Journal of Electrotechnology, Electrical Engineering and Management (2024) **DOI: 10.23977/jeeem.2024.070202**
Clausius Scientific Press, Canada **ISSN 2560-6697 Vol. 7 Num. 2**

Selective Protection Analysis Method for DC Power Plant Propulsion Systems in Electric Ships

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Keywords: DC Power Plant Propulsion Systems, Short Circuit Faults, Selective Protection, Modeling and Simulation

Abstract: Nowadays, a large number of ships utilize DC power plant propulsion systems. In the past, the selective protection of power systems in AC power propulsion system ships was generally achieved by selecting circuit breakers based on the short-circuit current calculation results and by setting the circuit breakers accordingly. For DC power plant propulsion systems, due to the extensive use of current-limiting protective devices, the peak short-circuit current is related not only to system parameters but also to the selection and characteristics of the protective devices. Protective selection in DC power plant propulsion systems is crucial for maritime safety. This paper elucidates the principles of selective protection during short circuits, proposes a selective protection design method, analyzes a selective protection scheme using a specific vessel as an example, and finally presents a modeling and simulation approach. This paper can serve as a reference for the design of selective protection in similar DC power plant propulsion systems. By selecting appropriate fuses and using selective protection analysis methods, system safety can be improved.

1. Introduction

In the past, the selective protection of the power system of ships with AC propulsion systems generally relied on selecting circuit breakers based on the results of short-circuit current calculations, and achieving selectivity through the settings of these circuit breakers [1]. However, for DC power plant propulsion systems, because a large number of current-limiting protective devices are commonly used, the peak short-circuit current not only depends on system parameters but also on the selection and characteristics of protective devices [2], which presents new requirements for protective selection.

This paper takes a certain all-electric ship's DC power plant propulsion system as an example. It first elaborates on the principles of selective protection when a short circuit occurs. Based on this foundation, a selective protection design method is proposed. Subsequently, an analysis of the selective protection scheme is conducted. Finally, a modeling and simulation method is proposed, which can provide reference for the selective protection design of similar DC power plant propulsion systems.

2. Introduction to the DC Power Plant Propulsion System of an All-Electric Ship

The single-line diagram of the DC power plant propulsion system for a certain electric ship is shown in Figure 1.

