Optimal Reactive Power Dispatch with SSSC Device Using NSGAII Approach

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Abstract
In an electric power systems, the transmission system become increasingly subject several constraints and difficulties to operate. In this paper, a Multi-Objective Evolutionary Algorithm (MOEA) to solve optimal reactive power (VAR) dispatch problem with Flexible AC Transmission System (FACTS) devices is presented, because their rapid response and enhanced flexibility to change the network parameters. This non linear Multi Objective Problem (MOP) consists to minimize simultaneously real power loss in transmission lines and voltage deviation at load buses. Static Synchronous Series Compensator (SSSC) is considered and described by mathematical models. Genetic algorithm is used to optimize the various functions in a power system with introduction of SSSC devices. The simulation was performed on the 6-bus system and implemented using MATLAB package.
Keywords:
Power Flow, Multi Objective Optimization, Evolutionary Algorithm, SSSC, Power Loss, Voltage Profile.

1. Introduction

In electric power network, the power flow calculations can be considered as the fundamental of power system network calculations, because they are the most frequently performed routine power network calculations which can be used in power system planning, operational planning, and operation/control.
In the literature, various power flow solution methods are proposed [1, 2]. Among the power flow proposed, the iterative Newton-Raphson method. This method is also used in present paper because of its quadratic convergence properties.
In recent years, there are emerging technologies available which can help to deal with problems of power system. One of such technologies is flexible AC Transmission system (FACTS) [3, 4]. There are a number of FACTS devices available, such as, the Static Synchronous Series compensator (SSSC) [5, 6] which can be used to generate and insert a series voltage, and it can be regulated to change the impedance of the transmission line. In this way, the power flow of transmission line, where the SSSC is connected is controlled. The generating stations, the transmission systems and the distribution systems are the three principles which compose an electric power system. It is through the transmission system that the electric power produced by generators will be consumed by loads. In the present day, the system of transmission became increasingly subjected several constraints and difficulties to operate, because the growing and tight demand of power flow.
With the advent of FACTS devices, in competitive electric power system, electric utilities can operate close to their limits [7]. In addition, FACTS devices can be used to minimize the total system power loss in the transmission lines, reduce the voltage deviation at load buses and maximize the power flow transfer capability.
This paper shows how easily and systematically an existing power flow program can be modified to include SSSC controllers [10], knowing that the traditional power flow programs do not include the newly developed controllers.
The objective of the present paper is to solve the VAR dispatch problem which is considered as a MOP. It consists to determine the optimal voltage profile and minimize the real power loss in transmission lines, using the genetic algorithm [11]. In particular, the elitist approach which is called No dominated Sorting Genetic Algorithm II (NSGAII) [12] was been used.
The remainder of the paper is organized as follows: Section 2 presents the model of power system with SSSC devices. Section 3 is consecrated to the formulation of the MOP. Application of MOEA and presentation of NSGAII approach are presented in section 4. Finally, Simulations results are given in section 5.

2. Principle of operation of SSSC

The operating principle of the SSSC can be explained using the simple two-bus system with associated voltage and current phasor diagram in Figure 1.

Manuscript received July 5, 2010
Manuscript revised July 20, 2010

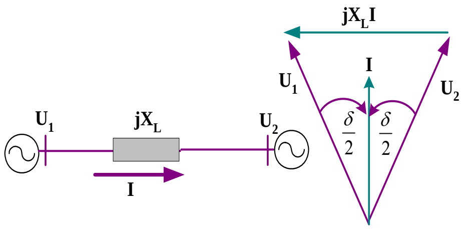

Figure 1. Simple two-bus power system

The active power flow between two buses can be expressed as :

$$P_{12} = \frac{U_1 U_2}{X_L} \sin\delta \qquad (1)$$

Where P_{12} is the active power flow from bus1 to bus 2.
U_1 is the magnitude of voltage at bus 1
U_2 is the magnitude of voltage at bus 2.
δ is a phase angle difference between two buses
X_L is the transmission line reactance.

If the SSSC is coupled to the transmission line, it will perform as controlled voltage source [13]. A single diagram and the phasor diagram of a transmission line with the series-compensated controllable voltage source are presented in Figure 2.

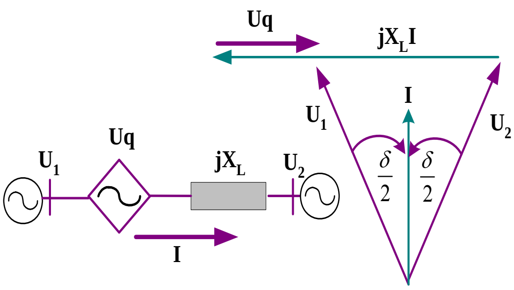

Fig.2. Two-bus system with controllable voltage source

The active power flow between two buses (P_{12}) of the compevsated transmission line is now expressed as follows :

$$P_{12} = \frac{U_1 U_2}{X_L} \sin\delta + \frac{U_1 U_q}{X_L} \cos(\frac{\delta}{2}) \qquad (2)$$

Where U_q is the quadrature voltage injected into the transmission line.

