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Voltage stability analysis of DC ship power system with pulse load

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Abstract: With the continuous development of pulse load represented by laser weapon and electromagnetic railgun, its application to the naval combat platform becomes a tendency. These pulse loads have the characteristic of high power as well as instantaneous which will impact the volume limited DC ship power system and challenge its stability. For this purpose, the simulation model of a medium voltage DC ship power system is built in PSCAD/EMTDC. Choose electromagnetic railgun which has two-level energy storage system as the representation of the pulse load. The model of the railgun is built through derivation then added to the DC ship power system to study the influence it does to the system voltage stability. The small disturbance method is used to compute the voltage stability of the whole system and the result is compared with the simulation figures. The comparison shows that the two-level energy storage based electromagnetic railgun can works normally in the system thus provides a new method to the way that the pulse load applies to the DC ship power system.

1 Introduction

The DC ship power system is a new type system used for electric power generation, electric propulsion, daily service loads, pulse load, and high-power detection device. It represents the development tendency of the vessel in the future [1, 2]. With the rapid development of the naval equipment and the increasingly demand for the ocean strategy, the study on the DC ship power system with pulse load becomes more and more important. These pulse loads include electromagnetic railgun, high-power radars, electromagnetic launch systems and so on which would lead to a big progress to the combat ability of the future vessels.

Since the pulse loads have the characteristic of high power as well as instantaneous, it will impact the volume limited DC ship power system thus challenged its stability. A lot of research on this field have been carried out and many methods have been put forward in the few decades. The goal of this paper is to study a new method of how the pulse load linked to the power system can work smoothly with the whole system.

One way to migrate the pulse load is through the energy storage system and their control strategy. There are many kinds of energy storage systems that can be used in the ship power system to coordinate the fluctuation that the pulse load does to the system, such as the battery, flywheel, and capacitor energy storage. Gattozzi *et al*. [3] take the power system of a destroyer class ship with laser weapons supported by the energy storage styles mentioned before as example, the typical results of the pulse load duty cycles, the energy storage technologies, and the volume as well as weight of the energy storage system were studied through simulation, and this method also can be transplanted to other similar power system.

As for the control strategies of these energy storage systems, one useful method to migrate the impact of pulse load is through the limit-based control (LBC). Its core idea is to charge the energy storage device as fast as possible within the power limit and the current limit of the system [4]. Simple and effective the strategy is, it also does disruption to the system. Similar to the LBC, the trapezoidal-based control was proposed to reduce the pulse load impact. Its core idea is to realise the control strategy based on the trapezoidal load profile. In this method, choose the parameters dominating the shape of the trapezoid to minimise the fluctuation the pulse load does to the system and verified though simulation [4, 5]. However, it does not include the experimental results. As an alternative, the generalised profile-based control was proposed. This method is based on the assumption that the requirement of energy needed to be accumulated from the power system in a set amount of time is constant, then achieve this requirement through the control strategy which can minimise the fluctuation of the power system [6]. The strategy was verified through both simulation and experiment.

Another method to compensate the fluctuation of pulse load is to equip the bus with an extra energy storage device. An example given in [7] shows that through the parallel of the supercapacitor energy storage system with the pulse load and control the charge/discharge cycle under the bus voltage fluctuation limitation, the supercapacitor can effectively compensate the pulse load. This method was validated through simulation but no experiment result was given. Hu [8] studied the flywheel energy storage system connected to the bus with relevant control strategy, the simulation and experiment results verified its effectiveness in power quality enhancement. However the pulse load is not under consideration.

The electromagnetic railgun is a typical pulse load in the DC ship power system which usually driven by supercapacitor or pulse machine [9]. However in [10], the two-level energy storage system based railgun was studied in which the railgun is driven by capacitor absorbed energy from the battery bank. Based on this condition, a new method of how the pulse load connected to the DC ship power system is put forward in this paper. In the studied DC ship power system, the railgun connected to the DC bus through this two-level energy storage system and the battery bank acts as an energy buffer, thus it can effectively reduce the system fluctuation caused by the pulse load. A medium voltage DC ship power system is given in detail in this paper. The effectiveness of the proposed method is verified through the computation and simulation results based on the given system.

