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A Hybrid Differential Evolution and Harmony Search for Optimal Power Flow With FACTS Devices

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ABSTRACT

This paper proposes a hybrid differential evolution (DE) and harmony search (HS) for solving optimal power flow (OPF) problem with FACTS devices including static Var compensator (SVC), thyristor-controlled series compensation (TCSA), and thyristor-controlled phase shifter (TCPS). The proposed hybrid DE-HS is to utilize the advantages of the DE and HS methods to enhance its search ability for dealing with large-scale and complex problems. The proposed method has been tested on the IEEE 30 bus system with the variety of objective functions including quadratic fuel cost, power loss, voltage deviation, and voltage stability index and the obtained results from the proposed hybrid DE-HS have been compared to those from other algorithms. The result comparison has indicated that the proposed hybrid DE-HS algorithm can obtain better solution quality than many other methods. Therefore, the proposed hybrid DE-HS method can be an efficient method for solving the OPF problem incorporating FACTS devices.

KEYWORDS

FACTS Devices, Hybrid Differential Evolution and Harmony Search, Optimal Power Flow, Power Loss, Static Var Compensator, Thyristor-Controlled Phase Shifter, Thyristor-Controlled Series Compensator

1. INTRODUCTION

In the power system operation, the OPF problem is a very popular one. The objective of an optimal power flow (OPF) problem is to find the steady state operation point of generators in the system so as their total generation cost is minimized while satisfying various generator and system constraints such as real and reactive power of generators, bus voltages, transformer taps, switchable capacitor banks, and transmission line capacity limits (Carpentier, 1979). In the OPF problem, the controllable variables usually determined: 1) real power output of generators, 2) voltage magnitude at generation

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buses, 3) injected reactive power at compensation buses, 4) and transformer tap settings. This is a classic and large-scale problem, but it is extensively studied due to its significance in the power system operation. Traditionally, mathematical programming techniques can effectively deal with the problem and the OPF problem has been widely studied in the literature (Happ and Wirgau, 1981; Huneault and Galiana, 1991; Momoh, Adapa, and El-Hawary, 1999; Pandya and Joshi, 2008). However, due to the incorporation of FACTS devices to systems, valve-point effects or multiple fuels to generators recently, the OPF problem becomes more complicated and the mathematical programming techniques are not a proper selection. Therefore, it requires more powerful search methods for a better implementation.

Several methods have been applied for solving this problem. The purpose of the solution methods applied to this problem is to find the optimal solution, so that the effectiveness of these methods can be evaluated. The better method is the one which can find better optimal solution than other methods for the problem in terms of the minimum objective function. However, not all methods can be successfully applied to solve this problem due to handling several variables and constraints. Therefore, the effective methods for successfully solving the OPF problem are usually the powerful method for solving optimization problems. The OPF problem has been solved by several conventional methods such as gradient-based method (Wood and Wollenberg, 1996), linear programming (LP) (Abou El-Ela and Abido, 1992; Mota-Palomino and Quintana, 1986), non-linear programming (NLP) (Dommel and Tinny, 1968; Pudjianto, Ahmed, and Strbac, 2002), quadratic programming (QP) (Burchett, Happ, and Vierath, 1984; Granelli and Montagna, 2000), Newton-based methods (Sun *et al.*, 1984; Santos and da Costa, 1995; Lo and Meng, 2004), semidefinite programming (Bai et al., 2008), and interior point method (IPM) (Yan and Quintana, 1999; Wang and Liu, 2005; Capitanescu *et al.*, 2007). Generally, the conventional methods can find the optimal solution for an optimization problem with a very short time. However, the main drawback of these methods is that they are difficult to deal with non-convex optimization problems with a non-differentiable objective. Moreover, these methods are also very difficult for dealing with large-scale problems due to large search space. In addition, meta-heuristic search methods recently developed have shown that they have the capability to deal with this complicated problem. Several meta-heuristic search methods have been also widely applied for solving the OPF problem such as genetic algorithm (GA) (Lai and Ma, 1997; Wu, Cao, and Wen, 1998; Osman, Abo-Sinna, and Mousa, 2004); simulated annealing (SA) (Roa-Sepulveda and Pavez-Lazo, 2003), tabu search (TS) (Abido, 2002), evolutionary programming (EP) (Wu and Ma, 1995; Yuryevich and Wong, 1999); particle swarm optimization (PSO) (Abido, 2001), and differential evolution (DE) (Cai, Chung, and Wong, 2008). These meta-heuristic search methods can overcome the main drawback of the conventional methods with the problem not required to be differentiable. However, the optimal solutions obtained by these methods for optimization problems are near optimum and the quality of the solutions is not high when they deal with large-scale problems; that is the obtained solutions may be local optimums with long computational time.

FACTS devices have recently applied to enhance the transmission capacity and stability ability of power systems. Therefore, the OPF problem with FACTS devices is considered as a new trend of research for application to power systems. The OPF with FACTS device problem has been studied by several researchers using different optimization methods such as a two-stage approach (Shaoyun and Chung, 1998; Chandrasekaran, Arul Jeayaraj, and Saravanan, 2009), GA (Arunya Revathi *et al.*, 2008, Panda and Padhy, 2008), PSO (Panda and Padhy, 2008), hybrid GA (Chung and Li, 2001), and linear programming (Shamukha Sundar and Ravikumar, 2012). These methods are relatively effective for the OPF problem with FACTS devices. In fact, the OPF problem with FACTS devices is a very complex one since the solution methods have to handle both the location and capacity of FACTS devices when incorporating in the OPF problem.

In this paper, a newly hybrid differential evolution and harmony search is proposed to solve optimal power flow with FACTS devices including static VAR compensator (SVC), thyristor controlled series compensation (TCSA), and thyristor-controlled phase shifter (TCPS). The proposed hybrid DE-HS is a hybrid method which combines the advantages of both DE and HS to form an effective method for dealing with the OPF problem. The DE method has many advantages to solve non-linear optimization problems such as simple structures, few control variables, high reliability and high-quality solution. The HS method is an algorithm inspired from the searching of harmony in music simulations and it has been extensively studied with high ability to combine with other algorithms to form powerful solution methods. Owning to the advantages of both HS and DE, the proposed hybrid DE-HS can find better optimal solution than other methods for the complex OPF problem with FACTS devices. For solving the OPF problem with FACTS devices, a min-cut algorithm has been implemented for determining the optimal position of FACTS devices and then the hybrid DE-HS is used for solving the OPF problem. The proposed method has been tested on the IEEE 30 bus system with the variety of objective functions including quadratic fuel cost, power loss, voltage deviation, and voltage stability index and the obtained results from the proposed hybrid DE-HS have been compared to those from other algorithms in the literature.

The organization of the remaining of the paper is as follows. Section 2 presents the problem formulation in mathematical model. Section 3 introduces to the proposed hybrid DE-HS algorithm and implements the proposed method for solving the problem. Section 4 addresses the numerical results by testing the proposed method on a benchmark system. Finally, the conclusion is given.

2. PROBLEM FORMULATION

In the OPF problem with FACTS devices, the considered variables include control variables and state variables. The control variables consist of real power injected at generation buses excluding the slack bus, voltage at generation buses, tap changer of transformers, reactive power injected by capacitor banks, and additional parameters from FACTS devices including the reactive power of SVC, inductance of TCSC, and angle of TCPS. The state variables comprise the power generation at the slack bus, voltage at load buses, reactive power output of generators, and power flow in transmission lines. The objective of the OPF problem with FACTS devices is to determine the control variables in order that an objective function of total fuel cost of thermal units, total power loss in transmission lines, total voltage deviation or stability index is minimized while satisfying equality constraints of power flow equations and inequality constraints of control variables and state variables.

Mathematically, the OPF with FACTS devices is formulated as follows.

