram of Indonesia Java-Bali 24-bus system

In this study, the SVC controller which is considered for the test system is modeled using a power system analysis toolbox (PSAT) [12]. The parameters of PSO for all optimization cases are summarized in Table I.

TABLE I
THE PSO PARAMETERS

c_1 , c_2	w_{max}	w_{min}	Number of generation	Population size
2.0	0.9	0.4	100	50

Loads were modeled as constant PQ loads with a constant power factor and they were increased as per the equation (3) and (4). The additional load is assumed to be borne by the slack generator. The PSO decision variables are the location and setting of SVC controller while the placement of the SVC controller is considered a discrete variable, where all the load buses of the system are selected as possible locations for the SVC placement.

A. Bi-objective Optimization

The optimization problem in the first step is only formulated as bi-objective optimizations problems considering Max SL and Min P_{loss} of the transmission lines within security and all stability margins. The optimal location and parameter setting of the SVC needed to attain the Max SL and the Min P_{loss} of the controller are shown in Table II. From table II, it is observed that installing SVC in bus 24 (NEW BLRJA) with setting of 1.00 pu. from reference gives the Max SL and the Min P_{loss} of 163.76 % and 4.6415 pu respectively, with all security and stability constrains are in acceptable margins.

TABLE II
PSO SOLUTIONS OF SVC PLACEMENT FOR BI-OBJECTIVE OPTIMIZATIONS

Cases	Location (bus)	Setting	Max SL	Min P_{loss}
		(pu)	(%)	(pu)
Base case	-	-	100	1.6649
With SVC	24	1.00	163.76	4.6415

The eigenvalue, represented the stability of system in term of small signal stability at the optimal solution depicts in Fig. 2. It is evident that the installation of SVC assures grid stability with all the eigenvalues in the left hand side of the S-plane during the optimal solution.

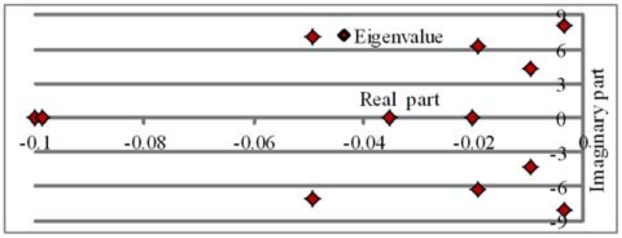

Fig. 2 Eigenvalue of optimal placement of SVC for Java-Bali 24-bus Indonesian system for bi-objective optimizations

Furthermore, the graph does not include the far end stable eigenvalues (real eigenvalue less than -0.1) in the chart, whereas Fig. 3 shows the stability of the system, represented by their *FVSI,* and *LPQ* results, at the optimal solutions of system loadability using the SVC.

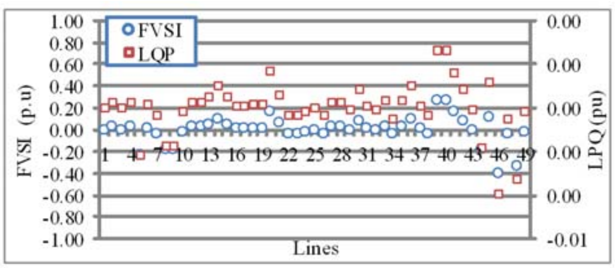

Fig. 3. *FVSI* and *LQP* of optimal placement of SVC for Java-Bali 24-bus Indonesian system for bi-objective optimizations

B. *Three-objective Optimization*

In the second step, the optimal location and parameter setting of the SVC controller have been implemented for the three-objectives optimization problem by considering Min *C* of the controller is shown in Table III. It is perceived from table III that placing SVC in bus 17 (UNGAR) with setting of 1.00 pu from reference gives not only the Max *SL* of 152.28 %, but also the Min P_{loss}, and Min *C* of 3.2469 pu and $ 3.3781 million respectively. Where compare the first and the second results with the ones obtained in the first step, it can be concluded that by applying the three-objective optimization problems, Max *SL* have been reduced from 163.76 % to 152.28 % whereas Min P_{loss} decreased from 4.6414 pu to 3.2469 pu. In this step, all security and stability constrains are in acceptable margin as well.