2 Medium voltage DC ship power system

2.1 System structure

According to the concept of medium voltage DC ship power system in the future, a system with pulse load is given in detail in this paper. The system adopts the medium voltage direct current plant structure and can be divided into two parts according to the properties of the voltage. One part is the medium voltage DC side which includes the DC bus connected with the generators, the

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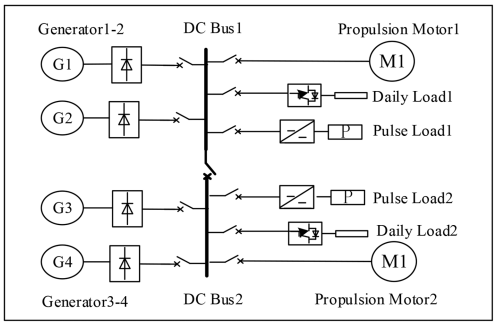


Fig. 1 *Structure diagram of integrated power system*

Table 1 Main parameters of each subsystem

Subsystem	Rated power
generator	SG1 = SG3 = 16 MW, SG2 = SG4 = 2 MW
propulsion motor	Spm1 = Spm2 = 12 MW
inverter	Sinv1 = Sinv2 = 2 MW
daily load	Sdl1 = Sdl2 = 2 MW
railgun	Ser = 4 MW
system voltage	V_{DC} = 5 kV; V_S = 380 V, f = 50 Hz

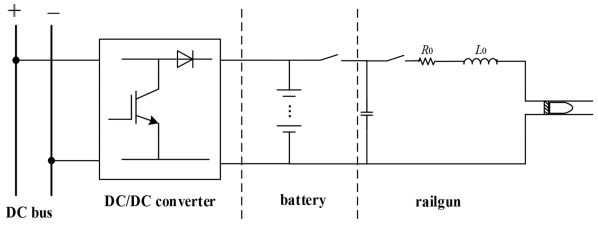


Fig. 2 *Structure of two-level energy storage system of the railgun*

propulsion machine, and the pulse load, while the other part is the low voltage AC side connected with the daily AC loads such as the lighting devices, air-conditioning and so on. The low voltage AC part is connected to the DC bus through the inverter. The plant of the system is shown in Fig. 1.

In the framework, G1 and G3 stand for the main generator system consists of two 12-phase synchronous machines with rectifying system. G2 and G4 represent the auxiliary generators which include two three-phase synchronous machine with rectifying system. All the output of the generating systems are medium-voltage direct current and directly connected to the DC bus to drive all the loads of the power system. The distribution system consists of two longitudinal busses connected with each other through the breaker. M1 and M2 stand for the propulsion load which include the variable frequency speed control system and the three-phase induction motor which supply the marine with propulsive force. R1 and R2 stands for the daily loads such as the air-conditioning and the light equipment connected to the DC bus through the inverter thus formed the low-voltage AC parts. Since the low-voltage AC parts play a fundamental role in the power system and its stability is of vital importance to the whole system, special attention should be paid to it. The pulse load is represented by P that is connected to the DC bus through the DC/DC converter. The whole system consists of two symmetrical parts descripted just as aforementioned and connected with each other through the breaker on the distribution bus. In general cases, the two parts work individually and act as mutually redundant, while in specific occasions, the power that the generating system supplied can be transported to the whole system through the distribution system. According to the practical application condition of the system, the main parameters of each subsystem are configured as in Table 1.

2.2 Pulse load

The pulse load refers to the facilities such as the radar, electromagnetic railgun, electromagnetic launch system, laser weapons and so on. Different pulse loads have their own structure while all of them have the common characteristic of high power as well as instantaneous which made it difficult for them to connect to the ship power system directly without causing serious impact. According to the battery-based electromagnetic railgun in [10], a new way of how the pulse load connected to the power system is put forward in this paper. Different from the usual methods showed in [5, 7], the battery energy storage system of the electromagnetic railgun is connected to the power system through the DC/DC converter and it absorbs energy from the DC bus then supplies to the capacitor to drive the railgun. Through this way, the battery energy storage system just acts as an energy buffer that makes the instantaneous of the pulse load affect the battery-based energy storage system rather than the power system itself. Also the charging time of the battery can be set as long as needed according to the demand of the whole system rather than the firing circles of the railgun thus effectively reduces the impact to the system. However, when the battery pack is on, it can also comparatively affect the power system slightly.

To verify the effectiveness of this method, the model of the railgun is built and simplified according to its characteristics, and then added to the DC ship power system to study the impact. Through the comparison of the small disturbance analysis computation result in MATLAB with the simulation result in PSCAD/EMTDC of the whole system, the method is identified to be effective.

The structure of the two-level energy storage system based electromagnetic railgun connected the DC bus of the ship power system is showed in Fig. 2.

