Regenerative energy management of electric drive based on Lyapunov stability theorem

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Abstract In recent years, urban rail systems have developed drastically. In these systems, when induction electrical machine suddenly brakes, a great package of energy is produced. This package of energy can be stored in energy storage devices such as battery, ultra-capacitor and fly-wheel. In this paper, an electrical topology is proposed to absorb regenerative braking energy and to store it in ultra-capacitor and battery. Ultra-capacitor can deliver the stored energy to DC grid and to charge the battery for auxiliary applications such as lighting and cooling systems. The proposed system is modeled based on large signal averaged modeling, which leads to the simplicity of calculations. The control system is based on Lyapunov stability theorem which guarantees system stability. Also, an energy management algorithm is proposed to control energy under braking and steady-state conditions. Finally, the simulation results validate the effectiveness of the proposed control and energy management system.

Keywords DC/DC converter, Lyapunov stability, Bidirectional converter, Energy management system (EMS), Ultra-capacitor, Battery, Switching function

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1 Introduction

Capacity, reliability and safety of urban rail systems make these devices suitable for public transportation in developed countries [1, 2]. Considering energy price and climate change, energy saving has become an important subject for research studies. Consumed energy in urban rail systems is divided into two parts, traction usage and non-traction usage. In such systems, about 50% of total consumed energy is related to the traction requirements and the rest is related to non-traction usage or auxiliary systems, such as cooling systems and lighting systems [3, 4], and therefore designing a power electronic topology capable of providing energy for these usages, apart from many benefits, can be useful to the economy.

The topic of energy saving in urban rail systems has been investigated in different aspects. In [5], an energy management strategy for capacitor is proposed to adjust charging and discharging threshold voltage based on analysis of train operation states. The main parameter for energy calculations is state of charge (SOC) of energy storage device. In [6], capacitor is used for energy saving in train systems and a hierarchical control strategy is proposed based on energy management section and converter control section. The energy management system works based on an introduced machine and converter control mainly consist of a proportional-integral (PI) closed-loop strategy. Also an optimization algorithm is proposed to estimate the control parameter values at different operations. In [7], a train system considering renewable energy sources (photovoltage and wind power) and the capabilities of using regenerative braking energy is investigated. Apart from these aspects, uncertainties of renewable energies are considered through different scenarios and the whole problem is considered and solved as a large-scale nonlinear

optimization problem. Energy and economic energy saving of the proposed system under different strategies is also studied.

In this paper, a topology for saving regenerative braking energy in storage devices is proposed and control system is designed. A bidirectional DC/DC converter and a unidirectional DC/DC converter are connected in series. Also, ultra-capacitor and battery are used as main energy storage devices. Regenerative energy generated by induction electrical machine (IEM) is a high power density package of energy which occurs during a very short period of time, so must be stored in a device with high power density such as ultra-capacitor [8–10]. To increase the reliability and system efficiency, ultra-capacitor is connected to DC link via a bidirectional DC/DC converter [11–14].

To control the proposed system, switching functions are extracted based on state-space equations [15]. Extraction of switching functions is a well-known method to control switching process of power electronic devices, in which, switching functions are obtained based on system's requirements [16]. In this paper, switching functions are extracted using fundamentals of Lyapunov stability theorem. Fast and accurate tracking of reference values and maintaining system's stability are main advantages of this method.

2 Modeling and control of proposed system

Schematic circuit diagram of the system is shown in Fig. 1a and power electronic model of the system is shown in Fig. 1b. As seen, the converter that is connected to the DC link and ultra-capacitor is bidirectional and the converter between ultra-capacitor and battery is unidirectional. I_m is the current from IEM to DC link capacitor. I_{L1} is the current of bidirectional converter and is positive if the converter works in buck mode, or negative if the converter works in boost mode. I_{L2} that is either positive or zero, is the current of buck converter. V_{dc} and C_{dc} are the voltage and capacitor of DC link, respectively. Also, C_{uc} , R_{uc} and V_{uc} are capacity, resistance and voltage of ultra-capacitor, respectively. V_b is voltage of the battery. d_1 , d_2 , d_3 are the duty cycles of switches S1, S2 and S3, respectively. L_1 and L_2 are the inductors of bidirectional and unidirectional converters, respectively. Moreover, there is a dynamic resistor $R_{dynamic}$ that must dissipate surplus energy when DC link capacitor and ultra-capacitor are fully charged. Therefore, S_d and u_d are the switch and its duty cycle of the circuit that connect the dynamic resistor to the DC link.

