International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 9 (2017) pp. 2095-2103
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Congestion Management and Voltage Profile Improvement in a Hybrid Power System with FACTS Controllers

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Abstract

This paper proposes a new congestion management (CM) approach to relieve congestion and to improve voltage profile in a system with Flexible AC Transmission System (FACTS) Controllers in the restructured power system. The optimal locations of Thyristor Controlled Series Compensators (TCSC) and Static VAR Compensators (SVC) are determined based on the V-Q sensitivity analysis. In this paper, two objectives, i.e., alleviation of overload and minimization of transmission losses are proposed, and they solved simultaneously using weighted summation approach. In this paper, a hybrid power system considering the conventional thermal generators, wind energy generators (WEGs) and solar photovoltaic (PV) plants are considered. The proposed optimization problem is solved using the Opposition based Bacterial Dynamics Algorithm (OBDA). The effectiveness of the proposed CM approach is examined on IEEE 30 bus test system.

Keywords: Congestion Management, FACTS Controllers, Sensitivity Analysis, Renewable energy sources, Evolutionary algorithms.

NOMENCLATURE

N	Total number of buses.
$\mathbf{N_{OL}}$	Number of overloaded/congested lines.
$\mathbf{S_i}$	Power flow in ith line (in MVA).
$\boldsymbol{S_i^{max}}$	Maximum power flow in ith line (in MVA).
$\boldsymbol{P_{loss}}$	Total power loss of transmission lines.
$\boldsymbol{G_{ij}}$	Conductance of transmission line connected between bus i and bus j.
$\boldsymbol{V_i}$	Voltage magnitude at bus i.
$\boldsymbol{\delta_i}$	Voltage phase angle at bus i.
$\boldsymbol{P_{Gi}}$	Active power generation at bus i.
$\boldsymbol{Q_{Gi}}$	Reactive power generation at bus i.
$\boldsymbol{P_{Di}}$	Active power demand at bus i.
$\boldsymbol{Q_{Di}}$	Reactive power demand at bus i.
$\boldsymbol{N_G}$	Number of thermal energy generators.
$\boldsymbol{N_W}$	Number of wind energy generators (WEGs).
$\boldsymbol{N_S}$	Number of solar photovoltaic (PV) generators.
$\boldsymbol{N_T}$	Number of transformer taps.
$\boldsymbol{N_C}$	Number of shunt VAR sources.
$\boldsymbol{N_D}$	Number of load demands.
$\boldsymbol{X^K}$	Primary bacterium in kth iteration.
$\boldsymbol{x_i^k}$	Component of $\boldsymbol{X^K}$ on ith dimension in kth iteration.
$\boldsymbol{\tilde{X}}$	Associated bacterium.
n	Number of dimensions for primary and associated bacterium.
LB	Lower bound.
UB	Upper bound.
$\boldsymbol{r_1}$	Random number between -1 to 1.
$\boldsymbol{C_1}$	Searching coefficient.
$\boldsymbol{FP_i^k}$	Fittest position on ith dimension at kth iteration.
$\boldsymbol{x_i^k}$	Primary bacterium on ith dimension at kth iteration.

INTRODUCTION

Congestion in a transmission system, whether in vertically integrated or restructured power systems, cannot be tolerated except briefly, since this may cause cascade outages with uncontrolled loss of load. Congestion in the system may prevent the existence of new contracts, increase the electricity prices in some regions of electricity markets, lead to additional outages, and can threaten system reliability and security [1]. Congestion management (CM) consists in controlling the system in such a way that all the operational and security constraints are satisfied. The voltage changes and load variation may be controlled by the voltage profile improvement and congestion management (CM). The CM can be performed via system current reduction using the Flexible AC Transmission Systems (FACTS) controllers. From last few years, the inclusion of renewable energy resources (RERs) in the power systems has increased, with special emphasis to the intermittent RERs such as wind and solar PV energy systems, because they create a new challenge in the system operation. With the increasing levels of wind and solar PV power penetration in the system, one of major challenges in the present and coming years is to develop an optimal power flow (OPF) including wind energy generators (WEGs) and solar PV modules. Due to the limited predictability and variability of wind and solar PV power generation, the lack of RERs will be quickly compensated by the conventional thermal units, otherwise it will cause, voltage variation, frequency variation and system crash. The aim of CM problem is to minimize the total cost of generation and to alleviate the overload, while satisfying the system operational constraints. This is the classical CM problem. However, with the development and introduction of RERs such as wind and solar energy, there is a need to modify the traditional CM problem. Some published literature [2-7] have discussed the CM problem incorporating the RERs.

