A Heuristic Approach to Reduce the Loss of Congested Distribution Line via FACTS Devices

H.IRANMANESH¹, M.RASHIDI-NEJAD²

¹ Islamic Azad University, Branch Jiroft, Iran
² Shahid Bahonar University of Kerman, Kerman, Iran

Iranmanesh_444@yahoo.com

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Abstract: Power systems may not capable of utilizing full transmission capacity. The process of re-regulation causes more challenges with regards to technical and trading issues. Restructuring of electricity industry may need some management criteria in order to improve technical as well as economical efficiency. Under the new scheme of power markets, congestion management is a crucial problem that is needed to be considered. Congestion relief can be handled using FACTS devices, where transmission capability may be improved. TCSC and SVC are two FACTS devices and they are used in this paper to reduce the congestion. In this paper, real genetic algorithm (RGA) is used for optimization process while analytical hierarchy process (AHP) with Dimensional Serialization Valuing Mechanism is implemented to evaluate RGA fitness function. The effectiveness of the proposed methodology is shown through a 33-bus radial distribution system [1].

1. Introduction
Electricity industry restructuring and re-regulation may dictate maximum power transfer using the existing facilities under transmission open access scheme. Procuring electricity contracts associated with market participants' requirements can cause more challenges considering energy management systems. Reregulation will impose new necessities to power systems such as transmission open access as well as non-discrimination access to the information. Transmission congestion management is an important mechanism in order to solve power transfer bottleneck both in the operation and planning horizons [2]. There are two issues with regards to applying transmission open access that should be considered, the so-called: transmission losses and transmission congestion. Congestion is dependent to the network constraints that may show the ultimate transmission capacity, while it can restrict the concurrent electric power contracts [3]. It can be said that, under congestion conditions the price of transferring electricity will be increased. In fact, congestion management is an overall as well as particular systematic way of improving electricity transfer in which power systems planning and operating can be regarded.
Transmission congestion is dealing with some restrictions of electricity transfer via transmission network. These restrictions are increased in the presence of open access considering electricity restructuring environment [4]. Under new conditions of power market, more constraints such as: economical, environmental problems and transmission rights as financial contracts will be added to technical limitations of transmission capacity [2]. Congestion relief is such a solution to release some blocked capacity of transmission network. In literature, there are some techniques suggested to increase the available transfer capability (ATC). Among the proposed solutions for ATC enhancement, the use of FACTS devices is reported considerably [5]. It can be said that the application of FACTS devices should be based upon the investigation of capital investment as well as operating costs and the impacts of these devices of ATC improvement [6]. On the other hand, the optimum placement of FACTS devices is an important issue in terms of planning horizon [5], especially considering different types of these devices. While from operating point of view the coordination among these devices is much of interest both by researchers and operation engineers.

2. Problem Definition and Modeling
In order to study congestion problem, it is needed to define mathematical statements as a proposed model. Mathematical modeling that is implemented in this paper is based upon a multi-objective optimization problem in which some new constraints are added to a conventional optimization model that can be found in literature[7]. In fact, the model includes different terms for objective function such as: improvement of voltage profile, reducing transmission losses and minimizing capital investment for FACTS devices incorporating ATC enhancement. The optimum location as well as the capacity of SVC and TCSC as two different types of FACTS devices can be derived considering the role of these elements. The study is carried out by implementing a performance index that can be defined as follow:

\[
PI = \sum_{m=1}^{N} \frac{W_m}{2n} \left( \frac{P_{lm}}{P_{lm}^{max}} \right)^{2n}
\]  

(1)

Where: \( P_{lm} \) is real power transfer in line \( m \), \( P_{lm}^{max} \) is the maximum transfer capacity of line \( m \), \( N \) is the number of lines in the network. \( W_m \) is a non-negative real number to show the importance of \( m \)th transmission line that can be defined as weighting factor and \( n \) is defined as an operating index that is usually less that one. When all transmission lines work at their permissible conditions (non-congestion situation) PI is very low, while if one or more lines are congested it will be increased considerably. To calculate the real power transfer in line \( m \), DC power flow is applied that is shown in the following relationship:

\[
P_{lm} = \begin{cases} 
\sum_{n=1, n \neq s}^{N} S_{mn} P_n & : m \neq k \\
\sum_{n=1, n \neq s}^{N} S_{mn} P_n + P_j & : m = k 
\end{cases}
\]  

(2)

The coefficients of \( S_{mn} \) is the \( mn \)th component of matrix \( S \) that is used in DC power flow and \( P_n \) is the real power injected at bus \( n \). \( K \) is the location of FACTS devices while \( P_j \) is the amount of power that is injected via FACTS employment [8-10].

