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Optimal Unified Power Quality Conditioner Allocation in Distribution Systems for Loss Minimization using Grey Wolf Optimization

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ABSTRACT
Compensation in power systems is essential to reduce the power loss and maintain the voltage profile. Reactive power compensation and voltage compensation are the different compensation techniques available in power systems. Series compensators aid to maintain the voltage profileby providing voltage compensation. Shunt compensators aid to reduce the power losses occurring in the networkby providing reactive power compensation. The functioning of series and shunt compensators are integrated in a device known as Unified Power Quality Conditioner (UPQC). This paper throws light on the loss reduction aspect of UPQC by determining the placement of UPQC using a single objective function of minimization of power losses. The voltage improvement aspect of UPQC is highlighted by determining the number of under voltage nodes in the network. The optimal location and rating of UPQC are obtained by Grey Wolf Optimization (GWO) method. UPQC is incorporated in Backward/Forward Sweep Load Flow method to determine the power flows in the branches and voltages at the nodes. MATLAB software is used to highlight the efficiency of the proposed device in two distribution systems.

***Keywords*–**Compensation, Grey Wolf Optimization (GWO), Power Loss, Unified Power Quality Conditioner (UPQC).

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I. INTRODUCTION

The primary objective of power system operation is efficiency. For efficient operation of power system the utility must take care of voltage limits and power losses in the network. Maintaining the voltage within the permissible limits is important on the part of the utilityfor the life of the equipment is mainly dependent on the voltage at which it is working. There are different devices to cope up with the problem of improving the voltage such as voltage regulators, series capacitors. The disadvantages with these devices are slow response and resonance. Static Series Voltage Regulator (SSVR) is a D-FACTS device used for improving the voltage in the distribution network. The effectiveness of SSVR to mitigate the problem of under voltage is illustrated in [1]. Reducing the power losses in the network is also important from the utility point of view. To accomplish this function shunt capacitors are used. Different techniques have been proposed to define the optimal locations and rating of capacitors with the aim of minimizing the power losses [2] -[4].The disadvantage with shunt capacitors is they cannot provide continuouslyvariable reactive power. The shunt D-FACTS device known as Distribution Static Compensator (DSTATCOM) also provides reactive power compensation to reduce the power losses. Different optimization methods have been proposed for optimal placement of D-STATCOM [5]. The functionality of series D-FACTS and shunt D-FACTS are provided by UPQC [6] -[10]. UPQC is a versatile D-FACTS device used for loss reduction and voltage improvement. The effectiveness of UPQC to improve the voltage in the distribution network is highlighted in [11]. The voltage improvement is specified with respect to Rate of Under Voltage Mitigated Nodes (RUVMN). RUVMN is defined as the percentage of nodes coming out of under voltage problem. Various optimization techniques have been proposed to define the optimal placement of UPQC [12] -[13]. In this paper, UPQC is applied to large distribution systems. The efficiency of UPQC is studied in terms of power loss reduction and voltage improvement. The mathematical expression for optimal placement of UPQC is given in Section II. Backward/ Forward sweep load flow method is adopted to determine the node voltages, phase angles, power injection at various buses in the network and power flows through the branches. The algorithm for load flow solution is detailed in Section III. The parameters to be modified in the load flow method are detailed in Section IV. For optimal placement of UPQC in radial distribution network, the optimization method adopted is Grey Wolf Optimization (GWO) method. GWO is inspired from the hunting behavior of grey wolves. GWO and the algorithm for optimal placement of UPQC are described in Section V. The performance of UPQC is estimated from the results described in Section VI. The conclusion is presented in Section VII.

II. PROBLEM FORMULATION

The problem of optimal placement of UPQC to provide voltage and reactive power compensation is dealt using GWO method. The objective function considered is minimization of power losses in the distribution network subjected to network operational constrictions. Mathematically the problem can be formulated as given in equation (1).

Minimization of

$$P_{TLoss} = \sum_{j=1}^{nb} P_{loss,j} \quad (1)$$

$$P_{loss,j} = \left((I_{branch,j})^2 . R_{branch,j}\right) \quad (2)$$

Here P_{TLoss} is the total real power loss occurring in the network, $P_{loss,j}$ is the real power loss in j[th] branch, nb is the number of branches in the network.

The network operational limitations are given as:

1. Voltage at each node in the network must be within the prescribed limits.
   $V_{min} \leq V_i \leq V_{max}$
2. The reactive power provided by UPQC at any node must not exceed the total reactive power demand on the network.
   $0 \leq Q_{UPQC} \leq Q_D$
3. The voltage at the optimal location is maintained at substation voltage.

