Optimization of Energy Management Control Strategy for Hydrogen-Electric Hybrid Train

Shijie Sun[1](✉), Yang Gao[1], Jian Wang[1,2], Lei Shi[1], Limei Chen[1], Weiran Xiang[1], and Wenrong Li[1]

[1] CRRC Changchun Railway Vehicles Co., Ltd., Changke Road 2001, Changchun 130062, China
ssj_crrc@163.com
[2] Central South University, Lu Shan Nan Road 932, Changsha, Hunan, China

Abstract. In order to enhance the stability of the energy regulation of the hydrogen-electric hybrid train and reduce the impact on the train bus of the hybrid system during the energy regulation process, an improved rule-based instantaneous power control strategy is proposed, in which the bus voltage is introduced into the control link to enhance the system stability. The simulation results prove that the optimized control strategy improves the stability of the high-voltage DC link of the hybrid system, avoids the high-voltage surging to the super-capacitor system and the traction system, and extends the service life of the super-capacitor at the same time.

Keywords: Hydrogen energy · Hybrid · Energy management strategy · Optimization

1 Introduction

Among many sources of energy, hydrogen is relatively abundant, with high efficiency in conversion to electricity and only water as the conversion product, which is green and clean. At present, the capacity of hydrogen fuel cell is about 120 kW, the technology is relatively mature, and it can achieve the technical breakthrough of 200 kW capacity in a short time, so the application potential of hydrogen fuel cell in rail transit vehicles is infinite. Compared with diesel or electrical locomotive, the obvious advantages of hydrogen-electric hybrid train are as follows, such as no need to set up contact networks, saving line construction, operation and maintenance costs; green and pollution-free; short project construction cycle and low fixed investment.

Since the electrical output characteristics of hydrogen fuel cells are relatively "soft" and the demand power response is slow, the design of rail vehicles requires the use of super-capacitors or lithium-ion batteries to provide transient response energy for trains and to recover the braking energy generated under train braking conditions [1, 2]. Since trains are equipped with multiple energy sources to power the trains, unified energy management and energy distribution for different energy sources are required to ensure safe and stable operation of the vehicles. For multi-energy coupled power supply

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technology, scholars at home and abroad have conducted a lot of research work. In the paper [3], the frequency of hydrogen consumption and power fluctuation of the hydrogen fuel cell is used as a reference in the control strategy, and a power-following control strategy is used to optimize the control of the fluctuation rate. In the paper [4], the control strategy of the state machine is optimized and a voltage equalization algorithm is used so that the train can guarantee the discharge equalization of the non-functional power supply under different operating conditions. Other scholars have proposed different optimal management control strategies in order to improve the economic effect of the power system, and the papers [5, 6] proposed an optimal control strategy with the minimum hydrogen consumption as the control objective, which can improve the efficiency of the power supply system and thus reduce the cost of hydrogen refueling. In the paper [7], an optimal control strategy based on dynamic planning was proposed, which is able to achieve coordinated control of the hybrid power system. Although scholars at home and abroad have proposed numerous optimal control strategies, the control strategies are relatively complex and not conducive to engineering practice, while a large number of optimal control strategies are based on optimization under fixed working conditions, without taking into account the complexity of the actual operating conditions of rail vehicles, and therefore do not have the feasibility of practical engineering applications.

In this paper, the rule-based instantaneous power control strategy is widely used as the benchmark of the whole vehicle energy management control strategy, and according to the problems encountered in the process of engineering practice, the control strategy is optimized, and an improved rule-based instantaneous power control strategy is proposed, which reduces the high-voltage impact on the super-capacitor system and traction system during the power regulation of the train, and helps to enhance the system stability and reduce the failure rate of the high-voltage system.

2 Train Configuration and Operation Mode

2.1 Train Configuration

In a typical series hybrid system, there shall be two or more power sources, including one energy storage system (ESS), and the traction equipment (TE) which serves as the primary power sink. The system may contain a secondary energy consuming device, such as a braking resistor (BR), in case the power system cannot fully recover or partially recover the energy regenerated by the traction system during regenerative braking. These subsystems shall be electrically connected to enable the exchange of energy between them. In addition to these main circuit subsystems, a series hybrid system may have one or more auxiliary power supplies (APS). The auxiliary loads have a large impact on energy consumption and should be considered if the APS is connected to the main circuit.

