Study on Configuration Method of Stationary Ultra-Capacitor Energy Storage System of Urban Rail Transit

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Abstract

This paper studied the configuration method of stationary ultra-capacitor energy storage system (ESS) of urban rail transit. The significance of ultra-capacitor ESS used in urban rail transit is analyzed first. Then the model of urban rail transit traction power supply system, the train converter system and stationary ultra-capacitor ESS system was built. Finally, the result of configuration method is obtained by simulation, the result was analyzed, and the principle of ESS configuration is provided.

1 Introduction

As the population growth and social development, the existing urban public transport cannot meet people's travel needs. Compared to other travel modes, urban rail transit has advantages of large capacity, good timeliness, and comfortable, etc., and has become a major focus of the construction of urban public transport.

The traction substation of urban rail transit generally gets AC power from the urban power grid, and use transformers and uncontrolled rectifying circuit to transform the AC power into 750V or 1500V DC. The advantage of this power supply method is the use of technology matured dry type transformer and diode rectifiers, and the reliability of power supply is higher. However, due to the diode rectifier only allows one-way flow of energy, and the energy is fed to the traction supply network when trains works in regenerative braking state. If this part of the energy can’t absorbed by other trains, it will cause the increase of traction voltage, and when the voltage of traction network increases to a certain value, the braking resistor is put into to prevent the input voltage rising to a dangerous value. Because this part of the energy is converted into heat, it can’t be reused, and can also cause the rise of tunnel temperature. If the fan is used to bring the heat out of the tunnel, a lot of energy will be consumed.

Using the ESS in urban rail transit can not only recover the regenerative braking energy of the train, but also avoid the energy converted into heat to cause the waste of energy. Compared to the battery energy storage, ultra-capacitor energy storage has advantages of high power density, free maintenance, and long life[4]. Using ultra-capacitor ESS in urban rail transit systems to recover the train braking energy that cannot be absorbed by other trains, and timely releasing to the traction network is a promising approach. Vehicle-mounted ultra-capacitor ESS occupies the small space of the train, and its energy management approach focuses on the vehicle rather than the entire traction supply network[8]. The ground ultra-capacitor ESS is installed in the station substation, the design of the system power and energy is not limited by space. Such as the power of Siemens SITRAS SES stationary ultra-capacitor ESS is 1MW, and the stored energy is 2.5kWh, either power level or energy storage is much larger than vehicle-mounted capacitor ESS. But now the study location setting and configuration method of stationary ultra-capacitor ESS is seldom. This paper establishes the model of urban rail transit traction power supply system, the train converter system and stationary ultra-capacitor ESS system. Combined with the actual parameters of one of urban rail transit lines, the result of location setting and configuration method of ESS is obtained by simulation. The configuration principle is obtained by analyzing result, and it has guiding significance to ESS configuration.

2 Modeling of Urban Rail Transit Traction Power Supply System

2.1 Substation Model

The electrical energy of urban rail transport is supplied by the city power grid which the voltage is 10~35kV AC. The energy is converted from AC into 750V or 1500V DC through the step-down substation, traction substation and the three-phase rectifier. Traction substation generally use a 24-pulse diode rectifier unit, the advantage of 24-pulse rectifier is lower output voltage ripple, and lower harmonic pollution to city grid. If the traction substation output voltage ripple is not considered, the output voltage can be equivalent to a model which consists of a voltage source, a resistor and a diode, such as Fig. 1, the mathematical model can be described below.

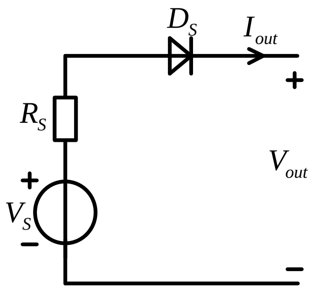

Fig. 1 Traction substation model

Where V_s is the DC side open circuit voltage of traction substation, R_s is equivalent series resistance of traction substation, diode D_s reflects the unidirectional flow characteristics of traction substation current. When $V_s > V_{out}$, the output voltage of traction substation decreases as the load increase, and the output voltage can be written as

$$V_{out} = V_s - I_{out} \times R_s \tag{1}$$

When $V_s > V_{out}$, the traction substation export power to the DC traction grid, the output voltage of traction substation decreases as the load increase, at this time, we can get:

$$V_{out} = V_s - I_{out} \times R_s \tag{2}$$

When $V_s \leq V_{out}$, the diode works on reverse blocking state, and the traction substation neither output power or absorbed power, so

$$I_{out} = 0 \tag{3}$$

The output characteristic curve of traction substation can be obtained. The horizontal axis represents the output current of the traction substation I_{out}, and the vertical axis represents the output voltage U_{out}. The curve is only in the first quadrant, which indicates that the traction substation can only output power and can't absorb power.