III. LOAD FLOW METHOD

Load flows give the solution of the network under steady state conditions. Load flows are important in the design as well as in the operational phase. Load flow is an important tool to assess the system parameters. There are different load flow methods which have been reported in [14]-[15]. The load flow method adopted in this paper is Backward/Forward Sweep method. The algorithm for the load flow is detailed in the following steps.

3.1 <u>Algorithm for Backward/Forward Sweep load flow method:</u>

Step 1: Read the bus data and line data for the test distribution system.

Step 2: Set the voltages at all nodes to 1p.u. Assume epsilon (ϵ) as the convergence criteria and maximum iterations (max_iter).

Step 3: Set the iteration count (t) to one. Perform backward sweep to find the branch currents.

$$S_i = P_i + jQ_i \quad (3)$$

$$I_{Load,i} = \left(\frac{S_i}{V_i}\right)^* = \left(\frac{P_i + jQ_i}{V_i}\right)^* \quad (4)$$

$$I_{branch,j} = I_{Load,i} + \sum I_{Load,beyond\ node\ i} \quad (5)$$

Step 4: Perform forward sweep to find the nodal voltages.

$$V_L = V_S - (I_{branch,j} \times Z_{branch,j}) \quad (6)$$

Here V_L is the receiving end voltage of j[th] branch and V_S is the sending end voltage of j[th] branch.

Step 5: Check for the convergence criteria

$$\Delta V_i^{(t)} = \left|abs(V_i^t) - abs(V_i^{t-1})\right| \quad (7)$$

Here t is the iteration number.

If $\Delta V_i^{(t)} > \epsilon$ or iteration count< max_iter (8)

Increase the iteration count and repeat the steps from 3 to 5 else go to step 6.

Step 6: Evaluate the power loss as given in equation (1)

Step 7: Print the results for the load flow.

IV. MODELING OF UPQC

The series compensator is modeled as a voltage source and shunt compensator is modeled as the source of reactive power. Hence series compensator provides voltage compensation and shunt compensator provides reactive power compensation.

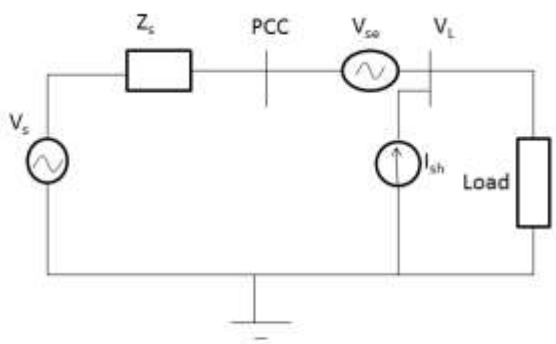

Fig 1: UPQC structure

Here V_s is the sending end voltage, Z_s is the source impedance, V_{se} is the voltage injected in series, V_L is the load voltage and I_{sh} is the shunt injecting current.

The series compensator injects voltage in series with the line at the receiving end node.

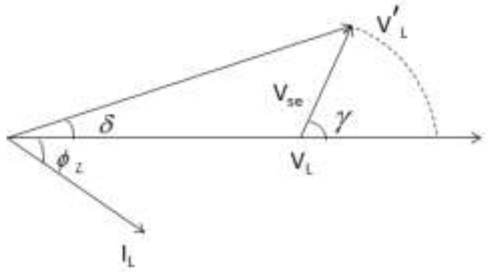

Fig 2: Phasor diagram for series voltage injection

The new load voltage obtained after injecting series voltage is computed by using equation (9).

$$V_L{}' \angle\ \delta = V_L + V_{se} \angle\ \gamma \quad (9)$$

The series power is obtained as follows:

$$S_{SE} = V_{se} * I^{*}_{branch} \quad (10)$$

Where S_{SE} is the complex power rating of series compensator.

V_{se} is the complex voltage injected by the series compensator.

I_{branch} is the branch current in which series compensator is included.

The shunt compensator provides reactive power as calculated by equation (11).

$$Q_{comp} = V_L^{'} I_c^{'} \quad (11)$$

$I_c^{'}$: Current flowing up to the branch in which series compensator is present. It is calculated as given in [16].

V. GREY WOLF OPTIMIZATION (GWO)

Grey Wolf optimization is a new Swarm Intelligence algorithm inspired by grey wolves proposed by Mirjalili et al. [17]. The behavior of the grey wolves is characterized by social hierarchy and hunting. These two phases are involved in Grey Wolf Optimization. Social hierarchy is a phenomenon in which the most powerful wolf guides the other wolves. The most powerful wolves are alpha, beta and delta wolves.

Muro et al., has classified grey wolf hunting into three categories (i) tracking, chasing, and approaching the prey, (ii) pursuing, encircling, and harassing the prey until it stops moving, and (iii) attacking towards the prey.

