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Application of whale algorithm optimizer for unified power flow controller optimization with consideration of renewable energy sources uncertainty

Purpose. *In this paper an allocation methodology of Flexible Alternating Current Transmission Systems (FACTS) controllers, more specifically, the Unified Power Flow Controller (UPFC) is proposed. As the penetration of Renewable Energy Sources (RESs) into the conventional electric grid increases, its effect on this location must be investigated. Research studies have shown that the uncertainty of RESs in power generation influences the reactive power of a power system network and consequently its overall transmission losses. The* ***novelty*** *of the proposed work consists in the improvement of voltage profile and the minimization of active power loss by considering renewable energy sources intermittency in the network via optimal location of UPFC device. The allocation strategy associates the steady-state analysis of the electrical network, with the location and adjustment of controller parameters using the Whale Optimization Algorithm (WOA) technique.* ***Methodology.*** *In order to determine the location of UPFC, approaches are proposed based on identification of a line which is the most sensitive and effective with respect to voltage security enhancement, congestion alleviation as well as direct optimization approach. The optimum location of UPFC in the power system is discussed in this paper using line loading index, line stability index and optimization method. The objective function is solved using the WOA algorithm and its performance is evaluated by comparison with Particle Swarm Optimization (PSO) algorithm.* ***Results****. The effectiveness of the proposed allocation methodology is verified through the analysis of simulations performed on standard IEEE 30 bus test system considering different load conditions. The obtained results demonstrate that feasible and effective solutions are obtained using the proposed approach and can be used to overcome the optimum location issue. Additionally, the results show that when UPFC device is strategically positioned in the electrical network and uncertainty of RES is considered, there is a significant influence on the overall transmission loss and voltage profile enhancements of the network.* References 31, tables 4, figures 14.

Key words: **unified power flow controller, optimal location, whale optimization algorithm, renewable energy sources, intermittency.**

Мета*. У статті пропонується методологія розподілу контролерів гнучких систем передачі змінного струму (FACTS), зокрема уніфікованого контролера потоку потужності (UPFC). Оскільки проникнення відновлюваних джерел енергії (ВДЕ) у звичайну електричну мережу збільшується, необхідно досліджувати їхній вплив на це. Наукові дослідження показали, що невизначеність ВДЕ у виробленні електроенергії впливає на реактивну потужність мережі енергосистеми і, отже, на її загальні втрати під час передачі.* ***Новизна*** *запропонованої роботи полягає в покращенні профілю напруги та мінімізації втрат активної потужності за рахунок обліку перемежування відновлюваних джерел енергії в мережі за рахунок оптимального розташування пристрою UPFC. Стратегія розподілу пов'язує стаціонарний аналіз електричної мережі з розміщенням та налаштуванням параметрів контролера з використанням методу алгоритму оптимізації кита (WOA).* ***Методологія****. Для визначення розташування UPFC пропонуються підходи, засновані на виявленні лінії, яка є найбільш чутливою та ефективною з точки зору підвищення безпеки за напругою, зменшення навантажень, а також прямий підхід до оптимізації. Оптимальне розташування UPFC в енергосистемі обговорюється в цій статті з використанням індексу завантаження лінії, індексу стійкості лінії та методу оптимізації. Цільова функція вирішується з використанням алгоритму WOA, а її продуктивність оцінюється шляхом порівняння з алгоритмом оптимізації рою частинок (PSO).* ***Результати****. Ефективність запропонованої методології розподілу перевірена за допомогою аналізу моделювання, виконаного на тестовій системі стандартної шини IEEE 30 з урахуванням різних умов навантаження. Отримані результати демонструють, що за допомогою запропонованого підходу виходять здійсненні та ефективні рішення, які можна використовувати для подолання проблеми оптимального розташування. Крім того, результати показують, що коли пристрій UPFC стратегічно розташований в електричній мережі і враховується невизначеність ВДЕ, це значно впливає на загальні втрати при передачі і поліпшення профілю напруги в мережі.* Бібл. 31, табл. 4, рис. 14.

Ключові слова: **уніфікований регулятор потоку потужності, оптимальне розташування, алгоритм оптимізації кита, відновлювані джерела енергії, переривчастість.**

Introduction. Nowadays, the global demand for electricity is increasing which increase the power system stress. The constraints on expanding power generation plants' construction and transmission lines have resulted in a significant gap between power generation and demand [1]. The reliable and secure operation of power systems is then an important task for operators to avoid improper performance such as excessive power losses, congested lines, voltage instabilities and stability problems [2]. In this context, a possible solution to improve the exploitation of the system was the use of Flexible Alternating Current Transmission Systems (FACTS) technologies. The FACTS devices should provide the highest advantage to power networks for maintaining stability and security constraints [3]. Moreover, FACTS can significantly improve the performance of the power system, i.e., improving the voltage profile, reducing power system losses, increasing the permissible power transfer capability, and enhancing the stability and reliability of the system [4]. Many FACTS controllers have been proposed and implemented to control the power system under normal states, as well as under contingency conditions [5]. Among these controllers, the Unified Power Flow Controller (UPFC) is a device which has the capacity to regulate the active power, reactive power, and the voltage of connecting buses.

Like any FACTS controller, UPFC can be deployed anywhere in the power system and its performance will be varied on different transmission lines. Therefore, we will face the problem of where we should install UPFC. For this reason, some performance indices must be defined and satisfied. The factors that can be considered in the selection of the optimal installation and parameter setting of UPFC may be the stability margin improvement, the power transmission capacity increase, and the voltage profile enhancement, etc [6].

However, the placement of UPFCs is a very complex problem, even under the consideration of steady-state conditions only. An optimal UPFC placement must incorporate not only each possible system topology but must also consider the entire range of possible control settings which may themselves be dependent on system topology [7]. The techniques for optimal location of FACTS devices are broadly classified into three categories, namely the classical optimization methods, sensitivity based methods and meta-heuristic methods [1, 8, 9]. Hybridization can be also used [4, 10].

The meta-heuristic approaches are the well-established method to achieve the best results in the FACTS device placement and location in the power system [11, 12]. Meta-heuristic based methods are inspired by human, natural biological systems intelligence and laws of nature and physics. Examples include but not limited to Genetic Algorithm [13], Particle Swarm Optimization [14], Cuckoo Search Algorithm [15], Grey Wolf Optimization [16], Harmony Search [17], Artificial Bee Colony Algorithm [18], Firefly Algorithm [9], Flower Pollination Algorithm [19], Brainstorm Optimization [20], and Biogeography based optimization [21].