The DC/DC converter is widely used in the power system due to the characteristics of high transform efficiency, light in weight as well as the wide range of voltage regulation. Since it is used as the charge device of the energy storage system, its state–space average mathematical model is shown in (1):

$$\frac{d}{\mathrm{d}t}\begin{bmatrix} I \\ V_\mathrm{o} \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1-d}{L} \\ \dfrac{1-d}{C} & -\dfrac{1}{RC} \end{bmatrix} \begin{bmatrix} I \\ V_\mathrm{o} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix} V_\mathrm{i} \tag{1}$$

where V_i stands for the charging voltage of the DC bus, V_o and I are the output voltage and current of the converter, while L and C stand for the parameters of the converter and R represents the load connected to the converter.

Fig. 2 shows the simplified structure of the electromagnetic railgun driven by the capacitor bank. Once the breaker is closed, the capacitor bank will suddenly produce a high initial current which will be prevented and elongated by the inductor then driving the amateur with the Lawrence force, thus finish the launch process. The math model of the electromagnetic railgun launch system can be described as follows [11]:

$$\begin{cases} U_\mathrm{c} = (R_0 + R_x)I(t) + L_\mathrm{o}\dfrac{\mathrm{d}I(t)}{\mathrm{d}t} + L'x(t)\dfrac{\mathrm{d}I(t)}{\mathrm{d}t} + L'\dfrac{\mathrm{d}x(t)}{\mathrm{d}t}I(t) \\ \dfrac{\mathrm{d}U_\mathrm{c}}{\mathrm{d}t} = \dfrac{I(t)}{C} \\ m\dfrac{\mathrm{d}v(t)}{\mathrm{d}t} = \dfrac{1}{2}\cdot L'\cdot I(t)^2 \\ v = \dfrac{\mathrm{d}x(t)}{\mathrm{d}t} \end{cases} \tag{2}$$

In this model, the R_0 and L_0 represent the resistance and the inductance of the railgun system, R_x stands for the resistance of the rail and it changes with the location of the armature represented by x. U_c stands for the voltage of the capacitor, I stands for the system current, m and v stand for the weight and velocity of the armature, respectively, L' stands for the inductance of the rail per unit length. According to the math model of the railgun and the energy stored in the two-level energy storage system, the efficiency in each launch cycle of the railgun can be described as follows:

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Table 2 Eigenvalue diagram of the DC side

−149.4 ± 476.7i	−72.82 ± 83.92i	−170.4 ± 54.25i
−0.9669 ± 0.8949i	−34.73 ± 1.772	−11.03 ± 10.07i
−4.207 ± 7.910i	−0.2321 ± 0.265i	−0.7103 ± 2.421i
−1.804 ± 227.1i	−208.3 ± 525.9i	−114.3
−0.8743 ± 9.318i	−8.521 ± 8.044i	−0.1991
−1.058	−0.3000	−114.3
−1.218	−4.849	—

Table 3 Eigenvalue diagram of the AC side

−33.95 ± 2.421e8i	−296.9 ± 4930i	−245.3 ± 235.3i
−6845 ± 2268i	−6845 ± 2276i	−312.5 ± 4852i
−3.750 ± 2.236e8i	−6928 ± 2301i	−504.6 ± 4234i
−3200 ± 4.482e-10i	−1198 ± 1630i	−1106 ± 1622i
−21.30 ± 0.2662i	−1.257 ± 6.586e-5i	−21.03
−812.9 ± 1743i	−3200 ± 2.212e-10i	−3200
−1.257	−3456	—

$$\eta = \frac{E_k}{E_c} \tag{3}$$

where E_k is the kinetic energy of the armature and E_c is the energy stored in the capacitor bank and both of them can be described separately as

$$E_k = \frac{1}{2}mv^2 \tag{4}$$

$$E_c = \frac{1}{2}CU_c^2 \tag{5}$$

Due to the existence of the two-level energy storage system, the charging time of the battery bank can be set as T rather than the firing frequency of the railgun. E_{ct} stands for the energy that the battery bank absorbed from DC power system in T which can be used to support the railgun for a certain firing circles n. Thus the power of the battery bank is

$$P = \frac{E_{ct}}{T} = \frac{nE_k}{\eta T} \tag{6}$$

After the battery bank is charged, the railgun system can work without connecting to the DC ship power system and its impact to the system can be equivalent as the charging device represented by an ordinary load R expressed as

$$R = \frac{\eta T V_o^2}{nE_k} \tag{7}$$

Equations (1) and (7) express the equivalent model of a railgun with the two-level energy storage system to the DC ship power system, and can be used for certain computation and simulation occasions.

