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Energy Conversion Process and Some Solutions to Recuperation of Regenerative Braking Energy in Urban Railway Electric Train

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Abstract: Railway systems, especially electric railway systems, are drawing more attention because they prove to be a more efficient and less emission compared to other means of transportation. Given that numerous and frequent stops are a considerable characteristics of urban railway, recuperation of braking energy offers a great potential to reduce energy consumption in urban rail systems. The paper presents a comprehensive overview of the energy conversion process and some solutions to recover brake energy by applying super-capacitor energy storage systems integrated with electric motor dive system, or front-end active rectifiers placed to traction substations with the capability of exchanging bi-directional energy between line utility and load. ESSs are an effective measure to reuse regenerative energy with voltage stabilization and energy saving, and front-end active rectifiers which enable energy to flow bi-directional installed at traction substations are also a feasible technology thanks to outstanding development of power electronics sector.

Keywords: Energy storage system, Active rectifier**,** Regenerative braking

1. INTRODUCTION

Nowadays, urban railway transits play an important role in the sustainable growth of densely populated areas for many reasons, yet mainly because of their low ratio between energy consumption and transport capacity compared with the other means of transportation. In Vietnam, The construction of urban railway transit systems in Hanoi and Ho Chi Minh cities are getting underway, and the typical DC transit system use 750V DC or 1500V DC. These voltage levels supplied by rectifier substations, generally connected to medium-voltage distribution networks 22kVAC. Fig.1 shows the metro network model including electrified train, unidirectional substations, connecting lines F. Du *et al* (2010)

Due to operation of electrified train in acceleration and deceleration being frequent, recuperation of brake energy has to complement. There are two types of electrical braking, comprising of dynamic and regenerative braking K.bose(2008). In dynamic braking, the recovered electrical energy at the machine terminal is converted to DC through the inverter (the inverter acts as a rectifier) and is dissipated in brake resistors (rheostatic braking). In regenerative braking, electrical energy is recovered in the source to improve drive efficiency, the braking power instead of dissipating in resistors can easily flow back to the source. Several studies have shown that application of regenerative braking in urban rail systems could potentially reduce their net energy consumption between 10% and 45%, depending on the characteristics of each system (Kim and Lee, 2009; Lee *et al.*,2011).

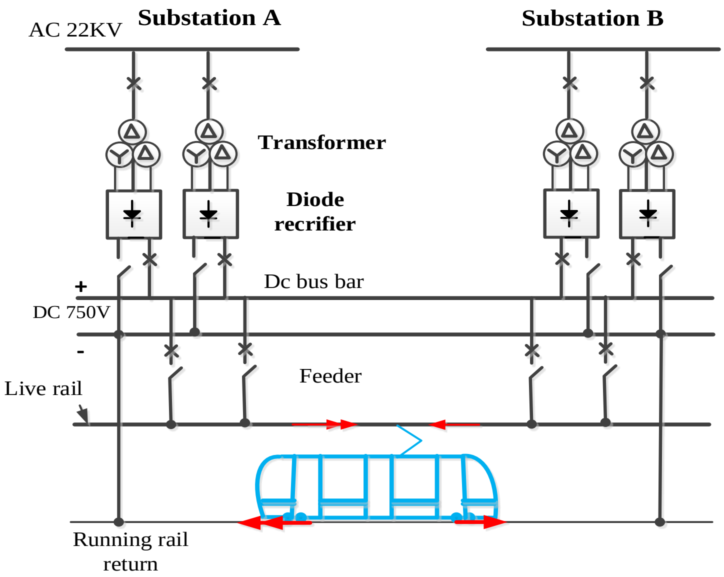

Figure 1.Typical DC transit system

Besides, regenerative braking may improve some problems involved in electrified transport systems, for instance, voltage drop or excess at feeder line, reduce peak power as well (Wang and Yang, 2009). With the rapid development of power electronics, a few solutions to recover regenerative braking energy are introduced in this paper, such as: Active rectifiers installed at traction substation, super-capacitor energy storage system integrated with traction drive system.

