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Optimal Control of Switched Capacitor Banks in Vietnam Distribution Network Using Integer Genetic Algorithm

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ABSTRACT

In distribution network, power and energy losses can be reduced by using switched capacitor banks. The capacitor banks can be switched on or off based on voltage profile or power factor or using timer. Due to variation of load, it is necessary to control the capacitor banks switching in function of load curve. This paper presents the application of integer genetic algorithm to determine optimal number of banks corresponding with hourly load to minimize total active power losses of distribution feeders. The problem constraints include voltage profile and heat conditions which are taken into account to the objective function by a penalty function. In this application, the structure of chromosomes is a set of numbers of the capacitor banks hourly connected to the grid. The proposed formulation is validated by a feeder. The result shows that in some cases, the active power losses at maximum compensation is greater than the ones of optimal control compensation, and the voltage reaches higher level than the maximum voltage limit. The optimal control of switched capacitor banks can reduce power and energy losses as well as ensure maximum voltage profile within the limit.

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1. INTRODUCTION

Power and energy losses reduction is an important problem in power system operation. In distribution networks, many solutions have been studied and applied to reduce the power and energy losses such as: reactive power compensation, optimal reconfiguration, demand-side management, distributed generation . . . Ref [1] solves voltage rise problem in distribution networks with distributed generation. Ref [2] presents methods to optimize sizing and location of distributed generation for loss minimazation. For reactive power compensation, capacitor banks are installed at substations on either medium or low voltage side. Major researches focus on optimal allocation of capacitors and sizing in distribution networks to reduce power losses and to improve voltage profile [3]-[7]. However, these studies are mostly limited and applied in design process. Optimizations are modeled in the cases that power loads are maximum. Ref [8] proposes a method to determine the optimum distribution system configuration and reactive power of capacitor banks for each interval of the planning period.

In Vietnam, the energy losses reduction is an important task which four power transmission companies (the power transmission company 1 in the north, the power transmission company 2 in the central, the power transmission company 3 in the south-central and central highlands and the power transmission company 4 in the south) and five power corporations (Ha Noi power corporation, Ho Chi Minh city power corporation, northern power corporation, central power corporation, southern power corporation) must accomplish. In 2016, the power loss rate is 7.57 and is reduced to 6.42% in 2020 [9]. In the period of 2022-2025, the Electricity of Vietnam aims to reduce the power loss of the entire power system to less than 6%. Many solutions have been implemented to achieve this goal. Among those solutions, the reactive power compensation is widely applied. The issue of reactive power compensation is specified by the Ministry of Industry and Trade in Circular No. 15/2014/TT-BCT [10]. In this circular, for loads with capacity from 40 kW and power factor less than 0.9, a reactive power compensation device must be installed. Otherwise, customers will have to pay a fine. The penalty depends on the violence of the accepted power factor. The lower the power factor, the greater the penalty.

At feeder lines with many domestic loads and low power factor, power companies must install compensating equipments on the upper or lower side of the distribution transformer to reduce power loss on the networks and ensure power quality. For example, Hanoi Power Corporation installs about 480 MVAr of capacitors at the 22 kV and 35 kV medium voltage side of 110 kV substations. At each substation, many capacitor banks with capacity of 100, 175, 200, 250, 300 and 350 kVAr are used. These capacitors are usually connected for operation from 8:00 a.m. to 10:00 p.m. daily. The low-voltage compensation capacitors are located at the low-voltage side of the load stations. The compensation power is usually taken as 10% of the rated power of the station. Each load station also has many sets of capacitors that can be switched on and off. The capacity of each capacitor is 10, 15, 20, 25, 30, 40, 50 kVAr. Figure 1 presents an example of 6 levels switched capacitor banks. The power of each bank is 10 kVAr. The banks are connected to the low voltage side of the substation through a controlled switching device. At some substations, the capacitor banks are switched on and off based on voltage profile or power factor or using timer. For some other substations, there is not switch control, so the reactive power compensation is always equal to the total capacity of the capacitors. Consequently, the reactive power compensation is very large.

