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Reactive Load Compensation Planning In Distribution Systems

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ABSTRACT

Background: In the effort of reducing power losses within distribution system, reactive power compensation has become increasingly important as it affects the operational, economical and quality of service for electric power systems. **Objective:** To optimization of reactive power and voltage profiles improvement and real power loss minimization. In this survey we work on 30 bus real distribution system. **Results:** Compared with conventional techniques, the proposed strategy prevents assets failure and increase system security and reliability by coordinating the operation of reactive power control and reliability centered maintenance with the view of assets life cycle. So damages, risks and failures are decreased and asset's life cycle increased. **Conclusion:** In this paper, a new approach to the optimization of reactive power and voltage profiles improvement and real power loss minimization is presented. The problem is formulated as a combinatorial nonlinear optimization problem. This paper presents the application of genetic algorithm approach for reactive power loss reduction in radial distribution system. MATLAB is used to perform load flow analysis and for the identification of capacitor current via GAtool, and also algorithm for the calculation of loss, and its particular capacitor size and location. Optimizing reliability is done through controlling loads of facilities and assets especially reactive loads; so damages, risks and failures are decreased and asset's life cycle increased.

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INTRODUCTION

One predominant expense for a utility is the cost of maintaining system assets, for example through adopting preventive measures, collectively called *preventive maintenance (PM)*. PM measures can impact on reliability by either improving the condition, or prolonging the lifetime of an asset. Reliability overall can be improved by lowering either the *frequency* or the *duration* of interruptions. PM activities could impact on the frequency by preventing the actual cause of the failure. One method for relating reliability to PM is known as reliability- centered maintenance (RCM). One way to apply RCM on the system is reducing assets loads. The more loads cross assets the more failure and the less life cycle results. So we should reduce loads of assets to improve reliability.

Consumer loads impose active and reactive power demand, which depending on their characteristics. Active power is converted into useful energy whereas reactive power must be compensated. This is to guarantee efficient delivery of active power to loads, thus releasing system capacity, reducing system losses and improving system power factor and bus voltage profile are achieved.

One of the important operating tasks of power utility operator is to maintain the voltage profile within specified limits for high quality of services at each consume load point.

Some customers, especially when equipped with sensitive loads, may highly concern about power quality issues. One problem which frequently found in practical is voltage drops.

Voltages at the terminal of device may experience drop in transmission systems, transformers, as well as some variations from load changes. Common devices which normally applied to control voltage and reactive power flow are on load tap changer (OLTC) transformers, shunt capacitors (SC) and automatic voltage regulator (AVR) of generators. These devices are dispersedly installed in power systems. In this survey we focused on the role of reactive power in distribution system specially sizing and allocation of capacitor banks (CB).

Over the years, many useful studies (Momoh, 1.A., *et al*., 1999; Bakare, G.A., 2001) based on classical techniques of capacitor placement for solving reactive power dispatch problem have been carried out. This

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includes nonlinear programming, successive linear programming, mixed integer programming, Newton and quadratic techniques. Most of these approaches can be broadly categorized as constrained optimization technique. In most power systems, by comparing measured voltages and desired values, voltage and reactive power are regulated independently through the controller of OLTC transformers, SC and AVR of generators and so on. That is without considering the system wide effect from other equipments, only the voltage error at the bus with control equipment is expected to stay within a pre-specified range.

For modern power system operation technology, system operating conditions are continuously monitored through the supervisory control and data acquisition system (SCADA). Especially with the congested transmission and distribution system, these data may be useful for improving the system voltage profile, preventing the systems from voltage collapse, and reducing undesired voltage/reactive power fluctuation. Even though these techniques have been successfully utilized in some sample power systems, there are still several issues to be addressed with regard to real power systems.

The main purpose of optimal reactive power flow (ORPF) is to minimize the total power losses of the network while maintaining the voltage profile of the network in an acceptable range. The control variable of the study is reactive power generation of VAR sources (banks of capacitors and reactors). Since the control variables include both discrete variables (VAR sources placement and the amount of VAR that must be injected in specified bus. The ORPF is inherently a mixed-integer nonlinear programming (MINLP) problem (Sharif, S.S. and J.H. Taylor, 1997).

