

Optimal Placement of FACTS Devices Based on Whale Optimization Algorithm for Power System Security Enhancement

H.Arul Devi, R. Kannan, S.Padma



Abstract: *The present-day power system is vulnerable to instability and security threats due to the continuously changing load pattern. To enhance the security of the power system and to avoid the electrical power system from collapsing, the condition of the system security has to be inspected by security analysis tools and it can be enhanced by the proper integration of FACTS devices into the network. This paper presents a methodology in which the security of the system can be analyzed with the help of an index called Line Overload Severity Index (LOSI). Unified Power Flow Controller (UPFC) is preferred to improve the security of the power system. Owing to the cost involved in placing UPFCs it is obligatory to use minimum number of devices, by optimally placing them in the network. It is obligatory to recognize an ideal location to install UPFC. Considering the Line overload Sensitivity Index, the optimal location identification for UPFC is done. The paper also presents the formulation of a new severity function using transmission line loadings. The severity function combines the objectives of reducing transmission line loadings and improvement of voltage profile during multi line contingencies. In the event of multi-line contingencies, the objective function for reducing the fuel cost and the severity function are analyzed. Optimal power flow method is followed to analyze the security of the electrical power system during contingency situations. This optimal location identification procedure and the OPF are solved using a metaheuristic technique, Whale Optimization Algorithm (WOA). The whole methodology that is proposed is experimented on a standard IEEE-30 bus test system.*

Keyword: *Contingency, Power system security, Severity function, Unified power flow controller, Whale optimization*

I. INTRODUCTION

The existing power grid is a more intricate, interconnected system due to hazardous increase in load demand and the continuously changing load pattern.

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The load will normally be unevenly distributed and it affects the voltage profile which may make the system security more vulnerable. The condition even worsens during contingencies.

So, in recent days, operating and controlling the power system has become one of the challenging tasks to sustain the reliability and continuity of the supply. The security of the system should be examined to evade unrestrained conditions such as overloading of lines, violations in bus voltages, and the extreme case of system collapse. Adding new infrastructure like installing new transmission lines and increasing power generation capabilities by inclusion of new generating units are restricted to technical and economical boundaries. So, the most preferable solution is to exaggerate the capabilities of existing power system infrastructure and generating capacities by the incorporation of FACTS devices into the network. The integration of FACTS devices is the best substitute for improving the performance of the electrical power system by enhancing the voltage profile, improving the power transfer capability and reducing the losses.

The applications of FACTS devices includes the enhancement of power transferring capacity of transmission line and regulation of different parameters in transmission network like line voltage, line current, line impedance and phase angle. The power flow can be made flexible or controllable with the help of the FACTS devices. FACTS devices aids in increasing the network's loadability by decreasing the flow of apparent power in the overloaded lines. Because of this the transmission line losses can also be reduced. FACTS devices are capable of tackling voltage collapse issues and system security improvement. Congestion management can be easily handled by the usage of such devices. The power system easily accommodates the changes that will occur with the addition of the FACTS devices. For upgrading the system performance and improving economic benefits, optimally locating FACTS devices and settings the parameters of the controllers is very essential.

To evade uninhibited conditions such as overloading of lines, violation of bus voltages and system collapse the analysis of system security is mandatory [1]. Since the power system operating conditions continuously changes dynamic security analysis is essential in finding the condition of the system.[3]. It can be analyzed based on loading of transmission lines and variations of bus voltages. The security constraints combined with Optimal Power Flow (OPF) can resolve this problem.[1].

FACTS devices perform a vital part in Demand Side Management (DSM) and by this means controls the transmission line congestion.

Integration of the FACTS devices boosts the desirable parameters of the power system like bus voltage magnitudes, apparent power flow in lines and diminishes the overall system losses [4-7]. The chore of security augmentation can be verbalized as a problem with multiple objectives. The numerous objectives considered are minimization of fuel cost and the cost involved in installing UPFC [2-3][15].

The UPFC can be designed as a power injection device. The device thus modelled includes both series injection branch and shunt injection branch. A power injection model is used for portraying the UPFC in load flow analysis [9-10,13,14]. Several metaheuristic and hybrid algorithms reported in [1-2] [4-6] are used for solving optimal power flow problems in the existence of FACTS devices in the electrical power system. Among the optimization techniques available the WOA's performance is better than the state-of-the-art meta-heuristic and conventional algorithms [11,12].

II. POWER SYSTEM SECURITY

The main goal of power system control operation is to meet the demand reliably without any interruptions. During this operation, sometimes the outage of transmission lines due to natural calamities or intentional removal of the line maintenance or outage of any generating unit because of failure of supporting devices may happen. The operating frequency of the power system might get affected and may lead to shedding of loads or unrestrained operation. This might sometimes end up in the complete collapse of the power system or complete blackout. This normally happens at the load buses as result of overloading in transmission lines, deviation in voltage and deficit of reactive power support.