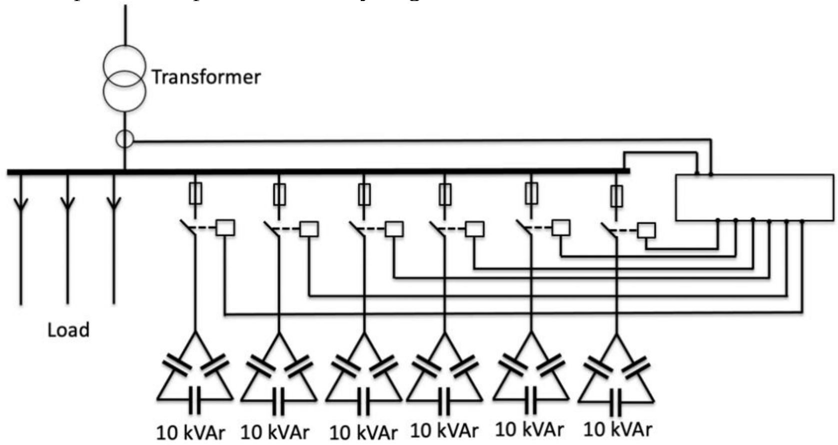

Figure 1. A switched capacitor banks of 60 kVAr at a MV/LV substation

At light load, overcompensation will affect the voltage profile and possibly increases power losses. Therefore, the calculation and selection of the switched capacitors size to obtain the optimal compensation capacity in the distribution network according to the variation of the load is very important. It is also a practical contribution to the operation of the electrical network to minimize the total power losses and still maintain the best voltage quality.

To solve the problem of controlling the compensation according to load curve of the distribution grid, we can use conventional or artificial intelligence methods such as Linear Programming [7], Newton's Method [11], Simulated Annealing [12], Ant Conoly Optimization [8], Mixed Integer Nonlinear Programming [13], Particle Swarm Optimization [14], Genetic Algorithm [2], [4], [15], [16]. As the number of capacitor banks are integer numbers, the integer genetic algorithm is a very suitable approach to this problem [15], [16]. This work therefore presents the application of integer genetic algorithm to optimal control of switched capacitor banks in Vietnam distribution network.

This paper consists of 04 sections: the first one is an introduction, the second one introduces the mathematical formulation of the problem and method, the third one is the results of application and discussion, the last one is conclusion.

2. PROBLEM FORMULATION AND METHOD

2.1. Problem Formulation

In this study, the operation of switched capacitor banks is optimized for every hour. Objective function is minimizing the total active power losses of the networks for every hour, as follows:

$$\text{Min } \Sigma \Delta P_{ij} = \Sigma R_{ij} I_{ij}^2 \quad (1)$$

Where ΔP_{ij} represents the active power losses of the branch ij, R_{ij} is the resistance of the branch ij, and I_{ij} is the current flowing through the branch ij. In this study, the total power losses is determined by using Backward-Forward Sweep Load Flow Method as presented in the next sub section.

Constraints of the problem are voltage profile and ampacity of the conductors. The voltage at every bus must be in the given range, as in (2):

$$V_{imin} \le V_i \le V_{imax} \quad (2)$$

Where V_{imin} and V_{imax} are the minimum and maximum voltage magnitude of bus i, respectively.

The condition of the maximum ampacity of the conductors is as follows:

$$I_{ij} \le I_{ijmax} \quad (3)$$

Where I_{ijmax} is the maximum current of the branch ij.

To take into account the voltage profile constraint and the ampacity condition, a penalty function is introduced as follows:

$$pf = \lambda_1 \Sigma\{\min(0, V_i - V_{imin})\}^2 + \lambda_2 \Sigma\{\max(0, V_i - V_{imax})\}^2 + \lambda_3 \Sigma\{\max(0, I_{ij} - I_{ijmax})\}^2 \quad (4)$$

Then, the objective function is modified as follows:

$$\text{Min } (\Sigma\Delta P_{ij} + pf) = \Sigma R_{ij} I_{ij}^2 + \lambda_1 \Sigma\{\min(0, V_i - V_{imin})\}^2 + \lambda_2 \Sigma\{\max(0, V_i - V_{imax})\}^2 + \lambda_3 \Sigma\{\max(0, I_{ij} - I_{ijmax})\}^2 \quad (5)$$

2.2. Backward-Forward Sweep Load Flow Method

The backward/forward sweep (BFS) is proved as one of the most suitable power flow methods for radial distribution networks [17]-[23]. The conventional BFS method is based on the calculation of Bus Injection current- Branch Current matrix (BIBC) and Branch Current - Bus Voltage matrix (BCBV). The branch currents can be obtained from the corresponding bus current by Kirchhoff's law. The BIBC matrix can then be written as below:

$$[B] = [BIBC] . [I] \quad (6)$$

BCBV matrix that includes zero elements and line impedances, can be obtained as:

$$[\Delta V] = [BCBV] . [B] \quad (7)$$

The bus voltage can be therefore calculated from bus injection current as below:

$$[\Delta V] = [BCBV] . [BIBC] . [I] \quad (8)$$

The power flow can be obtained through the iteration process by calculating the following equations:

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \quad (9)$$

$$[\Delta V^{k+1}] = [BCBV] . [BIBC] . [I^k] \quad (10)$$

$$[V^{k+1}] = [V^0] - [\Delta V^{k+1}] \quad (11)$$

Where I_{ik} and V_{ik} are bus current and bus voltage i at the iteration step k; P_i and Q_i are the active and reactive power at bus load i.