It can be observed from figure 3, that with the same line parameters as in (1), the active power flow (P_{12}) can be increased or decreased by assigning positive or a negative value to U_q.

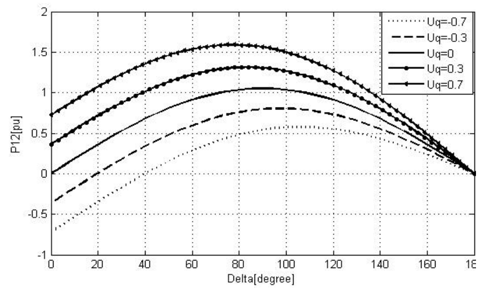

Figure 3. Power angle curve of the compensated

The SSSC can also perform a function of series impedance connected to the transmission line. The controllable series impedance compensator, which is inserted into the transmission line, can be viewed as a means to decrease the reactive line impedance. A single diagram and phasor diagram of a transmission line with a series impedance compensation is shown in Figure 4.

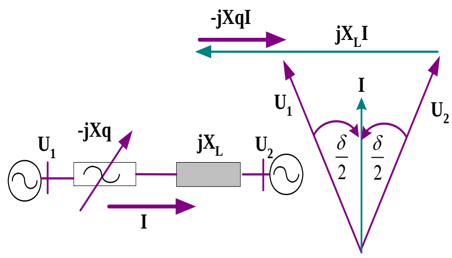

Figure 4. Two-bus system with series impedance compensation

The total transmission line impedance becomes equal to $X_L - X_q$ and the active power flow between two buses with series impedance compensation can be expressed as

$$P_{12} = \frac{U_1 U_2}{X_L(1-k)} \sin\delta \qquad (3)$$

Where :
Xq is the required series impedance compensation and k is the compensation ratio of Xq over XL.

$$k = \frac{X_q}{X_L}$$

The power equation (3) can be plotted by the power angle curve shown in Figure 5.

The power angle curve shows that power flow of the transmission line is increased with the positive compensation ration and it is decreased when the compensation ration is negative values.

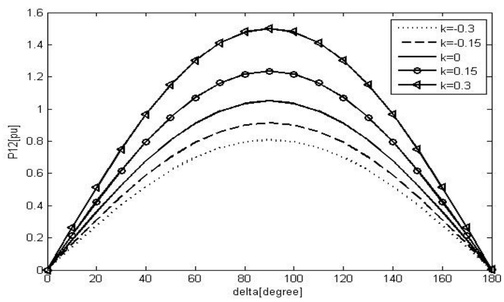

Figure 5. Power angle curve

The power flow of the transmission line can be represented again as a function of the compensation ratio as shown in Figure 6. It can be seen that the active power flow decrease when k is negative. This behaviour means that the controllable series impedance performs as a series inductor. On the contrary, the active flow increases when k is positive.

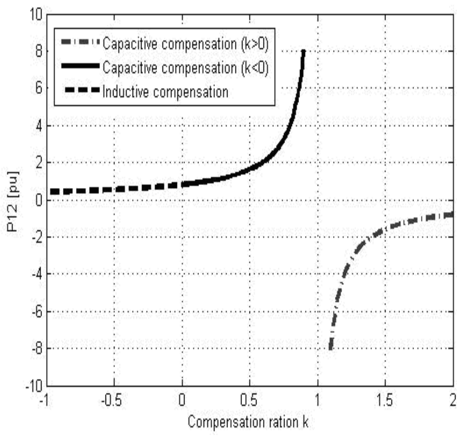

Figure 6. power flow versus compensation ratio

The transmittable active and the reactive powers can be expressed as :

$$P_{12} = \frac{U_1 U_2 k^2}{X_L\left(1+k^2\right)}\left(\sin\delta + \frac{1}{k}\left(1-\cos\delta\right)\right) \tag{4}$$

$$Q_{12} = \frac{U_1 U_2 k^2}{X_L\left(1+k^2\right)}\left(\frac{1}{k}\sin\delta + \left(1-\cos\delta\right)\right) \tag{5}$$

Where $k = \frac{X_L}{R}$

The normalized active and reactive power described respectively, by equations (4) and (5) are plotted as a parametric function of the ratio k in Figure 7. These plots clearly show that the maximum transmittable active and reactive powers decrease with decreasing the ratio k.

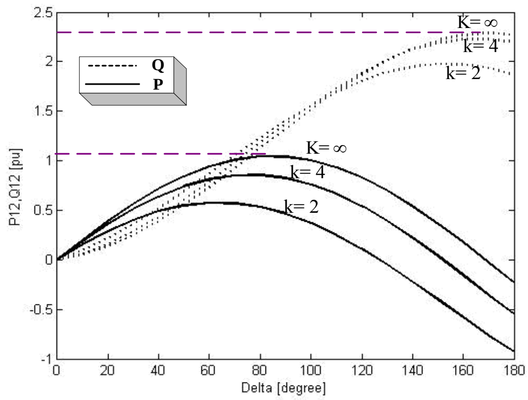

Figure 7. Transmitted real and reactive powers as a parametric function of the $\frac{X_L}{R}$ ratio.

