Journal of Energy and Power Engineering 15 (2021) 8-15
doi: 10.17265/1934-8975/2021.01.002

Research of Pure Electric Ferry System and Its Short-Circuit Protection and Calculation

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Abstract: System control and safety reliability are important links of the marine DC (Direct Current) power system. The simulation model is built by Matlab/Simulink, the battery and super-capacitor are supplied to the system through a three-phase interleaved DC/DC converter, the fuse and disconnector switch combination are used as the protection device, and the short-circuit point is set between each branch and the DC distribution board, performing short-circuit simulation. This paper also proposes a short-circuit calculation method for super-capacitors based on the simplified model of series RC (Resistors & Capacitors), and verifies its correctness through simulation data. The results show that the introduction of a three-phase interleaved DC/DC converter reduces the current ripple and makes the system control more convenient; short-circuit calculation and simulation have determined the short-circuit withstand capability of the DC distribution board, and verified the feasibility of the fuse selection method and the short-circuit calculation method of the super-capacitor. This provides reliable verification for the application and calculation of the actual project.

Key words: Matlab/simulink simulation, three-phase interleaved DC/DC, battery and super-capacitor, short-circuit protection and calculation.

1. Introduction

With the promotion of the policy of "green energy instead of traditional energy" [1], batteries and super-capacitors are gradually applied in the marine industry. Compared with AC vessel power system, DC (Direct Current) vessel power system not only simplifies the energy conversion process but also has simple control; therefore, DC power systems have become the focus of current vessel research and the direction of future development [2, 3].

In marine DC power systems, bi-directional DC/DC converters are used in the system design in order to make it easier for the batteries and super-capacitors to form a micro-grid, which improves the utilisation of the power supply and makes the system control simpler. The traditional single-phase bi-directional DC/DC converters have the disadvantage of large ripple on the power side, which can be harmful to the batteries and some equipment in the line. The most hazardous part of the vessel's power system is short-circuit faults, which has a high risk and frequency of occurrence [4]. In a vessel's DC power system, if a short circuit fault occurs on the line, the short circuit current rises rapidly and has a large peak value, so protection devices play an important role in the power system. To reduce the impact of short-circuit faults on the system, short-circuit calculations and short-circuit simulation experiments must be carried out to select suitable electrical equipment, current-carrying conductors and protective devices.

For related questions, the system is modelled using Matlab/Simulink and the simulation model is shown in Fig. 1. The bi-directional DC/DC converter uses a three-phase interleaved technique with two PI (Proportional-Integral) controls, which not only improves the dynamic control performance of the converter but also reduces current ripple of power side compared to a traditional single-phase bi-directional DC/DC

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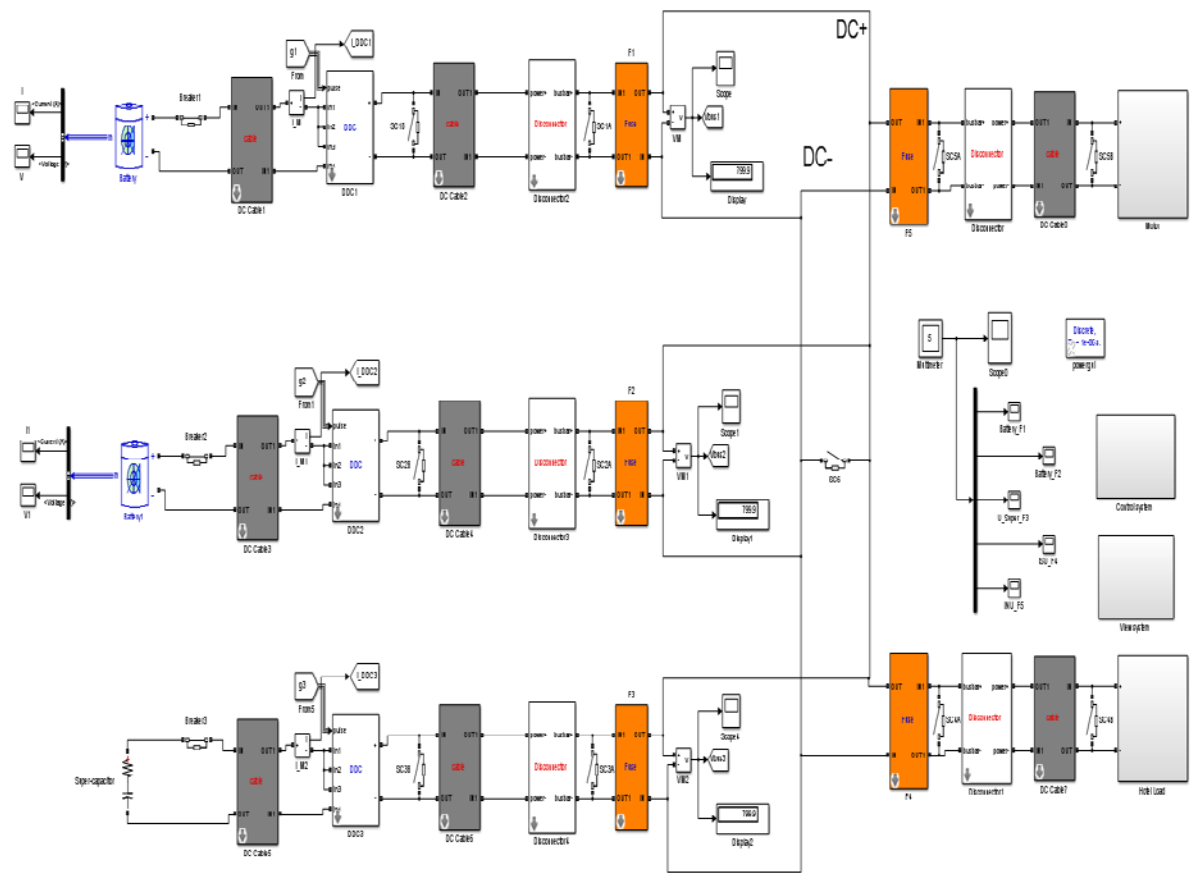