A comprehensive literature review on CM issues in the restructured electricity markets is presented in Reference [8]. Reference [9] describes the development of efficient and simple approaches for the optimal location of FACTS controllers that are used for CM by optimally controlling their parameters. An approach for solving the CM problem by optimally allocating the FACTS devices by utilizing an optimization approach which optimizes generation and installation costs while satisfying voltage stability index is proposed in [10]. Reference [11] mitigates the congestion in the system by using the generation rescheduling and selected load shedding by considering the fuel cost and congestion costs minimizations are the multiple objectives. A new CM methodology by using rescheduling of generators and load shedding, with practical voltage-dependent load modeling is proposed in [12]. A transactive framework for scheduling, controlling, authorizing, and managing distributed resources provides in a Smart Grid is presented in [13]. Reference [14] proposes two types of market mechanisms to solve the local CM problem by considering the compensation between renewable producers and both renewable and conventional productions. A new real-time hybrid controller of energy storage and wind power to manage congestion in a monitored corridor based on pre-processed historical data is proposed in Reference [15]. In Reference [16], a control mechanism regarding power flow and frequency constraints is proposed based on load frequency and governor free control. A frequency regulation technique by applying the renewable energy curtailment and by taking into account the CM in the transmission network based on price signals is presented [17]. A review on different optimization techniques for solving the CM problem is proposed in [18]. In Reference [19], the system voltage deviation reduction has been performed by allocating STATCOM device, and the fitness value comprising of power loss and total voltage deviation has been reduced by placing UPFC device. In [20], a generator rescheduling technique and wind farm is introduced to manage the congestion in the system. In Reference [21], a novel procedure has been proposed for the optimal locations and times of demand response programs implementation. In [22], a particle swarm optimization (PSO) and its variants are applied to determine the optimal active and reactive power rescheduling cost for managing the congestion in the system. Reference [23] proposes a new method by combining the OPF and optimized CM delivering a global optimum even with nonconvex functions. A single and multi-objective optimization methods for optimal choice, location and size of Thyristor Controlled Series Capacitors (TCSC) and Static VAR Compensators (SVC) in the restructured power system to improve voltage stability, branch loading and to reduce the line losses is proposed in [24]. A Disparity Line Utilization Factor for optimal location and Gravitational Search algorithm based optimal tuning of Interline Power Flow Controller to control congestion in the transmission lines is proposed in [25]. A hybrid firefly technique and differential evolution optimization search has been proposed in [26], to manage the congestion by rescheduling of generators while satisfying the system constraints both technically and economically in the deregulated market scenario.

Though in literature various methods have been proposed, to solve the problem of congestion management (CM), still there is a scope for improvement. This paper provides a solution to congestion management and voltage profile improvement problem by optimal location of FACTS controllers, i.e., TCSC and SVC using the Opposition based Bacterial Dynamics Algorithm (OBDA). The proposed CM approach has been tested on IEEE 30 bus system. The simulation results show the effectiveness of the proposed approach.

MODELING OF FACTS CONTROLLERS

Modeling of Thyristor Controlled Series Compensator (TCSC)

TCSC is a capacitive reactance compensator consisting a series capacitor bank shunted by a thyristor controlled reactor to provide a smoothly variable series capacitive reactance $(-jx_{TCSC})$ [27]. TCSC is used for increasing maximum power transmitted in the line. Generally, the TCSC is not placed for the voltage control, but it do contribute for the voltage control. In steady state power flow study, the TCSC can be considered as a static capacitor offering a reactance $(-jx_{TCSC})$. With a series compensated, the transmission line l is represented by a lumped π-equivalent parameters. In many cases, the shunt susceptances of a line are neglected, hence the TCSC's static capacitor will be directly in series with the line impedance [24]. The TCSC is modeled as variable impedance, where the equivalent reactance of the line x_{ij} is defined as,

$$x_{ij} = x_{line} + x_{TCSC} \qquad (1)$$

where x_{line} is the transmission line reactance. Figure 1 depicts a controllable reactance $(-jx_{TCSC})$ placed in the transmission line connected between buses i and j.

