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ANALYSIS OF POWER COMPENSATION OF ENERGY STORAGE DEVICE FOR MEDIUM VOLTAGE DC SYSTEM WITH SUDDEN-ADDED PULSE LOAD

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ABSTRACT

Aimed at solving the problem of DC bus voltage sudden drop in medium-voltage DC system, caused by the input of pulse power load such as high-energy weapon, the transient voltage changes of rectifier generator with sudden-added load is given by PSCAD simulation. The input of the pulse power load is equivalent to a small resistance load, and the input of the energy storage device is equivalent to a DC/DC converter in parallel with a DC voltage source to compensate the power required by the load. The simulation results show the relationship between the size of the pulse power load and the compensation power of the ES device.

Keywords: pulse load, transient voltage, energy storage equivalence, storage compensation power

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Abbreviations	
ES	Energy Storage
DC	Direct Current
VIPS	Vessel Integrated Power System
PWM	Pulse Width Modulation
DAB	Dual Active Bridge
IGBT	Insulated Gate Bipolar Transistor

1. INTRODUCTION

Without corresponding preventive measures, the sudden added pulse power load such as high-energy weapon will cause sudden drop of generator output voltage. Excessive voltage reduction or recovery time will affect the normal operation of load [1][2], which may not meet the needs of engineering applications. Especially impact load such as electromagnetic launch, electromagnetic railgun, and the application of free electron laser weapons, the high instantaneous power and aperiodic transient operation features have more severe influence on the output voltage of the generator rectifier module of vessel integrated power system[3].

In order to reduce its impact, it is necessary to keep the DC bus transient voltage in a certain range. Voltage fluctuation caused by the pulse power load is relatively severe, if adjusted by coordinating the generator and propulsion load, the problem is how to quantitatively limit the power of propulsion motor before charging the pulse power load [4], and it takes time for coordination and control, which is difficult to meet the power and energy demand of pulse power load in a short time. Configuring the ES device is a quick and effective method for power and energy compensation.

As the vessel integrated power system adopts the medium-voltage DC system, the pulse power load is usually directly supplied by the DC bus. Therefore, it is an alternative technology to connect the ES device directly to the DC bus, by which the power and energy required for the pulse power load could be supplied in a short time. The flywheel ES system which combines flywheel ES with bidirectional converter is studied in literature [5], and a control strategy based on magnetic field-oriented voltage space vector PWM is proposed to adjust the compensate power imbalance between DC bus voltage and generator, which improves the power quality and stability of VIPS. In literature [6], the ES device is connected in parallel with dual active bridge (DAB) converter, with coordinated control based on the difference between the load current and the total output current, DC bus voltage and the charge state of battery and super capacitor, the power distribution

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among different ESs are obtained to ensure the balance of power and the stability of voltage. Literature [7] adopts several different ES forms to compensate the voltage sag of the DC circuit, and gets the response time and corresponding voltage recovery curve.

According to the above studies, the problem of excessive voltage sags of DC bus can be alleviated by the power and energy compensation of ES. Therefore, the relationship between the voltage change of DC bus and the power and energy compensation of ES device should be fully considered in the design and configuration stage of ES device. The research focuses on quantitatively studying the effect of ES device on the improvement of transient voltage sags of medium voltage DC system, which provides theoretical basis for capacity configuration of ES device.

2. POWER COMPENSATION MODEL OF TRANSIENT VOLTAGE FOR RECTIFIER GENERATOR WITH PULSE LOAD

2.1 A simplified model of power compensation for ES device

To reduce the impact of the sudden added pulse power load on the output voltage of the rectifier generator, the instantaneous energy deficiency of the system can be supplemented by paralleling with the ES device. There are various forms of ES that can provide power and energy supplement for the load. The main types of ES applicable to the vessel integrated power system include battery, flywheel and supercapacitor ES, etc. Considering the pros and cons, this topic selects battery energy storage to compensate the power and energy required by the pulse power load.

