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Optimal Locating and Sizing of Unified Power Quality Conditioner- phase Angle Control for Reactive Power Compensation in Radial Distribution Network with Wind Generation

A. R. Moradi*[a], Y. Alinejad-Beromi[a], M. Parsa[b], M. Mohammadi[c]

[a] *Faculty of Electrical and Computer Engineering, Semnan University, Semnan, Iran*
[b] *Faculty of Electrical Engineering, Islamic Azad University of Damghan, Semnan, Iran*
[c] *Faculty of Electrical Engineering, Islamic Azad University of Semnan, Semnan, Iran*

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ABSTRACT

In this article, a multi-objective stochastic planning is demonstrated for reactive power compensation in radial distribution networks with wind generation via unified power quality conditioner (UPQC). UPQC model, based on phase angle control (PAC), is used. In presented method, optimal locating of UPQC-PAC is done by simultaneous minimizing of objective functions such as: grid power loss, percentage of nodes with voltage drop, and capacity of UPQC. The proposed model is a complicated non-linear optimization problem. For introducing group of non-dominated solutions, a multi-objective grey wolf optimizer (MOGWO) algorithm based on probabilistic load flow is used, then a fuzzy sets theory is used to achieve the best response. In order to evaluate reliability of mentioned approach, simulation is done on 33-bus distribution network. The results acquired from the simulation would illustrate that incase the wind uncertainty effect is analyzed in the article, the power loss and PNUVP percentage would be considerably decrease against the network without the wind uncertainty.

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1. INTRODUCTION

Lack of reactive power in power grids leads them to instability, which causes voltage drop and oscillation. Compensating reactive power in a proper place would solve voltage instability problems and could considerably improve a grid reaction. Compensation is considered as reactive power managing, compensators are usually installed in places where there are reactive loads. Various methods are presented for compensating reactive power in different articles. In [1], transformers equipped with tap changers are used to control reactive power, but this method because of limitation of transformers tap has low application range. In [2], a heuristic search-based approach is used to determine the optimal capacitor placement. This method has low approval rather than reactive power injection method, because of existing of controlling compensators, and economic damages of eliminating part of consuming loads, weak points of this strategy would be much more highlighted. In [3], a cuckoo search-based approach has been used to allocate static shunt capacitors in radial distribution networks. In [4], method of installing fixed and switchable capacitor bank is presented. The produced reactive power by capacitor banks, introduced in reference [4], has a very slow reaction for sudden changes of the load and swift applications such as wind turbine. In [5], a fuzzy concept-based approach is presented for multi-objective capacitor placement optimization in distribution networks. In addition, another method is distribution flexible AC transmission system (DFACTS) devices that are usually used for power quality, but they can be used for compensating optimized reactive power. Even though, DFACTS such as distribution static compensator (DSTATCOM) are very expensive [6]. As a general solution for reactive power compensation, a combination of series and

*Corresponding Author's Email: *kavi.aeiou@gmail.com* (G. Rajesh Kumar)

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parallel converters with a DC link, which is called UPQC, can be used. UPQC is a multi-purpose DFACTS which can compensate various aspects of power quality such as voltage drop, over voltage, voltage balance, flickers, harmonics, and reactive currents [7]. There are various UPQC models, such as UPQC-P, UPQC-Q, UPQC-S, and UPQC-VA$_{\min}$. The series inverter only provides active power in UPQC-P and reactive power in UPQC-Q by injecting a controllable in-phase and a controllable quadrature voltage, respectively so as to mitigate voltage sag problem [8]. A comparative evaluation of these models in reference [9] is presented. The series converter in UPQC-S can simultaneously provide both reactive and active power [10]. Almost in all researches, UPQC is used to protect a single load that is expected to be the most sensitive load, but there is a possibility that a grid contained the some loads with the same level of sensitivity. Putting importance some loads sensibility in a grid and protecting them via aid of UPQC is performed in a technic called phase angle control (PAC). UPQC-PAC can provide reactive power compensation in a distribution network. With this technic, the best place for situating optimizer compensator can be specified, where all grid elements are in the optimal condition. In reference [11], reactive power compensation done with phase angle control but in this reference compensation without considering of distributed generation (DG) is done. There is possibility to improve the result of reference [11] with aid of DG, sources which are glowing tendency to be used because of various consumption patterns. The presence of responsive loads in the promising active distribution networks (ADNs) would definitely affect the power system problems such as DGs studies. Hence, in Ref. [12], an optimal procedure is proposed which takes into account the simultaneous placement of DGs and smart meters (SMs) in ADNs.