Figure 1 shows an example block diagram of the series hybrid system, which has four main subsystems, i.e. one main primary power source (PPS) with a hydrogen fuel cell as the main energy source, one energy storage system (ESS) with a super-capacitor as the auxiliary power source, a traction unit (TE), and an auxiliary equipment (Aux).

Key

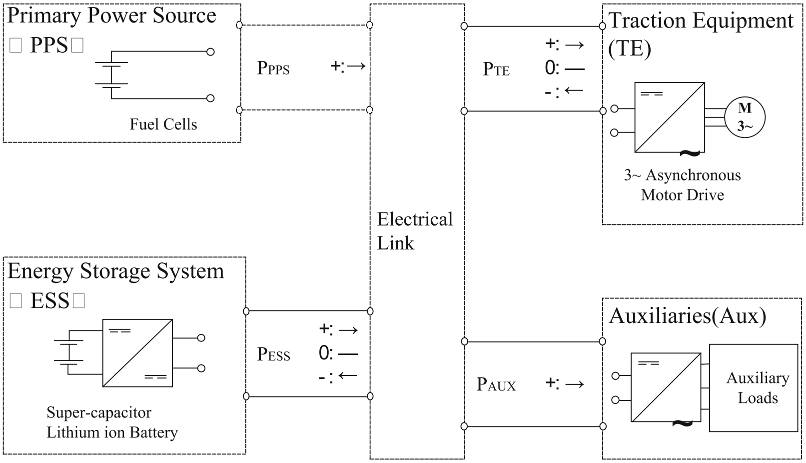

Fig. 1. Block diagram of a series hybrid system

P_{PPS}	Power of primary power source (PPS)
P_{TE}	Power of traction equipment (TE)
P_{ESS}	Power of energy storage system (ESS)
P_{BR}	Power of brake resistor (BR)
P_{AUX}	Power of auxiliaries (AUX).

2.2 Major Operation Mode

In Fig. 1, when the train is in operation, there can be power flows in the power supply system for four main subsystems, namely

(a) between the PPS and the electrical link, denoted as P_{PPS} in Fig. 1.
(b) between the ESS and the electrical link, denoted as P_{ESS} in Fig. 1.
(c) between the electric link and the traction equipment, denoted as P_{TE} in Fig. 1.
(d) between the electrical link and the Aux, denoted as P_{AUX} in Fig. 1.

Among these:

(b) and (c) are bidirectional and their values P_{ESS} and P_{TE} can both be positive and negative;
(a) is unidirectional and its value P_{PPS} can only be positive;
(d) is also unidirectional, but unlike (a), its value P_{AUX} is always positive and non-zero when the system is running.

In Fig. 1, the possible symbols of these variables (+, 0 and −) and the corresponding directions are also marked. Note that the directions are defined so that the power flow from the power subsystem to the electrical link and from the electrical link to the power subsystem becomes positive, e.g. when the hybrid vehicle is accelerated with electrical energy from the PPS or ESS.

Using these symbols, the major modes of operation of the system can be classified according to the symbols of these variables, as shown in Table 1.

Among the modes shown in Table 1, Mode II (pure power source) is a power supply mode in which the PPS provides all the power required by the traction equipment. Similarly, Mode VI (idling) is a mode in which the PPS provides all the power required by the auxiliary equipment when the power required by the traction equipment is zero. In addition, Mode VII (sliding) is a mode in which the PPS and ESS provide all the power required by the auxiliary equipment when the power required by the traction equipment is zero. The train charges the ESS in Modes I (supplementary charging during motoring), IV (Power source charging ESS) and V (supplementary charging during braking).