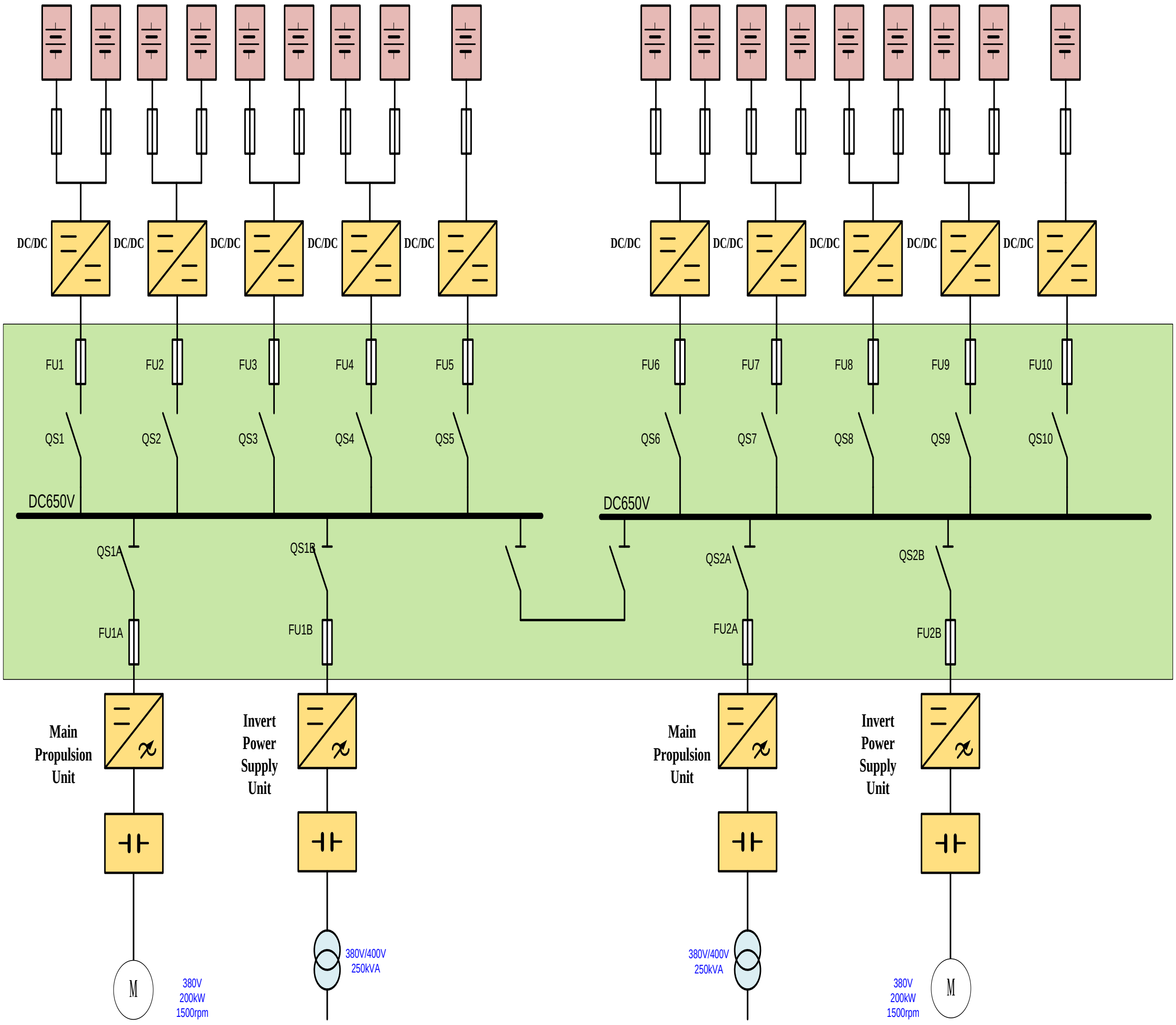

Figure 1: Single-line diagram of the DC power plant propulsion system

The DC power plant propulsion system consists of 2 sets of battery packs (total of 18 clusters, each cluster configured with a DC/DC converter unit), 2 sets of main propulsion units (each unit with a propulsion power of 200 kW, composed of 1 unit of 200 kW power module), and 2 sets of inverter power supply units (each unit with a capacity of 200 kW power module).

After passing through the DC/DC converter units, the battery packs are connected to the DC bus through DC load switches and fuses. Similarly, the main propulsion units and the inverter power supply units are also connected to the DC bus through DC load switches and fuses. FU01~FU10, FU1A~FU2A, and FU1B~FU2B are all DC fuses equipped with overcurrent and short-circuit protection functions. Coordination between the various levels of DC fuses enables selective short-circuit protection.

3. The Selective Protection Design of the System

3.1 Design Principles

According to regulatory requirements, electrical installations should be equipped with appropriate protective devices to safeguard against overcurrent, including short circuits, and other electrical faults [3].

In the DC bus system of a DC network, when a device experiences a short circuit fault, noticeable overcurrent will occur at the DC bus, inverters, or AC output terminals. Selective protection should avoid the following conditions:

1) Complete power loss of the entire ship;

2) Loss of maneuverability of the vessel, meaning loss of propulsion capability;

3) Other severe consequences resulting from the above, such as ship collision or fire.

The selective protection principles of this system are summarized as follows:

1) Ensure the safety of the battery system in the event of any short circuit fault.

2) When a single-point fault occurs, the fault branch fuse should promptly blow to quickly disconnect the faulty circuit, while the normal power supply to non-faulty branches remains unaffected.

3) Power devices remain undamaged after any short circuit fault.

4) The maximum short-circuit current on the bus does not exceed the stability requirements of the DC bus after any short circuit fault.

5) No open flames are caused by any short circuit fault.