2. ENERGY CONVERSION PROCESS OF ELECTRIFED TRAIN

To analyze energy conversion process of electric train, firstly, traction characteristic of a railway vehicle should be investigated. Fig.2 shows that for most transit operations, station-to-station movement represents a cycle of five different phases of motion: acceleration, constant speed, coasting, braking, and standing (ZongYu Gao *et al.*, 2014).

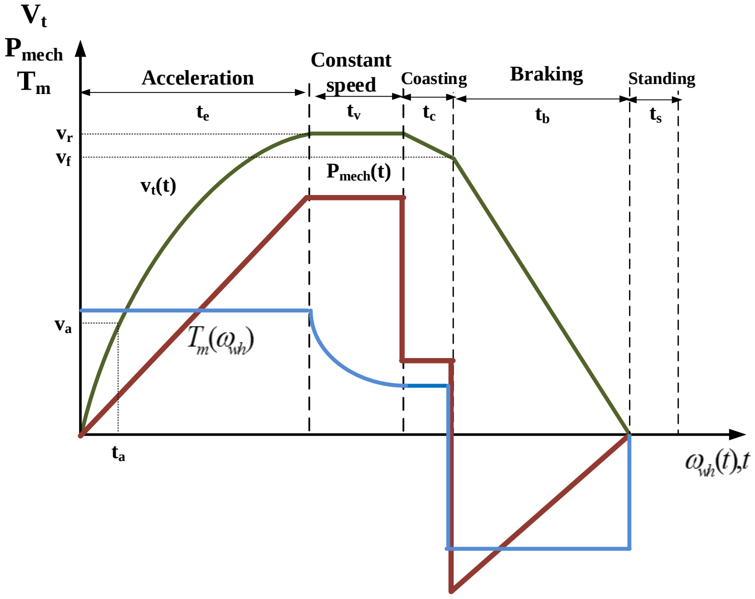

Figure 2. Mechanical characteristic, traction diagram and mechanical power at the wheel during the different motion phases for station-to-station travel for electrically powered vehicles

Phase 1: Acceleration is the starting phase of the station-to-station movement, in a first section up the time instant in which the speed of the vehicle passing from the value zero is still low, and the rate of initial acceleration is a maximum rate, the tractive effort is on average constant and the motion resistance is little variable, and then the acceleration can be considered constant; there is a section from v_a to v_r decreasing in acceleration; phase 2: Constant-speed, the duration of interval during which transit vehicle travels at constant, is the phase where the motors generally operate at a constant power value; phase 3: coasting, when the maximum speed v_r is reached, the motors are switched off and the vehicle coasts until the brakes must be applied for a stop at the next station. Since the deceleration rate is very low, coasting often results in a slightly increased travel time but also a considerable energy saving; phase 4: braking, in which the vehicle speed decreases from the v_f value; phase 5: Station standing time, because the average operating speed and the capacity of the transit line are strongly influenced by the duration of standing at stops or stations t_s, it is important to keep this interval as short as possible. As above analyses, an energy conversion process is made when electrified train operates follow *v(t)* - traction diagram. Energy from traction substations flowing through pantograph provides for electric traction motor drive system, turning electricity energy into mechanical energy to pull wheels. In operation, there are two regimes: acceleration, braking causing voltage fluctuation on DC bus to worsen the working quantity of traction drive system, namely, acceleration regime, machines acting as motor consume energy, causing voltage drops on DC bus, and braking regime, machines acting as generators, surplus braking energy sends back the power supply line causing voltage increase on DC bus; however, energy surplus may be returned into the power supply line for use of other vehicles shown in fig.3, for example, while the train is accelerating, another train decelerates in the same electric section, the regenerative energy directly transfers between both trains through the power supply line.

