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Reactive power compensation of Saudi electricity-western operation area using dynamic programming and genetic algorithm

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This paper presents a study of the 380-kV network of Saudi Electricity Company in the Western Operation Area (SEC-WOA). Where, the effect of using series, shunt, and mixed capacitors for reactive power compensation on the network is investigated. Three different load levels namely light, medium, and peak have been considered in the investigation. Power world simulator (PWS) is used to perform the network load flow analysis, the obtained results were identical to the real load flow in the company documents. PWS based Dynamic Programming is used to determine the size and optimal location of the capacitor used in each scheme used for reactive power compensation for the network and compared to the optimum solutions obtained by both the Genetic Algorithm (GA) and the Hybrid Genetic Algorithm (HGA). The comparison reveals better solutions of the proposed method compared with GA and HGA

Keywords: Load flow, Reactive power, Genetic algorithm, Capacitor, Compensation.

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1. Introduction

The problem of optimal reactive compensation has been addressed in many papers and reports. Linear and non-linear programming methods have been proposed to solve the placement problem. In the following, the previous work is reviewed in brief. A computerized trail and error heuristic method for optimizing the present worth of revenue savings [1-3]. The savings are associated with released system capacity and energy loss reductions. The non-uniform load distribution and conductor size were taken into consideration. Both fixed and switchable capacitor banks and their installation cost were also considered. The availability of the capacitor banks in accordance with the standards and released capacity cost were included as well. The effects of the main and lateral branches were studied. Dynamic programming has been used extensively by researchers in different power system studies. Linear programming to find the optimum capacitor placement [4-8], and applied dynamic programming in solving the problem in capacitor allocation in power systems. A treated VAR planning problem as a mixed integer programming problem using zero-one variables to establish whether new capacitor banks should be installed [9-10]. They presented a fast converging method for finding the optimal capacitor allocation in a power system for minimizing power losses and for improving the quality of the supply system which is achieved by optimal allocation of all reactive power sources in the system in a coordinated way. The optimization problem is solved by MILP based on Bender's decomposition algorithm in which the mixed problem is decomposed into two smaller sub-problems. The solutions of these two sub-problems are combined to get the solution to the original problem [11-15]. The problem of the capacitor placement for reactive power control has been extensively researched over the past several decades. Many solution methods and algorithms were used to solve the problem of capacitor allocation in power systems [16-18]. The solution techniques can be classified into four categories of analytical, numerical programming, heuristics, and artificial intelligence-based. More

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recently, the use of various nondeterministic methods to solve the VAR planning problem has been described. These new proposals include Genetic Algorithms (GA') Simulated Annealing (SA), Tabu Search (TS), Expert Systems (ES's) and Artificial Neural Networks (ANN's) [19-20]. Throughout the research, we prefer to use dynamic programming (DP) as it is more practical to the analysis of the effect of shunt and series capacitor compensation in the SEC-WOA. In this method, we place the shunt or series capacitor along the transmission lines and study the reflection of this compensation on releasing the system generating capacity, reducing the system losses and improving voltage profile at the specified bus. All the three types of capacitor compensation, shunt, series, and mixed compensations are investigated separately. At the end of each compensation case, the optimum recommended values of reactive power compensation will be given. The idea of this is to give the SEC-WOA a wide range of capacitor compensation vision and the expected outcome of each case if implemented. As a result of the investigation, this analysis should guide the network operators on what and where the capacitor compensation is needed during each load level. However, the extent to which these benefits are achieved depends on how the capacitors are placed on the system. Due to this, the optimization of the capacitor placement problem (CPP) is important for studying the effect of capacitor compensation of a certain system.

The problem of reactive power control for the SEC-WOA network has been addressed in this paper. Among reactive power compensator devices shunt, series, and mixed capacitors were considered in the problem formulation. The purpose was to study the effect of capacitor compensation in terms of operational point of view. The effect of capacitor compensation has been studied from three points. First, the problem of the series capacitor compensation was considered. The second type of compensation was considered is the shunt compensation. Finally, a mixed of shunt and series capacitors was implemented. The investigation of the effect of the above three types of capacitor compensation has been studied separately. In the proposed method, a systematic online placement of capacitors was considered. The results of the analysis were discussed based on the maximum reduction in the generated MVAR. The load variation is accounted for by considering three different load levels classified as light, medium and peak load levels with a pre-specified duration for each one. In the optimization stage, the objective function consists of two terms, namely the cost of energy losses and the cost of capacitors to be installed. The aim is to minimize the objective function while satisfying the system's constraints. System's constraints are intended to be realistic in order to have a more reliable solution. They include power flow constraints, load variation, operational constraints such as minimum and maximum allowable operating voltage, maximum and minimum limits of power generation. When solving the capacitor placement problem, the number, size, location and control settings of the capacitors at different load levels shall be determined. The load flow program is solved by the Power World Simulator PWS software.