Recently, some new stochastic search techniques have been developed to solve global optimization problems in an attempt to circumvent the extant computational complexity and other limiting mathematical assumptions. These search techniques include expert system (ES), genetic algorithm (GA), tabu search, simulated annealing (SA), particle swarm optimization (PSO), etc. However, the most popular among these search techniques is the application of GA to power system operational problems.

In this paper, Genetic algorithm has been considered as an approach to tackle the problem of optimal capacitor placement (OCP) in radial distribution systems. In this OCP algorithm, two considerations namely minimizing capacitor installation cost (by using the existed capacitor) and minimizing system losses need to be taken into account in order to achieve the objective.

Genetic algorithm (GA) is one kind of global optimization techniques with the advantage of dealing with the integer variables. Interior point method (IPM) offers fast convergence to solve large-scale nonlinear program problem. Both of them have been successfully applied to solving ORPF problem (Gomes, J.R. and O.R. Saaverdra, 1999; Lee, K.Y. and F.F. Yang, 1998; Bakirtzis, A.G., *et al.*, 2002; Granville, S., 1994; Jabr, R.A., *et al.*, 2002; Liu, M., *et al.*, 2002), but the difficulty of IPM in dealing with discrete variables and the tardiness of GA in searching optimal solution virtually remain unsolved.

The GA is a general evolution concept-based methodology, and its developing trend is to be combined with other algorithms (Mantovani, J.R.S., *et al.*, 2001; Soto, J.R.O., *et al.*, 2001). In (Mantovani, J.R.S., *et al.*, 2001), a combined methodology is presented, which consists of a successive linear programming (SLP) and a simple genetic algorithm (SGA). First, an initial solution is obtained by relaxing the discrete nature of all variables, and then a mixed linear integer problem is formulated and solved using the SGA and the SLP. The SGA deals with the optimization of discrete variables. The SLP works as a support technique for SGA, which provides the final system operating state by adjusting the existing continuous variables and finding the fitness function for each individual of the genetic algorithm population. A hybrid formulation using a GA combined with an IPM (HGI) has been reported in (Soto, J.R.O., *et al.*, 2001). Similarly, the IPM is embedded in the process of GA to replace the load flow calculation and is employed to find the fitness for each candidate solution. Although the hybrid method is more efficient than the SGA, the execution time is still considerable. Indeed, it is unnecessary to use the IPM to find the fitness for each candidate solution of the GA. Besides, the random city of discrete variables may make the final system operating state become infeasible, no matter what the continuous variables are. In this case, the IPM is non-convergent. In order to integrate the GA with the IPM in a more effective way, a novel hybrid algorithm is therefore proposed in this paper.

This paper is organized as follows: After the introduction, the concept of problem formulation is briefly described in section II. Section III discusses the application and realization of GA based reactive power/voltage control problem. Section IV explores the application of the proposed strategy to case studied. An actual 30 bus distribution system is employed for applying proposed strategy. Section V discusses the results of simulation and the conclusions of this paper.

Problem Formulation:

The formulation of the ORPF problem can be expressed as the following MINLP problem:

$$\begin{aligned} &\min \quad f(z) \qquad (1)\\ &\quad \text{s.t.} \quad g(z) = 0\\ &z_{min} \leq z \leq z_{max} \end{aligned}$$

Where the objective function is the total active power losses; is the nonlinear vectors function representing power flow equations; is the vector of decision variables including the vector of state variables (voltage magnitudes and angles of the load buses and injected reactive powers of the CBs),

Genetic Algorithm:

Genetic algorithm (GA) is an optimization algorithm based on the mechanics of natural selection and genetics. The approach is based on Darwin's survival of the fittest hypothesis. In the GA, candidate solutions to the given problem are analogous to individuals in a population. Each individual is encoded as a string, called chromosome. New candidate solutions are produced from parent chromosomes by the crossover operator. The mutation operator is then applied to the population. The quality of each individual is evaluated and rated by the so-called fitness function. Similar to the natural selection mechanism in the biological system, the fitter individuals have more chance to pass on information to the next generation. When a chromosome with the desired fitness is formed, it will be taken as the optimal solution, and the optimization process is terminated. Otherwise, the process is repeated until the maximum number of generations is reached and the fittest chromosome so far formed is taken to be the optimal solution.

