

# Analyzing the Optimal Reactive Power Dispatch in the Presence of Series and Shunt Facts Controllers

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**ABSTRACT:** The reactive power dispatch is one of the generalized optimal power flow (OPF) problems to dispatch reactive power optimally to maintain the voltage magnitude at the load buses. The OPF problem with total power loss as an objective is solved while satisfying system equality and in-equality constraints. It is necessary to solve the optimal power flow in the presence of series and shunt flexible AC transmission system controllers such as thyristor controlled series capacitor and static VAR compensators. The optimal location of these controllers is identified so as to maximize the system security. The optimal parameters of this controller and system are identified using the developed gravitational search algorithm. The effectiveness of the proposed methodology with TCSC and SVC is tested on standard IEEE-30 bus test system with supporting numerical and as well as graphical results.

**KEYWORDS:** Optimal power flow, Gravitational search algorithm, Reactive power dispatch, TCSC, SVC, Optimal location

## I. INTRODUCTION

In general, reactive power dispatch problem is the solution of OPF problem with total power system losses as objective whole satisfying system equality and in-equality constraints. Hence, the total power system losses depend on the voltage magnitude at system buses. The transmission loss in a transmission line is a function of voltage magnitude at the buses where the transmission line exists. From fundamentals, the voltage magnitude at a bus can be controlled by injecting/absorbing the reactive power at that bus. Finally, if the reactive power through the transmission lines is dispatched optimally, then the total power losses are reduced. Hence, the problem optimal reactive power dispatch is one of the most warranted problems in power system operation and control.

In [1], OPF problem formulation has been presented along with considering effects of FACTS devices and power flow constraints. To solve OPF problem a two stage problem formulation has been proposed. This reference [2], Presents the performance comparison of PSO and GA optimization techniques for FACTS based controller design. In [3], the main aim is the optimal allocation of TCSC device in the power system so the power loss becomes minimized and also increase power transfer capacity of the transmission line that ultimately yields minimum operating cost with different load conditions. In this, first the locations of the TCSC device is identified by calculating line flows. TCSC is placed in line where reactive power flows are very high. To solve OPF problem Hybrid GA incorporating TCSC is proposed. To select best control variables to minimize the generation cost and maintain the power flow within the control range Hybrid GA is integrated with conventional OPF [4].

The generation cost is minimized subjected to equality and inequality constraints. The optimal active power flow control strategy with TCSC is proposed. In this method problem is solved in two steps. First step is power flow control and second step is normal OPF problem [5]. In [6], presents solution of OPF with different objective functions such as generation cost and total power loss minimization using GA. In base case OPF solution is obtained with generation cost minimization and optimal setting of the control parameters are determined. In this OPF with TCSC is carried out with generation cost and total power loss as objective functions.

The literature concentrated on the application of evolutionary optimization techniques to OPF problems like, linear and non-linear programming [7-9], Newton's method [10], Quadratic Programming [11], Fast Successive Linear

# International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 5, Issue 2, February 2016

Programming algorithm [12], etc. At present, these evolutionary algorithms are promoted to overcome the drawbacks of the traditional optimization techniques, as their inherent capability of processing towards the best result and extensive exploration in search space [13].

In this paper, the detailed analysis of the former literature reveals that incorporation of TCSC and SVC for power flow management in transmission line. But, this paper describes the performance of one of series FACTS device which is TCSC and shunt FACTS device which is SVC. In this chapter a method to determine the optimal location of TCSC and SVC is suggested. A power injection mathematical model of TCSC and SVC is presented. Power injection model of TCSC and SVC is associated with NR load flow method to study the effects of device parameters and characteristics in power flow studies. The OPF problem is solved with total power losses as an objective is solved. Numerical analysis is carried out on standard IEEE-30 bus system to demonstrate the performance of the TCSC and SVC.

## II. OPERATING PRINCIPLE OF TCSC

TCSC is one of the series compensator; it can capable to control power flow in line, damping power oscillations[14]. Basic simple TCSC model is shown in Fig.1. TCSC is formed by connecting the capacitor in series with the transmission line and thyristor-controlled reactor (TCR) in parallel with capacitor.

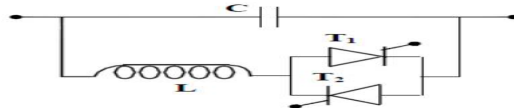


Fig.1 Model of TCSC

### 2.1 Power Injection Model of TCSC

The Fig.2 shows a  $\pi$  model of transmission line with TCSC connected between bus-k and bus-m [6]. Under the steady state condition, the TCSC can be represented as a static reactance  $-jX_C$ . In the power flow equations the controllable reactance  $X_C$  is directly used as the control variable.

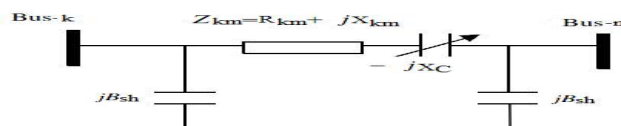


Fig.2 Transmission line with TCSC

The line data will be modified by placing TCSC in series with line. A new line reactance is given as follows

$$X_{km}^{new} = X_{km} - X_C \quad (1)$$

Therefore new line admittance between buses k and m can be derived as follows

$$Y'_{km} = \frac{1}{Z'_{km}} = \frac{1}{R_{km} + j(X_{km} - X_C)} \quad (2)$$

$$Y'_{km} = G'_{km} + jB'_{km} = \frac{R_{km} - j(X_{km} - X_C)}{R_{km}^2 + (X_{km} - X_C)^2} \quad (3)$$

