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CONGESTION MANAGEMENT BY INTELLIGENT APPLICATION OF UPFC IN POWER SYSTEM WITH INTERMITTENT RESOURCES

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Abstract- This paper proposes a Harmony Search Algorithm (HSA) to achieve the optimal location and proper parameters settings of Unified Power Flow Controller (UPFC) for congestion management in restructured electricity market while considering wind power in the system. Two different objective functions are considered in this study. In the first one, minimization of total operating cost including congestion rent and total generation cost is considered as the objective function. In the second one, objective is minimization of system loss. In order to verify and validate the effectiveness of the proposed method, IEEE 14-bus test system is employed. The results show that the congestion cost and loss of the power transmission system can be effectively reduced through the optimal location and proper parameters selection of the UPFC.

Keywords: Unified Power Flow Controller (UPFC), Harmony Search Algorithm (HSA), Congestion Management, Wind Power.

I. INTRODUCTION

Restructuring in electric power industry has resulted in exhaustive usage of transmission systems. The competition in electricity market has also led to an increased volume of electricity trade. This situation causes an unexpected need of power transfer through some transmission lines. As the power system becomes more complex and more heavily loaded, it will be operated in unstable or insecure situations.

Transmission congestion occurs when there is inadequate transmission capacity to meet the demands of all customers and generating units, which are more expensive, may have to be brought online, hereupon electricity markets will not be able to operate at its competitive equilibrium and imperil system security. Therefore, congestion management is one of the key issues for secure and reliable system operations in electric power markets [1]. New opportunities for controlling the power flow of the transmission line and extending the loadability of the available transmission system has been provided by development in Flexible AC Transmission Systems (FACTS) devices based on the progressive semiconductor technology.

FACTS devices can control the line reactance, bus voltage, and line active and reactive power flows. As a result, FACTS devices are used to increase the capacity over existing transmission lines by proper power flow control over designed corridors [2]. The Unified Power Flow Controller (UPFC) is one of the family members of FACTS devices for load flow control. The UPFC can either simultaneously or selectively control the active and reactive power flow along the transmission lines of the power system [3]. So far, many different methods have been proposed for optimal application of UPFC considering several objective functions in the literature.

In [4] Mixed-Integer method has been employed for optimal UPFC placement based on line flow-based equations. In [5] the optimal location of the UPFC is determined by the application of augmented Lagrange Multiplier method. Being a very complicated problem, different heuristic algorithms have been proposed to solve the problem of incorporating the UPFC in Optimal Power Flow (OPF) optimization. Reference [2] has located the UPFC for congestion management via hybrid OPF and Particle Swarm Optimization.

Reference [6] proposed the use of Genetic Algorithm to find the solution of the OPF in the presence of the UPFC. A hybrid method based on UPFC power injection model and OPF to optimally locating the UPFC in order to minimize generation cost of the system and to improve voltage profile of the network is proposed in [7]. Reference [8] proposes a neural controller based on UPFC for stabilizing and oscillation damping of controllers by producing a supplementary controlling signal.

In [9] UPFC is implemented for the same purpose. In [10] effect of load representation, from viewpoint of static, on UPFC performance and optimal placement has been discussed. Power system security can be enhanced through optimal placement of Thyristor Controlled Series Compensator (TCSC) and the UPFC [11]. A sensitivity based approach, derived in terms of change in a real power flow performance index with respect to their control parameters, has been proposed to determine the optimal location of the TCSC and the UPFC. Harmony Search Algorithm (HSA) as a powerful heuristic method is conceptualized using the musical process of searching for a perfect state of harmony [12].

Compared to the other meta-heuristic optimization algorithms, the HSA imposes fewer mathematical requirements that can be easily adopted for various types of engineering optimization problems [13]. The potential of the HSA in solving power system problems, which are complex, has been demonstrate in [14-16]. Authors in [17] have applied the HSA to the optimization problem of finding the optimal location and size of the UPFC. The main advantage of the HSA is reaching the solution with higher quality while needs less time in comparison with Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) in most of the optimization problems of power systems as shown in [14-17].

Considering Wind Turbine Generators (WTGs) with FACTS devices, especially UPFC is carried out in the literature [18-20]. However, in most of these studies FACTS devices are only used to compensate the reactive power of WTGs and/or only consider the dynamic stability. On the other hand, studies that consider the use of the UPFC for congestion management have not taken into account WTG [2, 7, 10]. As a result, there is no a comprehensive study that discusses about planning of the UPFC for congestion management while considering WTGs in the network and takes into account their stochastic nature in the optimization problem.

This paper proposes the use of the HSA for solving the problem of optimal locating and parameter setting of the UPFC when WTGs are considered in the network. Two different objective functions are considered for the optimization problem. The operating costs and transmission loss minimization are taken into account for optimal implementation of the UPFC. The results of simulations carried out on the IEEE 14-bus test systems demonstrate the effectiveness of the HSA in finding the optimal location and parameter settings of the UPFC that can effectively relief the congestion of the system and reduce transmission loss.

