Power Supply of Vertical Stability Coil in EAST

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Abstract: Power supply of vertical stability coil in EAST(Experimental Advanced Superconducting Tokamak) is a large capacity single phase inverter power supply, which traces displacement signal of plasma, and excites four fast-control coils in vacuum chamber to produce magnetic field that realizes plasma stabilization in large elongate model. It consists of HV switches, AC/DC converters, 24 inverters which is made of 3-level half bridge with diodes neutral point clamping IGBT modules in parallel and control to meet the requirement of large current and fast response. The technique of carrier wave phase-shift PWM is applied in IGBT modules to decrease switching loss of IGBT, raise equal switch-frequency of converter and improve performance of output wave. The validity of proposed scheme and control strategy were confirmed by simulation and experiments. It has been under operation since 2006 in the EAST Tokamak.

1. Introduction

EAST(Experimental Advanced Superconducting Tokamak) is a kind of fusion experimental facility. Power supply of vertical stability coil in EAST is a large capacity single phase inverter power supply, which traces displacement signal of plasma, and excites four fast-control coils in vacuum chamber to produce magnetic field that realizes plasma stabilization in large elongate model. The maximal output voltage is ±800V and maximal output current is ±5000A; Current responding time from -5000A to 5000A is less 5ms. To meet the demand of fast dynamic response, IGBT is used as power device in power supply. But large power device can not switch very fast, and the PWM control of low switching frequency results in plentiful low frequency harmonics in output wave. Thus the technique of multi-inverters in parallel and phase-shift PWM is the best solution to this power supply.

2. Structure of Power Supply

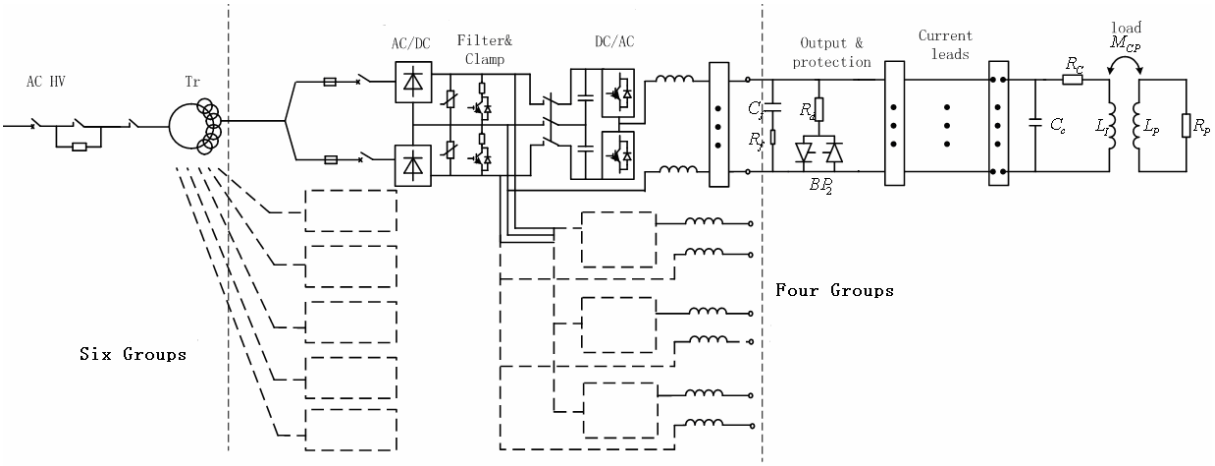


Fig.1.Structure of the power supply of Vertical Stability Coil of EAST

Power supply of vertical stability coil is made of transformer, rectifiers, filter and clamping circuits, inverters, current-shared and protection circuits as shown in Fig.1. The transformer converts input grid high voltage 10kV to 700V. There are 12 groups of secondary winding with ±5°, ±15°, ±25° phase shift to primary winding, the application of phase-shift can effectively improve quality of grid current. Each group of two identical windings supplies DC power for 4 inverters. All 24 inverters are connected in parallel, and divided to two groups in control.
In the case of IGBT module over-current, the drive signal of IGBT modules will be blocked and the corresponding AC switch of transformer will be opened. And in case of load over-current, IGBT modules will be blocked and the thyristor at the terminal of output will be fired, thus the load current will pass this crowbar. In the case of short-circuit, the AC breaker and the fuse in series with the AC/DC converter will work to isolate the AC power. The over-voltage will be depressed by the filter and clamp circuit shown in Fig.1. The IGBT in parallel will be triggered if the voltage is above the limit.
The structure of inverter unit in power supply is three levels half bridge with diodes neutral point clamping as shown in Fig.2. This structure can reduce voltage stress on power device, harmonic and switching frequency. [1] There is a current-shared inductor placed in AC output of each inverter to ensure output current to be shared averagely among inverters.