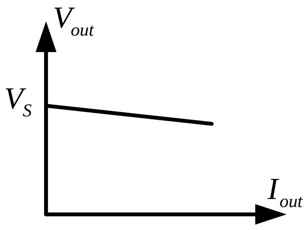

Fig. 2 Output characteristic curve of traction substation

2.2 Line Impedance Model

As the position of the train is changing with time, so the line impedance between trains or between substation and train also changes with time, in order to reflect the time-varying characteristic of line impedance in the model, it is defined as a function which related to the location of trains and substation[2]. Generally, there are maximum 2 trains between two substations in a line, as is shown in Fig. 3, and the line impedance can be described as:

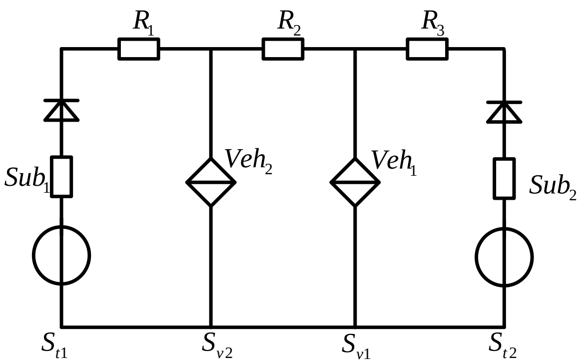

Fig. 3 Line impedance model with 2 trains

$$\begin{cases} R_1 = (S_{v1} - S_{t1}) \times \delta \\ R_2 = (S_{v1} - S_{v2}) \times \delta \\ R_2 = (S_{t2} - S_{v1}) \times \delta \end{cases} \quad (4)$$

When there is one train between two substations, the line impedance can be described as

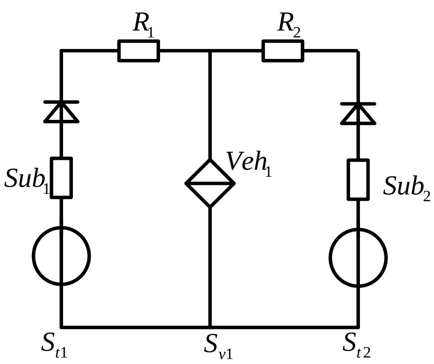

Fig. 4 Line impedance model with 1 train

$$\begin{cases} R_1 = (S_{v1} - S_{t1}) \times \delta \\ R_2 = (S_{t2} - S_{v1}) \times \delta \end{cases} \quad (5)$$

When there is no train between two substations, the line impedance can be described as

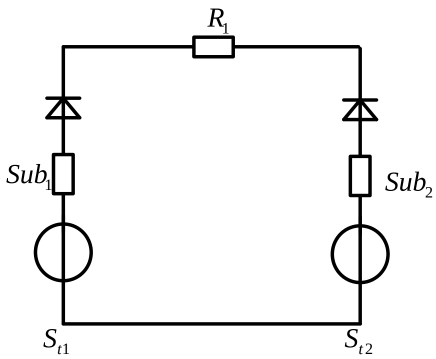

Fig. 5 Line impedance model with no train

$$R_1 = (S_{t2} - S_{t1}) \times \delta \quad (6)$$

2.3 Train Model

The inverter of the train can be equivalent to a controlled current source. The inverter power of the train at any time can be obtained by traction calculation results, and according to the terminal voltage of the train at this moment, the train current can be drawn[1]. If the current is positive, the train absorbed power from the grid, whereas the train releases power to the grid[5].

When the traction power supply network cannot absorb regenerative braking power, the DC voltage of the train V_{train} increases rapidly, then air brake or resistor brake of the train consume this part of the energy. The series model of diode and the voltage source embodies the resistor brake or air brake of the train, when $V_{train} \geq V_{\lim}$, the diode $D_{\lim}$ conducts, and the voltage source $V_{\lim}$ absorbs this part of the braking power. We can get the energy consumed by air brake or resistor brake in a period of time by the integral of product of $V_{\lim}$ and $I_{\lim}$.