In this paper, the simple genetic algorithm (SGA) in (Lee, K.Y. and F.F. Yang, 1998) is implemented with some modifications. The different components of GA are described as follows.

1) Chromosomes: Since the transformer tap ratios and shunt capacitor/reactor capacitors are all discrete control variables, they can be encoded as integer variables. When a discrete control variable is expressed by (2), the integer-encoded gene of the control variable can be represented by the integer. By this encoding method, the length of the chromosome is equal to the number of control variables, and each gene represents a control parameter of ORPF.

$$u_D = \{u_{D\,min} + N \times \Delta u_D \quad N \in \{0,1,\ldots\ ,N_{max}\}\} \tag{2}$$

Where and are the lower limit and the step size of the discrete control variable, respectively. is the maximum number of control steps for the corresponding variable.

2) Fitness Function: The objective of ORPF is to minimize the total active power loss. GA is designed to maximize the fitness, which is a measure of the quality of each candidate solution. Therefore, a transformation is needed to convert the objective of ORPF to an appropriate fitness function. The control variable constraints of ORPF are automatically satisfied by the encoding scheme, while the state variable constraints are needed to be included in the GA fitness function by penalty terms. In this paper, the fitness function is formed as follows:

$$F = -f(u_D - \textstyle\sum_j c_j Pen_j \tag{3}$$

$$Pen_j = \begin{cases} x_{j\,min} - x_j\,, & if\ \ x_j < x_{j\,min} \\ x_j - x_{j\,max}\,, & if\ \ x_j > x_{j\,max} \\ 0\,, & otherwise \end{cases} \tag{4}$$

Where $\int(u_D)$ is the objective function with control variables u_d; x_j is the j_{th} state variable; x_{jmin} and x_{jmaz} are the lower and upper limits of x_j; c_j is a penalty factor for x_j; pen_j is the violation value of x_j; and ;$\Sigma_j\, c_j\, pen_j$ is the penalty function for state variable constraints.

With every candidate solution, the chromosome is decoded to determine the control variables u_D, and the corresponding state variables x are computed by the power flow calculation. The fitness function of this candidate solution can then be calculated by (3).

3) Selection operation: Selection is a procedure to guarantee that individuals with higher fitness values have a higher probability of contributing new offspring to the next generation. The selection rule used in this paper is the tournament selection (Park, Y.-M., *et al.*, 1999).

4) Crossover operation: Crossover produces new chromosomes by the combination of parent individuals. In this paper, the uniform crossover method (Bakirtzis, A.G., *et al.*, 2002) is adopted with a crossover rate of 0.8. Single point crossover is shown in figure1.

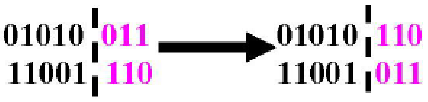

Fig. 1: Single point crossover

Mutation operation: Mutation is responsible for the injection of new information. For integer-coded chromosome, the mutation operation is defined as

$$N_{mut} = \begin{cases} N_{ini} + RAND(N_{max} - N_{ini}) & (\gamma = 1) \\ N_{ini} - RAND(N_{ini}) & (\gamma = 0) \end{cases} \tag{5}$$

Where ϒ is a random bit; N_{mut} is the gene after mutation; N_{ini} is the gene before mutation; and RAND(N) returns a random integer in the range of [0,N]. In this paper, the mutation operator is applied with a probability of 0.03 to every gene of the chromosome. You can find binary mutation operators at figure2.

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Fig. 2: Binary mutation operators

Proposed Strategy:

Genetic algorithm is a very powerful in performing various simulation works due to its distinctive characteristics as discussed. This project focuses greatly in the development of genetic algorithm for the reduction of reactive power losses. The strategy behind the idea of reduction of reactive power is to capitalize the superior features of genetic algorithm in performing the mathematical simulation of a radial distribution network. The fundamental mathematical expressions of reactive power become the input to the genetic algorithm tool in this project. The mathematical expressions (Than Khong Hom) involved in this project will be discussed in detail in the following section of the report.

