Fuzzy based evolutionary algorithm for reactive power optimization with FACTS devices

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A B S T R A C T

In this paper, optimization techniques such as Genetic Algorithm (GA) and Differential Evolution (DE) along with Fuzzy Logic (FL) is used for the optimal setting of power system variables, including Flexible AC Transmission Systems (FACTS) devices. Here, two types of FACTS devices, Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are used for the optimal operation of the power system as well as in reducing congestion in transmission lines. Optimal placement of FACTS devices in the heavily loaded power system reduces transmission loss, controls reactive power flow, improves voltage profile of all nodes and also reduces operating cost. In this proposed approach fuzzy membership function is used for the selection of weak nodes in the power system for the placement of SVC's as one of the FACTS devices while the location of TCSC's are determined by the reactive power flow in lines. The proposed technique is compared with other optimization methods using different globally accepted evolutionary algorithms where the nodes are detected by eigen value analysis and the amount of FACTS devices are determined by evolutionary techniques like, Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO). The superiority of the proposed fuzzy based optimization approach is established by the results and the comparative analysis with other methods.

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1. Introduction

In the present day scenario, due to increase in power demand, restriction on the construction of new lines, environment, unscheduled power flow in lines creates congestion in the transmission network and increases transmission loss. Effective control of reactive compensation on weak nodes improves voltage profile, reduces power loss and improves both steady state and dynamic performance of the system. With the development of FACTS devices, it has now become an obvious choice to use them in today's power system to extract maximum advantage out of it. The concept of flexible AC transmission system (FACTS) was first introduced by Hingorani [1]. FACTS devices are solid-state converters having the capability of control of various electrical parameters in transmission circuits. Optimal location of FACTS devices for congestion management by controlling device parameters is discussed in [2]. The optimal location of Thyristor Controlled Series Compensator (TCSC) is presented in [3] for the reduction of transmission loss. Optimal reactive power dispatch along with the setting of switchable series and shunt FACTS devices is discussed in [4].

Optimal placement of Var sources by loss sensitivity based method is presented in [5]. In [6] authors have presented a new generalized current injection model for power transfer using TCSC, Unified Power Flow Controller (UPFC), Generalized Unified Power Flow Controller (GUPFC). Steady state optimization with series FACTS devices was the main objective of the work in [7]. Power flow model with multiple FACTS controller is presented in [8]. In [9] author has used TCSC for inductive as well as capacitive reactance compensation to increase the transmission line capacity. Kumar and Sekhar in [10] presented an approach using rescheduling of generators for congestion management with voltage stability constraint taken as loadability parameter into consideration along with the line security limits. A new technique as teaching learning based optimization (TLBO) and quasi-oppositional TLBO (QOTLBO) is presented in [11] for the solution of multi-objective optimal reactive power dispatch (ORPD) problems of power system by minimizing real power loss and voltage deviation. Optimal coordination of FACTS devices using evolutionary strategy is presented in [12]. Genetic Algorithm (GA) is used for the optimal setting of multi-type FACTS devices in [13]. The optimal locations and sizing parameters of multi-type FACTS devices using a graphical user interface (GUI) based on a Genetic Algorithm (GA) in large power systems is presented in [14]. A security constraint GA based approach in defining maximum loadability limit of a power system
is presented in [15]. Particle Swarm Optimization (PSO) approach in handling FACTS devices in power system is presented in [16,17]. Various objectives of reactive power problem in interconnected power system and different solution techniques are addressed in [18]. Solution methodology and comparative analysis using DE and PSO algorithm with FACTS devices under different loading conditions is presented in [19], Basu in [20] proposed Differential Evolution (DE) algorithm for the minimization of generator fuel cost using FACTS devices. Hybridization of DE and PSO (DEPSO) to determine the maximum loadability limit of power system is presented in [21]. Reactive power flow control using fuzzy-sets is discussed in [22]. In [23] the authors have introduced a technique for the use of fuzzy membership function in reactive power optimization. An optimal reactive power scheduling method to minimize active power loss and maximizes Voltage Stability Margin (VSM) using Fuzzy-LP method is dealt in [24]. A technique for placement and sizing of shunt FACTS controller with combined Fuzzy and GA approach for optimal reactive power reinforcement is discussed in [25]. Integration of Fuzzy Systems with Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm to solve the optimal power flow (OPF) problem for optimal setting of control variables is the theme of the paper [26]. In [27,28] authors main work is focused on fuzzy-based reactive power and voltage control to minimize real power loss.

