Optimal Placement of A Series FACTS Controller in Java-Bali 24-bus Indonesian System for Maximizing System Loadability by Evolutionary Optimization Technique

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Abstract—**In this paper, a series FACTS controller namely Thyristor Controller Series Compensator (TCSC) has been suggested to enhance the power system loadability. The location of the controller and the setting of their control parameters are optimized by one type of Evolutionary Optimization Technique to improve the performance of the power network. The objective functions are to maximize the system loadability whereas maintaining system security and stability margins, e.g., small signal stability, voltage stability index, and line stability factor within limits by considering the investment costs of the controller and minimizing active power loss of the system. The series FACTS controller is modeled and incorporated in the Newton Raphson power flow problem. The effectiveness of the proposed methodology has been investigated on a practical Java-Bali 24-bus Indonesian grid system.**

Keywords-evolutionary optimization techniqu; FACTS controllers; system loadability; system security and stability margins.

I. Introduction

In recent decades, 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]. These basic ideas behind the FACTS concept play an active role in the operation and control of competitive power systems.

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 [4]. The range of FACTS controllers includes: Static Var Compensator (SVC); Thyristor Controlled Series Compensator (TCSC); Unified Power Flow Controller (UPFC); and Static Compensator (STATCOM).

In the last few years, in the research arena of computational intelligence, several cooperative and competitive stochastic search techniques have rapidly gained popularity as efficient optimization techniques. Such techniques include a hybrid Tabu Search (TS) and Simulated Annealing (SA) [7], Evolutionary Programming (EP) [8], Genetic Algorithm (GA) [9],[10], Bacterial Swarming Algorithm (BSA) [11], and Particle Swarm Optimization (PSO) [12],[13]. The GA and PSO techniques have been formulated to solve optimal location and parameter settings of multiple TCSCs and UPFCs to increase power system loadability [13],[14]. The application of PSO technique for optimal location of multiple FACTS controllers, taking into consideration the cost of installation and the system loadability, has been reported [5], [14].

From the previous works, it can be concluded that the problem of optimal location of FACTS controllers using PSO 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 considering the investment cost of FACTS controllers, active power loss, and their impact on placement to maximize system loadability in the network are not wholly considered yet.

In this paper, the PSO algorithm is developed for optimal placement of single TCSC device to maximize system loadability within system security and stability margins. By means of the optimal placement of TCSC device, system loadability is maximized and simultaneously the installation cost and active power loss of the controller is minimized as well.

II. Component Modelling

A. Power System Modeling

In this paper, the dynamic nature of the controller requires detailed dynamic modelling of power system components [15] have been considered as follow. Synchronous machine has been modelled as IEEE Type 5.2 whereas turbine governor model is considered as IEEE Type 1. In addition, AVR has been taken as IEEE Type 2 model.

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The robust controller continuously monitors and adjusts the grid parameters for achieving maximum system loadability. Among the various factors required for increasing the system loadability, which considered were voltage setting of slack and voltage controlled buses and the line loading of transmission line. Controller adjusts the settings of AVR and turbine governor for reactive and active power support and power requirement during increasing power system loadability. Eigenvalue based stability constraints and voltage and line stability indices have been used to assure the grid stability at various levels of increasing power system loadability.

B. TCSC Modeling

The basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactive correspondingly. The TCSC [4] is modeled as variable impedance where the equivalent reactance of line is defined as:

$$X_{ij} = X_{line} + X_{TCSC} \tag{1}$$

where, X_{line} is the transmission line reactance, and X_{TCSC} is the TCSC reactance. After installing TCSC, the new reactance of line is presented by:

$$X_{ij} = (1 - c_p) X_{line} \tag{2}$$

where, c_p is the percentage of reactance compensation. The level of the applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive.

III. Problem Formulation

As specified, the aim of optimization is to place the UPFC controller into a power network in the most favorable positions in order to optimize the location and setting of single UPFC controller. This is to maximize system loadability (MSL) by maintaining security and stability margins and to minimize the investment cost (C) of the UPFC controller. The objective functions taken into account in this paper are expounded in detail in this section.

A. Maximize the System Loadability (SL)

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

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

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; and is elaborated in (8) and (9); 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.