Table 1. Major operating modes of the series hybrid system

Mode	P_{PPS}	P_{ESS}	P_{TE}	P_{AUX}	Description
I	+	–	+	+	Supplementary charging during motoring
II	+	0	+	+	Pure power source
III	+	+	+	+	Boosting
IV	+	–	0	+	Power source charging ESS
V	+	–	–	+	Supplementary charging during braking
VI	+	0	0	+	Idling
VII	+	+	0	+	Sliding

3 Energy Management Control Strategy Determination and Optimization

3.1 Proposal of Energy Management Control Strategy

In a typical series hybrid system, the control strategy generally uses a thermostat-based control strategy and a power-following-based control strategy. In the thermostat-based control strategy, the SOC limits of the super-capacitor need to be set according to the train operating conditions. In the case of super-capacitor discharging condition and the SOC value is lower than the pre-set lower limit, the output power of hydrogen fuel cell is adjusted to provide energy for the train and charge the super-capacitor; in the case of super-capacitor charging condition and the SOC value is higher than the pre-set upper limit, the output power of hydrogen fuel cell is adjusted to standby power and the super-capacitor and hydrogen fuel cell jointly provide energy for the train. Under this control strategy, the hydrogen fuel cell can be operated in the optimal working area for a long time and the consumption of hydrogen fuel can be reduced. However, the super-capacitor is frequently charged and discharged, which shortens the service life of the super-capacitor. In the power following-based control strategy, the operating state of the hydrogen fuel cell is adjusted according to the SOC of the super-capacitor and the power demand of the train. When the super-capacitor is full and there is no power demand of train, the hydrogen fuel cell runs in standby mode and provides the minimum power output for the train; when the super-capacitor is hungry and there is power demand of train, the hydrogen fuel cell outputs power according to the demand and the power value is adjusted with the demand of train. Under such control strategy, the cycles of super-capacitor charging and discharging are reduced, which helps to extend the service life of super-capacitor, but the output power of hydrogen fuel cell fluctuates more and damages the fuel cell more.

The rule-based instantaneous power control strategy combines the advantages and disadvantages of the above two control strategies to realize the control of the super-capacitor SOC and the proper regulation of the hydrogen fuel cell output power to ensure the efficiency of the hydrogen fuel cell. This control strategy can make use of the fast response characteristic of super-capacitor energy output and alleviate the dynamic response requirement of hydrogen fuel cell power output. However, this control strategy is a switching control strategy based on a given threshold value. Under the extreme operating conditions of the train, such as when the super-capacitor is close to the discharge cutoff zone or the charging cutoff zone, the switching control strategy will cause a step change in the traction or electric braking load of the train, which will cause a shock to the high-voltage power supply system of the train. To address this problem, this paper proposes an optimized control strategy and introduces a bus voltage control strategy to realize the regulation of bus voltage, so as to avoid the high bus voltage caused by load fluctuation or other extreme operating conditions, which will impact on the hydrogen fuel cell and traction system and prolong the service life of the super-capacitor system.

3.2 Optimization of Energy Management Control Strategies

The main factors affecting the energy distribution of super-capacitor and hydrogen fuel cell in the hybrid system are the power demand of the train, such as the traction power, regenerative braking power and auxiliary power supply of the train, and the SOC of the super-capacitor (characterized by the voltage of the super-capacitor in this project), and the bus voltage control link is introduced in the energy management control strategy to enhance the stability of the system. This summary is presented in two aspects of super-capacitor's operating area division and rule-based optimization of transient power control strategy.

(1) Super-capacitor working area division

According to the output characteristics of the hybrid super-capacitor, the output voltage stability is relatively poor when the SOC of the super-capacitor is too higher or too lower, and the service life of the cell is seriously affected. In order to improve the smoothness of the power system during the train operation, avoid the over-charging or over-discharging condition of super-capacitor, and prolong the service life of super-capacitor, the working interval of super-capacitor is divided. According to the train operating conditions, the super-capacitor charging and discharging intervals are divided into five parts, namely, discharge reserve area, traction discharge area, SOC maintenance area, brake recovery area and charging reserve area, and the corresponding super-capacitor voltage judgment thresholds are set according to these five intervals for the energy management control strategy, details of which are shown in Fig. 2 and Table 2.