2.1 TCSC / SVC Mathematical Models

2.1.1 SVC Model
In steady state an SVC can be treated as a reactive power injection/absorption source, which can be presented as the following mathematical statement:

\[
Q_{SVC} = V_t (V_t - V_{ref})X_{SL}
\]  

(3)

Where: \( X_{SL} \) is the slope of voltage control characteristic, \( V_t \) is the terminal voltage of SVC and \( V_{ref} \) is the reference voltage. Doing some calculation the Equation (3) can be rewritten as:

\[
Q_{SVC} = B_{SVC} \times V_{ref}^2
\]  

(4)

The value of \( B_{SVC} \) can be varied between minimum and maximum susceptance the so-called capacitive susceptance and inductive
susceptance, where the desired reactive power can be maintained [11].

The SVC may have two characters: inductive or capacitive. In the first case it absorbs reactive power while in the second one the reactive power is injected. The SVC is modeled with two ideal switched elements in parallel: a capacitance and an inductance. It may take values characterized by the reactive power injected or absorbed at the voltage of 1 p.u. The values are between -40 MVar and 40 MVar[10].

2.1.2 TCSC Model

Generally, TCSC is a series compensator as a capacitive as well as an inductive element that can be added to a transmission line. Based upon the adding a TCSC to a transmission line the admittance matrix of the system should be modified. The difference between the susceptance and conductance of transmission line before and after including TCSC can be considered using Equation (5):

\[ \Delta y_{ij} = y'_{ij} - y_{ij} = (g_{ij} + jb_{ij})' - (g_{ij} + jb_{ij}) \]  

In which:

\[ g_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}} \quad b_{ij} = -\frac{x_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}} \]  

\[ g_{ij}' = \frac{r_{ij}}{\sqrt{r_{ij}^2 + (x_{ij} + x_c)^2}} \quad b_{ij}' = -\frac{x_{ij} + x_c}{\sqrt{r_{ij}^2 + (x_{ij} + x_c)^2}} \]  

The TCSC may have one of the two possible characteristics: capacitive or inductive, respectively to decrease or increase the reactance of the line \( X_L \). It is modeled with three ideal switched elements in parallel: a capacitance, an inductance and a simple wire, which permits the TCSC to have the value zero. The capacitance and the inductance are variable and their values are function of the reactance of the line in which the device is located. In order to avoid resonance, only one of the three elements can be switched at a time. Moreover, to not overcompensate the line, the maximum value of the capacitance is fixed at -0.5\( X_L \). For the inductance, the maximum is 0.6 \( X_L \) [10].

A multi-objective optimization model is represented as a compact form of Equation (7) [9].

\[
\begin{align*}
\min & \quad \frac{P_{ij}}{P_{ij\max}} \quad \text{Subject to the followings:} \\
& P_{gi} - P_{li} - \sum_{j=l} V_i |V_j| (G_{ij} \cdot \text{FACTS} \cdot \cos \delta_{ij} + B_{ij} \cdot \text{FACTS} \cdot \sin \delta_{ij} ) = 0 \\
& Q_{gi} - Q_{li} - \sum_{j=l} V_i |V_j| (G_{ij} \cdot \text{FACTS} \cdot \sin \delta_{ij} - B_{ij} \cdot \text{FACTS} \cdot \cos \delta_{ij} ) = 0 \\
& |V_i|_{\min} \leq |V_i| \leq |V_i|_{\max} \\
& P_{ij} \leq 0.8P_{ij\max} \\
& P_{k,gl_{\min}} \leq P_{k,gl} \leq P_{k,gl_{\max}} \\
& P_{SVC} = 0 \\
& Q_{gim_{\min}} \leq Q_{gi} \leq Q_{gim_{\max}} \\
& Q_{SVC_{\min}} \leq Q_{SVC} \leq Q_{SVC_{\max}} \\
& -0.5X_{mn} \leq X_{TCSC} \leq 0.6X_{mn} \quad [10] \\
\end{align*}
\]

