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Effectiveness and Optimal Placement of Bidirectional Substations for Regenerative Braking Energy Recovery in Electrical Network of Metro System

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ABSTRACT

Using bidirectional converters in Metro substations, regenerative braking energy can be fed back to the AC grid to decrease the braking energy loss. In this research the effectiveness of bidirectional rectifiers and their placement are investigated. A case study is provided for determination of optimal location and capacity of bidirectional rectifiers in 8 rectifier substations for different traffic scenarios in a part of line 1 of the Tehran Metro system. Particle swarm optimization (PSO) method is used for selection of optimal traction substation for inverter placement. The results of simulation and optimization by using the software built in MATLAB / SIMULINK are presented. Simulation results confirm the effectiveness of using bidirectional rectifiers as well as the optimization method.

1. Introduction

In a metro network system, since, most of the rectifiers used in substations are unidirectional, regenerative braking energy cannot be returned to the AC grid [1]. Therefore, the regenerative energy is usually wasted in the dynamic brake resistors or consumed in accessories [2]. Several solutions have been proposed in the literature to maximize the reuse of regenerative braking energy, including:

(1) Train timetable optimization, in which synchronization of multiple trains operation is investigated [3-4]. (2) Energy storage systems (ESS), in which regenerative braking energy is stored in a storage medium, such as super capacitor [5-7], battery [8] and flywheel [9], and released when demanded. The storage medium can be placed on board the vehicle or wayside [10]. (3) Reversible substation [11], in which a path is provided for regenerative energy to flow in reverse direction and feed power back to the main AC grid. Different structures are proposed for reversible substations, including [12-16]. To minimize the additional cost of reversible substation, the capacity and the place of reversible/bidirectional rectifiers should be optimally selected. The aim of this research is to solve the problem of optimal placement and capacity of bidirectional rectifiers for metro systems. Particle swarm optimization algorithm (PSO) is used for optimal capacity and placement of the bidirectional rectifiers. The overall cost of power consumption, inverter investment is included in the objective function. The idea for the optimization of inverter placement is extracted from reference [11-12].

2. The Case Study

As a case study, a part of line 1 of Tehran Metro is selected. The total length of this line is

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38 km, with 29 passenger stations. It runs from the north to the south of Tehran. This line is fed by unidirectional traction substations. The simulation is performed on 8 rectifier substations in 14 stations for different traffic scenarios. The proposed simulation is by considering metro network parameters, the total weight of a train with passenger on board for different traffic scenarios. The driving cycle that is used for the simulation is based on real data and route information, including the maximum speed during acceleration at 80 km/h, the maximum acceleration 1 m/s^2 the total journey time is 3484 sec., including forward and return path and the dwell time. The driving cycle and the speed limits that are used for the simulation are presented in Figures 1&2, [17].

3. Modeling of Metro Network

3.1. Line Electric Model

The resistance of the railway line depends on the location of trains and it varies with the train movement and temperature. These values are provided in Table 1 [17]. The rail temperature increases due to the train movement [18]. Therefore, for the purpose of simulations with the software, the rail resistance at a temperature of 40^{oC} is used. The connecting lines are modeled by electric resistances. Since trains move in between different stations, the electrical resistance between the train, initial station, and the next station is time variant. Therefore, in each time step, these values need to be recalculated.

Table 1. Rail line resistance

	15^{0c}	40^{0c}
Third rail electric resistance (mΩ / km)	21	22.4
Rail electric resistance (two parallel rails) (mΩ / km)	16.5	36.7

3.2. Line Physical Characteristics' Modeling

In the analysis of the rail transport system, the physical characteristics of the line are very important and affect the demanded power of the trains. In the modeling of the metro system, it is assumed that the speed and acceleration profiles of trains are specified at each point of trajectory. Moreover, the route specifications including the slope of the path, the radius of the arc and the tunnel are predetermined. The trains speed profiles are limited to specifics regarding trajectory position. In this case, some data for Tehran metro line 1 from the Shoush station to the Shahid Haqqani station is used. Meanwhile, the specifications that are used for the simulation purposes include station locations, traction substations, track curve radiuses, and the track slopes.