In this paper two types of FACTS devices have been discussed namely TCSC (Thyristor Controlled Series Capacitor) and SVC (Static Var Compensator). The main objective of this paper is to find the optimal location of FACTS devices in the transmission network to minimize the transmission loss and also for the simultaneous increase of power transfer capacity of the transmission network that ultimately results minimum operating cost under different loading conditions. There are three main issues that are to be considered for the selection of FACTS devices, its types, its capacity and location where to be installed. Placement of FACTS devices is done on IEEE-30 bus test system in the present work. TCSC's are placed in lines where reactive power flows are very high, placement of SVC's is determined by the fuzzy membership of loss sensitivity in the weak nodes and the optimal parameter settings of these FACTS devices are governed by Genetic Algorithm and Differential Evolution. This combined Fuzzy-GA and Fuzzy-DE approach is compared with other simple evolutionary algorithmic approaches like Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO), where detection of weak nodes is determined by eigen value analysis.

2. Modeling of FACTS devices

For an interconnected congested power network FACTS devices can be modeled as power injection model. The injection model describes the FACTS as a device that injects a certain amount of real and reactive power to a node. Both TCSC and SVC devices control the power flow and voltages by adjusting the reacance of the system.

2.1. Thyristor Controlled Series Compensator (TCSC)

Transmission line model with a TCSC connected between bus-i and bus-j is shown in Fig. 1. In steady state, the TCSC can be considered as an additional reacance $-jX_{TCSC}$. TCSC acts as either inductive or capacitive compensator by modifying transmission line reactance. By installing TCSC’s in transmission line power capacity increases and also the voltage profile improves. The injection model of TCSC is shown in Fig. 2. Transmission line admittance with TCSC is represented by:

$$Y_{TCSC} = \frac{1}{R_j X_{TCSC}}$$

where $R$ and $X_{line}$ are the resistance and reacance of the line without TCSC and $X_{TCSC}$ is the reacance with TCSC.

2.2. Static Var Compensator (SVC)

The SVC can operate either in capacitive mode or in inductive mode. The function of SVC is either to inject reactive power to the bus or to absorb reactive power from the bus where it is connected. It improves the voltage in static and dynamic conditions and reduces active power loss. The variable susceptance model of SVC is shown in Fig. 3.

Here, TCSC value and SVC value is the operating values of the FACTS devices.

3. Cost function and problem formulation

According to [29], cost functions for TCSCs and SVCs are given below:

TCSC:

$$C_{TCSC} = 0.0015(\text{TCSC value})^2 - 0.7130(\text{TCSC value}) + 153.75 \text{ (US/kVar)}$$

SVC:

$$C_{SVC} = 0.0003(\text{SVC value})^2 - 0.3051(\text{SVC value}) + 127.38 \text{ (US/kVar)}$$

Here, TCSC value and SVC value is the operating values of the FACTS devices.

The main objective is to find the optimal location of FACTS devices along with network constraints so as to minimize the total operational cost and relieve transmission congestion at different loading conditions. Installation costs of various FACTS devices and the cost of system operation, namely, energy loss cost are combined to form the objective function to be minimized. Besides FACTS devices, transmission loss can be minimized by optimization of reactive power, which is possible by controlling reactive generations of the generator, controlling transformer tap settings, and by the addition of shunt capacitors at weak buses.

The optimal allocation problem of FACTS devices can be formulated as:

$$C(T) = C_1(E) + C_2(F)$$

where $C_1$ ($E$) is the cost due to energy loss, $C_2$ ($F$) is the total investment cost of the FACTS devices and $C(T)$ is the operational cost of the system.

The active and reactive nodal power should be within the limits as:

$$P^\text{min}_m \leq P_m \leq P^\text{max}_m$$

Fig. 1. TCSC model.

Fig. 2. TCSC injection model.

Fig. 3. SVC model.
and

\[ Q_m^\text{min} \leq Q_m \leq Q_m^\text{max} \]

Again, these active and reactive nodal powers have to satisfy voltage magnitude constraints: \( V_i^\text{min} \leq V_i \leq V_i^\text{max} \) as well as the existing nodal reactive capacity constraints:

\[ Q_{gi}^\text{min} \leq Q_{gi} \leq Q_{gi}^\text{max} \]

Superscripts \( \text{min} \) and \( \text{max} \) are the minimum and maximum limits of the variables.

The power flow equations between the nodes \( i-j \) after incorporating FACTS devices would appear as:

\[
P_{ij} = V_i^2 G_{ij} - V_i V_j \left( G_{ij} \sin \delta_i + B_{ij} \sin \delta_j \right)
\]

\[
Q_{ij} = -V_i^2 B_{ij} - V_i V_j \left( G_{ij} \sin \delta_i - B_{ij} \cos \delta_j \right)
\]

\[
P_{ji} = V_j^2 G_{ji} - V_i V_j \left( G_{ji} \cos \delta_j - B_{ji} \cos \delta_i \right)
\]

\[
Q_{ji} = -V_j^2 B_{ji} + V_i V_j \left( G_{ji} \sin \delta_j + B_{ji} \cos \delta_i \right)
\]