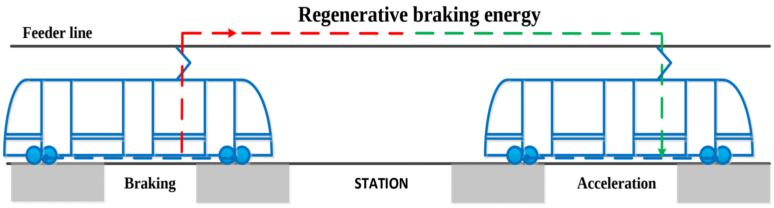

Figure 3. Schematic representation of regenerative energy exchange between trains

If trains both accelerate or decelerate at instant, the regenerated energy is regularly dissipated in brake resistors causing energy failure. Therefore, in this case, some energy recuperation measures should be taken.

3. SOME SOLUTIONS TO RECUPERATION OF REGENERATIVE BRAKING ENERGY

To prevent braking energy waste from dynamic braking, the authors introduced two measures to recuperate the regenerative braking energy.

3.1 The front- end active rectifier

In a DC electric railway system, conventional substations use diode rectifiers which only allow unidirectional flow of power. In contrast, traction substations installed active rectifiers-

IGBT converters instead of diode rectifiers enable current to circulate bi-directionally. When a train brakes, regenerated energy is created to transfer into the grid. If traction substations use front-end active rectifiers, they easily pump back regenerative energy in to the primary supply networks. Their configuration are shown in fig. 4, 5 (K.Bose, 2008; Nguyen and Dittrich, 2015)

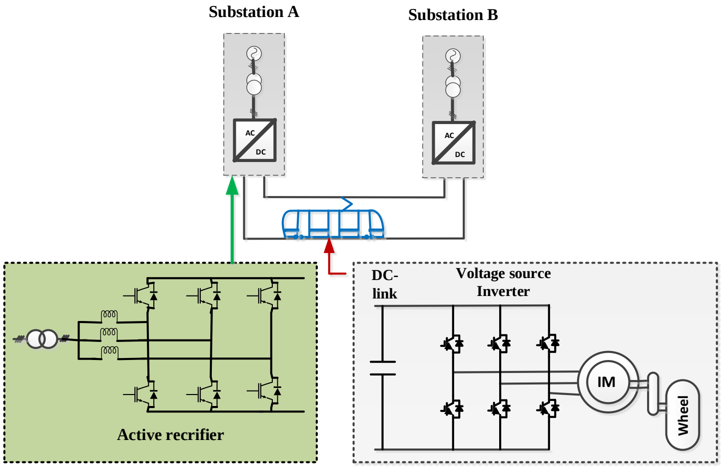

Figure 4. Front-end active rectifier and traction motor

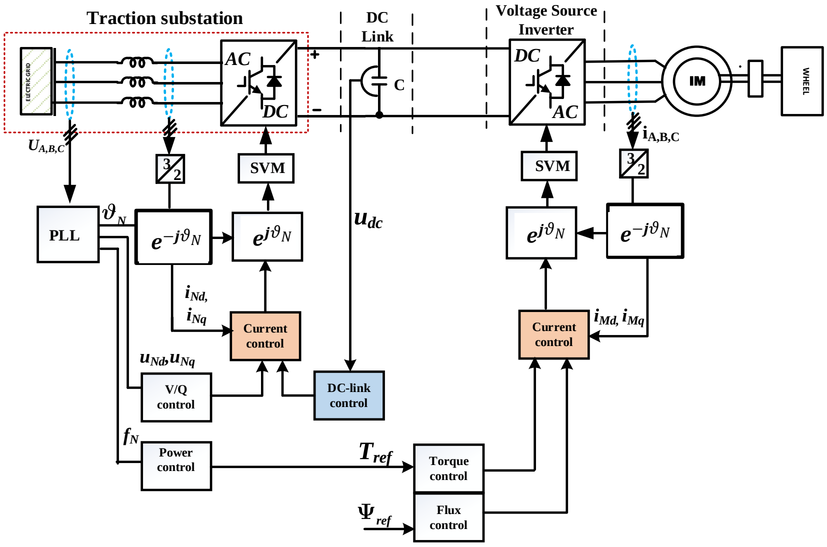

Figure 5. Block diagram of control strategy for the front-end active rectifier and traction motor

The cascaded control also shown in this topology aims to manage bidirectional energy flow from line source to load and vice versa, by keeping DC-link voltage at fix value with variations of load.