On the other hand, not only in Ref. [11], but also in all the other references, using DG beside UPQC is not mentioned. Renewable DG sources are one of the various kinds that because of not contaminating the environment, lack of fuel cost and etc., they are in great attention. It can be imagined that controlling these sources and accompanying them with compensation such as UPQC-PAC would provide higher level of reliability in grid which is the main issue of research in this article. Here, a multi objective planning is presented for reactive power compensation in radial distribution networks with wind generation with specifying UPQC-PAC. The optimal locating and sizing of UPQC-PAC is determined with simultaneous minimizing of three objective functions: 1- capacity of UPQC 2- grid power loss 3- percentage of nodes with under voltage problem (PNUVP) rather than the grid without UPQC. For introducing group of non-dominated solutions, a MOGWO algorithm based on probabilistic load flow is used, then a fuzzy decision making analysis is used to achieve the best response. Finally, in order to evaluate reliability for the proposed approach, simulation on radial distribution network with 33 buses is done.

Structure of the article is as follows: 2th chapter presents the mathematical modelling of UPQC-PAC and uncertainties. The multi-objective planning model via UPQC-PAC is in 3th chapter. 4th chapter describes the solution methodology of the proposed planning model. 5th, 6th chapters are simulation results and conclusion, respectively.

2. MODELING

2. 1. Modelling of Wind and Load Uncertainties

The probability density functions (PDFs) are useful for modelling the uncertainties related to load demand and wind speed. In order to specify the stochastic behavior of wind speed, Weibull distribution is taken into account.

$$f_{wd}(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where, k,c, f_{wd} and v are referred consequently shaping, scaling coefficients, probability density of wind speed and wind speed, respectively. The output wind power is calculated in every case as follows [13]:

$$P_W = \begin{cases} 0 & v \le v_i\,, v \ge v_o \\ \frac{v-v_i}{v_r-v_i} P_W^{rated} & v_i \le v \le v_r \\ P_W^{rated} & v_r \le v \le v_o \end{cases} \tag{2}$$

In above equation v_i, v_o, v_r are the cut-in, cut-out, and rated wind speeds, respectively. P_W and P_W^{rated} are the outputs and rated wind powers. The Gaussian distribution helps us simulate the variation of load demand such as [13]:

$$f_{ld}(l) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left[-\frac{(l-\mu)^2}{2\sigma^2}\right] \tag{3}$$

where, l, σ, μ, f_{ld} are the load, standard deviation, mean value, and PDF of the load, respectively.

2. 2. Modeling of UPQC-PAC

In this article, an integrated optimizer of power quality based on PAC is used which contains two series & shunt inverters as seen in Figure 1. In general, for mitigating sag and swell occurred in supply voltage, the series inverter is used. Moreover, in presence of reactive component of load current and harmonics shunt inverter is for compensation. In case of normal condition and voltage sag, series voltage (V_{Se}) and shunt compensating current (I_{Sh}) would be injected by series inverter and shunt inverter respectively. In the UPQC-PAC model, the series inverter injects during healthy operating condition to create a phase angle (δ), shift of the load end voltage.as seen in Figure 2(a). In case of reactive power provision, this aspect -phase angle shift- boosts the series inverter that leads to reduction of shunt inverter rate and overall rating of a UPQC. In other words, if phase angle (δ) would be controlled suitably, load reactive power could be divided between shunt and series active filters without influencing on nominal amounts of UPQC. While there is voltage sag, V_{Se} injection can provide a constant situation for load end voltage as seen in Figure 2(b). Maximum rating of series inverter is the key element to indicate the amount of V_{Se}.