A well-known method to model switching circuits is large signal averaged model, leading to simplicity of

Fig. 1 Complete proposed system for absorbing regenerative braking energy in battery and ultra-capacitor

Fig. 2 Large signal averaged model of proposed system

systems [17]. Averaged model of proposed system is shown in Fig. 2, where k is described as:

$$k = \begin{cases} 1 & I_{L1} < 0 \text{ (boost)} \\ 0 & I_{L1} > 0 \text{ (buck)} \end{cases} \quad (1)$$

Converters are controlled using switching functions, based on Lyapunov stability theorem. Switching functions are obtained separately for every state. In order to express the equations, first a new term named d_{12} combined of d_1 and d_2 is generated as [18]:

$$d_{12} = k(1 - d_2) + (1 - k)d_1 \quad (2)$$

where d_{12} is the switching function of bidirectional converter.

2.1 Switching functions extraction using Lyapunov stability theorem

Equation (3) indicates the state-space matrix of the averaged model of Fig. 2.

$$\begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{V}_{dc} \\ \dot{V}_{uc} \end{bmatrix} = \begin{bmatrix} \frac{-R_{uc}}{L_1} & \frac{d_3 R_{uc}}{L_1} & \frac{d_{12}}{L_1} & \frac{-1}{L_1} \\ 0 & 0 & 0 & \frac{d_3}{L_2} \\ \frac{-d_{12}}{C_{dc}} & 0 & 0 & 0 \\ \frac{1}{C_{uc}} & \frac{-d_3}{C_{uc}} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1} \\ I_{L2} \\ V_{dc} \\ V_{uc} \end{bmatrix} + \begin{bmatrix} 0 \\ -V_b \\ I_m \\ C_{dc} \\ 0 \end{bmatrix} \quad (3)$$

According to Lyapunov stability theorem, a non-linear autonomous system is globally stable if satisfies the following conditions [18]:

$$\begin{cases} V(0) = 0 \\ \alpha(\|x\|) < V(x) < \beta(\|x\|) \\ \dot{V}(x) < -\gamma(\|x\|) \\ \lim_{\|x\| \rightarrow \infty} V \rightarrow \infty \end{cases} \quad (4)$$

where Lyapunov function $V: \mathbb{R}^n \rightarrow \mathbb{R} \geq 0$ for $\dot{x} = f(x)$ is a continuously differentiable function such that there exist α, β belong to class K_∞ , a continuous positive definite function $\gamma: \mathbb{R}^n \rightarrow \mathbb{R} \geq 0$ for $x \in \mathbb{R}^n$ [19]. State variables of the system must be defined as a form of their errors:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} I_{L1} - I_{L1}^* \\ I_{L2} - I_{L2}^* \\ V_{dc} - V_{dc}^* \\ V_{uc} - V_{uc}^* \end{bmatrix} \quad (5)$$

where x_1 to x_4 are the errors of state variables; superscript * represents the reference values of corresponding variables. Matrix $\dot{X}$ is introduced as:

$$\dot{X} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} \frac{-R_{uc}}{L_1} & \frac{d_3 R_{uc}}{L_1} & \frac{d_{12}}{L_1} & \frac{-1}{L_1} \\ 0 & 0 & 0 & \frac{d_3}{L_2} \\ \frac{-d_{12}}{C_{dc}} & 0 & 0 & 0 \\ \frac{1}{C_{uc}} & \frac{-d_3}{C_{uc}} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + B \quad (6)$$

where B is the input matrix and includes system inputs and constant values of state matrix, calculated as:

$$B = \begin{bmatrix} -\frac{R_{uc}}{L_1} & \frac{d_3 R_{uc}}{L_1} & \frac{d_{12}}{L_1} & \frac{-1}{L_1} \\ 0 & 0 & 0 & \frac{d_3}{L_2} \\ -\frac{d_{12}}{C_{dc}} & 0 & 0 & 0 \\ \frac{1}{C_{uc}} & \frac{-d_3}{C_{uc}} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{L1}^* \\ I_{L2}^* \\ V_{dc}^* \\ V_{uc}^* \end{bmatrix} + \begin{bmatrix} -\frac{dI_{L1}^*}{dt} \\ -\frac{V_b}{L_2} - \frac{dI_{L2}^*}{dt} \\ \frac{I_m}{C_{dc}} - \frac{dV_{dc}^*}{dt} \\ -\frac{dV_{uc}^*}{dt} \end{bmatrix} \quad (7)$$