where \( G \) and \( B \) are the real and imaginary components of bus admittance matrix with the inclusion of FACTS devices such as TCSC and SVC. Whereas \( G \) and \( B \) are the real and imaginary part of Ybus matrix without FACTS devices. Inclusion of TCSC in lines modifies reactance of that line and Ybus matrix is modified accordingly. The real and reactive power flow will also change correspondingly in that line. Ybus matrix is modified with the new value of line reactance considering presence of TCSC in that line in the following manner:

\[
\text{for } j = 1: n_{\text{TCSC}}
\]

\[
\text{Linedata}(\text{TCSC}\_\text{pos}(j)) = \text{Linedata}(\text{TCSC}\_\text{pos}(j)) - \sqrt{-1} \cdot \text{TCSC}_{\text{value}}
\]

end

Similarly SVC placement at a weak node corresponds to reactive power injection at that node and accordingly there will be a change in reactive power flow in the line connected to that line. The Ybus matrix will also be modified with SVC in the following way:

\[
\text{for } j = 1: n_{\text{SVC}}
\]

\[
\text{Shunt}(\text{SVC}\_\text{pos}(j)) = \sqrt{-1} \cdot \text{SVC}_{\text{value}}
\]

end

where \( n_{\text{TCSC}} \) and \( n_{\text{SVC}} \) are the number of TCSC and SVC elements respectively.

\( \text{TCSC}_{\text{value}} \) and \( \text{SVC}_{\text{value}} \) are the values of TCSC’s and SVC’s respectively.

In this way original Ybus matrix is modified into:

\[
\text{Ybus} = G' - jB'
\]

Then load flow is executed with this modified admittance matrix in evaluating the objective function for each individual population of generation in the cases of GA, PSO and DE.

4. Weak node detection using fuzzy logic

The main objective of this work is the placement of FACTS devices in optimal locations of the interconnected power network. In this paper TCSC’s are placed at lines carrying significantly high reactive power while the locations of SVC’s are selected by calculating fuzzy membership of loss sensitivities of different buses in the standard IEEE-30 bus system. Transmission loss in an interconnected power system is given as:

\[
P_{\text{loss}} = \sum_{k=1}^{n} F_k \left( V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j) \right)
\]

and the incremental transmission loss may be written as:

\[
\Delta P_{\text{loss}} = \frac{\partial P_{\text{loss}}}{\partial V_i} \frac{\partial P_{\text{loss}}}{\partial V_j} \frac{\partial P_{\text{loss}}}{\partial \delta_i} \frac{\partial P_{\text{loss}}}{\partial \delta_j} \left[ \Delta V_1 \Delta V_2 \ldots \Delta V_n \right]^T
\]

or \( \Delta P_{\text{loss}} = C \cdot \Delta V \)

where \( C_i = \frac{\partial P_{\text{loss}}}{\partial V_i} \) is the loss sensitivity of each bus.

Fuzzy set is used to linearized objective function as:

\[
F_1 = C_1 \cdot \Delta V_1
\]

\[
F_2 = C_2 \cdot \Delta V_2
\]

\[
\ldots
\]

\[
F_n = C_n \cdot \Delta V_n
\]

where \( C_i = \frac{\partial P_{\text{loss}}}{\partial V_i} \) and \( i = 1,2,3 \ldots n \).

The minimization of active power loss will take place when each \( F_i \) is as negative as possible which indicates that if \( C_i \) is negative and \( \Delta V_i \) will attain its maximum positive value. So more the value of \( F_i \) at a bus more will be the voltage deviation at that bus. A fuzzy based reasoning approach is developed by assuming the maximum negative value of \( F_i \) as \( E_{mi} \). A large value of \( C_i \) or less sensitivity at \( i \)th bus indicates that this \( i \)th bus requires reactive power compensation by some means. Now fuzzy logic is used to determine membership values of these sensitivities and corrective action is to be taken according to the sensitivity observed at a particular bus.

The membership of the objective function is expressed as follows:

\[
\mu_i(F_i) = \begin{cases} 
1 & \text{if } F_i \leq E_{mi} \\
\frac{F_i}{E_{mi}} & \text{if } E_{mi} < F_i < 0 \\
0 & \text{if } F_i \geq 0
\end{cases}
\]

Based on the fuzzy membership function bus number 12, 6 and 27 are found as candidate buses for the placement of FACTS devices.
The main objective of this paper is to minimize the overall operating cost under different condition by the installation of FACTS devices at the optimal locations in the transmission system. Membership values of the bus sensitivities at different buses are determined according to the membership function as shown in Fig. 4. String representing control variables using Fuzzy-GA and Fuzzy-DE is shown in Fig. 5. It is already mentioned that the determination of TCSC placement position and detection of weak nodes for SVC installation is one of the primary and important task of the proposed work. TCSC’s placement locations are determined by observing reactive power flows in different lines without FACTS devices. It is found that lines 25, 41, 28, 5 carry very high reactive power and treated as candidate lines for the TCSC placement. Similarly the weak nodes for the SVC placement are determined by fuzzy membership values of loss sensitivities at buses. The five buses having higher membership values of loss sensitivities are shown in Table 1.