2.1. Mathematical model of power systems with SSSC devices

The objective of this section is to give a power flow model for a power system with a SSSC device. Modified Newton-Raphson algorithm as described in [10] is used to solve the power flow equations.

a. Power flow analysis without SSSC

Consider a power system with N buses. For each bus i, the injected real and reactive powers can be described as :

$$P_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{6}$$

$$Q_i = \sum_{j=1}^{N} V_i V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{7}$$

Where :

V_i and δ_i are respectively modulus and argument of the complex voltage at bus i.

Y_{ij} and θ_{ij} are respectively modulus and argument of the ij-*th* element of the nodal admittance matrix Y.

The power flow equations are solved using the Newton-Raphson method where the nonlinear system is represented by the linearized Jacobian equation given by the following equation :

$$\begin{bmatrix} J^1 & J^2 \\ J^3 & J^4 \end{bmatrix}\begin{bmatrix} \Delta\alpha \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{8}$$

The ij-*th* elements of the sub-jacobian matrices J^1, J^2, J^3 and J^4 are respectively

$J^1(i,j)=\frac{\partial P_i}{\partial \delta_j}$, $J^2(i,j)=\frac{\partial P_i}{\partial V_j}$, $J^3(i,j)=\frac{\partial Q_i}{\partial \delta_j}$ and $J^4(i,j)=\frac{\partial Q_i}{\partial V_j}$.

b. Power flow analysis with SSSC

Figure 8 shows the circuit model of an SSSC connected at position *d* between two buses *k* and *m*.

d : portion of the impedance of line *k-m*, $d \in [0,1]$.

In its equivalent circuit shown in figure 1, the SSSC is represented by a voltage source E_s in series with the transformer impedance X_s [8, 9]. In practice, E_s can be regulated to control the power flow of line *k-m* and the voltage at buses *k* and *m*.

The schematic diagram of SSSC is shown in figure8.

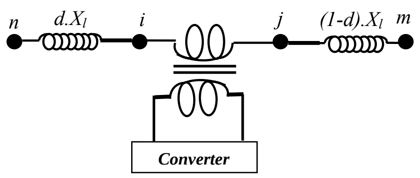

Figure 8 : Simplified diagram of SSSC

The series voltage source is modelled as an ideal series voltage E_s in series with impedance. E_s is controllable in magnitude and phase. Figure 9 represents the equivalent circuit of SSSC installed between buses *k* and *m*. Y_s is the admittance of the line *k-m* including the SSSC.

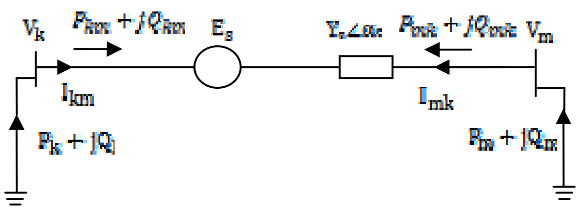

Figure 9 : Equivalent circuit of SSSC

The injected real and reactive powers for all buses of the system with SSSC remain same as those of the system without SSSC except for buses k and m, where they have the following expressions [10] :

$$P_k = P_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \cos(\delta_k - \delta_j - \theta_{kj}) \quad (9)$$

$$Q_k = Q_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \sin(\delta_k - \delta_j - \theta_{kj}) \quad (10)$$

$$P_m = P_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \cos(\delta_m - \delta_j - \theta_{mj}) \quad (11)$$

$$Q_m = Q_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \sin(\delta_m - \delta_j - \theta_{mj}) \quad (12)$$

Where :

$$P_{km} = V_k^2 Y_p \cos\theta_p + V_k^2 Y_s \cos\theta_s - V_k E_p Y_p \cos(\delta_k - \delta_p - \theta_p) + V_k E_s Y_s \cos(\delta_k - \delta_s - \theta_s) - V_m V_k Y_s \cos(\delta_k - \delta_m - \theta_s) \quad (13)$$

$$Q_{km} = -V_k^2 Y_p \sin\theta_p - V_k^2 Y_s \sin\theta_s - V_k E_p Y_p \sin(\delta_k - \delta_p - \theta_p) + V_k E_s Y_s \sin(\delta_k - \delta_s - \theta_s) - V_m V_k Y_s \sin(\delta_k - \delta_m - \theta_s) \quad (14)$$

$$P_{mk} = -V_m^2 Y_s \cos\theta_s - V_m E_s Y_s \cos(\delta_m - \delta_s - \theta_s) - V_m V_k Y_s \cos(\delta_m - \delta_k - \theta_s) \quad (15)$$

$$Q_{mk} = -V_m^2 Y_s \sin\theta_s - V_m E_s Y_s \sin(\delta_m - \delta_s - \theta_s) - V_m V_k Y_s \sin(\delta_m - \delta_k - \theta_s) \quad (16)$$

E_s and δ_s are magnitude and phase of the series voltage source.