$$G'_{km} = \frac{R_{km}}{R_{km}^2 + (X_{km} - X_C)^2} \quad (4)$$

$$B'_{km} = -\frac{(X_{km} - X_C)}{R_{km}^2 + (X_{km} - X_C)^2} \quad (5)$$

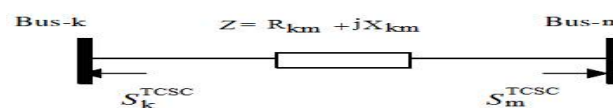


Fig.3 Power injection model of TCSC

# International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 5, Issue 2, February 2016

Due to TCSC, the change in line flow can be represented as a line without TCSC plus with power injected at the sending and receiving ends of the line with device as shown in Fig.3. The active and reactive power injections at bus-k and bus-m can be written as

$$P_k^{TCSC} = P_{km} - P_{km}^{TCSC} = V_k^2 \Delta G_{km} - V_k V_m [\Delta G_{km} \cos(\delta_{km}) + \Delta B_{km} \sin(\delta_{km})] \quad (6)$$

$$P_m^{TCSC} = P_{mk} - P_{mk}^{TCSC} = V_m^2 \Delta G_{km} - V_k V_m [\Delta G_{km} \cos(\delta_{km}) - \Delta B_{km} \sin(\delta_{km})] \quad (7)$$

$$Q_k^{TCSC} = Q_{km} - Q_{km}^{TCSC} = -V_k^2 \Delta B_{km} - V_k V_m [\Delta G_{km} \sin(\delta_{km}) - \Delta B_{km} \cos(\delta_{km})] \quad (8)$$

$$Q_m^{TCSC} = Q_{mk} - Q_{mk}^{TCSC} = -V_m^2 \Delta B_{km} + V_k V_m [\Delta G_{km} \sin(\delta_{km}) + \Delta B_{km} \cos(\delta_{km})] \quad (9)$$

Where,

$$\Delta G_{km} = \frac{X_C R_{km} (X_C - 2X_{km})}{(R_{km}^2 + X_{km}^2)(R_{km}^2 + (X_{km} - X_C)^2)} \quad (10)$$

$$\Delta B_{km} = \frac{-X_C (R_{km}^2 + X_C X_{km} - X_{km}^2)}{(R_{km}^2 + X_{km}^2)(R_{km}^2 + (X_{km} - X_C)^2)} \quad (11)$$

TCSC device is modeled with power injection model so far by using the TCSC control variable. It is possible to calculate the complex power injected  $S_k^{TCSC}$  and  $S_m^{TCSC}$  at bus-k and bus-m respectively.

$$S_k^{TCSC} = P_k^{TCSC} + jQ_k^{TCSC} \quad (12)$$

$$S_m^{TCSC} = P_m^{TCSC} + jQ_m^{TCSC} \quad (13)$$

Then new power flow equations can be expressed by the following relationship

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H_{new} & N_{new} \\ J_{new} & L_{new} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \frac{\Delta V}{V} \end{bmatrix} \quad (14)$$

here new mismatch vectors are

$$\Delta P_i = P_k^{spec} + P_k^{TCSC} - P_k^{calc} \quad (15)$$

$$\Delta Q_i = Q_k^{spec} + Q_k^{TCSC} - Q_k^{calc} \quad (16)$$

Where,  $P_k^{spec}$ ,  $Q_k^{spec}$  are the classical specified real and reactive powers,  $P_k^{TCSC}$ ,  $Q_k^{TCSC}$  are the power injection associated to TCSC devices,  $P_k^{calc}$ ,  $Q_k^{calc}$  are computed using the power flow equations. Now modified Jacobian matrix due to power injections of TCSC

$$H_{new} = H + \frac{\partial P^{TCSC}}{\partial \delta} ; \quad N_{new} = N + \frac{\partial P^{TCSC}}{\partial V} V \quad (17)$$

$$J_{new} = J + \frac{\partial Q^{TCSC}}{\partial \delta} ; \quad L_{new} = L + \frac{\partial Q^{TCSC}}{\partial V} V \quad (18)$$

$H$ ,  $M$ ,  $N$  and  $L$  are the classic sub-Jacobians.

## 2.2 Device limits

The following minimum and maximum limits are considered for TCSC reactance.

$$-0.8X_{line} \leq X_{TCSC} \leq 0.2X_{line} \quad p.u.$$

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

## III. OPTIMAL LOCATION FOR TCSC

The power flows of highest severe contingency are considered as base case. From these flows, the branch with least power flow can be considered as the best location for the TCSC device. Because the transmission line has inductive reactance where as the TCSC is a series controlled device which can provide a capacitive reactance so that the total reactance of the branch which leads to the increase of loadability of the line where the device was located. The objective is, to increase the power transfer capability of the transmission line. The power transfer capability of the transmission line depends on the line reactance as well as bus voltages. Hence the loadability of the line can be increased either by reducing line reactance or increasing voltage profile. In order to reduce the reactance of the transmission line TCSC can be used. The voltage profile can be improved by injecting the reactive power at a particular bus where the voltage is minimum. The optimal location of the device is that where it gives maximum benefit for optimal size of FACTS devices placed at selected location.