Lyapunov function can be introduced in any form, as a function of state variables and other parameters of the system. In this paper, in order to investigate the system stability, Lyapunov function is defined as:

$$V = \frac{1}{2} L_1 x_1^2 + \frac{1}{2} L_2 x_2^2 + \frac{1}{2} C_{dc} x_3^2 + \frac{1}{2} C_{uc} x_4^2 \quad (8)$$

The matrix form of (8) can be written as:

$$V = X^T P X = X^T \begin{bmatrix} \frac{L_1}{2} & 0 & 0 & 0 \\ 0 & \frac{L_2}{2} & 0 & 0 \\ 0 & 0 & \frac{C_{dc}}{2} & 0 \\ 0 & 0 & 0 & \frac{C_{uc}}{2} \end{bmatrix} X \quad (9)$$

According to the second condition of (4), V must be between the smallest and the largest eigenvalues of P [20]. Therefore α and β in (4) are equal to the smallest and the largest eigenvalues of P , respectively, namely $\lambda_{\min}$ and $\lambda_{\max}$:

$$\lambda_{\min}(P)\|x\| \leq V \leq \lambda_{\max}(P)\|x\| \quad (10)$$

The purpose is to find a relation for $\dot{V}$ condition in (4). Merging (9) and (11) results in:

$$X^T P X \leq \lambda_{\max}(P)\|x\| \quad (11)$$

Multiplying both sides of (11) with $-1/\lambda_{\max}$:

$$-\|x\| \leq -\frac{1}{\lambda_{\max}} X^T P X \quad (12)$$

According to $\dot{V} < -\gamma\|x\|$ in (4) and (12):

$$\dot{V} < -\gamma\|x\| < -\frac{\gamma}{\lambda_{\max}} X^T P X \quad (13)$$

Therefore, it is certain that:

$$\dot{V} < -\frac{\gamma}{\lambda_{\max}} X^T P X \quad (14)$$

A new parameter called δ is defined as:

$$\delta = \begin{bmatrix} \delta_1 & 0 & 0 & 0 \\ 0 & \delta_2 & 0 & 0 \\ 0 & 0 & \delta_3 & 0 \\ 0 & 0 & 0 & \delta_4 \end{bmatrix} = \frac{1}{2\lambda_{\max}} \begin{bmatrix} L_1\gamma_1 & 0 & 0 & 0 \\ 0 & L_2\gamma_2 & 0 & 0 \\ 0 & 0 & C_{uc}\gamma_3 & 0 \\ 0 & 0 & 0 & C_{dc}\gamma_4 \end{bmatrix} \quad (15)$$

Therefore:

$$\dot{V} < X^T \delta X \quad (16)$$

Equation (8) satisfies the first, second and fourth conditions of (4). According to (16), the system is globally stable if the derivation of V satisfies the following inequality:

$$\begin{aligned} \dot{V} &= L_1 x_1 \dot{x}_1 + L_2 x_2 \dot{x}_2 + C_{dc} x_3 \dot{x}_3 + C_{uc} x_4 \dot{x}_4 \\ &\leq \delta_1 x_1^2 + \delta_2 x_2^2 + \delta_3 x_3^2 + \delta_4 x_4^2 \end{aligned} \quad (17)$$

In this paper, references are time-invariant and constant. Therefore, the derivatives of reference values are zero and can be neglected in further calculations. Substituting (6) and (15) into (17), Lyapunov function's derivative form is calculated as (18) in which some terms (such as $-R_{uc}x_1^2$) are always negative and neglected and some are simplified. Furthermore, d_3 and d_{12} must be calculated in a way that (18) stays negative and system remains globally stable, therefore:

$$\begin{aligned} \dot{V} &= L_1 x_1 \left(\frac{-R_{uc}}{L_1} x_1 + \frac{d_3 R_{uc}}{L_1} x_2 + \frac{d_{12}}{L_1} x_3 - \frac{1}{L_1} x_4 \right. \\ &\quad \left. - \frac{R_{uc}}{L_1} I_{L_1}^* + \frac{d_3 R_{uc}}{L_1} I_{L_2}^* + \frac{d_{12}}{L_1} V_{dc}^* - \frac{1}{L_1} V_{uc}^* \right) \\ &\quad + L_2 x_2 \left(\frac{d_3}{L_2} x_4 + \frac{d_3}{L_2} V_{uc}^* - \frac{V_b}{L_2} \right) \\ &\quad + C_{dc} x_3 \left(\frac{-d_{12}}{C_{dc}} x_1 - \frac{d_{12}}{C_{dc}} I_{L_1}^* + \frac{I_m}{C_{dc}} \right) \\ &\quad + C_{uc} x_4 \left(\frac{1}{C_{uc}} x_1 - \frac{d_3}{C_{uc}} x_2 + \frac{1}{C_{uc}} I_{L_1}^* - \frac{d_3}{C_{uc}} I_{L_2}^* \right) \\ &\quad - \delta_1 x_1^2 - \delta_2 x_2^2 - \delta_3 x_3^2 - \delta_4 x_4^2 \leq 0 \end{aligned} \quad (18)$$

