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The Discharge Operation Analysis and Excitation Control of Pulse Motor Generators on HL-2A Tokomak

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The HL-2A is a magnetic fusion confinement device. The power of its Toroidal Field coils is supplied by four sets of parallel diode three-phase bridge rectifiers, which are connected with the outputs of two identical 80MVA pulse generators. The Poloidal Field power supplies, including Ohmic Heating, Vertical Field, Radial Field and Multi-Pole Field, and auxiliary heating power supplies are thyristor converters and connected to the 125MVA pulse generator by their transformers respectively. The loads of two 80MVA generators can be balanced, since the two generators with the same excitation current have the same output voltage. The excitation AC power source of 80MVA generators comes from the coaxial exciting generator. During the discharge, the output voltage frequency of the exciting generator decreases as the rotational speed of the shafting decreases. The PLL (Phase Locked Loop) on the excitation gate controller is used to track the frequency change, and PID feedback control program makes the DC excitation power supply stable.

Keywords: Excitation Control, Pulse Motor Generator, Discharge, PLL (Phase Locked Loop), HL-2A

1. Introduction

The total pulsed output power of magnetic field coil power supplies of HL-2A is around 250MW with duration 5s. However, it is not conducive to get power directly from the power grid because of huge load in short period and long whole discharge cycle, so flywheel with large mass is used for energy storage [1, 2]. It takes a longer period of time to store energy from power grid by induction motor dragging a huge flywheel, and then the stored energy is released in a short period of time by pulse synchronous generator to supply power for the magnetic field. The schematic diagram of the Toroidal Field power supply is shown in Fig. 1.

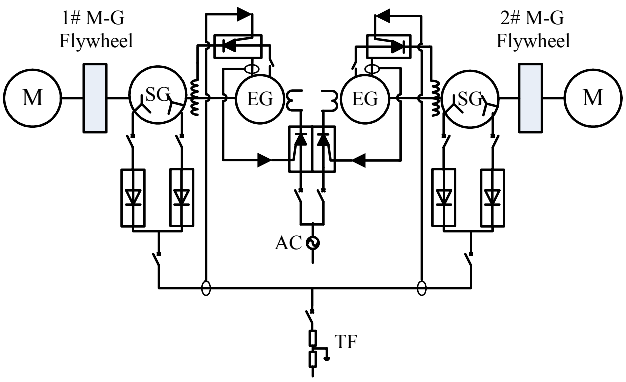

Fig. 1 Schematic diagram of Toroidal Field power supply

The pulse capacity of 1# generator and 2# generator is 80MVA; wound rotor asynchronous motor (M), flywheel, main generator (SG) and exciting generator (EG) are all coaxial. The excitation power supply of exciting generator is AC power grid; the outputs of exciting generator are designed as the excitation power supply of main generator. The rectifier outputs of 1# main generator and 2# main generator are parallel to supply power to Toroidal Field coils.

3# motor generator has similar structure with 1# and 2# motor generator except its power supply of excitation system. The schematic diagram of the Poloidal Field power supply is shown in Fig. 2. AC power grid is used as the excitation power supply for 3# generator, and the loads of 3# generator include the OH, RF, VF and MPF coils [3].

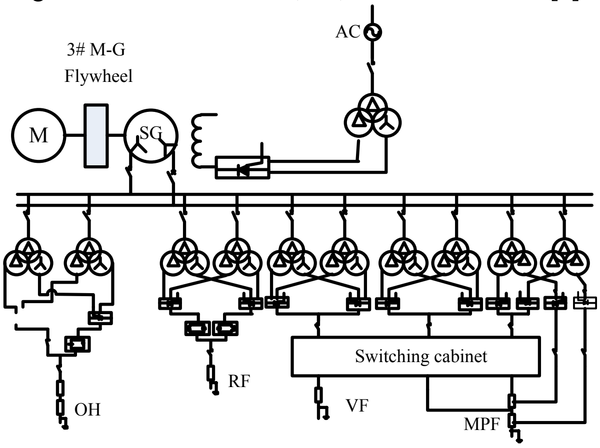

Fig. 2 Schematic diagram of the Poloidal Field power supplies

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The main parameters of 1#, 2# and 3# motor generator are given out by Tab. 1.