Finally, the modified power flow equations can be solved with the Newton-Raphson method by using equation (8).

3. Problem formulation as a multi- objective optimization problem

In this paper, the ORPD problem including SSSC is defined to search the optimal location and design of the SSSC in order to minimize the real power losses and voltage deviation under several constraints.

c.1.Real power losses

The real power losses can be presented by the following equation [14-16]:

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (17)$$

c.2.Voltage deviation

This objective consists to minimize the deviation in voltage magnitude at load buses. It can be expressed as [17]:

$$V_D = \sum_{i=1}^{N_L} \left| V_i - V_i^{ref} \right| \quad (18)$$

Where :

N_L : number of load buses;

V_i^{ref} : prespecified reference value of the voltage magnitude at the *i-th* load bus.
In this paper, $V_i^{ref} = 1\ p.u$.

c.3.Problem constraints

The equality constraints are the load flow equations given by (19) and (20).

$$P_{Gi} - P_{Di} = P_i \quad (19)$$

$$Q_{Gi} - Q_{Di} = Q_i \quad (20)$$

Where :
P_{Gi} and Q_{Gi} are generated real and reactive powers at bus i , respectively.
P_{Di} and Q_{Di} are real and reactive power loads at bus i , respectively.

For the system with SSSC , when the losses are neglected, the active power P_{Es} injected via the series connected voltage source is equal to zero. So, other equality constraint is considered :

$$P_{Es} = E_s V_k Y_s \cos(\delta_s - \delta_k - \theta_s) - E_s V_m Y_s \cos(\delta_s - \delta_m - \theta_s) = 0 \quad (21)$$

The inequality constraints are :

- **Security limits**

Two inequality constraints are considered. The first constraint includes voltage limits at load buses as shown in (22)

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max}, i = 1,,..., N_L \quad (22)$$

Where V_{Li}^{min} and V_{Li}^{max} are respectively lower and upper limits voltage at load buses.
The second is represented by the line flow limits. It considers that the real power flow P_{li} in each transmission line i among the N_{line} lines of the power system must be lower than its maximum value P_{li}^{max} . Mathematically, it can be written as :

$$P_{li} \le P_{li}^{max}, i = 1,..., N_{line} \quad (23)$$

- **Operating limits of the SSSC**

Voltage magnitude and phase of series voltage sources of SSSC must lie within their lower and upper limits.

$$E_s^{min} \le E_s \le E_s^{max} \quad (24)$$

$$0 \le \delta_s \le 2\pi \quad (25)$$

4. Multiobjective optimization

In a MOP, there may not exist one solution that is best with respect to all objectives. Usually, the aim is to determine the trade-off surface, which is a set of nondominated solution points, known as Pareto optimal solutions. Every individual in this set is an acceptable solution.
For any two X_1 and X_2 , we can have one of two possibilities : one dominates the other or none dominates the other. In a minimization problem, we say that the solution X_1 dominates X_2 , if the following two conditions are satisfied [14] :

$$\begin{cases} \forall\, i \in \{\, 1, 2, ..., N_{obj} \,\},\ f_i(X_1) \le f_i(X_2) \\ \exists\, j \in \{\, 1, 2, ..., N_{obj} \,\},\ f_j(X_1) < f_j(X_2) \end{cases} \quad (26)$$

Where :
N_{obj} : Number of objective functions.
f_i : *ith* objective function.
The goal of a multi-objective optimization algorithm is not only to guide the search towards the Pareto optimal front, but, also to maintain population diversity in the set of the nondominated solutions.
In the rest of this section, we will present the elitist MOEA NSGAII. So, we must be start with a presentation of the NSGA approach.

a. NSGA approach

The basic idea behind NSGA is the ranking process executed before the selection operation. The ranking procedure consists to find the nondominated solutions in the current population *P*. These solutions represent the first front F_1. Afterwards, this first front is eliminated from the population and the rest is processed in the same way to identify nondominated solutions for the second front F_2. This process continues until the population is properly ranked. So, can write [15] :

$$P = \bigcup_{j=1}^{r} F_j$$

Where, *r* is the number of fronts.
The same fitness value f_k is assigned to all of individuals of the same front F_k. This fitness value decreases while passing from the front F_k to the F_{k+1}. To maintain diversity in the population, a sharing method is used. Let consider d_{ij} the variable distance (Euclidean norm) between two solutions $\underline{X}_i$ and $\underline{X}_j$.

$$d_{ij} = \sqrt{\sum_{k=1}^{S} \left(\frac{X_k^{(i)} - X_k^{(j)}}{X_k^{max} - X_k^{min}} \right)^2} \qquad (27)$$

Where S is the number of variables in the MOP. The parameters X_k^{max} and X_k^{min} respectively the upper and lower bounds of variable X_k.

$$\underline{X}_i = \left(X_1^{(i)}, X_2^{(i)}, \ldots, X_S^{(i)} \right) \qquad (28)$$

The sharing procedure is as follows :
Step 1 : Fix the niche radius σ_{share} and a small positive number ε.
Step 2 : Initiate $f_{min} = N_{pop} + \varepsilon$ and the counter of front $j = 1$.
Step 3 : From the r nondominated fronts F_j which constitute P.

$$P = \bigcup_{j=1}^{r} F_j$$

Step 4 : For each individual $\underline{X}_q \in F_j$:

- associate the dummy fitness $f_j^{(q)} = f_{min} - \varepsilon$;
- calculate the niche count n_{cq} as given in [15] ;
- calculate the shared fitness $f_j^{'(q)} = \dfrac{f_j^{(q)}}{n_{cq}}$.