We see that, bus 12, 6 and 27 are chosen as candidate buses for the placement of FACTS devices but the bus no. 10 and bus no. 3 are not selected even if of having higher values of membership. The reason is as:

1. Bus no. 10 is connected with line 28 of the IEEE 30 bus system. But already a TCSC position is defined in the line 28. That is why, bus 10 is not selected.
2. Bus 3 is connected to bus 1 which is considered as slack bus. That is why bus 3 is also not selected for the placement of FACTS devices.

5. Proposed approach

The purpose of this work is to minimize the total operating cost. Hence minimization of the objective function is a combinatorial, i.e. only minimizing the energy loss will not serve the purpose, and simultaneously cost of the FACTS devices has to be considered. After detection of weak buses by fuzzy approach, the optimal setting of power system is done by Genetic Algorithm and Differential Evolutionary techniques. This proposed method is termed as Fuzzy-GA and Fuzzy-DE respectively. The other way of weak bus detection is by modal analysis or eigen value analysis and after detecting the weak buses by this method the optimal setting of the power system variables along with the FACTS devices can be done by GA, DE or PSO. This combined method is the approaches with which the result of the proposed approach is compared. These methods are nothing but conventional or simple GA (SGA), simple DE (SDE) and simple PSO (SPSO) based optimization approaches.

5.1. Genetic Algorithm in brief

Genetic Algorithms (GAs) is an optimization algorithms based on the mechanics of natural selection and genetics. GA consists of main three operators – reproduction, crossover and mutation. It initializes a population of solution string called chromosomes. GA starts with random generation of initial population then genetic operators are performed until the best solution is obtained.

Genetic algorithm (GA) techniques determines the optimal value of the FACTS devices to be connected with the existing system to maximize the system performance as the location of devices is already determined by power flow.

Two types of FACTS devices are discussed here. TCSC’s are to modify reactances of the lines and SVC’s control the reactive injection at buses. In addition transformer tap positions along with reactive generations of the generators are controlled. As a whole all these variables are to be optimized by Genetic Algorithm.

Following steps are used for the solution of objective function using GA.

1. Initialization: Generate random population of \( n \) chromosomes.
   \[ X_{ij}^{\text{init}} = X_{ij}^{\text{min}} + \text{rand}(X_{ij}^{\text{max}} - X_{ij}^{\text{min}}), \]
   where \( i = 1, 2, \ldots, N_p \) and \( j = 1, 2, \ldots, D. \)

2. Fitness: Evaluate the objective function of each chromosome in the initial population.

3. New population: Create a new population by repeating following steps until the new population is complete.
   (i) Selection: Select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected).
   (ii) Crossover: Crossover between two randomly selected chromosomes from the current population is done with a probability close to 1 (here 0.8) to form a new offspring. The crossover operation between two strings will take place

<table>
<thead>
<tr>
<th>Bus no.</th>
<th>( \Delta V = V_{\text{old}} - V_{\text{new}} )</th>
<th>( F_i = C_i \Delta V )</th>
<th>( \mu(F_i) )</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.1591 -0.0301</td>
<td>-0.0048</td>
<td>0.4486</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>0.1269 -0.0215</td>
<td>-0.0027</td>
<td>0.2523</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>0.3216 -0.0333</td>
<td>-0.0107</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.0890 -0.0309</td>
<td>-0.0028</td>
<td>0.2617</td>
<td>3</td>
</tr>
<tr>
<td>27</td>
<td>0.0834 -0.0310</td>
<td>-0.0026</td>
<td>0.2430</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1: Membership function of different buses.
are represented by $X_{ij}^{init}$ and $X_{ij}^{init}$, here $r$ is the randomly
generated integer whose maximum value is $N_p$, the number of
population and $r \neq i$.

(iii) Mutation: Mutation with a specific probability (very low)
completes one genetic cycle and strings of same population
with improved qualities are produced in the next
generation.

4. Use new generated population for a further run of algorithm.
5. The entire procedure from step 1 to step 4 is repeated as dis-
cussed above till satisfactory result is obtained.

It is to be mentioned that, during evaluation of objective func-
tion with the parameters inside a string which contains SVC and
TCSC besides Var generation by generators and transformer tap
setting arrangements, the modified power flow equations as
shown in (5)-(8) has to be included in the load flow program.