### 3.1 Contingency analysis

Usually, outage of one of the transmission lines can be considered as the contingency condition. This happens due to many reasons; it may be because of maintenance of the transmission lines, environmental conditions, etc. Because of this situation, the transmission lines get overloaded. This contingency analysis analyzes the system security and gives future directions for the proper planning and designing. Because of this analysis, the preventive and corrective measures under contingency conditions can be predicted. Usually, the contingency condition may be due to a transmission line or a generator failure or a transformer failure. Out of which, transmission line failure plays an important role to assess the power system security.

### 3.2 Performance Index and Ranking

It is not required to consider each and every line outage to assess power system security. Because, for a particular line outage, there are few lines and buses do not have line flow and voltage variations beyond the limits. If there are any line overloads and bus voltage variations then the outage line is considered as critical line. The critical lines or credible contingencies are identified by contingency analysis and only these critical lines need to be taken to assess the power system security. A parameter which is known as performance index used for security analysis [15]. It indicates how much a particular outage might affect the security of power system. In general the performance index (PI) or severity index (SI) is defined as

$$\text{Severity index} = \sum_{l=1}^{N_{line}} \left( \frac{S_l}{S_l^{max}} \right)^{2m} \quad (19)$$

Where,  $S_l$ ,  $S_l^{max}$  are the MVA flow in line 'l' and MVA rating of the line 'l' respectively. 'm' is an integer exponent taken as 0.5.

The line flows are obtained by using power flow solution method. In Eqn. (19), the performance index is defined only based on over loaded lines.

## IV. STATIC VAR COMPENSATOR

The IEEE definition of the SVC is as follows: "A shunt connected static VAr generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)."

SVCs are used in a given power systems to enhance the voltage levels so that system stability has been improved.

### 4.1 Power injection model of SVC

In practice the SVC can be seen as an adjustable reactance with either firing-angle limits or reactance limits [16]. The equivalent circuit shown in Fig.3.4 is used to derive the SVC nonlinear power equations and the linearized equations required by Newton's method. With reference to Fig.4, the current drawn by the SVC is

$$I_{SVC} = jB_{SVC}V_i \quad (20)$$

and the reactive power drawn by the SVC, which is also the reactive power injected at bus-i, is

$$Q_{SVC} = Q_i = -V_i^2 B_{SVC} \quad (21)$$

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

It is a bank of three-phase static capacitors and/or inductors. Under heavy loading conditions, when positive VAR is needed, capacitor banks are needed, when negative VAR is needed, inductor banks are used. In this thesis SVC is modeled as an ideal reactive power injection at bus-i shown in Fig.4.

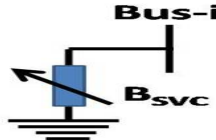


Fig.4. Power injection model of SVC

## 4.2 Installation cost of SVC

The Installation Cost (IC) [16] of SVC can be expressed as

$$IC_{SVC} = \frac{C_{SVC} \times S_{SVC} \times 1000}{n \times 8760} ; \quad \$/h \quad (22)$$

Here, Cost of Installation of SVC is

$$C_{SVC} = 0.0003S_{SVC}^2 - 0.3051S_{SVC} + 127.38 ; \quad \$/kVAr$$

Operating range of SVC ( $S_{SVC}$ ) in MVAR is  $S_{SVC} = |Q_{SVC}|$

Where,  $Q_{SVC}$  is the reactive power injected by SVC.

## 4.3 Device limits

The following limits are considered for SVC

$$-100 \text{ MVAR} \leq Q_{SVC} \leq 100 \text{ MVAR}$$

## 4.4 Selection of optimal location for SVC

The SVC should be placed in an optimal location to enhance the system stability.

### 4.4.1 Voltage Stability Index

The voltage stability index or  $L$ -index gives literally consistent results for voltage collapse prediction compared to other methods [17]. The  $L$ -indices are computed for all the load buses. The  $L$ -index gives a scalar integer to each load bus. The maximum of the  $L$ -indices gives the proximity of the system to voltage collapse. The benefit of this method is the simplicity of the numerical calculation and clarity of the results. For the given operating conditions, the voltage stability index is computed using load flow results and is given by

$$L_j = \left| 1 - \sum_{i=1}^{NG} F_{ij} \frac{V_i}{V_j} \right| \quad (23)$$

Where,  $j = NG + 1, \dots, NB$ ,  $V_i$  and  $V_j$  are the complex voltages of  $i^{th}$  and  $j^{th}$  bus respectively,  $F_{ji}$  are the complex elements of the matrix  $[F_{LG}]$ .

The matrix  $[F_{LG}]$  is obtained from the bus admittance matrix  $[Y_{bus}]$ .

If the  $L$ -index values for load buses are close to zero, indicates the system has maximum stability margin. If it is close to one, indicates the system is close to voltage collapse.

The following procedure is used to identify suitable SVC location and incorporation procedure.

**Step1:** Perform Newton Raphson load flow on a given system.

**Step2:** Obtain the system bus voltage magnitude values.

**Step3:** Calculate the Voltage Stability Index (VSI) at load buses.

**Step4:** Place the SVC at the bus, where the VSI value is high when compared to other buses.

**Step5:** In this location, with SVC, the VSI value has been enhanced.

## V.OPF PROBLEM FORMULATION

The aim of optimal power flow solution is, to optimize the selective objective function through proper adjustment of control variables by satisfying various constraints. The OPF problem can be represented as follows:

$$\text{Min } [A_m(x, u)] \quad (24)$$

Subjected to  $g(x, u) = 0$  and  $h_{min} \leq h(x, u) \leq h_{max}$

Where,

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

$A_m(x, u)$  is the function which is to be minimized  
 $g(x, u), h(x, u)$  represents equality and inequality constraints  
'x' and 'u' are dependent and independent variables