TABLE III
OPTIMAL LOCATION, PARAMETER SETTINGS, MAX SL, MIN P_{LOSS} AND MIN C OF INSTALLING SVC IN JAVA BALI 24-BUS SYSTEM

Cases	Location (bus)	Setting	Max *SL*	Min P_{loss}	Min. *C*
		(pu)	(%)	(pu)	(× 10^6)US$
Base case	-	-	100	1.6649	3.3781

From performance index evolution, which is depicted in Figure 4, can be observed that the convergence of proposed method is reached after 23[th] iterations.

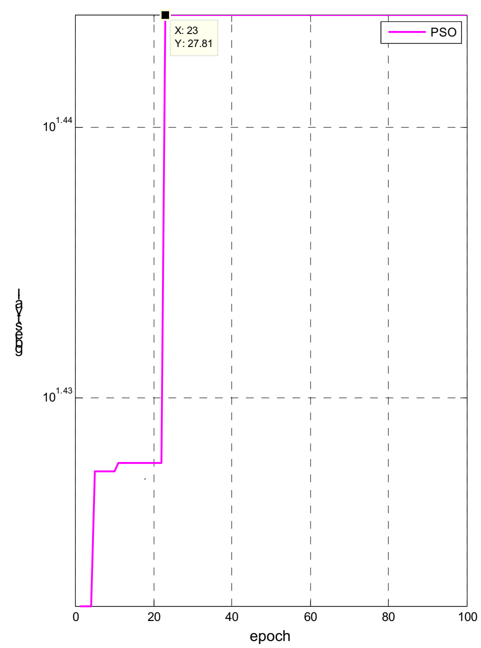

Fig. 4 Performance index evolution of PSO technique for optimal placement of SVC in Java-Bali 24-bus system

The eigenvalue represented the stability of system in term of small signal stability at the optimal solution shows in Fig. 5. Fig. 6 presents the stability of the system, denoted by their *FVSI,* and *LPQ* results, at the optimal solutions of system loadability using the SVC.

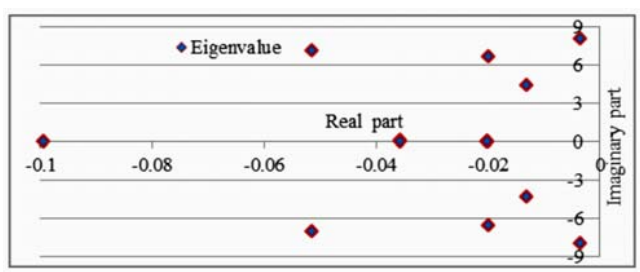

Fig. 5 Eigenvalue of optimal placement of SVC for Java-Bali 24-bus system for three-objective optimizations

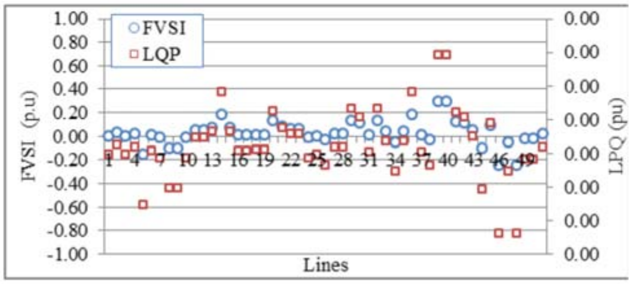

Fig. 6 FVSI and LQP of optimal placement of SVC for Java-Bali 24-bus system for three-objective optimizations

VI. CONCLUTION

In this paper, one type of the most powerful evolutionary optimization technique, namely, Particle Swarm Optimization (PSO) have been suggested to maximize system loadability by placing a SVC device in the best location of the network whereas to minimize the active power loss of transmission line by considering installation cost of the controller. By implementing the proposed algorithm with bi and three-objective optimization problems, the results obtained show that the proposed technique performed well to solve the multi objective optimization problems. Moreover the results indicate that the system's loadability can be enhanced efficiently using the PSO technique by maintaining all the security and stability in acceptable margins.

Furthermore, the algorithm is not only able to solve the optimal location and setting of the controller formulated as multi-objective optimizations problem but also it has superior features that include high quality solution, stable convergence characteristics, and good computation efficiency. Thus all the obtained results, which are applied to a realistic power system, validate and support the proposed technique.

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