2.1. Objective Function

The selected objective of the problem is the total fuel cost of thermal units, total power loss in transmission system, voltage deviation from buses to a reference value or stability index of the system as follows:

- **Total Fuel Cost of Thermal Units:** The objective is to minimize the total fuel cost of thermal units represented as:

$$\sum_{i=1}^{N_g} F_i(P_{gi}) \tag{1}$$

The fuel cost of each thermal generator $F_i(P_{gi})$ can be represented as a quadratic function:

$$F_i(P_{gi}) = a_i + b_i P_{gi} + c_i P_{gi}^2 \tag{2}$$

As the effects of valve points in boilers of thermal generating units are considered, the fuel cost is represented by a sinusoidal component added to the quadratic function:

$$F_i(P_{gi}) = a_i + b_i P_{gi} + c_i P_{gi}^2 + | e_i \sin(f_i (P_{gi,\min} - P_{gi})) | \tag{3}$$

where N_g is the number of generators, P_{gi} is the real power output of thermal unit *i*, and a_i, b_i, c_i, e_i, and f_i are the fuel cost coefficients of thermal unit *i*.

- **Total Power Loss in Transmission Lines:** The objective is to minimize the total power loss in transmission system represented by:

$$Min\ P_{loss} = \sum_{k=1}^{N_l} g_k \left[V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j) \right] \tag{4}$$

where N_l is the number lines in transmission system, g_k is the conductance of line *k*, V_i and V_j are voltage magnitudes at the two end buses *i* and *j* of line *k*, and δ_i and δ_j are the voltage angles at the two end buses *i* and *j* of line *k*.

- **Voltage Deviation:** The objective is to minimize the total voltage deviation from load buses to a reference voltage represented by:

$$Min \sum_{i=1}^{N_d} | V_i - V_{ref} | \tag{5}$$

where N_d is the number of load buses, V_i is the voltage magnitude at load bus *i*, and V_{ref} is pre-specified reference voltage at load buses, usually $V_{ref} = 1.0$ pu.

- **Stability Index:** The objective is to minimize the maximum stability index of load buses in the system represented by:

$$Min\ L_{Max} \tag{6}$$

where the maximum stability index L_{max} is calculated by:

$$L_{Max} = \left\{ L_j, j = 1, 2, \ldots, N_d \right\} \tag{7}$$

in which, each stability index L_j used to measure the voltage stability at each load bus of power system from 0 (no-load) to 1 (voltage collapse) (Abou El-Ela *et al.*, 2011). One of the most popular methods for calculation of the stability index proposed by (Kessel and Glavitsch, 1986) is as follows:

$$L_j = | L_j | = \left| 1 - \frac{\sum_{i \in \alpha_G} C_{ij} V_i}{V_j} \right| ; j \in \alpha_L \tag{8}$$

where α_L is the set of load buses, α_G is the set of generator buses, V_i is voltage at bus *i*, and C_{ij} is a component of *C*-matrix and determined by:

$$[C] = -\left[Y_{LL}\right]^{-1}\left[Y_{LG}\right] \tag{9}$$

in which, Y_{LL} and Y_{LG} are the matrices inside Y_{bus} matrix which is represented as follows:

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{10}$$

2.2. Constraints

2.2.1. Equality Constraints

The equality constraints of the problem include the real and reactive power balances at buses:

$$P_{gi} - P_{di} = \sum_{j=1}^{N_b} |V_i||V_j||Y_{ij}(FACTS)|\cos\left(\theta_{ij}(FACTS) + \delta_{ij}\right), i = 1,\ldots,N_b \tag{11}$$

$$\begin{aligned} &Q_{gi} + Q_{ci} + Q_i(FACTS) - Q_{di} \\ &= \sum_{j=1}^{N_b} |V_i||V_j||Y_{ij}(FACTS)|\sin\left(\theta_{ij}(FACTS) + \delta_{ij}\right), i = 1,\ldots,N_b \end{aligned} \tag{12}$$

where Q_{gi} is the reactive power outputs of generating unit *i*, P_{di}, Q_{di} are real and reactive power demands at load bus *i*, respectively, Q_{ci} is the reactive power injection from a switchable shunt capacitor bank at bus *i*, Q_i*(FACTS)* is the reactive power injection of FACTS devices at bus *i*, $|Y_{ij}$(FACTS)$|\angle\theta_{ij}$(FACTS) is a component of Y_{bus} matrix with FACTS devices.

2.2.2. Inequality Constraints

- The real power, reactive power, and voltage at generation buses should be between their lower and upper bounds:

$$P_{gi,\min} \le P_{gi} \le P_{gi,\max}, i = 1,2,\ldots,N_g \tag{13}$$

$$Q_{gi,\min} \le Q_{gi} \le Q_{gi,\max}, i = 1,2,\ldots,N_g \tag{14}$$

$$V_{gi,\min} \le V_{gi} \le V_{gi,\max}, i = 1,2,\ldots,N_g \tag{15}$$

where V_{gi} is the voltage magnitude at generation bus *i*.

- The switchable shunt capacitor banks and the tap setting of each transformer should be between their lower and upper limits:

$$Q_{ci,\min} \le Q_{ci} \le Q_{ci,\max}, i = 1,2,\ldots,N_c \tag{16}$$

$$T_{k,\min} \le T_k \le T_{k,\max}, k = 1,2,\ldots,N_t \tag{17}$$

where T_k is the tap-setting of transformer at branch k.

- The voltage at load buses and power flow in transmission lines should not exceed their limits:

$$V_{li,\min} \le V_{li} \le V_{li,\max}, i = 1,2,\ldots,N_d \tag{18}$$

$$S_l \le S_{l,\max}, l = 1,2,\ldots,N_l \tag{19}$$

$$S_l = \max\left\{|S_{ij}|,|S_{ji}|\right\} \tag{20}$$

where V_{li} is the voltage magnitude at load bus i, S_l is the maximum apparent power flow in transmission line l connecting between buses i and j, and S_{ij} and S_{ji} are the apparent power flow from bus i to bus j and vice versa.

- The parameters for FACTS devices including SVC, TCSC, and TCPS should not exceed their limits:

$$Q_{SVCi,\min} \le Q_{SVCi} \le Q_{SVCi,\max}, i = 1,2,\ldots,N_{SVC} \tag{21}$$

$$X_{TCSCi,\min} \le X_{TCSCi} \le X_{TCSCi,\max}, i = 1,2,\ldots,N_{TCSC} \tag{22}$$

$$\Phi_{TCPSi,\min} \le \Phi_{TCPSi} \le \Phi_{TCPSi,\max}, i = 1,2,\ldots,N_{TCPS} \tag{23}$$

where Q_{SVCi} is the reactive power inject from the SVC installed at bus i, N_{SVC} is the number of SVCs, X_{TCSCi} is the reactance of the TCSC in line i, N_{TCSC} is the number of TCSCs, Φ_{TCPSi} is the phase angle of TCPS in line i, and N_{TCPS} is the number of TCPSs.

In the formulated problem, the two vectors u and x are used respectively representing the control variables and state variables in power system where bus 1 is selected as the sack bus as follows:

$$u = \begin{bmatrix} P_{g2},\ldots,P_{gN_g},V_{g1},\ldots,V_{gN_g},Q_{c1},\ldots,Q_{cN_c},T_1,\ldots,T_{N_t} \\ Q_{SVC1},\ldots,Q_{SVC,N_{SVC}},X_{TCSC1},\ldots,X_{TCSC,N_{TCSC}},\theta_{TCPS1},\ldots,\theta_{TCPS,N_{TCPS}} \end{bmatrix}^T \tag{24}$$

$$x = \left\{P_{g1},Q_{g1},\ldots,Q_{gN_g},V_{l1},\ldots,V_{lN_d},S_{l1},\ldots,S_{lN_t}\right\}^T \tag{25}$$

3. PROPOSED HYBRID DIFFERENTIAL EVOLUTION - HARMONY SEARCH ALGORITHM

3.1. Differential Evolution

Differential evolution (DE) was developed by Storn and Price in 1997 based on the idea of GA with the reliability and effectiveness (Storn and Price, 1997). The main advantages of the DE are its stability and ability for searching global optimal solution in solving optimization problems. DE is based on individual's difference via random research in solution space with the mechanisms of mutation, recombination, and selection to obtain appropriate individual. DE has three main control parameters including rate constant (F) for controlling mutant process, dual crossover factor (C_R) for controlling the diversity of the population, and size of the population (N_p).

Consider an optimization problem having N variables, the optimization process of DE with a population of N_p individuals is included in the steps as follows:

- **Initialization:** The DE method randomly initializes a population where each individual is a candidate of solution as:

$$x_{ij}^{(0)} = x_{j,\min} + rand_1 * (x_{j,\max} - x_{j,\min}) \tag{26}$$

where x_{ij} is value of variable j of individual i, so called population X; $x_{j,min}$, $x_{j,max}$ are upper and lower limits of x_{ij}; and $rand_1$ is a random value in [0, 1].