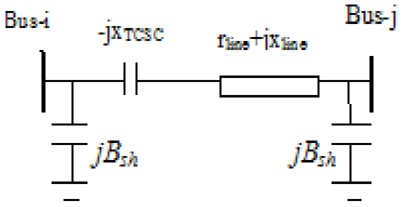

Figure 1: Representation of TCSC with controllable $((-jx_{TCSC}))$.

Modeling of static VAR compensator (SVC)

SVC based on thyristors without gate turn-off capability is considered as a shunt connected static VAR generator or absorber, whose output is adjusted to exchange inductive or capacitive current [28]. SVC controls the system voltage profiles without the topological changes or the generation rescheduling. The SVC models suitable for power flow and dynamic performance simulation. The equivalent SVC susceptance (i.e., B_{svc}) is represented by,

$$B_{SVC} = \frac{X_L - \frac{X_C}{\pi}[2(\pi - \alpha) + sin2\alpha]}{X_L X_C} \qquad (2)$$

Depending on the ratio of X_C/X_L, there is a corresponding value of firing angle (α) for which the steady state resonance occurs. From the operational point of view, the SVC can be modeled as a variable shunt reactance, and it is automatically adjusted to maintain a desired voltage with either firing angle limits or reactance limits [29]. Figure 2 depicts the representation of SVC as a continuous variable shunt susceptance that is adjusted to achieve a specified voltage magnitude [30].

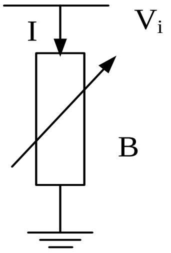

Figure 2: Representation of SVC as the variable shunt susceptance (B_{SVC}).

Considering the SVC is connected at bus i to maintain the bus voltage magnitude at V_i, the reactive power injected by the controller is expressed as [30],

$$Q_{SVC}^{i} = -V_i^2 B_{SVC}^{i} \qquad (3)$$

PROPOSED PROBLEM FORMULATION

In this paper, the CM method based on OPF uses derivative of objective function to determine the search direction [31]. The objective of CM problem is to alleviate the congestion and to improve the voltage profile. For this purpose, the FACTS devices, i.e., TCSC and SVC are incorporated in the proposed problem. These two objective are formulated next:

Objective 1: Minimization Overload/ congestion alleviation

This objective function is formulated as,

Minimize,

$$J_1 = \sum_{i=1}^{N_{OL}} (S_i - S_i^{max}) \qquad (4)$$

Objective 2: Transmission loss minimization

For the reactive power optimization or to improve the voltage profile in the power system, the transmission losses minimization is considered as the objective function.

Minimize, total system transmission losses, i.e.,

Minimize,

$$J_2 = \sum_{i=1}^{N_{line}} Loss_i \qquad (5)$$

that is,

Minimize,

$$J_2 = P_{loss} = \frac{1}{2}\sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} G_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \qquad (6)$$

In this paper, these two objectives are optimized simultaneously using the weighted summation approach. The augmented objective function using this approach is formulated as,

Minimize,

$$J = W_1(J_1) + W_2(J_2) \qquad (7)$$

The above objective function is solved subjected to the following constraints.

Equality Constraints:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{n} V_j \left(G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij} \right) \qquad (8)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{n} V_j \left(G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij} \right) \qquad (9)$$

where i=1,2,3,...,n.

Inequality Constraints:

These are the system operating constraints [32-33].

A. Generator Constraints: Generator active power (P_{Gi}), reactive power (Q_{Gi}) and voltage magnitudes (V_{Gi}) are limited by their minimum and maximum limits [34].