2.2. Application of integer genetic algorithm for optimal control of switched capacitor banks

The genetic algorithm is a search heuristic that is inspired by the process of natural selection. This algorithm was proposed by J.H. Holland for solving both constrained and unconstrained optimization problems. The algorithm initializes a set of solutions which is called population, a solution is called chromosome. A value which is the fitness or objective function is assigned to a chromosome. Three algorithm's operators are selection, mutation and crossover. Based on the fitness value, the algorithm applies selection operator to remove some chromosomes, and keep some best chromosomes for the next population.

The crossover chooses two chromosomes randomly whose some genes are interchanged to create new chromosomes for the next population. Figure 2 illustrates a crossover at third and fourth genes.

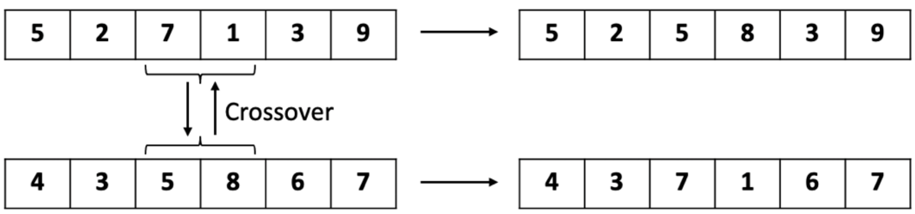

Figure 2. Example of two genes crossover in genetic algorithm

The mutation changes one or some gene values of chromosomes randomly to create a new chromosomes for the next population. Figure 3 illustrates mutation at second and third genes.

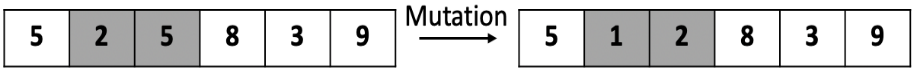

Figure 3. Example of two genes mutation in genetic algorithm

The flow chart of the genetic algorithm are shown in Figure 4. This paper presents application of the algorithm for solving the objective function (5).

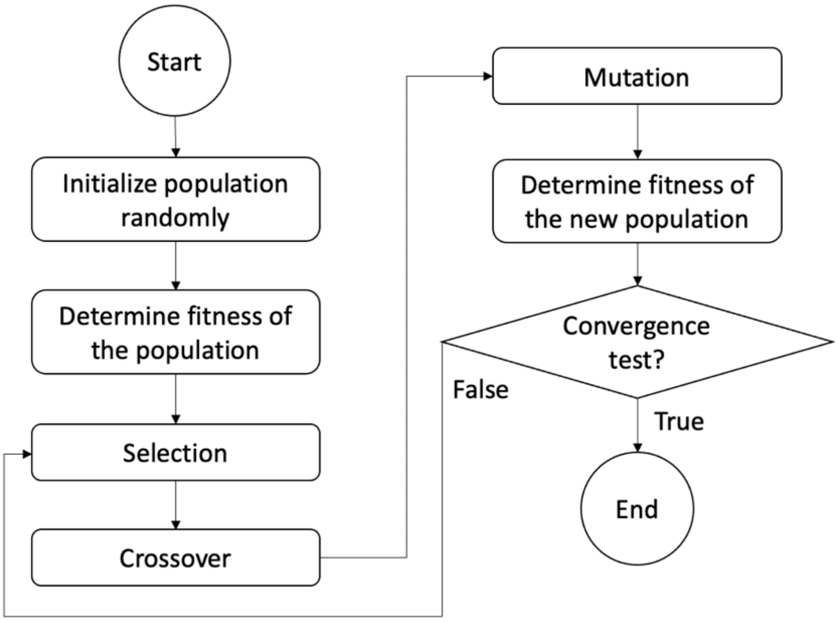

Figure 4. The flow chart of the genetic algorithm

As introduces above, the solution of our problem is the numbers of available capacitors hourly switched into to the networks. Consequently, a chromosome is a set of numbers of capacitor banks connected to the network. As the numbers of capacitor are integer numbers, the problem is solved by integer genetic algorithm [4], [15], [16], [24], [25] .