Fig. 1 System simulation model.

converters [5, 6]. Due to the rapid rise and large peak of short-circuit currents in DC power systems, suitable cable lengths are selected to limit short-circuit currents. To maintain normal system operation and improve system safety and reliability, a combination of fuse and disconnector is used as a protective device [7, 8] (disconnector does not provide protection). From the short-circuit calculations and simulation results, it is clear that the short-circuit withstanding capacity of the DC distribution board as well as the faulty branch fuse quickly removes the short-circuit fault and maintains the normal operation of the system.

2. Selection Basis for Fuse and Disconnector

2.1 Selection Basis for Disconnector

According to IEC 60947-3 [9], the selection of disconnectors is based on the following key parameters: rated operational voltage U_e, rated operational currents I_e, rated short-time withstand current I_{cw} and rated short-circuit making capacity I_{cm}. Rated operational voltage U_e is at least equal to the highest system voltage at the installation point; rated operational currents I_e should be greater than the maximum operating current of the installation branch; rated short-time withstand current I_{cw} and rated short-circuit making capacity I_{cm} correspond to the thermal and dynamic stability of the switch respectively. Thermal stability indicates that the short-circuit current flows through the switch over a certain period of time and produces a thermal shock to the switch. Dynamic stability indicates that the peak short-circuit current produces a huge electrodynamic effect on the individual conductive structural parts of the switch, and the switch must be able to withstand its impact, so I_{cw}

should be greater than the steady-state value of the short-circuit current and I_{cm} greater than the peak short-circuit current.

2.2 Selection Basis for Fuse

Fuse is divided into DC and AC types in power systems; both types of fuse can be used in marine DC power systems. AC fuse is used in marine DC power systems with a 20% voltage derating. In this paper, 1000V AC Fuse is used for 800V DC power system.

According to IEC 60269-1 and IEC 60269-5 [10, 11], the Fuse is melted by the energy generated by flowing through its own short-circuit current, and the energy required to melt the Fuse is called melting I^2t. The two most important parameters of Fuse are Pre-arcing I^2t and Clearing I^2t, which correspond to $T_{\text{Pre-arcing}}$ and T_{Clearing} respectively. Simply calculate the melting I^2t from the short-circuit current and the Clearing I^2t of the Fuse at the system voltage (the conversion factor is obtained on the conversion curve provided by the Fuse manufacturer), that is, the $T_{\text{Pre-arcing}}$ and T_{Clearing} of Fuse can be obtained, and the melting I^2t is calculated as follows:

$$I_{rms}=\sqrt{\frac{1}{\text{n}}\left(i_1^2+i_2^2+\cdots+i_n^2\right)} \tag{1}$$

$$I_{i+1}^2t=I_i^2t+\frac{1}{2}\left(I_i^2+I_{i+1}^2\right)\cdot(t_{i+1}\text{-}t_i) \tag{2}$$

In Eq. (1), $i_i(i = 1 \cdots n)$ is the short-circuit current value at each time point, I_{rms} is the root mean square value at each time point; In Eq. (2), I_i^2 is the root mean square value at the last time point, I_{i+1}^2 is the root mean square value at the current time point, t_i is the last time point, t_{i+1} is the current time point, I_i^2t is the short-circuit energy at the last time point and I_{i+1}^2t is the short-circuit energy at the current time point.

