Optimal Sizing and Siting of Capacitor Bank in AC Autotransformer Electrical Railway System to Improve the Pantograph Voltage Profile and Reduce the Power Losses

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Abstract

Recently, AC electrical rail systems have been playing the important role in urban transportation system. One of the main problems of these systems is the voltage drop of pantograph. Deploying the capacitor banks in appropriate place not only can improve the pantograph voltage profile and reduce the power losses, but also provide additional benefits for system operation, like reducing the minimum allowable headway time value and improving the social welfare indices. In this paper, first the train is dynamically simulated and then, according to results, the power flow calculation is done. To achieving this, the electrical network is modeled with complete details and the optimal sizing and siting of capacitor bank with objective function of improving voltage profile and reducing the power losses are done. Simulations and calculations are done by BBA Traction Simulator Program, which is designed and developed by Alucast Iran Co. R&D team. The 2*25 kv AC autotransformer electrical railway network of Sadeghieh to Hashtgerd, Tehran is utilized to validate the applicability of presented method.

Keywords: capacitor placement, improve voltage profile, loss reduction, electrical railway, AC autotransformer system.

Introduction

Conventional electrified railway systems face many problems. some of them are so critical and may influence the viability of electrification. Many of these complications result from the load mobility. One of the main problems generally affect a normal railway system is the voltage drop of pantograph due to the flow of the reactive current in the inductive components of the overhead system. In recent studies some of these problems were analyzed. In [1] the problem of voltage drop of pantograph and harmonic distortion were investigated. In that study by installing the thyristor switched capacitor system in proper location the voltage profile of pantograph improved. The installation of stationary super-capacitor energy storage system in metro systems for improving the pantograph voltage profile and saving breaking energy are investigated in [2]. Capacitor systems can be either stationary or on-board [3-6]. The allocation on board of the storage system increases the train mass and requires additional space for their accommodation. In [2], stationary capacitor systems set inside traction substations and their best energy management, location, and size are discussed. Optimal siting and sizing of capacitor banks are also investigated in detail in [7-14]. In [7] the configuration of capacitor system for voltage drop compensation, which takes account of the topology of the line and the vehicles movement, are discussed. Reference [8] proposes an optimization method based on a genetic algorithm, to obtain the preferable location and size of capacitor systems.

By analyzing the above studies, it seems that there are some drawbacks on them. For example, some of them involve only small amounts of substations and vehicles [7, 15-17] and some of them do not take into account the network topology changes with vehicle movement and regenerative braking of the network structure.

In this paper, the train movement is dynamically simulated and according to results of that, the power flow calculation is done. The electrical network which consist of contact wire (CW), messenger wire (MW), protection wire (PW), feeder wire (FW), running rail, traction substations (TSS), autotransformer substations (ATP) and trains, are modeled with complete details. Then the optimal sizing and siting of capacitor bank with objective function of improving voltage profile and reducing the power losses are done. All these simulations and calculations are done by BBA Traction Simulator Program, which is designed and developed by Alucast Iran Co. R & D group.

Modeling of System

a. Train movement

The fact that the train is moving only further perplexes the load flow calculation and it signifies the difference between a conventional power system and a supply system in railways. The number of trains in system is also vital to the calculation as they may be running at different speeds, drawing or feeding different amount of power and thus posing different effects on the network. Nominal separation among trains is yet another important consideration and it should follow the timetables schedules of the train services. Power drawn from the train depends on the train's speed and operation mode which are in turn determined by the traction equipment characteristics, train weight, aerodynamics, track geometry, train control strategies, rout characteristics and etc. The power demand may thus vary significantly within a very short period of time during an inter-station run.

b. 2*25 kV Electrical Network

The system 2x25 kV is based on the idea of distributing the voltage along the line at higher voltage (50 kV) and feeding the train at 25 kV. For this the substations feed the system at 50 kV and through intermediate autotransformer centers supply power to the rolling stock at 25 kV. To implement the system, the substation will have transformers with secondary at 50 kV with intermediate tap. This tap will be connected to rail and ground performing the functions of neutral in the system. From the two phases, one will be connected to the overhead contact line and the other to the auxiliary feeder also known as negative (voltage is 180º out of phase with respect to the overhead contact line). Thus, between the catenary and the rail there is the required 25 kV. The intermediate autotransformer centers will be connected between the catenary and the negative, with the midpoint connected to rail and ground. Fig. 1 shows the schematic diagram of 2*25 Kv electrical network. Catenary or CW is considered the equivalent of contact and messenger wire which they are paralleled by dropper wires. Also there is protection wire (PW) that is parallel with rail and both of them are carrying the return current of rolling stock system. The Impedance of all wires is influenced by the mutual induction between each other which have been considered in the power flow calculations. It is worth mentioning that calculation of mutual inductance is done by using Carlson method [18] which is considered in BBA Traction Simulator.

