Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 16 (2012) 585 – 591

Energy Procedia

2012 International Conference on Future Energy, Environment, and Materials

Design and analysis of emergency self-traction system for urban rail transit vehicles

Dengke Yuan[a,]*, Shuai Gu[a], Junjun Liu[a], Yicheng Zhang[a], Chuanxian Lv[b]

[a]Tongji University, No.4800 Cao'an Road, Shanghai, 201804, China
[b]Suzhou Phylion Battery Co., Ltd, No.81 Xiangyang Road, Suzhou, 215011, China

Abstract

This paper firstly proposes a concept of emergency self-traction system (ESTS) for the urban rail transit vehicles with an onboard hybrid energy storage system (ESS). The onboard ESS consists of the high-energy-density batteries and the high-power-density supercapacitors. The topology of the ESTS is elaborated in the second part. The DC/DC power converter for hybrid ESS is dedicatedly designed to take full advantage of different energy storage devices, and also suitable for the existing vehicle electric system. Then, the flowchart of the ESTS control system is presented to illustrate the ESTS operation in emergency self-traction mode. Finally, the simulation results from MATLAB are shown to demonstrate the validity of the architecture and the control strategy of ESTS.

Keywords: urban rail transit vehicle; emergency self-traction; onboard hybrid energy storage; supercapacitors

1. Introduction

Urban rail transit has been rapidly developed in most large and many middle cities in China recently on account of its countless merits, such as high speed, punctuality, mass transport capacity, low cost and environmental friendliness, etc. In a word, urban rail transit has been acting as an essential role to relieve the urban traffic congestion all around the world.

Because of the dependence of the electric power, it is vital to guarantee the safe operation of the power supply network of urban rail transportation. However, the power supply paralysis is yet inevitable because of man-made destruction, natural disasters, and mostly the contingent faults of urban rail transit power supply network itself, which may result in a blockage of the vehicles and a large number of stranded

* Corresponding author. Tel.: +86-13795480678; fax: +86-21-69589870.
E-mail address: ydk@tongji.edu.cn.

 doi:10.1016/j.egypro.2012.01.094

passengers. The worst scenario happens when the metro vehicle happens to stop in the tunnel, which probably causes personnel panic, and other serious consequences [1, 2]. Thus it is urgent to find an efficient and effective way to self-rescue the unpowered vehicle for urban rail transits.

Focusing on the line 11 vehicles of Shanghai metro in Fig 1, this paper designs and analyzes an emergency self-traction system (ESTS), in which an onboard energy storage system (ESS) is designed and installed in the metro vehicle. ESTS will assist the vehicle drive to the safe area with ESS in Fig 2 when the external power is off. At the same time, ESTS can recycle the vehicle regenerative energy, which buffers the peak power between the external power supply and the traction motors, to reduce power losses distributed in power supply network, transmission line as well as the input filter module of vehicles.

Fig. 1. Shanghai Metro Line 11 vehicle of in experiment line

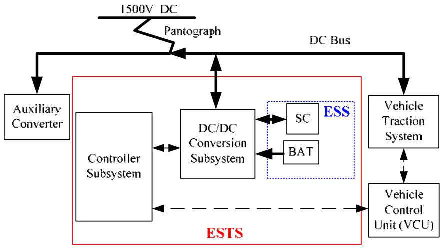

Fig. 2. Main electric system of the ESTS-equipped metro vehicle

2. Emergency self-traction system

2.1. ESTS architecture

In Fig 2, the emergency self-traction system of urban rail transit vehicles includes three parts: ESS, DC/DC power conversion subsystem (PCS) and ESTS control subsystem (CS) [3]. The bold lines and arrows represent the power flow paths and their directions. The dashed lines represent the control signal paths.

As the core of ESTS，ESS provides the metro vehicle with electric power instead of the pantograph under the externally unpowered condition. PCS is the bridge connecting the energy storage units and the vehicle traction systems. ESTS control subsystem communicates and cooperates with vehicle control unit (VCU) to govern the power of onboard ESS through PCS to satisfy power and energy demands of the vehicle traction system.