2. Applied Solution Methodology

Objective Function: The objective of the capacitor placement problem is to reduce the total reactive power generation of the system during all load levels, hence minimizing the system power losses while maintaining a minimum cost of capacitors to be installed in the system. With this, the formulated objective function consists of two terms. The first is the cost of capacitor placement and the second is the cost of the total energy losses. The cost associated with capacitor placement is composed of a fixed installation cost, purchase cost and maintenance cost. In the case of shunt capacitors, the cost function is a step-like function rather than a continuously differentiable function since capacitors, in practice, are grouped in banks of standard discrete capacities. The cost of the shunt capacitor coefficient is considered as KC=4$/kvar [20]. Likely, in the case of series capacitors, the cost function is also a step-like function. The cost of the series capacitor coefficient is considered as KSC=100$/kvar as prices [15]. The second term in the objective function represents the reduction of total reactive power generation. The effect of this reduction is measured as a reduction of total energy losses cost. This can be obtained by summing up the energy losses for each load level multiplied by the corresponding duration. The energy cost coefficient was considered as KE=0.06$/kwh [21-22].

Procedure and Framework: In this method, the optimization process consists of three major steps. First is the choice of the location. The program scans all the buses and calculates the objective function at each time for single bus shunt compensation. Second is the improvement of the solution considering the standard bank size. The aim of this step is to decrease the objective function. Third, the program will sort the best ten locations and their objective functions, the same process is done for the series compensation. The program will scan all the overhead lines and calculate the objective function at each time. Then, it will sort the best ten locations based on the minimum objective function. After the end of the single compensation case, the program will investigate the double-capacitor compensation case. In this time it will give a list of the best ten locations of dual-bus or dual-lines capacitor compensation. Genetic Algorithm: When applying a crossover operator, the algorithm designer shall choose among a single-point crossover or a multi-point crossover. Although a single-point crossover proved very powerful in a lot of GA applications, some researchers reported good performance of GA using a multi-point crossover. Genetic algorithm has many advantages in solving optimization problems. In addition to its simplicity, it has the ability to deal with practical constraints. Because of this, GA has been designed to solve the problem of reactive power planning for multi machines system.

Capacitor Size and Control Settings: In this investigation, both types of shunt and series capacitor compensation were considered. The size and control setting, for shunt or series compensation, were implemented based on the following. First, in the case of shunt compensation, the shunt capacitor units were added to the load buses. The control range, in which the optimization has been treated, from 0 MVAR up to 99% MVAR of the load at the specified bus. In order to speed up the solution process and reduce the search domain of the optimization problem, steps of 0.5 MVAR were taken in the control settings of shunt capacitors. The capacitor sizes and control settings are treated as discrete variables and this makes the formulated problem a combinatorial one. Second, in the case, if series compensation, the series capacitor units were added in series with the overhead lines only. The control range, in which the optimization has been treated, from 30 up to 70% compensation of line reactance. In order to speed up the solution process and reduce the search domain of the optimization problem, a step of 1% as taken in the control settings of series capacitors [22-23].

Features and shortcomings: One can conclude the following features and shortcomings of applying this method to the problem of the reactive power planning. The proposed method is simple and easy to be implemented for any power system. This investigation shows many different cases of reactive power compensation in each time. This help the planning people in the SEC-WOA to have a wide view for different compensation scheme. The algorithm deals with the system itself rather than dealing with mathematical models. This is done by placing the capacitor at each case and testing its reflection on the system practically. On the other hand, this method needs a huge time for investigating many cases. But, as this might be used in the planning stage, the time issue will not be a problem.

3. Test System Description and Data

The SEC-WOA consists mainly of four major subareas that are the main cities as shown in Fig. (1). These cities are Jeddah, Makkah, Taif, and Madinah. The peak load is about 7500 MW and is increasing at an average rate of 6.8% per year. The system consists of large steam units (250 to 380 MW) and many different sizes of gas turbines in about 10 major power plants and several other smaller plants. There are about 17 major power 380/110 kV bulk supply stations that feed corresponding zones. Within each zone the local 110/13.8 kV on supply the distribution system. There are almost one hundred substation and thirty 110-kV substations