The main purpose of active rectifiers is not only to absorb the braking energy as much as possible, but also minimize the level of harmonics, guaranteeing a good quality of power supply in both AC and DC sides.

When compared with ESSs, recuperation of braking energy through front-end active rectifiers having the greatest advantage is that the primary AC network is naturally receptive, as a result, all the regenerated energy may be potentially recovered. Additionally, the active rectifiers have a more efficient option of reducing space, and fewer transformation losses.

Conversely, the main drawback of this approach is related to the big cost of new equipment and the strong impact on the layout of existing substations (Ortega *et al.*,2010; Cornic 2010), so using front-end active rectifiers are faced with difficulties in costs, operation, and technical problems.

3.2 Traction drive system integrated with super-capacitor energy storage system for urban rail

Because of some disadvantages of front-end reactive rectifiers, so the next recovered braking energy solution for traction drive system integrated with super-capacitor energy storage system (SCESS) on board vehicles or track side has demonstrated excellent performance in reducing energy loss and stabilizing the line voltage (Alfred Rufer *et al, 2004)*. The energy storage systems comprise of DC-DC converters and energy storage components in which super-capacitors are chosen as the storage component because of super-capacitor's high power density, ability to charging and discharging fast in second, long cycle-life (Fronhlich *et al.*,2010; Wang and Yang, 2009). Onboard SCESSs permit electrified trains to temporarily store their own braking energy and reutilize it in the next acceleration stages. On the other hand, stationary SCESSs absorb the braking energy of any train in the system and deliver it when required for other vehicles' acceleration. In the paper, authors have concentrated on onboard SCESSs and designed dual-loop controllers to control bidirectional energy exchange between SCESS and traction drive system. Every system works independently, and the recovered energy is directly sent to the energy storage system placed on the train. When the electric train accelerates, energy is used in priority from the SCESS to propel the train (Steiner *et al.*, 2007; Allègre *et al.*, 2010).