- **Mutation:** After an initial population has been created, DE begins the mutant process to make a new population by:

$$v_{i,g} = x_{ro,g} + F(x_{r1,g} - x_{r2,g}) \tag{27}$$

where $v_{i,g}$ is the new created individual i, so called population V; r_o, r_1, r_2 are the random values in [0, N_p]; F is a rate constant has value in [0,1] to control evolution progress.

- **Recombination:** DE conducts a hybrid following the dual crossover type to create a new population $\boldsymbol{U}$ using random parameters selected from $\boldsymbol{X}$ and V populations. The hybrid technique can be shown as:

$$u_{i,g} = \begin{cases} v_{j,i,g} & if\ rand(0,1) \le C_R\ or\ j = rand(j) \\ x_{i,j,g} & otherwise \end{cases} \tag{28}$$

where C_R is the hybrid probability defined value in [0,1] to control a part of copied parameters from mutants population. Factor $j = rand(j)$ has been obtained from population V to ensure that the mutant candidates are not equal to the initial candidates $x_{i,g}$:

- **Selection:** In the natural selection and reproduction, the candidates in the mutant population U are compared to those from the initial population X and the candidate has lower value in object function will be selected to move to the new population Y. This selection technique can be shown as:

$$v_{ij}^{(G+1)} = \begin{cases} u_{i,g} & if\ f(u_{i,g}) \le f(x_{i,g}) \\ x_{i,g} & otherwise \end{cases} \quad (29)$$

The reproduction progress is continued with an assignment $X = Y$:

- **Stopping criteria:** The stopping criteria of DE are described as follows:

$$F(x)_{\min} - \frac{\sum_{i=1}^{N_P} F(x)_i}{N_P} \le \varepsilon \quad (30)$$

where $F(x)_{min}$ is the minimum value of the object function up to the current generation; $F(x)_i$ is the value of the object function at generation i; N_P is the number of individuals in the current population; and ε is a predetermined threshold.

3.2. Harmony Search

Harmony search (HS) is an optimization algorithm based on the music simulation inspired by the search of harmony where the music players try to improvise the pitches of their instruments so that a better harmony can be obtained (Geem, Kim, and Loganathan, 2001). HS has many control parameters including harmony memory size (*HMS*), harmony memory considering rate (HMCR), pitch adjusting rate (*PAR*), maximum number of improvisations (*MaxImp*), and fret width (*fw*). The HS algorithm includes the steps as follows:

Step 1: Select the algorithm parameters including HMS representing the number of solution vectors, HMCR representing the rate in the range [0,1] that HS randomly picks a value from the musician memory, PAR representing the rate in the range [0,1] that HS adjusts the value originally picked in the memory, MI representing the number of iterations, and FW is the arbitrary length for continuous variables . Therefore, the rate 1-HCMR indicates that the HS can randomly pick a value from the whole range and the rate (1-PAR) indicates that the HS can keep the original value picked from the memory.

Step 2: Initialize a random vector (x^1,….,x^{HMS}) and store it in harmony memory (HM) as:

$$x_j^i = x_j^L + rand_1^* \left(x_j^U - x_j^L\right); i = 1,...,HMS; j = 1,...,N \quad (31)$$

$$HM = \begin{vmatrix} x_1^1 & x_2^1 & ... & x_N^1 & F(x^1) \\ x_1^2 & x_2^2 & ... & x_N^2 & F(x^2) \\ . & . & ... & . & . \\ . & . & ... & . & . \\ x_1^{HMS} & x_2^{HMS} & ... & x_N^{HMS} & F(x^{HMS}) \end{vmatrix} \quad (32)$$

where $rand_1$ is the random number in the range [0,1], x_j^L and x_j^U are the lower and upper bounds of variable x_j, $F(x^1)$, …, $F(x^{HMS})$ are the objectives corresponding to the initialized vectors x^1, …, x^{HMS}, respectively.

Step 3: Create a new vector v^i in *HM*.

Each individual v_j^i in the new vector is set to a random value in the *HM* with a probability of *HCMR* or reinitialized with a probability of (1-*HCMR*):

$$v_j^i = \begin{cases} x_j^{\mathrm{int}[rand_3]} & rand_2 < HCMR \\ x_j^L + rand_4 * (x_j^U - x_j^L) & Otherwise \end{cases} \tag{33}$$

where $rand_2$, $rand_3$ and $rand_4$ are the random numbers in the range [0,1] and $x_j^{int[rand3]}$ is the random value picked in the HS.

Then, the new value of v^i_j obtained from *HM* is further mutated using *PAR* as follows:

$$u_j^i = \begin{cases} v_j^i \pm rand_6 * fw & rand_5 < PAR \\ v_j^i & Otherwise \end{cases} \tag{34}$$

where *fw* is the maximum change in the pitch adjustment, $rand_5$ and $rand_6$ are the random numbers in the range [0,1].

Step 4: If the new obtained vector v^i is better than the worst one in HM, replace the worst one in HM by v^i.
Step 5: Perform Steps 3 to 4 while the stopping criteria are not reached. Otherwise, stop the algorithm.

3.3. Maximum Flow - Minimum Cut Algorithm

The maximum flow (max-flow) was developed in 1956 (Ford and Fulkerson, 1956) to find the maximum feasible flow in a flow network from a single-source a single-sink. The minimum cut (min-cut) is the minimum sum of weights of edges in a graph that when removed from the graph will divide the graph into two groups. In the max-flow min-cut algorithm, the amount of maximum flow passing from the source to the sink in a flow network is equal to the total weight of the edges in the minimum cut (Cormen et *al.*, 2001).

In any flow network such as communication, transportation, water, gas supply systems, or power transmission system, a min-cut always exists and it contains a group of weakest branches or lines in the system. The basic of this algorithm is the initialization of a virtual flow runs in power network at the steady-state then increasing this flow step by step. After a very short time, the network will be overloaded in a first branch or line. Cutting out this branch and iterating until the power network is divided into two independent parts. The group of cut-out branch is called min-cut. In this paper, the max-flow min-cut algorithm has been implemented to find optimal locations of FACTS devices including SVC, TCSC, and TPSC before solving the OPF problem.

3.4. Hybrid DE - HS Algorithm

Although DE has several advantages, it has also several drawbacks such as unstable convergence in the last period and easy to drop into regional optimum. There have been many researches preformed for improvement of DE to overcome the drawbacks. However, it has also deficiencies such as the next pedigree created just from father and mother (two populations). This can decrease its diversity so that it also needs more improvements to enhance its search ability. In HS, a new vector is created from all current vectors, not only from two. HS can consider each variable in a vector while creating a new vector. This characteristic helps HS more flexible and can fix the DE's weaknesses. Therefore, this paper implements an improvement for DE by making a combination between DE and HS to create a new hybrid DE-HS algorithm.

The hybrid DE-HS does not only increase the diversity of population but also avoids selecting couple father and mother from two populations in the same generation. The hybrid DE-HS method is a method to create more potential candidates but does not cause increasing the number of candidates in population N_P. The hybrid DE-HS method can make changes to candidates to get a better optimal solution. The flowchart of the hybrid DE-HS method for solving an optimization problem is given in Figure 1.

3.5. Implementation of Hybrid DE-HS

For implementation of the hybrid DE-HS method to the OPF problem with FACTS devices, each candidate in the population represents the control variables as:

$$u_{FACTSd} = \begin{bmatrix} P_{g2d},\dots,P_{gN_gd},V_{g1d},\dots,V_{gN_gd},Q_{c1d},\dots,Q_{cN_cd},T_{1d},\dots,T_{N_td}, \\ Q_{SVC1d},\dots,Q_{SVCN_{SVC}d},X_{TCSC1d},\dots,X_{TCSCN_{TCSC}d},\Phi_{TCPS1d},\dots,\Phi_{TCPSN_{TCPS}d} \end{bmatrix}, d = 1,\dots,N_P \quad (35)$$

where u_{FACTSd} is a candidate of the population and N_P is the number of candidates in the population.