When operating power system, a factor has to be considered relating to the security of then power system and involved in designing the power system to sustain the system's security during various contingency conditions. In general, when there is a transmission line outage or generator outage some of the remaining transmission lines might get overloaded and at some load buses the magnitude of voltages may get violated from their limits. So, the minimization of system severity and analysis of system condition is necessary in enhancing the security of the system. In this paper, an index called LOSI (Line Overload Sensitivity Index) defined in Equation 2.1[4] is used to identify the most critical line in a given system.

The anticipated LOSI is assessed for each transmission line when a contingency occurs. The value of LOSI for the 'i'th transmission line is found by considering the additional apparent power flow in that line during 'Nc' number of contingencies. The numerical value of LOSI can be calculated using the formula given in Equation 2.1[4] under base load conditions

$$LOSI_i^{BL} = \sum_{N=1}^{Nc} \left(\frac{S_i^N}{S_i^{max}} \right) \quad (2.1) [4]$$

where S_i^N is the apparent power flow in 'i'th line during contingency and S_i^{max} is the maximum apparent power flow in the same line.

The optimum place for placing UPFC in the power system is selected such that the device can endure its controlled operation during different conditions of load. The

LOSI value of the system is evaluated under various load conditions like Base Load (BL), Increased Load (IL), and Decreased Load (DL). The increased load condition can be attained by increasing the real and reactive power values of the base load by 5%. The decreased load condition can be achieved by decreasing the same by 5%. The overall value of LOSI for the ith transmission line can be found using the expression

$$LOSI_i = \left(\frac{LOSI_i^{BL} + LOSI_i^{IL} + LOSI_i^{DL}}{3} \right) \quad (2.2) [1]$$

where $LOSI_i^{BL}, LOSI_i^{IL}, LOSI_i^{DL}$ are the LOSI values at base load, increased load and decreased load conditions.

The optimal location for UPFC device can be determined based on the LOSI value. The anticipated methodology is tested in a standard IEEE bus system.

III. MODELLING OF UPFC

The UPFC is one among the multipurpose FACTS devices available. In practical implementation the UPFC comprises of two voltage source converters, one connected in series ie. Converter-I and the another connected in parallel ie. Converter-II as shown in Figure 3.1. They are operated by a common DC link provided by a DC storage capacitor. The real power flow is facilitated by both shunt connected (STATCOM) and series connected (SSSC) output terminals. The Converter-II does the primary function of the UPFC .It injects a voltage with manageable voltage and phase angle via an insertion transformer. The reactive and real power exchange between the converter and transmission line to which it is connected is achieved as a result of the transmission line current that flows that flows through the converter [16]. The basic function of Converter-I is to supply or absorb the real power needed by Converter-II at the common DC link to support the real power exchange resulting from the injection of series voltage [16].

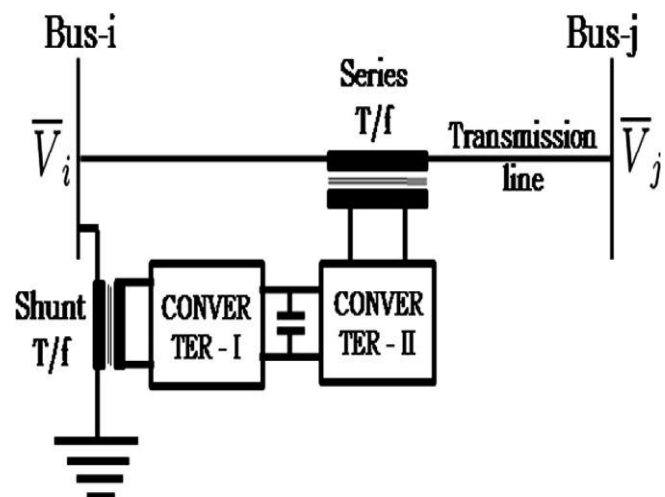


Fig. 3.1 Basic configuration of UPFC

The single line representation of UPFC as a combination of two governable voltage sources is depicted in Figure 3.2.

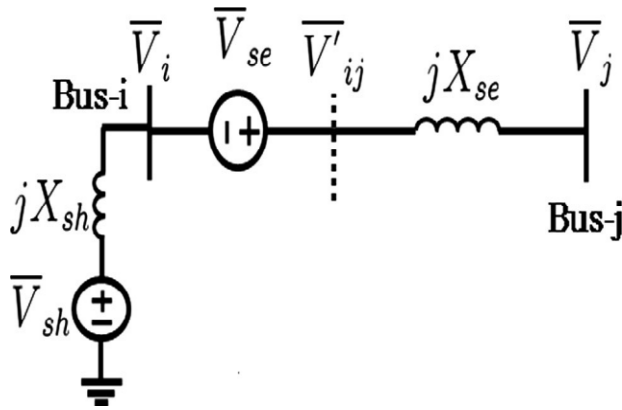


Fig. 3.2 Single Line diagram of UPFC

A pair of coupling transformers are used for controlling the magnitude and phase angles of the two voltage source converters. The series and shunt transformers are represented by their leakage reactances namely X_{se} and X_{sh} respectively. The UPFC can be incorporated into the power system via a transmission line connected in between two buses. Assuming that the UPFC is connected in a transmission line '1' which connects the two buses j and i . Let $V_i \angle \theta_{\delta_i}$ and $V_j \angle \theta_{\delta_j}$ be the magnitude of the bus voltages to which UPFC is connected

Let V_{se} be the controllable series voltage injected by converter-II.