The total power losses of a distribution system having n number of branches can be expressed as:

$$P_{LTOTAL} = \sum_{i=1}^{n} I_1^2 R_i \tag{6}$$

This power loss can be further associated into two components by separating the current, I into two namely the active branch, I_a and I, reactive branch. The individual power losses namely the active power loss and reactive power loss are given by (7) and (8).

$$P_L = \sum_{i=1}^{n} I_{\alpha i}^2 R_i \tag{7}$$

$$Q_L = \sum_{i=1}^{n} I_{ri}^2 X_i \tag{8}$$

The active and reactive components of branch currents are computed as:

$$I_\alpha = I \cos\theta \tag{9}$$

$$I_r = I \sin\theta \tag{10}$$

Where
I= magnitude of current
ϴ = angle of current

Assume that a single source radial distribution system with n branches. A capacitor is to be placed at bus m with a is the set of branches connected between the source and capacitor bus.

The capacitor that is inserted draws a reactive current I,. For a radial distribution system, the insertion of capacitor will only affect the reactive component of current of branch set o. Hence, the new reactive current I_{ri}^{new} of the i_{th} branch is expressed as:

$$I_n^{new} = I_n + D_i I_c \tag{11}$$

Where

$$D_i = \begin{cases} 1, & i \in \alpha \\ 0, & otherwise \end{cases}$$

The compensated reactive power is represented as the following:

$$Q_L^{com} = \sum_{i=1}^{n} (I_{ri} + D_i I_c)^2 X_i \tag{12}$$

Computing the overall saving as expressed.

$$S = Q_L - Q_L^{com} \tag{13}$$

$$= \sum_{i=1}^{n} I_{ri}^2 X_i - \sum_{i=1}^{n} (I_{ri} + D_i I_c)^2 X_i$$

$$= \sum_{i=1}^{n} I_{ri}^2 X_i - \sum_{i=1}^{n} (I_{ri}^2 + 2 I_{ri} D_i I_c + D_i I_c^2) X_i$$

$$= -\sum_{i=1}^{n} (2 I_{ri} D_i I_c + D_i I_c^2) X_i$$

From expression (12), further simplification on the expression arrives at (13).The typical method of locating the optimum value of capacitor current I, is achieved by performing a differentiation onto (13). The next step will be working on the differentiation of (7) to obtain an expression of the maximum saving per capacitor current.

$$\frac{\partial S}{\partial I_e} = -2 \sum_{i=1}^{n} (D_i I_{ri} + D_i I_c) X_i = 0 \tag{14}$$

In order to obtain the individual capacitor current at each of the branches on 30 bus network, it is necessary to equate the maximum saving per capacitor current to zero.

$$-2 \sum_{i=1}^{n} (D_i I_{ri} + D_i I_c) X_i = 0 \tag{15}$$

$$\sum_{i=1}^{n} D_i I_c X_i = -\sum_{i=1}^{n} D_i I_{ri} X_i$$

The following steps bring capacitor current I_c, to one side in order to compute the new capacitor current new reactive current I_{ri}^{new} of the i_{th} branch.

$$I_c = -\frac{\sum_{i=1}^{n} D_i I_{ri} X_i}{\sum_{i=1}^{n} D_i X_i} = -\frac{\sum_{i \epsilon \alpha} I_{ri} X_i}{\sum_{i \epsilon \alpha} X_i} \tag{16}$$

However by capitalizing the powerful features of MIATLAB GATool, finding the optimum values of capacitor current I_C can be performed by using (16). MATLAB GATool is initially designed to locate the minimum value of any mathematical expression. In the case of interest, in order to locate the individual capacitor current I_C value at which maximum savings is achieved, the entire expression (16) need to be negated. This allows the computation of capacitor current

IC within the multidimensional expression of the total reactive power saving. The computed set of capacitor currents I_C are optimized to obtain the maximum saving of reactive power.