Where: \( P_{ij} \) is the real power flow through transmission line \( ij \); \( P_{ij\max} \) is the maximum capacity of line \( ij \); \( P_{li} \) is the actual real load supply at bus \( i \); \( n \) is bus number of the system; \( P_{gi} \) is the real power generation at bus \( i \); \( Q_{gi} \) is the reactive power generation at bus \( i \); \( Q_{li} \) is the actual reactive load supply at bus \( i \); \( |V_i| \) is the voltage magnitude at bus \( i \); \( G_{ij} \cdot \text{FACTS}, B_{ij} \cdot \text{FACTS} \) are the real/reactive part of the \( ij \)-th element of the admittance matrix, which may be a function of the reactance of TCSC; \( \delta_{ij} \) is the angle difference between the voltage at bus \( i \) and that at bus \( j \); \( Q_{gim_{\min}}, Q_{gim_{\max}} \) are the minimum/maximum reactive power generation at generation bus \( i \); \( |V_i|_{\min}, |V_i|_{\max} \) are the minimum/maximum voltage magnitude at bus \( i \); \( X_{TCSC} \) is the reactance of TCSC; \( X_{mn} \) is the reactance of the line where TCSC has been installed; \( P_{SVC} \) is the real power generation of SVC; \( Q_{SVC_{\min}}, Q_{SVC_{\max}} \) are the minimum/maximum reactive power generation of SVC [12].

3. Solution Algorithm

In order to solve such a multi-optimization model, different techniques can be implemented either using conventional or heuristic criteria. In this paper a combinatorial heuristic criterion is suggested that can be used for such an optimization problem significantly.
The proposed hybrid methodology consists of real genetic algorithm (RGA) incorporating an intelligent valuing mechanism to include the merit as well as the importance of different terms in the objective function. The combination of AHP (analytical hierarchy process) and a valuing method for making dimensional similarization can create a significant collaborated methodology for solving multi-objective optimization problem.

3.1 Dimensional Serialization Valuing Mechanism

The valuing process that is used in this paper is based upon a L row vector with the dimension equal to the number of population in GA. As it is shown in Figure (1) the measure of each component of L is linearly decreasing as the row index increases, while the sum of these measures are equal to one. Determination of chromosome merit is applied for reproduction of new populations via n multi-process, where n is the number of constraints associated with the objective function. In the first stage all chromosomes are sorted in a descending order based upon the first constraints [13].

![Figure 1. Linearly Merit Arrangement Values](image)

The vector of a1L, in which a1 can be considered as the importance of the first constraint, is directly dependent on the merit arrangement and will be allocated to each individual chromosome. For the second stage, chromosomes are arranged in terms of the second constraint in a descending fashion and the vector a2L will be added to a1L correspondingly. This process will be continued to reach such a merit order chromosomes arrangement with regards to applying the RGA for optimization [14,15]. In this paper an AHP [16] technique is applied to derive the importance of constraints, in which a pair-wise comparison is employed associated with the relative importance.

4. Case Study and Results Analysis

A 33-bus radial distribution system is selected to implement the proposed methodology for congestion relief[1]. This system is simulated using MATLAB 2008a software. In order to enhance power transfer in the congested line, first the best location of FACTS devices are derived and then control parameters of the allocated devices are adjusted.

4-1 The 33-bus radial distribution system without Congestion

As it can be seen from Figure (2), under normal condition (having no congestion), real power that will be transferred through line 1-2 is 78.25% of the permissible line capacity. Congestion value of the 33-bus radial distribution system is also shown in Figure (3). Congestion can be taken into account if real power transfer increases more than 80% of the line capacity [17].(See Also Appendix 1)

![Figure 2. The 33-bus radial distribution system[1]](image)

![Figure 3. Congestion value of the 33-bus radial distribution system](image)
4-2 The 33-bus radial distribution with Congestion

The simulation results of this case is illustrated in Figure (4), in which increasing total demand by 5%, the congestion is going be happen in line 1-2 reaching to 93.48%. In this case real power transfer from line 1-2 reaches 4.6739MW. By considering congestion condition, it can be said that there will be no security violation, while from voltage profile point of view this system need to be compensated.