On the other hand, with the continuing increase in demand and unexpanded transmission system due to limitations, the integration of renewable energy sources (RES) into the electrical grid is experiencing a rapid increase across the world. This is facing the current trends in decreasing fossil fuels, increasing pollution levels, and uncontrolled increase in population. Among various types of RES [22], wind and solar photovoltaic based energy sources are the most adopting technologies even at end-user level. As compared to conventional energy sources (CES), the RES have various advantages like reduced active power losses, improved voltage profile and increased overall energy efficiency, etc., however the intermittency nature of RES need to be addressed by the researchers.

The **goal** of this paper is to locate UPFC device in the best possible location to reduce power loss and voltage deviation considering RES integration and intermittency. Stability index and congestion index values are used. A detailed description of the power flow problem incorporating UPFC model is provided. Moreover, the proposed methodology and the Whale Optimization Algorithm (WOA) method are presented. In the proposed methodology, IEEE 30 bus system is considered to validate the system performance.

Modeling of UPFC in the power flow. FACTS devices are equipment that, by means of high power electronics, allows acting on the electrical system in order to make it more reliable, efficient and flexible. The UPFC is a FACTS device able to control simultaneously active power flows, reactive power flows, and voltage magnitude at the UPFC terminals**.** The UPFC consists of two switching converters operated from a common DC link (Fig. 1). These converters are connected to the power system via coupling transformers. One converter is connected in shunt to the sending end node *i* while the second converter is connected in series between the sending and receiving end nodes *i* and *j*. The series converter performs the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line. The UPFC cannot generate or absorb active power and as such the active power in the two converters must balance when active power loss is neglected. This is achieved via the DC link. The converters, however, may generate or absorb reactive power. The shunt converter can generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. UPFC can then regulate active and reactive power simultaneously. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement in one and the same device.

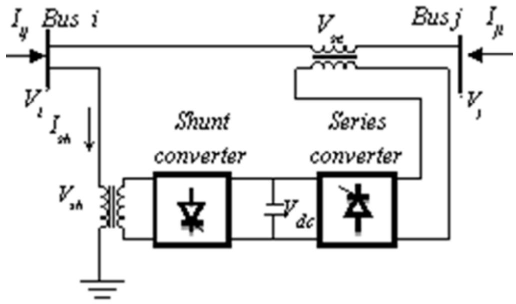

Fig. 1. Operating principle of UPFC

The power flow calculation method used is the traditional Newton-Raphson (NR) method. The following describes the adaptations made in it to incorporate the control representation of the UPFC in the solution process. The NR method is based on the solution of successive linear problems described by (1), where the sub-matrices *H*, *M*, *N* and *L* constitute the Jacobian matrix of the problem and represent the partial derivatives of the nodal power injections (*P* and *Q*) with respect to the state variables (phase angle δ and voltage magnitude *V*)

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}, \qquad (1)$$

The UPFC equivalent circuit (Fig. 2) is used to derive the steady-state model. The UPFC model can be incorporated to the power flow equations by adding the UPFC injection powers at buses *i* and *j*. The equivalent circuit allows us to model it in terms of power injection (Fig. 3).

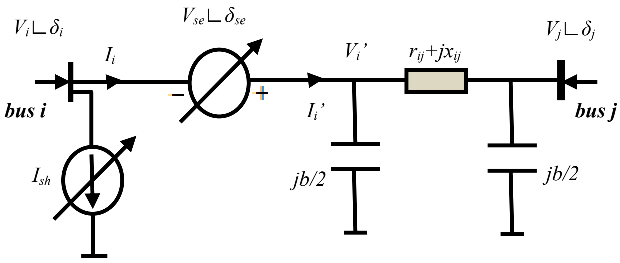

Fig. 2. The equivalent circuit of UPFC

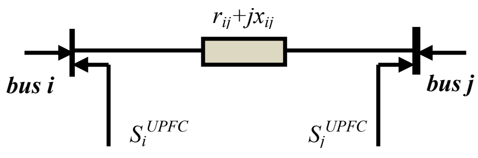

Fig. 3. Power injection model of UPFC

Based on the principle of UPFC and the vector diagram, the following equations can be written:

$$\overline{V_i'} = \overline{V_i} + \overline{V_{se}}\,, \qquad (2)$$

$$Arg(\overline{I_q}) = Arg(\overline{V_i}) \pm \frac{\pi}{2}\,, \qquad (3)$$

$$Arg(\overline{I_p}) = Arg(\overline{V_i}), \tag{4}$$

$$\overline{I_p} = \frac{\Re e\left(\overline{V_{se}} \cdot \overline{I_i'}^*\right)}{\overline{V_i}}, \tag{5}$$

where: $\overline{V_i}$ is the voltage at bus i; $\overline{V_{se}}$ is the voltage injected in series with the transmission line through the series transformer; V_{se} is the magnitude and δ_{se} the phase angle of this voltage; I_q is the shunt reactive current of UPFC flowing in the shunt transformer to improve the voltage of the shunt connected bus of UPFC; the current I_p represents the active power demanded by the series converter at the common DC link and supplied or absorbed by the shunt converter.

Then the shunt current of UPFC is

$$\overline{I_{sh}} = I_p + jI_q . \tag{6}$$

Then, the power flow equations from bus i to bus j and from bus j to bus i can be written as:

$$\overline{S_{ij}} = P_{ij} + jQ_{ij} = \overline{V_i} \cdot \overline{I_{ij}}^* = \overline{V_i}\left(j\overline{V_i'}\frac{b}{2} + I_p + jI_q + \overline{I_i'}\right)^*; \tag{7}$$

$$\overline{S_{ji}} = P_{ji} + jQ_{ji} = \overline{V_j} \cdot \overline{I_{ji}}^* = \overline{V_j}\left(j\overline{V_j}\frac{b}{2} - \overline{I_i'}\right)^*. \tag{8}$$

The active and reactive power flow in the line having UPFC can be written:

$$\begin{aligned} P_{ij} = &\left(V_i^2 + V_{se}^2\right)g_{ij} + 2V_iV_{se}g_{ij}\cos(\delta_{se} - \delta_i) - \\ &- V_jV_{se}\left[g_{ij}\cos(\delta_{se} - \delta_j) + b_{ij}\sin(\delta_{se} - \delta_j)\right] - \\ &- V_iV_j\left[g_{ij}\cos(\delta_i - \delta_j) + b_{ij}\sin(\delta_i - \delta_j)\right]; \end{aligned} \tag{9}$$

$$\begin{aligned} P_{ji} = &V_j^2 g_{ij} - V_jV_{se}\left[g_{ij}\cos(\delta_{se} - \delta_j) - b_{ij}\sin(\delta_{se} - \delta_j)\right] - \\ &- V_iV_j\left[g_{ij}\cos(\delta_i - \delta_j) - b_{ij}\sin(\delta_i - \delta_j)\right]; \end{aligned} \tag{10}$$

