Multi-Objective Optimization in the Presence of Hybrid Flow Controller

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Abstract

The planning and operation of an electrical power systems needs to satisfy the requirements as economic as possible. The system has to be included with Flexible AC Transmission (FACTS) controllers to enhance the system performance. With the help of these controllers the transmission capacity, flexibility in control can be achieved. Obtaining solution for multi-objective optimization problem with conventional methods is a tedious task. Hence the modern evolutionary algorithms are implemented to obtain solution for the optimization problems. In this paper, generation fuel cost, transmission losses and system loadability objectives are considered to formulate a multi-objective optimization problem. The system capability is increased by incorporating one of the popular FACTS shunt-series controllers, known as Hybrid Flow Controller (HFC). This paper develops an appropriate model of HFC for single and multi-objective optimization problems and also presents a methodology to find the optimal location of FACTS shunt-series controllers. This methodology is tested on IEEE-14 bus IEEE-30 bus test systems with analytical results.

Keywords: *Hybrid Flow Controller; Generation fuel cost; Transmission loss; Loadability; Optimal location.*

1. Introduction

It is necessary to meet the increasing load with less investment and enhancing the existing system capacity by installing new generation units along with the transmission lines. But this task is uneconomical for a load growth of small duration. It is possible to enhance the system capacity using FACTS controllers [1]. The flexibility in design of these controllers like series connected, shunt connected, and shunt-series connected, the requirements of the system can be satisfied. Therefore the system planner has to select a proper FACTS controller based on technical and economical considerations. FACTS controllers are characterized by their ability to have control algorithms structured to achieve multiple objectives in a transmission system [2]. With these controller not only enhancing capability, but also the system reliability, flexibility and controllability can be enhanced.

The technological development in semiconductor technology and in controllers design, one of the popularly used shunt-series controllers is Hybrid Flow Controller (HFC) and is also called as Dynamic Flow Controller developed by ABB [3]. This device is installed in a line between two PQ buses in a given system. To analyze the effect of this controller a planner has to perform optimal power flow on a given system. The OPF problem aims to achieve an optimal solution of a specific power system objective function by adjusting the power system control variables, while satisfying a set of operational and physical constraints [4].

The algorithms like Multi-Objective Stochastic Search Techniques (MOSST) [5], Multi-Objective Evolutionary Algorithm (MOEA) [6], Strength Pareto Evolutionary Algorithm (SPEA) [7], Niched Pareto Genetic Algorithms (NPGA) [8] and Nondominated sorting in Genetic Algorithms (NSGA) [9], etc., can be used to solve multi objective optimization problem.

It is possible to control the power flow using phase-shifting equipments [10-14]. There are variety of series controllers like TCSC, TSSC, TSSR, SSSC and TCPST etc to control power flow in a transmission line by varying the device control parameters [15, 16]. But the combination of some of the series controllers, phase shifters, and shunt capacitors formulates new device like Hybrid Flow Controller. Finding an optimal location to install this device requires steady state modeling [17-19].

The main contribution of this paper is that, modeling of HFC to incorporate in the NR load flow in a proper location, so as to optimize the system objectives like generation fuel cost, power loss and system load using PSO approach. The analysis consist single objective optimization problems along with the results on IEEE-14 bus and IEEE-30 bus test systems.

2. Hybrid Flow Controller [20,21]

The steady state model of HFC is derived to investigate power flow control of power transmission lines. HFC is a hybrid compensator (i.e., provides series and/or shunt compensation). HFC is not a new circuit configuration and rather an amalgamation of existing and well established power-flow controllers, like, Phase-Shifting Transformer (PST), Mechanically Switched Shunt Capacitor (MSC), Thyristor Switched Series Capacitor (TSSC), and Thyristor Switched Series Reactors (TSSR).