To stabilize the bus voltage around the reference value, DC/DC converter is also required and coupled to adjust the output voltage and current of the source through the control strategy. Since the voltage of the single battery is only 2.5v to 3.2v, the output voltage of the ES device composed of Multiple batteries should not be too high, and it is generally lower than the bus voltage. Therefore, when the energy storage composed of Multiple batteries provides power for sudden-added load, the DC/DC converter needs to own the boost function [8] as shown in Fig 1. To simplify the processing,

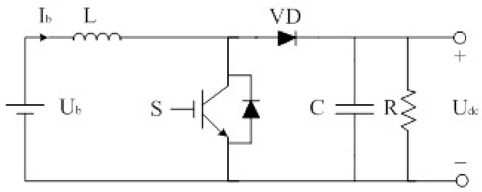


Fig1 Boost DC/DC converter model of battery energy storage

it only shows the discharge topology, charging interface is not considered.

U_b is the output voltage of the battery module, U_{dc} is the output voltage of the ES device, S is the control signal of IGBT, L is the boost inductance, and C is the filter capacitor, the switching frequency is f_s, then the period of control signal is $T_s=1/f_s$, and the duty cycle is D. when $t\in[0, DT_s]$, the switching tube S is on, the diode VD is off, and the state equation of the circuit is

$$\begin{cases} L\dfrac{di_L(t)}{dt}=u_b(t) \\ C\dfrac{du_{dc}(t)}{dt}=-\dfrac{u_{dc}(t)}{R} \end{cases} \tag{1}$$

When $t\in[DT_s, T_s]$, the switch tube S is off and the diode VD is on, and the state equation is

$$\begin{cases} L\dfrac{di_L(t)}{dt}=u_b(t)-u_{dc}(t) \\ C\dfrac{du_{dc}(t)}{dt}=-\dfrac{u_{dc}(t)}{R}+i_L(t) \end{cases} \tag{2}$$

Combined equations (1) and (2), it can be deduced that the transformer pressure ratio of the converter is

$$M=\frac{U_{dc}}{U_b}=\frac{D}{1-D} \tag{3}$$

2.2 The buffering effect of power compensation on voltage sags

To simplify the analysis, the input of ES device can be equivalent to the compensation of power and energy, since the energy compensation needs to take into account factors such as the discharge duration and discharge depth of the ES device, etc., and the improvement of instantaneous voltage sags is mainly considered here. Therefore, the influence of time is ignored temporarily. Assuming that the energy compensation can be completed at the moment of loading, only the buffering effect of power compensation on voltage sags is considered here.

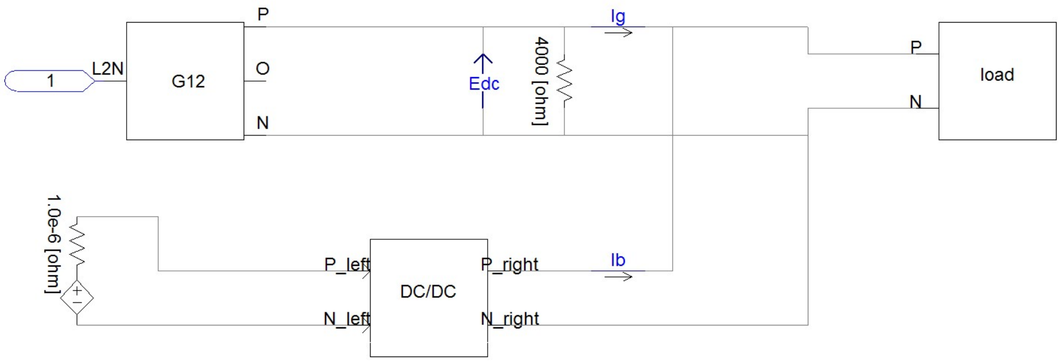


Fig 2 Equivalent model of energy storage service in parallel with rectifier generator

Ignoring the influence of the time constant, pulse power load is equivalent to the sudden-added minimum resistance, simulated the sudden increase of power, to characterize the short-term power and energy impact on the medium-voltage DC system. At the same time, the input of the ES device is equivalent to the DC voltage source connected to the main network through the DC/DC boost converter, which provides the power compensation required by the pulse power load. The equivalent model of ES service in parallel with rectifier generator supply power to sudden-added resistive load is built as shown in Fig 2. In the operation of rectifier generator, to ensure the voltage quality during sudden loading or unloading, a discharge resistor is generally shunt at DC side [9], the resistance is 4kΩ.