The capacitor current I_C which produces the highest saving is then used to compute the optimal capacitor size. This capacitor is then inserted to the respective branch in 30 bus real network where the capacitor current I_c is calculated to produces the highest saving. The optimal capacitor size is computed using (17).

$$Q_c = V_m I_c \tag{17}$$

RESULTS AND DISCUSSION

In this section the application of proposed strategy discussed at 6 steps.

A. Load Flow Analysis:

Utilizing the MATLAB software, the load flow analysis is conducted. The results are produced giving the values of total active and reactive power losses. Besides, the value interested from the load flow analysis is the bus voltage profile for further calculation and simulation of loss savings and capacitor sizing using the MATLAB. The 30 bus real network constructed for simulation of voltage profile and OCP is as shown in Fig. 3.

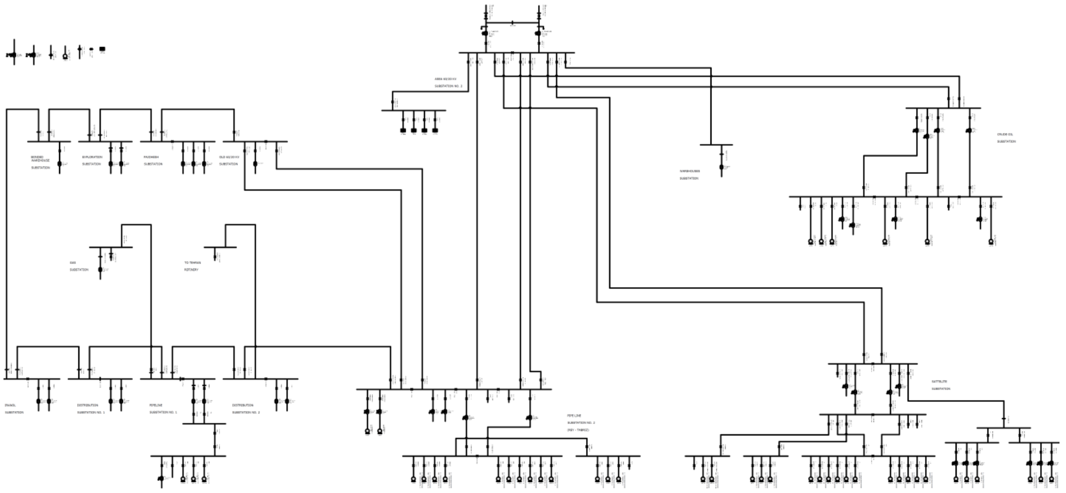


Fig. 3: Real 30-Bus System Simulation Setup

B. Gatool:

GAtool is utilized to obtain the capacitor current, I_c needed for the further simulation of the loss saving. Hence, the function is written in the M-file format to obtain the simulation result utilizing population of 30.

C. Matlab:

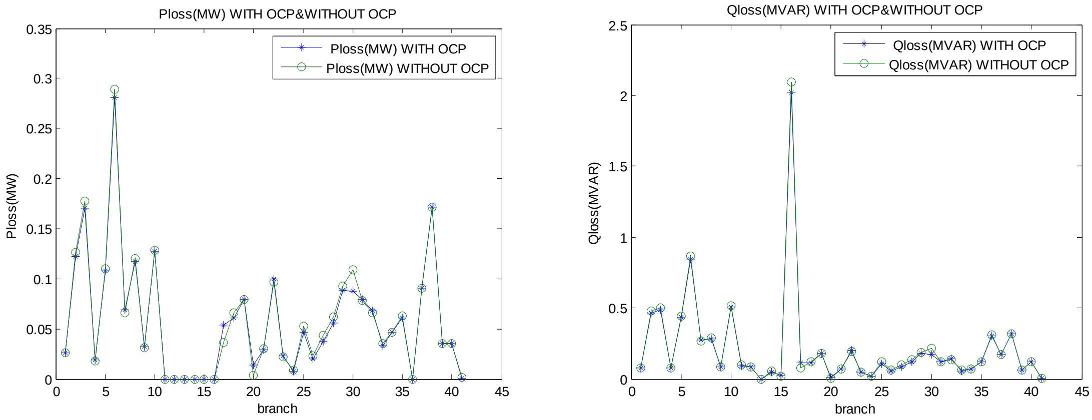
The source code of the MATLAB programming for the calculation of loss saving at each branch and its capacitor sizing is written. The generated output of the program shows the competence of the proposed algorithm and the efficiency of simulation. To make the proposed theory more applicable, we develop two scenarios that are explained in detail at D and E.