The rest of this paper is organized as follows. Section II explains the static model of the UPFC. An overview of the Harmony Search Algorithm is described in section III. Proposed method is presented in section IV. Section V provides the simulation results and discussions. The conclusion is drawn in section VI.

II. UPFC MODELING AND FORMULATION

A static model of UPFC is presented in this section. The formulation of incorporation of the UPFC in OPF problem is discussed. In order to model the UPFC in static studies, the injected power model is proposed and is widely used in the literature [2]. The main advantage of this model is that it does not change the existing admittance matrix, and so its implementation in power flow and OPF programs is easier comparing to the other models. As shown in Figure 1 the series inserted voltage (V_T) and active and reactive component of shunt branch of the UPFC (I_T and I_q) can be used to determine the status of the UPFC and model this device in the OPF studies.

The shunt branch of the UPFC can also be fed by an external power source but practically this external source does not exist, so the UPFC has only three controllable parameters, magnitude of series transformer injected voltage V_T, which is in series with the transmission line, phase angle of this voltage ϕ_T, and the shunt transformer reactive current I_q [21].

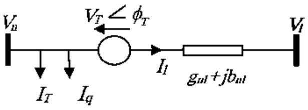

Figure 1. UPFC static equivalent circuit [2]

The UPFC control parameters (voltage source magnitude, phase angle and reactive component of the shunt current) limits can be written as follows:

$$\begin{cases} V_T^{\min} \le V_T \le V_T^{\max} \\ \phi_T^{\min} \le \phi_T \le \phi_T^{\max} \\ I_q^{\min} \le I_q \le I_q^{\max} \end{cases} \tag{1}$$

Therefore, in this paper, for the optimal power flow analysis, UPFC variables V_T, ϕ_T and, I_q are needed to be optimized. Equations (2) to (4) represent the derivation of the power flow equations of the UPFC from bus n to bus l.

$$\begin{cases} S_{nl} = P_{nl} + jQ_{nl} = V_n I_{nl}^* = V_n (I_T + I_q + I_l)^* \\ S_{ln} = P_{ln} + jQ_{ln} = V_l I_{ln}^* = V_l (-I_l)^* \end{cases} \tag{2}$$

$$\begin{cases} P_{nl} = (V_n^2 + V_T^2) g_{nl} + 2V_n V_T g_{nl} \cos(\phi_T - \delta_{nl}) - \\ -V_n V_T (g_{nl} \cos\phi_T + b_{nl} \sin\phi_T) \\ -V_n V_l (g_{nl} \cos\delta_{nl} + b_{nl} \sin\delta_{nl}) \\ Q_{nl} = -V_n V_T (g_{nl} \sin(\phi_T - \delta_{nl}) + b_{nl} \cos(\phi_T - \delta_{nl})) - \\ -V_n^2 b_{ij} - V_n I_q - V_n V_l (g_{nl} \sin\delta_{nl} - b_{nl} \cos\delta_{nl}) \end{cases} \tag{3}$$

$$\begin{cases} P_{ln} = V_n^2 g_{nl} - V_l V_T (g_{nl} cos\phi_T - b_{nl} \sin\phi_T) - \\ -V_n V_l (g_{nl} \cos\delta_{nl} - b_{nl} \sin\delta_{nl}) \\ Q_{ln} = -V_l^2 b_{nl} - V_l V_T (g_{nl} \sin\phi_T - b_{nl} \cos\phi_T + \\ +V_n V_l (g_{nl} \sin\delta_{nl} + b_{nl} \cos\delta_{nl})) \end{cases} \tag{4}$$

The above formulation shows the power injection model of the UPFC in the line and bus, which the UPFC is located at and can be incorporated in an appropriate OPF algorithm as a subroutine of siting and sizing program.

A. Congestion Management

The following OPF subroutine should be performed for each solution generated by the PSO algorithm in order to calculate the value of objective function.

A.1. The OPF Subroutine

For each solution created by the HSA, an OPF subroutine is performed including the UPFC. This subsection discusses the formulation. OPF tool has been used in the pool-based deregulated electricity markets to calculate generation dispatch as well as load schedules [22]. The OPF is based on finding an optimal solution, according to an objective function subjected to a set of nonlinear equality and inequality constraints. In restructured environment the OPF is performed based on bids submitted by the suppliers and customers, considering network constraints.