Optimal power flow solution gives an optimal control variable leads to the minimum generation fuel cost, emission and total power loss etc. subjected to all the various equality and inequality constraints. Here the vector 'x' consists of slack bus real power output ( $P_{G1}$ ), generator VAR output ( $Q_G$ ), load bus voltage magnitude ( $V_L$ ), line flow limits ( $S_l$ )

Thus 'x' can be written as,

$$x^T = [P_{G1}, V_{L1}, \dots, V_{L_{NL}}, Q_{G1}, \dots, Q_{G_{NG}}, S_{l1}, \dots, S_{l_{nl}}] \quad (25)$$

Where, NL=Number of load buses, NG=Number of generator buses, nl=Number of lines, u= is the independent variable vector such as continuous and discrete variables consists of

- (i) Generator active output 'P<sub>G</sub>' at all generators without slack bus
- (ii) Generator voltages V<sub>G</sub>
- (iii) Tap settings of transformer 'T'
- (iv) Shunt VAR compensation(or) reactive power injections Q<sub>C</sub>

Here P<sub>G</sub>, V<sub>G</sub> are continuous variables and T and Q<sub>C</sub> are the discrete variables. Hence 'u' can be expressed as

$$u^T = [P_{G2}, \dots, P_{G_{NG}}, V_{G1}, \dots, V_{G_{NG}}, Q_{C1}, \dots, Q_{C_{nc}}, T_1, \dots, T_{NT}] \quad (26)$$

'NT' and 'nc' re number of tap controlling transformers and shunt compensators.

## 5.1 Total power loss objective function

In power system, the active power loss should be minimized to enhance power delivery performance and can be calculated using

$$A_{TPL} = \sum_{i=1}^{N_{line}} g_i [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \quad MW \quad (27)$$

Where,  $N_{line}$  is total number of transmission lines,  $g_i$  is the conductance of ith line which connects buses  $i$  and  $j$ .  $V_i, V_j$  and  $\delta_i, \delta_j$  are voltage magnitude and angle of ith and jth buses.

## 5.2 Constraints

Constraints made in this OPF problem are usually two types. They are equality constraints and inequality constraints.

### 5.2.1 Equality constraints

These constraints mentioned in Eqn. (29) are usually load flow equations described as

$$P_{G,k} - P_{d,k} - \sum_{m=1}^{N_{bus}} |V_k| |V_m| |Y_{km}| \cos(\theta_{km} - \delta_k + \delta_m) = 0 \quad (28)$$

$$Q_{G,k} - Q_{d,k} - \sum_{m=1}^{N_{bus}} |V_k| |V_m| |Y_{km}| \sin(\theta_{km} - \delta_k + \delta_m) = 0 \quad (29)$$

where  $P_{G,k}, Q_{G,k}$  are the active and reactive power generation at the  $k^{th}$  bus,  $P_{d,k}, Q_{d,k}$  are the active and reactive power demands at the  $k^{th}$  bus,  $|V_k|, |V_m|$  are the voltage magnitudes at the  $k^{th}$  and  $m^{th}$  buses,  $\delta_k, \delta_m$  are the phase angles of the voltage at the  $k^{th}$  and  $m^{th}$  buses, and  $|Y_{km}|, \theta_{km}$  are the bus admittance magnitude and its angle between the  $k^{th}$  and  $m^{th}$  buses.

### 5.2.2 Inequality constraints:

These are the constraints represents the system operational and security limits which are continuous and discrete constraints.

Generator bus voltage limits:

$$V_{G_i}^{min} \leq V_{G_i} \leq V_{G_i}^{max} \quad \forall i \in NG$$

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

$$\begin{aligned}
 \text{Active power generation limits:} & \quad P_{G_i}^{min} \leq P_{G_i} \leq P_{G_i}^{max} \quad \forall i \in NG \\
 \text{Transformers tap setting limits:} & \quad T_i^{min} \leq T_i \leq T_i^{max} \quad \forall i \in nt \\
 \text{Capacitor reactive power generation limits:} & \quad Q_{sh_i}^{min} \leq Q_{sh_i} \leq Q_{sh_i}^{max} \quad \forall i \in nc \\
 \text{Transmission line flow limit:} & \quad S_{l_i} \leq S_{l_i}^{max} \quad \forall i \in nl \\
 \text{Reactive power generation limits:} & \quad Q_{G_i}^{min} \leq Q_{G_i} \leq Q_{G_i}^{max} \quad \forall i \in NG \\
 \text{Load bus voltage magnitude limits:} & \quad V_i^{min} \leq V_i \leq V_i^{max} \quad \forall i \in NL
 \end{aligned}$$

The control variables in this problem are self-constrained, whereas the in-equality constraints such as  $P_{G_i}$ ,  $V_i$ ,  $Q_{G_i}$ , and  $S_{l_i}$  are non-self-constrained by nature. Hence, these inequalities are incorporated into the objective function using a penalty approach [18]. The augmented function can be formulated as:

$$\begin{aligned}
 A_{aug}(x, u) = & A(x, u) + R_1 (P_{G_1} - P_{G_1}^{lim})^2 + R_2 \sum_{i=1}^{NL} (V_i - V_i^{lim})^2 \\
 & + R_3 \sum_{i=1}^{NG} (Q_{G_i} - Q_{G_i}^{lim})^2 + R_4 \sum_{i=1}^{nl} (S_{l_i} - S_{l_i}^{max})^2
 \end{aligned} \quad (30)$$

where  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  are the penalty quotients, which take large positive values. The limit values of the dependent variable  $x^{lim}$  can be given as:

$$x^{lim} = \begin{cases} x, & x^{min} \leq x \leq x^{max} \\ x^{max}, & x \geq x^{max} \\ x^{min}, & x \leq x^{min} \end{cases}$$

Where, ' $x^{lim}$ ', can be  $P_{G_1}$ ,  $V_i$ ,  $Q_{G_i}$ .