The load parameter λ_1 in (3) is defined as a function of a load factor λ_f:

$$\lambda_1 = \exp[\gamma |\lambda_f - \lambda_f^{\max}|] \qquad \lambda_f \in [1, \lambda_f^{\max}] \tag{5}$$

where γ is the coefficient to adjust the slope of the function, and $\lambda_f^{\max}$ is the maximal limit of λ_f. The load factor λ_f reflects the variation of power loads P_{Li} and Q_{Li}, which are defined as [10]:

$$P_i(\lambda_f) = \lambda_f P_i \qquad i = m+1, \ldots, N_b \tag{6}$$

$$Q_i(\lambda_f) = \lambda_f Q_i \qquad i = m+1, \ldots, N_b \tag{7}$$

where, m is the total number of generator buses. $\lambda_f = 1$ indicates the base case load.

The indexes of the system security state consist of two parts. The first part, OLL_i, relates to the branch loading and penalizes overloads in the lines. The value of OLL_i equals to 1 if the jth branch loading is less than its rating. OLL_i increases logarithmly (actual logarithm) with the overload and it can be calculated from:

$$OLL_i = \begin{cases} 1; & \text{if} \quad P_{ij} \le P_{ij}^{\max}, \\ \exp\left(\Gamma_{OLL}\left|1 - \dfrac{P_{ij}}{P_{ij}^{\max}}\right|\right); & \text{if} \quad P_{ij} \ge P_{ij}^{\max}, \end{cases} \tag{8}$$

where P_{ij} and $P_{ij}^{\max}$ are the real power flow between buses i and j and the thermal limit for the line between buses i and j respectively. Γ_{OLL} is the coefficient which is used to adjust the slope of the exponential function.

The second part BVV_j in (4) concerns the voltage levels for each bus of the power network. The value of BVV_j is defined as:

$$BVV_j = \begin{cases} 1; & \text{if } 0.9 \le V_b \le 1.1 \\ \exp\left(\Gamma_{BVV} |1 - V_b|\right); & \text{otherwise} \end{cases} \tag{9}$$

where BVV_j is the bus voltage violation factor at bus j and Γ_{BVV} represents the coefficient used to adjust the slope of the exponential function in the above equation. The equation shows that appropriate voltage magnitudes are close to 1 p.u. Similar to OLL_i, the value of BVV_j is equal to 1 if the voltage level falls between the minimal and maximal voltage limits. Outside the range, BVV_j increases exponentially with the voltage variation.

B. Minimize the installation cost (C) of TCSC

The installation cost of FACTS controllers has been mathematically formulated and is given by [5],[13].

$$F_2(\mathbf{x},\mathbf{u}) = IC(f) \times S \times 1000 \tag{10}$$

where, $F_2(\mathbf{x},\mathbf{u})$ is the optimal installation cost of FACTS controllers in US\$, $IC(f)$ is the installation cost of FACTS controllers in US\$/kVAR and f is vector that represents the variable of FACTS controllers.

Based on the Siemens AG Database [5],[10] the cost functions for FACTS controllers are developed. The cost function for TCSC is:

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \tag{11}$$

For UPFC:

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

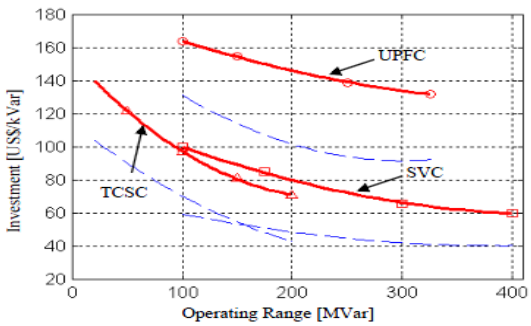

Fig. 1. Cost function of the FACTS controllers: TCSC, SVC and UPFC.

$$S = |Q_2| - |Q_1| \quad (12)$$

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

The cost function for TCSC, SVC, and UPFC are shown in Fig. 2.

C. Minimization of Active Power Loss (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:

$$F_3(\mathbf{x},\mathbf{u}) = \sum_{k=1}^{N_l} g_k \left[V_i^2 + V_i^2 - 2V_i V_j \cos t(\delta_i - \delta_j\right] \quad (13)$$

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.

D. Dependent and Control Variavble

In the two objective functions, $\mathbf{x}$ is the vector of dependent variables such as slack bus power P_{G1}, load bus voltage $V_{m+1........Nb}$, generator reactive power outputs Q_G and apparent power flow S_k; $\mathbf{x}$ can be expressed as:

$$\mathbf{x}^T = [P_{G_1}, V_{m+1}...V_{N_b}, Q_{G_1}...Q_{G_m}, S_1...S_{N_l}] \quad (14)$$

Furthermore, $\mathbf{u}$ is a set of the control variables, such as generator real power outputs P_G except at the slack bus P_{G1}, generator voltages V_G, and the locations of FACTS controllers, L, and their parameter settings. $\mathbf{u}$ can be expressed as:

$$\mathrm{u}^T = [P_{G_2}...P_{G_m}, V_{G_2}...V_{G_m}, L, X_{TCSC}, \lambda_f] \quad (15)$$

The equality and inequality constraints of the Newton Raphson Power Flow (NRPF) problem incorporating FACTS controllers are given in following subsection.