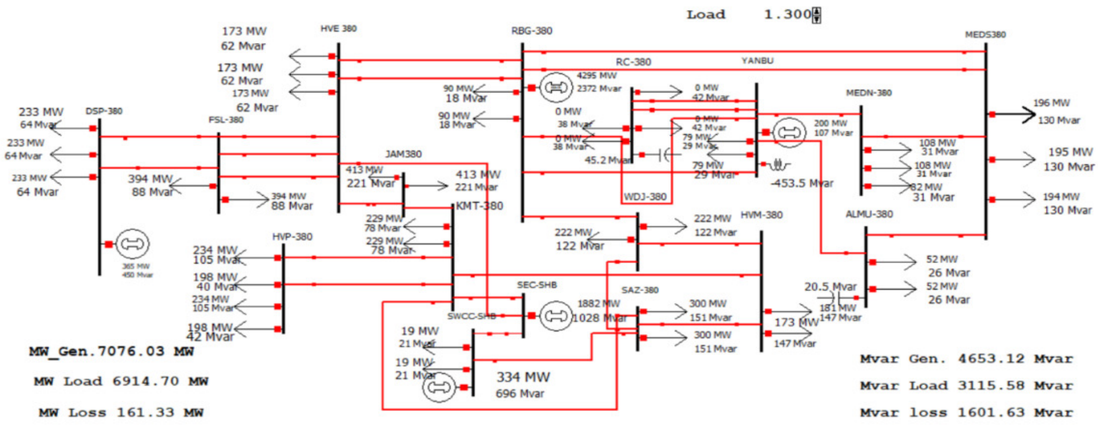

Fig. 1: Western Region 380-kV Electrical Network

4. Results and Discussions

The load flow solution shows that there are 33 transmission lines carrying the power between the 380-kV substations. The total generated active power from the network stations, at peak time, was about 5699 MW. On the other hand, the reactive power generation at peak time was about 1455 MVAR. The maximum voltage at peak time was 1.045pu at substation number 1250. On the other hand, the minimum voltage noticed was 0.955pu at substation number 1600. The total kW losses of the SEC-WOA system at peak was 71.4 MW. In this analysis, the investigation has been done for single capacitor and multi-capacitor compensation. These results were compared with the real load flow in the company documents and found indistinguishable.

4.1 The Economic Benefits of Compensation on SEC-WOE

In this analysis, the purpose is to find the optimal solution for the series, shunt, and mixed capacitor placement problem. This means to determine location, type, number and size of series, shunt, mixed capacitors to be installed in the system. The objective is minimized the energy losses while considering the capacitor installing costs. In other words, the revenue savings resulting from the energy loss reductions are weighted against the installation cost of capacitors. The objective is to achieve the optimal or maximum value while satisfying the system constraints. In this optimization, the series, shunt, and mixed compensation has been solved for the 380-kV overhead lines of the SEC-WOA system.

A. Effect of Series Compensation on the Network

The effect of series capacitor compensation on the 380-kV overhead lines has been studied. Single, double, and triple compensation were considered separately. Beyond triple capacitor compensation, the difference of benefits is not valuable and hence we don't recommend to implement more than three series capacitors at a time. With single capacitor compensation, it has been found that the best location to install will be in the transmission line connecting the 380 kV substations number 30 and 1250. By this, we can get a reduction in total generated reactive power about 21.3% of the total generation during peak time. By implementing the two overhead line connecting substations (30-1250), and (1102-1250) series capacitors the total reduction in the total generated complex power will be around 24.2% of the total generation, at peak time. It was found that the best locations of three capacitors at peak time should be in the lines connecting substations (30-1600), (30-1250), and (1102-1250). Installing these series capacitors will reduce the total generated MVAR in SEC-WOA by around 25.5%. Figure (2) presents the results of single, double, and triple capacitor compensation on 380 kV lines. In this figure, the impact of series compensation on peak, medium, and light load are shown.