$$\begin{aligned} Q_{ij} = &-V_iI_q - V_i^2\left(b_{ij} + \frac{b}{2}\right) - \\ &- V_iV_{se}\left[g_{ij}\sin(\delta_{se} - \delta_j) + \left(b_{ij} + \frac{b}{2}\right)\cos(\delta_{se} - \delta_j)\right] - \\ &- V_iV_j\left[g_{ij}\sin(\delta_i - \delta_j) - b_{ij}\cos(\delta_i - \delta_j)\right]; \end{aligned} \tag{11}$$

$$\begin{aligned} Q_{ji} = &-V_j^2\left(b_{ij} + \frac{b}{2}\right) - \\ &- V_jV_{se}\left[g_{ij}\sin(\delta_{se} - \delta_j) + b_{ij}\cos(\delta_{se} - \delta_j)\right] + \\ &+ V_iV_j\left[g_{ij}\sin(\delta_i - \delta_j) + b_{ij}\cos(\delta_i - \delta_j)\right], \end{aligned} \tag{12}$$

where

$$g_{ij} + jb_{ij} = \frac{1}{r_{ij} + jx_{ij}}, \tag{13}$$

r_{ij} and x_{ij} are the resistance and reactance of line i-j.

The real and reactive power flows for the line i-j without UPFC are:

$$P_{ij} = V_i^2 g_{ij} - V_iV_j\left[g_{ij}\cos(\delta_i - \delta_j) + b_{ij}\sin(\delta_i - \delta_j)\right]; \tag{14}$$

$$P_{ji} = V_j^2 g_{ij} - V_iV_j\left[g_{ij}\cos(\delta_i - \delta_j) - b_{ij}\sin(\delta_i - \delta_j)\right]; \tag{15}$$

$$\begin{aligned} Q_{ij} = &-V_i^2\left(b_{ij} + \frac{b}{2}\right) - \\ &- V_iV_j\left[g_{ij}\sin(\delta_i - \delta_j) - b_{ij}\cos(\delta_i - \delta_j)\right]; \end{aligned} \tag{16}$$

$$\begin{aligned} Q_{ji} = &-V_j^2\left(b_{ij} + \frac{b}{2}\right) + \\ &+ V_iV_j\left[g_{ij}\sin(\delta_i - \delta_j) + b_{ij}\cos(\delta_i - \delta_j)\right]. \end{aligned} \tag{17}$$

We can so derive the active and reactive power injections associated to the UPFC:

$$\begin{aligned} P_i^{UPFC} = &-V_{se}^2 g_{ij} - 2V_iV_{se}g_{ij}\cos(\delta_i - \delta_{se}) + \\ &+ V_jV_{se}\left[g_{ij}\cos(\delta_j - \delta_{se}) - b_{ij}\sin(\delta_j - \delta_{se})\right]; \end{aligned} \tag{18}$$

$$P_j^{UPFC} = V_jV_{se}\left[g_{ij}\cos(\delta_j - \delta_{se}) + b_{ij}\sin(\delta_j - \delta_{se})\right]; \tag{19}$$

$$\begin{aligned} Q_i^{UPFC} = &V_iI_q + \\ &+ V_iV_{se}\left[-g_{ij}\sin(\delta_i - \delta_{se}) + \left(b_{ij} + \frac{b}{2}\right)\cos(\delta_i - \delta_{se})\right]; \end{aligned} \tag{20}$$

$$Q_j^{UPFC} = -V_jV_{se}\left[-g_{ij}\sin(\delta_i - \delta_{se}) + b_{ij}\cos(\delta_i - \delta_{se})\right]. \tag{21}$$

Then, the NR power flow algorithm is expressed by the following relationship:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H_{new} & N_{new} \\ M_{new} & L_{new} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}, \tag{22}$$

where the new error vectors are

$$\Delta P_i = P_i^{spec} + P_i^{UPFC} - P_i^{calc}; \tag{23}$$

$$\Delta Q_i = Q_i^{spec} + Q_i^{UPFC} - Q_i^{calc}, \tag{24}$$

where P_i^{spec} and Q_i^{spec} are the classical specified powers; P_i^{UPFC} and Q_i^{UPFC} are the power injection associated to the UPFC device; P_i^{calc} and Q_i^{calc} and are computed using the power flow equations.

And, the Jacobian matrix is modified to introduce new power injections that are functions of the bus voltages:

$$H_{new} = H + \frac{\partial P^{UPFC}}{\partial \delta}; \tag{25}$$

$$M_{new} = M + \frac{\partial P^{UPFC}}{\partial V}; \tag{26}$$

$$N_{new} = N + \frac{\partial Q^{UPFC}}{\partial \delta}; \tag{27}$$

$$L_{new} = L + \frac{\partial Q^{UPFC}}{\partial V}. \tag{28}$$

Applied methodology. To enhance the power system performance in terms of reduced transmission loss, improved voltage profile as well security margin, it is necessary to integrate the UPFC in an optimal location. Then, it is necessary to define an objective function that measures the «goodness» of a particular setting. This objective function is formulated by considering some performance indices under the conditions of different RES penetration and load levels.

Optimal location. Keeping system security is one of the most important tasks of power system operators. Due to economic reasons, a transmission network of a power system is mandatory to function near its security boundaries [23]. FACTS devices, mainly UPFC, should be placed to prevent congestion in transmission lines and maintain bus voltages far from voltage collapse condition. In this paper and in addition to optimization method, line stability index (LSI) and line loading index (LLI) are used for placement of UPFC.

1) LSI based location.

The dependency of voltage stability on reactive power reserve in the network is well highlighted fact in the literature. For a transmission line connected between bus *i* and bus *j*, LSI can be assessed by (29) [23-25]

$$LSI_{ij} = \frac{4x_{ij}Q_{ij}}{\left[V_i \sin\left(\theta_{ij} - \delta_i + \delta_j\right)\right]^2} \leq 1, \qquad (29)$$

where Q_{ij} is the reactive power flow in line *i-j* and θ_{ij} is the impedance argument of the line.

If LSI_{ij} reaches or nearing to unity, it indicates that the line is losing its stability and voltage collapse will occur. For stable operation, the LSI should be less than 1 for all the lines. The LSI greater than 1 indicates the proximity of instability or voltage collapse. The stability or security margin improvement can be shown by decreasing the LSI of all the lines. By observing the parameters in LSI, it is directly proportional to reactive power flow through the line and inversely proportional to the square of the voltage magnitude. Since the UPFC device is able to control the reactive power flows as well as improve the voltage profile, the location which can moderate the LSI value of all the lines is selected as optimal location. An LSI index value away from 1 and close to zero indicates an improved system security.