Since HFC is a mixture of series and shunt compensation, its operation is similar to that of a Unified Power Flow Controller (UPFC). HFC does not generate any harmonics and hence no unpleasant impact on power quality compared to UPFC. HFC can control dynamic and steady state power flow due to electronically switched parts like TSSC and TSSR, and mechanically switched parts like PST and MSC. The power flow model for HFC has been proposed, but this model named Nabavi model is adaptable for conventional power flow analysis since one of HFC ends operates as a PV bus. The role of PST in power-flow control to solve the problem of overloads and minimizing losses has been well established.

2.1 Principle of operation of HFC:

The schematic diagram of an HFC that is connected between buses i and j within a transmission line is shown in Fig.1 and comprised of:

- A PST which can inject a lead/lag, quadrature-phase voltage
- Multi-module TSSC system that can insert a variable series capacitive reactance, in discrete steps, to adjust the line series reactance
- Multi-module TSSR system that can insert a variable series inductive reactance, in discrete steps, to prevent overflow and
- MSC for reactive power compensation.

Due to their inherent large time-constants, PST and MSC can only impact steady-state power flow, while the TSSC and the TSSR modules can provide both dynamic and steady-state power-flow control. By replacing one TSSC module with a thyristor-controlled series capacitor (TCSC) module, continuous control of series reactance also can be achieved.

A per-phase schematic representation of the HFC is shown in Fig.1.

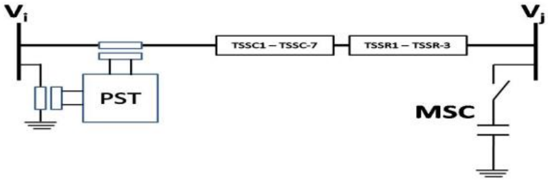

Fig.1 Per phase schematic diagram of HFC

2.2 HFC Power Flow Model

The injected current into bus-i from the Nabavi model is shown in Fig.2.

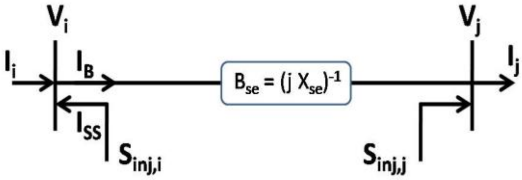

Fig.2. HFC power injection model

From Fig.2

$$I_{SS} = I_B - I_i \qquad -(1)$$

And

$$I_B = \frac{V_i - V_j}{jX_{Se}} \qquad -(2)$$

Current injection at bus-i can be given as,

$$I_i = (1 + k^2)Y_{ij}V_i - (1 - jk)Y_{ij}V_j \qquad -(3)$$

Substituting I_B and I_i expressions in Eq.3 and also simplifies

$$I_{SS} = \left(\frac{1 + k^2}{jX_{Se}} - \frac{1}{jX_B}\right)V_i + \left(\frac{1}{jX_B} - \frac{1 - jk}{jX_{Se}}\right)V_j \qquad -(4)$$

The current I_{SS} injects the apparent power S_{SS} into bus-i as follows:

$$S_{SS} = V_i\,I_{SS}^* = P_{SS} + jQ_{SS} \qquad -(5)$$

Where

$$P_{SS} = \frac{|V_i||V_j|}{X_B}\sin(\delta_i - \delta_j) - \frac{|V_i||V_j|}{X_{ij}}\left(k\cos(\delta_i - \delta_j) + \sin(\delta_i - \delta_j)\right)$$

$$Q_{SS} = \frac{|V_i|}{X_B}\left(|V_i| - |V_j|\cos(\delta_i - \delta_j)\right) - \frac{|V_i|}{X_{ij}}\left(|V_i|(1 + k^2) + k\,|V_j|\sin(\delta_i - \delta_j) - |V_j|\cos(\delta_i - \delta_j)\right)$$

The injected current into bus-j is

$$I_j = (1 + jk)Y_{ij}V_i + \left(-Y_{ij} + Y_{MSC}\right)V_j \qquad -(6)$$

$$I_{SR} = I_j - I_B \qquad -(7)$$

Similarly substituting I_j and I_B in Eq. (6) and simplifies

$$I_{SR} = \left(\frac{1 + jk}{jX_{ij}} - \frac{1}{jX_B}\right)V_i + \left(\frac{1}{jX_{MSC}} + \frac{1}{jX_B} - \frac{1}{jX_{ij}}\right)V_j \quad -(7)$$