3.2 Design Steps

For conventional AC systems, selective protection involves first calculating short-circuit currents under various operating conditions, selecting circuit breakers based on the calculated results, and achieving selectivity through the settings of these circuit breakers.

However, for DC systems, as a significant number of current-limiting protective devices are commonly used, the peak short-circuit current depends not only on system parameters but also on the selection and characteristics of protective devices.

For selective protection in this system, the following steps are taken:

1) Analyze selective protection principles and action sequences for different short-circuit points.

2) Select fuses based on rated parameters.

3) Model key components and verify the protection scheme through simulation.

4) If the selective protection requirements are met, design according to those parameters. If selectivity is not achieved, modify the fuse selection and busbar settings and then recheck.

5) Perform final verification during commissioning and testing.

4. System Selective Protection Analysis

Since the two busbars operate separately and have identical parameters, short-circuit current calculations and analysis can be performed considering only one section of the busbar, as shown in Figure 2.

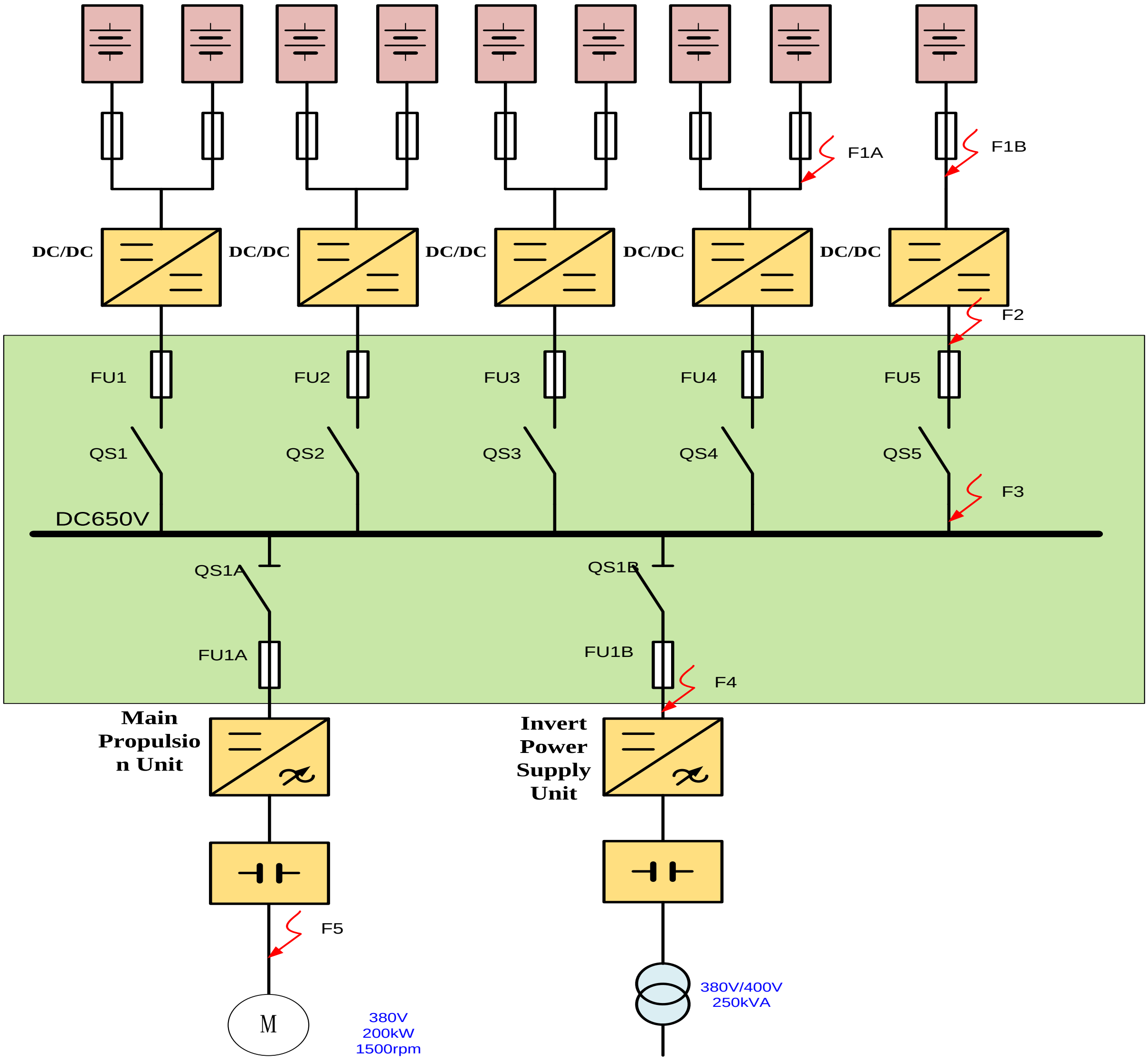

Figure 2: Short Circuit Fault Schematic

4.1 Analysis of Selective Protection Objectives

Analysis of Selective Protection Objectives for 5 Types of Characteristic Short-Circuit Points:

1) Short circuit at the output terminal of the battery pack. Points F1A and F1B as shown in Figure 2. Protection objective: The battery pack provides short-circuit current, the main output fuse of the battery pack blows, without causing damage to the fuse of each battery module.

2) Short circuit at the output terminal of the DC/DC converter unit. Point F2 as shown in Figure 2. Protection Objective: The battery pack, DC/DC converter unit capacitor, inverter power supply, and main propulsion unit capacitor provide short-circuit current. Fuse FU5 blows without damaging other fuses. The battery output fuse blows without causing damage to the fuse of each battery module and the reverse parallel diode of the DC/DC converter unit.

3) Short circuit at the DC busbar. Point F3 as shown in Figure 2. Protection Objective: The battery pack provides short-circuit current. Fuses FU1~FU5 blow without damaging the reverse parallel diodes of the DC/DC converter unit. The capacitors of the inverter power supply unit and