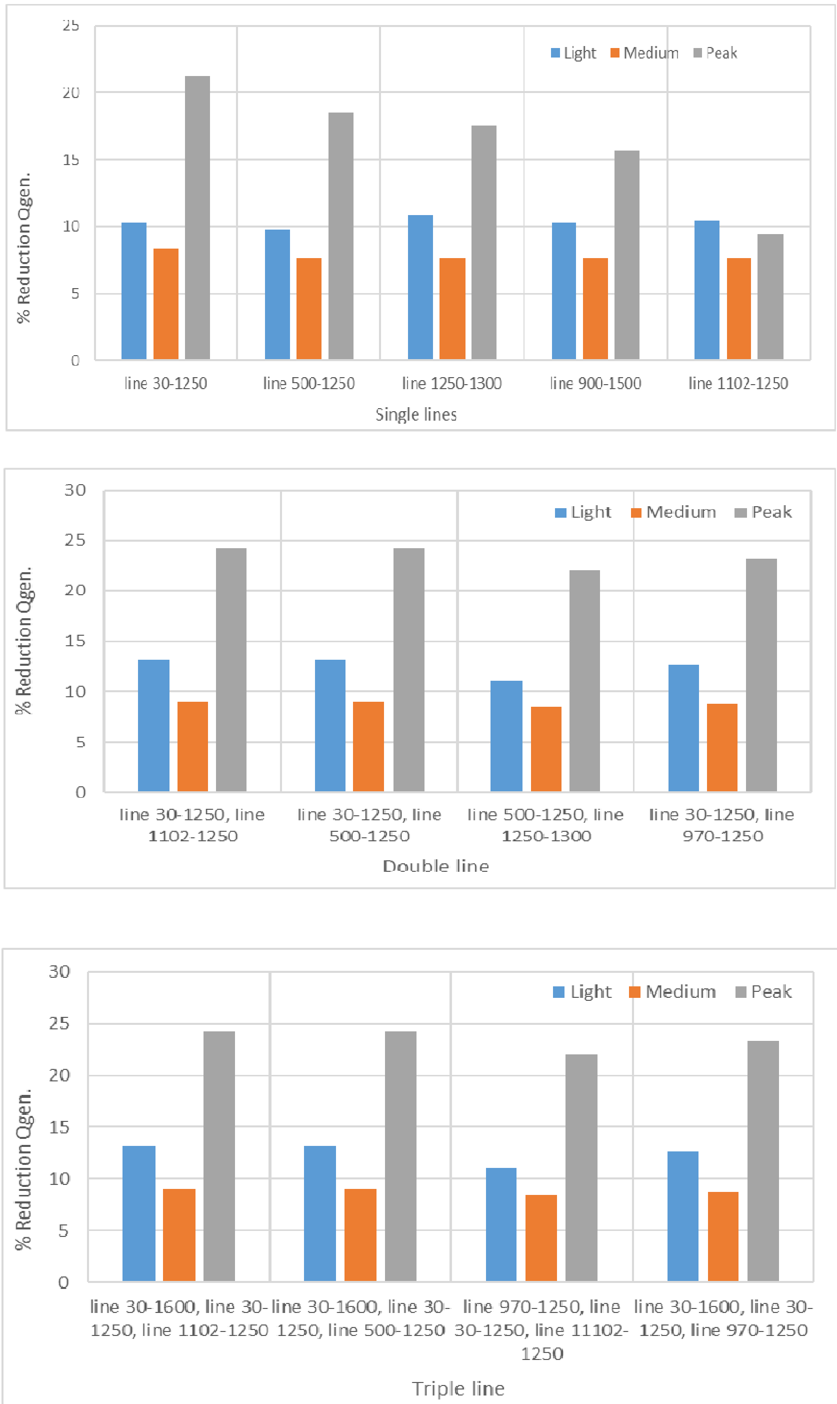

Fig. 2: Series compensation applied on the 380-kV network

B. Effect of Shunt Compensation on the Network

The results of shunt capacitor compensation for the 380-kV network are highlighted. This reduction represents around 52.3% of total system generation. The analysis has been conducted for single, double and triple capacitor compensation. In the case of single-bus compensation, this reduction is about 31% of the system generation. The reactive power compensation should be installed at substation number 500. On the other hand, the best location of shunt elements should be installed at buses 970 and 1550, the system generation can be declined by about 50.4% of system generation by applying for double-bus compensation. For 3-bus shunt compensation, the best reduction in the generated MVAR is better than a two-bus compensation case. This reduction is about 52.3% of total generated MVAR. To achieve this reduction, three shunt elements should be installed at buses 10, 970 and 1550. Figure (3) shows the results of single, double, and triple compensation for the SEC-WOA network.