Tab. 1 Main parameters of three sets of MG

Main parameters		1# & 2#	3#
Generator	Phase voltage	1500 V	3000 V
	Phase current	11 kA	12 kA
	Pulse capacity	90 MVA	125 MVA
	Synchronous speed	1500 rpm	3600 rpm
Motor	Rated capacity	2500 kW	2500 kW
	Rated voltage	6000 V	6000 V
	Synchronous speed	1500 rpm	3000 rpm
Shafting	Stored energy	500 MJ	214 MJ

2. Discharge Procedure and Analysis on Motor Generator

Before discharge order is given out, there is no load for generator, by decreasing the slip resistance of wound rotor asynchronous motor, motor generator is uniformly accelerated approximately to rated rotating speed of motor, and energy is stored by flywheel at the same time, the slip resistance is set to 0. After the shafting rotating speed achieves the rated rotating speed of motor, the slip resistance is set to operation again before discharge to reduce the impact on power grid, the generator begins to supply power to Toroidal Field coils as excitation order is given out by CCC (Central Control Computer) [4], meanwhile the slip resistance is adjusted to 0 again during discharge, the stored energy is released. The excitation order can be divided into four stages: force excitation, inversion, flat topping and de-excitation.

1# and 2# generator supply power to Toroidal Field coils through the non-controlled diode rectifiers, the advantage is that the investment of rectifier equipments is about half of SCR devices and a complex trigger system is not needed. The terminal voltage of 1# and 2# generator is controlled by the excitation output current; thereby the Toroidal Field current waveform can be regulated by excitation system. To Poloidal Field power supply, the stable output voltage of 3# generator is required.

The waveform of the main exciter current (1#If), exciter voltage (1#Vf), input on exciter (1#Vin), outputs of generator (1#IA1: current of phase A in first Y winding, 1#UAB1: line voltage between phase A and B in first Y winding), rotational speed of 1# motor generator (1#N) and Toroidal Field current (It) is shown in Fig.3. It takes more than 1 second to establish the terminal voltage of generator; the load current still exists when the input on exciter is changed to 0 because of remanence, which gravely affects the cooling system of generator and the load coils. Therefore fast de-excitation is needed when flat topping is over. In addition, internal fault of generator and short circuit between the outputs of generator also need fast de-excitation.

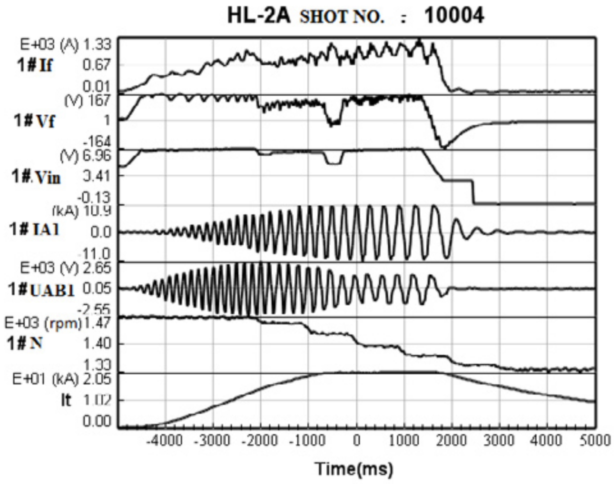

Fig. 3 Waveform of 1# motor generator for Toroidal Field power supply during discharge

As all the three controlled rectifiers of excitation system work in full-bridge mode, completed SCR inverter can be used for de-excitation. The energy of excitation windings from the DC side can be delivered to the AC side through completed SCR inverter. By adding a constant negative voltage to the excitation windings, the rotor current decreases basically in straight line, thus it spends less time on de-excitation.

3. Excitation System of Motor Generator on HL-2A

The outputs of generator are adjusted by excitation system, in order to accommodate the requirement of discharge; excitation system must perform such functionalities: the input waveform order from CCC must be changed into trigger pulse on exciter by excitation system [4], PID feedback control on exciter and measurement protection. The typical excitation system can be divided into three sections, the excitation control program, the gate controller and the exciter.

1# and 2# exciting generator is coaxial with main generator and supply power to 1# and 2# excitation system, the output voltage frequency of exciting generator is changing irregularly as shafting rotational speed is falling down during discharge; the exciter power supply of 1# and 2# exciting generator is AC grid.

The power supply of 3# excitation system is also AC grid, the same as 1# and 2# exciting generator. The frequency and amplitude of AC grid can be considered as fixed.

Fig. 4 shows the diagram of the power supply of 1# and 2# generator. The excitation control program of the three sets of motor generator is similar with each other. Especially, the outputs of 1# and 2# excitation system are not only determined by the trigger angle on main exciter but also by the output of exciting generator. The output amplitude of exciting generator must be kept constant by adjusting exciter of exciting generator during discharge, and then output of the whole excitation system can be controlled by adjusting the trigger angle on main exciter.