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \qquad i = 1,2,3, \dots, N_G \qquad (10)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \qquad i = 1,2,3, \dots, N_G \qquad (11)$$

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \qquad i = 1,2,3, \dots, N_G \qquad (12)$$

B. Transformer Constraints: Transformer taps have lower and upper setting limits are expressed as,

$$T_i^{min} \leq T_i \leq T_i^{max} \qquad i = 1,2,3, \dots, N_T \qquad (13)$$

C. Switchable VAR sources: The switchable VAR sources are restricted by,

$$Q_{Ci}^{min} \leq Q_{Ci} \leq Q_{Ci}^{max} \qquad i = 1,2,3, \dots, N_C \qquad (14)$$

D. Security constraints: These constraints include the limits on load bus voltage magnitudes and line flow limits. They are expressed as,

$$V_{Di}^{min} \leq V_{Di} \leq V_{Di}^{max} \qquad i = 1,2,3, \dots, N_D \qquad (15)$$

$$S_{Li} \leq S_{Li}^{max} \qquad i = 1,2,3, \dots, N_{line} \qquad (16)$$

E. Wind and Solar Power Generation Constraints: The wind and solar power generation active power outputs are limited by [35],

$$P_{Wj}^{min} \leq P_{Wj} \leq P_{Wj}^{max} \qquad i = 1,2,3, \dots, N_W \qquad (17)$$

$$P_{Sk}^{min} \leq P_{Sk} \leq P_{Sk}^{max} \qquad i = 1,2,3, \dots, N_S \qquad (18)$$

F. FACTS Controllers Constraints

The TCSC reactance (X_{tcsc}) and SVC susceptance (B_{SVC}) limits are expressed as [30],

$$X_{TCSC,i}^{min} \leq X_{TCSC,i} \leq X_{TCSC,i}^{max} \qquad (19)$$

$$B_{SVC,j}^{min} \leq B_{SVC,j} \leq B_{SVC,j}^{max} \qquad (20)$$

The constraint on the location of SVC is expressed as,

$$1 \leq Loc_i \leq N_{Bus} \qquad (21)$$

The constraint on the location of TCSC is expressed as,

$$1 \leq Loc_j \leq N_{Line} \qquad (22)$$

G. Modeling of Wind and Solar PV Energy Systems

Wind and solar PV power prediction plays a vital role in the integration of large scale wind and solar power into the grid. Different probability distribution models were used for the statistical analysis of recorded wind speeds. In this paper, Weibull probability density function (PDF) is assumed for the wind speed, and then it is transformed to the corresponding power distribution. For each wind energy generator, the power output for a given wind speed input is expressed as [36-37],

$$P_{Wj} = \begin{cases} 0 & for\ v < v_i\ and\ v > v_o \\ P_{rj} \left\{ \frac{v - v_i}{v_r - v_i} \right\} & for\ v_i < v < v_r \\ P_{rj} & for\ v_r < v < v_o \end{cases} \qquad (23)$$

In the present paper, the wind speed is modeled using the Weibull PDF, and the detailed probabilistic wind turbine model is presented in [35].

The power output from the solar PV generator is represented as,

$$P_{PV} = \begin{cases} P_{sr} \left(\frac{G^2}{G_{std} R_c} \right) & for\ 0 < G < R_c \\ P_{sr} \left(\frac{G}{G_{std}} \right) & for\ G > R_C \end{cases} \qquad (24)$$

The distribution of hourly solar irradiation follows a bi-modal distribution, which can be considered as a linear combination of two uni-modal distribution functions. The uni-modal distribution functions are modeled by using the Weibull, log-normal and beta PDFs. Here, the Weibull distribution function is applied.

DETERMINATION OF OPTIMAL LOCATION USING V-Q SENSITIVITY ANALYSIS

In this paper, the V-Q sensitivity analysis is used to determine the optimal location of SVC. Here, the Newton-Raphson (NR) load flow is used to find the information pertaining to voltage stability indices at all load buses without any computational effort. These indices are very crucial in identifying the suitable locations for shunt compensation. The linearized form of power flow equations using the NR solution is given by [30],

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \qquad (25)$$

Both P and Q affect the voltage stability. But, at each operating point, we may keep P as constant and determine the voltage stability by considering the incremental relationship between V and Q. With ΔP = 0,

$$[J_1][\Delta\delta] + [J_2][\Delta V] = 0 \qquad (26)$$

$$[J_3][\Delta\delta] + [J_4][\Delta V] = [\Delta Q] \qquad (27)$$

Solving for Δδ using equation (26) and substituting in equation (27) reduces to,

$$[\Delta Q] = [J_R][\Delta V] \qquad (28)$$

where $[J_R] = [J_4 - J_3 J_1^{-1} J_2]$ is the reduced Jacobian. Equation (28) can be written as,

$$[\Delta V] = [J_R]^{-1}[\Delta Q] \qquad (29)$$

In the above equation (29), the j^th^ diagonal element of $[J_R]^{-1}$ is the V-Q sensitivity at the bus-j. V-Q sensitivity at a bus represents the slope of Q-V curve at the given operating point. A positive V-Q sensitivity is indicative of stable operation. The smaller the value of sensitivity index, larger will be the voltage stability of power system. Bus with maximum V-Q sensitivity is the effective location for reactive power support.