V_{se} is expressed as, $\overline{V_{se}} = V_{se} \angle \theta_{se}$ (3.1)

Where V_{se} and θ_{se} are the magnitudes of voltage and the corresponding phase angles injected by the converter-II, expressed in per unit values. Their control limits of operation is given by

$$0 \leq V_{se} \leq V_{se}^{max}; \quad 0 \leq \theta_{se} \leq \theta_{se}^{max}; \quad (3.2)$$

The simplified model of UPFC can be attained by merging the series connected and shunt connected models of the voltage source injectors. The simplified model of UPFC is shown in Figure 3.3.

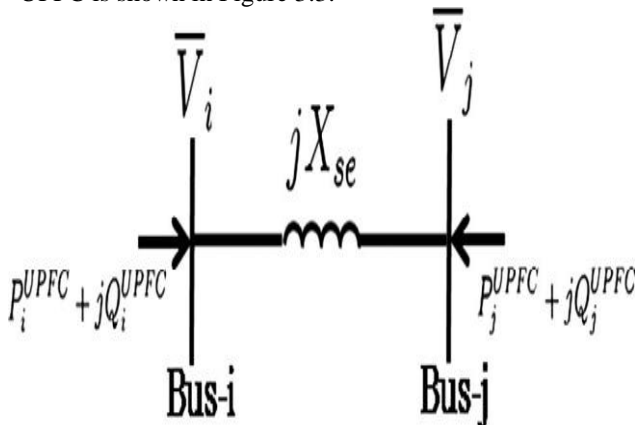


Fig. 3.3 Simplified UPFC model

The real and reactive powers injected at the buses to which UPFC is connected are given by the expressions,

$$P_i^{UPFC} = 0.02 V_i V_{se} B_{se} \sin(\theta_{se} - \delta_i) - 1.02 V_j V_{se} B_{se} \sin(\theta_{se} - \delta_j) \quad (3.3)$$

$$Q_i^{UPFC} = -V_i V_{se} B_{se} \cos(\delta_i - \theta_{se})$$

$$(3.4)$$

$$P_j^{UPFC} = -V_j V_{se} B_{se} \cos(\delta_j - \theta_{se})$$

$$(3.5)$$

$$Q_i^{UPFC} = -V_i V_{se} B_{se} \cos(\delta_i - \theta_{se})$$

$$(3.6)$$

The reduced mathematical model of UPFC must be integrated in the required system to investigate its impact on the system.

Since the insertion of UPFC into the network has notable effect on the real and reactive power, the Jacobian matrix used in Newton-Ramphson load flow methods has to be updated, considering also the power mismatch equations of the buses where UPFC is connected. The performance equation of the modified network is expressed as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} + \begin{bmatrix} P_{UPFC} \\ Q_{UPFC} \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} + \begin{bmatrix} H_{UPFC} & N_{UPFC} \\ J_{UPFC} & L_{UPFC} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (3.7)$$

While conducting load flow using NR method the inclusion of the above model may result in improved results predicting the effects of UPFC in the system.

IV. WHALE OPTIMIZATION ALGORITHM

The methodology proposed in this thesis for solving the optimum location identification problem and OPF is Whale Optimization Algorithm.

The WOA is a nature inspired meta-heuristic algorithm that is proposed by Seyedali Mirjalili and Andrew Lewis in the year 2016. This algorithm imitates the communal behavior of one of the intelligent species of whale called Hump back whales.

Whales are the largest mammals in the earth which never sleeps. There are seven species of whales in the world among which the hump-back whales are considered the most intelligent one with emotions.

They have a special kind of cells called spindle cells in their brain similar to that of humans. Scientific researches have proved that whales can think, learn, judge, communicate, and become even emotional as humans do, but perceptibly with a much lower level of smartness.

Whales can develop their own dialect, which is a particular form of peculiar communication linguistic to remain interconnect among their specific group.

The utmost exciting thing about the humpback whales is their unique hunting method. Their rummaging behavior is called bubble-net feeding method.

Humpback whales normally craves to hunt schools of small fishes adjacent to the water surface. Researchers have observed that this rummaging is done by creating distinctive bubbles along a circle or '9'-shaped path as shown in Fig. 4.1. This rummaging is done by forming typical bubbles along a circle or '9'-shaped path as shown in Figure 4.1.