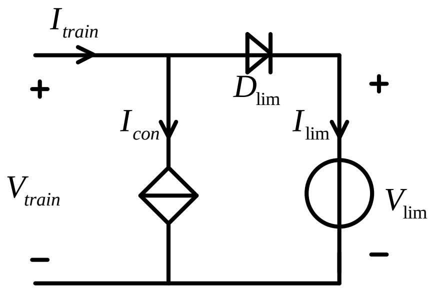

Fig. 6 Train model

$$P_{con} = \frac{P_{wheel}}{\eta_{gear} \times \eta_{motor} \times \eta_{converter}} \quad (7)$$

$$I_{con} = \frac{P_{con}}{V_{train}} \quad (8)$$

$$W_{\lim} = \int V_{\lim} \times I_{\lim} dt \quad (9)$$

2.4 Ultra-capacitor ESS Model

Ultra-capacitor ESS generally consists of DC/DC converters and ultra-capacitor bank, The high voltage side of DC/DC converter is connected to DC bus of urban rail transit traction substation, and the low voltage side is connected with the ultra-capacitor bank, as is shown in Fig. 7. When the energy transmits from left to right, the DC/DC converter works in the buck model, and when the energy transmits from right to left, the DC/DC converter works in the boost model[7]. The control algorithm is generally double loop control, and the outer loop is DC bus voltage control loop. The current command signal of ultra-capacitor is obtained by the error of bus voltage passing through PI regulator. The inner loop is current control loop, and PI regulator is also used. The output of PI regulator is the duty cycle of the switching device. The pulse signal of two switching devices in the same bridge arm of DC/DC converter is complementary. One signal is 0, the other signal is 1.

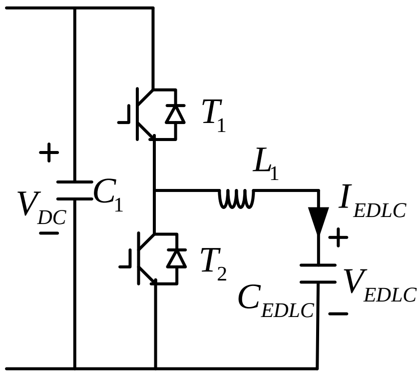

Fig. 7 Topology of ultra-capacitor ESS

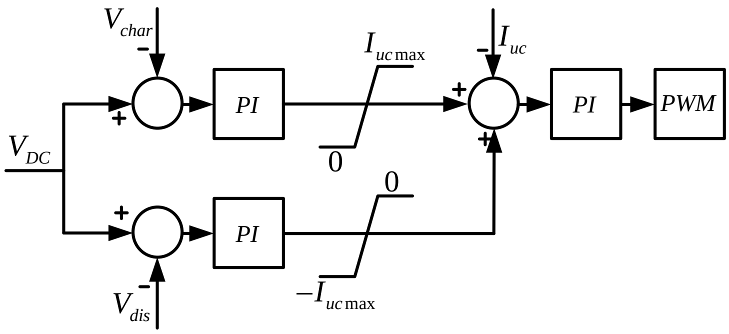

Fig. 8 Control algorithm of ultra-capacitor ESS

It is difficult to describe the ultra-capacitor ESS accurately, because the mathematical model is very complex. So this paper proposes a linear ultra-capacitor ESS model. As the outer loop of ultra-capacitor ESS is the voltage loop, the terminal voltage is constant whether the ESS is charging or discharging, so it can be substitute by a constant voltage source, the values of the voltage sources are different when the ESS is charging or discharging, and the initial energy value of one voltage source is the final energy value of another voltage source[10]. The mathematical model of ESS can be described as follows,

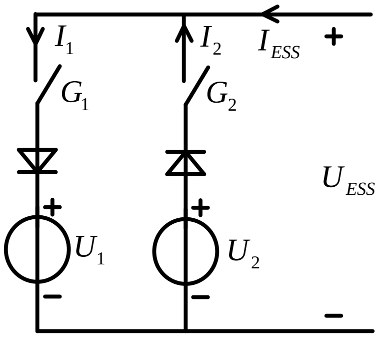

Fig. 9 Equivalent model of ultra-capacitor ESS

$$\begin{cases} P_1 = U_1 \times I_1 \\ W_1 = \int U_1 \times I_1 dt + W_2 \\ P_2 = U_2 \times I_2 \\ W_2 = W_1 - \int U_2 \times I_2 dt \end{cases} \tag{10}$$

3 Case Study

In order to study configuration method of ultra-capacitor ESS, we build a simulation model based on Matlab/Simulink. The simulation uses data of a Beijing subway line, this metro line are totally 22 stations, 13 traction substation which average distance is 1.89km. Fig. 10 shows the speed, position and power curve of a train on this line, which the positive power is the train traction power, and the negative power is the train braking power. When the train departure interval is 600s, we can derive four pairs of trains running on this line at the same time. The position and power curve of trains are used as input conditions of simulation.

