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.

**Meta.** 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 вагітну енергетичну мережу збільшується, необхідно досліджувати їхню вплив на це. Наукові дослідження показали, що невизначеність ВДЕ у вироблені електроенергії впливає на реактивну потужність мережі енергосистеми і, отже, на її загальні втрати навіть при передачі. Новизна запропонованої роботи полягає в покращенні профілю напруги та мінімізації втрат активної потужності за рахунок обліку перемежування відповідних джерел енергії в мережі за рахунок оптимального розташування пристрою UPFC. Спроба розподілу пов'язує стаціонарний аналіз електричної мережі з розміщенням та налаштуванням параметрів контролера з використанням методу алгоритму оптимізації кита (WOA).

**Результати.** Для визначення розташування UPFC пропонується підход, зосереджений на виведенні лінії, яка є найбільш критичною та ефективною з точки зору підвищення безпеки за напругою, зменшення навантажень, а також прямих підходів до оптимізації. Оптимальне розташування UPFC в енергосистемі обумовлюється в цій статті з використанням індексу зацікавленості лінії, індексу стійкості лінії та методу оптимізації. Цільова функція виришується з використанням алгоритму WOA, а її продуктивність оцінюється шляхом порівняння з алгоритмом оптимізації розподілу (PSO).

**Результати.** Ефективність запропонованої методології розподілу переверена за допомогою аналізу моделювання, виконаного на тестовій системі стандартної номінальної IEEE 30 з урахуванням різних умов навантаження. Отримані результати демонструють, що за допомогою запропонованого підходу виходять здійснені та ефективні рішення, які можна використовувати для подолання проблем 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, переносність.
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](image1)

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):

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

(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](image2)

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

$$
\overrightarrow{V_i} = \overrightarrow{V_j} + \overrightarrow{V_{se}},
$$

(2)

$$
\text{Arg}(\overrightarrow{I_i}) = \text{Arg}(\overrightarrow{V_i}) \pm \frac{\pi}{2},
$$

(3)
absorbed by the shunt converter.

The shunt current of UPFC is

\[
\bar{I}_{sh} = I_p + jI_q .
\]

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

\[
\bar{S}_{ij} = P_{ij} + jQ_{ij} = \bar{V}_{i} \cdot \bar{I}_{j^*} = \bar{V}_{j} \cdot \bar{I}_{i^*} = \bar{V}_{j} \left( jV_r \frac{b}{2} + I_p + jI_q + \bar{I}_i \right) ;
\]

\[
\bar{S}_{ji} = P_{ji} + jQ_{ji} = \bar{V}_{j} \cdot \bar{I}_{i^*} = \bar{V}_{i} \left( jV_r \frac{b}{2} + I_p + jI_q + \bar{I}_j \right) .
\]

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

\[
P_{ij} = \left| V_{ij} \right|^2 \frac{b}{2} + V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
P_{ji} = \left| V_{ij} \right|^2 \frac{b}{2} + V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
Q_{ij} = -V_{ij} I_q - V_{ij} \left( b_j + \frac{b}{2} \right) - V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
Q_{ji} = -V_{ij} I_q - V_{ij} \left( b_j + \frac{b}{2} \right) - V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

where:

\[
g_{ij} \equiv \frac{1}{r_{ij} + jx_{ij}} ,
\]

\[
r_{ij} \] 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:

\[
P_{ij} = V_{ij}^2 g_{ij} - V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
P_{ji} = V_{ij}^2 g_{ij} - V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
Q_{ij} = -V_{ij}^2 \left( b_j + \frac{b}{2} \right) - V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
Q_{ji} = -V_{ij}^2 \left( b_j + \frac{b}{2} \right) - V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right).
\]