3 Stability analysis

3.1 Voltage stability computation

The plant of the system is showed in Fig. 1. All the mathematical models and relevant parameters of each subsystem refers to [11]. The model of the railgun system is given in (1) and (7), and the relevant parameters are referred to [9]. Due to the existence of the two-level energy storage system of the railgun, its charging power is no longer that heavy as connected directly to the system. Comparing its volume to the whole system, the impact it does can be calculated through the small disturbance analysis. According to this theory, the DC ship power system can be described as differential-algebraic equations. Then obtain its Jacobi matrix through the linearisation of the differential-algebraic equations and valuate the stability of the system according to its eigenvalue. If the real part of all the eigenvalues are negative, the system is stable according to the Lyapunov stability theory, if not, the system is unstable [12].

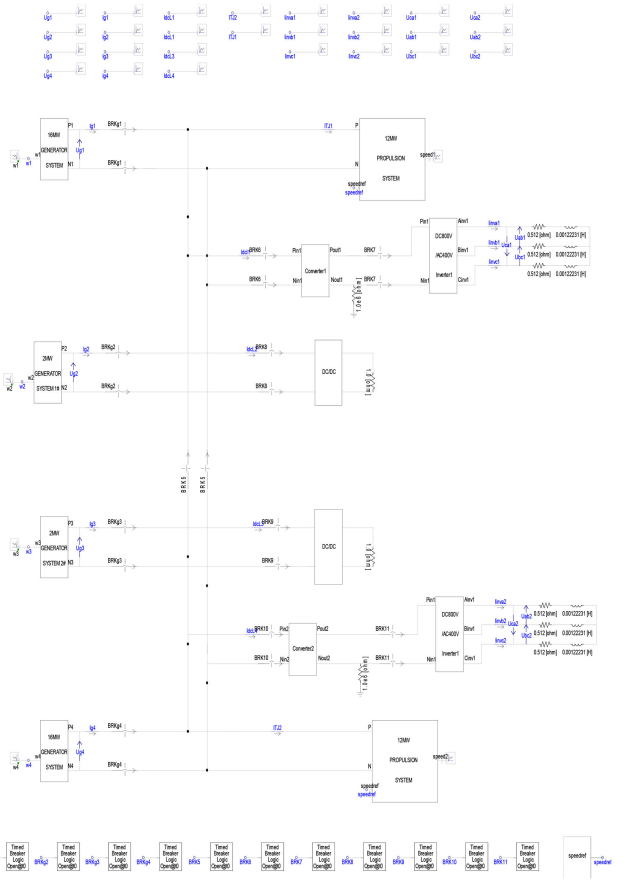


Fig. 3 *Simulation diagram of the DC ship power system*

The typical scenario, in which all the generators and the daily loads work normally, the propulsion motor runs in high speed, and the charging device of the pulse load starts to work, is studied. Based on the aforementioned small disturbance analysis theory, the evaluation process of the system can be separated into two parts as the medium-voltage DC side and the low-voltage AC side for their unique properties. All the linearisation and the computation process of these two parts are realised through programing in MATLAB. The computation results are shown in Tables 2 and 3.

The results in Tables 2 and 3 show that the eigenvalues of both the DC side and the AC side have negative real part. According to the aforementioned theory, the system is stable under this condition. It indicates that since the two-level energy storage system prolongs the charging time of the pulse load and reduces its instantaneous power, this method can effectively reduce the impact of the pulse load to the DC ship power system.

3.2 Voltage stability simulation

To verify the aforementioned result, the simulation model of the same DC ship power system described in part II is built in PSCAD/EMTDC just as Fig. 3 shows:

The equivalent model of the electromagnetic railgun is added to the system to study the impact it does to the system when it works. To compare with the computation results in 3.1, the same scenario is simulated. When the exciting process of the system is finished and the daily load works normally, the propulsion motor starts to speed up from 0 to 150 r/min at 30th second. Then the railgun system is put in at 100th second, the main volume of each subsystem is shown in Table 1. The detailed simulation results are shown in Figs. 4–9.

Since the system is symmetrical, the waveforms of the upper part are the same as the lower part under this normal scenario,

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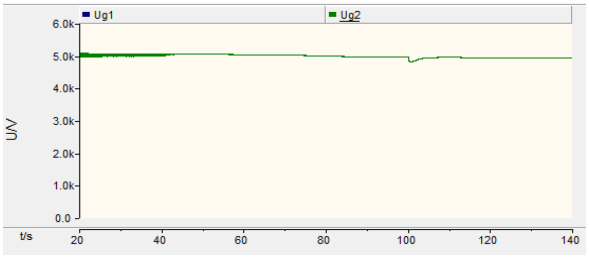