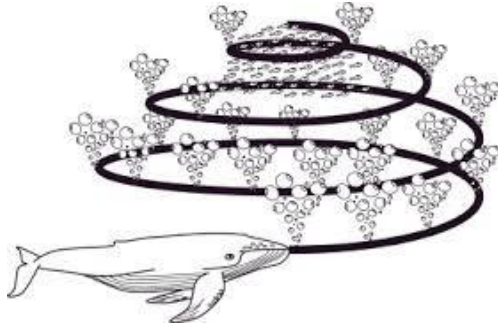


Fig. 4.1 Bubble-net hunting strategy of humpback whales

The bubble-net hunting technique is an exclusive talent of the HUMP back whales. This hunting mechanism can be mathematically modeled and optimized. The hunting mechanism of whales involve three distinct steps namely

A. Encircling the Prey

The humpback whales can identify position of the prey and the circle them. The WOA algorithm adopts the current solution as the best solution i.e. the prey which is the target or the prey which is near the optimal one. After defining the best search agents, the remaining agents will attempt to update their position targeting the best search agent. This behavior is verbalized as:

$$\vec{D} = |\vec{C} \cdot \vec{X}^*(t) - \vec{X}(t)| \quad (4.1)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D} \quad (4.2)$$

where t denotes the current iteration, \vec{A} and \vec{C} are the coefficient vectors, X^* is the position vector of the best solution obtained so far, \vec{X} is the position vector, $||$ is the absolute value, and \cdot is an element-by-element multiplication. It is worth mentioning here that in each iteration X^* should be updated, if there is possibility of getting a better solution. The vectors \vec{A} and \vec{C} are calculated as:

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \quad (4.3)$$

$$\vec{C} = 2 \cdot \vec{r} \quad (4.4)$$

where \vec{a} can be gradually reduced to 0 from 2 during the progress of iterations in all the phases and \vec{r} is a random vector in $[0,1]$.

The Humpback whales also assault the preys with bubble net hunting strategy. This strategy is mathematically formulated as follows.

B. Bubble Net Attacking Method (Exploitation Phase)

The bubble net behaviour of humpback whales can be formulated mathematically by using the two approaches:

(i) Shrinking encircling mechanism: Here, the value of \vec{a} is decreased in (4.3). Also, the variation range of \vec{A} is also decreased by \vec{a} . The current position of the search agent can be updated to a new position that can be defined anywhere between the actual position and the position of the current best agent. This can be achieved by randomly setting the values for \vec{A} in $[-1,1]$.

(ii) Spiral updating position: Here, firstly, the separation between the whale and the prey located at (X, Y) and (X^*, Y^*) , respectively, is calculated. A spiral equation is then created between the position of whale and prey as follows

$$\vec{X}(t+1) = \vec{D} \cdot e^{bl} \cos(2\pi l) + \vec{X}^*(t) \quad (4.5)$$

where $\vec{D} = |\vec{X}^*(t) - \vec{X}(t)|$ and specifies the distance between the i^{th} whale and the target prey (current best solution), b is a constant that defines the logarithmic shape of the spiral, and l is an arbitrary number in the range $[-1,1]$.

It has to be noted that humpback whales will move towards the prey by means of shrinking the circle and along a spiral-shaped path at the same time. To model this simultaneous behaviour, it is assumed that there is a likelihood of 50% to choose between either the shrinking encircling mechanism or the spiral model for updating the whales' position during optimization. The precise model is as follows:

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A} \cdot \vec{D} & \text{if } p < 0.5 \\ \vec{D} \cdot e^{bl} \cos(2\pi l) + \vec{X}^*(t) & \text{if } p \geq 0.5 \end{cases} \quad (4.6)$$

where p is a random number in $[0,1]$.

C. Search for Prey (Exploration Phase)

In this case, \vec{A} is used with the arbitrary values that lies between $+1$ and -1 to trigger the search agent to move far away from the whale that is considered as a reference. This practice and $|\vec{A}| > 1$ stress the exploration and allows the WOA to perform a global search. The mathematical model is given by:

$$\vec{D} = |\vec{C} \cdot \vec{X}_{rand} - \vec{X}| \quad (4.7)$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A} \cdot \vec{D} \quad (4.8)$$

where \vec{X}_{rand} is a random position vector (a random whale) selected from the existing population.

V. PROBLEM FORMULATION

5.1 OPF PROBLEM FORMULATION

OPF provides the remedy for power flow problems by properly setting the control parameters of the electrical power system in order to meet the demand by optimizing the objective functions that are predefined. While optimizing the objective function the system constraints should also be satisfied. An elementary form of this OPF will normally be articulated as

$$\begin{aligned} &\text{Minimize/maximize } J(x, u) \\ &\text{subjected to } g(x, u) = 0; h(x, u) \leq 0 \quad [1] \end{aligned} \quad (5.1)$$

Where g - the set of equality constraints to be satisfied

h - the set of inequality constraints to be satisfied. ' g ' and ' h ' are formulated based on a list of dependent and independent variables.