Mathematical details and formulation of UPQC-PAC for reactive power compensation in distribution network can be found in [11].

3. MULTI-OBJECTIVE PLANNING MODEL VIA UPQC-PAC

In this article, a multi-objective planning model is formulated to determine the optimal locating of UPQC, the optimal amount of compensating reactive power at the desired location, and the optimal amount of K_{Se}. These optimizing variables would be calculated by simultaneous minimizing three targets.
They include [11]:

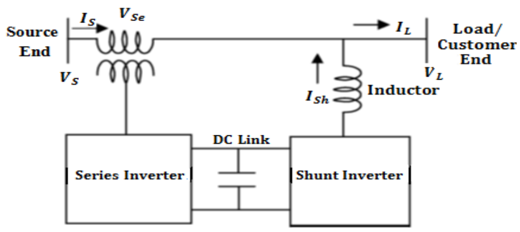
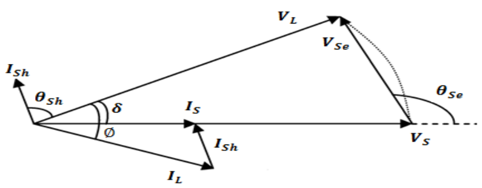


Figure 1. General schematic of UPQC



a) Normal condition

b) Voltage sag

Figure 2. Phasor diagram of UPQC

Target 1: Capacity of UPQC (VA)

Target 1: $S_{UPQC} = S_{Sh} + S_{Se}$ (4)

This objective function would be recognized with S_{UPQC}.

where S_{Se} , S_{Sh} are nominal powers of series and shunt inverter, respectively.

Target 2: Network power loss

Target 2: $P_{Loss}^{UPQC} = \sum_{jk\in\gamma}\{I_L(mn)\}^2 r(mn)$ (5)

where, $I_L(mn), r(mn)$ show line current & resistance of the branch mn, and set γ consists of all branches in a network.

Target 3: Percentage of nodes with under voltage problem (PNUVP)

Target 3: $PNUVP = 100\left(\frac{N_{UPQC}^{UV}}{N_{Base}^{UV}}\right)$ (6)

N_{UPQC}^{UV} illustrates number of nods having voltage drop with UPQC, and N_{Base}^{UV} shows number of nods with voltage drop without UPQC.

4. MULTI-OBJECTIVE PLANNING ALGORITHM

4. 1. MOGWO This section summarizes the main steps in MOGWO algorithm. The GWO [14] is a new meta-heuristic algorithm inspired by grey wolves. The GWO algorithm mimics the hunting mechanism and headship hierarchy of grey wolves in nature. Four kinds of grey wolves such as alpha, beta, delta, and omega are used for simulating the leadership hierarchy. In addition, three main steps of hunting, entitled seeking for hunt, encircling hunt, and attacking to hunt are accomplished. The hierarchy of grey wolf is shown in Figure 3 which the dominance to decreases from top to down.

For mathematical social hierarchy modelling of grey wolf it is assumed that the best solutions are obtained by the wolves, alpha (α), beta (β) and delta (δ), respectively and other wolves are assumed omega (ω). In fact, hunting would be guided by three wolves, alpha, beta and delta and other wolves follow these three wolves.
Encircling prey can be modelled by the following equations:

$$\vec{D} = \left|\vec{C}.\vec{X}_p(i) - \vec{X}(i)\right| \quad (7)$$

$$\vec{X}(i+1) = \vec{X}_p(i) - \vec{A}.\vec{D} \quad (8)$$

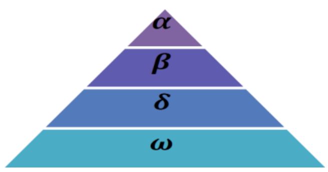


Figure 3. Hierarchy of grey wolf

where is the present iteration, $\vec{C}$ and $\vec{A}$ are coefficient vectors, $\overrightarrow{X_p}$ represents the position vector of the victim, and $\vec{X}$ represents the position vector of a grey wolf.