The current I_{SR} injects the apparent power S_{SR} into bus j as follows:

$$S_{SR} = V_j\,I_{SR}^* = P_{SR} + jQ_{SR} \qquad -(8)$$

As per assumption

$$P_{SR} = -P_{SS}$$

$$Q_{SR} = \frac{|V_j|}{X_{ij}}\left(|V_i|\cos(\delta_i - \delta_j) - k\,|V_i|\sin(\delta_i - \delta_j) - |V_j|\right) + \frac{|V_j|}{X_B}\left(|V_j| - |V_i|\cos(\delta_i - \delta_j)\right) + k_m Y_{MSC}|V_j|^2$$

Here k_m determines amount of Y_{MSC} in service, since the reactance X_B is located between buses i and j, this model does not increase the sparsity of admittance matrix compared to nabavi model, It should be noted that in this model line impedance between buses i and j is added to X_B.

2.3 Incorporation of HFC device:

The HFC injection model [22, 23] can easily be incorporated in a load flow program, if a HFC is located between bus i and j in a given power system, the admittance matrix is modified by adding a reactance equivalent to X_S between bus-i and bus-j .The power mismatches are modified by addition of appropriate injection powers, if consider the linearized load flow model as:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}H & N\\ J & L\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \frac{\Delta V}{V}\end{bmatrix}$$

The modifications in Jacobian matrix is given below (The superscript 'o' denotes the Jacobian elements without HFC)

$H_{ii} = H_{ii}^{0} - Q_{sj}$ $H_{ij} = H_{ij}^{0} + Q_{sj}$ $H_{ji} = H_{ji}^{0} + Q_{sj}$ $H_{jj} = H_{jj}^{0} - Q_{sj}$	$N_{ii} = N_{ii}^{0} - P_{sj}$ $N_{ij} = N_{ij}^{0} - P_{sj}$ $N_{ji} = N_{ji}^{0} + P_{sj}$ $N_{jj} = N_{jj}^{0} + P_{sj}$
$J_{ii} = J_{ii}^{0}$ $J_{ij} = J_{ij}^{0}$ $J_{ji} = J_{ji}^{0} - P_{sj}$ $J_{jj} = J_{jj}^{0} + P_{sj}$	$L_{ii} = L_{ii}^{0} + 2Q_{si}$ $L_{ij} = L_{ij}^{0}$ $L_{ji} = L_{ji}^{0} + Q_{sj}$ $L_{jj} = L_{jj}^{0} + Q_{sj}$

3. Problem formulation

3.1 Generation Cost

The generation cost function can be mathematically stated as follows [24].

$$F_1(x,u) = \sum_{i=1}^{N_G} a_i P_{G_i}^2 + b_i P_{G_i} + c_i \qquad \$/h \qquad -(9)$$

where $F_1(x)$ is the total fuel cost $(\$/h)$, 'x' is a control vector of dependent variables like slack bus active power generation $(P_{g,slack})$, load bus voltage magnitudes (V_L) and generator reactive powers (Q_G) and vector 'u' consist control variables like active powers (P_G) and voltages (V_G) of generators, transformer tap ratios (T) and shunt compensation (Q_C). a_i, b_i, c_i are fuel cost coefficients of the i^{th} unit, P_{G_i} is the real power generation of the i^{th} unit, V_{G_i} is the voltage magnitude of the i^{th} generator, N_G is the total number of generation units,

3.2 Transmission loss

The power flow solution gives all bus voltage magnitudes and angles. Then, the active power loss in transmission line can be computed as follows [7]

$$F_2 = \text{Losses }(L) = \sum_{k=1}^{N_{line}} P_{loss,k}$$
$$= \sum_{i=1}^{N}\sum_{j=1}^{N} g_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \quad MW \quad -(10)$$

Where N is total number of buses, N_{line} is total number of transmission lines, g_{ij} is the conductance of i^{th} line which connects buses i and j. V_i, V_j and δ_i, δ_j are voltage magnitude and angle of i^{th} and j^{th} buses.