If a network has compensation at m buses, the problem solves for m variables x_i - the number of capacitors switched into the bus i at the considered hour. The structure of a chromosome will have m integer numbers as shown in Figure 5.

x_1	x_2	x_3	.	.	.	x_m

Figure 5. Chromosome's structure of a network comprising m compensation buses

The searching space of x_i depends on the maximun number of available capacitor banks at bus i. If the maximum number of capacitor banks at bus i is 7, the value of xi will be an integer between 0 and 7.

In this study, fixed capacitors are also considered by limiting the searching space of x_i between the minimum and maximum number of capacitors switched into operation. For example, there is 10 capacitor banks at bus 2, among them, four banks are fixed, the searching space of x_i is an integer between 4 and 10. This will accelerate the convergence of the problem.

3. RESULTS AND DISCUSSION

The above proposed formulation is applied for a typical 22 kV radial distribution feeder in Vietnam.
The network consists of 49 buses, 24 lines, 24 transformer 23/0.4 kV, and 24 loads as shown in Figure 6. The total hourly active and reactive power load curve of a typical day is shown in Figure 7. The bus 1 is a slack bus, its voltage is 1.045 pu. The voltage is limited from 0.95 to 1.05 pu.

Table 1 shows the number of available capacitor banks at 24 load buses. The reactive power of each bank is 10 kVAr.

Table 1. Number of capacitor banks at load buses in the network modeling

Bus	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49
Number of capacitor banks	19	38	75	15	38	6	38	38	45	24	38	6	24	19	24	15	24	38	38	24	24	38	15	38

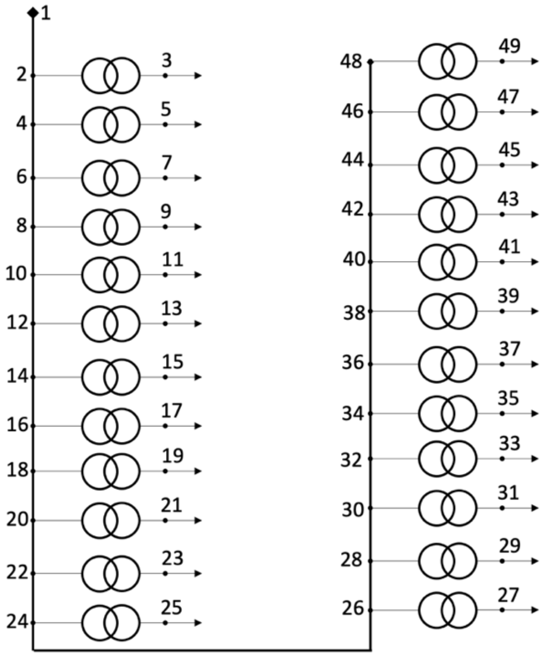

Figure 6. Single diagram of 22 kV distribution network modeling

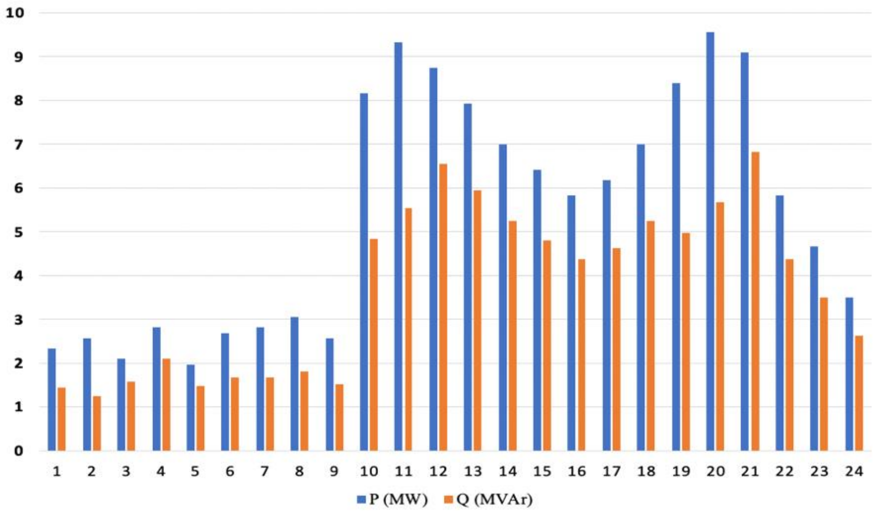

Figure 7. Total hourly active and reactive power load curve used for the modeling

Figure 8 shows the optimal number of capacitor banks switched on at bus 49. The proposed method gives different numbers of operating banks for every hour. The maximum number of banks is switched in at some hours such as 10^{th}, 11^{th}, 12^{th}, 13^{th}, 19^{th}, 20^{th}, and 21^{th}.