## VI.GRAVITATIONAL SEARCH ALGORITHM

The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. More precisely, masses obey the following laws:

The gravitational constant,  $G$ , is initialized at the beginning and will be reduced with time to control the search accuracy. In other words,  $G$  is a function of the initial value ( $G_0$ ) and time ( $t$ ):

$$G(t) = G(0) \times \exp\left(\frac{-\alpha t_i}{T}\right) \quad (31)$$

Where,  $\alpha$  is a constant,  $t_i$  is the iteration number and 'T' is the total number of iterations.

Consider a system of  $N$  agents. The position of  $i^{th}$  agent is defined as

$$X_i = (x_i^1, \dots, x_i^d, \dots, x_i^n) \quad ; \quad i = 1, 2, 3, \dots, N \quad (32)$$

For each position fitness function is evaluated.

### 6.1. Calculation of masses

Let  $fit_i(t)$  be the fitness function of  $i^{th}$  particle at  $t^{th}$  iteration.

Now we introduce new variables  $worst(t)$  and  $best(t)$ .

For a minimization problem,  $worst(t)$  and  $best(t)$  are defined as follows:

$$best(t) = \min(fit_j(t)) \quad ; \quad j = 1, 2, \dots, N \quad (33a)$$

$$worst(t) = \max(fit_j(t)) \quad ; \quad j = 1, 2, \dots, N \quad (30b)$$

For a maximization problem,  $worst(t)$  and  $best(t)$  are defined as follows:

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

$$best(t) = \max(fit_j(t)) \quad ; \quad j = 1, 2, \dots, N \quad (34a)$$

$$worst(t) = \min(fit_j(t)) \quad ; \quad j = 1, 2, \dots, N \quad (34b)$$

Gravitational and inertia masses are simply calculated by the fitness evaluation. A heavier mass means a more efficient agent. This means that better agents have higher attractions and walk more slowly. Assuming the equality of the gravitational and inertia mass, the values of masses are calculated using the map of fitness. We update the gravitational and inertial masses by the following equations:

$$M_{ai} = M_{pi} = M_{ii} = M_i \quad (35a)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (35b)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (35c)$$

## 6.2. Calculation of force

For iteration  $t$ , we define the force acting on mass  $i$  from mass  $j$  as following

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t)M_{aj}(t)}{R_{ij} + \epsilon} (x_j^d - x_i^d) \quad (36)$$

Where,  $M_{ai}$ ,  $M_{pi}$  are the active and passive gravitational masses related to agent  $j$ ,  $G(t)$  is gravitational constant at iteration  $t$ ,  $\epsilon$  is a small constant and  $R_{ij}$  is the Euclidian distance between two agents  $i$  and  $j$  given by

$$R_{ij}(t) = \|X_i(t) - X_j(t)\|_2 \quad (37)$$

Since  $M$  is a function of  $m$ , which is function fitness, in every iteration, one value of  $m$  is zero. Hence  $M$  is zero at this value of  $m$ . At this value of  $M$  acceleration becomes an indefinite value from above equations. To obtain integer value of  $K_{best}$ , it is rounded in terms of population. Hence we introduce another variable  $E$  which is defined as follows:

$$E_{ij}^d = \frac{F_{ij}^d}{MG} = \frac{M}{R_{ij} + \epsilon} (x_j^d - x_i^d) \quad (38)$$

$$E_i^d(t) = \sum_{j=1, j \neq i}^N rand_i E_{ij}^d(t) \quad (39)$$

## 6.3. Calculation of acceleration

Hence, by the law of motion, the acceleration of the agent ' $i$ ' at iteration  $t$ , and in direction  $d$ , is given as:

$$a_i^d = E_i^d(t) \times G(t) \quad (40)$$

Furthermore, the next velocity of an agent is considered as a fraction of its current velocity added to its acceleration. Therefore, its position and its velocity could be calculated as follows:

$$V_i^d(t+1) = rand_i \times V_i^d(t) + a_i^d(t) \quad (41a)$$

$$x_i^d(t+1) = x_i^d(t) + V_i^d(t+1) \quad (41b)$$

## VII. RESULTS AND ANALYSIS

In order to demonstrate the effectiveness and robustness of the proposed GSA method with TCSC, IEEE 30 bus system is considered. The existing and proposed methodologies are implemented on a personal computer with Intel Core2Duo 1.18 GHz processor and 2 GB RAM. The input parameters of the proposed GSA method for the considered test system are given in Table.1.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

**Table.1 Input parameters for test system**

| S. No | Optimization Method | Parameters                                           | Quantity                |
|-------|---------------------|------------------------------------------------------|-------------------------|
| 1     | GSA method          | Population                                           | 50                      |
|       |                     | Maximum iterations                                   | 100                     |
|       |                     | Initial gravitational constant ( $G_0$ )             | 100                     |
|       |                     | Decay constant ( $\alpha$ )                          | 5/10                    |
|       |                     | Constant ( $\epsilon$ )                              | $8.854 \times 10^{-12}$ |
|       |                     | Percentage of number of particles in final iteration | 2                       |
|       |                     | Rnorm                                                | 2                       |

This section presents the details of the study carried out on IEEE-30 bus test system to analyze OPF problem. The network and load data for this system is taken from [19]. In the IEEE 30-bus system consist 41 branches, six generator buses and 21 load buses. Four branches 6-9, 6-10, 4-12 and 27-28 have tap changing transformers. The buses with possible reactive power source installations are 10 and 24.