Also, the stressful condition of the line from its LSI value can be used to identify/rank the critical lines in network. The lines with higher LSI are the weakest and critical lines and are chosen as candidates for installing UPFC. We exclude the lines which are having regulating transformers and those incidents to generator/synchronous condenser buses.

2) LLI based location.

The overloading of lines provides an indication about the power system reliability. In order to remove congestions of the lines and to distribute the load flows uniformly, the UPFC has to be placed in a line that may minimize the average loadability. This can be achieved by considering the line loading index (LLI) used for determining the congestion of the transmission lines and defined below [21, 26]

$$LLI_l = \left(\frac{S_l}{S_{l\max}}\right)^2, \qquad (30)$$

where LLI_l is the line loading index of the line; S_l is the actual MVA rating of the line; $S_{l\max}$ is the maximum MVA rating of the line.

LLI is proposed to rank the most severe lines to allocate the UPFC controller. The power transmission lines which have most amount of LLI are recognized as critical lines from the viewpoint of congestion phenomenon and are chosen as candidates for installing UPFC.

3) Optimization based location.

The optimization algorithm is utilized to decide the optimal location and parameters of UPFC. The algorithm is proposed to execute the optimization process. Here also, UPFC can be incorporated in any line excluding the lines which are incident to generator buses as well as those are having tap changing transformer.

The UPFC is situated between two buses so from location and to optimal location are distinguished.

Definition of the objective function. The definition of the objective function of problems related to allocation of control devices is usually associated with improvement of the efficiency and / or operational safety of the power [3]. Two objectives are considered in this study, reduction of the active power losses of transmission lines and voltage profile improvement.

1) Minimization of losses.

Active power line transmission losses are a very important factor to optimize in a power network. Minimizing losses of active power of the system implies a decrease in the use of system generators and optimization of the circulation of power in the electrical network. Power losses P_{loss} can be expressed as:

$$P_{loss} = \sum_{k=1}^{nl} g_k \left[V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_i - \delta_j\right)\right], \qquad (31)$$

where g_k is the conductance of line *k* and *nl* the number of lines.

2) Voltage deviation.

Excessive high or low voltages can lead to an unacceptable service quality and can create voltage instability problems. UPFC connected at appropriate locations play a leading role in improving voltage profile thereby avoiding voltage collapse in the power system. To have a good voltage performance, the voltage deviation at each load bus must be made as small as possible in order to prevent the under or over voltages at network buses. The voltage deviation index to be minimized is as follows:

$$VD = \sum_k \left(V_k - V_{refk}\right)^2, \qquad (32)$$

where V_k is voltage magnitude of bus *k*; V_{refk} is the reference value for this voltage.

3) Aggregated objective.

The overall objective function is formulated to minimize voltage deviation and total real power loss simultaneously and expressed as

$$F = w_1\left[P_{loss}\right] + w_2\left[VD\right], \qquad (33)$$

where w_1 and w_2 are the weighting factors used for adjusting the network total active power loss and voltage deviation functions respectively. In this case, $w_1 = w_2 = 1$.

4) Vector of control variables.

The aim is then to minimize the voltage deviation and real power loss by optimizing the UPFC parameters considering RES integration. These objectives are highly dependent on adequate voltage profile. Hence, the vector of control variables consists of generator bus voltage magnitudes, tap-changer settings, eventual shunt MVAr injection, and control variables of UPFC device and generations at RES locations. For the UPFC, the associated control variables to be considered are: magnitude and voltage angle of the series controller and the shunt injected current of the device.

Consideration of renewable energy sources. The renewable energy is incorporated into the optimization problem and plays the role of negative loads in order to decrease the demand load. In general, any types of RES may not produce always at its maximum capacity due to dependency on various parameters involved in their operation. For example, wind turbine power is dependent on wind velocity and solar photovoltaic (PV) system generation is dependent on solar radiation etc.

Hence, it is assumed that the power generated by any RES is less than its maximum capacity. Then, a random number $r_{int,i}$ will be considered for the RES at bus i in the range of ($0 \le r_{int,i} \le 1$) to simulate intermittency of this power source.

The power generation at a RES bus is then

$$P_{res,i} = r_{int,i} P_{res,i}^{\max} , \quad (34)$$

where $P_{res,i}^{\max}$ is the real power injection capability (maximum capacity) of RES installed at bus i.

The total RES intermittency in the network can be formulated as

$$r_{int} = \frac{\sum_i P_{res,i}}{\sum_i P_{res,i}^{\max}} . \quad (35)$$

Today PV inverters are working with very small values of reactive power. Then, the power factor (PF) is very close to the unit. So, the PV installations only inject active power into the grid. However, induction machines are mostly used as generators in wind power based generations and may draw reactive power from the system to which they are connected.

Consideration of operating conditions – load levels. Many studies do not consider operational variations in the allocation process, using, for example, a constant load condition. This can interfere inappropriately in the allocation of the FACTS controllers, since they must, obviously, have their performance adjusted to the different operating conditions of the system.

To overcome this possibility, we can represent the different load conditions of the system in levels. The levels are defined from the discretization of daily consumption averages at intervals of consumption. Seeking to reduce the computational effort required to carry out large studies such as the one that characterizes device allocation problems, a usual division of the loads' behavior is to represent them, at three levels consumption: light, medium and heavy [27]. The objective is to represent the effect of changes in consumption control devices acting on the electrical network and that should interfere with the allocation process. In the present work, we consider only the base case and a heavy one with overloading of 30 %.

System constraints.

1) Equality constraints.

As per load flow studies, the residual powers at any bus should be equal to generation minus demand. Power flow equations corresponding to both real and reactive power balance equations are the equality constraints that can be written, for all the buses expect UPFC incident buses, as

$$P_{Gi} - P_{Di} - P_i(\delta, V) = 0 , \quad (36)$$

$$Q_{Gi} - Q_{Di} - Q_i(\delta, V) = 0 , \quad (37)$$

where P_{Gi}, P_{Di}, Q_{Gi} and Q_{Di} are the real and reactive power generations and loads at bus i respectively.

The equality constraints represent the typical load flow equations as follows:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{nb} V_j \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] = 0 , \quad (38)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{nb} V_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] = 0 , \quad (39)$$

$$i = 1, \ldots, nb$$

where nb is the number of buses of the power system.

For buses with RES powers, generation is expressed in terms of conventional and RES powers

$$P_i = \left(P_{Gi} + r_{int} P_{Gi,r}\right) - P_{Di} ; \quad (40)$$

$$Q_i = \left(Q_{Gi} + r_{int} Q_{Gi,r}\right) - Q_{Di} , \quad (41)$$

where r_{int} is the random numbers in the range of [0, 1] to represent the intermittence of the RES at bus i related to maximum real power $P_{Gi,r}$ and reactive power generations $Q_{Gi,r}$ respectively.