The vectors $\vec{A}$ and $\vec{C}$ are calculated from the following equations:

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \tag{9}$$

$$\vec{C} = 2.\overrightarrow{r_2} \tag{10}$$

In Equations (9) and (10), coefficient $\vec{a}$ decreases linearly from 2 to 0 in each iteration and $\vec{r}_1$ and $\vec{r}_2$ are random vectors between [0,1].

For mathematical modelling of hunting assume that α is the best answer and β, δ are best knowledge for prey position. With saving these three answers and updating other search agents such as ω by the following equations, the new answers may be achieved. This continues once to reach the best answers. In this algorithm, for searching a prey, grey wolves diverge from each other. Mathematically modelling, when $|\vec{A}| > 1$ forces the wolves to diverge from wide search space, hopefully find a better position. Afterwards, estimating a prey converge they would get ready to raid the prey. Also, $\overrightarrow{C}$ vector component has random values between [0-2] that not linearly decrease in contrast to $\overrightarrow{A}$. This parameter helps to avoid algorithm to stop on local optimum.

$$\vec{D}_\alpha = |\vec{C}_1.\vec{X}_\alpha - \vec{X}| \ ,\vec{D}_\beta = |\vec{C}_2.\vec{X}_\beta - \vec{X}| \ ,\vec{D}_\delta = |\vec{C}_3.\vec{X}_\delta - \vec{X}| \tag{11}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha) \ ,\vec{X}_2 = \vec{X}_\beta - \vec{A}_2.(\vec{D}_\beta) \ ,\vec{X}_3 = \vec{X}_\delta - \vec{A}_3.(\vec{D}_\delta) \tag{12}$$

$$\vec{X}(i+1) = \frac{\vec{X}_1+\vec{X}_2+\vec{X}_3}{3} \tag{13}$$

Figure 4 shows that in a two-dimensional space, how the search agents are updated by alpha, beta and delta positions. In other words, Figure 4 shows that α, β and δ estimate probable position of the prey (best answer) in the search space and other wolves update their position in the random place within a circle around the α, β and δ.

Two new components: first, an archive that is responsible for storage of optimal solutions of non-dominated Pareto and second, leader selection strategy that helps to choose the best leader between archive, are added here in order to create multi objective GWO algorithm [15]. Auxiliary components added are similar to MOPSO method. An archive which is added for creating multi objective GWO algorithm is a simple storage unit. This unit stores the best optimal solutions of non-dominated Pareto obtained so far.

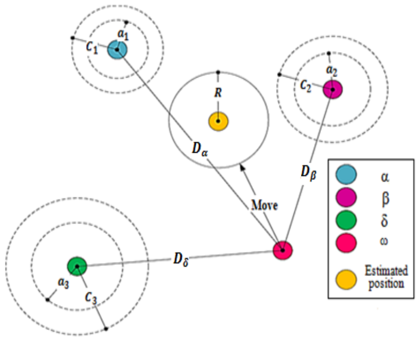


Figure 4. Position updating in GWO

The second component helps to choose the leader by using roulette wheel method and probability function which is introduced in the following:

$$p_i = {C1}/{N_i} \tag{14}$$

$C1$: a constant number greater than 1
N_i: Number of obtained Pareto optimal solutions.

More comprehensive description of the MOGWO algorithm is given in reference [15].