The fitness function in the hybrid DE-HS for the OPF problem with FACTS devices is based on the problem objective function and depends on the variables including real power generation at the slack bus, reactive power outputs at the generation buses, load bus voltages, and apparent power flow in transmission lines. The fitness function is defined as:

$$x^{\lim} = \begin{cases} x_{\max} & if \;\; x > x_{\max} \\ x_{\min} & if \;\; x < x_{\min} \\ x & otherwise \end{cases} \quad (36)$$

where x and x^{lim} respectively represent the calculated value and limits of P_{gref}, Q_{gi}, V_{li}, or S_l.

The overall procedure of the proposed hybrid DE-HS for solving OPF problem with FACTS devices is addressed as following steps:

Step 1: Set the controlling parameters for DE-HS including *HMS*, *HMCR*, *PAR*, *fw*, *CR*, and *MaxImp* and penalty factors K_{ref}, K_q, K_v, K_s for constraints.

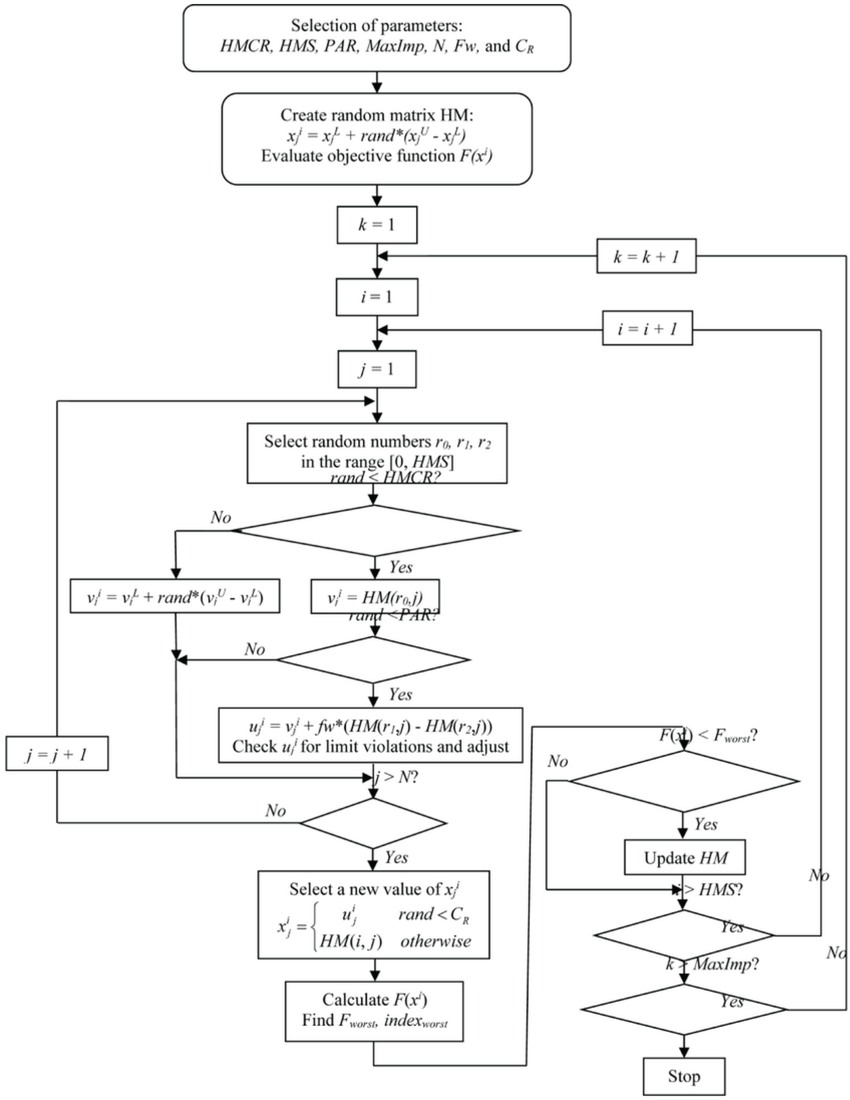
Step 2: Initialize a population in HS, each row of *HM* matrix is created by:

$$u_{FACTS}^{id} = u_{FACTS}^{\min} + rand * (u_{FACTS}^{\max} - u_{FACTS}^{\min}) \quad (37)$$

where *rand* is a random value in [0,1].

Step 3: Solve power flow problem by Newton - Raphson method using Matpower (Zimmerman, Murillo-Sanchez, and Thomas, 2011).

Figure 1. Flowchart of the hybrid DE-HS method



Calculate the objective function of the problem:

Step 4: Calculate the fitness function for the problem in (30).
Step 5: Set the iteration counter $k = 1$.
Step 6: Change the value of *HM* matrix.

Run power flow by Newton-Raphson method using Matpower and calculate fitness function:

Step 7: Update the matrix *HM*.
Step 8: Calculate value of the objective function.
Step 9: If $k < MaxImp$, $k = k + 1$ and return to Step 6. Otherwise, stop.

4. NUMERICAL RESULTS

Like many other methods, the proposed hybrid DE-HS has been tested on a benchmark system to verify its effectiveness. In fact, all the methods in the literature are always tested on benchmark systems. The successful application to benchmark systems is a very important basis to implement the methods to the real power systems. In the case studies, we usually compare the obtained results from the case without FACTS devices and the case with FACTS devices for an evaluation of difference. Moreover, we also compare the results obtained by the proposed method to those from other methods for different cases to evaluate the effectiveness of the used methods. The proposed DE-HS method has been tested on the IEEE 30 bus system with different object functions from (Dabbagchi and Christie, 1993; Alsac Stott, 1974; Zimmerman, Murillo-Sánchez, and Thomas, 2011). In this paper, different case studies with many sub-case studies have been tested to evaluate the effectiveness of the proposed method. In all test cases, the upper and lower voltage magnitudes are set to 1.10 and 0.95 pu, respectively. The upper and lower limits of transformer tap changer are 1.10 and 0.9 pu, respectively. All penalty factors are set to 10^6 in normal case and 10^3 in congestion cases. In this research, the power flow problem is solved by Matpower (Zimmerman, Murillo-Sánchez, and Thomas, 2011). The algorithm of the DE-HS methods has been coded in Matlab platform and run on a 2.1 GHz with 4 GB of RAM PC. In this paper, three cases are studied including:

Case Study 1: The OPF problem with FACTS devices including TCSC, SVC, and TCPS.
Case Study 2: The OPF problem with TCSC for normal and emergency case.
Case Study 3: The OPF problem with TCSC for different objectives of power loss, voltage deviation, and stability index.

For implementation of the hybrid DE-HS, the control parameters are set as follows. *HMS* is set to 15 in case of one FACTS device and to 20 in case of multiple FACTS devices used in the system. *HMCR* is set equal to 0.95, *PAR* to 0.8, *fw* to 0.7, C_R to 0.5, *MaxImp* to 200. For each case, the best result was obtained after 50 independent runs. For each case study, the results obtained by the proposed methods for the cases with and without FACTS devices have been compared together to evaluate the difference between the two cases. Moreover, the obtained result from the proposed method has been also compared to that from other methods in the literature for each case to evaluate the effectiveness of the used methods.

4.1. Case Study 1

In this case study, the hybrid DE-HS has been used to test on the IEEE-30 bus system (Alsac Scott, 1974; Zimmerman, Murillo-Sánchez, and Thomas, 2011) with FACTS devices. In this paper, the quadratic fuel cost function is used as the objective function and three types of FACTS device are considered including TCSC, SVC, and TCPS.

4.1.1. OPF Problem With TCSC

The optimal location of TCSC in the system obtained by the loss sensitivity index (Ongsakul and Bhasaputra, 2002) is on line 3-4. The value of reactance of TCSC varies in the range 0 to 0.02 pu. The obtained optimal solutions for the OPF problem with and without TCSC are given Table 1. The total cost for the case with TCSC is slightly lower than that from the case without TCSC.

The obtained results from the proposed hybrid DE-HS for the problem considered in this case is compared to that from hybrid TS/SA (Ongsakul and Bhasaputra, 2002) and PSO (Puttanon, 2007) as shown in Table 2. As observed from the table, the proposed method can obtain better solution than the other.