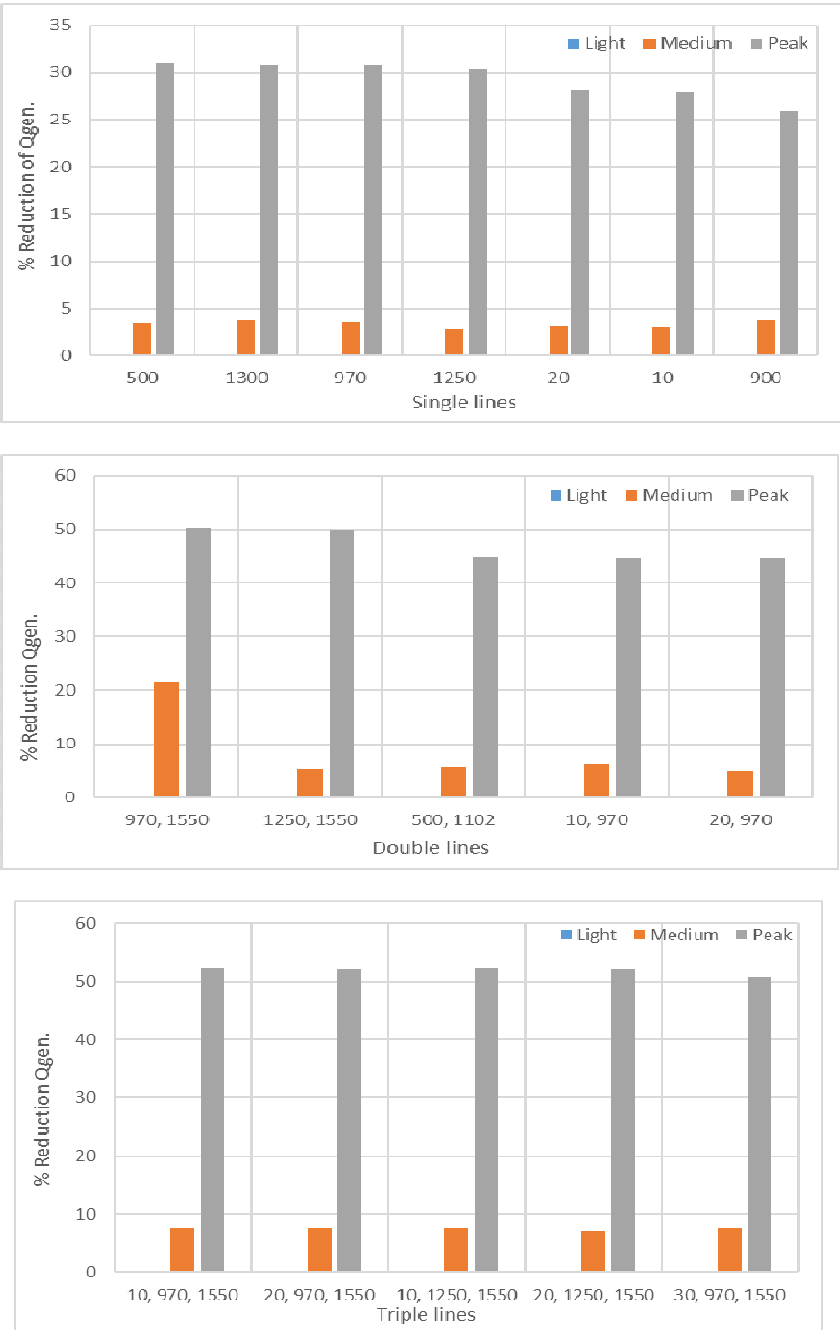

Fig. 3: shunt compensation applied on 380-kV network

C. Effect of Mixed Compensation on the Network

Applying for mixed capacitor compensation on 380-kV system results in a reduction about 46.6% of total system generated MVAR. This investigation was performed for single, and double capacitor compensation. Test results experienced no valuable reduction in the generated MVA beyond double compensation. It will not be recommended to go with more than double mixed compensation. In the single mixed compensation case, the maximum reduction in the generated MVAR obtained in during peak load is 41.3% of total generated MVAR. The single shunt compensation should be added on bus number 870. On the other hand, the single series compensation should be added into the 380-kV transmission connecting substations (30-1250). In the case of double mixed compensation, a total reduction is about 46.4% of the system generation. The two shunt elements to be added are on buses 500 and 970. On the other hand, two 380 kV lines, connecting substations (1102-1250) and (20-500), should be compensated by series capacitive elements of double-mixed compensation case on 380 kV system. Figure (4) shows the test results of single and double mixed compensation on 380-kV system. In this figure, the best locations are sorted based on the maximum reduction of the generated MVAR. Compensation values of all three load levels peak, medium, and light are also presented. The power losses as shown in Fig. (5). The proposed method is based on online placement and testing of the series, shunt, and mixed capacitors to the network and hence there is no need to check the load flow of this solution as shown in Fig. (6).

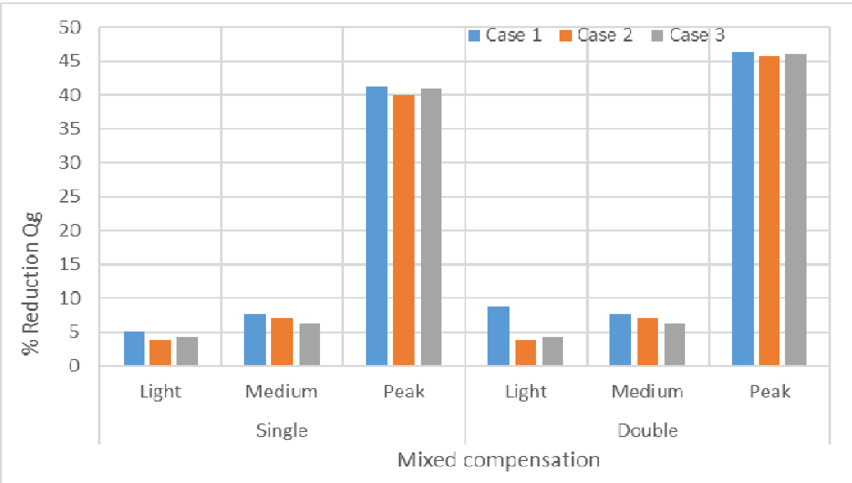

Fig. 4: Mixed compensation on 380-kV network, $\%Q_{Red}$.