Fig. 4 *Curve of DC bus voltage*

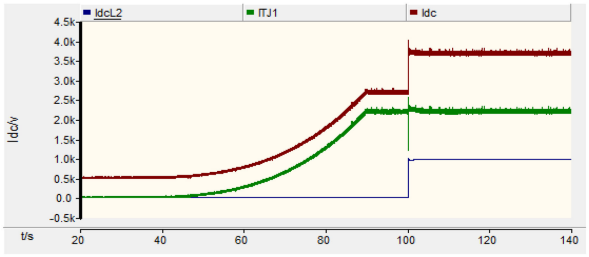


Fig. 5 *Current curve of each subsystem*

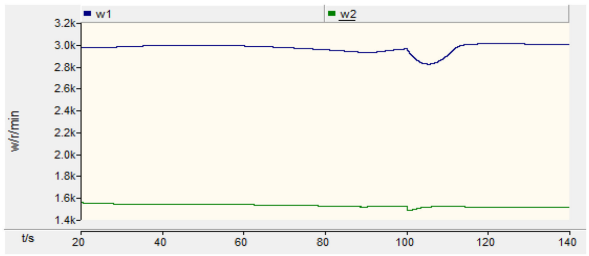


Fig. 6 *Curve of generator speed*

herein only the waveforms of the upper part are given. The DC bus voltage waveform in Fig. 4 shows that when the railgun system is put in, the voltage starts to fluctuate ∼3 s then back to normal automatically. Fig. 5 shows the current of the DC bus (red), the motor (green), and the railgun system (blue) separately, it indicates that when the railgun is put in, both the current of the DC bus and the propulsion motor will be affected heavily but within the normal range. Fig. 6 shows the speed of the generators, both of them can work normally under this circumstance. Fig. 7 shows the given speed of the propulsion motor, it keeps constant after the speed up stage. Figs. 8 and 9 show the current and voltage waveform of the AC side, due to the control strategy of the DC/DC converter and inverter, the AC side is scarcely affected. All the simulation results show that under the two-level energy storage system of the pulse load, the DC ship power system has voltage stability with the pulse load on.

Compared to the small disturbance analysis result, the simulation conclusion is identical with it. Both of them indicate that under the two-level energy storage system, the DC ship power system is stable thus verified the effectiveness of the proposed method.

4 Conclusion

In this paper, the two-level energy storage based railgun is connected to the DC ship power system to study the system voltage stability. The computation and simulation results of the whole system show that under this proposed structure, the system has voltage stability. Due to the proposed structure the battery bank can act as an energy buffer to reduce the impact of the pulse load effectively. This structure can also be adopted when dealing with other pulse load such as high-power radars, electromagnetic launch systems and so on in the ship power system. Though there maybe the volume problems, the battery energy storage system can also serve the DC bus when the pulse load is not on, thus makes it a feasible way to be adopted in the future.

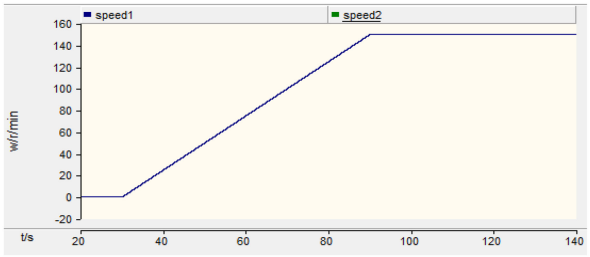


Fig. 7 *Curve of propulsion motor speed*

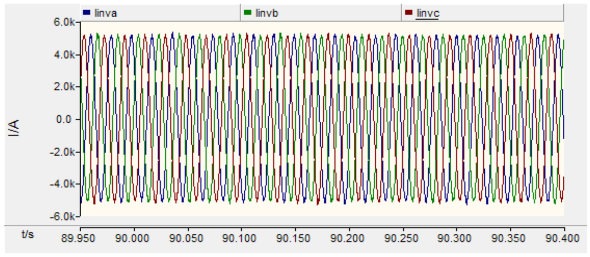


Fig. 8 *Curve of inverter AC current*

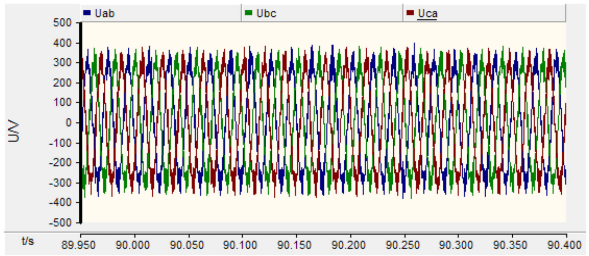


Fig. 9 *Curve of inverter AC voltage*

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