3.3 Loadability

The third objective function is to maximize the system loadability that can be described in [25, 26]

$$F_3 = \rho\,(x, u) \qquad -(11)$$

ρ Can be obtained by assuming the constant power factor at each load in the real and reactive power balance equations as follows:

$$P_{G_i} - \rho P_{D_i} - P_{i,inj} = 0$$
$$Q_{G_i} - \rho Q_{D_i} - Q_{i,inj} = 0$$

3.4 Constraints

The OPF problem has two sets of constraints, including equality and inequality constraints. These constraints can be expressed as follows [27, 28].

3.4.1 Equality Constraints

These constraints are typically load flow equations.

$$\sum P_G - \sum P_{Load} - \sum P_{Losses} = 0$$
$$\sum Q_G + \sum Q_{Sh} - \sum Q_{Load} - \sum Q_{Losses} = 0$$

3.4.2 In-equality Constraints

These constraints represent the system operating constraints. The self restricted constraints satisfied within OPF are

Generator bus voltage limits: $V_{G_i}^{min} \le V_{G_i} \le V_{G_i}^{max}; \quad \forall\, i \in N_G$

Active Power Generation limits: $P_{G_i}^{min} \le P_{G_i} \le P_{G_i}^{max}; \quad \forall\, i \in N_G$

Transformers tap setting limits: $T_i^{min} \le T_i \le T_i^{max}; \; i = 1,2,3, \dots n_t$

Capacitor reactive power generation limits :

$$Q_{C_i}^{min} < Q_{ci} < Q_{C_i}^{max}; \quad i = 1,2 \dots\dots n_c$$

Transmission line flow limit : $S_{l_i} \le S_{l_i}^{max}; \quad i = 1,2,3, \dots\dots N_{line}$

Reactive Power Generation limits : $Q_{G_i}^{min} \le Q_{G_i} \le Q_{G_i}^{max}; \quad \forall\, i \in N_G$

Bus voltage magnitude limits : $V_i^{min} \le V_i \le V_i^{max}; \quad i = 1,2,3, \dots\dots N_{load}$

FACTS constraints: The FACTS shunt-series controller settings are bounded as follows

$$k^{min} \le k \le k^{max}, 0 \le k_c \le k_c^{max}, 0 \le k_L \le k_L^{max}, 0 \le k_m \le k_m^{max}, S_{HFC} \le S_{HFC}^{max}$$

where n_t is the total number of tap changers, n_c is the total number of VAr sources, N_{load} is the total number of load buses, S_{HFC} is the apparent power of HFC controllers in MVA.

4. Multi objective mathematical modeling

In general, aggregating the objectives and constraints, the problem can be mathematically formulated:

$$Minimize\ F_1\ \&\ F_2\ /\ Maximize\ F_3$$

$$\text{Subject to:} \quad g(x,u) = 0 \quad \& \quad h(x,u) \leq 0$$

where g(x,u) and h(x,u) are the set of equality and inequality constraints, respectively. The multiobjective optimization problem can be converted into a single objective optimization and then solved by using the e-constraint method in the next section

4.1 e-constraint method

This method optimizes one of the objective functions while the other objective functions are considered as constraints [28]

$$\min F_{1,k}(x)$$

$$\text{Subjected to } F_{2,k}(x) \leq e_{2,k}, F_{3,k}(x) \leq e_{3,k}, \dots, F_{p,k}(x) \leq e_{p,k}$$

where subscripts ‘p’ and ‘k’ indicate the number of objective functions and the number of transmission lines which include the FACTS controller, respectively. In order to properly handle this method, the range of every objective function at least for the (p-1) objective functions are required that will be used as constraints.