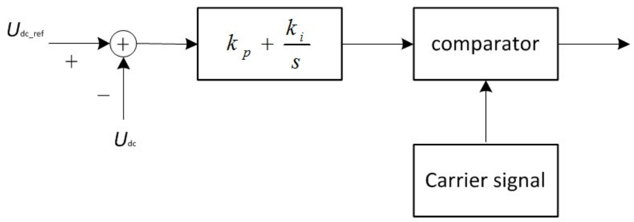


Fig 3 Control block diagram of Boost DC/DC converter

DC/DC boost converter adopts voltage source control mode, and its closed voltage-loop control block diagram is shown in Fig 3. PI controller is adopted for closed-loop control to achieve zero-difference tracking of input signals. After comparison of controller output signals and carrier signals, pulse signals are generated to control on and off of IGBT switch tubes. U_{dc_ref} is the reference value of output voltage of ES device, U_{dc} is the output voltage of ES device, k_p is the proportional parameter of PI controller, and k_i is the integral parameter of PI controller.

In normal operation, the reference voltage of energy storage battery is set to be slightly lower than that of generator, and the ES device does not output current. When load disturbance is applied suddenly, the bus voltage drops below the output voltage of the ES device, the ES device feeds to the main network actively to compensate the insufficient transient power of the generator.

3. ANALYSIS OF POWER COMPENSATION FOR TRANSIENT VOLTAGE OF RECTIFIER GENERATOR BY ES DEVICE

On the basis of the three-phase rectifier generator model, the 12-phase equivalent rectifier generator model is built as shown in Fig 4.

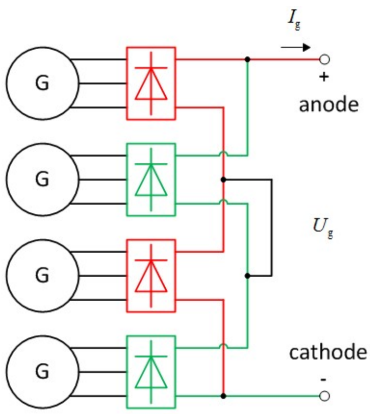


Fig 4 12-phase equivalent rectifier generator

Tab 1 Simulation parameters of of Boost DC/DC converter

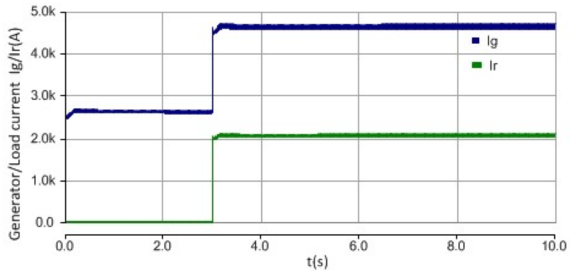
circuit parameter/unit	value	control parameter	value
boost inductance L/μH	$5*10^{-6}$	K_p	0.05
filter capacitor C/μF	$2*10^{5}$	K_i	$1.5*10^{-4}$

The reference value of output voltage of 12-phase equivalent rectifier generator [10] is U_{dcb}=4kV, Relevant parameters of DC/DC boost converter are given in Tab1.

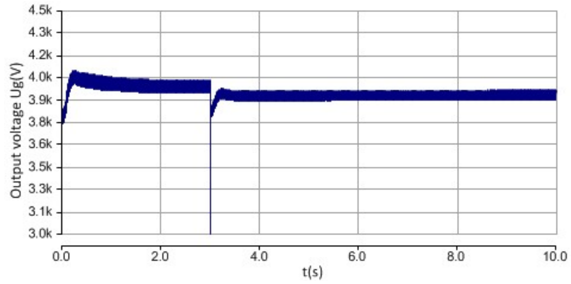
It is assumed that the rectifier generator is loaded with 50% load when the pulse power load is added suddenly, which is equivalent to 40% rated load, the power compensation of ES device for the transient voltage of rectifier generator is as follows:

3.1 Rectifier generator load alone, no ES

The current and voltage waveforms of the rectifier generator with sudden-added load are given, as shown in Fig 5.