Fuse is selected mainly on the basis of its rated current, which corresponds to its Pre-arcing I^2t and Clearing I^2t. According to IEC 60269-1, the rated current of the fuse applied to the system is calculated, as the fuse is also a temperature sensitive component, the temperature inside the OMG (Onboard Micro-grid) cabinet is higher than the ambient temperature, the temperature derating rate T_f needs to be considered, as well as the current derating factor O_f (on the IEC standard $O_f = 1.0$, so the actual steady-state operating current is equal to I_n). Therefore, the fuse rated current is calculated as follows:

$$I_n = \frac{1.6(or\ 1.25) \cdot I_{dc}}{T_f \cdot O_f} \tag{3}$$

In Eq. (3), I_{dc} is the maximum operating current on the DC side of the branch, T_f is the temperature derating rate and O_f is the current derating factor.

3. Feasibility Analysis of Fuse

According to the Fuse selection method presented in Section 1.2, short-circuit simulation was carried out after the Fuse selection was completed to verify the correct operation of the faulty branch Fuse and to ensure the normal operation of the vessel's DC power system. Only if the verification of multiple short-circuit points in each operating mode of the vessel's power station at the maximum and minimum operating voltages is validated, it means that the Fuse selection is perfectly suitable for the system. To determine the correct melting of the faulty branch Fuse, firstly, the I^2t generated by the short-circuit current flowing through each branch Fuse is calculated from the simulation data to derive the $T_{\text{Pre-arcing}}$ and T_{Clearing} of each branch Fuse, and then the T_{Clearing} of the faulty branch Fuse and the $T_{\text{Pre-arcing}}$ of the non-faulty branch Fuse are compared, when $T_{clearing}^{(f)} < T_{pre-arcing}^{(nf)}$ (f for faulty line, *nf* for non-faulty line) is valid, the faulty branch Fuse is correctly melted. When the basis for the evaluation is not valid, the Fuse rated current should be corrected, with the Fuse rated current being at least greater than the maximum operating current on the DC side of the branch, and after the correction has been made, the verification should be repeated until the basis for the evaluation is valid.

Table 1 Schedule of fuse operation in each branch circuit.

	Bat1	Bat2	Super-cap	ISU	INU
Pre-arcing time (ms)	0.059	0.217	0.217	0.136	0.137
Clearing time (ms)	0.108				
Pre-arcing time (ms)	0.217	0.059	0.217	0.136	0.137
Clearing time (ms)	0.108				
Pre-arcing time (ms)	0.217	0.217	0.059	0.136	0.137
Clearing time (ms)	0.108				
Pre-arcing time (ms)	0.222	0.222	0.222	0.045	0.138
Clearing time (ms)	0.079				
Pre-arcing time (ms)	0.222	0.222	0.222	0.137	0.045
Clearing time (ms)	0.079				

The red fonts show the melting time of the faulty branch Fuse.

In order to illustrate the feasibility of the Fuse selection and the verification basis, this paper takes the vessel power station in the maximum operating mode at the maximum operating voltage as an example, and carries out short-circuit verification at the SC × A short-circuit point of each branch, the verification results are shown in Table 1.

From the data in Table 1, it can be seen that when a short-circuit fault occurs, the faulty branch Fuse melts correctly and quickly removes the short-circuit fault, ensuring the normal operation of the vessel's power system and improving the safety and reliability of the system.

4. Simulation and Short-Circuit Calculation

In the system simulation model shown in Fig. 1, the impact of cables, disconnector and Fuse impedance on the marine DC power system is considered with reference to the actual project. Batteries and super-capacitors bank are used as the marine power station with a cut-off voltage of 591.6 V and a full voltage of 714 V, supplying power to the 800V DC power system via a three-phase interleaved DC/DC converter. The DC/DC converter is controlled by a three-phase interleaved technology with double closed-loop, making the system busbar voltage stable at 800V DC, the use of three-phase interleaved technology makes the DC/DC converter phase currents differ from each other by 120°, the current ripple of each phase is superimposed on each other, thus reducing the total current ripple on the power side. The simulation results are shown in Figs. 2 and 3.