Step 5 : $\mathrm{F_{min}} = \min(\mathrm{F_j^{'(q)}}; \mathrm{q} \in \mathrm{P_j})$ and $j = j+1$.
Step 6 : If $j \le r$, then, return to step 4. Else, the process is finished.
The MOEAs using nondominated sorting and sharing have been criticized mainly for their $O\left(MN^3\right)$ computational complexity (M is the number of objectives and N is the population size). Also, these algorithms are not elitist approaches and they need to specify the sharing parameter. To avoid these difficulties, we present in the following an elitist MOEA which is called Nondominated Sorting Genetic Algorithm II (NSGAII).

b. NSGAII approach

In this approach, the sharing function approach is replaced with a crowded comparaison.
Initially, an offspring population Q_t is created from the parent population P_t at the *tth* generation. After, a combined population R_t is formed [15].

$$R_t = P_t \cup Q_t$$

R_t is sorted into different no domination levels F_j as shown in the NSGA approach. So, we can write :

$R_t = \bigcup_{j=1}^{r} F_j$, where, r is number fronts.

Finally, one iteration of the NSGAII procedure is as follows :
Step 1 : Create the offspring population Q_t from the current population P_t.
Step 2 : Combine the two population Q_t and P_t to form R_t.
Step 3 : Find the all nondominated fronts F_i and R_t.
Step 4 : Initiate the new population $P_{t+1} = \varnothing$ and the counter of front for inclusion $i = 1$.
Step 5 : While $\left|P_{t+1}\right| + \left|F_i\right| \le N_{pop}$, do :

$P_{t+1} \leftarrow P_{t+1} \cup F_i$
$i \leftarrow i+1$

Step 6 : Sort the last front F_i using the crowding distance in descending order and choose the first $\left(N_{pop} - \left|P_{t+1}\right|\right)$ elements of F_i.
Step 7 : Use selection, crossover and mutation operators to create the new offspring population Q_{t+1} of size N_{obj}.
To estimate the density of solution surrounding a particular solution $\underline{X}_i$ in a nondominated set F, we calculate the crowding distance as follows:
Step 1 : Let's suppose $q = |F|$. For each solution $\underline{X}_i$ in F, set $d_i = 0$.
Initiate $m = 1$.
Step 2 : Sort F in the descending order according to the objective function of rank m.
Let's consider $I^m = sort_{[f_m >]}(F)$ the vector of indices, i.e. I_i^m is the index of the solution $\underline{X}_i$ in the sorted list according to the objective function of rank m.
Step 3 : For each solution $\underline{X}_i$ which verifies $2 \le I_i^m \le (q-1)$, update the value of d_i as follows:

$$d_i \leftarrow d_i + \frac{f_m^{I_i^{m+1}} - f_m^{I_i^{m-1}}}{f_m^{max} - f_m^{min}} \qquad (29)$$

Then, the boundary solutions in the sorted list (solutions with smallest and largest function) are assigned an infinite distance value, i.e. if, $I_i^m = 1$ or $I_m^i = q$, $d_i = \infty$.
Step 4 : If $m = M$, the procedure is finished. Else, $m = (m+1)$, and return to step 2.

c. Implementation of the NSGAII

The proposed NSGAII has been implemented using real-coded genetic algorithm (RCGA) [15]. So, a chromosome X corresponding to a decision variable is represented as a string of real values x_i, i.e. $X = x_1 x_2 ... x_{lchrom}$. $lchrom$ is the chromosome size and x_i is a real number within its lower limit a_i and upper limit b_i. i.e. $x_i \in [a_i, b_i]$. Thus, for two individuals having as chromosomes respectively X and Y and after generating a random number $\alpha \in [0,1]$, the crossover operator can provide two chromosomes X' and Y' with a probability P_C as follows [14, 15] :

$$\begin{aligned} X' &= \alpha X + (1-\alpha) Y \\ Y' &= (1-\alpha) X + \alpha Y \end{aligned} \tag{30}$$

In this study, the non-uniform mutation operator has been employed. So, at the *t*th generation, a parameter x_i of the chromosome X will be transformed to other parameter x_i' with a probability P_m as follows :

$$x_i' = \begin{cases} x_i + \Delta(t, b_i - x_i), & if \quad \tau = 0 \\ x_i - \Delta(t, x_i - a_i), & if \quad \tau = 1 \end{cases} \tag{31}$$

$$\Delta(t, y) = y\left(1 - r^{(1-t/g_{max})^{\beta}}\right) \tag{32}$$

Where τ is random binary number, r is a random number $r \in [0,1]$ and g_{max} is the maximum number of generations. β is a positive constant chosen arbitrarily.