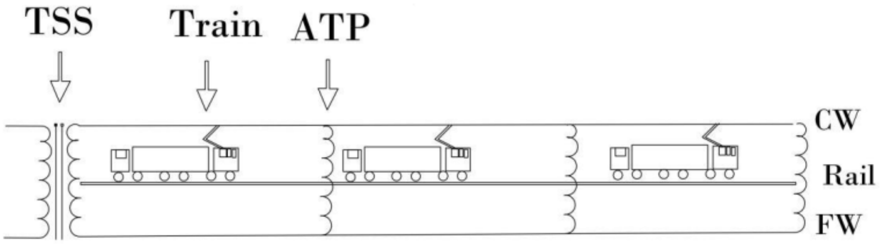

Figure 1. Schematic diagram of 2*25 Kv electrical network.

Principle of voltage compensation using capacitor bank

Due to the load current through the impedance ($Z = R + jX$) of feeding circuit, voltage drop occurs as shown in Fig. 2. Vector diagrams of system before using the capacitor bank is presented in Fig. 3. Fig.4 shows the vector diagrams of compensation using capacitor bank. The voltage drop ratio is expressed by Eq. 1.

$$\Delta V_R = \frac{V_0 - V_R}{V_0} \times 100 \qquad (1)$$

Where V_0 represents the no load voltage at the point of train and, V_R represents the full load voltage. When the phase angle between V_0 and V_R is very small, Eq. 1 can be rewritten as follows.

$$\Delta V_R = \frac{I_L Z}{V_0} \cos(\theta - \gamma) \times 100 \qquad (2)$$

With regards to Eq. 3 to Eq. 6, the ΔV_R can be consider as Eq. 7.

$$Z = \sqrt{R^2 + X^2} \qquad (3)$$

$$\gamma = tan^{-1} \frac{X}{R} \qquad (4)$$

$$P_L = V_0 I_L \cos\theta \qquad (5)$$

$$Q_L = V_0 I_L \sin\theta \qquad (6)$$

$$\Delta V_R = \frac{1}{\mathrm{V}_0^2}(P_L \mathrm{R} + Q_L \mathrm{X}) \times 100 \qquad (7)$$

Where, Z represents equivalent value of catenary impedance by considering the mutual inductance values with adjacent wires. P_L is the train's drawing or feeding real power (depends on its mode of movement) and Q_L represents the reactive power of train, which are changed in different train's position. When capacitor bank injects the reactive power Q_c, the Eq. 7 can be written as bellow.

$$\Delta V_R = \frac{1}{\mathrm{V}_0^2}(P_L \mathrm{R} + (Q_L - Q_c)\mathrm{X}) \times 100 \qquad (8)$$

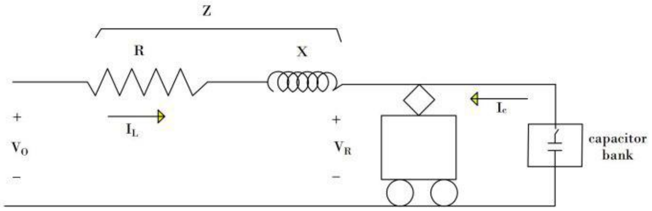

Figure 2. Voltage drop showing in pantograph

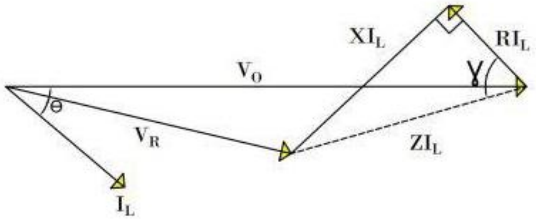

Figure 3. Vector diagrams of system before using the capacitor bank

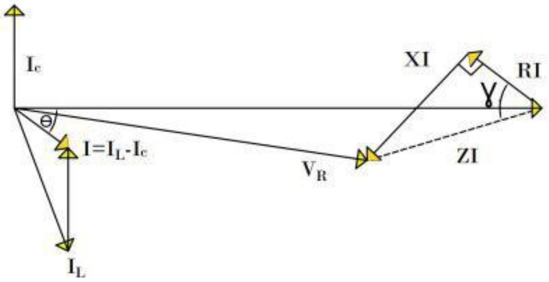

Figure 4. Vector diagrams of system after using the capacitor bank

Solution methodology for capacitor bank siting and sizing

There are lots of methods to solve optimization problems. Heuristic algorithms are used to solve sizing and siting problems in recent papers [19-23]. Also some studies used mathematical algorithm [24]. In this paper for obtaining optimal size and place of capacitor bank the enumeration algorithm is used which is explained bellow. All simulations are done by BBA Traction Simulator software.