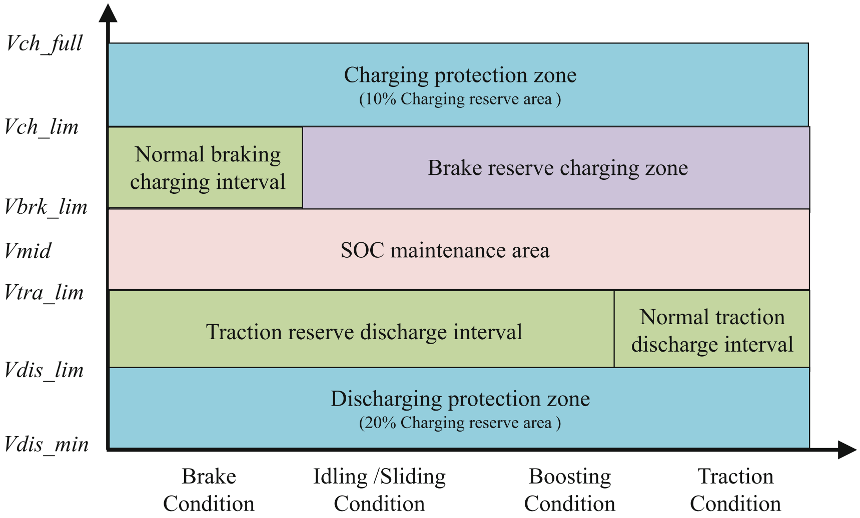

Fig. 2. The division of super-capacitor SOC working area

Table 2. The parameter description of voltage

Symbols	Description
V_{dis_lim}	Discharging limit voltage
V_{tra_lim}	Allowable traction voltage
V_{mid}	Operating median voltage
V_{brk_lim}	Upper limit voltage of hydrogen fuel cell charging
V_{chg_lim}	Charging limit voltage

In order to fully protect the super-capacitor and provide backup energy for emergency train traction, 20% SOC of the super-capacitor is reserved for this function. If the super-capacitor voltage is lower than V_{tra_lim} in non-traction conditions, the hydrogen fuel cell must be activated to charge the super-capacitor to ensure the traction demand of the train. In the electric braking condition, the super-capacitor needs to absorb the braking energy and ensure that the super-capacitor will not be overcharged, so it is necessary to set the upper limit of hydrogen fuel cell charging voltage V_{brk_lim} and the upper limit of charging voltage V_{chg_lim}.

(2) Control strategy optimization

According to the vehicle operating conditions, such as stopping, idling, starting acceleration, traction and braking conditions, and combined with the real-time voltage of the super-capacitor, the rules of the output power P_{fc} of the hydrogen fuel cell were formulated according to the demand power of the train, as detailed in Table 3, where P_{tc} is the power consumed by the train, V_c is the voltage of the super-capacitor, P_{aux} is the power consumed by the train auxiliary equipment, P_{fc_max} is the maximum power output by the hydrogen fuel cell, and P_{fc_min} is the minimum power output by the hydrogen fuel cell.

The hydrogen fuel cell outputs power according to the above rule-based control strategy. If there is a sudden jump in the train power demand, the hydrogen fuel cell cannot change the output power, it will cause a sudden rise in the train high-voltage bus, which will endanger the super-capacitor system and the train traction system. Therefore, a bus voltage controller is introduced in the train energy management control strategy to stabilize the train bus voltage within the target voltage DC1450–DC1950 V to ensure the safe operation of the vehicle. The equivalent control structure diagram of the optimized rule-based instantaneous power control strategy is shown in Fig. 3, where V_{fc} is the hydrogen fuel cell output voltage, I_{fc}^{*} is the hydrogen fuel cell output reference current, and I_{fc} is the hydrogen fuel cell output current output by the controller. From the figure, it can be seen that two compensation loops are introduced in the control link, which are PI control compensation based on the lower limit voltage DC1475 V as the target and PI control compensation based on the upper limit voltage DC1925 V as the target, and after this compensation, the bus voltage can be effectively controlled in the range of DC1450–DC1950 V.

4 Simulation Verification

Matlab/Simulink simulations were performed to verify the proposed improved rule-based instantaneous power control strategy, and the key parameters involved in the simulations are shown in Table 4. To verify the effect of load fluctuation on the bus voltage, the pre-optimized and post-optimized control strategies were compared by abruptly removing traction at 70 s to simulate the effect of power fluctuation on the bus voltage. From Fig. 4, it can be seen that the peak bus voltage fluctuation after optimization is 1947 V, which does not exceed the upper bus voltage limit, but the bus voltage before optimization is nearly 2000 V, which far exceeds the upper bus voltage limit.