E. Equality Constraint

These constraints represent the typical load flow equations as follows:

$$P_{G_i} = P_{L_i} + V_i \sum_{i=1}^{N_b} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right), \quad 1 = 1,2,3...N_b \quad (16)$$

$$Q_{G_i} = Q_{L_i} + V_i \sum_{i=1}^{N_b} V_j \left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right), \quad 1 = 1,2,3...N_b \quad (17)$$

where, N_b is the number of buses in the system.

F. Inequality Constraint

The inequality constraints $h(\mathbf{x}, \mathbf{u})$ are limits of control variables and state variables. Generator active power P_G, reactive power Q_G, voltage V_i, and phase angle δ_i are restricted by their limits as follows:

$$\left.\begin{array}{ll} P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max} & i = 1,......,m \\ Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max} & i = 1,......,m \\ V_i^{\min} \le V_i \le V_i^{\max} & i = 1,.......,N_b \\ -0.9 \le \delta_i \le 0.9 & i = 1,.......,N_b \end{array}\right\} \quad (18)$$

The parameter settings of multi-type FACTS controllers are restricted by their limits as follows:

$$\left.\begin{array}{l} X_{TCSC}^{\min} \le X_{TCSC} \le X_{TCSC}^{\max} \\ b_{SVC}^{\min} \le b_{SVC} \le b_{SVC}^{\max} \\ v_S^{\min} \le v_S \le v_S^{\max} \\ i_{SH}^{\min} \le i_{SH} \le i_{SH}^{\max} \end{array}\right\} \quad (19)$$

The constraint of transmission loading P_{ij} is represented as

$$|P_{ij}| \le P_{ij}^{\max}; \quad ij = 1,.......,N_l \quad (20)$$

The load factor λ_f is constrained by its limits as:

$$1 \le \lambda_f \le \lambda_f^{\max} \quad (21)$$

Power System Stability Constraints

- Small signal stability

The system used for the small signal stability analysis is a differential algebraic equation (DAE) set, in the form:

$$\left.\begin{array}{l} \dot{x} = f(\mathbf{x},\mathbf{y}) \\ 0 = g(\mathbf{x},\mathbf{y}) \end{array}\right\} \quad (22)$$

where, $\mathbf{x}$ is the vector of the state variables and $\mathbf{y}$ the vector of the algebraic variables, which are only voltages amplitudes V and phases θ. The system state matrix A_s is thus computed by manipulating the complete Jacobian matrix A_c, which is defined by the linearization of the DAE system equations (30) as follow.

$$\begin{bmatrix}\Delta\dot{\mathbf{x}} \\ 0\end{bmatrix} = \begin{bmatrix}\nabla_x f & \nabla_y f \\ \nabla_x g & \nabla_y g\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x} \\ \Delta\mathbf{y}\end{bmatrix} = \begin{bmatrix}F_x & F_y \\ G_x & G_y\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x} \\ \Delta\mathbf{y}\end{bmatrix} = [A_c]\begin{bmatrix}\Delta\mathbf{x} \\ \Delta\mathbf{y}\end{bmatrix} \quad (23)$$

The state matrix A_s is simply obtained by eliminating the algebraic variables as follow.

$$A_s = F_x - F_y G_y^{-1} G_x \quad (24)$$

where, F_x, F_y, G_x, G_y are Jacobian Matrices as given in (30).

If the complex eigenvalues of the linearized system have negative real parts, then the power system would be able to withstand small disturbances and is thus, considered stable in the small-signal sense. The eigenvalue stability analysis is incorporated in the constraint by the equation in PSAT [15], [23]:

$$E_i(F_x, F_y, G_y, G_x) = 0 \quad (25)$$

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 [16] 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

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \quad (26)$$

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.

The line that exhibits *FVSI* close to 1.00 implies that it is approaching its instability point. If *FVSI* goes beyond 1.00, one of the buses connected to the line will experience a sudden voltage drop leading to the collapse of the system. *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* [17]. The formulation begins with the power equation in a power system and is expressed as

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \quad (27)$$

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

Particle Swarm Optimization (PSO) is a relatively new and robust stochastic heuristic optimization technique introduced by Eberhart and Kennedy [6]. It is based on the movement and intelligence of swarms of insects or flocks of birds and other such groups. In a PSO system, the group is a community made up of all flying particles moving around in a multidimensional space. While in flight, each particle modifies its position according to its own experience, as well as the experience of neighboring particles, until it finds a relatively static point or until - computational limitations are surpassed.