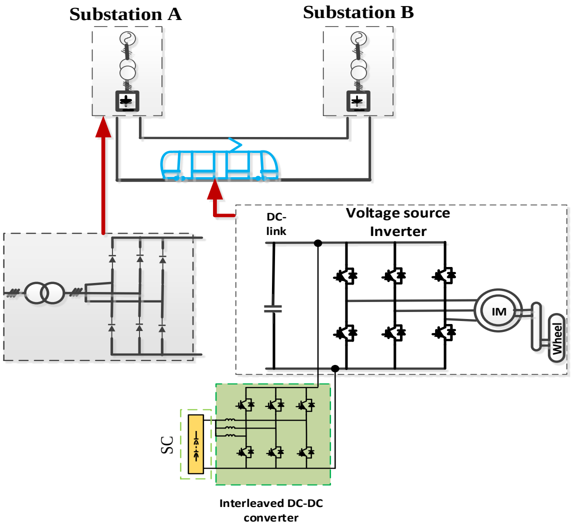

Figure 6. Configuration of traction motor with SCESS

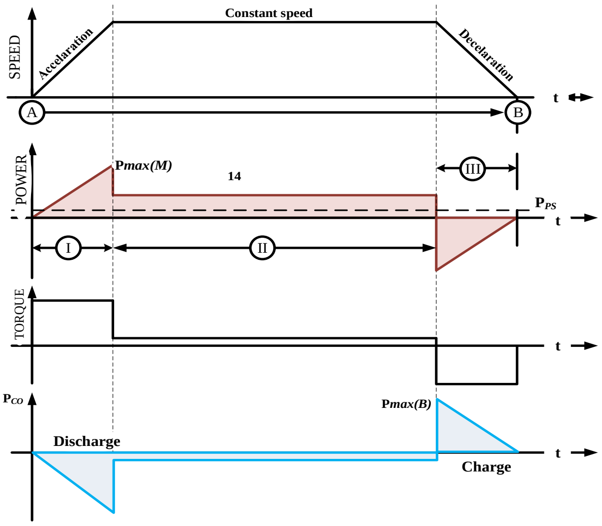

Figure 7. Characteristics of vehicle traction motor with SCESS

The traction system integrated with SCESS for urban railway shows in fig.5,6. In fig.6, characteristics of vehicle traction motor with SCESS demonstrate energy charge/discharge of super-capacitors; namely, when electrified train starts, power mobilized from line utility supplying the train motion is partly supported by energy from the SCESS with discharge regime of super-capacitors, and the SCESS operates in charge regime if the train brakes. Traction electric motor drive system is regarded as a voltage source inverter (VSI) feeds a large power induction motor (IM) by means of a DC-link. The current can be either drawn from or injected into the DC-link by the motor drive operation. It is required to ensure the energy balance between the primary power source (line source) and the motor drive (load) by regulating the DC-link voltage to a fixed value, for this control purpose, authors designed control structure of cascaded-loops.

The cascaded control shown in fig.8 is designed by nesting two-control loops. The inner plant captures the inductor current dynamics; namely, managing charge or discharge of super-capacitor system (SC). The inductor current of a leg is controlled by FRT controller while the outer loop-PI controller embed DC-link voltage at a constant value An (2016).
This structure requires separation of the dynamics in the sense that the inner loop must act much faster than the outer loop.

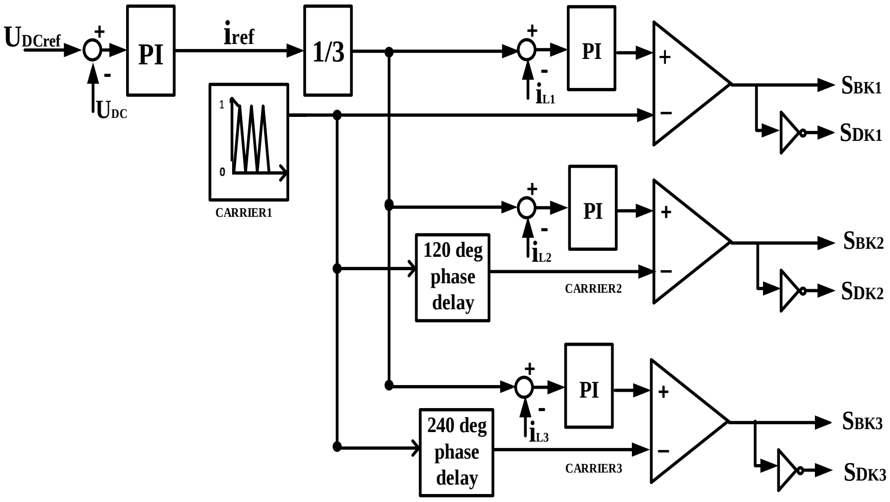

Figure 8. Cascaded loop control structure of the bidirectional DC-DC converter

FRT controllers of 4T with transfer function

$$G_R(z^{-1}) = \frac{z^{-1}\frac{1}{r_L}(1-e^{\frac{-T_s}{T}})}{1-z^{-1}e^{\frac{-T_s}{T}}}\,\frac{0.2z^{-1}+0.3z^{-2}+0.2z^{-3}+0.3z^{-4}}{1-0.2z^{-1}+0.3z^{-2}+0.2z^{-3}+0.3z^{-4}} \qquad (1$$

Where,

T_s: sampling time of inter loop**,**

$T = \frac{L}{r_L}$: Constant time.

The outer loop is the PI controller with transfer function

$$G_V(z) = k_{Pv} + \frac{T_S k_{Iv} z^{-1}}{1-z^{-1}} \qquad (2$$

Where,

T_s: Sampling time of outer loop (value of T_s of outer loop is 10 times more than value of T_s of inter loop)

k_{Pv} : Proportional coefficient

k_{Iv} : Integral coefficient

4. SIMULATION RESULTS

In order to veryfy above theoretical analyses, some simulation results are performed by Matlab/Simulink/Simpower System softwave with simulation parameters in table 1, table 2.