During the normal operation of the external power supply, the ESS absorbs the regenerative energy from DC bus in the braking or decelerating phase and releases the energy back to the vehicle traction system in the accelerating phase through the bidirectional PCS.

2.2. Power and energy demands analysis

In order to cover over most route conditions of Shanghai line 11, the typical condition for emergency self-traction is defined as follows. The vehicle operates with AW3 load, i.e. the mass of the vehicle is about 370 tons. The distance between the vehicle and the destination is 1500 meters. The 500-meter-long ramp with the gradient of 10‰ is just at the beginning of the track. The cruise velocity is 10km/h. The electric power and energy demands are simulated with the popular software of MATLAB and testified in the experiments. In Fig 3, the horizontal axes represent time (s), and the vertical axes are the vehicle velocity (km/h), distance (km), electric power (kW), electric energy (kWh) and traction effort (kN) respectively.

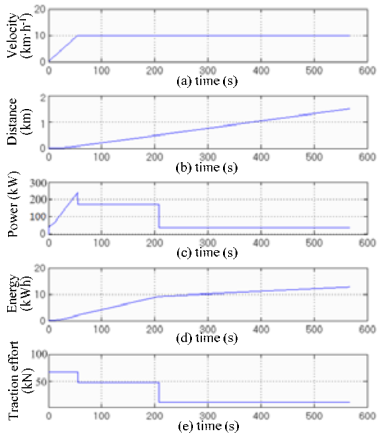

Fig. 3. Power and energy requirement of the metro vehicle under the typical condition

It can be easily obtained from Fig 3 that the vehicle accelerates at $0.05m/s^2$ for about 55 seconds, and the maximum electric power demand reaches approximately 240kW just before the acceleration stage ends. In the cruise phase the vehicle maintains the velocity of 10 km/h for about 512 seconds. The electric power demand is about 160kW in the ramp and about 40kW in the horizontal route. The total energy consumption for ESTS is 12.5kWh approximately.

2.3. Onboard energy storage subsystem

Overall, the peak power demand and the energy consumption of metro vehicle is extremely high, hence the appropriate energy storage devices should be selected to constitute a high performance ESS using the available energy storage devices.

In recent years, supercapacitor (abbreviated as SC in this paper) is becoming more and more attractive for its high-power density, large charge and discharge current, high efficiency, long cycle lifetime, environmental friendliness, and wide work temperature range [4, 5]. As a result, SC has been widely employed to buffer power between the electric source and load in many industries [6, 7]. Though other high power density energy storage devices, like flywheels, lithium batteries and fuel cells, have also been utilized in related fields, concerning the safety along with long cycle lifetime, SC is more suitable to satisfy the peak power demand of the vehicle traction system and to buffer the power flow between the external power supply and the traction motors.

The characteristics of the batteries are exactly opposite to SC, which commonly have higher specific energy and more stable voltage, while the charge and discharge current is lower and the cycle lifetime is especially limited compared to SC. With a view of the price ratio, nickel cadmium battery is commonly chosen as the emergency backup power in Shanghai urban rail transit vehicles.

To sum up, it seems that SC together with nickel cadmium battery is much more suitable for the onboard ESS. The line 11 vehicle of Shanghai metro has already been installed with two groups of MRX160 (nickel cadmium battery of SAFT). Each group consists of 80 cells. Table 1 gives the configuration of ESS. Four groups of MRX160 are utilized to supply most part of the power and energy in

ESTS. In addition, 660 cells of BCAP3000 (the typical SC product of Maxwell) are applied to provide the remaining peak power in acceleration period and also part of power in the ramp.

Table 1. Onboard ESS configuration

Energy storage device	Supercapacitor (BCAP3000)	Nickel Cadmium battery (MRX160)
Capacity (F or Ah)	3000F	160Ah
Nominal voltage (V)	2.7	1.4
Terminal voltage (V)	1.3	1.0
Cell mass (kg)	0.51	6.6
Discharge current (A)	300	400 at 2.5C
Serial number of one group	330	80
Number of groups	2 parallel	4 series
Maximum power (kW)	495	160
Nominal stored energy (kWh)	2	70
Total mass (kg)	336	2218

2.4. DC/DC converter topology

Based on the ESS configuration in Table 1, the maximum voltage of the SC tank approaches 864V while the voltage of batteries reaches about 420V. Considering the power supply network voltage varies from 1000V to 1800V under different conditions, DC/DC power converters are necessarily attached into the vehicle electric system in Fig 2.