Table 1. Optimal results for the OPF problem with TCSC by the hybrid DE-HS

	Without FACTS Device	With TCSC
P_{g1} (MW)	177.0158	177.1857
P_{g2} (MW)	48.3280	48.7178
P_{g5} (MW)	21.8674	21.4255
P_{g8} (MW)	21.6914	20.8597
P_{g11} (MW)	11.2231	11.8648
P_{g13} (MW)	12.0000	12.0633
V_{g1} (pu)	1.1000	1.1000
V_{g2} (pu)	1.0831	1.0847
V_{g5} (pu)	1.0466	1.0528
V_{g8} (pu)	1.0622	1.0609
V_{g11} (pu)	1.1000	1.1000
V_{g13} (pu)	1.0945	1.1000
T_{11} (pu)	1.0900	1.0500
T_{12} (pu)	0.9000	0.9100
T_{15} (pu)	0.9900	0.9800
T_{36} (pu)	0.9700	0.9500
Q_{c10} (MVar)	19.0000	19.0000
Q_{c24} (MVar)	4.3000	4.3000
$TCSC_{3-4}$ (pu)	-	0.0200
P_{loss} (MW)	8.7256	8.7169
Total Cost ($/h)	**799.5762**	**799.3743**
Total voltage deviation	1.3579	1.5875
Voltage stability index	0.1325	0.1287

Table 2. Result comparison for the OPF problem with TCSC

	TS/SA (Ongsakul and Bhasaputra, 2002)	PSO (Puttanon, 2007)	Hybrid DE-HS
P_{g1} (MW)	192.6018	175.9641	177.1857
P_{g2} (MW)	48.4147	48.95	48.7178
P_{g5} (MW)	19.5561	21.526	21.4255
P_{g8} (MW)	11.6615	22.309	20.8597
P_{g11} (MW)	10	12.189	11.8648
P_{g13} (MW)	12	12	12.0633
TCSC_{3-4} (pu)	0.02	0.011093	0.0200
Total cost ($/h)	**804.6497**	**802.6552**	**799.3743**

4.1.2. OPF Problem With SVC

In this case, the optimal location of SVC is at load bus 21 where the reactive power is consumed higher than any other load buses. The reactive power of the SVC varies in the range 0 to 11.2 MVAr. The optimal solution obtained by the hybrid DE-HS for the problem is given in Table 3. The total cost for the case with SVC is slightly lower than that from the case without FACTS devices.

The optimal result from the proposed method is also compared to that from other methods such as hybrid TS/SA (Ongsakul and Bhasaputra, 2002) and PSO (Puttanon, 2007) as in Table 4. As indicated in the table, the proposed hybrid DE-HS can obtain slightly better than that from TS/SA and PSO.

Table 3. Optimal result for the OPF problem with SVC by the hybrid DE-HS

	Without FACTS Device	With SVC
P_{g1} (MW)	177.0158	176.5996
P_{g2} (MW)	48.3280	48.8110
P_{g5} (MW)	21.8674	21.5180
P_{g8} (MW)	21.6914	21.3499
P_{g11} (MW)	11.2231	11.7695
P_{g13} (MW)	12.0000	12.0000
V_{g1} (pu)	1.1000	1.0998
V_{g2} (pu)	1.0831	1.0834
V_{g5} (pu)	1.0466	1.0579
V_{g8} (pu)	1.0622	1.0655
V_{g11} (pu)	1.1000	1.1000
V_{g13} (pu)	1.0945	1.1000
T_{11} (pu)	1.0900	1.0500
T_{12} (pu)	0.9000	0.9100
T_{15} (pu)	0.9900	0.9600
T36 (pu)	0.9700	0.9600
Qc10 (MVar)	19.0000	19.0000
Qc24 (MVar)	4.3000	3.7000
SVC21 (MVar)	-	8.7746
P_{loss} (MW)	8.7256	8.6480
Total cost ($/h)	**799.5762**	**799.2825**
Total voltage deviation	1.3579	1.7640
Voltage stability index	0.1325	0.1285

4.1.3. OPF Problem With TCPS

For the optimal location of TCPS, the loss sensitivity index method is applied (Ongsakul and Bhasaputra, 2002). In this case, the optimal location of TCPS is in line 3-4. The phase of TCPS varies in the range from 0 to 0.1 rad. The optimal solution for the OPF problem with and without TCPS by the hybrid DE-HS is given in Table 5.

Table 4. Result comparison for the OPF problem with SVC

	TS/SA (Ongsakul and Bhasaputra, 2002)	PSO (Puttanon, 2007)	Hybrid DE-HS
P_{g1} (MW)	192.5895	176.1519	176.5996
P_{g2} (MW)	48.412	49.197	48.8110
P_{g5} (MW)	19.5554	21.533	21.5180
P_{g8} (MW)	11.6559	24.031	21.3499
P_{g11} (MW)	10	10	11.7695
P_{g13} (MW)	12	12	12.0000
SVC_{21} (MVar)	11.196	6.4178	8.7746
Total cost ($/h)	**804.5763**	**802.6454**	**799.2825**

Table 5. Optimal result for the OPF problem with TCPS by the hybrid DE-HS

	Without FACTS Devices	With TCPS Devices
P_{g1} (MW)	177.0158	177.4251
P_{g2} (MW)	48.3280	48.6722
P_{g5} (MW)	21.8674	21.3368
P_{g8} (MW)	21.6914	20.6788
P_{g11} (MW)	11.2231	11.9211
P_{g13} (MW)	12.0000	12.0004
V_{g1} (pu)	1.1000	1.0998
V_{g2} (pu)	1.0831	1.0836
V_{g5} (pu)	1.0466	1.0546
V_{g8} (pu)	1.0622	1.0684
V_{g11} (pu)	1.1000	1.1000
Vg13 (pu)	1.0945	1.0991
V_{g13} (pu)	1.0945	1.0991
T_{11} (pu)	1.0900	1.0500
T_{12} (pu)	0.9000	0.9000
T_{15} (pu)	0.9900	0.9700
T_{36} (pu)	0.9700	0.9500
Q_{c10} (MVar)	19.0000	19.0000
Q_{c24} (MVar)	4.3000	4.2000
$TCPS_{3-4}$ (rad)	-	0.1000
P_{loss} (MW)	8.7256	8.6344
Total cost ($/h)	**799.5762**	**799.0130**
Total voltage deviation	1.3579	1.6984
Voltage stability index	0.1325	0.1275

The obtained optimal result by the proposed DE-HS for this case has been compared to that from hybrid TS/SA (Ongsakul and Bhasaputra, 2002) and PSO (Puttanon, 2007) as given in Table 6. As observed, the total cost from the proposed hybrid DE-HS is slightly better than that from the other methods.

Table 6. Result comparison for the OPF problem with TCPS

	TS/SA (Ongsakul and Bhasaputra, 2002)	**PSO (Puttanon, 2007)**	**Hybrid DE-HS**
P_{g1} (MW)	192.5743	176.055	177.4251
P_{g2} (MW)	48.4088	49.267	48.6722
P_{g5} (MW)	19.5545	21.599	21.3368
P_{g8} (MW)	11.6491	21.569	20.6788
P_{g11} (MW)	10	12.429	11.9211
P_{g13} (MW)	12	12	12.0004
$TCPS_{3-4}$ (rad)	0.0594	0.06212	0.1000
Total cost ($/h)	**804.4862**	**802.519**	**799.0130**

4.1.4. OPF Problem With TCSC, SVC, and TCPS

For determining the optimal location of different FACTS devices in this case, the loss sensitivity index method is applied (Ongsakul and Bhasaputra, 2002). As a result, one SVC is installed at bus 21, one TCSC installed in line 4-5, and one installed at line 8-9. The optimal solution for the OPF problem with multiple FACTS devices and without FACTS devices has been given in Table 7. From the table, the total cost from the case with FACTS devices is slightly lower than that from the case without FACTS devices about 0.06%.

4.2. Case Study 2

In this case study, the optimal location of TCSC is determined using max-flow min-cut algorithm (Duong, Gang, and Truong, 2013) and the OPF problem with TCSC for the IEEE-30 bus system (Alsac Stott, 1974; Zimmerman, Murillo-Sánchez, and Thomas, 2011) is solved by the hybrid DE-HS algorithm. The quadratic fuel cost function is used as the objective function for two operating conditions including the normal case and emergency case *N*-1. In this case, some problems are considered as follows:

- OPF problem without TCSC without transmission limits, called OPF-1;
- OPF problem without TCSC with transmission limits, called OPF-2;
- OPF problem with TCSC and transmission limits, called OPF-3.