As the SVC is a shunt controlled FACTS device, the bus which suffers from high voltage stability index is required to install SVC. From the VSI values at load buses, it is identified that, bus-30 has the highest VSI value and is suitable to install SVC, because of this the VSI value has been enhanced.

From the base case analysis and from the power flows, it is observed that, the best location to install TCSC is between buses 29 and 30 i.e. line-39. For this line, the actual thermal limits is 16 MVA but at the actual flow is 3.753 MVA, there is a margin of 12.247 MVA for which we can increase the power flow.

From the above analysis, the optimal location to install SVC is bus 30 and for TCSC is line-30 between buses 29 and 30. The further analysis is assumed by placing these devices in these locations.

In this, the results of optimized values for all control variables for minimization of total power losses objective with proposed GSA method.

The summary of test results with TCSC or/and SVC are given in Table 2. The convergence characteristics of the proposed algorithm for all the cases are shown in Fig.5. From Table.2, it is observed that the transmission losses are reduced by 0.089697 MW with TCSC, 0.168259 MW with SVC and 0.29412 MW with both devices. Similarly, the respective losses with all devices are also tabulated.

**Table.2. OPF results of transmission losses with SVC or/and TCSC for IEEE-30 bus system**

| S. No | Control parameters             |            | Without Device | With     |          |            |
|-------|--------------------------------|------------|----------------|----------|----------|------------|
|       |                                |            |                | TCSC     | SVC      | TCSC & SVC |
| 1     | Real power Generation (MW)     | $P_{G1}$   | 51.67054       | 51.58084 | 51.50228 | 51.51396   |
|       |                                | $P_{G2}$   | 80             | 80       | 80       | 79.86245   |
|       |                                | $P_{G5}$   | 50             | 50       | 50       | 50         |
|       |                                | $P_{G8}$   | 35             | 35       | 35       | 35         |
|       |                                | $P_{G11}$  | 30             | 30       | 30       | 30         |
|       |                                | $P_{G13}$  | 40             | 40       | 40       | 40         |
| 2     | Generator voltages (p.u.)      | $V_{G1}$   | 1.081391       | 1.081725 | 1.1      | 1.1        |
|       |                                | $V_{G2}$   | 1.002046       | 1.075221 | 1.00795  | 1.1        |
|       |                                | $V_{G5}$   | 1.053754       | 1.053592 | 1.075769 | 1.084266   |
|       |                                | $V_{G8}$   | 1.044406       | 1.058184 | 1.1      | 1.090986   |
|       |                                | $V_{G11}$  | 0.95           | 1.04845  | 1.011929 | 1.023489   |
|       |                                | $V_{G13}$  | 1.085215       | 1.067607 | 1.0995   | 1.1        |
| 3     | Transformer tap setting (p.u.) | $T_{6-9}$  | 0.975477       | 0.976419 | 0.939681 | 0.935357   |
|       |                                | $T_{6-10}$ | 0.977022       | 1.029996 | 1.074929 | 1.088371   |
|       |                                | $T_{4-12}$ | 1.06188        | 1.0181   | 0.962218 | 0.986728   |

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

|    |                             |             |          |          |          |          |
|----|-----------------------------|-------------|----------|----------|----------|----------|
|    |                             | $T_{28-27}$ | 0.994792 | 0.992762 | 0.973932 | 0.978284 |
| 4  | Shunt compensators (MVar)   | $Q_{C,10}$  | 5        | 7.099966 | 26.85667 | 21.87159 |
|    |                             | $Q_{C,24}$  | 13.34311 | 20.37869 | 13.34461 | 12.72627 |
| 5  | $X_{TCSC}$ , P.u.           | -           | -        | -0.01955 | -        | 0.10293  |
| 6  | $Q_{SVC}$ , MVar            | -           | -        | -        | -0.93934 | -0.56373 |
| 7  | Total generation (MW)       | 286.6705    | 286.5808 | 286.5023 | 286.3764 |          |
| 8  | Non-convex fuel cost (\$/h) | 1149.539    | 1149.342 | 1149.169 | 1148.636 |          |
| 9  | Emission (ton/h)            | 0.207161    | 0.207148 | 0.207138 | 0.207066 |          |
| 10 | Total power losses (MW)     | 3.270536    | 3.180839 | 3.102277 | 2.976416 |          |

From Fig.5, it is observed that, in the presence of both devices, the iterative process starts with good function value and reached final best value in more number of iterations when compared to without and with TCSC and SVC. This is because of solving OPF in the presence of devices.

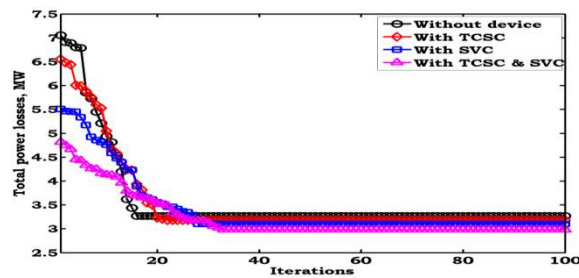


Fig.5. Convergence characteristics of transmission losses with SVC or/and TCSC for IEEE-30 bus system

The voltage magnitude at buses in transmission lines are tabulated in table.3 and the variation of voltage magnitudes are enhanced in the presence of both of the devices (SVC or/ and TCSC) instead of single device.