The aim of optimization in restructured power systems is social welfare maximization. The GENCOs provide the ISO with their offers to supply energy. In order to maximize the social welfare, ISO minimize the payment to the GENCOs. The general minimization problem of the OPF can be stated as follows:

$$\text{minimize } F=\sum_{k=1}^{N_G} C_k(P_{G_k}) \tag{5}$$

In fact, Equation (5) shows the OPF objective function. The offered energy cost functions for the generating units are assumed to be quadratic that typically defined as follow:

$$C_k(P_{G_k})=a_k+b_k P_{G_k}+c_k P_{G_k}^2 \tag{6}$$

The optimization problem is subjected to the following constraints:

a. Active and reactive power balance equations in all buses:

$$\sum_{i=1}^{N_B} P_{G_i}=\sum_{i=1}^{N_B} P_{D_i}+P_{loss} \tag{7}$$

$$\sum_{i=1}^{N_B} Q_{G_i}=\sum_{i=1}^{N_B} Q_{D_i}+Q_{loss} \tag{8}$$

b. Generation limits:

$$P_{Gk}^{\min}\le P_{Gk}\le P_{Gk}^{\max} \tag{9}$$

$$Q_{Gk}^{\min}\le Q_{Gk}\le Q_{Gk}^{\max} \tag{10}$$

c. Transmission line limits:

$$|T_l|\le T_l^{\max} \qquad l=1,\ldots,N_L \tag{11}$$

d. Bus voltage limits:

$$V_i^{\min}\le V_i\le V_i^{\max} \tag{12}$$

Lagrange function of such optimization problem incorporating all constraints associated with the objective function can be formed as shown by Equation (13). The solution of the OPF gives the values of all Lagrange multipliers along with the dispatch results [1].

$$\begin{aligned}
L=&\sum_{k=1}^{N_G} C_i(P_{Gi})+\sum_{i=1}^{N_B}\lambda_{Pi}(P_i-P_{Gi}+P_{Di})+\\
&+\sum_{i=1}^{N_B}\lambda_{Qi}(Q_i-Q_{Gi}+Q_{Di})+\sum_{l=1}^{N_L}\mu_{Ll}(T_l-T_l^{\max})+\\
&+\sum_{k=1}^{N_G}\mu_{P_{Gk}}^{-}(P_{Gk}^{\min}-P_{Gk})+\sum_{k=1}^{N_G}\mu_{P_{Gk}}^{+}(P_{Gk}-P_{Gk}^{\max})+\\
&+\sum_{k=1}^{N_G}\mu_{Q_{Gk}}^{-}(Q_{Gk}^{\min}-Q_{Gk})+\sum_{k=1}^{N_G}\mu_{Q_{Gk}}^{+}(Q_{Gk}-Q_{Gk}^{\max})+\\
&+\sum_{i=1}^{N_B}\mu_{Vi}^{-}(V_i^{\min}-V_i)+\sum_{i=1}^{N_B}\mu_{Vi}^{+}(V_i-V_i^{\max})
\end{aligned} \tag{13}$$

where, λ and μ are vectors of Lagrangian multipliers, where λ is associated with equality constraints and μ is associated with inequality constraints based on Karush-Kuhn-Tucker (KKT) conditions that are zero when the constraint is not activated. The solution of OPF gives the values of all Lagrangian multipliers along with the dispatch results.

A.2. *LMP* and Congestion Rent

LMP at a particular bus location is defined as the marginal cost of supplying the next increment of electric energy at a specific bus considering generation marginal cost and physical aspects of the transmission system [1]. Hence, the real power *LMP*s and the reactive power *LMP*s are Lagrange multipliers, λ_{P_i} and λ_{Q_i}, associated with the corresponding real and reactive power balance equations. *LMP* is consisted of three constituents, a marginal energy component (same for all buses), a marginal loss component and a congestion component [16]:

$$\rho_i=\lambda+\lambda\frac{\partial P_L}{\partial P_i}+\sum_{l=1}^{N_L}\mu_{L_l}\frac{\partial P_l}{\partial P_i} \tag{14}$$

$$\rho_i=\lambda+\lambda_{L,i}+\lambda_{C,i} \tag{15}$$

where, λ is marginal energy component, $\lambda_{L,i}$ is the marginal loss component and $\lambda_{C,i}$ is the congestion component.

Therefore, the spot price at each bus is determined specifically and the difference in *LMP*s between the two ends of a congested line is related to the extent of congestion and MW losses on this line [23]. If the injection (or extraction) of power at a particular bus increases the total system losses, then the price of power at that location increases. Similarly, if any transmission line limit is binding, then corresponding μ_{L_l} will be non-zero and will have an impact on prices at all buses. If the power injection (or extraction) at a particular bus increases the flows across the congested interface, spot price at that bus increases [1].