The problem in this case is performed in the following steps:

Step 1: Determine the overload line from the OPF solution without TCSC neglecting the transmission limits.
Step 2: Determine a group of lines near the overload line.
Step 3: Determine a certain group of lines by min-cut based on the max-flow min-cut algorithm (Duong, Gang, and Truong, 2013).

Table 7. Optimal result for the OPF problem with multiple FACTS devices by the hybrid DE-HS

	Without FACTS Devices	Multiple FACTS Devices
P_{g1} (MW)	177.0158	177.1514
P_{g2} (MW)	48.3280	48.7117
P_{g5} (MW)	21.8674	21.2736
P_{g8} (MW)	21.6914	20.9976
P_{g11} (MW)	11.2231	11.9064
P_{g13} (MW)	12.0000	12.0000
V_{g1} (pu)	1.1000	1.1000
V_{g2} (pu)	1.0831	1.0858
V_{g5} (pu)	1.0466	1.0572
V_{g8} (pu)	1.0622	1.0670
V_{g11} (pu)	1.1000	1.0999
V_{g13} (pu)	1.0945	1.1000
T_{11} (pu)	1.0900	1.0200
T_{12} (pu)	0.9000	0.9800
T_{15} (pu)	0.9900	0.9700
T_{36} (pu)	0.9700	0.9500
Q_{c10} (MVar)	19.0000	19.0000
Q_{c24} (MVar)	4.3000	4.3000
SVC (MVar)	-	11.1994
TCSC (pu)	-	0.0200
TCPS (rad)	-	0.1000
Power loss (MW)	8.7256	8.6406
Total cost ($/h)	**799.5762**	**799.0988**
Total voltage deviation	1.3579	1.7875
Voltage stability index	0.1325	0.1268

Step 4: From the lines list given in Steps 2 and 3, the lines appear in the both lists are selected to place TCSC.
Step 5: Use the hybrid DE-HS to solve the OPF problem with the location of TCSC determined in Step 4.
Step 6: Store and compare results.

4.2.1. OPF Problem in Normal Operating Condition

By using the max-flow min-cut algorithm (Duong, Gang, and Truong, 2013), the optimal locations of TCSC are determined in lines 8-28 and 10-22. The optimal solution for the OPF problems by the hybrid DE-HS is given in Table 8. In the three cases, the OPF-1 problem has the lowest total cost with overloaded transmission lines and the highest total cost is corresponding to the OPF-2 problem with no transmission lines overloaded while the OPF-3 problem can obtain low total cost satisfying transmission limits. Therefore, the TCSC placement is a good solution to eliminate the overload in

Table 8. Optimal solution for OPF problem of the three cases by the hybrid DE-HS

Generators	OPF-1	OPF-2	OPF-3
P_{g1} (MW)	46.1623	22.9432	45.9355
P_{g2} (MW)	80.0000	80.0000	80.0000
P_{g22} (MW)	50.0000	35.3390	50.0000
P_{g23} (MW)	16.2808	40.8224	16.5270
P_{g27} (MW)	0.0000	13.3500	0.0000
P_{g13} (MW)	0.0000	0.0000	0.0000
Total cost ($/h)	1700.0729	1795.1791	1700.4088
$TCSC_{8\text{-}28}$	-	-	56.4256%
$TCSC_{10\text{-}22}$	-	-	46.2261%

transmission lines. The power flow solutions in transmission lines for the three cases are depicted in Figures 2-4. As shown in the figures, the OPF-1 results in lines 6-8 and 21-22 overloaded while there are no transmission lines overloaded for both OPF-2 and OPF-3 problems.

The optimal solution for the OPF-3 problem obtained by the hybrid DE-HS method has been compared to that from a two-stage method in (Duong, Gang, and Truong, 2013) as in Table 9. As observed from the results, the total costs obtained by the two methods are nearly the same.

Table 9. Result comparison for the OPF-3 problem

Generators	Two-Stage Method (Duong, Gang, and Truong, 2013)	Hybrid DE-HS
P_{g1} (MW)	46.2600	45.9355
P_{g2} (MW)	80.0000	80.0000
P_{g22} (MW)	50.0000	50.0000
P_{g23} (MW)	16.2200	16.5270
P_{g27} (MW)	0.0000	0.0000
P_{g13} (MW)	0.0000	0.0000
Total cost ($/h)	1700.42	1700.4088
TCSC	60% (line 8-28)	56.4256% (line 8-28)
TCSC	46.66% (line 10-22)	46.2261% (line 10-22)

4.2.2. OPF Problem in Emergency Operating Condition

As calculated from the case of normal operating condition, the overload in transmission lines can be eliminated by placing TCSC. For the case of emergency operating condition, an outage line is considered and the difference in total costs for the cases with TCSC. As calculated, when one of lines 2-4, 2-6, 4-6, 15-18, and 23-24 is outage, lines 6-8 and 21-22 will be overloaded. The overload is eliminated as TCSC are installed in lines 8-28 and 10-22. Table 10 shows the result comparison for the cases with TCSC installed in lines 8-28 and 10-22 and without FACTS devices for the mentioned outage lines. As observed from the table, the total cost savings from the TCSC installation are from 5.83% to 14.41% compared to the case without FACTS devices. Therefore, the placement of FACTS devices has led to many benefits such as overload reduction in transmission lines and total cost saving for transmission line outage.

4.3. Case Study 3

In this case study, the other objective functions such as total of active power loss function, total of voltage deviation function, and voltage stability index improvement have been considered. The