The most common approach is to calculate these ranges from the payoff table (the table with the results from the individual optimization of the ‘p’ objective functions) [28]. After placing the FACTS controller on each line of the power system, the individual optima of the objective functions are calculated to construct the payoff table ($F_{i,k}$ indicates the optimum value of the i^{th} objective function by placing the FACTS controller on the k^{th} line.), where the value of other objective functions is computed which are depicted by $F_1^{i,k}, \dots\dots, F_{i-1}^{i,k}, F_{i+1}^{i,k}, \dots\dots, F_p^{i,k}$. Consequently, the i^{th} row of the payoff table contains $F_{1,k}^{i}, \dots, F_{i-1,k}^{i}, F_i^{k}, F_{i+1,k}^{i}, \dots\dots, F_{p,k}^{i}$, in this way, all rows of the payoff table are calculated. The range of the j^{th} objective function is obtained among the minimum and maximum values of the j^{th} column of the payoff table that is divided into q_j equal intervals using $(q_j - 1)$ intermediate equidistant grid points. Thus, we have a total of $(q_j + 1)$ grid points for the j^{th} objective function where the total number of optimization sub problems for placing the FACTS controller on each line becomes $(q_2 + 1) \times (q_3 + 1) \times \dots\dots \times (q_p + 1)$. The density of the Pareto optimal set representation can be controlled by properly assigning the values to the q_i.

The optimization sub problems become the following form:

$$\min F_1(x)$$

$$\text{Subjected to } F_2(x) \leq e_2, F_3(x) \leq e_3,$$

$$e_{2,i}(x) = max(F2) - \left(\frac{\max(F2) - \min(F2)}{interval}\right).i \qquad \forall\, i = 0,1,2, \dots\dots, interval$$

$$e_{3,j}(x) = max(F3) - \left(\frac{\max(F3) - \min(F3)}{interval}\right).j \qquad \forall\, j = 0,1,2, \dots\dots, interval$$

where max (.) and min (.) represent the maximum and minimum values of the individual objective function while placing the FACTS controller on the line, respectively. Note that the optimization sub problems should be accompanied by the constraints of the MMP problem.

4.2 Fuzzy decision maker

After placing the FACTS controller on each line of the power system, the Pareto optimal solutions are obtained by solving the optimization sub problems. Thereafter, the decision maker needs to choose the optimal location of the FACTS controller according to the best compromise among the Pareto optimal solutions. In this paper, a fuzzy decision-making approach [29] is proposed for the optimal location process wherein a linear membership function is defined for each objective function as follows:

For minimized objective function

$$\mu_m = \begin{cases} 1 & ;for \quad F_m \leq F_m^{min} \\ \dfrac{F_m^{max} - F_m}{F_m^{max} - F_m^{min}} & ;for \quad F_m^{min} < F_m < F_m^{max} \\ 0 & ;for \quad F_m \geq F_m^{max} \end{cases}$$

For minimization of objectives and

$$\mu_m = \begin{cases} 0 & ;for \quad F_m \leq F_m^{min} \\ \dfrac{F_m - F_m^{min}}{F_m^{max} - F_m^{min}} & ;for \quad F_m^{min} < F_m < F_m^{max} \\ 1 & ;for \quad F_m \geq F_m^{max} \end{cases}$$

where $F_{i,k}^{n}$ and $\mu_{i,k}^{n}$ are the value of the i^{th} objective function in the n^{th} Pareto optimal solution of the k^{th} line which includes the FACTS controller and its membership function, respectively. The membership functions are used to evaluate the optimality degree of the Pareto optimal solutions. The most preferred solution can be selected as follows:

$$\mu_{opt}^{n} = max \left\{ \frac{\sum_{i=1}^{N_{obj}} \omega_{p,i} \cdot \mu_{p,i}^{n}}{\sum_{p=1}^{M} \sum_{i=1}^{N_{obj}} \omega_{p,i} \cdot \mu_{p,i}^{n}} \right\}$$

Considering $w_i \geq 0 \; and \; \sum_{i=1}^{p} w_i = 1$.