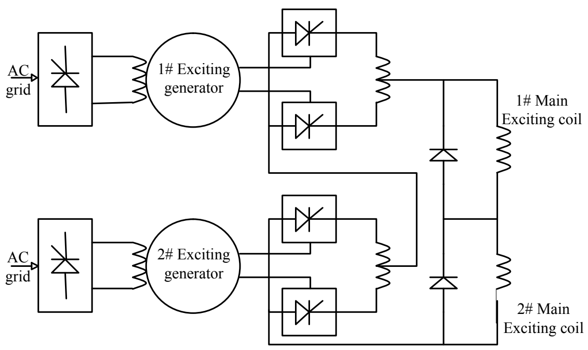

Fig. 4 Power supply of 1# and 2# generator

3.1 Excitation control program

The 1# and 2# excitation control program is programmed by object-oriented language. Each program must control two objects: the exciter of the exciting generator and main exciter. Every object includes waveform parameters from CCC, local control parameters which input is included in and acquired parameters from output. The code of every object remains the same with different parameters.

PID control is used on every object. The specific feedback control diagram of Toroidal Field power supply is simplified and shown in Fig. 5, where T_f is the time constant of excitation system, T_g is the time constant of generator and T_t is the time constant of Toroidal Field coils.

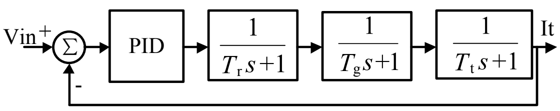

Fig. 5 Control diagram of power supply for Toroidal Field coils

Based on the parameters of the whole system where the excitation inductance is 600mH, excitation resistance is 161mΩ, the inductance of Toroidal Field coils is 230mH and the resistance of Toroidal Field coils is 60 mΩ, so T_f is 3.727s, T_t is 3.833s; and T_g is 5.8s from the factor parameters of main generator. The feedback gain and stability can be analyzed from the control diagram, based on Nyquist Stability Criterion, the feedback gain can't be over 72.296.

Similar to the control diagram of Torodal Field power supply in Fig. 5, the control diagram of exciting generators for 1# and 2# main generator, excitation system of 3# motor generator also can be normalized, and meanwhile feedback gain can be required accuracy in the same way.

3.2 Gate Controller of Excitation System

The gate controller acquires the voltage signal from the AC input side, and then transforms the control signal into trigger angle to control the excitation rectifier. Its structure schematic diagram is shown in Fig. 6.

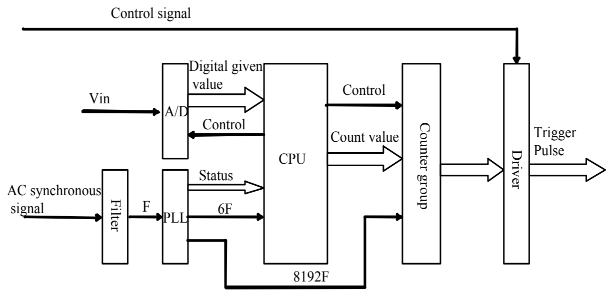

Fig. 6 Structure schematic diagram of gate controller

The phase-shift trigger pulse is generated by counting function of the counter group. At natural commutation point of three-phase AC, the counter group is started with an initial value which is decided by the digital input value; when the counter value becomes equal to zero, the counter group will give out pulse signal to driver to trigger the exciter. RC filter is used for elimination of interference from harmonic wave and EMI (Electro Magnetic Interference) of AC synchronous signal, the comparison circuit transforms the signal into square-wave frequency F. PLL (Phase Locked Loop) with its frequency divider and signal F composes the closed-loop circuit. By the closed-loop circuit, the output frequency can be locked in frequency of N times of the input signal with no phase difference; in the trigger phase-locked loop, the input signal F is square wave from the main circuit with the same frequency, the output signal includes 6F, 8192F and power status signal S. There are a total of six counters, their serial number is from 0 to 5, the counters are respectively Counter 0, Counter 1, Counter 2, Counter 3, Counter 4, Counter 5, which are used for time delay to generate the trigger pulses corresponding to +A, -C, +B, -A, +C, -B phase, where symbols +A, -C, +B, -A, +C, -B are the six corresponding thyristors of three-phase (phase A, phase B and phase C) rectifier bridge; CPU determines working time and initial number of the six counters.

The relationship among the PLL input signal F, output signal 6F, and the power status signal S is shown in Fig.7. The signal 6F describes the natural commutation point of three-phase AC; the power status signal S (S2S1S0) describes the status of AC input, determines which counter must be started. As the role of PLL, when the input AC synchronous signal frequency fluctuation occurs, the signal 6F, 8192F, and S is adjusted by the PLL to follow the frequency fluctuation.