Table.3 Voltage magnitudes of transmission losses with SVC or/and TCSC for IEEE-30 bus system

| Bus No | Without Device | With      |            |            |
|--------|----------------|-----------|------------|------------|
|        |                | TCSC      | SVC        | TCSC & SVC |
| 1      | 1.0817254      | 1.0813909 | 1.1        | 1.1        |
| 2      | 1.0752206      | 1.0696171 | 1.1        | 1.0884304  |
| 3      | 1.0666997      | 1.0728291 | 1.09022437 | 1.0869737  |
| 4      | 1.0626532      | 1.0701083 | 1.08723417 | 1.0833121  |
| 5      | 1.0535923      | 1.0537538 | 1.08426624 | 1.075769   |
| 6      | 1.05692        | 1.0636716 | 1.0851551  | 1.084987   |
| 7      | 1.0481142      | 1.0521913 | 1.07761538 | 1.0739883  |
| 8      | 1.0581843      | 1.0745874 | 1.09098561 | 1.0958487  |
| 9      | 1.0520652      | 1.049413  | 1.10258579 | 1.1072686  |
| 10     | 1.0393846      | 1.0408689 | 1.08441794 | 1.094416   |
| 11     | 1.0484497      | 1.0274089 | 1.08184976 | 1.0866369  |
| 12     | 1.047948       | 1.0463689 | 1.0897663  | 1.0986409  |
| 13     | 1.0676068      | 1.0852148 | 1.1        | 1.0994996  |
| 14     | 1.0358693      | 1.033854  | 1.0776871  | 1.0868812  |
| 15     | 1.0330547      | 1.030748  | 1.07456596 | 1.083948   |
| 16     | 1.0368287      | 1.0365391 | 1.0802862  | 1.089683   |
| 17     | 1.0331828      | 1.0341342 | 1.07795643 | 1.0878148  |
| 18     | 1.0230467      | 1.0220606 | 1.06629489 | 1.0759986  |

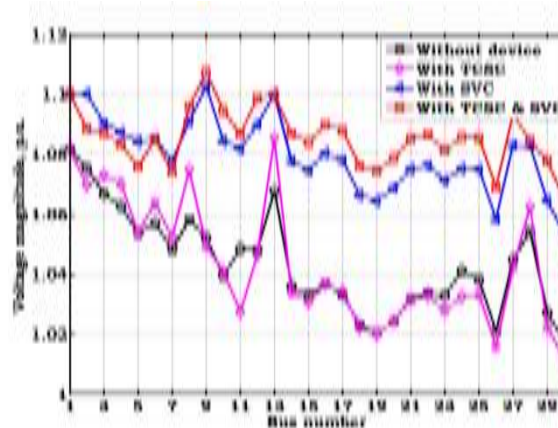
# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

|    |           |           |            |           |
|----|-----------|-----------|------------|-----------|
| 19 | 1.020284  | 1.0200867 | 1.06443416 | 1.0743016 |
| 20 | 1.0242574 | 1.0244769 | 1.06865673 | 1.0785625 |
| 21 | 1.031728  | 1.0313223 | 1.07502094 | 1.0852116 |
| 22 | 1.0337644 | 1.0327616 | 1.0763254  | 1.0865365 |
| 23 | 1.0327969 | 1.0277856 | 1.07123976 | 1.0811859 |
| 24 | 1.0411298 | 1.032475  | 1.0750817  | 1.0857169 |
| 25 | 1.0381138 | 1.0331131 | 1.07491032 | 1.0853114 |
| 26 | 1.0208037 | 1.0157161 | 1.05821389 | 1.0687805 |
| 27 | 1.0447505 | 1.0421229 | 1.0830711  | 1.0932478 |
| 28 | 1.0542603 | 1.0622911 | 1.082884   | 1.0843264 |
| 29 | 1.0270442 | 1.0225179 | 1.06443675 | 1.0777168 |
| 30 | 1.0176813 | 1.0117867 | 1.0536544  | 1.065149  |

From the figure.6,the variation of voltage magnitudes are enhanced in the presence of both of the devices (SVC or/ and TCSC) instead of single device.



**Fig.6. Variation of voltage magnitudes of transmission losses with SVC or/and TCSC for IEEE-30 bus system**

The power flow in transmission lines are tabulated in table.4 and from table.4 the variation of the power flow through transmission line loadings are enhanced in the presence of both of the devices instead of single device.

**Table.4 Power flows of transmission losses with SVC or/and TCSC for IEEE-30 bus system**

| Line No | Without Device | With      |           |            | MVA Limit |
|---------|----------------|-----------|-----------|------------|-----------|
|         |                | TCSC      | SVC       | TCSC & SVC |           |
| 1       | 29.304874      | 27.727674 | 29.244105 | 30.238681  | 130       |
| 2       | 24.283595      | 23.873914 | 23.976872 | 23.937027  | 130       |
| 3       | 22.159084      | 20.462955 | 21.144443 | 20.355171  | 65        |
| 4       | 21.496982      | 21.529276 | 21.521189 | 21.250916  | 130       |
| 5       | 39.423045      | 39.521004 | 39.541733 | 39.604265  | 130       |
| 6       | 26.743024      | 25.965155 | 27.059411 | 25.807392  | 65        |
| 7       | 26.849804      | 25.704492 | 27.212455 | 24.567664  | 90        |
| 8       | 5.9958593      | 8.0293128 | 6.0499415 | 8.8617463  | 70        |
| 9       | 28.898821      | 28.403584 | 28.805962 | 28.27255   | 130       |
| 10      | 27.897855      | 3.5442189 | 28.318977 | 15.325793  | 32        |
| 11      | 21.732755      | 16.120561 | 26.519436 | 32.310597  | 65        |