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

\[
P_{ij}^{UPFC} = V_{ij}^2 g_{ij} - 2V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
P_{ji}^{UPFC} = V_{ij}^2 g_{ij} - 2V_{ij} \left( V_{ij} \frac{b}{2} + V_{ij} c_{ij} \right) + V_{ij} g_{ij} c_{ij} \sin \left( \delta_{ij} - \delta_{ij} \right) - V_{ij} V_{ij} c_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
Q_{ij}^{UPFC} = V_{ij}^2 g_{ij} \left( \delta_{ij} - \delta_{ij} \right) + V_{ij} g_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right);
\]

\[
Q_{ji}^{UPFC} = V_{ij}^2 g_{ij} \left( \delta_{ij} - \delta_{ij} \right) + V_{ij} g_{ij} \cos \left( \delta_{ij} - \delta_{ij} \right).
\]

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

\[
\Delta P = \begin{bmatrix} H_{new} & N_{new} \end{bmatrix} \Delta V \]

\[
\Delta Q = \begin{bmatrix} M_{new} & L_{new} \end{bmatrix} \Delta V .
\]

\[\text{where the new error vectors are}\]

\[
\Delta P = P_{ij}^{spec} + P_{ij}^{UPFC} - P_{ij}^{calc} ;
\]

\[
\Delta Q = Q_{ij}^{spec} + Q_{ij}^{UPFC} - Q_{ij}^{calc} ,
\]

where \(P_{ij}^{spec}\) and \(Q_{ij}^{spec}\) are the classical specified powers; \(P_{ij}^{UPFC}\) and \(Q_{ij}^{UPFC}\) are the power injection associated to the UPFC device; \(P_{ij}^{calc}\) and \(Q_{ij}^{calc}\) 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:

\[
H_{new} = H + \frac{\partial P_{ij}^{UPFC}}{\partial \delta} ;
\]

\[
M_{new} = M + \frac{\partial Q_{ij}^{UPFC}}{\partial \delta} ;
\]

\[
N_{new} = N + \frac{\partial Q_{ij}^{UPFC}}{\partial \delta} ;
\]

\[
L_{new} = L + \frac{\partial Q_{ij}^{UPFC}}{\partial \delta} .
\]

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]

$$LSI_{ij} = \frac{4x_{ij}Q_{ij}}{V_{ij}^2 \sin^2(\delta_i - \delta_j)} \leq 1,$$  

(29)

where $Q_{ij}$ is the reactive power flow in line $i-j$ and $\theta_{ij}$ 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]

$$LLI_{ij} = \left( \frac{S_{ij}}{S_{ij}^{max}} \right)^2,$$  

(30)

where $LLI_{ij}$ is the line loading index of the line; $S_{ij}$ is the actual MVA rating of the line; $S_{ij}^{max}$ 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:

$$P_{loss} = \sum_{k=1}^{nl} g_k \left( \frac{1}{2} V_k^2 + V_j^2 - 2V_kV_j \cos(\delta_i - \delta_j) \right),$$  

(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:

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

(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

$$F = w_1 P_{loss} + w_2 VD,$$  

(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 \((0 \leq r_{int,i} \leq 1)\) to simulate intermittency of this power source.

The power generation at a RES bus is then

\[
P_{\text{res},i} = r_{int,i} P_{\text{res},i}^{\text{max}}, \tag{34}
\]

where \( P_{\text{res},i}^{\text{max}} \) 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

\[
r_{\text{int}} = \sum_i P_{\text{res},i}^{\text{max}}. \tag{35}
\]

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 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 except UPFC incident buses.

\[
P_{Gi} - P_{Di} - P_{\delta,i} = 0, \tag{36}
\]

\[
Q_{Gi} - Q_{Di} - Q_{\delta,i} = 0, \tag{37}
\]

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:

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

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

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

\[
P_i = P_{Gi} + r_{int} P_{Gi,r} - P_{Di}, \tag{40}
\]

\[
Q_i = Q_{Gi} + r_{int} Q_{Gi,r} - Q_{Di}, \tag{41}
\]