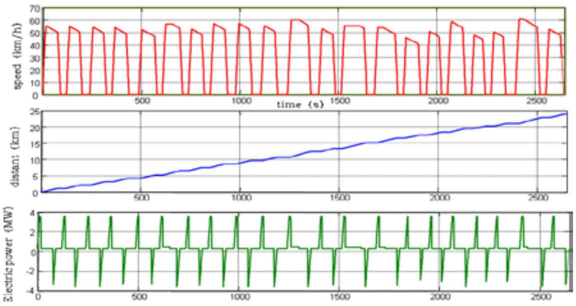

Fig. 10 Speed, position and power curve of a train on a Beijing subway line

In order to study the location setting of traction substation, this paper introduces 3 setting methods for ultra-capacitor ESS of 13 traction substation on this line. They are uniformly distributed 3 ESSs, 6 ESSs and 12 ESSs. The distribution of the ESS is shown in Table I.

Table I Setting methods for ultra-capacitor ESS

Substation	1	2	3	4	5	6	7	8	9	10	11	12	13
3ESSs			Δ				Δ				Δ		
6ESSs		Δ		Δ		Δ		Δ		Δ		Δ	
12ESSs	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	

The simulation result is shown in Fig. 11; the horizontal axis of the curve is the total energy storage of ultra-capacitors on the whole line, for example, if a ESS capacity is x and ESS amount is y, then x*y is total ESS capacity. Under the condition of the same total stored energy, it can be found the more intensive of the ultra-capacitor ESS, the less energy of each ultra-capacitor ESS used. The vertical axis of the curve is the sum of regenerative braking energy absorbed by ultra-capacitor ESS in one hour. According to the simulation result, the following conclusions can be obtained:

i. If the total ultra-capacitor configuration is same, set more storage systems can help absorb more regenerative braking energy, which is due to the existence of line impedance, the power absorbed by ESS will reduce as the increase of braking distance of the train. If the position setting of ESS is relatively sparse, the place of the braking train is far away from ESS, resulting in the train braking power can't be effectively absorbed by ESS and more braking energy is consumed by braking resistor or air brake. So in this configuration method, the energy absorbed by ESS is not very much.

ii. For a certain position setting scheme, the trend of ESS absorption curve is: When the configuration amount of ESS is low, the slope of the curve is large, and the capacity configuration is low for the regenerative braking, and the SoC of ESS always works on the limit state of 0.25~1. As the increase of capacity configuration of ESS, the slope of the curve will decrease, and now SoC of some ESS works on less than 0.25~1, which manifests as the excess capacity configuration of ESS. Since there are only 3 ESSs in 3ESSs scheme, these three ESSs work out of the range from 0.25 to 1 quickly. With the further increase of capacity configuration, all of the ESSs work out of the range from 0.25 to 1, and the absorbed energy in per hour will no longer increase, and then the approaching value of the curve at can be used as ESS configuration value on this line. From the configuration curve of 12ESSs we can know that when the total capacity is more than 25kWh, the amount of energy saving will not increase, so it is recommended that the capacity configuration of each ESS on this line is 2kWh. If the capacity configuration of ESS is too much, it will result in a waste of ESS capacity.

When the total ESS capacity is a fixed value, compare the energy-saving effect of different position setting schemes. From Fig. 11, we can know that the more intensive of ESS setting, the better recovery of braking energy. So set an ESS for each traction substation is a proper scheme.

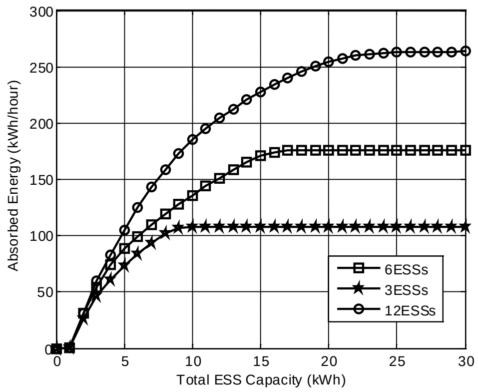

Fig. 11 Simulation result of ultra-capacitor ESS

4 Conclusion

This paper built the model of urban rail transit traction power supply system, the train converter system and stationary ultra-capacitor ESS system, and the result of configuration method is obtained by simulation. ESS configuration is proposed by two principles: set more ultra-capacitor ESS as much as possible, and one traction substation one ESS is the best. If the capacity configuration of ESS is too much, it will result in a waste of ESS capacity.

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