$$d_3 = \frac{x_1 V_{uc}^* + x_2 V_b + \delta_1 x_2^2 + \delta_2 x_4^2}{R_{uc} x_1 x_2 + R_{uc} x_1 I_{L_2}^* + x_2 V_{uc}^* - x_4 I_{L_2}^*} \quad (19)$$

$$d_{12} = \frac{R_{uc} x_1 I_{L_1}^* - x_4 I_{L_1}^* - x_3 I_m + \delta_4 x_1^2 + \delta_3 x_3^2}{x_1 V_{dc}^* - x_3 I_{L_1}^*} \quad (20)$$

2.2 Energy management algorithm

As shown in Fig. 3, the switching between the modes is carried out according to SOC of battery, ultra-capacitor and DC link voltage, i.e., SOC_b , SOC_{uc} and V_{dc} . The maximum and minimum values of SOC_{uc} , SOC_b and V_{dc} are chosen according to the systems' requirements. In this case, SOC_{uc} , SOC_b are chosen as a value between 0 and 100%, and $V_{dc,max}$ and $V_{dc,min}$ are voltage parameters based on operator's choice. The system has three operational modes that are not enabled together, and priority of these modes is based on the followings: ① ultra-capacitor charging by DC link voltage when $V_{dc} > V_{dc,max}$, $SOC_{uc} < SOC_{uc,max}$; ② DC link capacitor charging by ultra-capacitor when $V_{dc} < V_{dc,min}$, $SOC_{uc} > SOC_{uc,min}$; ③ battery charging by ultra-capacitor when $V_{dc,min} < V_{dc} < V_{dc,max}$, $SOC_{uc} > SOC_{uc,min}$, $SOC_b < SOC_{b,max}$. And an auxiliary mode with following conditions: $V_{dc} > V_{dc,max}$, $SOC_{uc} > SOC_{uc,max}$.

Figure 4 shows the complete system diagram based on different sections, including controller, energy management system, IEM, inverter, and rectifier, where u_1 , u_2 and u_3 are gating signal of S1, S2 and S3, respectively.

3 Simulation results

Parameters of the system are shown in Table 1. Figure 5a shows the speed characteristics of IEM during a 16 s cycle. It must be noted that the acceleration and the deceleration rates of IEM should be within a permissible

Fig. 3 Flowchart of energy management algorithm of proposed system

Fig. 4 Complete system circuit model

Table 1 Parameters of electrical machine, grid and proposed drive

Parameter	Value
Nominal power	37.3 kW
Nominal voltage and frequency	460 V, 60 Hz
Grid voltage	367 V
Grid inductor	2 mH
DC link capacitor	1.6 mF
Bidirectional converter inductor	3.3 mH
Unidirectional converter inductor	33 mH
Ultra-capacitor	21.27 F
Series resistance	0.1 Ω
Battery voltage	24 V

range (less than 1 m/s²). As observed in the figure, the speed reaches 100 rad/s in 2 s and when braking, it decreases from 150 rad/s to 0 rad/s in 3 s.

Figure 5b shows torque curve during cycle. When the IEM accelerates, torque is positive and when the IEM brake, torque is negative. Figure 5c shows DC link voltage

(a) IEM speed curve for 16-second period

(b) IEM torque curve

(c) DC link voltage due to IEM activity

Fig. 5 IEM speed curve for 16-second period, IEM torque curve and DC link voltage due to IEM activity

during this cycle. When the IEM accelerates at 5 s, V_{dc} drops and when IEM brakes at 11 s, V_{dc} increases.

The main idea of the proposed control system is to store regenerative energy in ultra-capacitor and battery. Besides that, whenever V_{dc} drops down, ultra-capacitor will supply DC link capacitor with its charged energy. The proposed system must work accurately based on flowchart shown in Fig. 3 and track the reference values of state variables, $I_{L1}^* = 1$ A (buck), $I_{L1}^* = 20$ A (boost), $I_{L2}^* = 2$ A, $V_{dc}^* = 500$ V and $V_{uc}^* = 30$ V.