Each particle in search space is defined by the following elements [2, 3]: x_i^k is the value of particle i at generation k. The update of particle i in the search space is defined by (24); p_{best_i} 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 (24); g_{best} is the best particle found in the group until generation k

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (28)$$

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand_1 \times \left(p_{best_i} - x_i^k\right) + c_2 \times rand_2 \times \left(g_{best} - x_i^k\right) \quad (29)$$

where,

w: weighting function,

c_j : weighting factor,

$rand_i$: random number between 0 and 1,

p_{besti}: *pbest* of particle i,

g_{best}: g_{best} of the group.

The following weighting function is usually utilized [2]:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (30)$$

where:

w_{max}: initial weight,

w_{min}: final weight,

$iter_{max}$: maximum iteration number,

$iter$: current iteration number.

B. Calculation of Fitness Function

The controlled problem of optimization for the best possible placement of single TCSC device is changed into an unconstrained optimization problem using a penalty factor (PF) as given in (31). This becomes the fitness function in the PSO technique.

$$\text{Fitness function} = \mu_1 F_1 - \mu_2 F_2 - \mu_3 F_3 + PF \times |VL - 1| \quad (31)$$

There are forth terms to the equation. The first term corresponds to maximize *SL* of the TCSC device formulated by (3). The second and the third terms correspond to minimize system installation costs of the TCSC device and simultaneously to minimize active power loss of transmission system represented by (10) and (13), respectively. The last term corresponds to a constraints violation that is multiplied by a PF to calculate the fitness function given by (31) for each particle. 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 its TCSC device's setting and location and the current system loadability (*SL*). 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 fitness function of each particle is calculated by using (31). 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 (29) and (28), 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 (25), (26) and (27) for the g_{best} particle is checked. 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 installation cost and *SL*. *SL* is 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

A. Be-objective Optimization

Firstly, the optimization problem is formulated as bi-objective optimizations problem considering maximization of the system loadability and minimization of the installation cost (*C*) of the TCSC device within security and all stability margins.

In order to give a more practical aspect to this paper, the proposed method has been applied on the realistic Java-Bali 24-bus Indonesian grid system [18]. Single line diagram of the system is shown at Fig. A.1, the bus and line data 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.

TABLE I
NSGA-II SOLUTIONS OF CASE 1 FOR BI-OBJECTIVE OPTIMIZATIONS

Location (line)	Compensation	Max. *SL*	Min. *C*	P_{loss}
	(%)	(%)	($\times 10^6$) US$	(pu)
18-19	20	166.34	0.44	4.93

The optimal locations and parameter settings of the TCSC needed to attain the maximum *SL* and the minimum *C*, of the systems are shown in Table I. From Table I, it is observed that placing TCSC in the line 18-19 (KMBNG-GNDUL) with setting of 20 % from reference gives the maximum *SL* and the minimum *C* of $ 0.44 million by considering stability constrains, respectively with total P_{loss} of 4.93 pu.

The eigenvalue, represented the stability of system in term of small signal stability at the optimal solution solution depicts in Fig. 2. It is evident that the installation of TCSC assures grid stability with all the eigenvalues in the left hand side of the S-plane during the optimal solution. Furthermore, the graph does not include the far end stable eigenvalues (real eigenvalue less than -0.2) 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 TCSC.

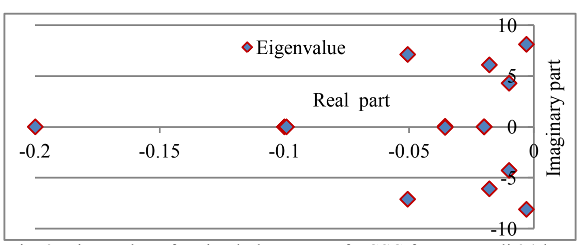

Fig. 2 Eigenvalue of optimal placement of TCSC for Java-Bali 24-bus Indonesian system for bi-objective optimizations.

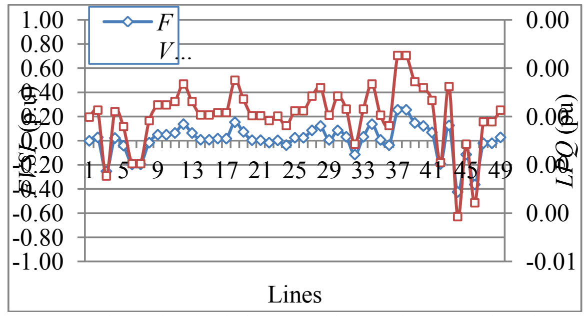

Fig. 20 Pareto front of optimal placement of TCSC for Java-Bali 24-bus Indonesian system for bi-objective optimizations.