OPPOSITION BASED BACTERIAL DYNAMICS ALGORITHM (OBDA)

In OBDA, one primary bacterium and two secondary bacteria, i.e., associated and opposite associated bacterium are used. The primary bacterium is initialized randomly within the decision space. Then, the an associated bacterium is generated by moving the primary bacterium in one dimension between upper and lower bounds. After that an opposite associated bacterium is generated by moving the primary bacterium in the same dimension, but in the opposite direction to that of associated bacterium [36].

A. Dynamic Random Search:

The primary bacterium performs a dynamic random search to obtain the associated bacteria. In the bacterial dynamics, primary bacterium occupies a position in the *n* dimensional space. The primary bacterium in k^{th} iteration is expressed as [36],

$$X^k = (x_1^k, x_2^k, x_3^k, \dots\dots.., x_n^k) \epsilon R^n \qquad (30)$$

The $\tilde{X}$ is generated from X by using the dynamic random search. A dimension $l \in \{1,2,3,.......,n\}$ $l\epsilon\{1,2,3,\dots\dots..,n\}$is randomly chosen for the mutation. The associated bacterium is generated in k^th^ iteration is expressed using,

$$\tilde{X}^k = X^k + \delta D^k \qquad (31)$$

where $\delta D^k = (0,0,0,......,d_l^k)$. d_l^k is generated randomly between the lower and upper bounds on l^{th} dimension, and it is expressed as,

$$d_l^k = c_1 r_1 (UB\text{-}LB), \qquad (32)$$

c_1 plays a vital role in maintaining the diversity of the population. Here, c_1 is taken as 0.23.

B. Opposition based Search:

To implement the opposition based search, relative opposition point is introduced in this paper. Let x and $\tilde{x} = x + \delta x$ are the two real numbers. $\tilde{x} = x + \delta x$Then, the opposite point of $\tilde{x}$ with respect to x is expressed as,

$$\tilde{x}^* = x\text{-}\delta x. \qquad (33)$$

Suppose, a bacterium $B = (x_1, x_2, x_3, ..., x_n)$ be located at a point in *n*-dimensional space, where $x_i \in R \forall i \in \{1,2,3,.......,n\}$. The other bacterium is expressed as $\tilde{B} = B + \delta B$. Then, the opposite oriented bacterium of $\tilde{B}$ with respect to B is expressed as,

$$\tilde{B}^* = B\text{-}\delta B \qquad (34)$$

By using the above relative opposite point, the opposite associated bacterium can be obtained. If the primary bacterium is $X^k = (x_1^k, x_2^k, x_3^k, \dots\dots.., x_n^k)$ $X^k = (x_1^k, x_2^k, x_3^k, ..., x_n^k)$, then the associated bacterium becomes $\tilde{X}^k = X^k + \delta D^k$ $\tilde{X}^k = X^k + \delta D^k$. The opposite associated bacterium ($\tilde{X}^*$ $\tilde{X}^*$) is represented by,

$$\tilde{X}^* = X^k\text{-}\delta D^k \qquad (35)$$

RESULTS AND DISCUSSION

In this paper, the IEEE 30 bus, 41 branch system [38] is used to test the effectiveness of the proposed congestion management (CM) approach. This system consists of 6 generator buses, 21 load buses and 41 branches [38]. In this paper, to create the congestion in the system, the loading of the system has been increased to 120% of base case and by removing the line 36, i.e., line connected between buses 27 and 28. The optimal location of SVC is determined using the V-Q sensitivity analysis, whereas the optimal location of TCSC is determined based on the overloaded/congested line. In this paper, the following three case studies are performed, and they are,

- Case 1: Solving the proposed CM problem without considering the FACTS controllers.
- Case 2: Solving the proposed CM problem by incorporating the SVC at the potential bus.

- Case 3: Solving the proposed CM problem by incorporating SVC at potential bus, and TCSC in the congested line.