First, the train movement with regard to specifications of rolling stock and rout is simulated. This simulation was done for all types of considered trains. The output of this simulation is all train's drawing or feeding power, speed, and acceleration in every points of rout. After that the matrix of train power by considering the time table diagram is prepared and inters to the power flow calculation as an input data. In power flow calculation which have done by Newton and Raphson method, the mutual inductance of all lines are considered. From the results of power flow calculation, the voltage profile of pantograph for every types of trains are obtained and also the power losses of network can be reach. Now the capacitor bank with its special size is located in one of candidate places of installation and the results are calculated. The size of capacitor bank changes by software and again the calculations are done and the best size obtains for that location. After that, mentioned process done for all other candidate location. Finally, the optimum location and the best size for that location obtain.

Case study

To validate the applicability of presented method the 2*25 kv AC electrical railway network of Sadeghieh to Hashtgerd, Tehran is simulated. In table 1 the location of ATPs and TSS are presented. By considering the rout's slope and curve, aerodynamically coefficient and rolling stock's characteristics the train movement is simulated. Fig. 5 and 6 are represent the real power of train in all point of the rout from Sadeghieh to Hashtgerd and reverse direction, respectively. This diagram shows that when train is near to station because of dynamic breaking the train injects some power to the network. This can be cause over voltage in system. In the passenger stations when train accelerating, the drawing power from the network has its maximum values and it cause a voltage drop on pantograph. It is expected that by installing capacitor bank the voltage profile should be smoother. In Fig. 7 the considered time table diagram is shown. In this simulation the headway time and dwell time is considered 10 and 2 minutes, respectively. So the power flow calculation is done for 10 minutes. Fig. 8 and Fig. 9 are show the voltage profile of pantograph from Sadeghieh to Hashtgerd and reverse direction, respectively. Fig. 10 represents the power losses of network in one headway time (10 minutes). Because of the Iterative feature of time table diagram, this diagram periodically repeats.

Table 1. Location of ATPs and TSS

Element	substation	Location (km)
ATP	Azadi	0
ATP	Vardavard	15
TSS	Bonyadrang	25
ATP	Golshahr	40.1
ATP	Kordan	52
ATP	Hashtgerd	62.9

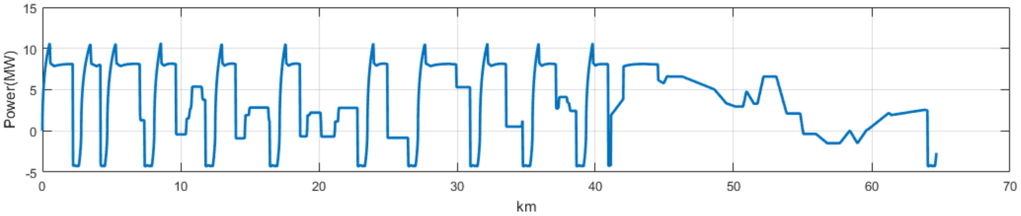

Figure 5. Real power of train in Sadeghieh to Hashtgerd direction.

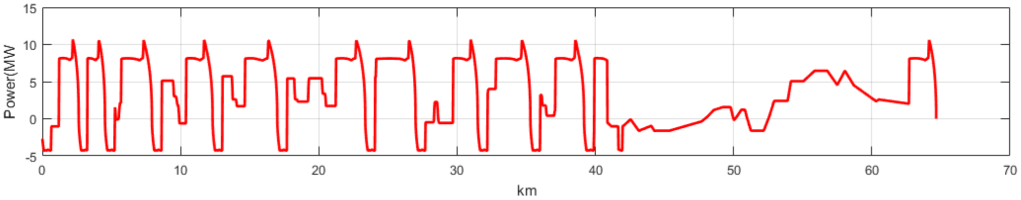

Figure 6. Real power of train in Hashtgerd to Sadeghieh direction.