Here, k=0 means without FACTS device optimization if k ≠ means with FACTS device optimization, is the weight value assigned to the objective function and M is the number of Pareto optimal solutions in each line which includes the FACTS controller. The weight values can be selected by the power system dispatcher based on the importance of the economical and technical aspects. Therefore, the optimal location and settings of the FACTS controller based on the adopted weighting factors are obtained by the proposed algorithm as the best Pareto optimal solution.

5. Results and Analysis

In this section, the multi objective OPF solution using e-constraint method, the effects of the HFC location and its settings on the indices of power system operation and the performance of HFC are investigated on IEEE 14-bus system and IEEE 30-bus system. The optimal location of HFC device was identified using fuzzy decision making tool, the results of single objective optimization are analyzed. The HFC settings considered are

$$X_E = 0.001 \text{ p.u}; \; X_B = 0.007 \text{ p.u.}; \; S_{base} = 100\text{MVA}$$

$$\text{HFC:} -0.26 \leq k \leq 0.26;\ X_c = 0.0076\ \text{p.u.};$$
$$X_L = 0.0038\ \text{p.u.};$$
$$0 \leq k_c \leq 7; 0 \leq k_L \leq 3; 0 \leq k_m \leq 2; Y_{MSC} = 0.25\text{p.u.}$$

5.1 Example-1

The IEEE-14 bus system consists of 5 generator units as well as 20 transmission lines [30]. The total active power load is 245.0 MW while the total reactive power load is 73.5 MVAr. The maximum number of iterations and number of populations are set to 100.

The single objective OPF problem with PSO is formulated for three different objectives individually namely minimization of fuel cost, transmission loss and maximization of loadability. The possible location to install device are identified with the assumption is that the device is not placed in the lines which have transformer. The device installation location is identified based on the multi-objective optimization by placing device in all possible locations.

5.1.1 Fuel cost minimization

In this case, PSO is applied to minimize the total fuel cost with and without installation of HFC device. The obtained results are tabulated in Table.1.

Table.1 Fuel cost minimization with out and with HFC device

Control variables	Without device	With HFC device
PG1 (MW)	76.385	42.351
PG2 (MW)	140	140
PG3 (MW)	15	15
PG4 (MW)	10	17.497
PG5 (MW)	10	28.887
Fuel Cost ($/h)	19143.22	17847.14
Power Loss (MW)	4.042	2.435

From Table.1, It is observed that the total fuel cost is reduced from 19143.22 to 17847.14($/h) with HFC device, for this objective the optimal location of HFC is between buses 1-5 with the parameters $k_L = 0;\ k_c = 3; k = 0.066982;\ k_m = 1$.

5.1.2 Transmission loss minimization

In this case, PSO is applied to minimize the transmission loss with and without HFC device. The obtained results are tabulated in Table 5.2

Table.2 Transmission loss minimization without and with HFC device

Control variables	Without device	With HFC device
PG1 (MW)	18.063	17.943
PG2 (MW)	38.574	38.715
PG3 (MW)	40	50.98
PG4 (MW)	60.944	58.605
PG5 (MW)	44.336	44.458
Power Loss (MW)	1.238	0.939
Fuel Cost ($/h)	20650.7	24906.797

From Table.2, It is observed that the total power loss is reduced from 1.238 MW to 0.939 MW with HFC device, for this objective the optimal location of HFC is between buses 2-4 with the parameters $k_L = 0;\ k_c = 2; k = 0.00759;\ k_m = 2$.

5.1.3 Loadability maximization

In this case, PSO is applied to the maximization of loadability with and without installation of HFC device. The obtained results are tabulated in Table.3

Table.3 Loadability maximization without and with HFC device

Control variables	Without device	With HFC device
PG1 (MW)	200	216.3985
PG2 (MW)	38.31247	39.02627
PG3 (MW)	39.5229	21.3121
PG4 (MW)	21.09357	13.11601
PG5 (MW)	22.85308	41.00965
Loadability	1.45	1.495
Fuel Cost ($/h)	31046.97	27663.987
Power Loss (MW)	6.03947	4.2925

From Table.3, It is observed that the loadability factor is increased from 1.45 to 1.495 with HFC device, for this objective the optimal location of HFC is between buses 2-3 with the parameters $k_L = 0;\ k_c = 0; k = 0.228;\ k_m = 1$.