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,

\[
P_i = P_{Gi} - (P_{Di} + P_{nadj,i}), \tag{42}
\]

\[
Q_i = Q_{Gi} - (Q_{Di} + Q_{nadj,i}), \tag{43}
\]

where \( P_{nadj} \) and \( Q_{nadj} \) 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:**

\[
P_{\text{Gmin}} \leq P_G \leq P_{\text{Gmax}}. \tag{44}
\]

- **Reactive power generation limits:**

\[
Q_{\text{Gmin}} \leq Q_G \leq Q_{\text{Gmax}}. \tag{45}
\]

- **Bus voltage limits:**

\[
V_{\text{min}} \leq V_i \leq V_{\text{max}}. \tag{46}
\]

- **Bus voltage phase angle limits:**

\[
\delta_{\text{min}} \leq \delta_i \leq \delta_{\text{max}}. \tag{47}
\]

- **Tap-changers limits:**

\[
a_{\text{min}} \leq a_i \leq a_{\text{max}}. \tag{48}
\]

- **Line power flow limits:**

\[
S_i \leq S_{\text{max}}. \tag{49}
\]

**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:

\[
\hat{X} = \bar{X} + \bar{X}_{\text{rand}} - \bar{X}_r; \tag{50}
\]
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:

$$A = 2a \cdot r - a; \quad (52)$$

$$C = 2 \cdot r, \quad (53)$$

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:

$$\overrightarrow{D} = \left| C \cdot \overrightarrow{X} - \overrightarrow{X}_t \right|; \quad (54)$$

$$\overrightarrow{X}_{t+1} = \overrightarrow{X}_t - A \cdot \overrightarrow{D}, \quad (55)$$

where $\overrightarrow{X}$ 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:

$$\overrightarrow{D} = \left| \overrightarrow{X} - \overrightarrow{X}_t \right|; \quad (56)$$

$$\overrightarrow{X}_{t+1} = \overrightarrow{D} \cdot e^{bl} \cdot \cos(2\pi t) + \overrightarrow{X}, \quad (57)$$

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

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.

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 9.9744 from 16.5231.

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.

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 $r_{int}$ ($0 \leq r_{int} \leq 1$), 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 $V_D$ and $P_{loss}$ for IEEE 30-bus system under different RES intermittency conditions is shown in 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 $V_D$ 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.
### Table 4

<table>
<thead>
<tr>
<th>Case</th>
<th>Line #34</th>
<th>Line #7</th>
<th>Line #7</th>
<th>Line #34</th>
<th>Line #7</th>
<th>Line #7</th>
</tr>
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<tbody>
<tr>
<td>Variable</td>
<td>LSI based location</td>
<td>LLI based location</td>
<td>WOA based location</td>
<td>LSI based location</td>
<td>LLI based location</td>
<td>WOA based location</td>
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<td>$V_1$</td>
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<td>1.0472</td>
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<td>$V_2$</td>
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<td>1.1</td>
<td>1.0069</td>
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<tr>
<td>$V_6$</td>
<td>1.0595</td>
<td>1.0299</td>
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<td>0.9843</td>
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<tr>
<td>$V_{11}$</td>
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<td>0.9551</td>
<td>1.0402</td>
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<td>$V_{13}$</td>
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<td>0.9679</td>
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<td>$a_{11}$</td>
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<td>10972</td>
<td>1.1</td>
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<td>$a_{12}$</td>
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<td>0</td>
<td>3.4186</td>
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<tr>
<td>$L_e$</td>
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<td>-0.15</td>
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<td>$I_{bus,wind}$</td>
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<td>0.4854</td>
<td>0.3997</td>
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<td>$I_{bus,solar}$</td>
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<tr>
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<td>0.0491</td>
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<td>0.0789</td>
<td>0.0771</td>
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<tr>
<td>$VD$</td>
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<td>0.0071</td>
<td>0.0023</td>
<td>0.0178</td>
<td>0.0074</td>
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<td>7.5613</td>
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</tbody>
</table>

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

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

**Fig. 13.** Line losses under normal 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...