4.1 Basis for Short-Circuit Calculation

In the system simulation model, the battery uses the existing battery model in Matlab/Simulink, while the super-capacitor uses the series RC (Resistors & Capacitors) simplified model, as shown in Fig. 4, which has a simple structure, and it is very convenient for the analysis and calculation of the discharge process. The IEC 62391-1 international standard for supercapacitors shows that it is also known as electrochemical capacitors and electric double-layercapacitors. It is an electrochemical component developed in the 1970s and 1980s to store energy by polarising the electrolyte, and is a power source with special properties between traditional

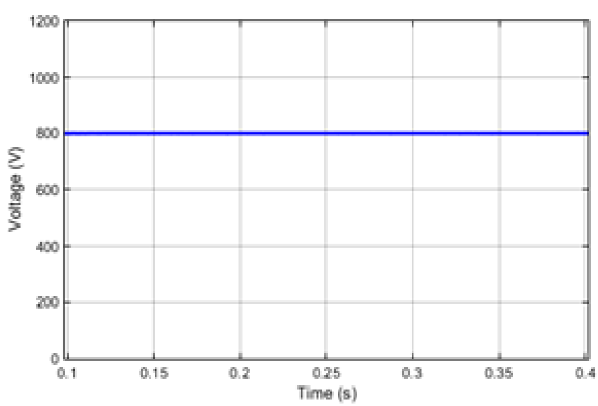

Fig. 2 System DC busbar voltage.

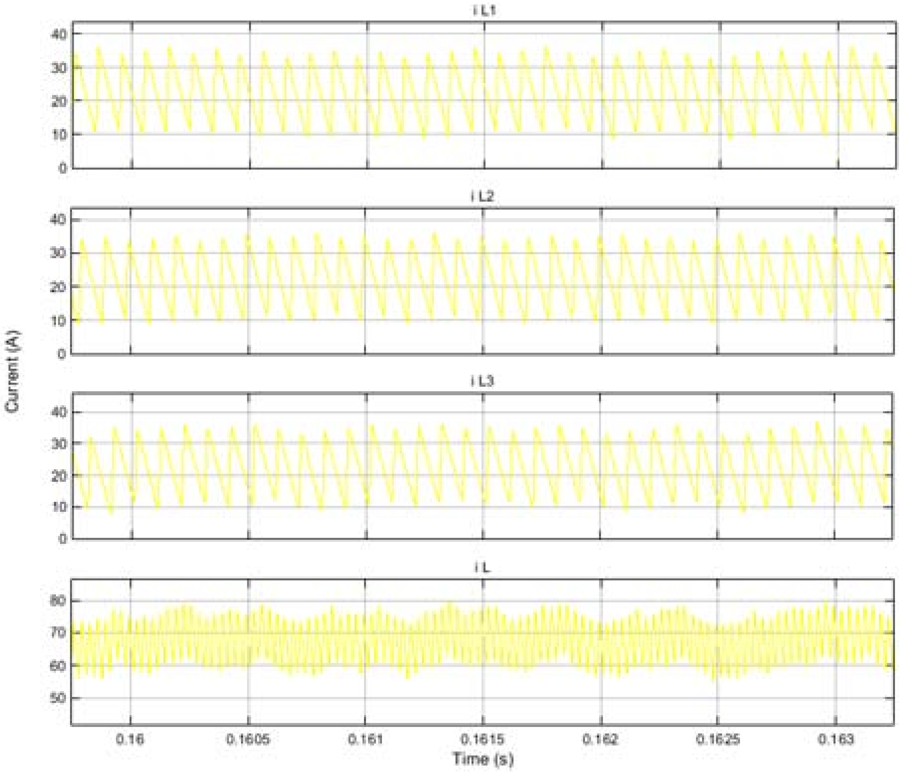

Fig. 3 DC/DC converter each phase and total current ripple.