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

|    |           |           |           |           |    |
|----|-----------|-----------|-----------|-----------|----|
| 12 | 12.419016 | 7.8209338 | 16.886227 | 17.087561 | 32 |
| 13 | 32.300045 | 30.119287 | 32.22319  | 32.228897 | 65 |
| 14 | 34.283447 | 35.450336 | 35.991062 | 38.398362 | 65 |
| 15 | 17.423019 | 9.2843328 | 15.318523 | 10.660665 | 65 |
| 16 | 48.853058 | 42.285493 | 40.000805 | 40.613259 | 65 |
| 17 | 8.302466  | 8.3113549 | 8.3532564 | 8.3611318 | 32 |
| 18 | 20.249018 | 20.440528 | 20.537465 | 20.487468 | 32 |
| 19 | 9.2169708 | 9.4614708 | 9.566383  | 9.4899012 | 32 |
| 20 | 2.0022929 | 2.091412  | 2.0977188 | 2.0644721 | 16 |
| 21 | 5.7026739 | 5.7859532 | 6.1604488 | 6.0039854 | 16 |
| 22 | 6.9390358 | 7.1265022 | 7.1098921 | 7.083002  | 16 |
| 23 | 3.6557578 | 3.7628732 | 3.8749381 | 3.8209059 | 16 |
| 24 | 6.9040442 | 6.5307439 | 6.8737955 | 6.8271748 | 32 |
| 25 | 9.3346971 | 8.9661679 | 9.268081  | 9.2312826 | 32 |
| 26 | 7.7791057 | 7.1652087 | 7.9858466 | 7.753558  | 32 |
| 27 | 17.053424 | 16.187801 | 17.092119 | 17.146654 | 32 |
| 28 | 7.9718264 | 7.6249603 | 7.986438  | 8.012283  | 32 |
| 29 | 5.7332529 | 8.2318361 | 5.5400441 | 5.3953452 | 32 |
| 30 | 6.8892441 | 7.5723451 | 7.1427027 | 7.0025614 | 16 |
| 31 | 7.1350229 | 9.819002  | 6.9326396 | 6.8085216 | 16 |
| 32 | 4.8420981 | 6.0918419 | 5.1006022 | 4.8351297 | 16 |
| 33 | 0.9686747 | 0.8532351 | 1.0241381 | 0.9803194 | 16 |
| 34 | 4.2598111 | 4.2590968 | 4.2528557 | 4.2541575 | 16 |
| 35 | 4.0988673 | 3.433169  | 3.7947467 | 3.8706088 | 16 |
| 36 | 17.712324 | 17.00405  | 16.983428 | 17.436137 | 65 |
| 37 | 6.7510337 | 6.3038222 | 5.0473889 | 6.3904516 | 16 |
| 38 | 6.9244866 | 7.1589482 | 8.4931277 | 7.2594531 | 16 |
| 39 | 4.1119836 | 3.7050918 | 2.420351  | 3.7473294 | 16 |
| 40 | 4.9233534 | 4.21448   | 4.6694581 | 3.9664072 | 32 |
| 41 | 12.251381 | 12.352884 | 12.306503 | 12.050331 | 32 |

From the figure.7 the variation of the power flow through transmission line loadings are enhanced in the presence of both of the devices instead of single device.

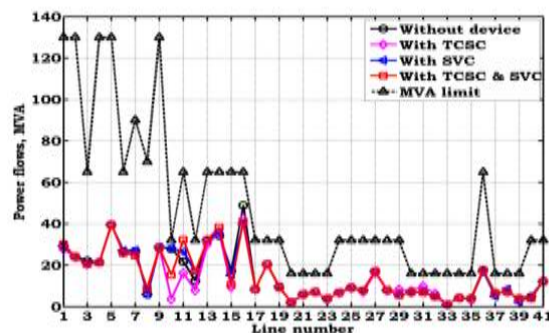


Fig.7. Variation of power flows of transmission losses with SVC or/and TCSC for IEEE-30 bus system

To support the effectiveness of the proposed method, obtained results are compared with the existing literature methods. The comparison is given in Table.5. From this table, it is identified that, the proposed method yields good results when compared to existing methods.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 2, February 2016

**Table.5. Validation of SCOPF results of TPL for IEEE-30 bus system**

| S. No | Method         | TPL (MW) |
|-------|----------------|----------|
| 1     | CLPSO [20]     | 4.5615   |
| 2     | HBMO [21]      | 4.4087   |
| 3     | CPVEIHBMO [22] | 4.3783   |
| 4     | Proposed GSA   | 3.3168   |

## VIII. CONCLUSION

In this paper, the OPF problem with reactive power dispatch is solved in the presence of TCSC and SVC while satisfying system, constraints and device limits. The effect of these controllers on bus voltage magnitudes and line power flows has been analyzed. The OPF results obtained in the presence of TCSC and SVC are compared with that of the results obtained without controller. The proposed methodology has been tested on standard IEEE-30 bus test system. The complete numerical results and graphical results are presented for the considered system. The obtained results are further validated with supporting literature methods.

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