String representing control variables using SGA are shown in
Fig. 6.

5.2. Differential Evolution in brief

Differential Evolution (DE) is a population based algorithm was
proposed by Strom and Price (1995) to solve real-parameter optimi-
zation problems. The optimization process in DE is carried out
using three basic operators: crossover, mutation, and selection.

Following are the steps used for the solution of objective func-
tion using DE.

1. Initialization: An initial population ($x_i^d$) of $d$-dimensional vectors
of size $N_p$ is generated randomly. Each vector is referred to as
one chromosome and each vector constitute the random value
of the control parameter. These values must lie inside the upper
and lower bounds of the control variables as

$$X_{ij} = X_{ij}^{min} + \text{Rand}(X_{ij}^{max} - X_{ij}^{min})$$

$i = 1,2, \ldots, N_p$ and $j = 1,2, \ldots, D$.

where $X_{ij}^{max}$ and $X_{ij}^{min}$ are the lower and upper bounds of the $j$th
decision parameter. $N_p$ is the population size, Rand is the random
number generated within $[0, 1]$, $D$ is the total number of param-
eters within a string. And, each individual population is represented
by a string.

Again in DE, each vector in the population becomes a target
vector.

2. Mutation: Mutation is an operation that adds a vector differen-
tial to a population vector. Mutation operation creates donor
vector ($V_i$) of each $i$th chromosome by randomly selecting a
chromosome vector from the initial population.

3. Crossover: Crossover is used to generate a trial vector by replac-
ing certain parameters of the target vector by the corresponding
parameters of a randomly generated donor vector. Mathemati-
cally, it can be illustrated as:

$$u_{ij} = \{u_1,u_2 \ldots u_D\}$$

Each vector is combined with a donor vector from the population
and a random vector differential in order to produce a trial vector
such that

$$u_{ij} = V_{ij} + CR \cdot (X_{ij}^{r1} - X_{ij}^{r2})$$

where $r_1$ and $r_2$ are two randomly generated integers are not equal.
The upper limit of these randomly generated integers is the popula-
tion size, $N_p$ CR is the cross over rate and $CR \in [0,1]$. The cross over
rate CR is used to determine if the newly generated individual is to
be recombined. Here CR is taken as 0.8.

4. Selection: The selection operator determines the population by
choosing from between the trial vectors and the target vectors
that present a better fitness function or more optimal solution.
The selection criteria in DE can be expressed as:

$$X_{ij} = \begin{cases} u_{ij} & \text{if } (u_{ij}) < f(X_{ij}) \\ X_{ij} & \text{otherwise} \end{cases}$$

where $i = 1,2, \ldots, N_p$.

5. The objective function is calculated for all the individual of the
new generation and the procedure is repeated till the final goal
is reached.

String representing control variables using SDE are shown in
Fig. 6.

5.3. Particle Swarm Optimization approach in brief

Particle Swarm Optimization (PSO) is a population based stochas-
tic optimization technique developed by Dr. Eberhart and Dr.
Kennedy in 1995, inspired by social behavior of bird flocking or fish
schooling. A population is initialized of random feasible solutions
and searches for optima by updating generations. In PSO, the po-
tential solutions, called particles have their own positions and
velocities move in the search space of an optimization problem
by following the current optimum particles. Each particle tracks
its own best position found so far in the exploration and each par-
ticle searches for better positions in the search space by updating
its velocity. The movement of each particle naturally evolves to
an optimal or near-optimal solution.

The position of each agent is represented by $x_y$-axis position
and the velocity (displacement vector) is expressed by $V_x$ (the
velocity along $x$-axis) and $V_y$ (the velocity along $y$-axis). Modification
of the agent position is realized by using the position and
the velocity information.

Each agent knows its best value so far ($p_{best}$) and its $x,y$ position.
Each agent knows the best value so far in the group ($g_{best}$) among
$p_{best}$. Each agent tries to modify their position using the following
information:

- The current positions $(x,y)$.
- The current velocities $(V_x,V_y)$.
- The distance between the current position and $p_{best}$.
- The distance between the current position and $g_{best}$.

The basic equation for the optimization of nonlinear functions
using Particle Swarm Optimization technique is:

<table>
<thead>
<tr>
<th>TCSC</th>
<th>SVC</th>
<th>Transformer</th>
<th>Reactive Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 nos.</td>
<td>4 nos.</td>
<td>4 nos.</td>
<td>5 nos.</td>
</tr>
</tbody>
</table>

Fig. 6. Strings representing the control variables for SGA, SDE and SPSO.
Table 2
Location of FACTS devices in the transmission network:

<table>
<thead>
<tr>
<th>TCSC in Lines</th>
<th>SVC in Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE-30 bus 25, 41, 28, 5</td>
<td>SGA, SDE and SPSO, Fuzzy-GA and Fuzzy-DE</td>
</tr>
<tr>
<td>21, 7, 17, 15</td>
<td>12, 6, 27</td>
</tr>
</tbody>
</table>

Table 3
Limits of FACTS devices and other controlling parameters.