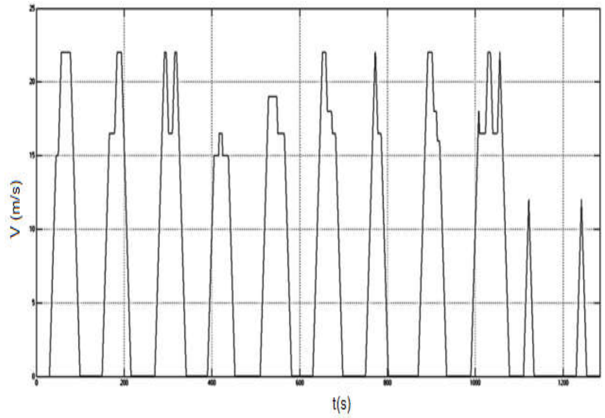


Figure 1. Speed cycle of trains in forward path [17]

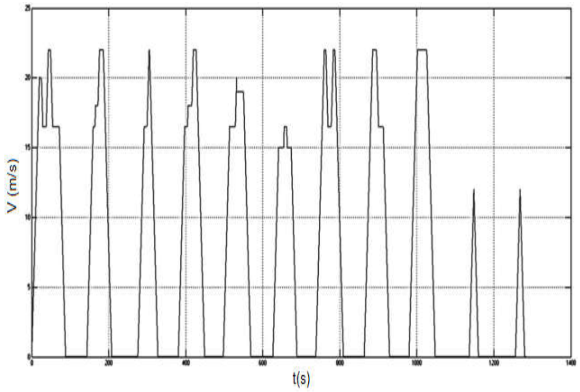


Figure 2. Speed cycle of trains in return path [17]

3.3. Substation Model

Since traction substations are substations with DC output, an ideal DC voltage source, connected in series with a small resistance, is used for modeling such substations. Because these substations are unidirectional, a diode will also be connected in series with this resistance. Additionally, a capacitor filter, placed in parallel with the set composed of the voltage source, and a resistance in series together with a diode is used to reduce the voltage ripple.

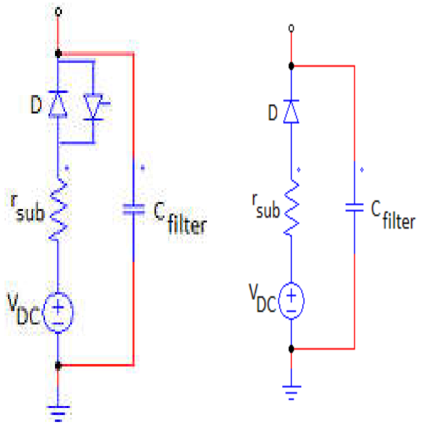
The value of the resistance in the feed substation model is due to the resistance of transformer, the connections of transformer to the rectifier, the internal resistance of the diodes and commutation overlap effect caused by the reactance of the transformer. Nevertheless, the resistor used for modeling the commutation effect only causes voltage drop, and it does not consume any power [18]. As indicated in Tables 2 and 3, the value of the ideal voltage source and the parallel capacitor are considered to be 803 Volts and 1 Farad, respectively. Figure 3(b) shows the model that is used for the power supply substation in the network analysis software.

Table 2. Power transformer data

Specification	Size	Unit
Nominal Power	2500	kVA
Primary voltage	20	kV
Secondary voltage	592	V
Short circuit impedance	6	%

Table 3. Diode rectifier data

Specification	Size	Unit
Converter	12 pulse	
Nominal Power	2250	kW
Output nominal voltage	750	V
Output nominal current	3000	A
No load voltage	803	V
Equivalent resistor	6	mΩ
Output filter	1	F



(a) (b)

Figure 3. (a) Model of a DC-750 V metro supply network

(b) Bidirectional substation configuration

3.4. Reversible Substation Model

A reversible substation, also known as bidirectional or inverting substation, provides a path through an inverter for regenerative braking energy to be fed back to the AC grid. In this research an Insulated-Gate Bipolar Transistor (IGBT) based inverter is connected in reverse parallel with the diode rectifiers to return surplus energy to the main grid. The inverting substation model is presented in Figure 3(a) [18]. A schematic diagram of reversible substation is presented in Figure 4 [10]. It is worth mentioning that in the above approach the existing diode rectifier and transformer can be kept and some additional equipment need to be added for the reversible energy conduction. For analyzing metro network two variables must be considered. The first one is the RD (1/0) variable that shows the existence or absence of a reverse path in each supply substation. The second variable is the inverting substation capacity (SR) which determines the reversal power from DC metro grid to the AC power grid. According to the model that is presented in Figure 3(b), the circuit current is obtained from the Equation (1). The substation voltage in the third rail is VR, this voltage is applied to one side and VDC (substation power supply) is applied to the other side.