Grey wolf optimizationcontributes exploitation and exploration. Encircling the prey and attacking the prey are the two exploitation phases used to explore the optimal solution in a local search space. Exploration phase involves search for prey.In this phase, the grey wolves search for the prey in a global search space.

In encircling the prey, grey wolves recognize the location of theprey and encircle them. In this phase, the position vector of the prey is defined and other search agents adjust its position based on the best solution obtained. The equation of encircling prey is given in equation (12) and (13).

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_p}(t) - \vec{X}(t)\right| \quad (12)$$

$$\vec{X}(t+1) = \overrightarrow{X_p}(t) - \vec{A}.\vec{D} \quad (13)$$

Here t represents the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\overrightarrow{X_p}$ is the position vector of the prey, $\vec{X}$ is the position vector, || is the absolute value and .is the element by element multiplication.

The vectors $\vec{C}$ and $\vec{A}$ are defined as follows:

$$\vec{C} = 2.\vec{r} \quad (14)$$

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \quad (15)$$

Here $\vec{a}$linearly decreases from 2 to 0 in each iteration and $\vec{r}$ is a random vector in the range [0, 1]. The coefficient vectors$\vec{A}$ and $\vec{C}$ are adjusted to achieve the best search agent in different places.

$\vec{A}$lies in the range [-2a, 2a], $\vec{C}$ lies in the range [0, 2].

The hunting phase of GWO involves selection of first three best solutions as alpha, beta and delta. In all the iterations these three solutions are saved and updated to adjust the position of lowest ranking solution omega. Mathematically, this phase is formulated as

$$\left.\begin{aligned} \overrightarrow{D_\alpha} &= \overrightarrow{C_1}.\overrightarrow{X_\alpha} - \vec{X} \\ \overrightarrow{D_\beta} &= \overrightarrow{C_2}.\overrightarrow{X_\beta} - \vec{X} \\ \overrightarrow{D_\delta} &= \overrightarrow{C_3}.\overrightarrow{X_\delta} - \vec{X} \end{aligned}\right\} \quad (16)$$

$\overrightarrow{D_\alpha}$,$\overrightarrow{D_\beta}$ and $\overrightarrow{D_\delta}$are the modified distance vectors between the alpha, beta, and delta positions to the other wolves.

$\overrightarrow{X_\alpha}, \overrightarrow{X_\beta}$ and $\overrightarrow{X_\delta}$ are alpha, beta and delta position vectors.

Where$\overrightarrow{C_1}, \overrightarrow{C_2}$ and $\overrightarrow{C_3}$are the coefficient vectors which helps to adjust distance vector and calculated using equation (14), $\vec{X}$ is the position vector of the other grey wolves (omega wolves).

$$\left.\begin{aligned} \overrightarrow{X_1} &= \overrightarrow{X_\alpha} - \overrightarrow{A_1}.(\overrightarrow{D_\alpha}) \\ \overrightarrow{X_2} &= \overrightarrow{X_\beta} - \overrightarrow{A_2}.(\overrightarrow{D_\beta}) \\ \overrightarrow{X_3} &= \overrightarrow{X_\delta} - \overrightarrow{A_3}.(\overrightarrow{D_\delta}) \end{aligned}\right\} \quad (17)$$

$\overrightarrow{X_1}$is calculated based on $\overrightarrow{X_\alpha}$ and $\overrightarrow{D_\alpha}$, $\overrightarrow{X_2}$ is calculated based on $\overrightarrow{X_\beta}$ and $\overrightarrow{D_\beta}$, $\overrightarrow{X_\delta}$ is calculated based on $\overrightarrow{X_\delta}$ and $\overrightarrow{D_\delta}$.The coefficient vectors $\overrightarrow{A_1}$, $\overrightarrow{A_2}$ and $\overrightarrow{A_3}$ are calculated using equation (15).

$$\vec{X}(t+1) = (\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3})/3 \quad (18)$$

$\vec{X}(t+1)$is the new position vector obtained by taking the average sum of the position vectors denoted by $\overrightarrow{X_1}$, $\overrightarrow{X_2}$and $\overrightarrow{X_3}$. These are obtained by using alpha, beta and delta position vectors.

The solution space convergence is dependent on the parameters$\vec{A}$ *and* $\vec{C}$. If$|\vec{A}| > 1$, the solution diverges else if $|\vec{A}| < 1$, the search agents perform local search. The vector$\vec{C}$helps to avoid local optima.

5.1 : Algorithm for finding the optimal location and sizing of UPQC using GWO:

Step 1: Initialize the number of search agents, number of variables, limits of the variables and maximum iterations. Here the variables are location and series injected voltage.

Step 2: Generate search agents of dimension [m×n], where m is the number of search agents in the population and n is the number of variables to be optimized i.e., the dimension of the problem. Here the dimension is 3.