4. 1. 1. Utilization of MOGWO in Locating and Sizing of UPQC-PAC In this section, the MOGWO algorithm for optimal locating and sizing of UPQC-PAC is presented. In this algorithm, first, initial population of wolves, parameter $\vec{a}$, coefficient vectors $\overrightarrow{A}$, $\vec{C}$ and maximum numbers of iteration are defined. Then, initial population of wolves is spread randomly in the defined search space that the position of each wolf is composed of three variables such as location, size, and the parameters of UPQC-PAC. For each position, load flow algorithm runs in order to calculate the fitness functions according to Equations (4) to (6). Then, the non-dominant solutions are determined and the archive is initialized according to them. The best position of wolves in the archive, are named as α, β and δ and the position of the rest of wolves called ω. Then, the value of parameter $\vec{a}$ decreases linearly from 2 to 0 in each iteration in order to confirm exploration and exploitation. At this point, the position of the rest of wolves (ω) relative to top wolves' position (alpha, beta and delta), is updated according to Equations (11) to (12). This update, takes places depending on the distance of the rest of wolves (ω) from top wolves' position (alpha, beta and delta) and are named as X_1, X_2 and X_3. Then, next new position is obtained by calculating average of the positions X_1, X_2 and X_3 according to Equation (13). The value of fitness functions for this position is calculated. At this time, the non -dominant solutions consists of location, size, and the parameters of UPQC-PAC are determined and the archive is updated according to them. Then if the archive be full, the grid mechanism runs to omit one of the current archive members and add the new solution to the archive. Else, if each of the new added solutions to the archive is located outside the hypercube, update the grids to cover the new solution(s). Else, select leaders from the archive. These processes will be continued until to reach favorable position or maximum iteration. The flowchart of utilization of MOGWO algorithm is shown in Figure 5.

4. 2. Point Estimate Method (PEM) In this paper, the two-point estimate method (2PEM) which is a variation of the original PEM, has been used for modelling the uncertainties. The probable input variables of the load flow problem are wind power and load demand. Moreover, the output variables (power loss & number of buses with voltage drop) for this problem are also probable variables. The algorithm of computing the moment for the probable output variables by using the 2PEM is described in reference [16].

4. 3. Fuzzy Sets Theory In order to specify a set of solutions, we need to get a pliable solution and demonstrate a trade-off among various objectives. In case of selecting an agreed-upon solution among a set of solutions, there are different approaches. A fuzzy method is of great interest because of its ease.

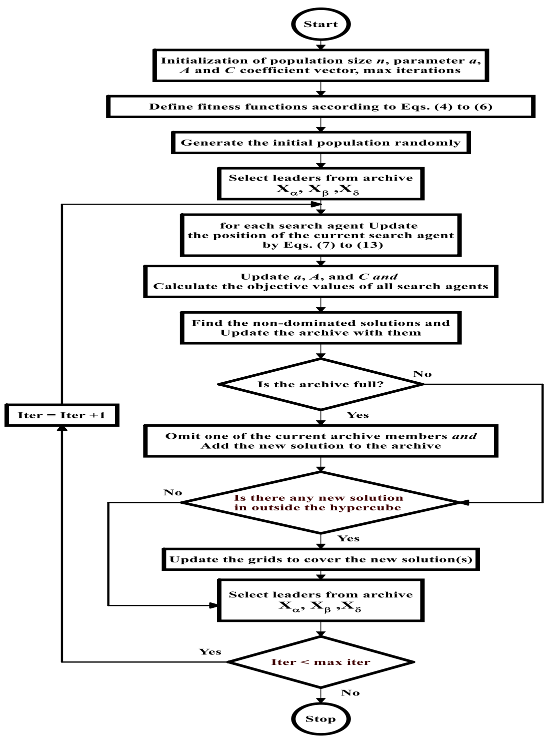


Figure 5. The flowchart of utilization of MOGWO algorithm

The fuzzy sets are specified by membership functions that represent the grade of membership in a fuzzy set, with values from 0 to 1 [17]. In the fuzzy approach, a strictly monotonically decreasing and continuous membership function is defined to each objective. The membership function illustrates the extent to which a solution is satisfying the objective functions q. A linear membership function can be applied for all objectives:

$$\mu_{f_q}(\bar{X}) = \begin{cases} 0 & f_q(\bar{X}) > f_q^{max} \\ \frac{f_q^{max} - f_q(\bar{X})}{f_q^{max} - f_q^{min}} & f_q^{min} \le f_q(\bar{X}) \le f_q^{max} \\ 1 & f_q(\bar{X}) < f_q^{min} \end{cases} \quad (15)$$

Figure 6 shows the graph of this membership function.

By taking the individual minimum and maximum values of each objective function into account, the membership function $\mu_{f_q}(\bar{X})$ for each objective function can be specified in a subjective method. Then, for a multi-objective optimization problem with Q objective functions, the final solution can be found as:

$$max\left\{min\ \left\{\mu_{f_q}(\bar{X})\right\}\right\} \quad ; q = 1,2, \dots Q \quad (16)$$

5. SIMULATION RESULTS AND DISCUSSION

The proposed model is tested on the 33-bus distribution network. The model is simulated in MATLAB R2014a software. The evaluation platform is a workstation system with a 2.66 GHZ Intel Core 2 Duo CPU and 4GBs of RAM. This distribution network contains one substation at bus 1, a wind turbine with an initial capacity of 1000 KW at bus 12, and other buses are considered as load buses. The parameters of this wind turbine are as follows:

Cut-in speed is 4 m/s, rated speed is 11 m/s and cut-out speed is 23 m/s.

The substation voltage is specified to be $1\angle 0$ p.u. The needed information for studied network is available in reference [18]. The total harmonic distortion (THD) of the load current is assumed to be 20% and the minimum voltage sag is guessed as 25% (i.e., $K_{se} \ge 0.5$) [11]. In this paper, the forward-backward sweep load flow algorithm is used [19]. The MOGWO optimized parameters for this simulation is shown in Table 1.

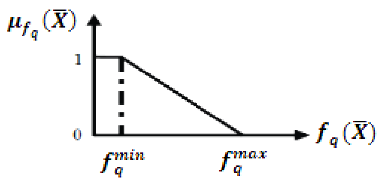


Figure 6. Linear type membership function

In order to accurate analyzing of results, two test systems are simulated and their results in each part are compared with other articles. Brief descriptions of simulated test systems in this paper are tabulated in Table 2.

5. 1. Test System1 In this case, results of the proposed planning model in 33-bus distribution network with wind generation without considering of UPQC-PAC are analyzed.

Purpose in simulation of this case is to determine power loss data and number of buses with voltage drop in distribution network. The results acquired of this case are shown in Table 3.

Regarding acquired results in Table 3, power loss for distribution network is 130.07 (KW). Figure 7 shows the number of buses with voltage drop for 33-buses distribution network with wind generation without considering of UPQC-PAC.

Regarding to acceptable voltage drop limit shown in Figure 7, the number of buses with voltage drop are 7 nodes of the 33-node (i.e., 21.21%).

5. 2. Test System 2 In this case, optimal locating and sizing of UPQC-PAC in 33-bus distribution network with wind generation is simulated. The optimized results for the second case are shown in Table 4.

TABLE 1. MOGWO parameters

Grey wolves number	100
Maximum number of iterations	100
Repository size	50
Number of grids per each dimension	5
Grid inflation parameter (alpha)	0.1
Leader selection pressure parameter (beta)	2
Extra (to be deleted) repository member selection pressure (gamma)	2

TABLE 2. Brief descriptions of simulated test systems

Test system 1	33-bus distribution network without considering of UPQC
Test system 2	33-bus distribution network with considering of UPQC