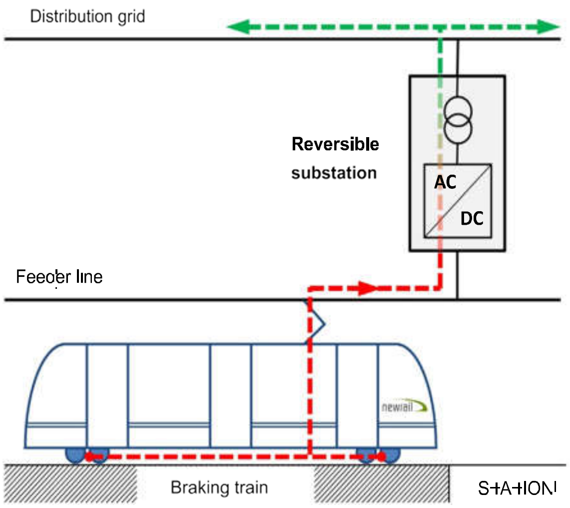


Figure 4. Schematic of reversible substation in urban rail [10]

$$IR = \frac{VR - V_{DC}}{R_{sub}} \qquad (1)$$

VR is the maximum output voltage of the substation, when the inverter diode is turned on. Therefore, VR is greater than or equal to VDC. According to the current that is acquired, the power is calculated from Equation (2). As is, the inverting substation capacity (SR) is proportional to the VR voltage.

$$SR = VR * IR \qquad (2)$$

In the section for the circuit analysis, a term is added for substations containing reverse diode. If a substation has a reverse post, the post is allowed to increase the voltage up to VR, i.e. higher than 803 V, by passing current through itself. Obviously, the current drawn from the substation will take a negative value for voltages higher than 803 up to the value of VR.

3.5. Electrical Model of the Train

Trains play the role of moving consumers of power generators for the metro system, demanding different power from the grid by changing the number of their passengers, changing of the line characteristics, speed and acceleration changes, etc.

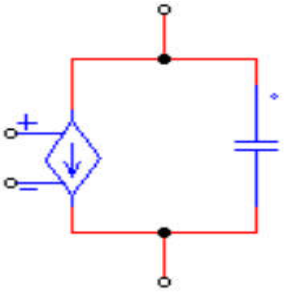
In order to model trains in the metro system, they should be modeled as circuit elements. Since the consumption power or braking power of the train is constant at any instance of simulation, the current that it draws/gives from/to the grid depends on the voltage of the train in the grid. Therefore, the train is modeled as a voltage-dependent current source, which its current value is considered as in Equation (3).

$$I_{Train} = \frac{P_{Train}}{V_{Train}} \qquad (3)$$

On the other hand, since a capacitor filter is used in the converter of trains, the overall model of the train will be a voltage-dependent current source in parallel to the capacitor filter. According to the above explanations, Figure 5 presents the model used for the train in the network analysis software. In the following equations governing the train motion, it focuses on how to calculate the amount of consumption or braking power of trains.

3.6. Train Motion Equations

As mentioned, trains are modeled as current sources that consume power during train accelerating time or generate power at the regenerating time. For modeling the train as the current source, traction force and resistive forces are calculated by Newton's second law as in Equation (4), [19-20].



$I_{Train}=P_{Train}/V_{Train}$

Figure 5. Electric model of train

$$F_{Trac} - F_{Resist} = M \times a \qquad (4)$$

where F_{Trac}, M, a, represent the traction effort [N], total mass of the train [kg], and the train acceleration [m/s^2], respectively. F_{Resist} is the total resistive forces [N. m] . F_{Resist} is computed as the sum of two single terms including the basic resistance consisting of the rolling friction and aerodynamic drag $F_{base,}$ and the line resistance F_{line} that is caused by track grade and curves. Finally, the basic resistance is written as in Equation (5):

