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Stationary super-capacitor energy storage system to save regenerative braking energy in a metro line

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ABSTRACT

In this paper, the stationary super-capacitors are used to store a metro network regenerative braking energy. In order to estimate the required energy storage systems (ESSs), line 3 of Tehran metro network is modeled through a novel approach, in peak and off-peak conditions based on the real data obtained from Tehran metro office. A useful method is proposed to predict the maximum instantaneous regenerative energy which is delivered to each station before applying ESS and based on that the ESS configuration for each station is determined. Finally, the effectiveness of the proposed ESS is confirmed by economic evaluations and benefit/cost analyses on line 3 of Tehran metro network.

1. Introduction

In recent years, energy plays an important role in human being's life. Among the energy sources, fossil fuels are the main source of electricity generation. However, fossil fuels are going to be finished in the near future and the price of that is remarkably increasing. Moreover, fossil fuels are the main source of pollution. So, it is necessary to study about other energy sources or at least find some solutions to reduce the energy consumption. Today, super-capacitors are used in the transport systems as a mean to store energy and reuse it during short periodic intervals [1–6]. In a metro network system, the trains are accelerated and braked frequently. Since, most of rectifiers in the metro network are unidirectional, the regenerative braking energy cannot be returned to the supply network and it should be wasted in the braking resistors or stored in an energy storage system. One way to store the braking energy is by using super-capacitors. In this study, design of an appropriate ESS based on super-capacitors is presented.

An efficient energy storage system not only reduces the energy consumption but also it stabilizes the line voltage and reduces the peak input power, resulting in lower losses in the electric lines [7,8]. The metro trains generate high instantaneous currents when they brake. The braking time is around 10–15 s, therefore the ESS power is very high and it is hard to find a convenient ESS that can store these high currents in such a few period of time. Super-capacitors have special features such as long life, rapid charging, low internal resistance, high power density, and simple charging method [9,10]. These features make super-capacitors suitable for recovery of the regenerative braking energy in a metro network line.

In Refs. [11,12], electrical trains have been considered as an useful public transportation that their efficiencies can be improved by applying the ESSs, however, ESSs sizing and network modeling have not been discussed. In Ref. [13], different mechanical and electrical techniques have been overviewed in order to improve the energy efficiency in electrical railway systems. Some researches have been done about the advantages of the onboard ESS in electrical trains [14–19]. Optimization of storage devices for regenerative braking energy in subway systems has been presented in Ref. [20], but no benefit/cost calculations has been reported. Moreover, the control algorithm and ESS sizing have not been discussed. In Refs. [21–24], stationary ESS has been applied to save the regenerative energy in a metro network. Stationary ESS has been proposed for voltage regulation of weak points in Ref. [25]. But, the driving cycle and characteristic of the studied metro system has not been throughly explained. Additionally, the metro network has not been modeled and the algorithm of ESS sizing has not been presented.

In this paper, the metro supply network and metro trains are modeled using real data obtained from Tehran line-3 metro office. The model shows the behavior of the metro line, trains, stationary ESSs, and irreversible substations. The network model is simulated in the digital simulation environment of PSCAD software. In comparison to previous modeling methods presented in Refs. [21–24], the proposed approach presents a good physical insight into