5 Summary and Prospect

The improved rule-based transient power control strategy proposed in this paper has significant effects on improving the train bus voltage stability and avoiding the shocks to the components. It can help to improve the stability of train operation, reduce the impact on the component life and reliability because of the voltage jumping, and reduce the operation and maintenance cost.

In view of the rule-based control strategy in the rail vehicles, there are still problems such as low conversion efficiency of hydrogen fuel cell, frequent charging and discharging of power battery, etc. It is necessary to optimize the control strategy in the future to enhance energy utilization and extend the service life of components.

Table 3. Hydrogen fuel cell output power rules

	P_{tc}			
V_c	$P_{tc} < 0$ Braking condition	0 ≤ Ptc < Paux Idling/sliding condition	Paux ≤ Ptc < Pfc_max Boosting condition	Ptc ≥ Pfc_max Traction condition
$V_c < V_{dis\_lim}$	P_{fc_min}	P_{fc_max}	Pfc_max	
$V_{dis\_lim} \leq V_c < V_{tra\_lim}$	P_{fc_min}	P_{fc_max}	P_{fc_max}	P_{fc_max}
$V_{tra\_lim} \leq V_c < V_{mid}$	P_{fc_min}	P_{fc_max}	P_{fc_max}	P_{fc_max}
$V_{mid} \leq V_c < V_{brk\_lim}$	P_{fc_min}	P_{aux}	P_{tc}	P_{fc_max}
$V_{brk\_lim} \leq V_c < V_{chg\_lim}$	P_{fc_min}	P_{fc_min}	P_{aux}	P_{fc_max}
$V_{chg\_lim} \leq V_c$	Shutdown	Shutdown	P_{fc_min}	P_{fc_max}

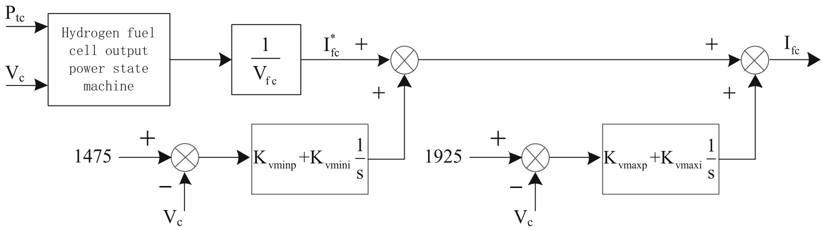

Fig. 3. Equivalent structure diagram of control strategy

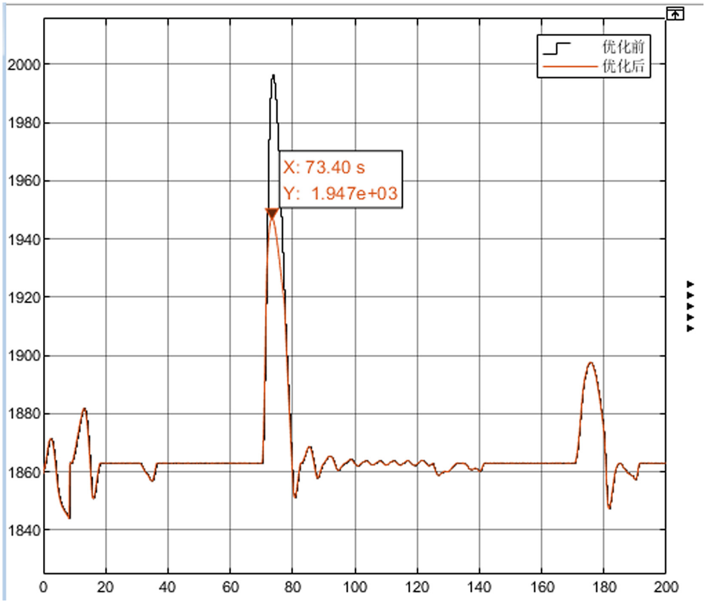

Fig. 4. The DC bus voltage fluctuation comparison

Table 4. Key parameters

Symbols	Value	Symbols	Value
V_{dis_lim}	1602 V	V_{chg_lim}	1917 V
V_{tra_lim}	1717 V	V_{brk_lim}	1894 V
V_{mid}	1765 V	P_{aux}	202 kW
P_{fc_max}	800 kW	P_{fc_min}	80 kW

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