The dependent variables are active and reactive power generation at the slack and load buses respectively ($P_{g \text{ slack}}$ and Q_G).

The load bus voltage magnitudes (V_L) are also the dependent variables. The power flow in transmission lines coined as a state vector (X) is also considered.

The independent variables are active power generation at all the generator buses excluding the slack bus (P_G). The magnitude of voltage at all the generator buses (V_G), tap settings of the tap-changing transformers (T) and a control vector (u) introduced by the reactive power injected by the shunt compensators (Q_{sh}).

All the combined expressions can be summarized as

$$uT = [P_{G2}, \dots, P_{GN_G}, V_{G1}, \dots, V_{GN_G}, Q_{sh1}, \dots, Q_{shN_G}, T_1, \dots, T_{NT}]$$

$$xT = [P_{G1}, V_{L1}, \dots, V_{LN_L}, Q_{G1}, \dots, Q_{GN_G}, S_{L1}, \dots, S_{L_{nl}}]$$

Here, ' N_G ', ' N_C ', ' N_T ', ' N_L ' and ' nl ' are the total number of generators, total number of shunt compensators, total number of tap-changing transformers, number of load buses and number of transmission lines respectively.

5.2 OBJECTIVES FORMULATION

To verify the efficiency of the anticipated OPF the objective for reducing the fuel cost for generation and the severity functions for the system are combined in to a single function. The corresponding expressions for the objectives that are considered is given as follows.

5.2.1 Generation fuel cost

The cost of generation of electric power is also significant while meeting required power demand. The cost of generation must be minimized for meeting the demand economically. Considering this the reduction of fuel cost is also included as one of the functions to be optimized in to the OPF. While optimizing this functions the system constraints should also be satisfied. The generators cost characteristics is given by the following expression

$$J_{cost} = \sum_{i=1}^{N_G} (a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \text{ \$/hr} \quad (5.2)$$

where a_i , b_i and c_i are the fuel cost coefficients, and P_{Gi} is the active power generation at bus- i .

5.2.2 System severity function

In recent day power system the demand is increasing day by day. With such increased demands, the operation and control of the system is becoming more and more complicated. Among the various system parameters to be controlled the apparent power flow in transmission lines and the deviation in bus voltage magnitudes are more significant. So the severity function that is proposed is framed by considering these two parameters. The function thus verbalized is given by

$$J_{severity} = W_1 \sum_{i=1}^{nl} \left(\frac{S_i}{S_i^{max}} \right)^{2m} + W_v \sum_{i=1}^{N_{bus}} \left(\frac{V_i^{ref} - V_i}{V_i^{ref}} \right)^{2n} \quad (5.3)$$

where W_1 and W_v are the weight coefficients related to line loadings and bus voltage violations. The sum of the values of W_1 and W_v should be unity. The values for W_1 and W_v are chosen based on which parameter is given more preference.

S_i -actual power flow in the i^{th} line.

S_{imax} -The maximum power transfer limit of the i^{th} line.

V_j -Actual voltage at the j^{th} line.

V_{jref} -reference value of voltage magnitudes at the j^{th} bus.

' m ' and ' n ' are the coefficients used to penalize the over loadings of lines and violations in bus voltages. Here the values of both coefficients are considered as 2.

5.2.3 Multi-objective function

The Multi Objective Optimal Power Flow problem is verbalized by combining the fuel cost of generating units and severity function of the system. The corresponding mathematical expression is given by:

$$J_{objective} = (W_1 \times J_{cost}) + (W_2 \times J_{severity}) \quad (5.4)$$

where J_{cost} - generation fuel cost

$J_{severity}$ -power system severity function

W_1 and W_2 -Weights allocated to the objective function.

5.3 CONSTRAINTS

The OPF problem formulated is resolved by satisfying a set of constraints namely equality constraints, security constraints and UPFC limits.

5.3.1 Equality constraints

These constraints are nothing but the load flow equations that are solved and fulfilled in traditional load flow method. The active and reactive power balance expressions in load flow can be given as

$$P_{Gi} - P_{Di} = \sum_{j=1}^{N_{bus}} |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (5.5)$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{N_{bus}} |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (5.6)$$

where P_{Gi} , Q_{Gi} -Active and reactive power generations at i^{th} bus

P_{Di} , Q_{Di} -the active and reactive power demand at i^{th} bus

N_{bus} - the total number of buses

$|Y_{ij}|$ and θ_{ij} - the measure of the bus admittance and its angle between j^{th} and i^{th} buses.