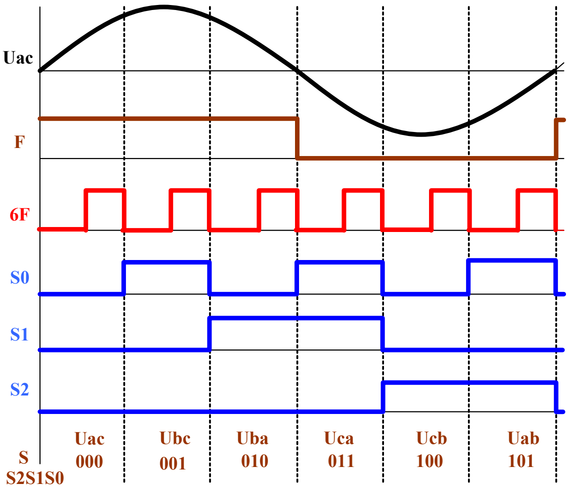

Fig.7 The relationship among the PLL, power status and AC synchronous signal

No matter how the natural commutation point changes, the angle between the adjacent natural commutation point and the trigger pulse resolution remain constant, which can make the orderly trigger pulse be generated and not affected by AC frequency.

4. Experimental Results of Excitation System

Experimental results of 1# and 2# motor generator discharge with their load are shown in Fig. 8. Where the output coils of the two exciters are connected in series, there is only small difference between the output currents, and the stored energy is released equally.

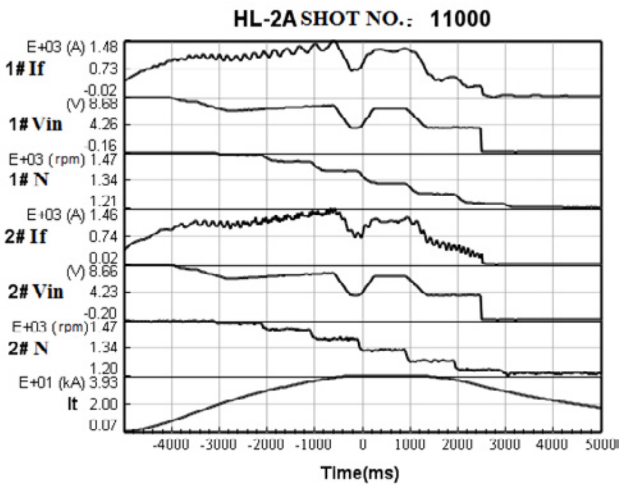

Fig. 8 Experimental results of 1# and 2# motor generator discharge with their load

Experimental results of 3# motor generator discharge with load are shown in Fig. 9, where 3#If is the excitation current, 3#Vf is the excitation voltage, 3#Vin is the input of excitation system, 3#IA1 is the current of phase A of the first winding, 3#UAB1 is the line voltage between phase A and B of first winding, 3#N is the rotating speed, Ip is the current in Poloidal Field coils. The load current is controlled not only by the excitation system, but also controlled by the convertors which are connected with output of 3# generator.

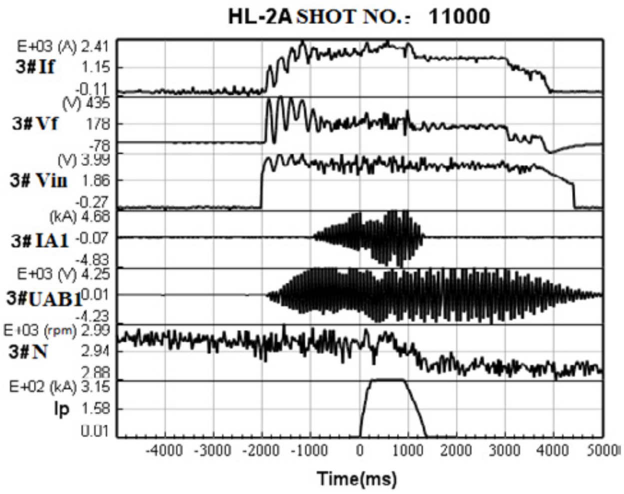

Fig. 9 Experimental results of 3# motor generator discharge with load

5. Conclusions

The structure of HL-2A power supply and discharge procedure is analyzed. Based on that, in order to control power supply, the typical excitation system of motor generator is introduced, which consists of control program, gate controller and exciter. PLL on gate controller is used to trace the output frequency of exciting generator, so that the thyristors of main exciter can be triggered at correct time point. The output coils of 1#, 2# excitation system are connected in series. With the same input value on the excitation control system, there is the same exciting current on 1# and 2# generator. Therefore 1# and 2# generator give out the same voltage and the load is balanced.

6. References

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