The simulation gives hourly active energy losses as shown in Figure 9. The figure shows that the active power losses at some hours in the optimal compensation is smaller than in maximum compensation. The total daily energy losses in the optimal compensation is 3.64 MWh, corresponding to 2.79 %. The total daily energy losses in the maximum compensation is 3.96 MWh, corresponding to 3.03 %. The proposed compensation control reduces 0.24 % of energy loss. This reduction is small but significant because the power loss of the system is relatively small and very near to the limit of technical loss. Moreover, this is only the reduction of a feeder, a cumulative reduction of all feeders of the system will be significant.

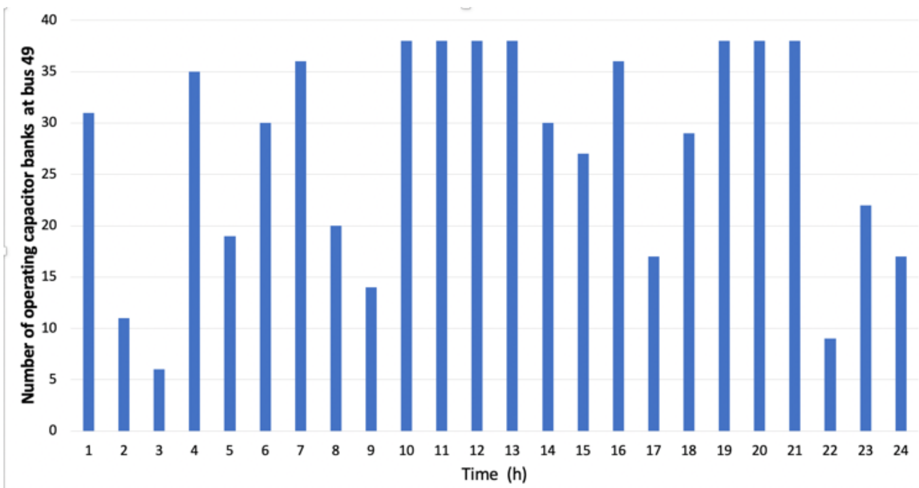

Figure 8. Number of capacitor banks switched on at bus 49

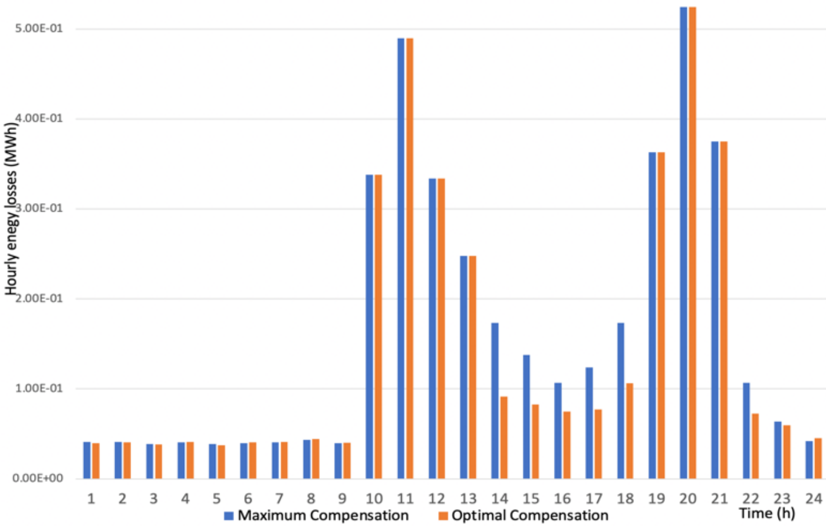

Figure 9. Power loss curve in 2 cases: maximum compensation and optimal control compensation

Figure 10 shows the maximum voltage in two cases: maximum compensation and optimal compensation. The results show that the voltage exceeds the limit (1.05 pu) in the case of maximum compensation. The maximum voltage of optimal compensation case is within the limit range.