5.3.2 Security constraints

- Power limits in transmission lines:

$$S_{ii} \leq S_{ii}^{max}, i \in nl \quad (5.7)$$

- Load bus voltage magnitude limits:

$$V_i^{min} \leq V_i \leq V_i^{max}, i \in NL \quad (5.8)$$

5.3.3 Limits of the UPFC device used.

The voltage, angle, impedance and reactive power limits of the device is given by

$$\begin{aligned} 0 &\leq V_{se} \leq V_{se}^{max}; \\ 0 &\leq \theta_{se} \leq \theta_{se}^{max}; \\ 0 &\leq X_{se} \leq X_{se}^{max}; \\ 0 &\leq Q_{ish} \leq Q_{ish}^{max} \end{aligned} \quad (5.9)$$

Here Q_{ish}^{max} , X_{se}^{max} , V_{se}^{max} , θ_{se}^{max} , are considered to be 0.1P.P., 0.1P.U., 0.1P.U. and 360 degrees respectively.

VI. PROPOSED WORK IMPLEMENTATION

The problem implementation involves the calculation of various line loadings during multiple line outage contingencies, the optimal placement of UPFC in the severely affected lines and the analysis of system security in the presence of UPFC.

The steps are given below.

STEPS INVOLVED IN PROPOSED WORK IMPLEMENTATION

Step 1: Read the line data, bus data & tolerance of convergence.

Step 2: The Newton–Raphson load flow procedure is run and bus voltages and line flows are obtained.

Step 3: Simulate contingency in Kth line, where K=1 to nl and calculate the line loading and load voltage deviations.

Step 4: Calculate Line Overload Sensitivity Index (LOSI) value of the system.

Step 5: Determine the real and reactive power limits of the UPFC device to be used.

Step 6: Read the whale optimization parameters and constants.

Step 7: Find the optimum location of UPFC based on LOSI values.

Step 8: Run the load flow after optimally placing UPFC to determine the line loading and load voltage deviations.

Step 9: The multi-objective severity function is optimized using WOA and also SCOPF is run using WOA.

VII. RESULTS AND DISCUSSIONS

The proposed methodology is implemented in a standard IEEE 30 bus system which has 41 lines and 6 generators, for examining its effectiveness.

Initially various line contingencies are generated intentionally and the LOSI values for each line is calculated without placing UPFC. From the LOSI values obtained and the constraints of UPFC the ideal location for placing the UPFC has to be determined. From the Table 7.1 and Figure 7.1 it is recognized that the optimal place for fixing UPFC is line 1 which is connected between buses 1 and 2, since it has the highest value for LOSI. The UPFC is fixed considering bus 1 as common bus for UPFC converters I and II.

The same procedure of finding LOSI as described earlier is done after placing UPFC at optimal location. The values of

Table 7.1 LOSI Values with and without UPFC

LINE NO.	LOSI VALUES		LINE NO.	LOSI VALUES	
	WITH OUT UPFC	WITH UPFC		WITH OUT UPFC	WITH UPFC
1	38	32.8	22	18.4	15.6
2	21.2	14	23	12.9	8.1
3	22.6	15.5	24	12.6	7.9
4	20.5	14.2	25	12.3	9.1
5	21	16	26	12.8	7
6	29.1	22	27	24.6	20.5
7	25.3	19.5	28	13.8	9.5
8	11.6	4.2	29	6.7	3.1
9	10.2	8.5	30	17.2	13.8
10	21.1	17.2	31	18.2	12.8
11	13.5	8.9	32	12.3	8.2
12	12.5	7.2	33	8	3.2
13	16.4	12.1	34	12.9	7.5
14	19.9	17.2	35	12.5	7.8
15	22.3	17.5	36	11.9	8.2
16	21.9	17.9	37	18.3	13.5
17	15.2	9.5	38	17.2	15.7
18	27.8	23.2	39	6.5	9.3
19	13.8	11.5	40	6.8	4.2
20	7.5	4.9	41	19.2	15.5
21	16.8	13.1			

LOSI calculated in the presence and absence of UPFC device is tabulated in Table 7.1

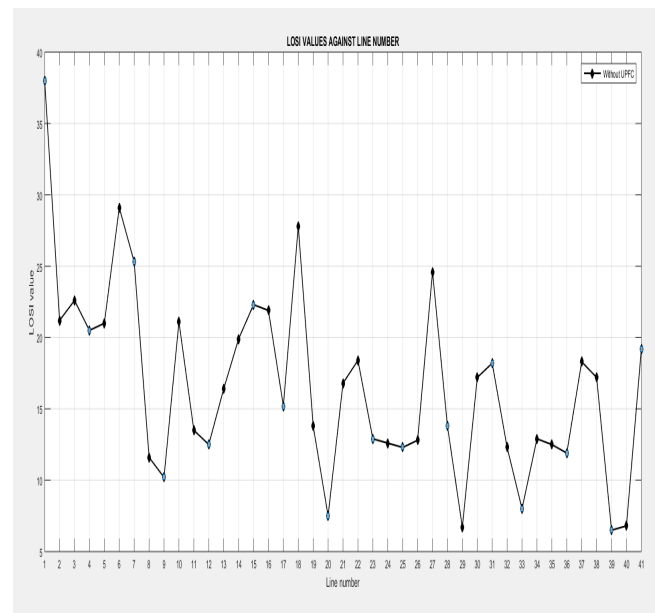


Fig.7.1 Variation of LOSI under Contingencies

The change in LOSI values before and after placing UPFC is plotted against the line number in Figure 7.2 and is clear that the value of LOSI has reduced after the placement of UPFC. The reduction in LOSI values predict that the overloading of the lines has been considerably reduced after placing UPFC.