5.1.4 Multi Objective OPF problem

The proposed e-constraint based multiobjective OPF has been discussed in section.4. The optimal location of HFC device for multiobjective optimization is identified using fuzzy decision making tool. The multi-objective OPF problem is implemented with different combinations of objectives in two cases namely fuel cost, transmission loss, and Loadability factor.

Case 1: Multi Objective problem with two objectives

In this case, the proposed methodology handles two objectives together as multiobjective optimization problem. There are three possible two combinations with the three objectives.

The obtained result with and without placing HFC device is given in Table.4 and the optimal location of HFC device is calculated by using fuzzy decision making tool for that one taken weight value are 0.5 and 0.5 for all the combinations.

Table.4 Multi-objective obtained best compromised results for two different objectives

Objectives	Without device	With HFC device	HFC Location	HFC Settings
F1&F2	17007.19 & 1.2885	14992.05 & 1.014461	1-5	$k_c = 0;$ $k = 0.135;$ $k_m = 1; k_L = 0$
F1&F3	37845.83 & 1.36	29715.67 & 1.54	2-3	$k_c = 0;$ $k = 0.1765;$ $k_m = 1; k_L = 0$
F2&F3	10.43516 & 1.39	3.539445 & 1.34	1-5	$k_c = 5;$ $k = 0.186;$ $k_m = 1; k_L = 0$

where F1-fuel cost, F2-transmission loss, F3-loadability.

Case 2: Multi Objective problem with three objectives

In this case, the proposed methodology handles three objectives together as multiobjective optimization problem. There is one possible combination with the three objectives. obtained result with and without placing HFC device is shown in Table.5 and the optimal location of HFC device is calculated by using fuzzy decision making tool for that one the weight values are 0.4,0.3 and 0.3,

Table.5 Multi-objective obtained best compromised results for three objective combinations

Objectives	Without device	With HFC device	HFC Location	HFC Settings
F1&F2& F3	40207.31 & 8.95207 & 1.44	39318.15 & 5.1721 & 1.54	1-5	$k_c = 0;$ $k = 0.176;$ $k_m = 1; k_L = 0$

where, F1-fuel cost, F2-transmission loss, F3-loadability

It is observed that from all the cases, with HFC the obtained result is improved from its base case (i.e. without HFC). The multi objective obtained result with HFC based on required criterion improved the result. It is also observed that, increase in loadability results increase of cost and loss to a higher values. In case of cost and loss minimization there is no chance for getting loadability.

5.2 Example-2

The IEEE-30 bus system with 6 generator units as well as 41 transmission lines [31] is considered. The total active power load is 289.2 MW while the total reactive power load is 126.2 MVAr. The maximum number of iterations and population are set to 100.

5.2.1 Fuel cost minimization

In this case, PSO is applied to minimize the total fuel cost with and without installation of HFC device. The obtained results are tabulated in Table.6.

Table.6 Fuel cost minimization without and with HFC device

Control variables	Without device	With HFC device
PG1 (MW)	117.43	200
PG2 (MW)	80	26.809
PG3 (MW)	50	15
PG4 (MW)	13.651	10
PG5 (MW)	10	10
PG6 (MW)	12	12
Fuel Cost ($/h)	862.79	743.991
Power Loss (MW)	12.602	6.228

From Table.4, It is observed that the total fuel cost is reduce from 862.79 ($/h) to 743.991 ($/h) with HFC device, for this objective the optimal location of HFC is between buses 1-3, with the parameters $k_L = 2;\ k_c = 6; k = -0.021;\ k_m = 1$.

5.2.2 Transmission loss minimization

In this case, PSO is applied to minimize the transmission loss with and without installation of HFC device. The obtained results are tabulated in Table.7.