$$S_0 = K_1 + K_2 v + K_3 v^2 \qquad (5)$$

v is train speed, K_1, K_2 are the experimental coefficients and K_3 is the aerodynamic coefficient. S_0 is determined by using the Davis formula. When the train is accelerating, the power (P_{Train}) that is drawn from the substation to feed the train is determined as in Equation (6):

$$P_{Train} = (P_{Wheel} \div \eta) + P_{Accessories} \qquad (6)$$

$$P_{Wheel} = F_{Trac} \times V \qquad (7)$$

$$\eta = \eta_{Gearbox} \eta_{Driver} \eta_{Traction\ Motor} \qquad (8)$$

P_{Wheel} is the power applied to the train wheels, $P_{Accessories}$ are the power required for the lighting system, ventilation and auxiliary equipment, and η is the product of the gearbox efficiency, the driver efficiency and the traction motor efficiency. η is calculated from Equation (8). V is the train speed [m/s].

Therefore, the current which is drawn from the substation (or delivered to it) is calculated by using Equation (9):

$$I_{Train} = \frac{P_{Train}}{V_{Train}} \tag{9}$$

3.7. General Model of Metro Network

The overall model of the Metro network that is used in the purpose made software with bidirectional substations and unidirectional substations is shown in Figure 6.

The network analysis software is configured to work under MATLAB engineering software. This software is composed of two parts, which are:

- Analysis of dynamic equations of train movements and calculation of various powers (required power, mechanical and electrical braking power) related to trains during train travel time.
- Analysis of the electric equations of the metro network and the calculation of the voltages of different trains and substations of this network during train travel time.

In the first part, based on the position of the trains (which is determined according to the traffic scenario and characteristics of the lines, including slope, the presence or absence of tunnels, the curves on the lines); power consumption of trains; mechanical braking power of trains and electric braking power of trains are calculated.

In the second part, considering the position of traction substations and trains and the values calculated in part one, the analysis of the network equations is performed. The required outputs, including the voltages of substations and trains, the amount of energy provided by the substations, the rate of the energy losses in substations and lines, as well as the amount of energy losses in the train's dynamic resistances, are calculated. It is noted that the system is non-linear due to the dependence of the train current to its voltage. To simplify the solution, the voltage of the train is considered as a constant voltage of 750 V. Therefore, train's current can be calculated by using Equation (1). As a result, the equations are linearized. In subsequent iterations, this voltage is constantly updated to achieve the final result. To obtain the solution for the network, the network admittance matrix is formed, and then the impedance matrix is calculated by inverting the admittance matrix. In the next step, with regard to the voltage of substations (pre-iteration voltage) and assuming that the voltage of trains is a constant voltage of 750 V, the network current matrix is formed and by using the matrix Equation (10), the network voltage matrix is obtained. The iteration process will continue such that the status of the voltage of substations can be adapted to the state of the diodes and thyristors.

The Nodal Analysis is used to derive the voltage of different nodes of the equivalent circuit [18].

$$[I] = [Y] \times [V] \tag{10}$$

Equation (10) can also be written as:

$$[V] = Y^{-1} \times [I] \tag{11}$$

For the train, an additional equation is added to account for the instantaneous train power:

$$P_T = V_T \times I_T \tag{12}$$

where P_T is the power demand for the train at some point and it is a known variable when the driving strategy is confirmed. By adding a new equation, a new unknown variable is also added, which is the train voltage (V_T).

However, the train voltage can be denoted by nodal voltages, [21]:

$$V_T = V_{up-train} - V_{down-train} \tag{13}$$

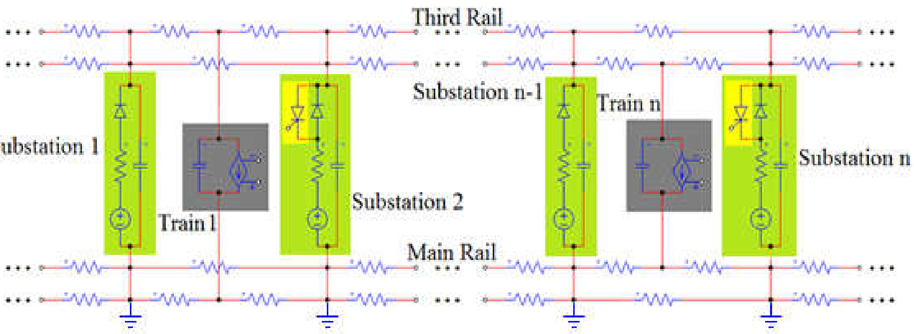


Figure 6. Metro network model for the simulation purposes

At this stage of simulation there are a number of unknown variables and the corresponding equations that need to be justified. An iterative method is applied to solve these nonlinear equations. Therefore, after calculating of various nodes voltage, the power supplied from the substations, the power dissipated in the lines and substations, power losses in the dynamic resistors, and mechanical braking power losses are calculated.