The impact of UPFC on the parameters of the system like voltage magnitudes of buses, apparent power flow in the transmission lines, total power losses in the system are evaluated by changing the different controlling parameters.

The values of voltage magnitudes at all the buses during line contingency after placing UPFC is given in table 7.2. The variation of voltage magnitudes in all the thirty buses is depicted in figure 7.3

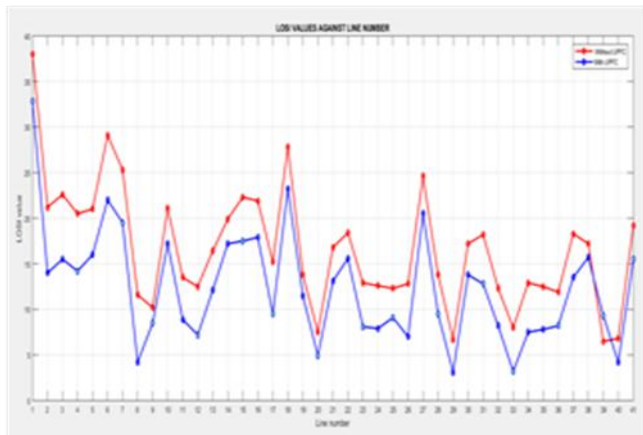


Fig. 7.2 Variation of LOSI with and without the presence of UPFC

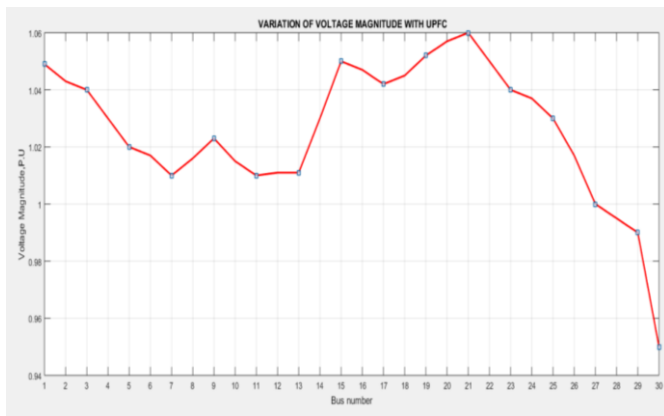


Fig. 7.3 Variation of bus voltage magnitudes with UPFC

From the Figure 7.3, it is recognized that the voltage magnitudes are well within the limits in the incidence of UPFC. The least voltage value is 0.95 P.U. at the 30th bus and the maximum voltage is 1.06 P.U. at the 21st bus.

The variation of net power flow in the lines after the optimum placement of UPFC is shown in Figure 7.4.

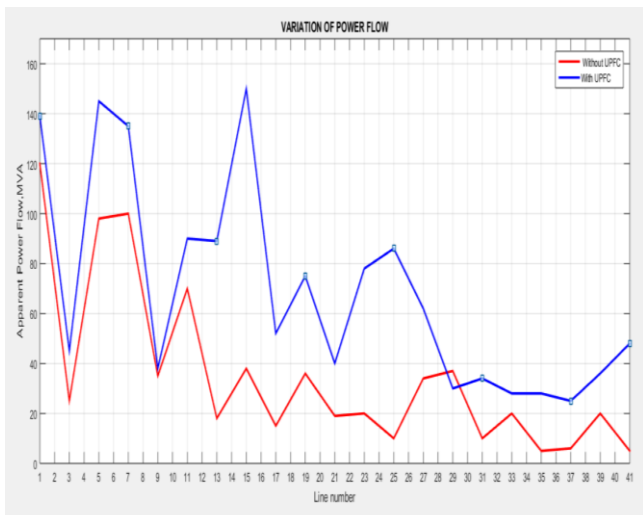


Fig.7.4 Variation of apparent power flow with UPFC

From the Figure 7.4, it is recognized that the apparent power flow has increased in the presence of UPFC which depicts that inclusion of UPFC has increased the power carrying capacity of the transmission lines. The difference in active power losses in the power system at different voltage levels is depicted in the Figure 7.5. From the Figure 7.5, it is recognized that the power losses are increased when the P.U. voltage levels vary from 0.05 to 0.1. It is also detected that the losses are minimum when the series voltage is at 0.05 P.U. and the phase angle is at 200°. Like wise the maximum losses occur at 280° when the series voltage is at 0.1 P.U.

From the above examination it is known that by means of controlling the device parameters desirable power system parameters can be controlled. That is it is resolved that when the control parameters of the device are optimally controlled then the benefits can be exaggerated to the maximum possible extent.