In order to minimize the quantity of DC/DC converters as well as to improve the reliability of the ESTS, one power converter is elaborately designed to meet different demands of the traction system [8]. Fig 4 shows the detailed electric circuits of the ESTS. S1 and S2 are two contactors. T1, T2, T3 and T4 are four IGBT semiconductor switches. The four IGBTs and the inductor L2 constitute a bidirectional, up and down DC/DC converter.

Switch S2 is disconnected and switch S1 is closed during normal operation as the DC/DC converter recycles the regenerative energy between the SC tank and vehicle traction system. The DC/DC converter operates in either mode A or B in Table 2. In mode A, T1 is controlled by PWM signal while T2, T3 and T4 are off. As long as the metro vehicle brakes, voltage of DC bus will be higher than no-load voltage. Controlled by DC/DC converter and traction inverter, the voltage of SC tank is regulated between 400V and 600V in advance to absorb the power flow from traction motor. In mode B, the duty ratio of T2 is controlled to adjust the power from the SC tank to motor when the vehicle accelerates.

Table 2. Operation modes of DC/DC converter

Mode	T1	T2	T3	T4	DC bus voltage (V)	SC tank voltage (V)	Power flow direction
A	PWM	OFF	OFF	OFF	1700-1800	400-600	motor to SC
B	OFF	PWM	ON	OFF	1100-1200	600-800	SC to motor
C	OFF	OFF	PWM	OFF	400	600-800	SC to motor
D	ON	OFF	OFF	PWM	>400	400-600	motor to SC

External power supply is off during emergency self-traction operation. DC bus voltage is then mainly sustained by batteries to approximate 400V. The DC/DC converter operates in mode C and D with the connected switch S2 and closed S1. T3 is controlled by PWM signal in mode C to release the energy from the SC tank to the traction motors.

In mode D, the electric energy flows from batteries to SC tank which can be utilized to adjust the energy level of the SC tank within the appropriate range. This mode plays a crucial role when the route from the metro vehicle to the destination comprises some long steep ramps occasionally.

The power demand is predicted according to Fig 3 by control subsystem of ESTS. DC/DC converter transmits the predetermined electric power from the SC tank to the traction system when electric power demand is overlarge, while the surplus is complemented from batteries. Thus two different kinds of energy storage devices can be coordinated well with the assistance of the converter.

3. ESTS control strategy

If the metro vehicle loses the power supply from the external grid suddenly, the grid voltage will drop quickly. The vehicle firstly judges whether the network can keep working. One possible result is that the traction system breaks down and doesn't work any longer. The driver in that case should turn on the emergency lighting and ventilation as well as inform the passengers to wait for being rescued. The other possible result, which may happen more likely, is that the vehicle traction system still works well. Then ESTS will be activated manually by the driver. It will adjust the output voltage to the level of onboard batteries (U_{BAT} in Fig 4). Based on the communication and coordination with vehicle control unit (VCU), the control subsystem of ESTS predicts the prospective power and energy demand of the vehicle. After coordinating the demands and the capacity of the SC tank, the control subsystem of ESTS calculates the reference current of inductor L2, and then converts it to PWM signals to control DC/DC [9].

As long as the vehicle reaches the destination, the driver will immediately evacuate the passengers. Fig 5 illustrates the ESTS flowchart for the metro vehicle.