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Nomenclature

η_g	gear box efficiency
η_m	motor efficiency
η_i	inverter efficiency
ρ	curve radius
a	acceleration in (m/s^2)
C	electricity price in dollar per joule
d	total distance between two stations (km)
E_r	regenerative energy of each station
E_s	percentage of energy saving in each station
F_r	total resistive forces in (N m)
h	rise per 1000 m of horizontal distance in (m)
i	yearly inflation of electricity price
I_r	regenerative current in station #i
I_t	regenerative or drawn current of the train
K	resistive coefficient
l	lifetime of the super-capacitor
l_e	life time of the ESS (in year)
m	dollar per energy constant
n	number of the axles
n_c	number of charge and discharge cycles
n_t	number of the train entrances to the station in a day
P_t	instantaneous power of the train
P_a	power required for lighting and air-conditioning (cooling or heating)
P_s	instantaneous power of the station
r	rate of return constant
R'	electrical resistance between train and last departing station (Ω/km)
R''	electrical resistance between train and next stop (Ω/km)
R_c	curve resistance
R_L	sum of rolling resistance, journal, flange and air resistance in the wagons which have motor
R_g	grade resistance
R_v	sum of rolling resistance, journal, flange and air resistance in the wagons which do not have motor
S_c	required investment on the converter
S_e	total profit from regenerative energy during l years at a station
S_s	cost of investment for super-capacitor
SOC	capacitor's state of charge
V	train speed in (km/h)
V_c	capacitor voltage
V_l	line DC bus voltage
Vs	station DC bus voltage
Vs_i	voltage of station #i
Vs_{i-1}	voltage of station #$i-1$
Vs_{i+1}	voltage of station #$i+1$
R_{i+1}	resistance between stations (i, $i+1$)
R_{i-1}	resistance between stations ($i-1$, i)
W_s	maximum regenerative energy of the station at each period
W_{ys}	yearly regenerative energy of the station
W_t	total weight of the train in (tn)
W_w	weight of each wagon in (tn)
$x(t)$	distance between train and last departing station in each time step

the network model. Moreover, it can be extended easily. Unlike [21–24] which use trial and error method to find the best ESS configuration with the highest energy saving, in this paper, an effective method is proposed to calculate the maximum instantaneous regenerative energy of each station analytically. Then, appropriate ESS configuration is suggested for each station. Unlike the pervious works, in this study, economic evaluations and benefit/cost analyses are performed for the suggested ESS.

2. Case study

This study is applied to the line-3 of Tehran metro network. The total length of the line is about 33 km. It connects the south west of Tehran to the north east of it with 26 stations.

2.1. Assumptions

- Driving cycle used for this study is based on the real measurements and is demonstrated in Fig. 1. This figure shows the speed cycle of first 10 stations and details of driving cycle between station 1 and 2.
- The maximum speed during acceleration is 70 km/h and the maximum acceleration is 1 m/s^2.
- Line parameters and the efficiency of different components used in the simulations are given in Tables 1 and 2 respectively. The traction motors are 3-phase, 380 V, 180 kW AC motors equipped with AC drives.

2.2. Network model

The metro model includes trains, unidirectional substations, energy storage systems (ESSs), and connecting lines that are shown in Fig. 2. Each substation is modeled by an ideal DC voltage source connected in series with a resistance of 6 mΩ/km. The track lines are modeled by constant resistances. Since a train is moving between two stations, the electrical resistance between the train and the corresponding stations are modeled with the time varying resistances R' and R'' as follows:

$$R' = \frac{k \times x(t)}{1000} \tag{1}$$

$$R'' = \frac{k \times (d - x(t))}{1000} \tag{2}$$

where R' is the electrical resistance between the train and the last departing station (Ω/km), and R'' is the electrical resistance between the train and the next stop (Ω/km). K represents the resistive coefficient which is 0.033 (Ω/km), d is the distance between the two adjacent stations (km), and $x(t)$ is the distance between the train and the last departing station in each time step. Because of the mobility of trains and therefore variation of resistances, the model of the network is time varying. In PSCAD environment, the value of resistors can change during the simulation. Thus in this paper, the value of resistors is updated in each time step, according to (1) and (2). This procedure provides a good physical insight and precise model for the case study. The network model includes the first 10 stations of the line-3 as a sample of the whole line. In addition, some of the stations do not have rectifier but they have stationary ESS, e.g. station 7. Moreover, the headway (the interval between two trains) at off-peak period is 5 min which means that the cycle of braking or supplying energy is repeated every 5 min in each station. During peak period, the headway is 2.5 min.

Tables 3 and 4 demonstrate the leaving time of trains in forward and return path for off-peak period. The shaded cells (selected times) are in the studied time duration (9:13:49–9:18:49). As it