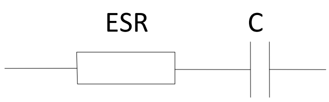

Fig.4 The series RC simplified model for super-capacitor.

capacitors and batteries [12], however, the IEC 61660-1 standard for calculating short-circuit currents in marine DC power systems [13] does not give a short-circuit calculation method for super-capacitors. Combining the electrochemical similarities between super-capacitors and batteries, this paper proposes a short-circuit calculation method for super-capacitors based on a simplified model of series RC. When calculating the steady-state short-circuit current and peak short-circuit current generated by the super-capacitor, the formulae for calculating the steady-state short-circuit current and peak short-circuit current of the battery is used, and when calculating the peak short-circuit current of the super-capacitor, the capacitive characteristics of the supercapacitor are considered and a correction factor is applied to the formulae.

Battery:

$$I_{kB} = \frac{0.95E_B}{R_{BBr} + 0.1R_B} \tag{4}$$

$$i_{pB} = \frac{E_B}{R_{BBr}} \tag{5}$$

In Eqs. (4) and (5), I_{kB} is for the steady-state short-circuit current generated by the battery, i_{pB} for the peak short-circuit current generated by the battery, E_B for the battery terminal voltage, R_{BBr} for the total resistance to the short-circuit point, R_B for the internal resistance of the battery.

Capacitor:

$$I_{kC} = 0 \tag{6}$$

$$i_{pC} = k_C \frac{E_C}{R_{CBr}} \tag{7}$$

In Eqs. (6) and (7), I_{kC} is for the steadystate short-circuit current generated by the capacitor, i_{pC} for the peak short-circuit current generated by the capacitor, E_C for the capacitor terminal voltage, R_{CBr} for the total resistance to the short-circuit point, k_C for the correctionfactor.

Super-capacitor:

$$I_{ksC} = \frac{0.95E_{sC}}{R_{sCBr} + 0.1R_{sC}} \quad (8)$$

$$i_{psC} = k_{sC}\frac{E_{sC}}{R_{sCBr}} \quad (9)$$

The following auxiliary equation is needed to calculate the short-circuit current of the super-capacitor:

$$R_{sCBr} = 0.9R_{sC} + R_{sCL} + R_Y \quad (10)$$

$$L_{sCBr} = L_{sCL} + L_Y \quad (11)$$

$$\frac{1}{\delta} = \frac{2}{\frac{R_{sCBr}}{L_{sCBr}} + \frac{1}{T_{sC}}} \quad (12)$$

$$\omega_d = \sqrt{\delta^2 - \omega_0^2} \quad (13)$$

$$T_d = \frac{1}{2\omega_d}\ln\left(\frac{\delta + \omega_d}{\delta - \omega_d}\right) \quad (14)$$

$$k_{sC} = \frac{2\delta}{\omega_d}e^{-\delta T_d}\sinh(\omega_d T_d) \quad (15)$$

In Eqs. (8)-(15), I_{ksC} is for the steady-state short-circuit current generated by the super-capacitor, i_{psC} for the peak short-circuit current generated by the super-capacitor, E_{sC} for the super-capacitor terminal voltage, R_{sCBr} for the total resistance to the short-circuit point, L_{sCBr} for the total inductance to the short-circuit point, R_{sC} for the internal resistance of the super-capacitor, k_{sC} for the correction factor, R_{sCL}, L_{sCL} are the resistance and inductance of the conductor of the super-capacitor branch, R_Y, L_Y are the resistance and inductance of the common branch, and ω_0 is the resonant frequency, δ, ω_d, T_d are intermediate coefficients, T_{sC} is the time constant and is taken as 5 ms.

4.2 Short-Circuit Calculation and Analysis of Simulation Results

When the battery and super-capacitor are at full voltage, a short-circuit fault occurs in the DC distribution board and the maximum short-circuit current flows, and the DC distribution board should withstand the thermal stress generated by the maximum short-circuit current. The short-circuit current supplied to the DC distribution board by each branch is calculated using Eqs. (4)-(9), as shown in Table 2, and the short-circuit simulation results and data are shown in Fig. 5 and Table 3.

Analysis of Tables 2 and 3 shows that the short-circuit calculation method for super-capacitors proposed in Section 3.1 is feasible, and its calculated steady-state short-circuit current and peak short-circuit current have a small difference compared to the simulated data, while the calculated peak short-circuit current of the battery has a slightly larger difference compared to the simulated data, so it is correct to apply a conversion factor when calculating the peak short-circuit current of the super-capacitor using the peak short-circuit calculation formula for the battery. According to Fig. 5 and Table 3, it can be clearly known the short-circuit withstanding capacity of the DC distribution board, and according to Table 2, a certain margin is proposed in the design requirements for the DC distribution board.