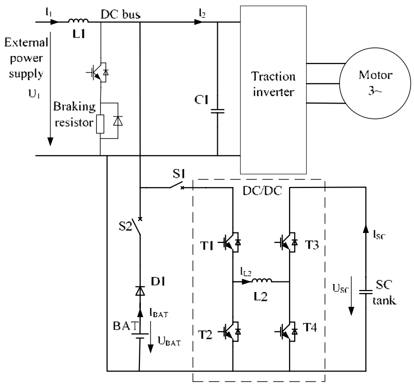

Fig. 4. Bidirectional, up and down DC/DC converter

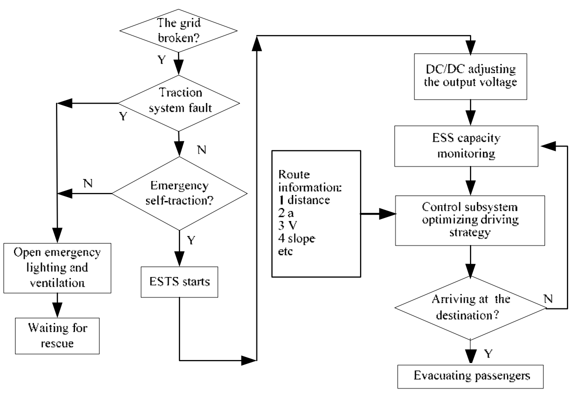

Fig. 5. Flowchart of the ESTS for the metro vehicle

4. Simulation verification

Fig 6 shows the simulation interface in MATLAB. Part 1 is the model of supply network. The breaker is controlled to sever the feeding line at 47s. Part 2 is the power model of auxiliary electric system of the vehicle. Part 3 models the electric power of the vehicle traction system. Part 4 comprises the model of the ESS, DC/DC converter and the control subsystem of ESTS.

Fig 7 presents the simulation results of ESTS for urban rail transit vehicles. The horizontal axes are time (s). The vertical axes from (a) to (g) are voltage and current of the DC grid (U_1 and I_1), current of vehicle traction system (I_2), current of inductor L2 in Fig 4, voltage of the SC tank and the current of the batteries respectively.

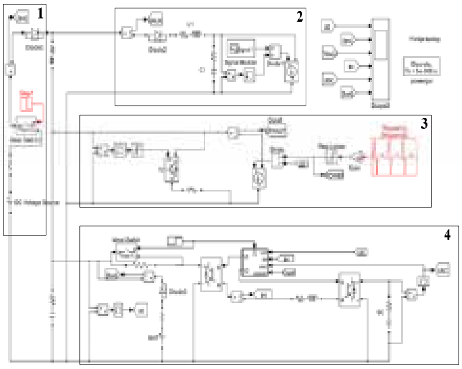

Fig. 6. MATLAB simulation diagram of ESTS

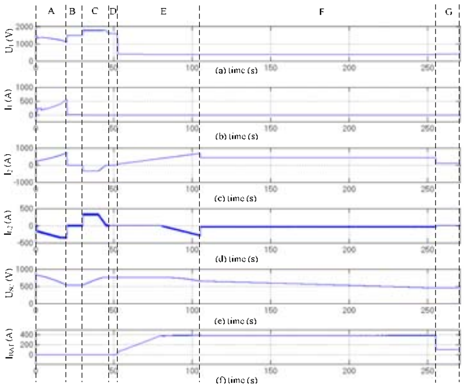

Fig. 7. Simulation results of ESTS for urban rail transit vehicle

There are 7 phases named from A to G in Fig 7. Phase A represents the start and acceleration stage of the vehicle under normal power supply. With the increase of the vehicle traction power in (c), the voltage of the external grid lowers in (a) and the current of the grid in (b) increases obviously. In order to alleviate the line voltage decrease and reuse the regenerative energy stored in ESS, SC tank are controlled by the DC/DC converter to discharge. It is obvious that the voltage of SC tank lowers gradually. Phase B represents the idle stage of the train and there is not much electric power consumed in this period. Phase C stands for the braking stage of the vehicle. The kinetic energy of the vehicle is changed to the electric energy through the traction motors and to the DC energy through the traction inverter. So the line voltage of the DC grid is raised to near 1800V and kept constant with the operation of the braking circuit. The SC tank absorbs part of the braking energy and U_{SC} rises consequently. In phase D, the breaker in Fig 6 severs the external power supply. The voltage of the DC grid drops rapidly, and then is supported by onboard batteries to near 400V. In phase E, F and G, the vehicle drives itself with ESTS. The electric power in Fig 7 is the same as the power in Fig 3(c). In the latter part of the phase E, the SC tank discharges to meet peak power demand of the traction system to alleviate the burden of batteries. In phase F, the traction power is mainly provided by batteries and only a small part is from the SC tank. In phase G, the power demand decreases to only about 40kW which implies the batteries discharge at only about 0.6C.