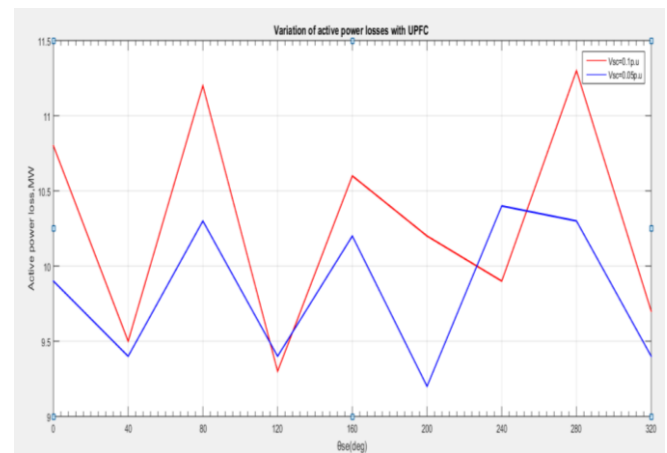


Fig.7.5 Variation of power losses with UPFC at different voltage levels.

Table 7.2 Voltage magnitudes at all the buses after placing UPFC

Bus No.	Voltage Magnitude in P.U	Bus No.	Voltage Magnitude in P.U
1	1.049	16	1.047
2	1.043	17	1.042
3	1.04	18	1.045
4	1.03	19	1.052
5	1.02	20	1.057
6	1.017	21	1.06
7	1.01	22	1.05
8	1.016	23	1.04
9	1.023	24	1.037
10	1.015	25	1.03
11	1.01	26	1.017
12	1.011	27	1
13	1.011	28	0.995
14	1.03	29	0.99
15	1.05	30	0.95

The Security Constrained Optimal Power Flow(SCOPF) results obtained using the proposed WOA considering the generation fuel cost under line contingencies is revealed in Table 7.3.

From this table 7.3 it is identified that the prescribed WOA algorithm the generation fuel cost is reduced by 0.105 \$/h when compared with the existing ITLBO.

Table 7.3 SCOPF results

S. No	Control parameters		During Line contingencies with UPFC		During line outages Without UPFC
			WOA	ITLBO	
1	Real power generation (MW)	PG1	179.6827	178.2065	129.7393
		PG2	49.4953	47.6668	65.2268
		PG5	24.325	21.237	25.3845
		PG8	23.6529	21.9448	35
		PG11	12.7052	11.6916	21.1808
		PG13	11.92	12	19.6162
2	Generator voltages (p.u)	VG1	1.07	1.07	1.07
		VG2	1.0645	1.0545	1.0589
		VG5	1.03	1.0215	1.0303
		VG8	1.037	1.0361	1.0635
		VG11	1.001	0.9927	1.0679
		VG13	1.0684	1.0548	1.0602
3	Total generation (MW)		301.7811	292.7467	296.1475
4	Generation fuel cost (\$/h)		801.4321	801.5371	844.0512
5	Total power losses (MW)		9.3299	9.3466	12.7475

From Table 7.3, it is evident that the total generation cost is considerably reduced by the presence of UPFC. Also the variation in total generation during these two conditions and the change in loss is also given in this table.

VIII. CONCLUSION

In this paper a new algorithm to analyse the power system security during multi line contingencies is presented To find the severity of system a new objective function considering the loading of transmission lines and aberration in bus voltage magnitude is formulated. A new optimization technique called WOA is recommended for cracking the OPF problem

coupled with the generation cost reduction objective. The OPF thus formulated is solved by taking the power system constraints into consideration. A voltage source power injection model of UPFC and its incorporation into the system , the method for solving load flow using NR method after incorporation of UPFC for improving the security of the system is described. Finally it is concluded that the power system security was evaluated during transmission line contingencies , the optimal power flow and security if the power system have improved in the existence of UPFC. The proposed methodology has been tested on standard IEEE-30 bus test system with supporting numerical as well as graphical results.

From the results obtained it is inferred that among the 41 lines in the system ,line -1 was heavily loaded when compared to other lines. After placing UPFC the value of LOSI has reduced from 38 to 32.8 , which indicates that the overloading of line-1 has been considerably reduced .The reduction in overloading of lines improves the overall security of the system. Similarly the bus voltage magnitudes are also maintained between a maximum of 1.06 P.U. at bus number 21 and a minimum of 0.95 P.U. at bus 30 even during contingencies which is highly desirable for maintaining voltage stability of the system. Similarly it is evident from the results that the apparent power flow in the lines has been improved and losses were considerably reduced. From the SCOPF results it is also inferred that the total generation has increased from 296.1475 MW to 301.7811 MW for the same amount of fuel which reduces the fuel cost by 42.5141 \$/h with the presence of UPFC.

Finally it is evident from the results that the overall system security has been enhanced and the multi objectives formulated are also achieved by optimally placing UPFC using WOA.

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