B. Three-objective Optimization

In this step, the problem is formulated as three-objective optimisations, by added the minimization of active power losses (P_{loss}) of the power system to the first problem. The optimal locations and parameter settings of TCSC device of the three-objectives by considering security and all the stability constraints is presented in Table II. From this table, it is clear that the installation of TCSC in line 19-1 (GNDUL-SRLYA) provides the maximum *SL* of 265.33 %, whereas the minimum *C* of the device and Ploss are $1.30 million and 3.08 pu, respectively. The stability constraints at the optimal solutions that represented by its eigenvalue, *FVSI*, and *LQP* within acceptable limits are depicted in Figs. 3 and 4.

When compared with first step, from table II can be concluded that placing the TCSC in the line 19-1 with compensation setting of 20 % significantly reduced the P_{loss} of transmission system from 4.93 pu to 3.08 pu with similar maximum *SL*, but of course the installation cost (*C*) in this step increased almost three times. Figs. 3 and 4 show the stability of the system, represented by their eigenvalues, *FVSI,* and *LPQ* results, at the optimal solutions of system loadability using the TCSC.

TABLE II
NSGA-II SOLUTIONS OF CASE 1 FOR THREE -OBJECTIVES OPTIMIZATIONS

Location (line)	Compensation	Max. *SL*	Min. *C*	Min. P_{loss}
	(%)	(%)	($\times 10^6$) US$	(pu)
19-1	20	165.33	1.30	3.08

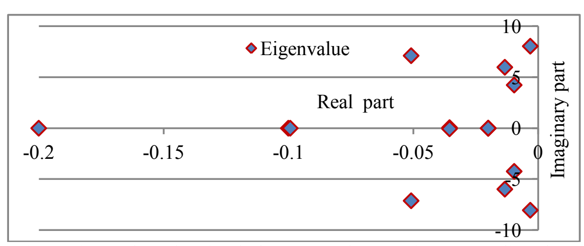

Fig. 3 Eigenvalue of optimal placement of TCSC for Java-Bali 24-bus Indonesian system for three-objective optimizations

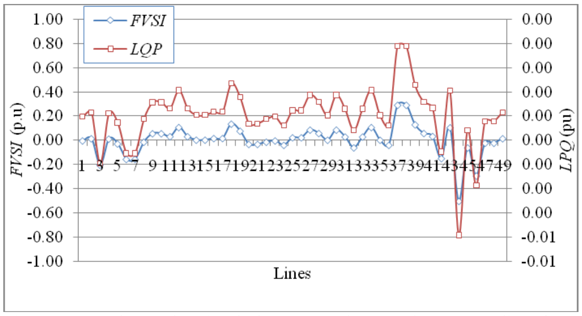

Fig. 4. Pareto front of optimal placement of TCSC for Java-Bali 24-bus Indonesian system for three-objective optimizations

VI. CONCLUTION

This research uses the most powerful evolutionary optimization technique, namely, Particle Swarm Optimization (PSO) to maximize system loadability by placing single TCSC device in the most optimal location. Since the TCSC device is expensive, maximizing system loadability is subject to minimizing the investment costs of TCSC device and active power loss of transmission line. The results obtained from implementing this show that the proposed technique performed well.

This technique has superior features that include high quality solution, stable convergence characteristics, and good computation efficiency. Moreover the results show that the system's loadability can be increased efficiently by the PSO algorithm within the security and stability margins. In addition, the algorithm is able to solve the optimal location and settings of the one type of series FACTS controllers formulated as multi-objective optimizations problem and applied to realistic power system. Thus all the obtained results validate and support the proposed technique.

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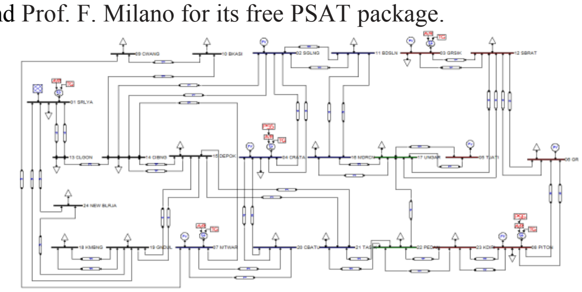

Figure A.1. Single line diagram of Java-Bali 24-bus Indonesian system

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