5. Numerical analysis

The proposed procedure for solving dispatch VAR including FACTS devices is tested on the 6-bus system [16].

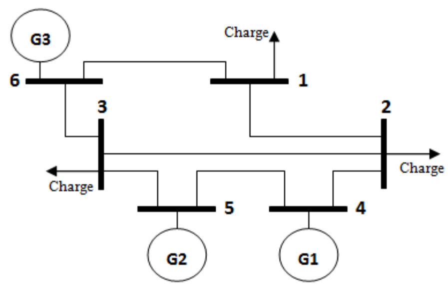

Figure 10. IEEE 6-bus test system

The one-line diagram of this system is shown in figure 10. The system consists of three generators at buses 4, 5 and 6. Bus 6 is considered at the slack bus. Buses 1, 2 and 3 are the load buses.

a. Presentation of the test System

The characteristics of lines and buses are marked in the tables 1 and 2 respectively. These values are given in pu. Considering a base power of 100 MVA for the overall system and base voltages of 100 KV. The lower voltage magnitude limits at all buses are 0.9 pu and the upper limits are 1.1 pu. Two cases of power analysis are considered. Case 1 assumes the study without any compensation. Case 2 assumes an SSSC in link 1-2. R, X, V, P_G, Q_G, P_L and Q_L are given in *p.u*.

Table1: Data lines

Line		Impedance	
Bus i	Bus j	*R*	*X*
1	2	0.02	0.4
1	6	0.01	0.15
2	3	0.05	0.5
2	4	0.015	0.15
3	5	0.05	0.5
3	6	0.05	0.5
4	5	0.08	0.8

Table 2: Data buses

Bus	V	P_G	Q_G	P_L	Q_L
1	-	0	0	0.700	0.200
2	-	0	0	0.700	0.200
3	-	0	0	0.800	0.100
4	1.025	0.350	-	0.100	0.100
5	1.084	0.450	-	0.100	0.100
6	1.000	-	-	0.100	0.100

For the system without FACTS controllers, the voltage magnitude of load buses are not maintained within their permissible limits (table 3). The corresponding values of voltage deviation and real power loss are respectively :
$V_D = 0.3571 pu$ and $P_L = 0.2010 pu$

Table 3 : Voltage magnitudes and phase angles for the system without FACTS controllers

Bus	1	2	3	4	5	6
V	0.828	0.868	0.947	1.025	1.084	1.00
α [rad]	-0.29	-0.36	-0.19	-0.26	-0.14	0

Figure 11 shows the convergence characteristics of the load flow program after 5 iterations with a tolerance of 10^{-5}.

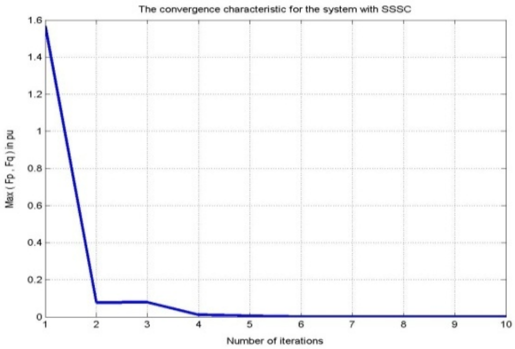

Figure 11. Convergence of the load flow

b. Optimisation With SSSC

Figures 12 and 13 show respectively, the convergence of voltage deviation and power loss to 0.22 pu and 0.106 pu., where, the system is with SSSC. These objectives are optimized individually.