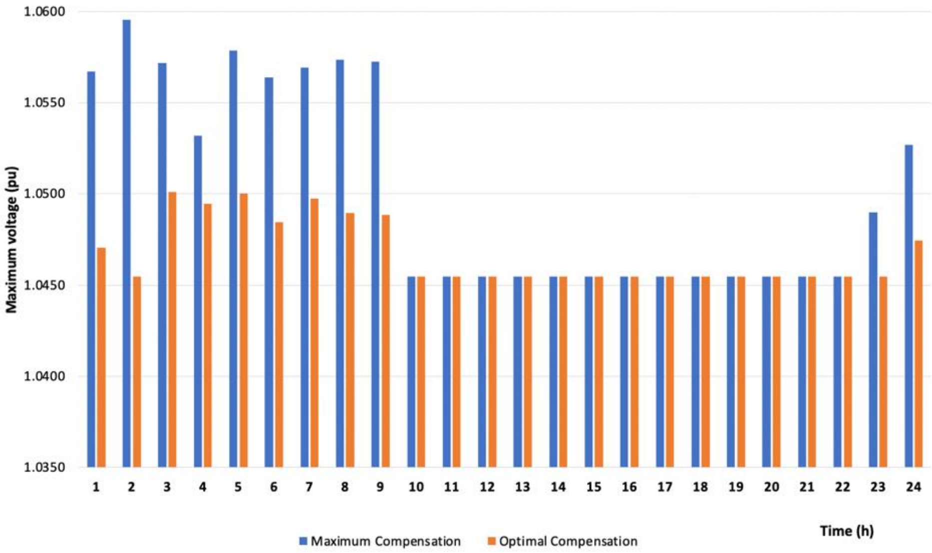

Figure 10. Maximum voltage curve in 2 cases: maximum compensation and optimal control compensation

Figure 11 shows the minimum voltage in two cases: maximum compensation and optimal control compensation. It must be noted that at some hours, the minimum voltage is smaller than 0.95 pu although all the banks are switched into operation.

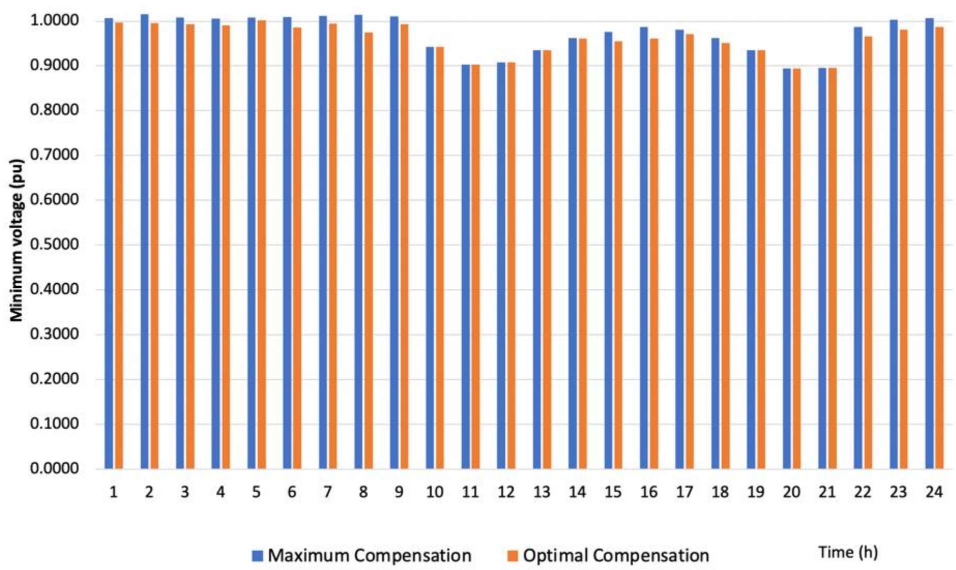

Figure 11. Minimum voltage curve in 2 cases: maximum compensation and optimal control compensation

4. CONCLUSION

This paper proposes an optimal strategic control of the switched capacitor banks in function of hourly load to reduce energy losses and ensure voltage quality. The upper and lower voltage range and ampacity of conductors conditions are included in the objective function. This work applied the integer genetic algorithm for solving the problem. The chromosome consists of a set of interger numbers which are the number of capacitor banks at each bus. The simulation results show that the hourly control of switched capacitor banks can reduce the losses and ensure that the maximum voltages are within the limit range. The future work can focus on minimizing the number of switching and improving the minimum voltage.

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