4 Simulation Results

4.1. Simulation without Reversible Substation

In this section, the rail transport system is simulated without an inverting substation. Simulations are made with the assumption that all the braking energy is wasted in the dynamic resistors. Therefore, the braking energy will be completely dissipated in dynamic resistors. The simulations are considered for a period of 58.07 minutes (3,484 seconds), the simulation results are presented in Table 4.

4.2. Simulation Using Bidirectional Substation

In this section, the metro system is simulated by assuming the inclusion of 4 inverters at 8 traction substation. The capacity and locations are regarded as in Table 5.

The simulations are considered for a period of 58.07 minutes, (3484 seconds). The simulation results are presented in Table 6. From

Table 4. Simulation results without energy storage system with dynamic electric brake

The kind of system	**Without ESS with dynamic braking**				
Traffic condition	1	2	3	4	5
Headway of train(minute)	14 -13	11 -10	9 -8	6 -5	5 -4
Number of trains in metro-line	3	4	5	7	10
Number of trains with DC traction motor	1	2	2	3	4
Number of trains with AC traction motor	2	2	3	4	6
The amount of energy supplied by substation (Kwh)	3407.88	5138.55	6663.50	9723.59	15444.4
Energy losses in substation (Kwh)	28.44	52.55	77.26	141.17	288.94
Energy losses in line (Kwh)	392.48	698.33	995.46	1604.8	2917.25
Energy wasted in the dynamic braking resistors (Kwh)	1046.5	1610.3	2246.2	3446.9	5573.5
Energy wasted in mechanical brakes (Kwh)	34.02	51.59	73	112.30	175.87
voltage maximum (V)	803	803	803	803	803
voltage minimum (V)	732.44	716.43	694.6	685.25	662.27
$\frac{\text{Total recoverable braking energy}}{\text{The total energy of trains traction and auxiliaries}}$ (%)	35.03	36.7	40.77	43.20	45.54

Table 5. Hypothetical reversible substation data

Substation number		1	2	3	4	5	6	7	8
Reversible substation			*		*		*		*
Capacity	**V**		818		833		813		828
	MVA		2.045		4.165		1.355		3.450

Table 6. Simulation results with hypothetical bidirectional rectifiers in 4 substations

Type of system	**Metro system with bidirectional substations**				
Traffic condition	1	2	3	4	5
Headway of train (minute)	14 -13	11 -10	9 -8	6 -5	5 -4
Energy losses in substation (Kwh)	29.72	53.61	77.22	128.53	274.66
Energy losses in line (Kwh)	418.59	730.02	1034.3	1656.66	2999.01
Energy wasted in the dynamic braking resistors (Kwh)	803.58	1107.5	1382.4	1783.7	2571.3
Energy wasted in mechanical brakes (Kwh)	34.02	51.59	73	112.30	178.87
voltage maximum (V)	895.2	895.79	895.89	898.37	898.14
voltage minimum (V)	732.44	716.43	694.06	685.25	662.27
$\frac{\text{Recoverd braking energy}}{\text{Recoverable braking energy}}$ (%)	23.21	31.22	38.45	48.25	53.86
The amount of energy saving(Kwh)	510.58	625.45	763.9	988.19	1486.26
Energy Saving(%)	14.98	12.17	11.46	10.16	9.62

the results it is clear that by recuperation of braking energy through hypothetical reversible substations, 23 to 53 percent of recoverable energy is restored. It is resulted in 9 to 15 percent of energy saving.

4.3. Optimal Reversible Substation Placement

The goal is to determine the optimal location and capacity of the reversible substation for the metro system. For this purpose, the cost of energy and inverter cost in the objective function is considered. By using PSO algorithm [22], optimization in economic mode is obtained and the results are verified. The voltage level and power consumption of traction substations along line-1 of Tehran Metro network system are investigated. The annual headways and scenarios are adjusted with the passenger ridership noted in reference [17].