Similar to Equation (15) for any other bus like *j*, *LMP* can be written as:

$$\rho_j=\lambda+\lambda_{L,j}+\lambda_{C,j} \tag{16}$$

By taking the spot price difference between two buses *k* and *l* it can be written as:

$$\Delta\rho_{ij}=(\lambda_{L,i}-\lambda_{L,j})+(\lambda_{C,i}-\lambda_{C,j}) \tag{17}$$

Equation (17) shows that the *LMP* difference between any two buses of the system pertained two parts, marginal losses and congestion throughout system. Since marginal energy component is same for all buses in network it is not involved in nodal price difference [16]. Total Congestion Rent is defined as the operation costs imposed to the system due to congestion and is calculated as follows:

$$TCR=\sum_{l=1}^{N_L}\Delta\rho_l P_l \tag{18}$$

III. HARMONY SEARCH ALGORITHM

In the last few decades, due to advances in science and technology the dimension and size of the optimization problems has increased considerably. As a result the conventional classic mathematical method are no longer applicable in many combinatorial problems and in case they could be used the execution time is relatively high. On the other hand, heuristic method can solve these complicated problems in an acceptable time and retrieve results, which are adequate. Heuristic methods can solve complicated combinatorial multi-objective optimization problems. Therefore, these algorithms are today widely applied in many area of study including power system optimization [12-13].

There are several heuristic algorithms that are implemented broadly including: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Tabu Search, each of which has its own merits and drawbacks. Depending on the size, complexity and constraints of the optimization problem under study the best suitable heuristic method should be applied. In this study, Harmony Search Algorithm is chosen as the optimization tool and has been proved able to solve very complicated optimization problem in different areas of the power system [14-16].

Geem et al. in [12-13] introduced the HSA that was developed in an analogy with music improvisation process in which music players improvise the pitches of their instruments to obtain better harmony [12]. Just like the value of objective function determined by the set of values assigned to each of the decision variables, the pitch of each musical instrument governs the aesthetic quality [13]. Different steps are applied in finding the optimal solution of a problem by the HSA [12-13]:

Step 1. Initialize the optimization problem and algorithm parameters.
Step 2. Initialize the Harmony Memory (*HM*).
Step 3. Improvise a new harmony from the *HM*.
Step 4. Update the *HM*.
Step 5. Repeat steps 3 and step 4 until the termination criterion is satisfied.

A. Initialization

The parameters of HSA, including the Harmony Memory Size (*HMS*) or numbers of solution vectors, Harmony Memory Considering Rate (*HMCR*), Pitch Adjusting Rate (*PAR*), and termination criterion (maximum number of searches), are first specified in the optimization procedure. Along with that, the optimization problem is specified as presented in the following:

$$\begin{aligned} &\text{minimize} \quad f(x) \\ &\text{subject to} \Rightarrow x_i \in X_i, \quad i = 1, 2, ..., N \end{aligned} \tag{19}$$

where, *f*(*x*) is the objective function of the optimization problem that is aimed to be minimized, *x* represents a candidate solution consisting of *N* decision variables (x_i). X_i is the set of possible range of values for each decision variable, that is ${}_L x_i \le X_i \le {}_U x_i$ for continuous decision variables where ${}_L x_i$ and ${}_U x_i$ denote the lower and upper bounds for each decision variable, respectively, finally *N* indicates the number of decision variables.

B. Initialization of the *HM*

The Harmony Memory (*HM*) matrix, shown in Equation (19), is filled with as many randomly generated solution vectors as the size of *HMS* in this step. These vectors are sorted by the values of the objective function, as a result of the solution they represent.

$$HM = \begin{bmatrix} x^1 \\ x^2 \\ . \\ . \\ x^{HMS} \end{bmatrix} \tag{20}$$

C. Improvising New Harmony

A new Harmony vector $x' = (x_1', x_2', ..., x_N')$ is created from the *HM* based on different parameters including memory considerations, randomization. As an example, let us consider the first decision variable represented by (x_1'), its value for the new vector can be chosen from any value in the specified *HM* range. Other decision variables are specified by the same trend. Another possibility, skillfully elaborated in the HSA, is that the new value can be specified using the *HMCR* parameter, which is between 0 and 1:

$$x_i' \leftarrow \begin{cases} x_i' \in \left\{x_i^1, x_i^2, ..., x_i^{HMS}\right\} & \text{with probability } HMCR \\ x_i' \in X_i & \text{with probability } \left(1 - HMCR\right) \end{cases} \tag{21}$$

The *HMCR* specifies the rate of choosing one value from the historic values stored in the *HM*, while on the other hand (1-*HMCR*) specifies the rate of randomly choosing one feasible value. With a lower possibility, each component of the new harmony vector, $x' = (x_1', x_2', ..., x_N')$ is exposed to the *PAR* and is examined to determine whether it should be pitch-adjusted or not. This process implements the *PAR* parameter that sets the rate of adjustment for the pitch chosen from the *HM* as presented in the following:

$$\begin{matrix} \text{pitch adjusting} \\ \text{decision for } x_i' \end{matrix} \leftarrow \begin{cases} \text{Yes} \rightarrow \text{with probability } PAR \\ \text{No} \rightarrow \text{with probability } \left(1 - PAR\right) \end{cases} \tag{22}$$

In case the pitch adjustment decision for x_i' is Yes, the pitch-adjusted value of x_i' will be $x_i' + \alpha$ where α indicates the value of $bw \times u$ (-1, 1), where *bw* denotes an arbitrary distance bandwidth for the continuous design variable, and *u* represents a uniform distribution between −1 and 1.