<table>
<thead>
<tr>
<th>TCSC (pu)</th>
<th>SVC (pu)</th>
<th>Transformer tap positions (pu)</th>
<th>Reactive generation Qg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(min)</td>
<td>9(max)</td>
<td>0.5(max)</td>
<td>With in the minimum and maximum value of reactive generations of the generators of the IEEE-30 bus system.</td>
</tr>
</tbody>
</table>

Table 4
Total reactive power flow in IEEE 30 bus system without and with FACTS devices.

<table>
<thead>
<tr>
<th>Reactive loading (%)</th>
<th>Without FACTS devices (\sum_{i=1}^{n}Q) (pu)</th>
<th>With FACTS devices (\sum_{i=1}^{n}Q) (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGA</td>
<td>Fuzzy-GA</td>
<td>SDE</td>
</tr>
<tr>
<td>100</td>
<td>0.2988</td>
<td>-0.7624</td>
</tr>
<tr>
<td>200</td>
<td>0.5489</td>
<td>-0.5894</td>
</tr>
</tbody>
</table>

\[
V_i^{\text{gen}} = wV_i^{\text{gen-1}} + C_1 \text{rand} \times (p_{\text{besti}} - V_i^{\text{gen-1}}) + C_2 \text{rand} \times (g_{\text{besti}} - V_i^{\text{gen-1}})
\]

where \(V_i^{\text{gen-1}}\) is the current velocity of agent \(i\) at previous generation.

\[
w = W_{\text{max}} - \frac{W_{\text{min}}}{\text{gen}_{\text{max}}} \times \text{gen}
\]

Table 5
Bus voltages and phase angles with and without FACTS devices for 200% reactive loading using SGA, SDE and SPSO.

<table>
<thead>
<tr>
<th>Bus no.</th>
<th>Bus voltage without FACTS (pu)</th>
<th>Bus voltages with FACTS using SGA (pu)</th>
<th>Bus voltages with FACTS using SDE (pu)</th>
<th>Bus voltages with FACTS using SPSO (pu)</th>
<th>Bus angle (in radian) without FACTS</th>
<th>Bus angle (in radian) with FACTS using SGA</th>
<th>Bus angle (in radian) with FACTS using SDE</th>
<th>Bus angle (in radian) with FACTS using SPSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.0014</td>
<td>1.0044</td>
<td>1.0045</td>
<td>0.9952</td>
<td>-0.1387</td>
<td>-0.1420</td>
<td>-0.1399</td>
<td>-0.1383</td>
</tr>
<tr>
<td>15</td>
<td>1.0036</td>
<td>1.0094</td>
<td>1.0646</td>
<td>1.0574</td>
<td>-0.1797</td>
<td>-0.1760</td>
<td>-0.1746</td>
<td>-0.1711</td>
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<tr>
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<td>1.0366</td>
<td>1.0650</td>
<td>1.0662</td>
<td>-0.1775</td>
<td>-0.1810</td>
<td>-0.1746</td>
<td>-0.1696</td>
</tr>
<tr>
<td>21</td>
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<td>1.0369</td>
<td>1.0566</td>
<td>1.0684</td>
<td>-0.1811</td>
<td>-0.1889</td>
<td>-0.1794</td>
<td>-0.1773</td>
</tr>
</tbody>
</table>

Table 6
Bus voltages and phase angles without and with FACTS devices for 200% of base reactive loading using Fuzzy-GA and Fuzzy-DE approach.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.0182</td>
<td>1.0123</td>
<td>1.0127</td>
<td>-0.1127</td>
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<td>-0.1129</td>
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<td>12</td>
<td>1.0295</td>
<td>1.0379</td>
<td>1.0136</td>
<td>-0.1644</td>
<td>-0.1526</td>
<td>-0.1512</td>
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<tr>
<td>27</td>
<td>1.0079</td>
<td>1.0518</td>
<td>1.0229</td>
<td>-0.1859</td>
<td>-0.1852</td>
<td>-0.1845</td>
</tr>
</tbody>
</table>

Table 7
Comparative analysis of active power loss using SGA, SDE, SPSO, Fuzzy-GA and Fuzzy-DE methods.