Figure 2. Power flow in transmission lines for the OPF-1 problem

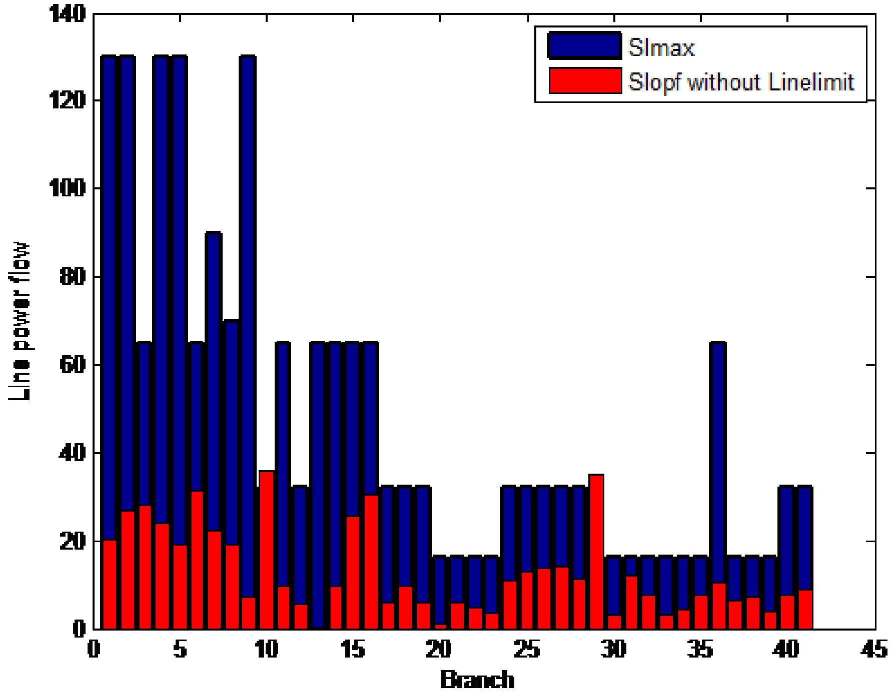


Figure 3. Power flow in transmission lines for the OPF-2 problem

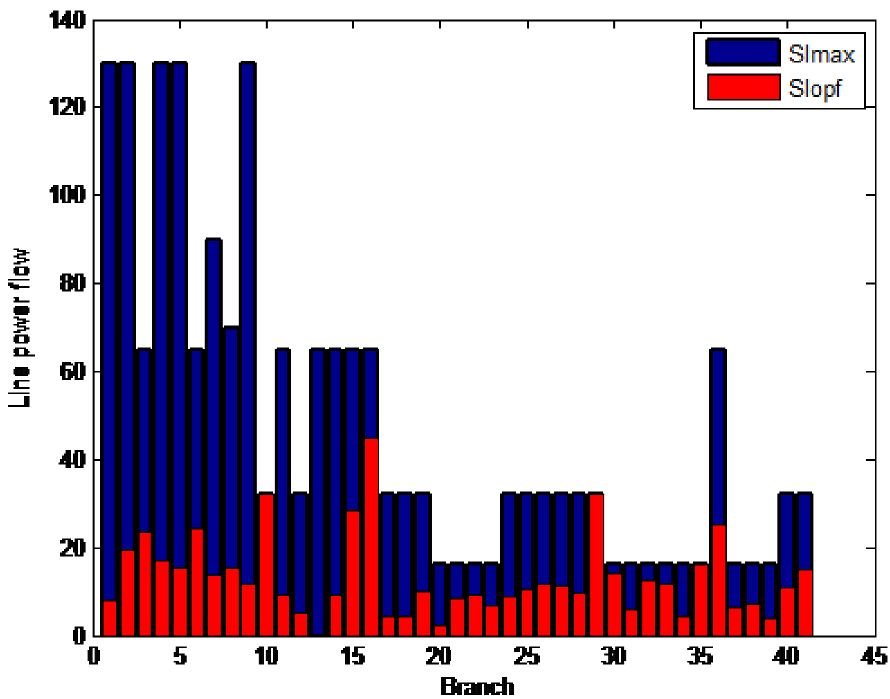


Figure 4. Power flow in transmission lines for the OPF-3 problem

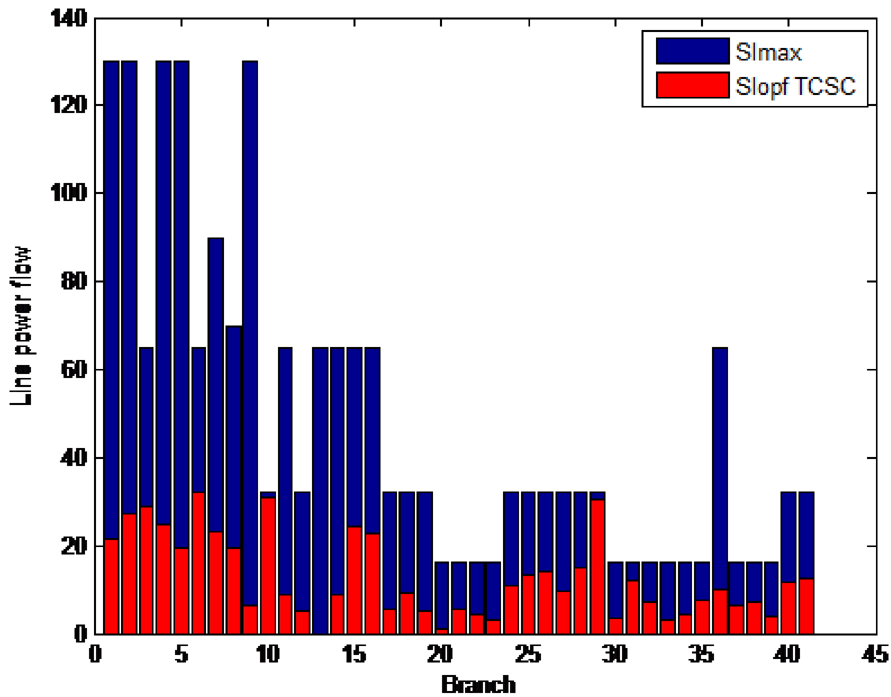


Table 10. Solution for OPF-3 with TCSC and outage lines

Outage Lines	2-4	23-24	4-6	15-18	2-6
With TCSC: $TCSC_{10-22}$ $TCSC_{8-28}$ Total cost	 45.064% 55.0543% 1707.9501	 58.9342% 67.0822% 1702.6463	 58,5373% 52,6972% 1703.2668	 54.084% 63.2006% 1701.5198	 56.8439% 51.6477% 1709.4763
Without FACTS devices: Overloaded lines Total cost ($/h)	 6-8, 21-22 1995.5612	 6-8, 21-22 1937.3675	 6-8, 21-22 1808.8607	 6-8, 21-22 1941.0185	 6-8, 21-22 1912.3473
Savings %	14.41%	12.13%	5.83%	12.33%	10.6%

proposed method has been also tested on the IEEE 30-bus system (Alsac Stott, 1974; Zimmerman, Murillo-Sánchez, and Thomas, 2011) for the cases with and without FACTS device where TCSC is considered.

4.3.1. OPF Problem With the Objective Function of Total Power Loss

In this case, TCSC is installed in lines 8-28 and 10-22 using the max-flow min-cut algorithm. The optimal results from the proposed hybrid DE-HS method for the test system with and without TCSC are given Table 11. As the result, the power loss in the system with TCSC is reduced about 11.92% compared to the case without TCSC. The convergence characteristic for power loss objective function with and without TCSC is given Figure 5.

Table 11. Optimal solutions for the OPF problem with power loss objective

	Min	Max	OPF Without TCSC	OPF With TCSC
P_{g1} (MW)	0	80	4.6660	6.4604
P_{g2} (MW)	0	80	52.0293	55.2318
P_{g22} (MW)	0	50	30.9772	41.0052
P_{g23} (MW)	0	55	46.0319	31.5136
P_{g27} (MW)	0	30	17.4071	16.6726
P_{g13} (MW)	0	40	40.0000	40.0000
V_{g1} (pu)	0.95	1.05	1.0246	1.0384
V_{g2} (pu)	0.95	1.1	1.0275	1.0376
V_{g22} (pu)	0.95	1.1	1.0318	1.0431
V_{g23} (pu)	0.95	1.1	1.0688	1.0595
V_{g27} (pu)	0.95	1.1	1.0434	1.0517
V_{g13} (pu)	0.95	1.1	1.0868	1.0872
Q_{c5} (MVar)	0	0.19	0.1300	0.0000
Q_{c24} (MVar)	0	0.04	0.0000	0.0000
$TCSC_{10\text{-}22}$ $TCSC_{8\text{-}28}$				49.2986% 30.0116%
P_{loss} (MW)			**1.9115**	**1.6836**
Total voltage deviation			0.5647	0.7075
Max voltage stability index			0.0508	0.0484

4.3.2. OPF Problem With the Objective Function of Total Voltage Deviations

TCSC is also installed in lines 8-28 and 10-22 using the max-flow min-cut algorithm for this case. The optimal solutions from the proposed hybrid DE-HS method for the test system with and without TCSC are given Table 12. As observed from the table, the total voltage deviation in the system with TCSC is reduced about 4.068% compared to the case without TCSC. Figure 6 shows the convergence characteristic of total voltage deviations objective function with and without TCSC.

4.3.3. OPF Problem With the Objective Function of Voltage Stability Index

For the case with FACTS device, TCSC is also installed in lines 8-28 and 10-22 using the max-flow min-cut algorithm. The optimal solutions from the proposed hybrid DE-HS method for the test system with and without TCSC are given Table 13. As seen from the table, the maximum voltage stability index for the system with TCSC is reduced about 5.455% compared to the case without TCSC. In Figure 7, the Convergence characteristic for improve voltage stability objective function without and with TCSC is depicted.