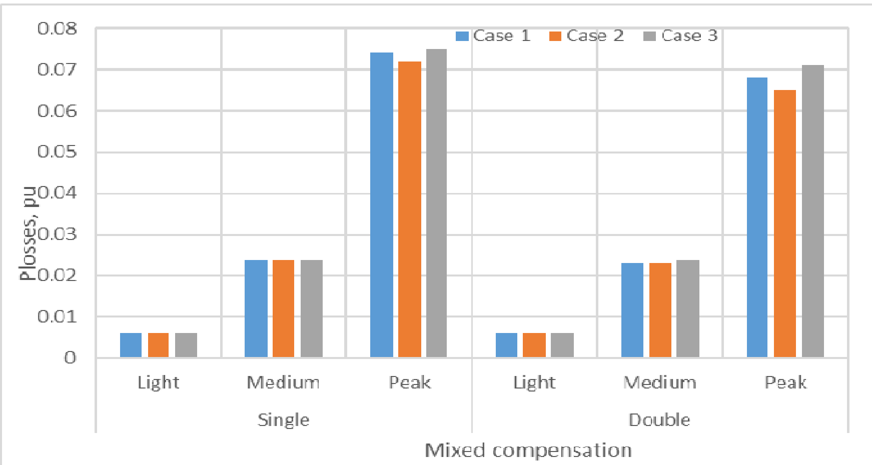

Fig. 5: Mixed compensation on 380-kV network, P_{Loss}.

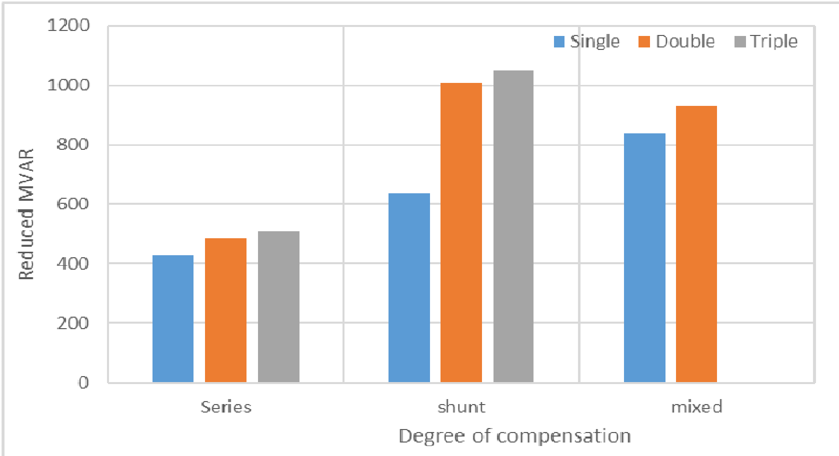

Fig. 6: Reduced generated MVAR of 380-KV compensation.

4.2 The Optimum Compensation on SEC-WOE System

The first method is based on the proposed method used in the previous analysis. In this method, a practical placement of shunt and series capacitors has been done is a systematic way, as explained earlier, in order to reach the best solution. The second method that had been to find the optimal solution was a genetic algorithm (GA) technique. The third method solves the optimization problem based on hybridization of a genetic algorithm with ordinary optimization technique. However, GA and hybrid GA methods are both based on theoretical calculations. Hence, the obtained solution by these two methods should be tested in real load flow of the system. When applying the optimum solution of GA and Hybrid GA, the system was found to be working inductive and within the specified limits. Figure (7), shows the performance of the GA, and hybrid GA optimization technique over 200 generations for the peak load level. By hybridization, a new powerful optimization technique is formed, by combining two optimization methods together, having advantages from each method. The efficiency of the new hybrid algorithm is expected to increase.

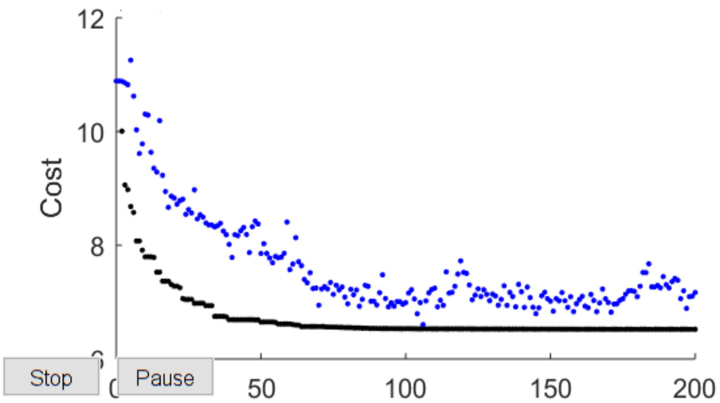

Fig. 7: GA, and Hybrid-GA performance over 200 generations.