D. Updating

The new harmony vector is compared with the worst harmony vector in the *HM* regarding the value of the objective function, in this stage. If the new harmony vector is better than the existing worst harmony, the later one gives its place to the new harmony.

E. Termination Criterion

Whenever the termination criterion is satisfied, the computations are completed. While it is not met, steps 3 and 4 are repeated. The termination criterion is considered as the maximum number of improvisations in this paper.

IV. PROPOSED METHOD

In restructured environments, the objective of power system operation and planning is maximization of social welfare through minimization of system costs. Having a relatively high investment cost, there is a considerable risk in application of the UPFC. Therefore finding the optimal location and proper parameter setting of the UPFC is very important in its application. The focus of this study is on minimizing operating costs and loss minimization of the power system through proper implementation of UPFC.

A. The Objective Functions

To achieve the best utilization of the existing transmission systems, the UPFC should be installed in such a place to minimize the system operating costs while have the minimum installation cost. Two different objective functions are considered for placement and parameter setting problem of the UPFC implementation. The first one is the total operating cost including congestion rent and generation costs that is considered to be minimized. The first Objective function is defined as follows:

$$\text{minimize} \quad Obj = F + TCR \tag{23}$$

where, F is the generation cost which is calculated in the OPF subroutine in Equation (13) and TCR is the total congestion rent retrieved from Equation (18).

As the second objective function, the optimization is aimed at loss minimization.

$$\text{minimize} \quad Obj = Loss \tag{24}$$

where, $Loss$ is the power loss which is calculated in the OPF subroutine using Equation (25).

$$Loss = \sum_{l=1}^{N_L} \left| T_{ij} + T_{ji} \right| \tag{25}$$

where, i and j are sending and receiving ends of line l.

B. Simplified Multistate Wind Turbine Generator Model

A two-state model in power system evaluations usually represents a conventional generating unit. These two states are the unit operating state with rated power output, and the unit failure state with zero output. A Wind Turbine Generator (WGT) unit, however, cannot be modeled by a two-state model since the power output can vary continuously and intermittently from zero to the rated value depending on the wind speed at the wind farm site [24]. WTG units are represented by multistate models in analytical methods.

Accurate modeling can be obtained by representing a wind farm by a large number of discrete output states. This can be obtained from a wind speed model with a large number of discrete wind speed steps. The model can be simplified by reducing the number of steps at the cost of accuracy [24]. It is very important to determine the minimum number of steps that can be used in a simplified wind speed model while a reasonable accuracy for all practical purposes is obtained. It was shown in [24] that using six or more steps in the wind speed model is adequate for WTG studies with reasonable accuracy.

The output power of wind turbine generator mainly depends on wind speed. Different shape has been obtained for their relationship curves, which linear is closer to the experimental data [25]. The power output P_W depends on the wind speed and it is calculated by the following relationship:

$$P_W = \begin{cases} 0 & V \le V_{ci} \,\&\, V \ge V_{co} \\ P_r \dfrac{V - V_{ci}}{V_r - V_{ci}} & V_{ci} \le V \le V_r \\ P_r & V_r \le V \le V_{co} \end{cases} \tag{26}$$

where, V is the wind speed at height of the wind turbine generator hub. V_{ci}, V_{co}, V_r are the cut-in speed, the rated speed, the cut-out speed, respectively. P_r is the rated power of the WTG. Wind speed in wind farms at reading height for historical wind data is converted into wind speed at WTG hub [25].

The 6-step common wind speed model that can be used for WTG studies of power systems with reasonable accuracy is thoroughly handled in [24]. The model is consisted of six wind speed steps and the corresponding probabilities. The wind speeds for a geographic site can be obtained from this model using Equation (26) [24]:

$$SW_m = \mu + (m-3) \times (\frac{5\sigma}{3}) \quad \text{for} \quad m = 1, \ldots, 6 \tag{27}$$

where, SW_m stands for wind speed at step m and μ and σ are variables of the site. The application of the six-step common wind speed model is illustrated in [24] by applying it to a real case study. The data for this site is used for this study. Table 1 shows the wind speeds in km/h and their corresponding probabilities.