<table>
<thead>
<tr>
<th>Reactive loading (%)</th>
<th>Active power loss without FACTS (pu)</th>
<th>Active power loss with FACTS (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SGA</td>
<td>SDE</td>
</tr>
<tr>
<td>100</td>
<td>0.0711</td>
<td>0.0406</td>
</tr>
<tr>
<td>150</td>
<td>0.0742</td>
<td>0.0433</td>
</tr>
<tr>
<td>200</td>
<td>0.0795</td>
<td>0.0573</td>
</tr>
</tbody>
</table>

In this paper emphasis is given on the usefulness of the fuzzy induced evolutionary algorithms over simple evolutionary optimization approach. Detection of weak nodes by standard technique of modal analysis and simultaneous use of simple evolutionary algorithms (like GA, DE and PSO) active power loss and system operating cost can be reduced. Significant reduction of active power loss and operating cost is noticed except in the case of SPSO. But the system loss and the operating cost of the system still can be reduced considerably by detecting weak nodes by fuzzy memberships and parameter setting of the power system by GA and DE. Combination of Fuzzy and PSO is not considered as PSO yields much inferior results when used alone in optimizing power system variables compared to SGA and SDE. Difference in modal analysis and fuzzy membership based detection results SVC placement in different buses. By modal analysis probable SVC’s positions are found in 21st, 7th, 17th and 15th buses, whereas by fuzzy membership based detection method decides 12th, 6th and 27th buses as candidate buses for the SVC’s placement where as TCSC’s positions are determined from reactive power flow in lines. So TCSC positions are kept fixed both in the non-fuzzy and fuzzy induced environment. The existing power system variables (like generators Var generations, transformer tap positions) along with
FACTS devices are represented in a string as shown in Fig. 6. Table 2 shows the locations of FACTS devices in the transmission network using SGA, SDE, SPSO and Fuzzy-GA methods. Limits of FACTS devices and other controlling parameters such as transformer tap positions and reactive generation of generators is shown in Table 3. Table 4 shows the total reactive power flow in lines without and with FACTS devices for base reactive loading and 200% of base reactive loading using different techniques. It is observed that with the combined effect of series and shunt FACTS controller, not only the reactive power flow is reduced and redistributed, the overall reactive power flow is reduced considerably. Table 5 shows the magnitudes and phase angles of the bus voltages before and after placement of SVC for 200% of base reactive loading using SGA, SDE and SPSO. Table 6 shows the magnitudes and phase angles of the bus voltages before and after placement of SVC for 200% of base reactive loading using Fuzzy-GA and Fuzzy-DE methods. A comparative study of the operating cost of the system without and with FACTS devices under different loading conditions for all techniques are shown in Tables 8 and 9. Fig. 7 shows the variations of operating costs with generation for 200% of base reactive loading using Fuzzy-GA, SDE, SPSO and SGA based techniques, whereas Fig. 9 shows the variations of operating costs with generation for 200% of base reactive loading using Fuzzy-GA and Fuzzy-DE methods. The standard IEEE-30 bus system is taken as a test system.

From the comparative study of different techniques, it is found that best result both in the basis of loss reduction and operating cost reduction is achieved using Fuzzy based evolutionary algorithms as seen from Tables 7–9. Both Fuzzy-GA and Fuzzy-DE techniques produces a better solution when compared with SGA, SDE and SPSO based techniques.

Energy cost is taken as 0.06 $/kWh. No. of populations are taken as 80.

### Table 8
Comparative analysis of operating costs with and without FACTS devices using SGA, SDE, SPSO and Fuzzy-GA methods.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3,737,016</td>
<td>2.1786</td>
<td>2.1770</td>
<td>2.4052</td>
<td>2.1297</td>
<td>1,558,416</td>
<td>1,557,052</td>
<td>1,331,816</td>
<td>1,607,216</td>
</tr>
<tr>
<td>150</td>
<td>3,899,952</td>
<td>2.3429</td>
<td>2.3470</td>
<td>2.6080</td>
<td>2.2707</td>
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<td>1,552,952</td>
<td>1,291,952</td>
<td>1,629,252</td>
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<tr>
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<td>3.1024</td>
<td>3.1118</td>
<td>3.4460</td>
<td>2.7919</td>
<td>1,076,120</td>
<td>1,060,520</td>
<td>732,520</td>
<td>1,386,620</td>
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</tbody>
</table>

### Table 9
Comparative analysis of operating costs with and without FACTS devices using SGA, SDE, SPSO and Fuzzy-DE methods.