4.4. Calculation of the Energy Cost in the Objective Function

The optimization period is 10 years. It is assumed that the rail transport displacement for passengers is 18 hours a day and the share of traffic scenario is presented in Table 7. The total energy consumption cost EC of the metro system is expressed as in Equation (14):

$$EC = 10 \times 365 \times \sum_{j=1}^{5} E_j \times N_j \tag{14}$$

where, j is the traffic scenario number. E_j is the amount of energy supplied by the network in the j traffic scenario and N_j is the share of each jth traffic scenario per day.

4.5. Modeling of the Cost of Reversible Substation

In the optimization process, the inverter cost is determined in terms of the maximum transmission capacity (S), using $600,000 as the price of a 3 MW capacity [12] and applying the curve fitting on lookup table data that is presented in [23].

As a result a second degree equation for the inverter cost model is obtained as in Equation (15). The resulted inverter cost graph is presented in Figure 7.

$$\cos t = (120S^2 + 584.45 + 579.4)\$ \tag{15}$$

5. Economic Optimization

5.1. Objective Function

The total energy consumption of the system (for ten years) and the reversible substation cost are considered in the economic objective function in Equation (16):

Table 7. The share of traffic scenario

The share of traffic number per day	The share per day %	Traffic scenario
1	8	1
4	24	2
6	36	3
4	24	4
1	8	5

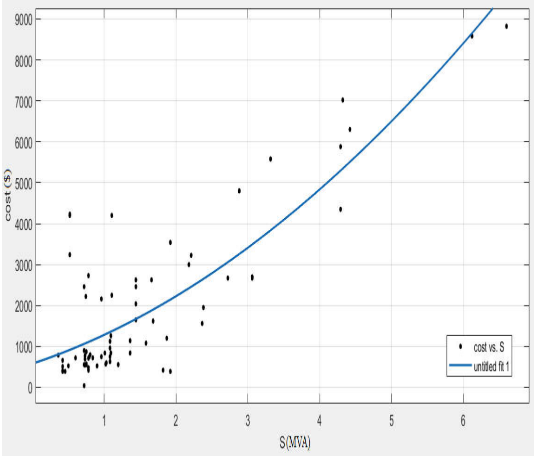


Figure 7. Inverter cost graph

$$f_{obj} = 10 * 365 * K * \sum_{j=1}^{5} (E_{s,j} N_j) + \sum_{i=1}^{N} C_{RD,i}(S) \tag{16}$$

where K is the cost of the unit of energy, which is considered 9.68 cents per kilowatt hour [24]. $E_{s,j}$ is the amount of energy consumed by the system in each traffic scenario. N_j is the contribution of each traffic scenario per day. $C_{RD,i}$ is the cost of installing an inverter of substation, which is a function of capacity. The goal of the optimization is to reduce the total cost of energy consumption and the cost of procurement and installation of the inverter.

5.1.1. Optimization Process

In PSO algorithm, variable values of RD and VR are determined randomly (in the initial iteration) or after moving the particles (in next iterations). At the particle evaluation stage, the Metro system analysis with the presence or absence of (RD) and capacity (VR) of the inverting substation is performed. Then the value of the objective function is obtained for each particle, and the position of each particle is determined. With implementation of the optimization algorithm, the results are presented in Table 8 and Figure 8.

Table 8. Results for the optimal location and capacity of bidirectional substation

Substation number		2	6
Required Inverter(*)		*	*
V	**Inverter capacity**	828.79	827.05
MVA		3.5628	3.3151