Table 1. Six-step WTG model

Step	Wind Speed (km/h)	Probability
1	0	0.0051
2	2.7633	0.1920
3	19.5300	0.6120
4	36.2967	0.1796
5	53.0633	0.0109
6	69.8300	0.0003

A simplified multistate power generation model for a WTG can be obtained by combining the 6-step common wind speed model with the power curve relation of the WTG in Equation (26).

C. Implementation of Harmony Search Algorithm

The objective of power systems operation and planning in the restructured electricity markets is to maximize the social welfare through minimizing operational costs of the system. Figure 2 shows the procedure of the proposed optimization based on the HSA. In this procedure, initially the optimization problem parameters, including load data, wind speed and etc. as well as the parameters of the harmony search are defined.

After initializing optimization problem and algorithm parameters, the *HM* is initialized. All transmission lines of the system are considered as a potential location for application of UPFC in this study. Therefore, for each solution the following parameters in Table 2 are randomly set. However, each of the following parameters has its own limits, discussed earlier, that should be satisfied. For example, the first parameter is an integer variable that varies between 1 and N_L. Therefore, even though parameters are randomly generated they are under control and supervision to meet their boundaries.

Table 2. Randomly set parameters after *HM* initializing

Line Number	V_T	ϕ_T	I_q

After initializing *HM*, the power productions of WTGs are calculated considering the proposed model using wind speed, and by taking into account different scenarios and probabilities (shown in dash form because it is only used when WTGs are considered in the network and when WTGs are not taken into account this stage this step is not performed).

After that, based on each solution UPFC is located in a line of the system based on that solution, its parameters are taken from the same solution. Then an OPF subroutine is performed for the new system with UPFC. This process is performed for all of the harmony vectors (each solution). Based upon results of the OPF, the objective function is calculated for each harmony vector.

Next, a new harmony is improvised from the *HM*. After that, based on the calculated objective function of harmony vectors, *HM* is updated. Finally, the termination criterion is checked. Termination criterion is set to be a pre-defined number of iterations.

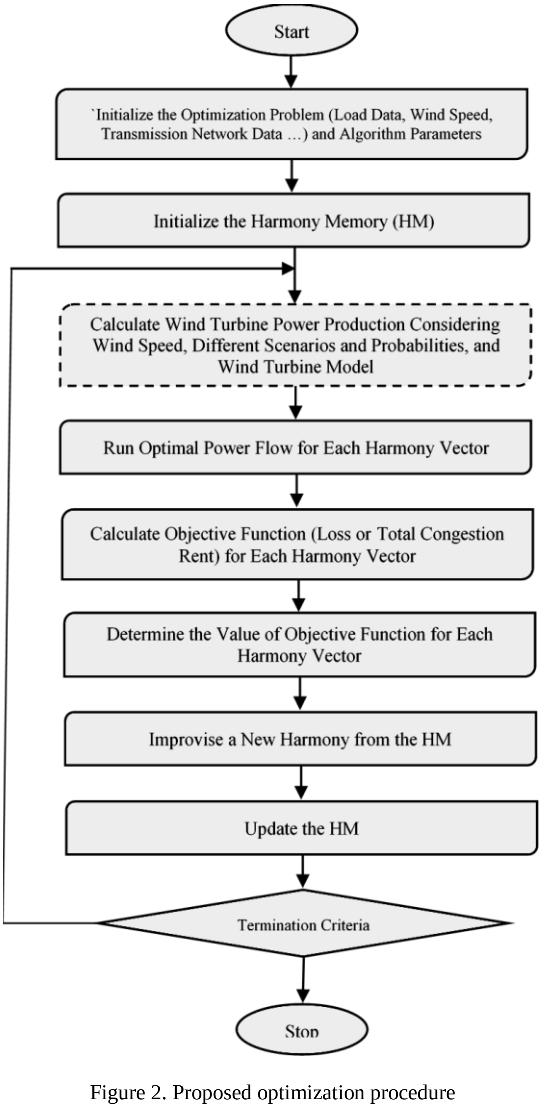

Figure 2. Proposed optimization procedure

V. SIMULATION RESULTS

Modified IEEE 14-bus test system is used to show the effectiveness of the proposed method to find the optimal locations and proper parameter settings of UPFC. The network and load data for this system are available in [26].

For this test system, both objective functions are considered. Lines limits are taken from [22]. It should be noted that the contribution of this paper is considering and analyzing the effects of the WTG on UPFC placement. Therefore, only HSA as the optimization tools is utilized here and the results in the presence and in case there is no WTG in the network are compared. The capability of HSA on finding the optimal location and size of UPFC has been demonstrated by authors [16]. The HSA parameters are presented in Table 3.

Table 3. Harmony search algorithm parameters

HMS	$HMCR$	PAR	$Iter_{max}$
20	0.9	0.35	50

WTG cut-in wind speed is 10.8 km/h, rated speed of 36 km/h, and the cutout wind speed is 60 km/h and P_r is 10 MW for each wind farm [25]. Table 4 shows different possibilities for power output of the WTG and its corresponding probability. %P_r indicates the percentage of the rated power of wind turbine that will be available to be delivered to the network at each possibility.