Step 3: Initialize a, parameter in the optimization.

Step 4: Run the load flow by compensating the voltage at the desired location as given in equation (9). Compute the shunt compensation value by using equation (11). Compute the fitness of all the search agents in the population using equation (1).Check the constraints. If any of the search agents violate the constraints, then the corresponding fitness is set to the base case real power loss. The first best search agent is (X_α), the second best search agent is (X_β) and the third best search agent is (X_δ).

Step 5: Set the iteration count (t) to one.

Step 6: Calculate new search agents by using equation (18)

Step 7: Run the load flow by compensating the voltage at the desired location as given in equation (9). Compute the shunt compensation value by using equation (11).Calculate the fitness of the search agents. Check the constraints.

Step 8: Update X_α,X_β and X_δ.

Step 9: Update the parameter **a** given by equation (19)

$$a = 2 - t * ((2)/\max imum\ iterations) \quad (19)$$

Update the coefficient vectors $\vec{C}$ and $\vec{A}$using equations (14) and (15).

Step 10: If convergence criteria is satisfied or the iteration count has reached maximum iterations,perform steps 11 and 12 else increase the iteration count and repeat the steps from 6 to 10.

Step 11: End the while loop.

Step 12: Retain the value of X_α , which is the optimal location and rating of UPQC and corresponding fitness is the real power loss.

VI. RESULTS

The effect of UPQC on power loss minimization is evaluated with Grey Wolf Optimization method. The efficacy of the optimization method to determine the optimal location and rating of UPQC is tested using two distribution networks, 33-bus network and 69-bus network. 33-bus network is a 12.66 kV network with real and reactive load of the network as 3715 kW and 2300 kVAr respectively. The data of the network is obtained from [18]. 69-bus network is a 12.66 kV network with real and reactive load of the network as 3802.19 kW and 2694.6 kVAr respectively. The data of the network is obtained from [19].

Load flow parameters: epsilon (ϵ) =0.0000001; maximum iterations=1000.

Grey Wolf Optimization method parameters: maximum iterations=3000; number of search agents=100 for 33-bus network and 200 for 69-bus network.

The results for 33-bus network without and with UPQC placement are given in Table 1.The results for 69-bus network without and with UPQC placement are given in Table 2.

Table 1: Results of 33-bus test network

33-bus network		
Description	**Without UPQC**	**With UPQC**
Location	-	31
Total real power loss (kW)	202.6771	123.4237
Total real power loss (kVAr)	135.141	83.6298
Voltage injected by series compensator (p.u.)	-	0.3080i
Reactive power injected by shunt compensator (kVAr)	-	954.2685
Min Voltage (p.u)	0.9131 @ bus 18	0.9273 @ bus 18

Table 2: Results of 69-bus test network

69-bus network		
Description	**Without UPQC**	**With UPQC**
Location	-	62
Total real power	225.0044	107.5717

loss (kW)		
Total real power loss (kVAr)	102.2057	51.784
Voltage injected by series compensator (p.u.)	-	0.3302i
Reactive power injected by shunt compensator (kVAr)	-	1194.4
Min Voltage (p.u)	0.9092 @ bus 65	0.9448 @ bus61

Table 3: Number of under voltage nodes in the test networks without and with UPQC placement

Description	Test network	Without UPQC	With UPQC
Number of under voltage nodes	33-bus network	21	10
	69-bus network	9	2

As observed from Table1, the reduction in real power loss is 39.10% for 33-bus network. The improvement in minimum voltage is from 0.9131 to 0.9273 @ bus 18 in the 33-bus network.

As observed from Table 2, the reduction in real power loss is 52.19 % for 69-bus network. The improvement in minimum voltage is from 0.9092@ bus 65 to 0.9448 @ bus 61 in the 69-bus network.

The voltage at any node less than the specified limit of 0.95 p.u. is termed as under voltage node. Table 3 shows the number of under voltage nodes in 33-bus network and 69-bus network respectively without UPQC placement are 21 and 9 respectively. After UPQC placement the number of under voltage nodesis 10 and 2 respectively.

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VII. CONCLUSION

The optimization method known as Grey Wolf Optimization (GWO) inspired by the hunting mechanism of Grey Wolves is detailed in this paper. The optimization method is applied to determine the optimal location and rating of Unified Power Quality Conditioner (UPQC). The series compensator of UPQC compensates the voltage at the desired location in steady state conditions and shunt compensator participates in load reactive power compensation satisfying the system operational constraints. The placement of UPQC for power loss minimization and voltage improvement is validated with two distribution systems. There is a significant reduction in power loss and also considerable decrease in the number of under voltage nodes with UPQC placement. The results validate the effectiveness of the proposed method in the distribution systems.

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