main propulsion unit lose power after discharging, and during the capacitor discharge process, minimal damage is caused to the circuit fuses. The main output fuse of the battery pack blows without causing damage to the fuse of each battery module.

4) Short circuit at the output side fuse of the converter unit. Point F4 as shown in Figure 2. Protection Objective: The battery pack and capacitors of the non-faulty side converter unit provide short-circuit current. The fuse of the faulty side blows without damaging the fuses of the non-faulty side. No damage is caused to the battery pack output fuse.

5) Short circuit at the output side of the converter. Point F5 as shown in Figure 2. Protection Objective: Short-circuit protection is achieved by the current-limiting protection function of the converter unit, without affecting the DC grid system.

4.2 System Selective Simulation Modeling Method

When a short circuit fault occurs, the main equipment in the system related to selectivity includes the battery pack, asynchronous motor, frequency converter, and inverter power supply. The modeling of the above equipment can be equivalently processed as follows:

1) Battery Pack:In the event of a short circuit at the battery output, the battery pack is protected by the output fuse.In the event of other short circuit faults, since the battery pack is connected to inductors, power-type boost units, and their capacitors, which are coupled low to the rear system, the battery voltage remains essentially unchanged and is maintained until the short circuit fault is cleared.

2) Asynchronous Motor:During a short circuit, the asynchronous generator is protected instantaneously due to the use of IGBT rectifier units. The residual magnetism of the asynchronous generator is minimal, providing limited energy and not generating short-circuit currents, thereby not affecting other systems.

3) Frequency Converter:The energy source during a short circuit fault comes from the DC support capacitor on the frequency converter's DC bus. Before the fuse separates the fault point from the DC bus, the energy stored in the DC capacitor provides energy to the short circuit fault loop. The capacitance value is determined by the corresponding frequency converter's DC support capacitor value. Once the frequency converter's selection is determined, the capacitance value is determined, and the specific value can be found in the frequency converter's data manual.

4) Inverter Power Supply:The inverter power supply uses IGBT devices for inversion and does not feedback energy. The main source of energy is the discharge of internal support capacitors. Therefore, the inverter power supply, like the frequency converter, only needs to consider the impact of capacitor discharge.