Table 2 Short-circuit current calculation results.

	Bat1/2	Super-cap	ISU	INU
i_{pC} (kA)	32.74	32.74	32.46	32.46
i_{pB}/i_{psC} (kA)	18.58	18.7	-	-
I_{kB}/I_{ksC} (kA)	16.18	17.6	-	-

Table 3 Short-circuit simulation data.

	Bat1/2	Super-cap	ISU	INU	SWBD
i_{pC} (kA)	32.25	32.25	31.85	31.72	160
i_{pB}/i_{psC} (kA)	16.77	18.19	-	-	51.6
I_{kB}/I_{ksC} (kA)	16.41	17.86	-	-	50.7

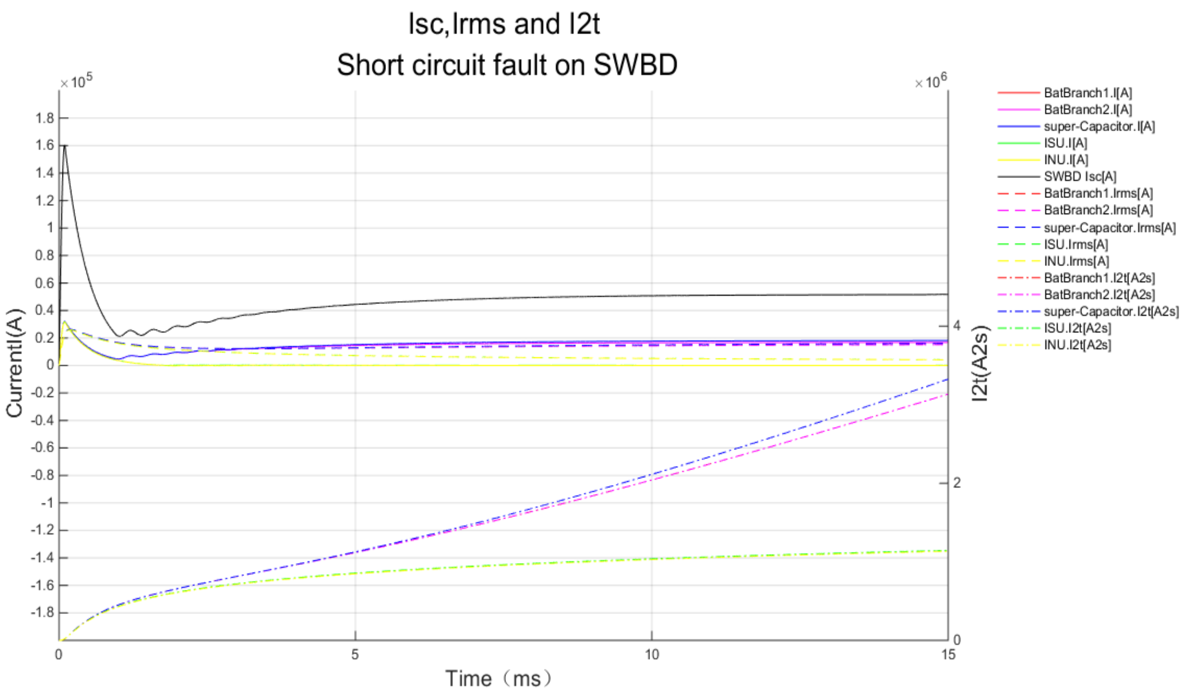

Fig. 5 Short-circuit currents, root mean square and I^2t for each branch.

5. Conclusions

The analysis of the simulation waveforms, simulation data and short-circuit calculation results shows that the following conclusions can be drawn:

(1) The use of three-phase interleaved control technology in the DC/DC converter reduces the current ripple on the power side, and each DC/DC converter has a stable output of 800 VDC, with no voltage difference on the output side, making it easier to control the onboard DC micro-grid.

(2) When a short-circuit fault occurs in the system, fuse can quickly break the short-circuit fault to ensure the normal operation of the system. As the filter capacitor discharges faster than the battery and super-capacitor, the energy required to melting fuse is mainly provided by the filter capacitor.

(3) The short-circuit calculation method proposed in this paper based on the series RC simplified model of supercapacitor has a small difference, which verifies the feasibility of its calculation method.

(4) As there is difference between the short-circuit calculation results and the short-circuit simulation data, a certain margin can be retained on the basis of the short-circuit simulation data for the selection of suitable electrical equipment and current-carrying conductors.

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