Simulation scripts include three situations: Induction motor traction drive system with dynamic brake resistor without SCESS**,** traction substation installed the front-end active rectifier, induction motor traction drive system integrated with SCESS. Due to limitations of computer figuration, simulation results are performed in a short time, however, these results have comprehensively shown dynamic behaviors of system.

Table 1: Parameters of traction motor

Parameters of IM	**Symbol**	**Value**
Nominal power	P_{nom}	630 kW
Nominal speed	n_{nom}	2983 rpm
Nominal voltage	U_{nom}	400V
Nominal current	I_{nom}	1039A
Stator frequency		50Hz
Pole pairs	z_p	2
Rotor resistance	R_r	0.00262Ω
Stator resistance	R_s	0.00262Ω
Rotor leakage inductance	σ_s	0.1727 mH
Stator leakage inductance	σ_r	0.1544 mH
Mutual inductance	L_m	0.002783mH
Inertia	J	26.8 kgm^2
Power coefficient	$cos\varphi$	0.9

Table 2: Parameters of interleaved DC-DC converter

Parameters of DC-DC converter	**Symbol**	**Value**
Switching Frequency	f_s	5 KHz
DC Link voltage	U_{DC}	600V
Capacitor of DC-Link capacitor	c	1000 µF
Phase inductance	$L_1 = L_2 = L_3$	2 mH
Phase resistance	r_L	0.05 Ω
Parameters of super-capacitor BMOD0063 P125 B08 63F/125V		

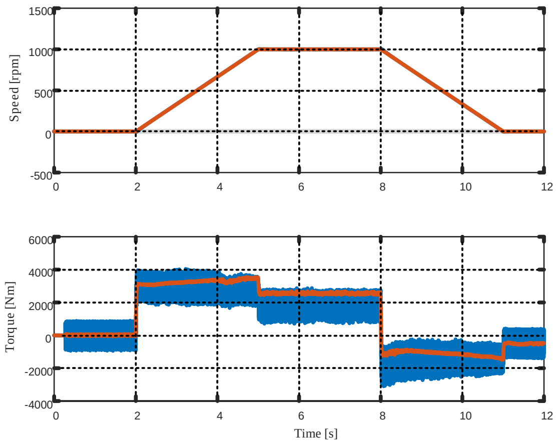

Figure 9. Dynamic behaviors of speed and electromagnetic torque of traction motor traction with dynamic brake resistor without SCESS

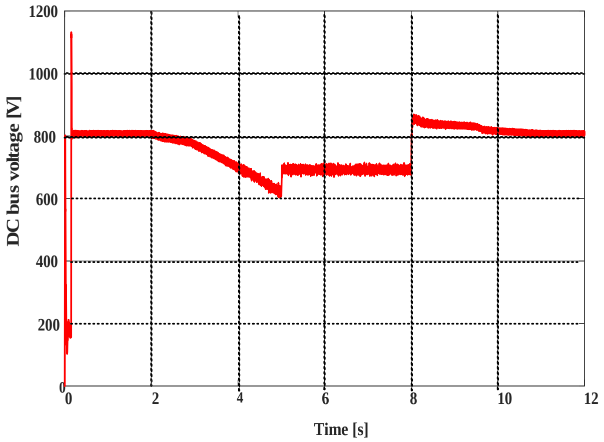

Figure 10. Dynamic behavior of voltage of DC-link capacitor with dynamic brake resistor without SCESS

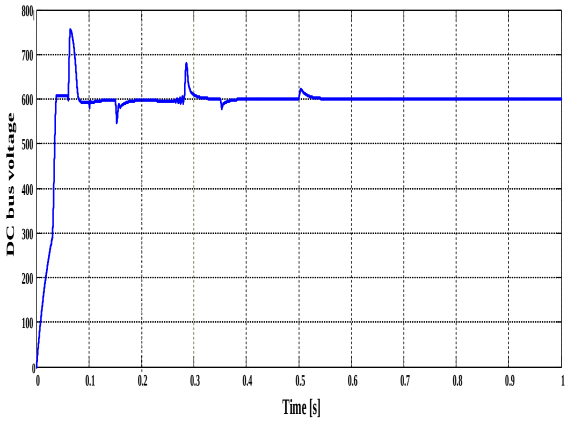

Figure 11. Dynamic behavior of voltage of DC-link capacitor with front -end active rectifier