TABLE 3. The results acquired of distribution network simulation

Test system 1	
Power loss (KW)	**number of buses with voltage drop**
130.07	7

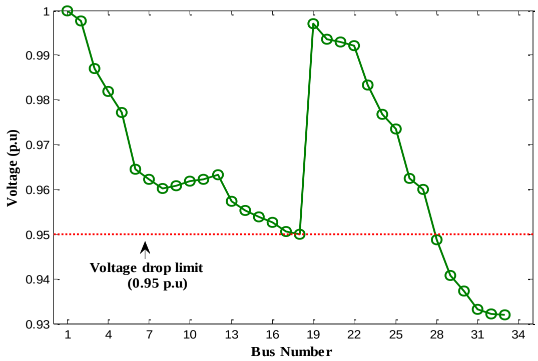


Figure 7. Number of buses with voltage drop in the test system 1

TABLE 4. Optimal solutions based on the test system 2

	Optimal locating of UPQC	Optimal sizing of UPQC (MVA)	K_{Se}
Test System 2	Branch5: 5-6	1.59	0.5

In order to show the strength of simulation which is done in network, obtained results from this case are compared with results of test system 1 and reference [11] as shown in Table 5. It should be mentioned that in reference [11], optimal locating and sizing of UPQC-PAC in the 33-bus distribution network is determined without considering of wind and load uncertainties by using two cases: Case A: The optimal locating of UPQC-PAC with simultaneous minimizing of two objective functions: 1- capacity of UPQC 2- power loss. Case B: The optimal locating of UPQC-PAC with simultaneous minimizing of two objective functions: 1- capacity of UPQC 2- percentage of nodes with under voltage problem (PNUVP) rather than the grid without UPQC. In this paper, the obtained results from this case are compared with results of the test system 1 and Case A in reference [11] as Table 5.

As it can be observed in Table 5, optimal locating and sizing of UPQC-PAC in distribution network with wind generation is able to reduce power loss from 130.07 (KW) in test system 1 to 90.6 (KW) in test system 2. Figure 8 shows the number of buses with voltage drop for 33-buses distribution network with considering of UPQC-PAC (test system 2) compared with the test system 1 and Case A in reference [11].

TABLE 5. Obtained results for this test system in comparison with the test system 1 and reference [11]

Test System 1	Test System 2	CaseA [11]
Power loss (KW)	**Power loss (KW)**	**Power loss (KW)**
130.07	90.6	147.5

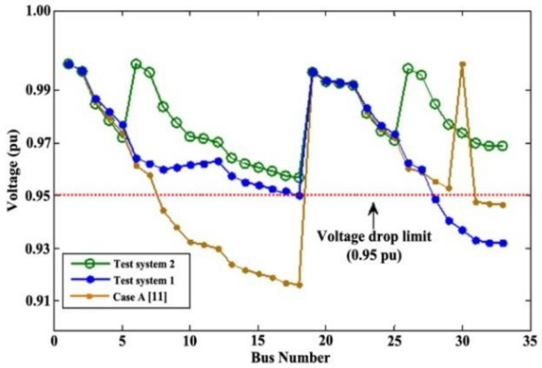


Figure 8. Number of buses with voltage drop for this test system in comparison with the test system 1 and reference [11]

As it can be observed in Figure 8, optimal locating and sizing of UPQC in distribution network with wind generation is capable to reduce the number of buses with voltage drop from 7 nodes of the 33-node (i.e., 21.21%) in the test system 1 to zero node in the test system 2. Also, in Case A [11], the number of buses with voltage drop are 14 nodes of the 33-node (i.e., 42.42%).

Figure 9 shows the Pareto-approximation fronts (PAFs) achieved from the proposed planning model. As shown in Figure 9, by using the UPQC the power loss and PNUVP are decreased considerably in distribution network.