Similarly, for the UPFC incident buses, the real and reactive power balance equations can be written as,

$$P_i = P_{Gi} - \left(P_{Di} + P_{inj,i}\right); \quad (42)$$

$$Q_i = Q_{Gi} - \left(Q_{Di} + Q_{inj,i}\right), \quad (43)$$

where $P_{inj,i}$ and $Q_{inj,i}$ are the real and reactive power injections by UPFC device as given in equations (18)-(21) for incident buses.

2) Inequality constraints.

The inequality constraints represent the system operating limits like limits on reactive generation and bounds on tap settings of transformers.

Real power generation limits:

$$P_{G\min} \le P_G \le P_{G\max} . \quad (44)$$

Reactive power generation limits:

$$Q_{G\min} \le Q_G \le Q_{G\max} . \quad (45)$$

Bus voltage limits:

$$V_{i\min} \le V_i \le V_{i\max} . \quad (46)$$

Bus voltage phase angle limits:

$$\delta_{i\min} \le \delta_i \le \delta_{i\max} . \quad (47)$$

Tap-changers limits:

$$a_{i\min} \le a_i \le a_{i\max} . \quad (48)$$

Line power flow limits:

$$S_l \le S_{l\max} . \quad (49)$$

Optimization method. WOA is a new nature-inspired metaheuristic for optimization problems proposed in 2016 [28-30]. It mimics the hunting behavior of one of the biggest baleen whales called humpback whales. This kind of whales feeds a small prey as krill, herrings, and other small fishes near the surface. They have a special hunting method to find and hunt the prey called bubble-net feeding which is a complex and coordinated tactic for catching many fish at once. The hunt begins as the whales dive down and then start to create a ring of bubbles to encircle the fishes, which are too frightened to pass through the bubbles, in meantime the whales swim upward to the surface through the bubble net and swallowing a huge number of fishes in one swig.

In the optimization process, a population of whales (search agents) evolves to find the global optima after a specified number of iterations. WOA begins with the initialization of search agents randomly upon the interval bounds of the problem variables. After that, WOA evaluates the fitness score for each search agent by using the fitness function. The best solution is saved for further processing later.

Exploration phase: Searching for prey.

In the whale optimization algorithm, individual whales perform a random search through the positions of other individuals within the population to increase the exploration capability of the algorithm, and this behavior can be expressed by the following mathematical equation:

$$\vec{D} = \left| C \cdot \vec{X}_{rand} - \vec{X}_t \right| ; \quad (50)$$

$$\vec{X}_{t+1} = \vec{X}_{rand} - A \cdot \vec{D}\ , \tag{51}$$

where t specifies the current iteration; X_t is the current individual; X_{rand} is the other randomly selected individuals within the population; D is the distance between the current individual and the randomly selected individuals.

The parameters A and C in (50) and (51) are coefficient vectors defined as follows:

$$A = 2a \cdot r - a\ ; \tag{52}$$

$$C = 2 \cdot r\ , \tag{53}$$

where a is the parameter that decreases linearly with the number of iterations from 2 to 0; r is the uniformly distributed random number in the range of [0, 1].

Therefore, A is used with the random values $|A| > 1$ in order to guarantee the global search for the WOA algorithm. The position of every search agent is renewed according to a randomly chosen search agent.

Exploitation phase.

The local search performed by individual whales is realized by encircling predation and bubble net attack, respectively. These two behaviors can be simulated by the following mathematical model:

1) Encircling the prey.

After locating the prey, humpback whales circle around this prey to start hunting them. The WOA presumes that the current best candidate solution is the target prey or is close to the optimum. Accordingly, the overall search agents will update their new positions towards the best-determined search agent.

The following equations represent the encircling behavior:

$$\vec{D} = \left| C \cdot \vec{X^*} - \vec{X}_t \right|\ ; \tag{54}$$

$$\vec{X}_{t+1} = \vec{X^*} - A \cdot \vec{D}\ , \tag{55}$$

where $\vec{X^*}$ is the position vector of the best solution obtained so far. The position of a search agent can be updated, according to the position of the current best record, by adjusting the values of A and C vectors.

2) Bubble-net attacking strategy: Spiral updating position.

After locating the prey and encircling them, humpback whales start the hunting step using the bubble-net mechanism. Two approaches to model the bubble-net demeanor of humpback whales are proposed as represented below.

The humpback whales swim around the prey within a shrinking circle and along a spiral path at the same time. To model this simultaneous behaviour, it is supposed that there is a probability of 50 % to choose the technique that will be used to update the position of whales during optimization.

The mathematical spiral equation for position update between whale and prey designed as follows:

$$\vec{D} = \left| \vec{X^*} - \vec{X}_t \right|\ ; \tag{56}$$

$$\vec{X}_{t+1} = \vec{D} \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X^*}\ , \tag{57}$$

where b is the constant that determines the shape of the spiral and l is the random number uniformly distributed in the range of [–1, 1].

$$l = (a_2 - 1) \cdot r + 1\ , \tag{58}$$

where a_2 is the linearly decreasing parameter from –1 to –2; r is the uniformly distributed random number in the range [0, 1].

When $|A| \geq 1$, the exploration phase is executed according to (50) and (51), and when $|A| < 1$, the encircling predation is executed according to (54) and (55). In addition a uniformly distributed hyper parameter p is set by which the WOA can switch between the two strategies of surround predation or bubble-net attack. Mathematically, it is modeled as follows:

$$\vec{X}_{t+1} = \begin{cases} \vec{X^*} - A \cdot \vec{D} & p < 0.5 \\ \vec{D} \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X^*} & p \geq 0.5 \end{cases}. \tag{59}$$

Simulations and results. The proposed approach is applied on the standard IEEE 30 bus test system. The test system data is taken from [31]. The simulation studies were carried out in MATLAB environment. MATLAB programming codes for optimization algorithms and modified power flow algorithm to include UPFC are developed and incorporated together for the simulation purposes. In all simulation results quantities are in p.u. on a 100 MVA base.

Without RES integration. The IEEE-30 bus benchmark system consists of six generator buses, 24 load buses and 41 transmission lines. The system generator units are located at buses 1, 2, 5, 8, 11, and 13 of the network. Also, four tap-controlled transformers are connected between the transmission lines 6 to 9, 6 to 10, 4 to 12, and 27 to 28. In addition, the bus data and line data are detailed in [31]. Moreover, the voltage magnitudes of PV buses are limited from 0.9 to 1.1 (p.u.). Operating limits of the load buses are subjected from 0.9 to 1.1 (p.u.).