Table 4. Power output of the WTG (percentage of its rated power)

Power Output (%P_r)	Probability
0	0.0994
0.3464	0.6120
1	0.2886

Wind turbine generators are assumed to be located in buses number 10, 11, 12 and 13. In order to investigate the system under the joint operation of the wind generator models proposed in the previous section, the IEEE 14-bus test system is modified as shown in Figure 3 to accommodate four wind farms based on the information provided in [27].

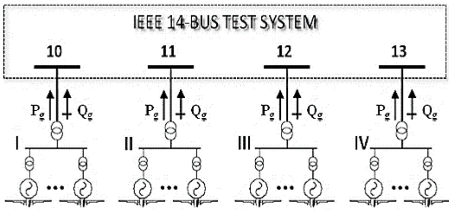

Figure 3. Modified IEEE 14-bus test system

A. Operating Costs as Objective Function

The congestion rent of the system when no UPFC is in operation is 2071.71 $/h and the generation cost is 6334.39 $/h. Therefore the operating costs of the system is 8106.10 $/h. On the other hand when WTG are applied to the system congestion rent of the system with no UPFC is 1768.93 $/h and the generation cost is 5045.79 $/h.

A.1. IEEE 14-Bus without Wind Power

Table 5 shows the results of optimal locating and parameter setting of the UPFC when the operating cost is considered as the objective function. Total congestion rent and total generation cost for IEEE 14-bus test system is also presented for the selected lines.

Saving refers to reduction in total congestion rent and generation cot of the system due to implementation of UPFC. As is shown in this table line 6 (3-4) is the best location for application of UPFC. With a UPFC at line 6, the operating costs of the system can be effectively reduced. This device has reduced the generation cost to 3163.8 \$/h that is about 50% reduction. It also result in about 68% reduction in congestion rent of the system and reduced it to 666.50 \$/h. As the results depict implementation of the UPFC has reduced the operating costs of system 52.7% and has led to 4275.78 \$/h saving.

Table 5. UPFC Placement and parameters selection for IEEE-14 bus without WTG (operating cost as objective function)

Priority	Line	From Bus	To Bus	V_T	ϕ_T	I_q	F (\$/h)	TCR (\$/h)	Saving (\$/h)
1	6	3	4	0.2	2.5	0.2	3163.9	666.5	4275.8
2	7	4	5	0.05	3.1	0.3	3090.0	1185.6	3830.9
3	3	2	3	0.2	2.3	0.3	3960.9	1161.1	2984.2

A.2. IEEE 14-Bus with Wind Power

The results of optimal locating and parameter setting of UPFC when the operating cost is considered as the objective function and WTG are included are provided in Table 6.

Table 6. UPFC Placement and Parameters Selection for IEEE-14 Bus with WTG (Operating Cost as Objective Function)

Priority	Line	From Bus	To Bus	V_T	ϕ_T	I_q	F (\$/h)	TCR (\$/h)	Saving (\$/h)
1	6	3	4	0.2	2.2	0.4	2866.4	623.7	3324.6
2	6	3	4	0.1	3.3	0.6	4109.9	1137.7	1567.2
3	15	7	9	0.07	2.6	0.04	3838.5	1423.9	1552.4

Total congestion rent and total generation cost for IEEE 14-bus test system is presented for the best solutions. As is shown in this table line 6 (3-4) is also the best location for application of UPFC when WTG is installed in the system. With a UPFC at line 6 the operating costs of the system can be effectively reduced. This device has reduced the total operation cost 3324.6 \$/h that is about 50% reduction. The second best solution is also line number 6 but because of a different parameter setting it yield a non-optimal solution. It demonstrates the importance of proper parameter setting.

B. Transmission Loss as Objective Function

The loss of the system with no UPFC is 3.9094 MWh that is about 1.5% of system load. However, when WTG is added to the system the total loss of the system is 3.6742 MWh.

B.1. IEEE 14-Bus without Wind Power

Table 7 shows the results of optimal locating and parameter setting of UPFC when the transmission loss is aimed to be minimized. The lines in which installation of UPFC resulted in reduction in transmission loss of the system are lines 4 (2-4) and 3 (2-3), as depicted in Table 7. Transmission loss after application of the UPFC as well as loss reduction is presented for IEEE 14-bus test system in this table. Application of the UPFC in other lines has not resulted in reduction in transmission loss of the system, so only two candidate lines are shown in this table. With transmission loss as objective function, line 4 is the optimal location and can reduce the system loss about 67%.