A. The Optimum Series Compensation on the Network

First, the optimum solution by the proposed method was to place series capacitors with the values (0.201, 0.352, 0.23) on the 380kV OHL's (500-1250), (1102-1250) and (1250-1300) respectively. The transmission lines compensated by 49%, 53% and 55% of their impedance respectively. The total generated reactive power reduced by around 25.5% at peak time. By this solution, a total saving in the system annual cost 461300 $/year was reached. Second, optimum solution by using the GA method was to place series capacitors with the values (0.144, 0.206, 0.153) on the 380 kV OHL's (500-1250), (1102-1250) and (1250-1300) respectively. The transmission lines compensated by 35%, 31% and 36% of their impedance respectively. The total generated reactive power reduced by around 18% at peak time. Using the genetic algorithm method, the total system cost was reduced by 459213 $/year. Thirdly, the optimum solution, using a hybridization of GA method with another ordinary optimization method, was to place series capacitors with the values (0.156, 0.224, 0.153) on the 380 kV OHL's (500-1250), (1102-1250) and (1250-1300) respectively. The transmission lines compensated by 38%, 34% and 36% of their impedance respectively. The total generated reactive power reduced by around 18% at peak time. Using the hybridization method, the total system cost was reduced by 480609 $/year.

B. The Optimum Shunt Compensation on the Network

The optimum solution by the proposed method was to put shunt capacitors on the 380-kV buses numbered 20, 970 with the following MVAR ratings 202, 150 respectively at peak time. By this solution, a total saving in the system annual cost of 352340 $/year was reached. The total generated reactive power reduced by around 44.5% at peak time. The optimum solution by using the GA method was to place shunt capacitors with the MVAR values 214, 20 in the 380 kV buses 20, 970 respectively. Using the genetic algorithm method, the total system cost was reduced by 366349 $/year. The total generated MVAR is reduced by around 30% at peak time. Thirdly, the optimum solution, using a hybridization of GA method with another ordinary optimization method, was to place shunt capacitors with the values 210, 23 MVAR on the 380 kV buses 20, 970 respectively. Using the hybridization method, the total system cost was reduced by 374685 $/year. The total generated MVAR is reduced by around 30% at peak time.

C. The Optimum Mixed Compensation on the Network

The optimum solution by the proposed method was installing shunt capacitors on the 380 kV buses number (500, 970, 20) with the following MVAR ratings (240, 190, 20) respectively at peak time. In addition, series capacitors with the values (0.071) and (0.076) pu should be added to the 380 kV overhead lines joining the substations (20-500) and (900-1500) respectively. As a result of this solution, the total cost of the system will be reduced by 656610 $/year was reached. The total generated reactive power reduced by almost 46% at peak time. Second, the optimum solution using the GA method alone was to place shunt capacitors the MVAR values (22, 21, 39) at the 380 kV buses (500, 970, 20) respectively at peak load. With this shunt capacitors, the 380 kV lines between the stations (20-500) and (900-1500) should be compensated by series capacitors with the following values (0.071) and (0.076) pu respectively during peak time. Economically, the total annual savings will be 652847 $/year. The total generated reactive power reduced by around 22% at peak time. Thirdly, the optimum solution, using a hybridization of GA method with another ordinary optimization method, was to place shunt capacitors with the values (22, 23, 32) MVAR on buses (500, 970, 20) respectively at peak time. In addition to that, series capacitors of (0.071) and (0.076) pu should be added to the lines between the following substations (20-500) and (900-1500). Using the hybridization method, the total system cost was reduced by 655056 $/year. The total generated reactive power was reduced by around 22% at peak time. Figure (8) shows the percentage reduction of total generated reactive power for the conditions of the system with this these optimum solutions. Furthermore, the power losses are illustrated in figure (9) at all the three load levels peak, medium and light. Finally, figure (10) shows the maximum saving achieved by using the hybrid GA optimization technique. However, the proposed method is reducing the generated reactive power by about 300 MVAR, compared to the GA solutions. Although, there is no big difference in the annual savings between the three solutions. Hence, the proposed solution has the advantage of the highest reduction in the generated reactive power.