Initially, the system base case load flow analysis is done by the standard NR algorithm. It has real and reactive loads. The system is suffering with 17.52 MW real and 68.87 MVAr reactive power losses for a generation schedule of 40MW at bus 2 and the remaining load is supplied by slack bus 1. The components of the objective function for this operating condition are VD = 0.0222 and P_{loss} = 17.52 MW. The proposed methodology for finding optimal location of UPFC is then applied below.

For each loading condition LSI, LLI indices at each line and power losses are calculated. Based upon LSI or LLI index the critical line is identified i.e., the line with highest values of these indices and in that line UPFC is placed and again the above parameters are calculated.

1) LSI based optimal location.

At first, the LSI values are determined for all the lines and the lines are ranked in descending order. By excluding the lines which are incident to generator buses as well as those are having tap changing transformer, the top ranked lines as per LSI values associated with line number are given in Table 1 for the test system. Line # 34 (25–26) is ranked first with LSI value of 0.0493 and chosen for UPFC integration. The second is line # 38 (27–30) with LSI value of 0.0415 and so on. Considering the case of heavy load (130 %), the line (# 34) is still ranked first with respect to LSI values in descending order.

Table 1

LSI ranking

case	rank	1	2	3	4	5
Base load 100%	Line	**# 34 (25–26)**	#38 (27-30)	#18 (12-15)	#7 (4-6)	#27 (10-21)
	LSI	**0.0493**	0.0415	0.0368	0.0353	0.0323
Heavy load 130%	Line	**# 34 (25–26)**	#18 (12-15)	#33 (24-25)	#27 (10-21)	#19 (12-16)
	LSI	**0.0760**	0.0623	0.0533	0.0487	0.0482

2) LLI based optimal location.

In the same way, the LLI values are determined for all the lines and the lines are ranked in descending order. By excluding the lines which are incident to generator buses as well as those are having tap changing transformer, the top ranked lines as per LLI values associated with line number are given in Table 2 for the test system. Line # 7 (4–6) is ranked first with LLI value of 0.8253 and then chosen for UPFC integration. The same line is obtained for the case of heavy load.

Table 2

LLI ranking

case	rank	1	2	3	4	5
Base load 100 %	Line	**#7 (4-6)**	#18 (12-15)	#41 (6-28)	#27 (10-21)	#38 (27-30)
	LLI	**82.53**	60.04	59.46	57.97	45.52
Heavy load 130 %	Line	**#7 (4-6)**	#4 (3-4)	#18 (12-15)	#27 (10-21)	#41 (6-28)
	LLI	**111.13**	70.43	64.62	58.57	57.93

3) Optimal parameters of UPFC.

The WOA algorithm is applied for three cases: optimization of parameters of UPFC located according to LSI index, according to LLI index, and optimization of both location and parameters simultaneously by the optimizer. The WOA parameters considered are: number of populations is 30 and number of maximum iterations is 70.

In the optimization problem, variables are related to generator bus voltages, tap-changers, parameters in UPFC modeling and line location (depending on the case). The optimization results are summarized in Table 3.

Table 3

Optimization solution by WOA

Case / Variable	Base load (100 %) without UPFC	Line #34 LSI based location	Line #7 LLI based location	Line #41 WOA based location	Heavy load (130 %) without UPFC	Line #34 LSI based location	Line #7 LLI based location	Line #7 WOA based location
V_1	1.06	1.0796	1.0069	1.0423	1.06	1.1	1.068	1.0456
V_2	1.043	1.1	1.0046	0.9782	1.003	1.1	1.0398	1.0449
V_5	1.01	1.0064	0.9895	1.0177	0.93	1.0684	1.1	1.0183
V_8	1.01	0.9512	0.9721	1.0621	0.94	1.0438	1.1	1.0367
V_{11}	1.082	1.1	1.1	1.1000	1.032	1.0425	0.95	1.0459
V_{13}	1.071	1.1	1.1	1.1000	1.031	1.023	1.1	1.1
a_{11}	0.978	1.0924	1.1	1.1	0.978	0.9732	0.9622	1.1
a_{12}	0.969	0.9047	0.9	0.9	0.969	1.1	1.1	0.9
a_{15}	0.932	1.0243	1.0111	1.1	0.932	0.9848	1.0154	1.0047
a_{36}	0.968	0.9882	0.9597	0.9824	0.968	0.9943	0.9738	0.9577
V_{se}		0.2498	0.3	0.3		0.3	0.3	0.3
δ_{se}		3.1653	6.2832	6.2832		3.0381	6.2832	6.2832
I_q		0.0431	0.15	–0.1427		0.1023	–0.15	–0.15
P_{loss}	0.1752	0.1578	0.0495	0.0731	0.3345	0.2645	0.0873	0.0884
VD	0.0396	0.0044	0.0024	0.0065	0.0768	0.0091	0.0146	0.0059
$\sum LSI$	1.6749	1.1010	1.2823	1.3969	2.0972	1.1776	1.7657	1. 3385
$\sum LLI$	10.2120	10.5340	6.2287	11.3710	17.8972	16.5231	10.2989	9.9744

From these results, it is observed that LLI based case has provided better results than in all other cases. The optimal location based on the LLI index is line 4-6. Voltage deviation index and active losses which constitute the objective function are both minimized. The values of the control variables, voltage, turns ratios and UPFC settings are clearly shown in Table 3. LSI is decreased to 1.2823 from 1.6749 and LLI-index decreased from 10.2120 to 6.2287 for the base load. For the high load and UPFC placed in the same location, LSI is decreased to 1.3385 from 2.0972 and LLI index decreased to 9.9744 from 16.5231.

Figures 4, 5 show convergence performance for WOA method for the two loading conditions and compared with Particle Swarm Optimization (PSO) algorithm. The performance of WOA is outlined.

Then voltage profile and system losses without UPFC and with UPFC are presented in Fig. 6–9 respectively for both base load and heavy load. The voltage profiles at the network nodes depicted in Fig. 6, 7 clearly show its improvement. Figures 8, 9 indicate that globally the result based on LLI location gives losses lower for both normal load and heavy load cases.

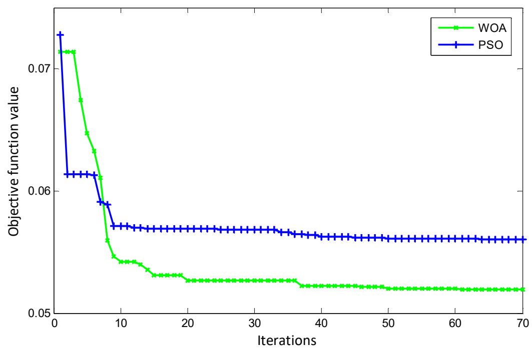

Fig. 4. Convergence performance for normal load

As the performance of UPFC has been tested on system with normal loading and 130 % loading conditions, we can notice that is providing good voltage profile as well as reduced the system losses which can be observed from the Table 3. But congestion or improved active power flow performance is better when UPFC is placed in line 4-6 than line 25-26 as well as voltage stability improvement is good when UPFC is in line 4-6 even if it is less than in line 25-26.