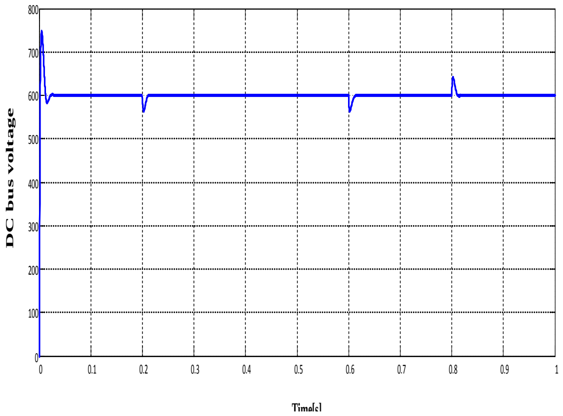

Figure 12. Dynamic behavior of voltage of DC-link capacitor with SCESS

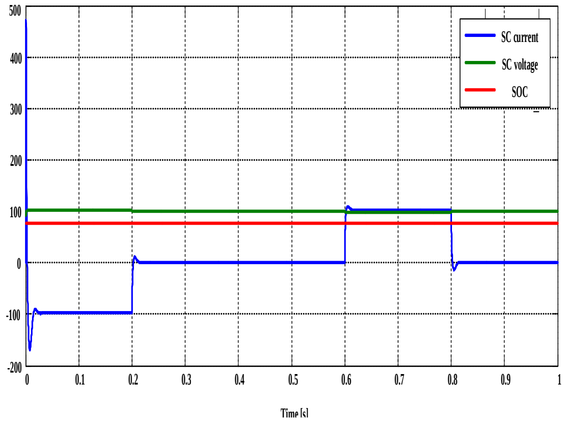

Figure 13. Performance of energy process of a super-capacitor module (SCcurrent: Current of super-capacitor, SCvoltage: Voltage of super-capacitor SOC: State of charge)

See fig.9, characteristic of train operation includes three regimes: acceleration, constant-speed, deceleration with dynamic behavior of torque in accordance with analyses in theory of fig.2. Fig 10 shows dynamic behavior of voltage of DC-link capacitor fluctuating from 600VDC to more 850 VDC when electric train operates in acceleration mode (0-5s), in braking mode (8-12s); Fig.11-dynamic behavior of voltage of DC-link capacitor with front-end active rectifier shows variations of load at 0.1, 0.25, 0.35, 0.5 s; the voltage still keeps constant value at 600VDC. Fig 12 illustrates dynamic behavior of voltage of DC-link capacitor with SCESS; with variations of load at 0.2, 0.4, 0.6 s the DC-bus voltage stable of value at 600VDC tracks reference voltage value. Fig. 13 demonstrates performance of energy process of a super-capacitor module; in interval time $0 \leq t \leq 0{,}2$s charging super-capacitors (corresponding with braking phase of drive motor); $0{,}2 < t \leq 0{,}6$s no charging/discharging super-capacitors (corresponding with constant-speed phase); $0{,}6<t\leq0{,}8$s energy discharging from super-capacitors (corresponding with powering phase of drive motor).

5. CONCLUSION

The paper has investigated energy conversion process via charecteristic of train operation, and proposed two solutions to recuperate regenerative braking energy when the electrified train operates in braking regime; namely, traction substations installed front-end active rectifiers enable energy to flow bidirectionally or traction motor drive system integrated with SCESS being able to exchange energy between SCESS and drive system. Finally, simulation results has also verified that designing the control strategy has ensured to control bi-directional energy flow by managing DC-bus voltage at fixed value when load varies.

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