Figure 6 shows DC link voltages before and after applying the proposed system with control parameters $\delta_1 = -60$, $\delta_2 = -0.2$, $\delta_3 = -5$, $\delta_4 = -0.1$. After applying the proposed system, the extra energy resulted by braking process must be stored in ultra-capacitor. Also, DC link voltage drop resulted by acceleration process is compensated by energy stored in ultra-capacitor. As seen, at 11 s, V_{dc} rises during the braking of IEM. Before applying the

Fig. 6 Comparison of DC link voltage before and after applying proposed system

Fig. 7 Currents of bidirectional converter and unidirectional converter

proposed system, in this moment V_{dc} reaches 1800 V but after applying the proposed system, V_{dc} is limited near to 500 V. Energy management system decides whenever V_{dc} is higher than $V_{dc,max}$ and SOC_{uc} is lower than $SOC_{uc,max}$, and then the bidirectional converter operated in buck mode. Other modes are basically applicable according to the requirements of the system and the energy management system designed in the previous section. As shown in Fig. 6, in the 5–7 s, DC link voltage drops, ultra-capacitor charges the DC link capacitor.

The energy management system works according to defined modes of Fig. 3. As seen in Fig. 7, there is not any interference between three modes, and it can be concluded that EMS works properly and in accordance with system's needs. Reference values for modes 1, 2 and 3 are 1 A, 20 A and 2 A, respectively. As seen in the Fig. 7a ultra-capacitor

Fig. 8 SOC of ultra-capacitor and SOC of battery

charging and discharging currents are 20 A and 1 A, respectively, the same as reference values. Also, Fig. 7b shows battery charging current which is exactly 2 A, as seen the reference value is effectively followed.

Figure 8 shows the SOC of ultra-capacitor and battery during the 16-second period. It can be observed that ultra-capacitor charges DC link capacitor or battery, or is charged by V_{dc} , and therefore the SOC of ultra-capacitor is always alternating (decreasing or increasing). However, since battery is operating only when unidirectional converter is activated, its SOC is sometime constant and the other times increasing.

As seen in Fig. 1b, there is an auxiliary load that uses the energy stored in battery. Due to different reference currents of ultra-capacitors in modes 1 and 2, whenever the system operates in mode 2, SOC_{uc} rises sharply and whenever system works in mode 1, SOC_{uc} falls slowly. On the other hand, the incline of SOC_b is always constant because reference current of battery is always 2 A and doesn't change. Because of very high amount of regenerative energy that is generated while braking, whenever the IEM enters braking mode, the SOC of ultra-capacitor sees the biggest changes. It is also observed that all of ultra-capacitor energy that is consumed by DC link capacitor and battery before 11 s, is compensated after 11 s due to braking process.

Figure 9 shows voltages during the 16-second period. It can be seen that whenever V_{dc} increases (and SOC_{uc} is lower than $SOC_{uc,max}$), bidirectional converter works in buck mode, ultra-capacitor gets charged and battery voltage remains constant. Whenever V_{dc} decreases, ultra-capacitor voltage decreases to charge the DC link capacitor and compensate voltage drop in DC link. In mode 3,

Fig. 9 Ultra-capacitor voltage and battery voltage

Fig. 10 DC link voltage and SOC of ultra-capacitor

whenever DC link voltage is in admissible range and SOC_{uc} is higher than $SOC_{uc,max}$, battery gets charged by the energy stored in ultra-capacitor. Whenever battery is being charged, a 0.9 V growth in battery voltage can be seen.

As seen in Fig. 10, the surplus energy must be consumed and dissipated in dynamic resistor to prevent any damage to DC link equipment. As seen in the figure, when the IEM starts to regenerate energy, ultra-capacitor gets charged and as soon as it reaches its maximum capacity, the surplus energy in DC link is consumed in dynamic resistor and dissipated as heat. When DC link enters its permissible range again, ultra-capacitor starts charging the battery with its stored energy. As mentioned before, only one mode can be enabled at any moment, therefore ultra-

capacitor charging the battery and dynamic resistor modes can't be enabled together.

4 Conclusion

In this paper, a topology for saving regenerative braking energy in ultra-capacitor and battery was proposed. The proposed circuit is also able to compensate DC link voltage drop, while IEM needs to accelerate. The topology is based on cascade structure of DC/DC converters. The controller is designed based on Lyapunov stability theorem that guarantees system's global stability. Simulation results validate that the proposed system works properly and all reference values are accurately tracked. It is also shown that energy management algorithm works in coordination with the controller. The proposed system can be implemented in all devices and facilities equipped with induction machines in order to store additional energy and consequently reducing the total costs.

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