(a)Current of generator and suddenly-applied load



(b)Output voltage of generator

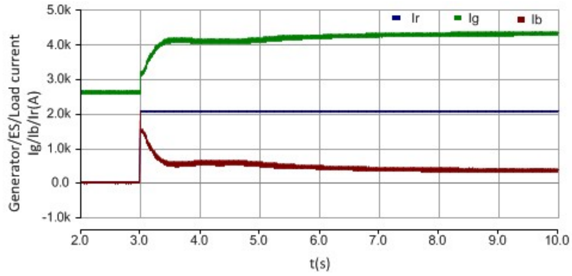
Fig 5 Waveform diagram of rectifier generator with a sudden-added load

It shows that the output current of the rectifier generator increases from 2620A to about 4660A, and the instantaneous voltage drops to about 3830V, which returns to stability within 0.5s. As the generator excitation adopts voltage droop control, the output voltage drops to about 3950V after the load rate rises, and the power provided by the rectifier generator for the load is 18.407MW.

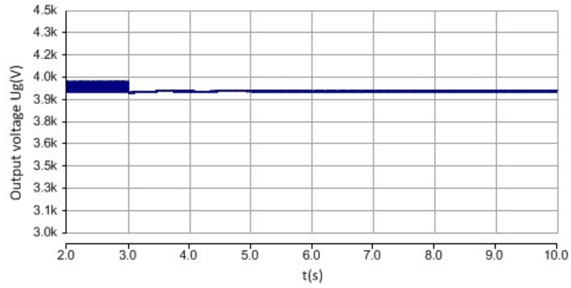
3.2 *Rectifier generator parallel with ES*

The waveforms of current and voltage when the rectifier generator with sudden-added load are given, as shown in fig6. The parameter changes under different running states with sudden-added load were compared as shown in Tab 2.

To avoid the influence of ES device on the normal operation of rectifier generator, the reference value of its output voltage is set as 3950V. According to Fig 6 and Tab 2, the reference value of ES output voltage is lower than that of rectifier generator, therefore, when the



(a)Current of generator and ES and suddenly-applied load



(b)Output voltage of generator

Fig 5 Waveform diagram of rectifier generator in parallel with energy storage device with a suddenly-applied load

generator is loaded with 50% rated load, the bus voltage remains 4000V around, the ES does not output power and is in the cut-off state (the ES equivalent model does not consider the charging part), and the current is close to 0. The output voltage of rectifier generator drops abruptly with sudden-added pulse load, once the voltage is lower than the reference value of the ES output voltage, the ES starts to supply power, instantaneous voltage of the DC bus is about 3940V. Compared with rectifier generator load alone, the voltage sags decreased by 110V and recovered to the reference value of ES output voltage around 3950V within 0.5s, the current of the rectifier generator increases from 2620A to about 4320A, which is 340A lower than that without ES, the power provided for the load is 17.064MW.

Tab.2 Parameter variation comparison under different running states with sudden-added load

running state	transient voltage (V)	stable voltage (V)	generator current (A)	ES current (A)
load alone	3830	3950	4660	--
load parallel	3940	3950	4320	380

4. CONCLUSIONS

The load equivalent method is adopted to simulate the transient voltage changes of the rectifier generator, and the parallel equivalent model of energy storage device and rectifier generator is given. The simulation results show that the larger the pulse power load, the greater the bus voltage sags. The voltage sags can be alleviated by the parallel ES device, and the transient voltage can be recovered to the stable operating range. It provides a technical premise for the further research on the optimal configuration of the ES device when the pulse power load such as the high-energy weapon is suddenly added.

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