Table 7. UPFC Placement and parameters selection for IEEE-14 Bus without WTG (transmission loss as objective function)

Priority	Line	From Bus	To Bus	V_T	ϕ_T	I_q	Loss	Loss Reduction
1	4	2	4	0.13	1.84	-0.75	1.3	66.96%
2	3	2	3	0.16	1.15	0.9	1.86	53.36%

B.2. IEEE 14-Bus with Wind Power

Table 8 shows the results of optimal planning scheme of the UPFC when the transmission loss is aimed to be minimized while WTGs are located at the predefined locations.

Table 8. UPFC Placement and parameters selection for IEEE-14 bus with WTG (transmission loss as objective function)

Priority	Line	From Bus	To Bus	V_T	ϕ_T	I_q	Loss	Loss Reduction
1	14	7	8	0.13	3.12	0.51	2.4	34.82%
2	8	4	7	0.17	2.47	0.44	2.9	21.28%

Transmission loss after application of the UPFC along with loss reduction percentage is provided for IEEE 14-bus test system in this table. Lines 14 (7-8) and 8 (4-7) that installation of the UPFC in them resulted in highest reduction in transmission loss of the system are selected as the best locations. As it is depicted in Table 8 in both solutions bus 7 is included that demonstrates the accuracy of the proposed method. It can be seen in Figures 3 and 4 that bus 7 is not a bus with conventional generator or WTG, therefore lines that are connected to this bus are suitable locations for placement of UPFC. With transmission loss as objective function, line 14 is the optimal location and can reduce system loss about 35%.

VI. CONCLUSIONS

The application of the UPFC for restructured electricity market considering intermittent energy resources has been proposed in this paper. Harmony Search Algorithm as an optimization tool has been employed to achieve the optimal location and proper parameters settings of the UPFC. Minimization of total operating cost including congestion rent and total generation cost and minimization of transmission system loss has been considered as the two objective functions of the optimization problem.

A simplified model of wind turbine generators has been borrowed from literature to model the stochastic nature of WTG. Impact of WTG on application of the UPFC in the system has been investigated for both objective functions. The proposed method is conducted on IEEE 14-bus test system. The results demonstrate that the congestion cost, transmission loss, and the generation costs of the system can be effectively reduced through the optimal implementation of the UPFC.

APPENDIX

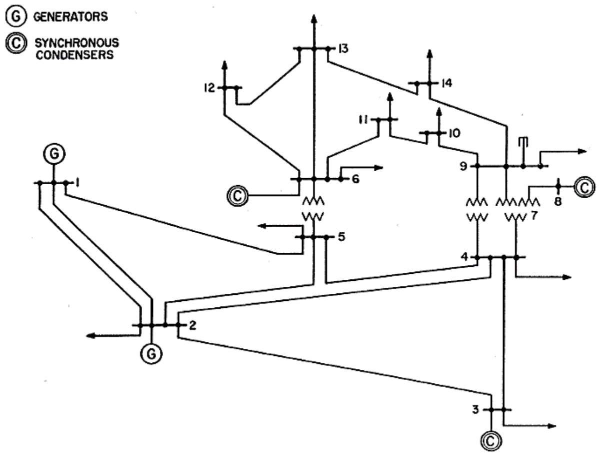

Figure 4. Schematic of IEEE 14-bus test system [26]

NOMENCLATURES

λ : Vectors of Lagrangian multipliers associated with equality constraints

$\lambda_{C,i}$: Marginal cost of congestion at bus i

$\lambda_{L,i}$: Marginal cost of losses at bus i

λ_P : Marginal cost of energy

μ : Vectors of Lagrangian multipliers associated with inequality constraints, Karush-Kuhn-Tucker conditions

ϕ_T : Phase angle

$\phi_T^{\min}$, $\phi_T^{\max}$: Minimum/maximum phase angle

a_k , b_k & c_k : Bid coefficients of unit k

$C_k(\ )$: Offered energy generation bid of unit k

i, j : Bus index

l : Line index

N_B : Number of buses

N_G : Number of generating units

N_L : Number of transmission lines

P_{D_i} , Q_{D_i} : Real power and reactive power demand

P_{G_i} , Q_{G_i} : Real power and reactive power generation

P_{G_k} : Real power output of unit k

$P_{G_k}^{\min}$, $P_{G_k}^{\max}$: Minimum/maximum real power generation capacities of unit k

P_i , Q_i : Real and reactive power injections at bus i

I_q : Current magnitude

$I_q^{\min}$, $I_q^{\max}$: Minimum/maximum Current magnitude

T_l : Active power transferred through line l

$T_l^{\max}$: Max allowable active power transfer through line l

V_i : Voltage magnitude at bus i

$V_i^{\min}$, $V_i^{\max}$: Minimum/maximum voltage magnitude at bus i

V_T : Voltage source magnitude

$V_T^{\min}$, $V_T^{\max}$: Min/max voltage source magnitude

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