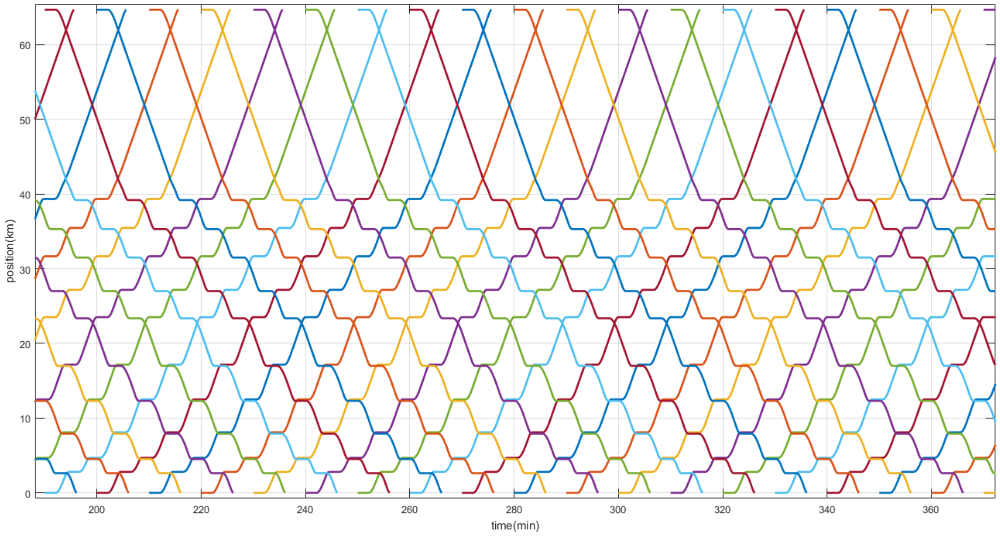

Figure 7. Time table diagram of system.

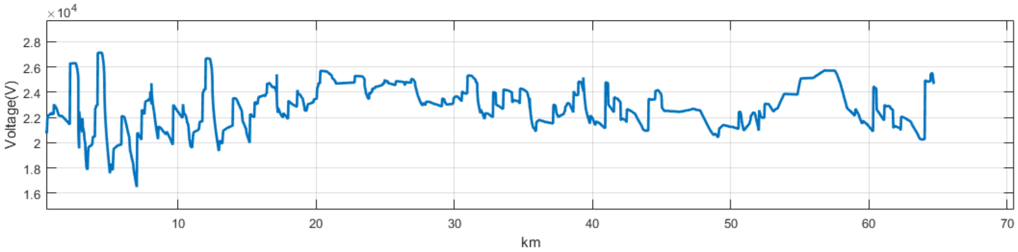

Figure 8. Voltage profile of pantograph in Sadeghieh to Hashtgerd direction before capacitor bank installation.

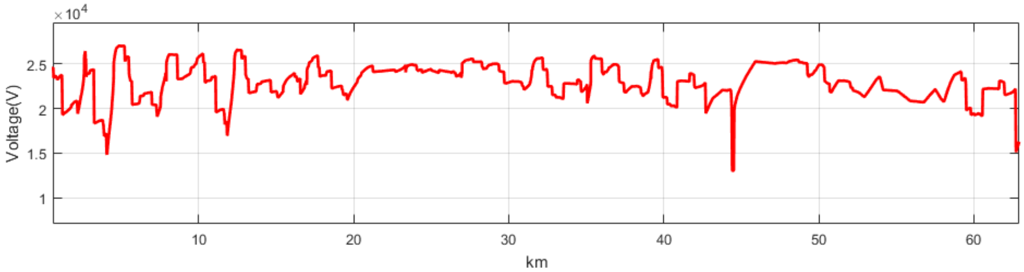

Figure 9. Voltage profile of pantograph in Hashtgerd to Sadeghieh direction before capacitor bank installation.

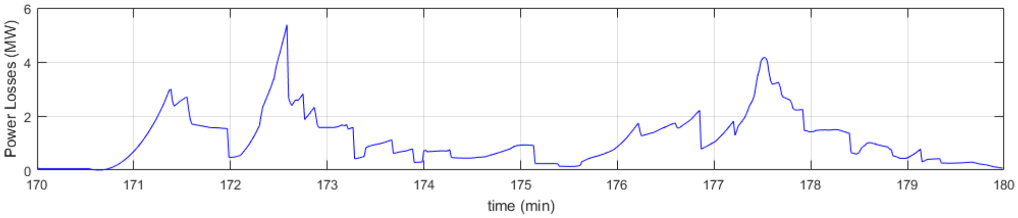

Figure 10. Power losses of network in one headway time before capacitor bank installation.