As mentioned earlier, in this paper, the TCSC and SVC are considered to alleviate the congestion in the system and to improve the voltage profile of the system. Figure 3 depicts the V-Q sensitivity analysis of load demand buses. From this figure, it can be observed that bus 26 is more suitable for optimal location/potential bus for the shunt compensation.

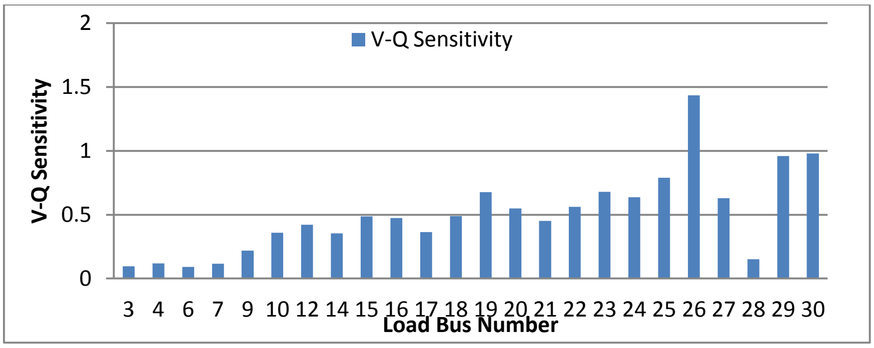

Figure 3: V-Q sensitivity analysis of load demand buses.

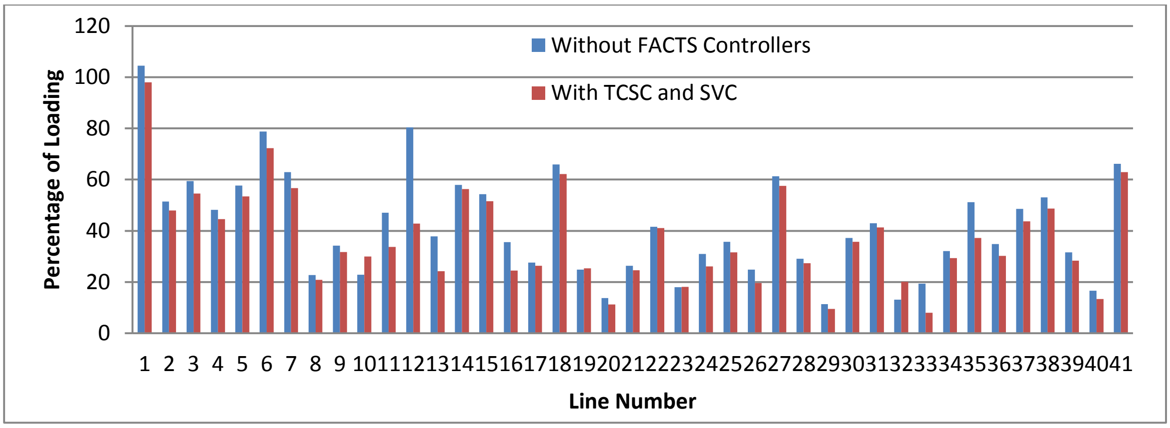

Figure 4: Percentage of loading in the transmission lines with and without FACTS devices.

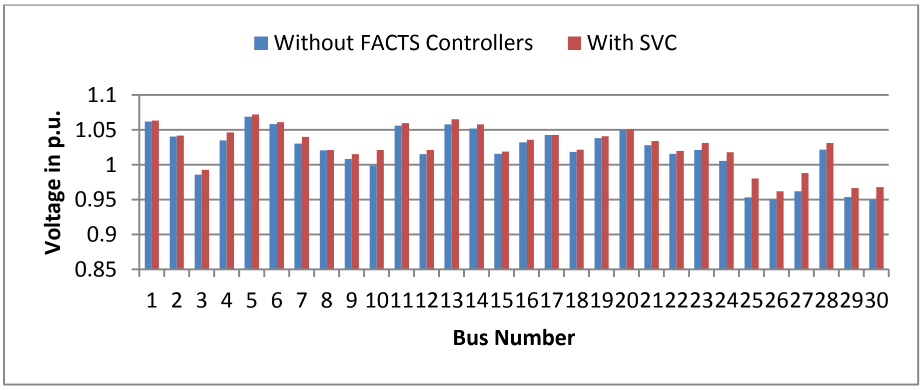

Figure 5: Voltage profile before and after placing the SVC.