Voltage profile under congestion is depicted in figure (5) where it is shown that the minimum voltages are 0.8926 pu and 0.8932 pu at buses 18 and 17 respectively under congestion pressure.

4-3 Voltage Profile Improvement and Congestion Relief Using SVC/TCSC

In the case of having congestion SVC & TCSC can be used to improve voltage profile as well as to relieve congestion associated with reducing transmission losses. To derive the importance of constraints in the objective function, AHP technique is applied where weighting matrix is presented by equation (8) with regards to three variables: voltage, congestion and losses.

\[
P = \begin{bmatrix}
1 & 1 & 7 \\
3 & 1 & 9 \\
1 & 1 & 1
\end{bmatrix}
\]

(8)

The following weighting (W) vector is obtained via some matrix manipulations.

\[
W = E_n = [0.4032 \ 0.9119 \ 0.0764]^T
\]

A = \[a_1 \ a_2 \ a_3\] = \[0.2897 \ 0.6554 \ 0.0549\]^T

Maximum eigenvalue of this matrix is \(\lambda_{max} = 3.0803\) which is approximately equals to the number of three variables. Weighting vector (W) and the normalized importance vector (A) can then be derived. Implementing RGA with the recombination rate of 76%, mutation rate of 3% and regeneration of 21% considering ellipsis is applied as it is depicted in Figures(6) and(7).

These figures show that with congestion, after 47 generation the algorithm is converged while the best solution is obtained after 60
generation. But voltage profile improvement is converged again after 46 generation, reaching the best profile after 60 generations.

The Modal Analysis technique is applied to investigate the stability of power systems. The method computes the smallest eigenvalue and the associated eigenvectors of the reduced Jacobian matrix using the steady state system model. The magnitude of the smallest eigenvalue gives a measure of how close the system is to voltage collapse. Then, the Participating Factor can be used to identify the weakest node or bus in the system associated with the minimum eigenvalue.

By using modal analysis it can be seen that bus 26 with higher participation factor is the best place for SVC location, where it is illustrated in Figure (11). This result significantly consistent with the result obtained from the proposed algorithm.

Active power losses are improved from 0.210388 MW to 0.173932 MW corresponding to 17.3% improvement. Reactive power losses are also improved from 0.237046 MVAr to 0.189102 MVAr which means 20.22% improvement. By installing TCSC and SVC at their locations, power transfer at line 1-2 decreases to 76.18% of its maximum capacity(figures(12) & (13)) and the worst voltage is 0.95. This belongs to bus 33, which it is improved significantly. Figure (14) shows bus voltage profile using the allocated FACTS devices.

As it is shown, by using FACTS devices at their optimal locations, it can facilitate more transmission capability. TCSC and SVC support system congestion relief while voltage profile, improves simultaneously. These features increase power transfer capability as well as voltage security margin of power systems.

4.Conclusions

Congestion management is an important issue in the reregulated environment of power systems. Congestion should be relieved in order to use the maximum capacity of transmission networks. It is well known that FACTS technology can control voltage magnitude, phase angle and circuit reactance clearly. Using these devices may redistribute the load flow associated with regulating bus voltages. Therefore, it is worthwhile to investigate the effects of FACTS controllers
on the congestion management. SVC and TCSC are the main commercially available FACTS controllers. This paper presents an implementation of the RGA associated with Fuzzy-AHP to determine the location and capacity of these devices. The proposed methodology is employed incorporating dimensional serialization valuing mechanism. Case studies and the obtained results show the effectiveness of the suggested criterion significantly.

### Appendix 1

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### 5. References


[7]. M. Esmaili, H.A. Shayanfar, N. Amjadi, “Multi-objective congestion management incorporating voltage and