D. Capacitor Placement With Available Var Capacity:

For, inserting available capacitors at optimal locations, we must set some limitation to the algorithm. First is the nominal voltage of available capacitors that must mach to the bus voltage second is the size of each capacitor and total VAR that is available. Minimum and maximum size of capacitors is given to the program and selected buses are defined. The simulation is done, so location and size of CBs are designated; then the load flow is run again from the modified system to obtain the voltage profile and losses. 8.4 MVAR capacity is inserted at specified buses in the 30- bus real network which is show at table 1. Figure 4 summarized the result of real and reactive power losses before and after OCP.

Table 1: Location and size of CBs after simulation.

Bus number	Size of Capacitor bank
3	0.2
8	0.1
14	4.4
17	1.7
18	2



(a) (b)

Fig. 4: Active (a) & reactive (b) power loss before and after OCP with available capacity

From Figure 4, it is noticed that active and reactive power loss are decreased after OCP. The extra advantage of utilizing shunt capacitor insertion is that it helps to improve the voltage profile of the entire system. This is due to the current flowing in the line is decreased due to flow of less reactive component branch current, the voltage drop will decrease which in turn improve the voltage profile. This is clarified at figure 5.

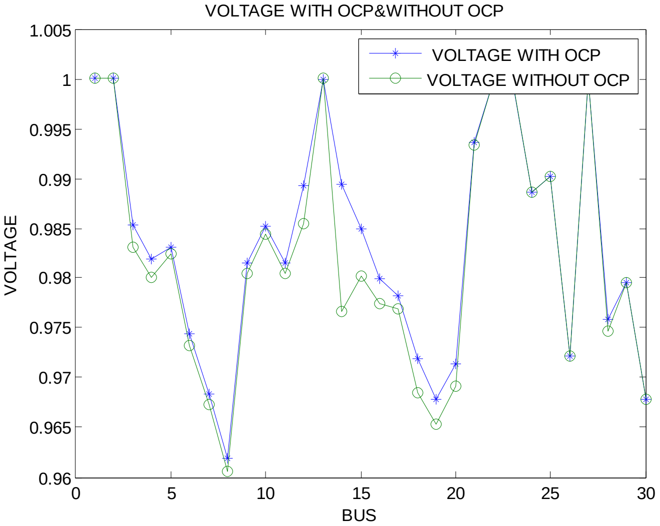


Fig. 5: Voltage profile before and after OCP with available VAR capacity

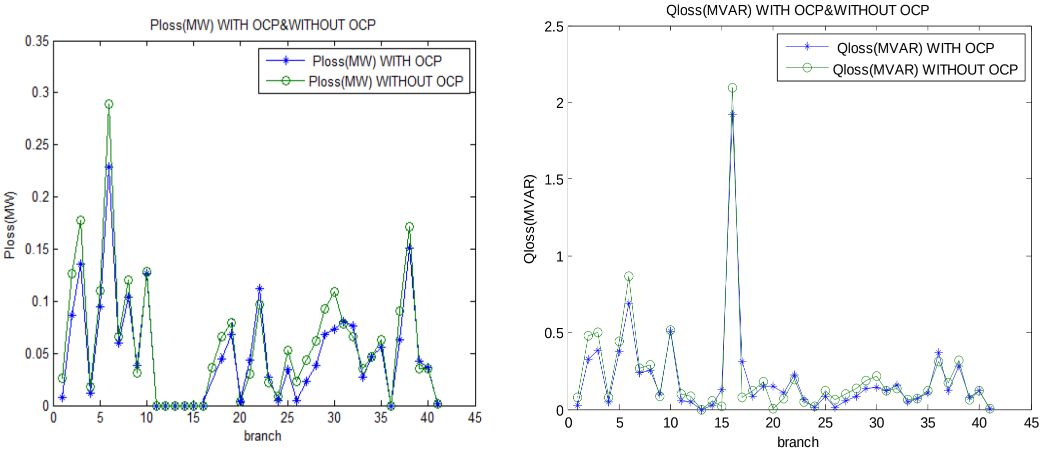
E. Optimal Capacitor Placement With Maximum Var Capacity:

To compensate maximum reactive power which is necessary for the mentioned distribution system, and allocating the place of CB we must run the algorithm again without specifying previous limits

After simulation of OCP, the capacitors are inserted simultaneously to reduce the losses and improving voltage profile. At this simulation, 7 CBs are inserted to the specific buses with the total capacitor size of 20.4MVAR. Figure 6 and table 2 summarized the result of simulation.

Table 2: Location and size of CBs with maximum capacity after simulation.

Bus number	Size of capacitor bank
3	0.1
10	0.4
15	8.3
16	2.3
19	5
20	2.2
21	2.1



(a) (b)

Fig. 6: Active (a) and reactive (b) power loss before and after OCP with maximum VAR capacity insertion.

As it is said before, after reactive power optimization the voltage profile will also improved. The voltage profile after OCP with maximum needed capacity insertion is shown below and it is compared with the voltage profile before OCP in figure 7.

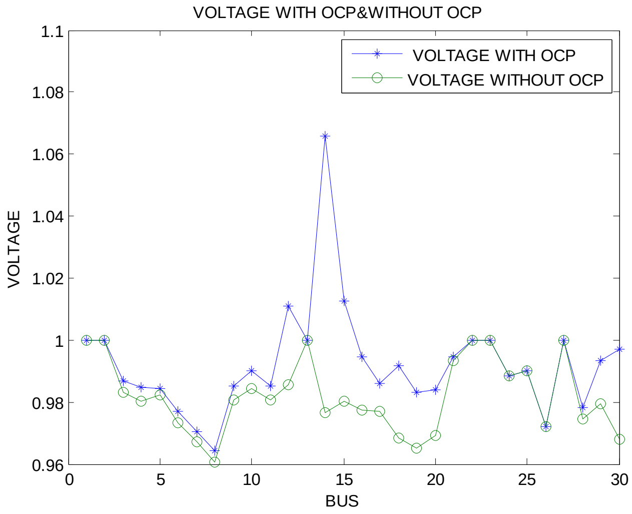
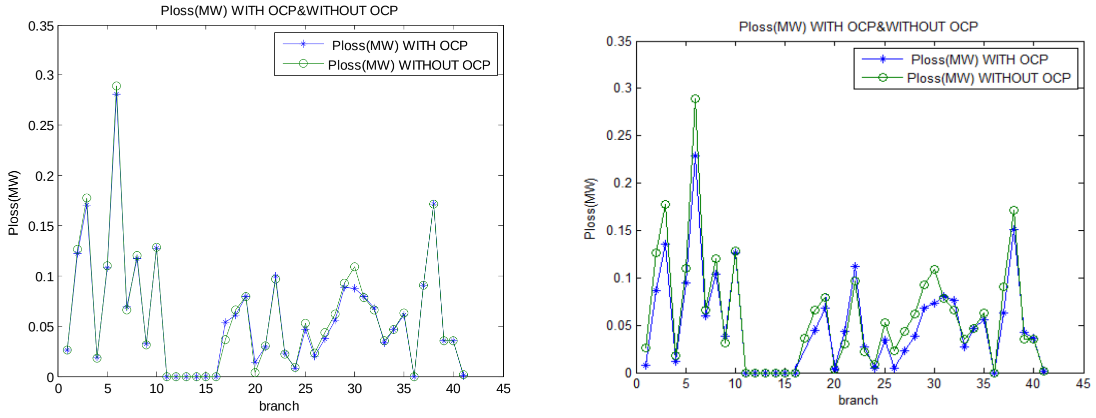