The capacitor bank by using the mentioned method is optimally allocated and the best size obtained. The optimal location to install is ATP Hashtgerd, with the best size of that which can produce 20 MVAR. In the Fig. 11 and 12 the voltage profile of pantograph from Sadeghieh to Hashtgerd and reverse direction is depicted after installing capacitor bank. These diagrams show that after installing capacitor bank, the voltage profile of pantograph improved and the power losses of network reduced.

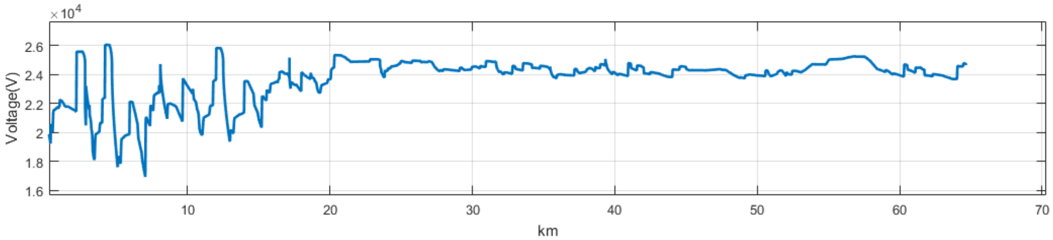

Figure 11. Voltage profile of pantograph in Sadeghieh to Hashtgerd direction after capacitor bank installation.

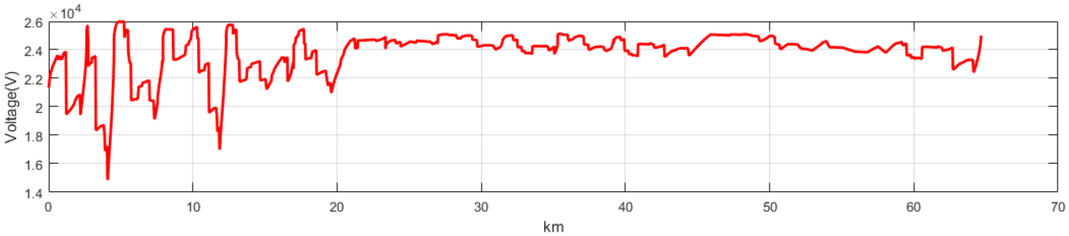

Figure 12. Voltage profile of pantograph in Hashtgerd to Sadeghieh direction after capacitor bank installation.

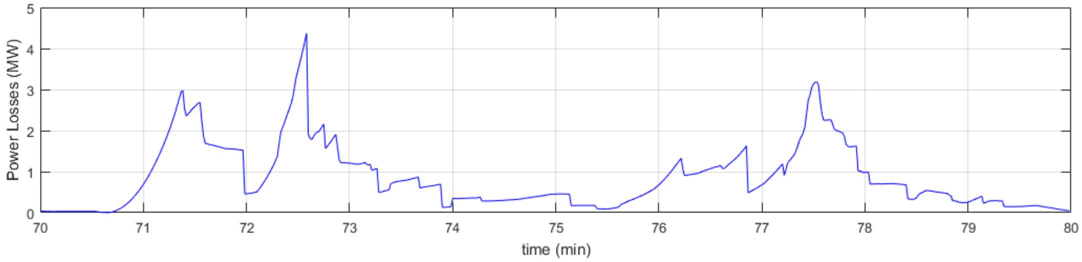

Figure 13. Power losses of network in one headway time after capacitor bank installation.

Conclusion

In this paper the capacitor bank was optimally allocated in 2*25 electrical railway system to improve voltage profile of pantograph and reducing the system's power loss. The system was modeled in details and train movement was simulated dynamically. The power flow calculation on electrical system was done and the capacitor banks in candidate places checked with different sizes by software and optimum place and size of that was founded. The simulation results show that by installing the capacitor bank in proper place and proper size, the voltage profile of pantograph improves and the power losses of system reduce. To validate the applicability of method the 2*25 kv AC electrical railway network of Sadeghieh to Hashtgerd, Tehran was simulated. All the simulations and calculations were done by BBA Traction Simulator which was designed and developed by Alucast Iran Co. R & D group.

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