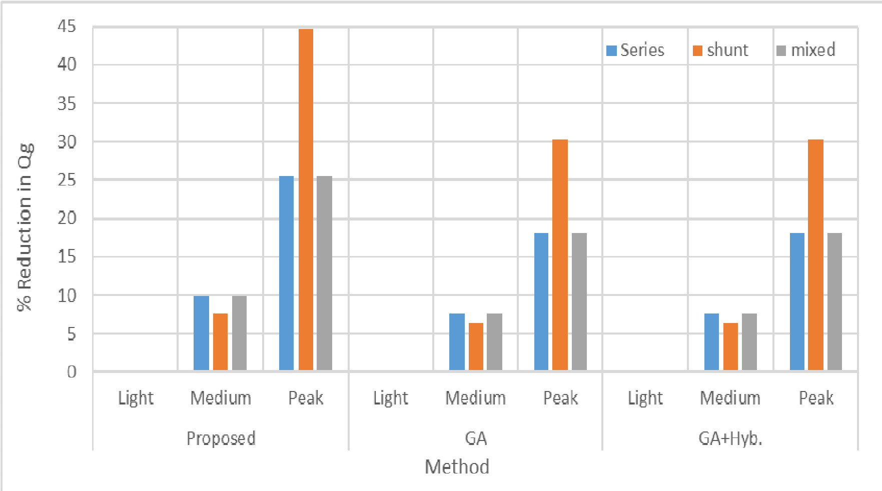

Fig. 8: % Reduction of Q_g for optimum compensation system

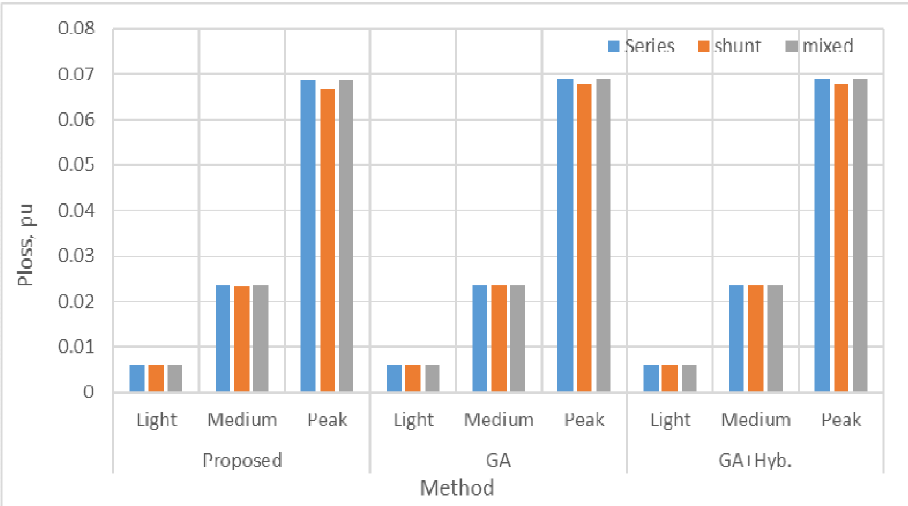

Fig. 9: P_{Loss}, pu for optimum compensation system

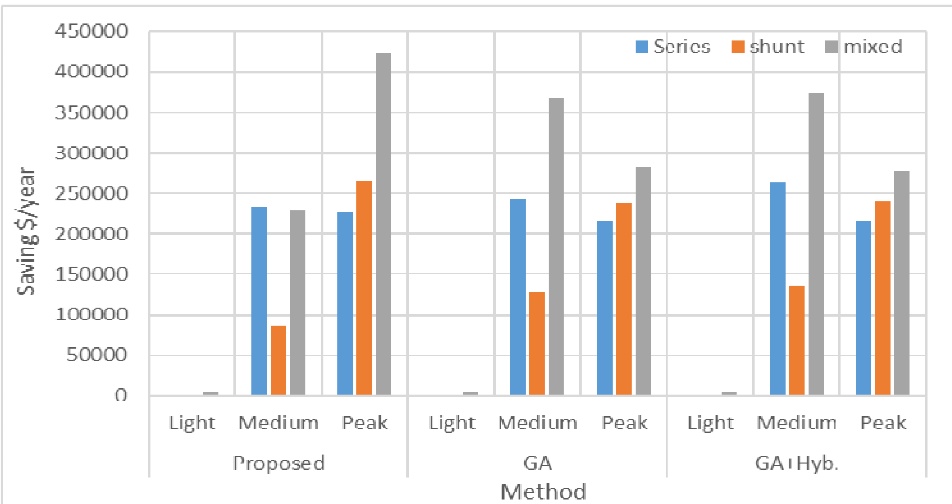

Fig. 10: Saving, $/year for optimum compensation system

Conclusion

As for a list of references, the journal Advances in the investigation of installation series, shunt, and mixed capacitors for SEC-WOA network is introduced. For each compensation scheme single, double, and triple compensation is studied. The application of PWS based Dynamic Programming as an optimization method to determine the size and optimal location of the capacitor in SEC-WOA network is presented. The optimization solutions obtained by the proposed method are compared with that of GA and HGA. In series capacitor compensation, the maximum reduction in generated MVAR was 25% for the network. Moreover, the reduction in the cost is about 461000$/year. While, in shunt capacitor compensation, the reduction in generated MVAR was 44.5% for the network. Additionally, the reduction in the cost is about 352000 $/year. Installation of mixed shunt and series capacitors is more economical than installation of shunt or series capacitors alone. In mixed capacitor scheme the reduction in generated MVAR was 46% for the network while the reduction in the cost is about 65600 $/year. HGA results in the largest annual savings for series and shunt capacitors however, the proposed method results in the largest reduction of the generated reactive power. PWS is easy to implement and provides flexibility in determining optimal size and locations of the capacitors. The results reveal that the dynamic programming (PWS) produces greater reduction in power loss greater voltage stability enhancement and total cost reduction than GA and HGA.

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