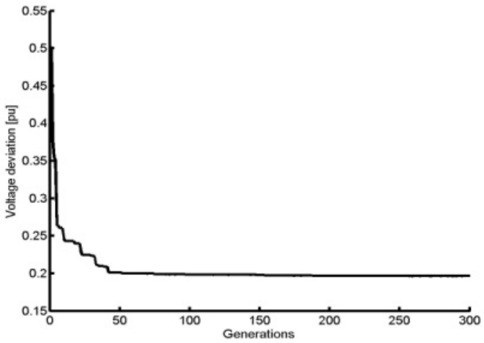

Figure 12. Convergence of voltage deviation

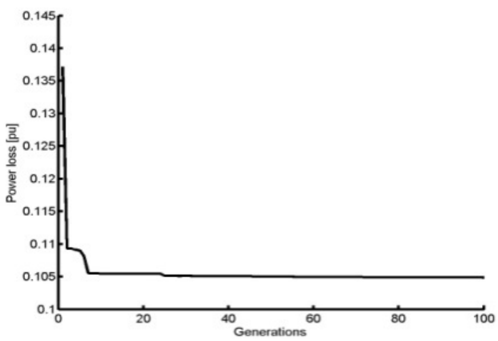

Figure 13. Convergence of power loss objective

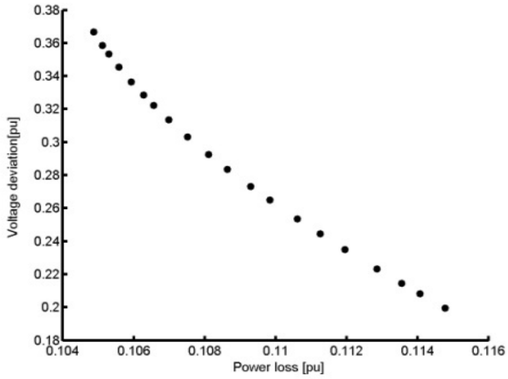

Figure 14. Pareto-optimal front

The diversity of the pareto optimal set over the trade off surface is shown in figure 14.

After optimization by the NSGAII approach, we have obtained the tables 4 and 5 giving the best solutions for minimum voltage deviation and minimum real power loss respectively for the system with SSSC. The values of E_s, d , V_D and P_L are given in $p.u.$ δ_s is in radian.

Table 4 : The best solution for voltage deviation

E_s	δ_s	d	V_D	Correspondent P_L
0.19	5.06	0.95	0.41	0.133

Table 5 : The best solution for real power loss

E_s	δ_s	d	P_L	Correspondent V_D
0.11	4.74	0.33	0.131	0.473

The profile voltage in load buses corresponding to the best solutions given in table 4 and table 5 are shown in tables 6 and 7.

Table 6 : for minimum voltage deviation

	V_1	V_2	V_3
SSSC	0.9015	0.9591	0.9467

Table 7 : For minimum real power loss

	V_1	V_2	V_3
SSSC	0.9070	0.9541	0.9406

V_i is in pu and α_i is in rad.

c. Effect of SSSC

The effect of SSSC on active power flow of line 1-2, where it is installed, for a full circle of the angle δ_s . Four values of E_s are considered. It is shown that the

active power in this line without SSSC is 0.9 pu and its maximum change in positive or
is placed at the beginning of the lower line between buses 1 and 2 in order to see the influence on the power flow through that line as well as on the bus voltages. The SSSC has two control parameters, E_s and δ_s , the magnitude and the phase of the injected voltage respectively. Thereby. Figures 15 and 16 shows active power flow in line 1-2, where the SSSC is located.

Figure 15 shows the power flow in line 1-2 where δ_s is kept constant at various values while E_s varies from 0 to 0.2. It can be see that the controllability of the power flow with r is maximal when δ_s =π/2 for increasing power flow and when δ_s =3π/2 for decreasing load flow. The relationship between E_s and active power flow is monotonic for fixed δ_s .

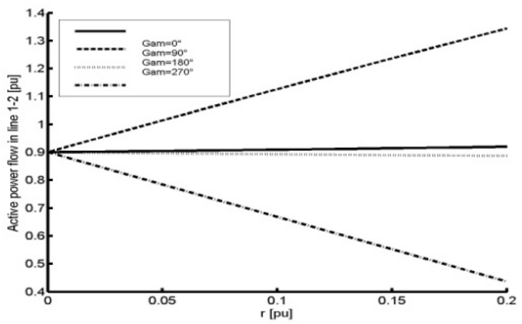

Figure 15. Active power flow in line 1-2

Figure 16 shows the same active power flow in line 1-2 but with respect to rotational change in E_s and δ_s . That means , r is kept constant at some values for a full circle of the angle δ_s (0° : 360°). Is it obvious that the active power flow is maximal when r is maximal.

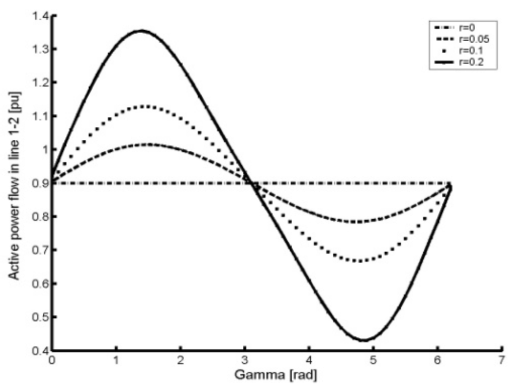

Figure 16. Active power flow in line 1-2 With SSSC

Figure 17 shows the relation of the both parameters in single three dimension picture.

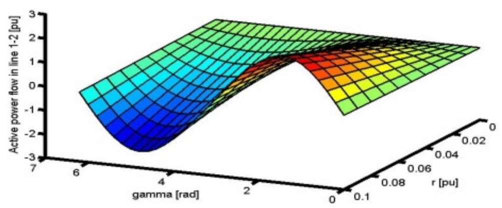

Figure.17. Effect of both parameters on Active power flow

Figures 18 and 19 show the bus voltages at the bus 1 and bus 2 , with respect to the rotational change in E_s and δ_s of SSSC. V_i and V_j are controlled in this case. As can be seen the voltage magnitude have opposite directions. One of them has magnitude increased when the other one is decreased. egative direction is obtained when E_s is maximal.