<table>
<thead>
<tr>
<th>Reactive loading (%)</th>
<th>Operating cost due to the energy loss (in $) (A)</th>
<th>Operating costs with FACTS devices by SGA × 10^6 (in $) (B)</th>
<th>Operating costs with FACTS devices by SDE × 10^6 (in $) (C)</th>
<th>Operating costs with FACTS devices by SPSO × 10^6 (in $) (D)</th>
<th>Operating costs with FACTS devices by Fuzzy-DE × 10^6 (in $) (F)</th>
<th>Net saving using SGA method (in $) (A-B)</th>
<th>Net saving using SDE method (in $) (A-C)</th>
<th>Net saving using SPSO method (in $) (A-D)</th>
<th>Net Saving using Fuzzy-DE method (in $) (A-F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3,737,016</td>
<td>2.1786</td>
<td>2.1770</td>
<td>2.4052</td>
<td>2.1171</td>
<td>1,558,416</td>
<td>1,557,052</td>
<td>1,331,816</td>
<td>1,619,916</td>
</tr>
<tr>
<td>150</td>
<td>3,899,952</td>
<td>2.3429</td>
<td>2.3470</td>
<td>2.6080</td>
<td>2.2660</td>
<td>1,555,052</td>
<td>1,552,952</td>
<td>1,291,952</td>
<td>1,633,952</td>
</tr>
<tr>
<td>200</td>
<td>4,178,520</td>
<td>3.1024</td>
<td>3.1118</td>
<td>3.4460</td>
<td>2.7872</td>
<td>1,076,120</td>
<td>1,060,520</td>
<td>732,520</td>
<td>1,391,320</td>
</tr>
</tbody>
</table>
Fig. 8. Variations of operating cost with generation for 200% of base reactive loading using Fuzzy-DE, SDE, SPSO and SGA method.

Fig. 9. Variations of operating cost with generation for 200% of reactive loading using Fuzzy-GA and Fuzzy-DE method.

Table 10
Amount of FACTS devices and other reactive sources in the transmission network by SGA and Fuzzy-GA based approach.

<table>
<thead>
<tr>
<th>Reactive loading (%)</th>
<th>SVC amount using SGA (pu)</th>
<th>SVC amount using Fuzzy-GA (pu)</th>
<th>TCSC amount using SGA in lines (pu)</th>
<th>TCSC amount using Fuzzy-GA in lines (pu)</th>
<th>Reactive generation Qg using SGA (pu)</th>
<th>Reactive generation Qg using Fuzzy-GA (pu)</th>
<th>Transformer tap position using SGA (pu)</th>
<th>Transformer tap position using Fuzzy-GA (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.0822</td>
<td>0.1906</td>
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<td>0.3409</td>
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</tr>
<tr>
<td></td>
<td>0.0511</td>
<td>0.0051</td>
<td>0.0419</td>
<td>0.0002</td>
<td>0.1815</td>
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<tr>
<td></td>
<td>0.0398</td>
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<td>0.0016</td>
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<td>0.9501</td>
</tr>
<tr>
<td></td>
<td>0.0621</td>
<td>0.0515</td>
<td>0.0009</td>
<td>0.1975</td>
<td>0.1023</td>
<td>0.8512</td>
<td>0.9344</td>
<td>0.9217</td>
</tr>
<tr>
<td>200</td>
<td>0.2399</td>
<td>0.2886</td>
<td>0.0011</td>
<td>0.0005</td>
<td>0.3318</td>
<td>0.4107</td>
<td>0.9366</td>
<td>0.9010</td>
</tr>
<tr>
<td></td>
<td>0.1673</td>
<td>0.2222</td>
<td>0.0051</td>
<td>0.0008</td>
<td>0.2240</td>
<td>0.3469</td>
<td>0.9880</td>
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<tr>
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<td>0.1149</td>
<td>0.1304</td>
<td>0.0004</td>
<td>0.0009</td>
<td>0.2751</td>
<td>0.1843</td>
<td>0.9189</td>
<td>0.9510</td>
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<tr>
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<td>0.1579</td>
<td>0.0500</td>
<td>0.0024</td>
<td>0.2145</td>
<td>0.1357</td>
<td>0.0786</td>
<td>0.9001</td>
<td>0.9360</td>
</tr>
</tbody>
</table>
Here even if with less number of variables in fuzzy based approach than non-fuzzy based approach the operating cost and active power loss found less than non-fuzzy based evolutionary algorithmic optimization. The test system is loaded from the base to 200% of base reactive loading and system behavior with respect to active power loss, voltage profile, the system cost is observed both in fuzzy induced and non-fuzzy induced techniques. The applicability of this proposed approach is well supported by the results under different loading conditions as observed from Tables 7–9. Finally optimal settings of parameter including FACTS devices with fuzzy induced and non-fuzzy induced techniques are shown in Tables 10 and 11.

7. Conclusion

A new approach using Fuzzy membership for weak node detection and simultaneous optimal parameter settings along with FACTS devices in an interconnected power system is presented. The viability of using this approach is supported by the solution it yields and the solutions are compared with other global optimization techniques. As the behavior of the power system faces challenge under increased loading conditions, the proposed approach is applied on the standard system with increased loading conditions, the system is found stable and even satisfactory loss and cost reduction observed. So, this approach can be a new technique for optimal coordination of FACTS devices along with the other existing Var generators of a power system.

References