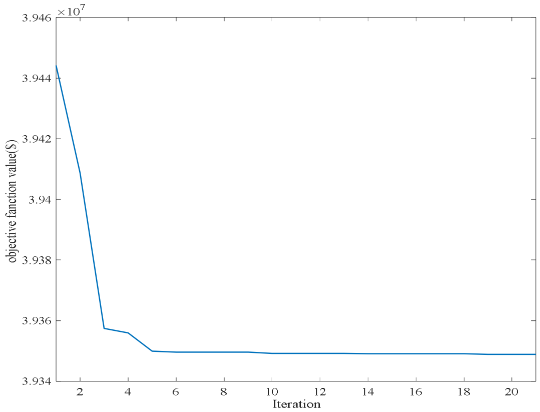


Figure 8. Cost reduction procedure by PSO

According to the results of the optimization, the objective function value is reached to 39.349 million dollars at ten years which is the energy consumption cost 37.939 million dollars at 10 years (391929 MWh) and the cost of inverter procurement and installation 1.41 million dollars. It should be noted that the consumed energy is 431696 MWh at ten years without reversible substation. As a result, this design would provide economic savings of 2.439 million dollars, that is equal to 5.84% and energy consumption savings of 9.21%. In order to validate these results the reversible substation power of substation 2 is changed and the value for the objective function is calculated for various powers. The results are presented in Figure 9. In these sets of the results the selected value is the minimum value of the curve that is validated.

From Figure 9, at low capacity of reversible substation, the total cost is initially incremental and then, it decreases with regard to converter cost. In addition, the graph of variations in each terms of the objective function, including the cost of energy consumption and the cost of converter, are presented in Figures 10&11, respectively.

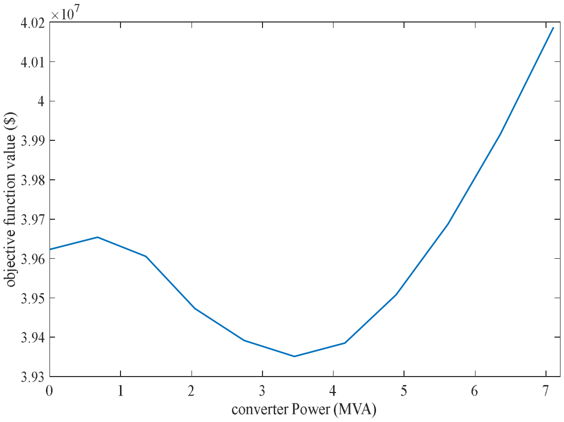


Figure 9. Effect of the capacity of substation no.2 on the objective function

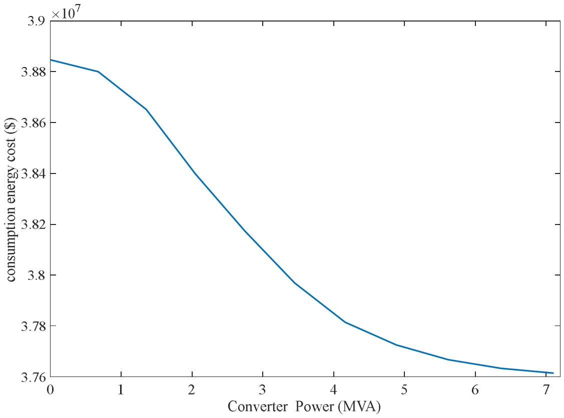


Figure10. Effect of the capacity of substation no.2 on energy consumption cost

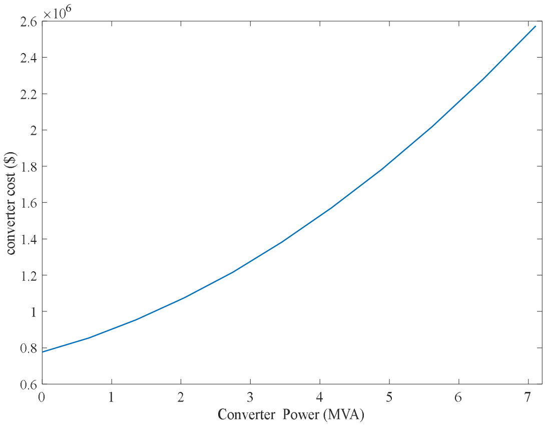


Figure 11. Inverter procurement cost for substation no.2

6. Conclusions

The article proposed the braking energy recovery by applying bidirectional substations. In order to illustrate the effectiveness of bidirectional rectifiers and their placement, line 1 of Tehran Metro was selected for computer simulations. In addition, a software program is worked out that can be used in conjunction with the MATLAB/SIMULINK engineering software. The PSO method was used to solve the optimal traction substation for inverter placement and capacity. In economic optimization, the objective function included the inverter cost and energy consumption cost of the system. Optimization results predict the financial savings by 5.84% and energy consumption savings of 9.21%.

It is found that significant braking regeneration energy can be restored by proper installation of inverters to achieve the energy savings. The simulation results presented that the example system is optimized and its energy savings are notable and valid.

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