Table.7 Transmission loss minimization without and with HFC device

Control variables	Without device	With HFC device
PG1 (MW)	50	56.977
PG2 (MW)	80	80
PG3 (MW)	50	45.880
PG4 (MW)	35	34.929
PG5 (MW)	28.998	28.872
PG6 (MW)	38.709	25.5
Power Loss (MW)	3.227	2.721
Fuel Cost ($/h)	953.198	879.47

From Table.5, It is observed that the total power loss is reduce from 3.227 MW to 2.721 MW with HFC device, for this objective the optimal location of HFC is between buses 5-6 with the parameters $k_L = 0;\ k_c = 3; k = 0.03737;\ k_m = 1$.

5.2.3 Loadability maximization

In this case, PSO is applied to maximization of loadability with and without installation of HFC device. The obtained results are tabulated in Table.8.

Table.8 Loadability maximization without and with HFC device

Control variables	Without device	With HFC device
PG1 (MW)	225	200.0
PG2 (MW)	20	31.02
PG3 (MW)	15	23.72
PG4 (MW)	11.150	17.12
PG5 (MW)	27.906	20.59
PG6 (MW)	18.47	27.67
Loadability	1.39	1.46
Fuel Cost ($/h)	914.45	912.606
Power Loss (MW)	29.96	22.93

From Table.6, It is observed that the loadability is increased from 1.39 to 1.46 with HFC device, for this objective the optimal location of HFC is between buses 4-6 with the parameters $k_L = 0;\ k_c = 5; k = 0.1247;\ k_m = 1$.

5.2.4 Multi Objective OPF problem

The multi-objective OPF problem is implemented with different combinations of objectives given in two cases.

Case 1: Multi Objective problem with two objectives

In this case, the proposed methodology handles two objectives together as multiobjective optimization problem. There are three possible two combinations with the three objectives. The obtained result with and without placing HFC device is given in Table.9 The optimal location of HFC device is calculated by using fuzzy decision making tool the weight values are 0.5 and 0.5 for all the two objective combination

Table.9 Multi-objective obtained best compromised results for two different objectives

Objectives	Without HFC device	With HFC device	HFC Location	HFC settings
F1&F2	925.3114 & 3.379779	896.0164 & 3.022051	6-8	$k_c = 0;$ $k = 0.0771;$ $k_m = 1; k_L = 0$
F1&F3	826.7537 & 1.4	781.977 & 1.43	2-4	$k_c = 4;$ $k = 0.1933;$ $k_m = 1; k_L = 0$
F2&F3	14.3693 & 1.43	10.38882 & 1.46	12-13	$k_c = 7;$ $k = 0.1894;$ $k_m = 1; k_L = 0$

where F1-fuel cost, F2-transmission loss, F3-loadability

Case 2: Multi Objective problem with three objectives

In this case, the proposed methodology handles three objectives together as multiobjective optimization problem. There is one possible combination with the three objectives. obtained result with and without placing HFC device is shown in Table.10, the optimal location of facts device is calculated by using fuzzy decision making tool for that one consider weight values are 0.4 0.3 and 0.3,

Table.10 Multi-objective obtained best compromised results for three objective combinations

Objectives	Without HFC device	With HFC device	HFC Location	HFC settings
F1&F2&F3	1057.796 & 14.6194 & 1.42	974.877 & 8.2305 & 1.44	2-4	$k_c = 4;$ $k = 0.1407;$ $k_m = 1; k_L = 1$

where F1-fuel cost, F2-transmission loss, F3-loadability,

It is observed that, increase in loadability results increase of cost and loss to a higher values. In case of cost and loss minimization there is no chance for getting loadability.

6. Conclusion

In this paper, using HFC proposed model, the optimization of the power system objectives are improved from its base values (without HFC). The multi-objective obtained result has the choice to choose the device settings. Using this model, the optimal installation location of HFC is identified in a given network. The used fuzzy logic can identify the proper location, so that the effect of device can be easily identified. The control parameters of the device are selected within its limits and the system objectives like generation fuel cost, transmission losses are minimized and the system loadability is maximized

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