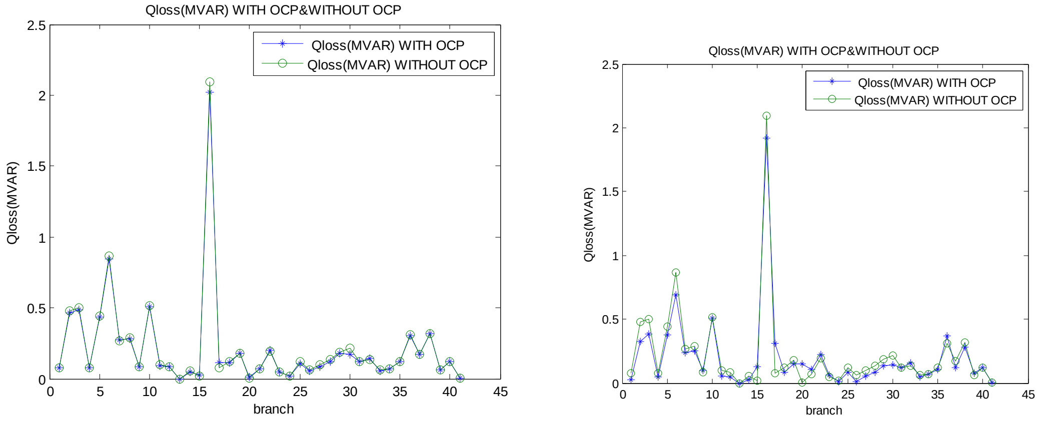
Fig. 7: Voltage profile before and after OCP with maximum VAR capacity insertion.

F. Comparisons:

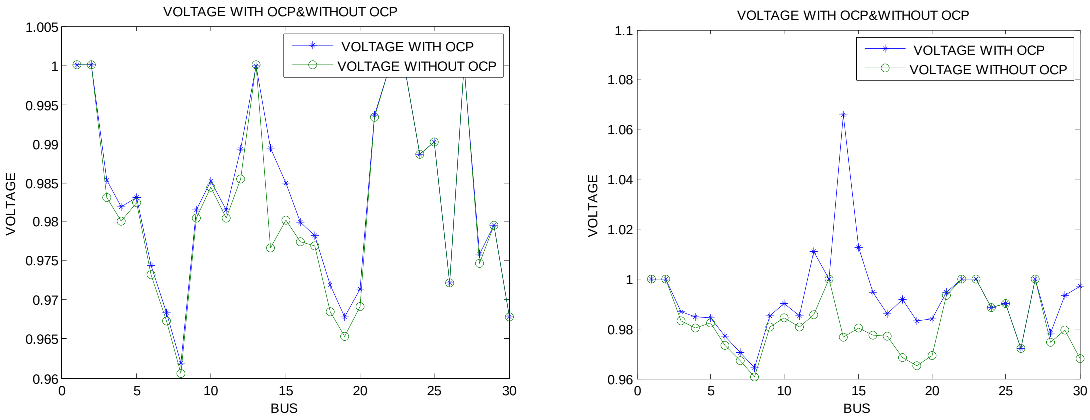
The results of both simulations are analyzed and compared with each other. The outcome shows that we could have better voltage profile and lower power loss if we use the maximum capacity of reactive power that is needed for grid without voltage and size limitation in the simulation. You can find the comparison in the figure 8.



(a) Active power loss of first scenario. (b) Active power loss of second scenario.



(c) Reactive power loss of first scenario. (d) Reactive power loss of second scenario.



(e) Voltage profile of first scenario.

(f) Voltage profile of second scenario.

Fig. 8: Comparison between simulation results of two scenarios.

Conclusion:

The proposed strategy aims to prevent assets failure and increase system security and reliability by coordinating the operation of reactive power control and reliability centered maintenance with the view of assets life cycle. As a conclusion, the results of simulated algorithm of both scenarios shows that by applying OCP, active power loss and reactive power loss are decreased and voltage profile improved, therefore system capacity is released, loads of facilities and assets especially reactive loads are decreased so damages, risks and failures are decreased too and asset's life cycle increased.

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