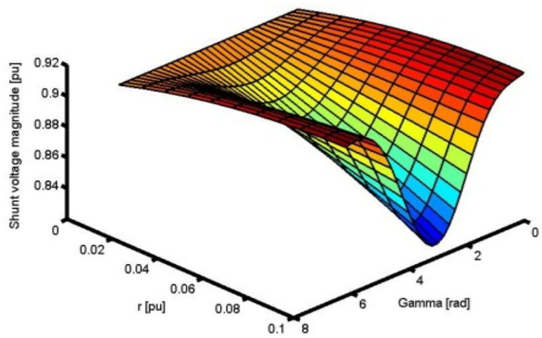

Figure 18. Side bus voltage magnitude V_i

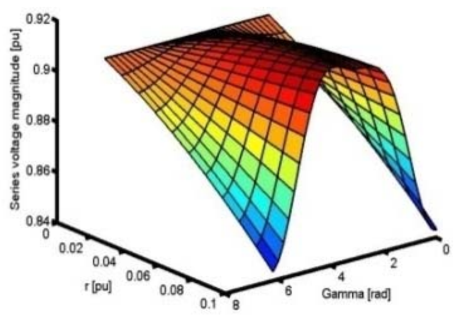

Figure 19. Side bus voltage magnitude V_j

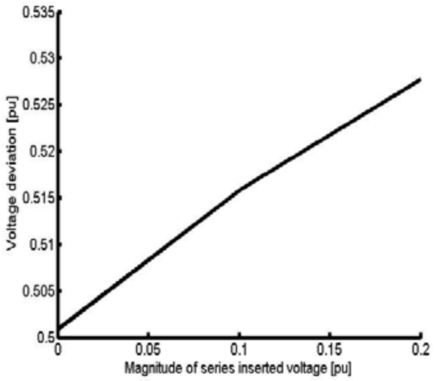

Figure.20. Voltage deviation for δ_s = 90°

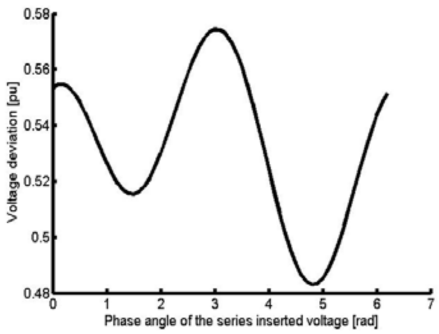

Figure 21. Voltage deviation for E_s = 0.1 pu

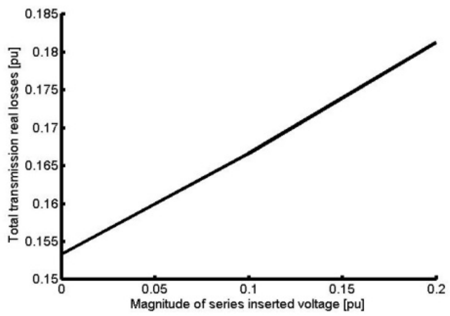

Figure 22. Total transmission real losses for δ_s = 90°

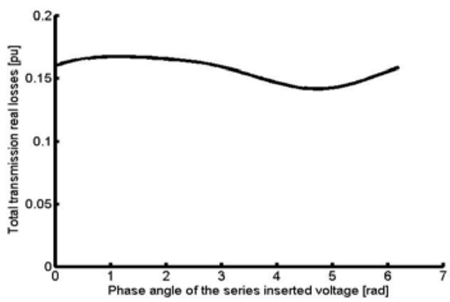

Figure 23. Total transmission real losses for E_s = 0.1 pu

SSSC device is positioned on the middle of line 1-2, so the line 1-2 is the controlled line. Effects of SSSC on system parameters such as; total transmission real losses and voltage deviation of the system are investigated. During simulations, when SSSC parameter is controlled, another is kept constant. Namely, while E_s is controlled, is kept constant, and vice versa. The constant values of E_s and δ_s are 0.1 pu and 90°, respectively. From the results of total transmission real losses and voltage deviation of each simulation task are graphically presented in figures 20 to 23.

6. Conclusion

In this paper, an approach based on the NSGAII has been presented and applied to multiobjective VAR dispatch optimization problem with system FACTS. The problem has been formulated as multiobjective optimization problem with computing real power loss and deviation voltage objectives. By tuning parameters and location of SSSC. The different simulations of SSSC, indicates the following results:There were no significant changes both on voltage deviation in IEEE 6-bus test system. But only a 10% decrease of real power loss is obtained with SSSC, when is positioned on the line 1-2.

The user-defined model approach for SSSC is effective and reliable in terms of the computational speed, accuracy and computing resources requirement in commercial software. A SSSC can be theoretically located anywhere along a transmission line in a power system. With this respect, the effects of SSSC allocation on power flow solution have been thoroughly investigated.

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