The results obtained from this comparative analysis prove the dominating performance of the optimization technique with the LLI based location.

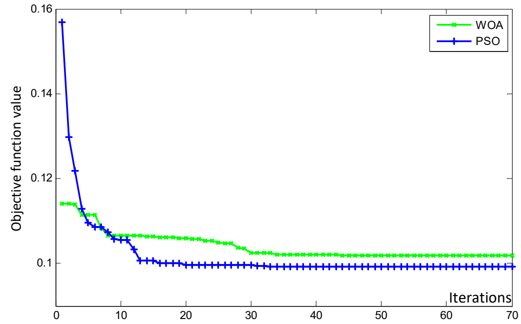

Fig. 5. Convergence performance for heavy load

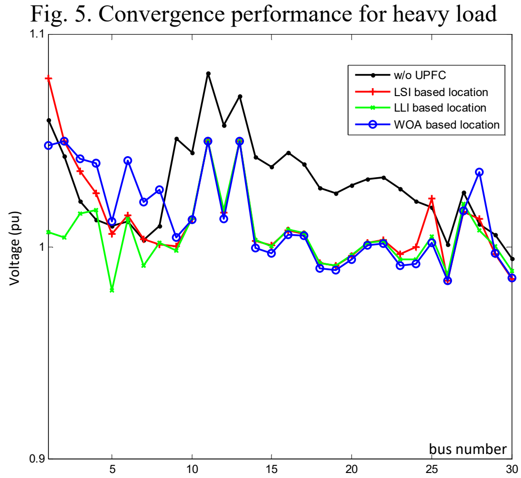

Fig. 6. Voltage profile under normal loading condition

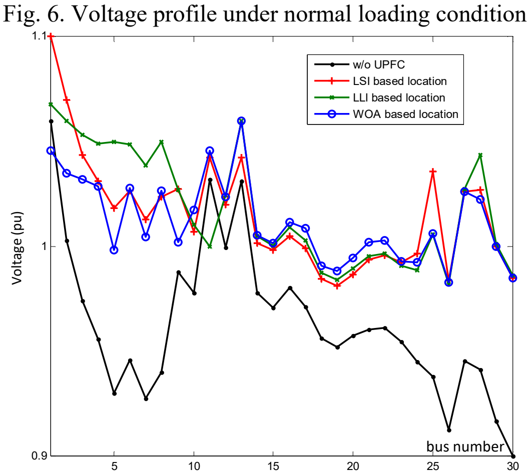

Fig. 7. Voltage profile under heavy loading condition

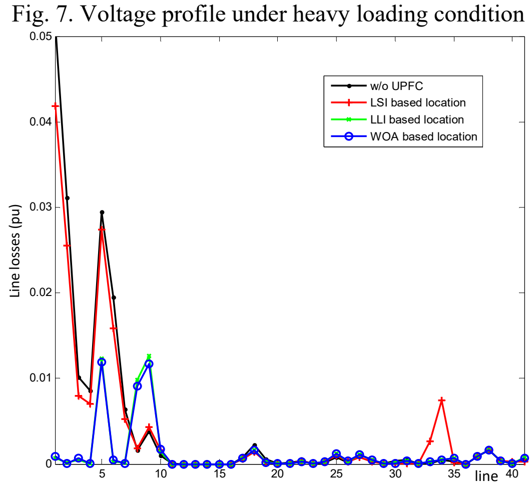

Fig. 8. Line losses under normal loading condition

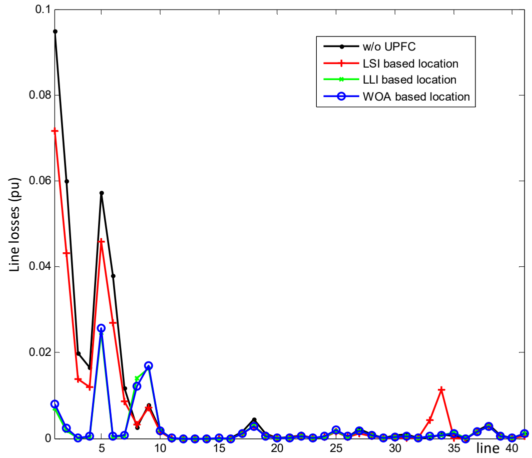

Fig. 9. Line losses under heavy loading condition

Integration of RES. In this case, the standard IEEE 30-bus system is considered by including two RES: wind farm located at bus numbers 24 and solar farm at bus 10. Moreover, the wind farms consist of several units of wind turbine generation (WTG) with a total capacity of 30 MW. The solar RES is also having a capacity of 30 MW. Unity power factor is considered for solar and 0.8 power factor for wind farm.

Their capacity will be considered as an input to the program for every case study. For different values of r_{int} ($0 \le r_{int} \le 1$), the total power supplied may or` not equal to RES installed capacity. The ratio of total RES generation to RES installed capacity is considered randomly to simulate the RES uncertainty.

The performance of UPFC integration in terms of *VD* and P_{loss} for IEEE 30-bus system under different RES intermittency conditions is shown Table 4.

The convergence performance of WOA for this case is given in Fig. 10 for moderate and heavy load. The results are summarized in Table 4. From this table, the locations obtained for the UPFC are the same as for the case without integration of RES but the set values of the voltages of the generators and the settings of the UPFC depend on the integration rate of the renewable power. Compared to the base case, the objective functions *VD* and P_{loss} are reduced for all levels of intermittency RES. Moreover, it can also be concluded that the effect of RES intermittency on the system performance is also significantly controlled by the UPFC controls by having reduced losses and improved voltage profile in all cases. This is clearly shown by voltage profile presented by Fig. 11, 12 and system losses depicted in Fig. 13, 14.