Based on the analysis above, Figure 3 provides the equivalent circuit model of the system. The calculation of short-circuit currents and selective analysis will be performed using the simulation software Matlab. In this equivalent circuit model:

1) At the moment of fault, the frequency converter and inverter power supply are modeled as capacitors.

2) At the moment of fault, conductors and copper bars are modeled as resistors and DC inductances.

3) At the moment of fault, DC fuses are modeled using nonlinear methods based on their fuse characteristics.

4) At the moment of fault, the battery is equivalent to a constant voltage source with internal resistance.

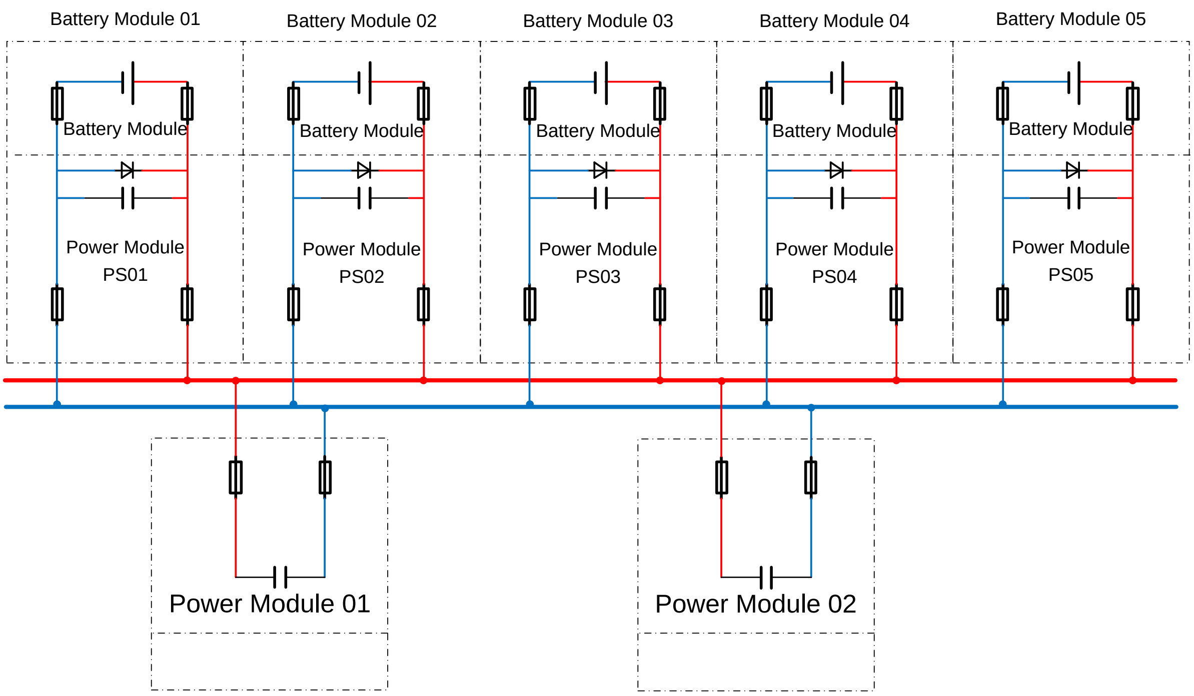

Figure 3: The equivalent circuit model of the system

The simulation analysis is conducted according to the following principles:

1) System short-circuit simulations are performed based on the distribution of fault points. Except for the minor impact on the system from short circuits after the propulsion frequency converter and inverter power supply, a total of four types and 16 scenarios of short-circuit situations are simulated.

2) Short-circuit points are created using DC switches, and the starting time of the short circuit is uniformly set to 100 microseconds.

3) The current waveform at the fault points represents the total current waveform.

5. Conclusion

Selective protection for the DC power plant propulsion system of electric ships can be achieved through the coordination of fuses. By selecting appropriate fuse types and employing selective protection analysis methods, system safety can be enhanced. The selective protection design method and modeling approach proposed in this paper can provide reference for similar systems.

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