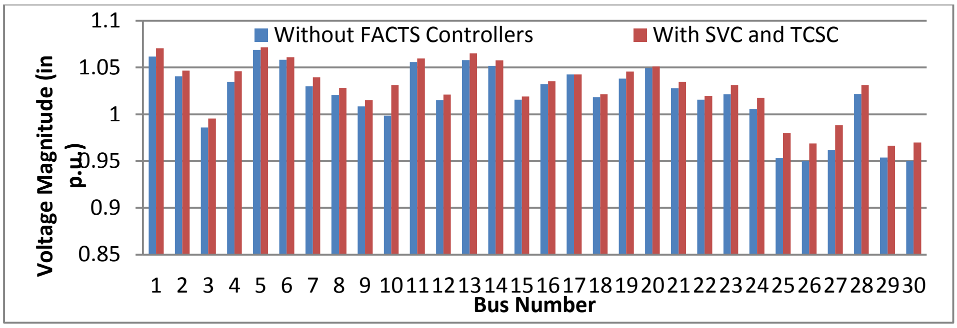

Figure 6: Voltage profile before and after placing the TCSC and SVC.

In this paper, the overloading condition is created by increasing the loading of the system to 120%. The maximum power flow/thermal limits for IEEE 30 bus system are given in Reference [39]. For the overloaded case, the line number 1 is loaded to 104.76% of its maximum loadability limit. To remove this overloading condition, TCSC is placed in the first line. The proposed objective function (i.e., Equation (7)) is solved using the OBDA. The maximum MVA flow limit of line 1 is 130MVA. Before placing the FACTS controllers, the loading of the line bus has been increased to 136.19MVA. To overcome this situation, TCSC is placed in line number 1. After placing the TCSC, the loading of line number 1 has been decreased to 127.35MVA.

Table 1 presents the comparison of scheduled power generations and objective function values for with and without FACTS controllers. The total cost and transmission losses obtained for Case 1 (i.e., without any FACTS controllers) are 1019.79$/hr and 12.61MWs, respectively. Whereas, the total cost and transmission losses obtained for Case 3 (i.e., by including the TCSC and SVC) are 1014.42$/hr and 12.46MWs, respectively.

Table 1: Comparison of scheduled power generations and objective function values for with and without FACTS controllers.

Scheduled Power Generations	Without any FACTS devices	With TCSC and SVC
P_{G1} (MW)	193.17	182.77
P_{G2} (MW)	68.12	65.71
P_{G5} (MW)	23.05	26.08
P_{G8} (MW)	32.68	36.10
P_{W11} (MW)	20.35	23.20
P_{S13} (MW)	14.71	18.86
Generation Cost ($/hr)	**1019.79**	**1014.42**
Loss (MW)	**12.61**	**12.46**

Figure 4 depicts the percentage of loading in each transmission line with and without FACTS controllers. From this figure, it can be observed that before placing the FACTS controllers, the line 1 is overloaded. However, after placing the FACTS controllers, the overloading condition is alleviated. Figure 5 depicts the voltage profile obtained before and after placing the SVC. However, the voltage profile can be improved further by placing both TCSC and SVC in the system. The voltage profile obtained after placing the TCSC and SVC is depicted in Figure 6.

From the above simulation results it is evident that SVC effects the voltage profile and TCSC influences the power flows through the lines. This paper showed that by optimally placing the FACTS controllers, the congestion is removed and the voltage profile has been improved.

CONCLUSIONS

This paper presents an approach for managing the congestion and to improve the voltage profile using the Flexible AC Transmission Systems (FACTS) controllers in a hybrid power system consisting the conventional thermal generators, wind energy generators, solar PV modules. In this paper, two objectives, i.e., overloaded alleviation and transmission losses minimization are considered and they are solved using the weighted summation approach. The proposed congestion management (CM) approach is solved using the opposition based bacterial dynamics algorithm (OBDA). The effectiveness of the proposed approach is tested on IEEE 30 bus test system. From the simulation results, it can be observed that static VAR compensator (SVC) effects the voltage profile in the system and the thyristor controlled series compensator (TCSC) influences the power flows through the transmission lines

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