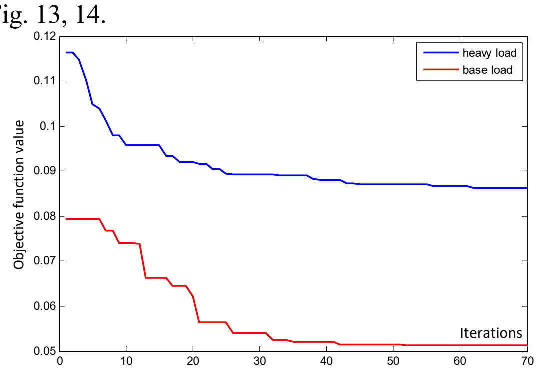

Fig. 10. Convergence performance for heavy load

Table 4

Optimization solution by WOA considering RES

Case	Base load (100 %)			Heavy load (130 %)		
Case	Line #34	Line #7	Line #7	Line #34	Line #7	Line #7
Variable	LSI based location	LLI based location	WOA based location	LSI based location	LLI based location	WOA based location
V_1	1.0599	1.0472	0.9982	1.1	1.0503	1.0511
V_2	1.0776	1.1	0.95	1.1	1.1	1.1
V_5	1.0252	1.009	0.95	1.0693	1.0031	1.0069
V_8	1.0595	1.0299	1.045	0.9843	1.0737	1.0532
V_{11}	0.9937	0.9551	1.0402	1.1	0.9500	0.9500
V_{13}	0.9831	1.0166	0.9507	1.0906	0.9679	0.95
a_{11}	1.0655	0.9872	10972	1.1	0.9776	1.0956
a_{12}	1.0738	1.0849	0.9	1.0077	1.1	0.9294
a_{15}	0.9629	1.0108	0.9234	1.0575	0.9614	0.9366
a_{36}	0.9563	0.9874	0.9728	1.1	0.9897	0.9873
V_{se}	0.1330	0.2311	0.2790	0.2203	0.3	0.3
δ_{se}	3.7511	0	0	3.4186	6.2832	0
I_q	–0.1058	–0.1447	0.15	0.15	–0.15	0.15
$r_{int,wind}$	0.9287	0.4854	0.3997	0.8524	0.7595	0.6039
$r_{int,solar}$	0.7920	0.3881	0.1402	0.9453	0.6983	0.7226
P_{loss}	0.1168	0.0461	0.0491	0.2004	0.0789	0.0771
VD	0.0069	0.0071	0.0023	0.0178	0.0074	0.0083
$\sum LSI$	1.5310	1.2192	1.2355	2.0247	1.4287	1.4920
$\sum LLI$	8.0148	4.5651	4.8779	14.5057	7.4804	7.5613

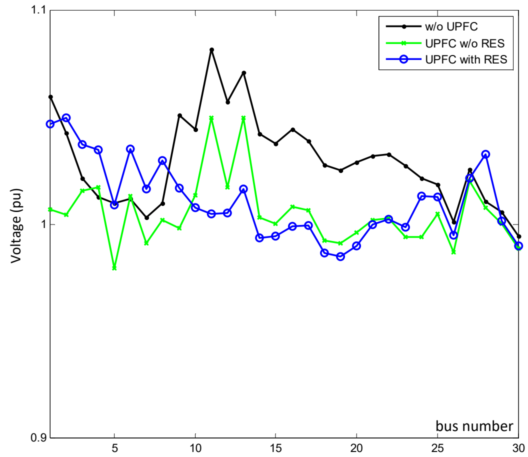

Fig. 11. Voltage profile under normal loading condition with RES

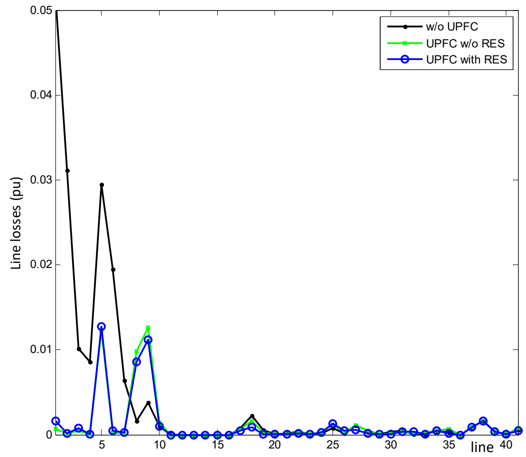

Fig. 13. Line losses under normal loading condition with RES

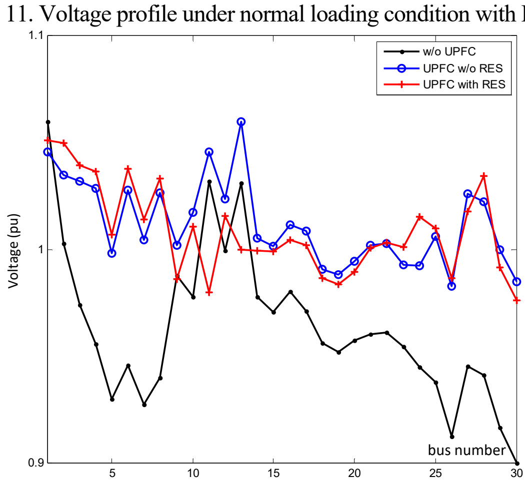

Fig. 12. Voltage profile under heavy loading condition with RES

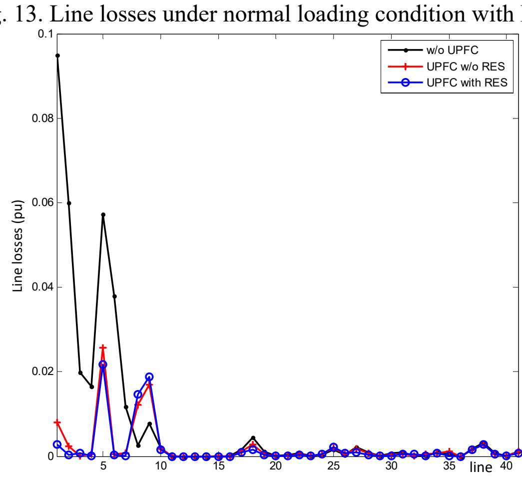

Fig. 14. Line losses under heavy loading condition with RES

Conclusions. In this work, a methodology was presented to evaluate the WOA meta-heuristic for the allocation of UPFC in electrical power systems where the penetration of renewable energy sources (RES) and their intermittency are considered. The location of UPFC device is determined by using line stability index (LSI) and line loading index (LLI) with combination of the meta-heuristic technique. The simulation studies on standard 30-bus system highlighted the effectiveness of the search process for the solution of the allocation problem of UPFC by providing improved voltage profile and reduced losses. The parameters involved in the optimization problem are optimized using WOA algorithm towards improved performance system. Indeed, the results showed that using the UPFC at optimal location in the network yields a significant reduction in power loss and minimization of voltage deviation while satisfying the network equality and inequality constraints.

On the other side, as power systems become more complex with deeper penetration of RES, the impact of RES uncertainty was also analyzed indicating a significant influence on the overall transmission loss and voltage profile enhancements of the network. The performance of WOA was evaluated by comparison with PSO algorithm which indicates more efficiency.

Conflict of interest. The authors declare that they have no conflicts of interest.

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