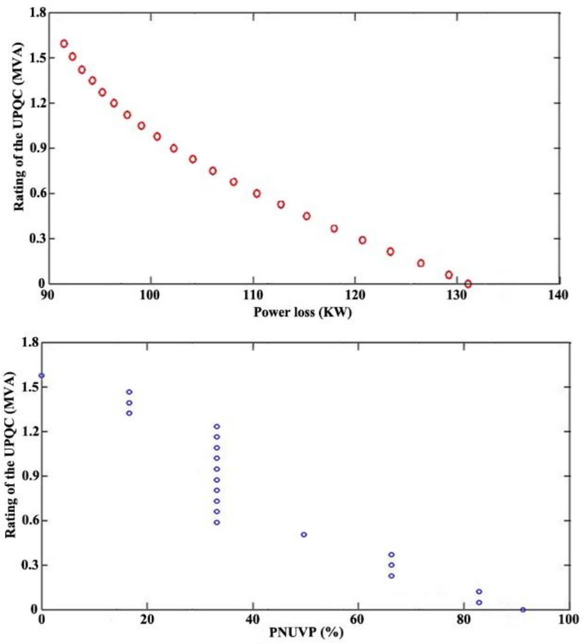


Figure 9. PAFs achieved from the proposed planning model

6. CONCLUSION

In this article, a stochastic structure for reactive power compensation of radial distribution network via UPQC-PAC under wind and load uncertainties is presented. In order to optimal compensating of reactive power of distribution network, UPQC model based on phase angle control is used. Presented structure shows a multipurpose model for optimal locating and sizing of UPQC-PAC in presence of uncertainties. For explaining non-dominated answers, grey wolf optimizer algorithm based on probabilistic load flow is used. Then fuzzy method for choosing the best final answer is applied.

In order to evaluate reliability of mentioned approach, simulation is done on distribution network with 33-bus. Simulation results are compared with other researched articles. The results show, with using offered method, the power loss in distribution network would be decreased significantly and also the voltage profile in distribution network could be improved.

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Optimal Locating and Sizing of Unified Power Quality Conditioner- phase Angle Control for Reactive Power Compensation in Radial Distribution Network with Wind Generation

A. R. Moradi[a], Y. Alinejad-Beromi[a], M. Parsa[b], M. Mohammadi[c]

[a] *Faculty of Electrical and Computer Engineering, Semnan University, Semnan, Iran*
[b] *Faculty of Electrical Engineering, Islamic Azad University of Damghan, Semnan, Iran*
[c] *Faculty of Electrical Engineering, Islamic Azad University of Semnan, Semnan, Iran*

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چکیده

در این مقاله، یک برنامه ریزی تصادفی چند هدفه برای جبران سازی توان راکتیو در شبکه های توزیع شعاعی با منابع بادی از طریق بهساز یکپارچه کیفیت توان (UPQC) ارائه شده است. مدل UPQC بر پایه کنترل زاویه فاز (PAC) استفاده شده است. در روش ارائه شده، جایابی بهینه UPQC-PAC با حداقل کردن همزمان اهدافی مانند: تلفات توان شبکه، درصد شین های دچار افت ولتاژ شده و ظرفیت UPQC انجام شده است. مدل مطرح شده یک مساله بهینه سازی غیر خطی پیچیده می باشد. برای تعیین کردن مجموعه جواب های غیر مغلوب، الگوریتم چند هدفه بهینه ساز گرگ خاکستری (MOGWO) بر پایه پخش بار احتمالاتی استفاده شده است، سپس تئوری تصمیم گیری فازی برای دستیابی بهترین پاسخ استفاده شده است. به منظور ارزیابی قابلیت اطمینان روش مطرح شده، شبیه سازی بروی شبکه توزیع ۳۳ باسه انجام شده است. نتایج به‌دست آمده از شبیه‌سازی نشان می‌دهد در صورتی که تاثیر عدم قطعیت باد در شبکه مورد مطالعه لحاظ شود تلفات توان و درصد گره‌های دچار افت ولتاژ نسبت به شبکه بدون عدم قطعیت به صورت چشمگیری کاهش می‌یابد.

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