It is distinctly shown in Fig 7 that not only ESS, including the SC tank and batteries, but also DC/DC converter dedicatedly designed for the ESTS function properly.

5. Conclusion

This paper analyzes and designs the emergency self-traction system for the urban rail transit vehicle. The architecture of ESTS and the DC/DC converter topology are proposed. Some key features of ESTS are summarized as follows.

- The architecture of ESTS enables the vehicle drive itself to the destination based on the onboard ESS which improves the flexibility of the metro vehicle in rescue.
- The architecture of ESTS also enables the ESS to recycle the regenerative energy of the vehicle by using bidirectional DC/DC converter.
- The SC tank are controlled to absorb and release the braking energy in normal mode, as well as to supply part of the peak power to the traction motors in self-traction mode. With the assistance of

DC/DC converter, the SC tank can be charged from the batteries when the state of charge (SOC) decreases to a certain extent.

- Batteries on board are utilized to supply the main power and energy demand of the traction motors.
- The DC/DC converter is elaborately designed to control the bidirectional power flow between the SC tank and the vehicle traction system.

Acknowledgements

This research has been supported by the National Science Foundation of China (Number: 50877054) and by the Shanghai Shentong Metro Co., Ltd ("Study of Emergency Self-Traction System Combining Regenerative Energy Recycle for Urban Rail Transit Vehicles", Number: KY10R018). The technical support of Jiqi Li and Xuewei Guo is gratefully acknowledged.

References

[1] http://zh.wikipedia.org/wiki/1222%E4%B8%8A%E6%B5%B7%E5%9C%B0%E9%93%81%E4%BA%8B%E6%95%85.

[2] http://jingji.cntv.cn/20111029/103631.shtml.

[3] Junjun Liu, Dengke Yuan, Qiaolian Zhou, Jiqi Li, Li Wei, Yicheng Zhang, et al. Simulation and analysis of emergency self-traction system for urban rail vehicles. Mechatronics, July 2011, Vol.17, No.7, p. 20–23 (in Chinese).

[4] Luis Mir, Izaskun Sarasola, Txomin Nieva. A Super capacitor Based Light Rail Vehicle: System design and operations modes. Energy Conversion Congress and Exposition, ECCE 2009, p. 1632–1639.

[5] Yimin Gao, Mehrdad Ehsani. Parametric Design of the Traction Motor and Energy storage for series hybrid off road and military vehicles. IEEE Transactions on Power Electronics, May 2006, Vol.21, No.3, p. 749–755.

[6] S. Lu, D. H. Meegahawatte, S. Guo, S. Hillmansen, C. Roberts, C. J. Goodman. Analysis of Energy Storage Devices in Hybrid Railway Vehicles. Railway Engineering - Challenges for Railway Transportation in Information Age, March 2008, ICRE 2008, p. 1–6.

[7] W. Lhomme, P. Delarue, P. Barrade, A. Bouscayrol, A. Rufer. Design and Control of a Supercapacitor Storage System for Traction Applications. Industry Applications Conference, Fourtieth IAS Annual Meeting 2005, Vol.3, p. 2013–2020.

[8] R. Li, A. Pottharst, N. Fr?hleke, J. B?cker. Analysis and Design of Improved Isolated Full-Bridge Bi-Directional DC-DC Converter. Power Electronics Specialists Conference 2004, IEEE 35th Annual, Vol.1, p. 521–526.

[9] Shuai Gu, Dengke Yuan, Yicheng Zhang, Qiaolian Zhou. Research on Control Strategy of the Emergency Self-Traction System in Urban Rail Transit. International Conference on Electrical and Control Engineering 2011, September 2011, p. 303–306.