5. CONCLUSION

In this paper, the proposed hybrid DE-HS method has been effectively implemented for solving OPF problem with FACTS devices. The considered OPF problems in this paper has different objectives such as total cost, power loss, total voltage deviation, and voltage stability index with different FACTS devices such as SVC, TCSC, and TCPS satisfying many constraints including power balance, real

Figure 5. Convergence characteristic for power loss objective function with and without TCSC

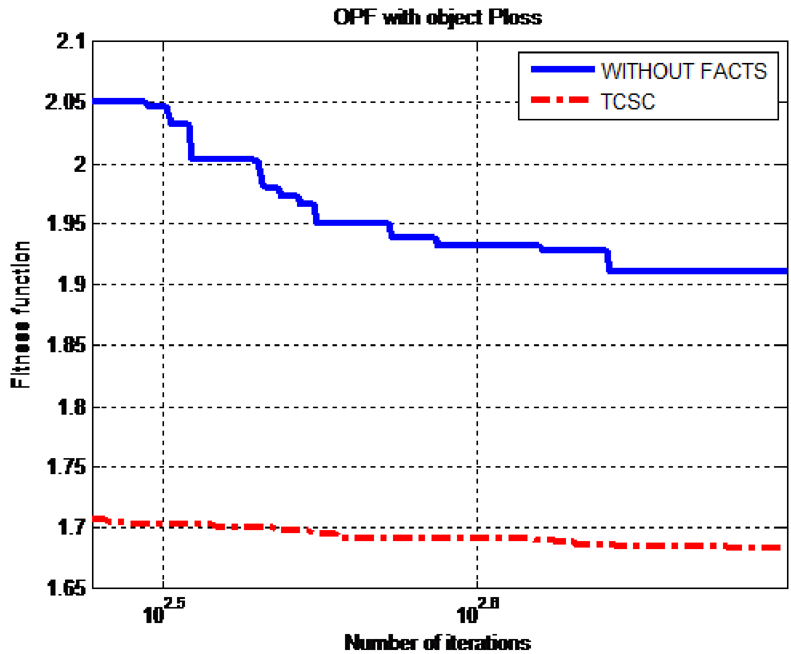


Table 12. Optimal solutions for the OPF problem with total voltage deviations objective

	Min	Max	OPF Without TCSC	OPF With TCSC
P_{g1} (MW)	0	80	28.5836	4.5594
P_{g2} (MW)	0	80	23.8752	80.0000
P_{g22} (MW)	0	50	20.9317	32.1518
P_{g23} (MW)	0	55	54.8132	45.2793
P_{g27} (MW)	0	30	23.7686	0.0000
P_{g13} (MW)	0	40	40.0000	29.8897
V_{g1} (pu)	0.95	1.05	1.0092	1.0147
V_{g2} (pu)	0.95	1.1	1.0164	1.0274
V_{g5} (pu)	0.95	1.1	1.0173	1.0119
V_{g8} (pu)	0.95	1.1	1.0294	1.0273
V_{g11} (pu)	0.95	1.1	1.0087	1.0125
V_{g13} (pu)	0.95	1.1	1.0419	1.0323
Q_{c5} (MVar)	0	0.19	0.0600	0.0000
Q_{c24} (MVar)	0	0.04	0.0000	0.0000
$TCSC_{10\text{-}22}$ $TCSC_{8\text{-}28}$				49.2804% 45.3948%
Total voltage deviation			**0.1404**	**0.1347**
P_{loss} (MW)			2.7723	2.6802
Max voltage stability index			0.0528	0.0507

Figure 6. Convergence characteristic of total voltage deviations objective function with and without TCSC

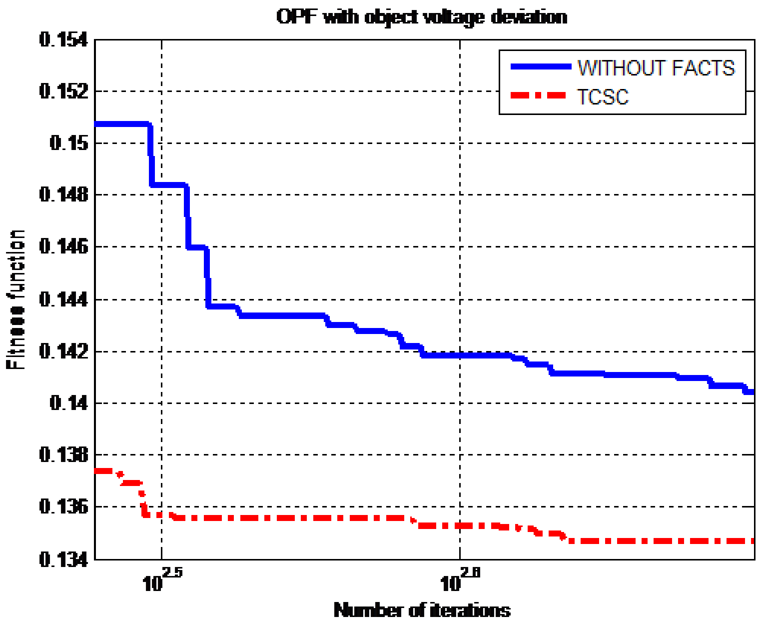
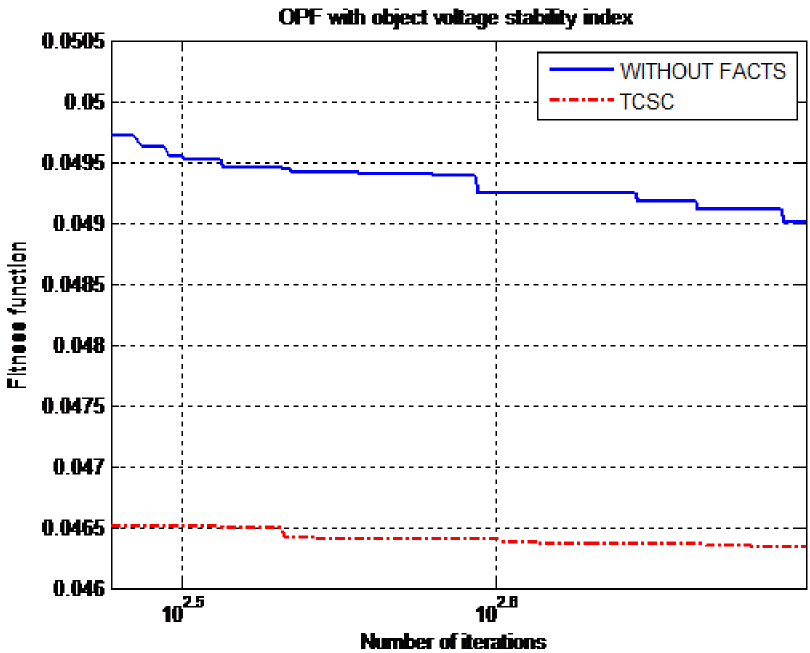


Table 13. Optimal solutions for the OPF problem with voltage stability index objective

	Min	Max	OPF Without TCSC	OPF With TCSC
P_{g1} (MW)	0	80	31.3932	9.4410
P_{g2} (MW)	0	80	24.1217	49.5887
P_{g22} (MW)	0	50	20.2875	20.5716
P_{g23} (MW)	0	55	54.6227	52.0600
P_{g27} (MW)	0	30	23.3771	21.0005
P_{g13} (MW)	0	40	37.8841	38.9752
V_{g1} (pu)	0.95	1.05	1.0499	1.0500
V_{g2} (pu)	0.95	1.1	1.0532	1.0597
V_{g5} (pu)	0.95	1.1	1.0506	1.0555
V_{g8} (pu)	0.95	1.1	1.0633	1.0556
V_{g11} (pu)	0.95	1.1	1.0511	1.0701
V_{g13} (pu)	0.95	1.1	1.0786	1.0661
Q_{c5} (MVar)	0	0.19	0.1600	0.0300
Q_{c24} (MVar)	0	0.04	0.0100	0.0000
$TCSC_{10\text{-}22}$ $TCSC_{8\text{-}28}$				49.9667% 50.0000%
Max voltage stability index			**0.0490**	**0.0463**
Total cost ($/h)			2264.5334	2162.0270
P_{loss} (MW)			2.4863	2.4371
Voltage stability index			0.8650	0.9378

Figure 7. Convergence characteristic for improve voltage stability object function without and with TCSC



and reactive power limits of generators, voltage magnitude limits at buses, shunt capacitor limits, transformer tap limits, power flow limits in transmission lines, and parameter limits of FACTS devices. The hybrid DE-HS is an algorithm employs the advantages of DE and HS to enhance its search ability. Therefore, the proposed method can deal with large-scale and complex optimization problems such as the OPF problem with FACTS devices in this paper. The proposed method has been tested on the IEEE 30-bus system for different study cases. The obtained result has verified that the proposed method can properly deal with the complex problem and obtain better optimal solution than other methods solving the same cases of the problem. Therefore, the proposed hybrid DE-HS method can be a favorable method for solving the complex OPF problem with FACTS devices.

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