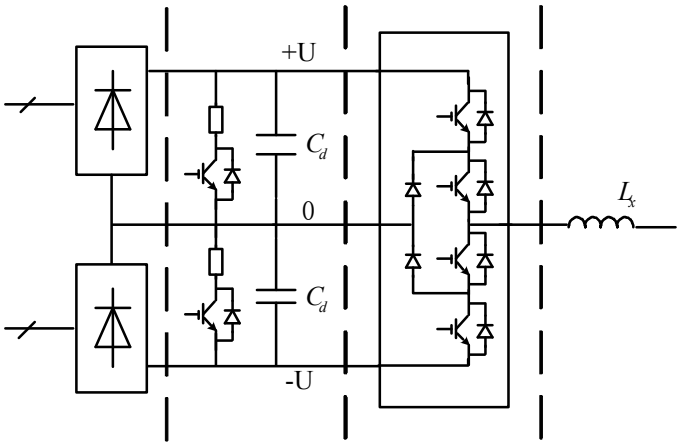


Fig.2. Main circuit of inverter unit

To decrease switching loss, large power device can't switch very fast, so the switch frequency of IGBT is 7.5k Hz in inverters, but the PWM control of low switching frequency results in plentiful low frequency harmonics in output wave. Thus the technique of Phase-shift PWM in multi-inverters paralleled is the best solution. Phase-shift PWM means adopting common modulation wave in a combined PWM system, if there is n inverters paralleled in the system, the stagger phase angle of triangle carrier in each inverter will be $2\pi/n$. [2] The stacking of PWM wave produces Phase-shift PWM, which can raise equivalent switch frequency in the system, reduce low frequency harmonics and improve output wave. The simulation result shows that with 24 inverters connected in parallel with phase-shift PWM, the amplitude of the largest harmonic reduces to only 3.3% and THD is 9.47%.

3. Control and Monitoring

The system principle of Power supply of vertical stability coil in EAST is shown as Fig.3. PCS detects vertical motion of plasma and sends command to power supply. Power supply makes output current to track input signal real time and amplifying it linearly. The range of input signal is -10V to 10V, correspondingly output current is -5000 A to 5000 A.

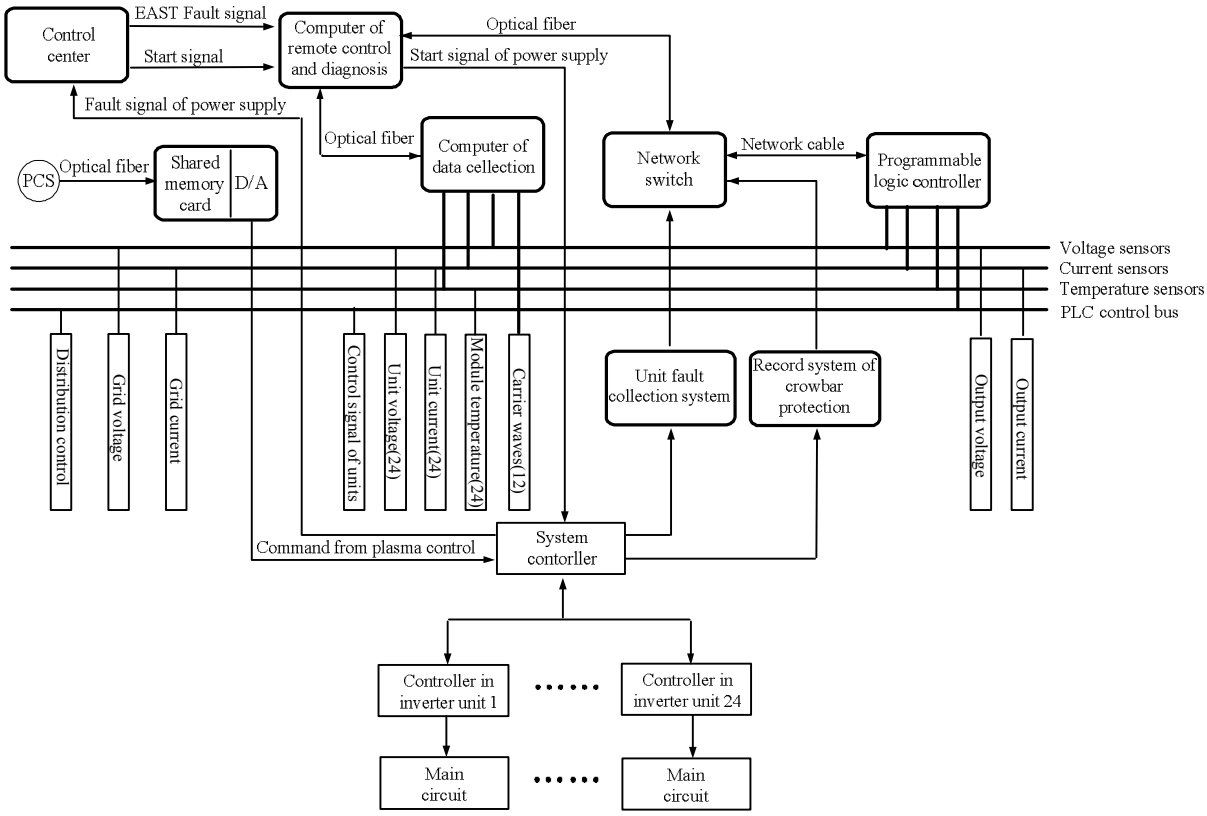
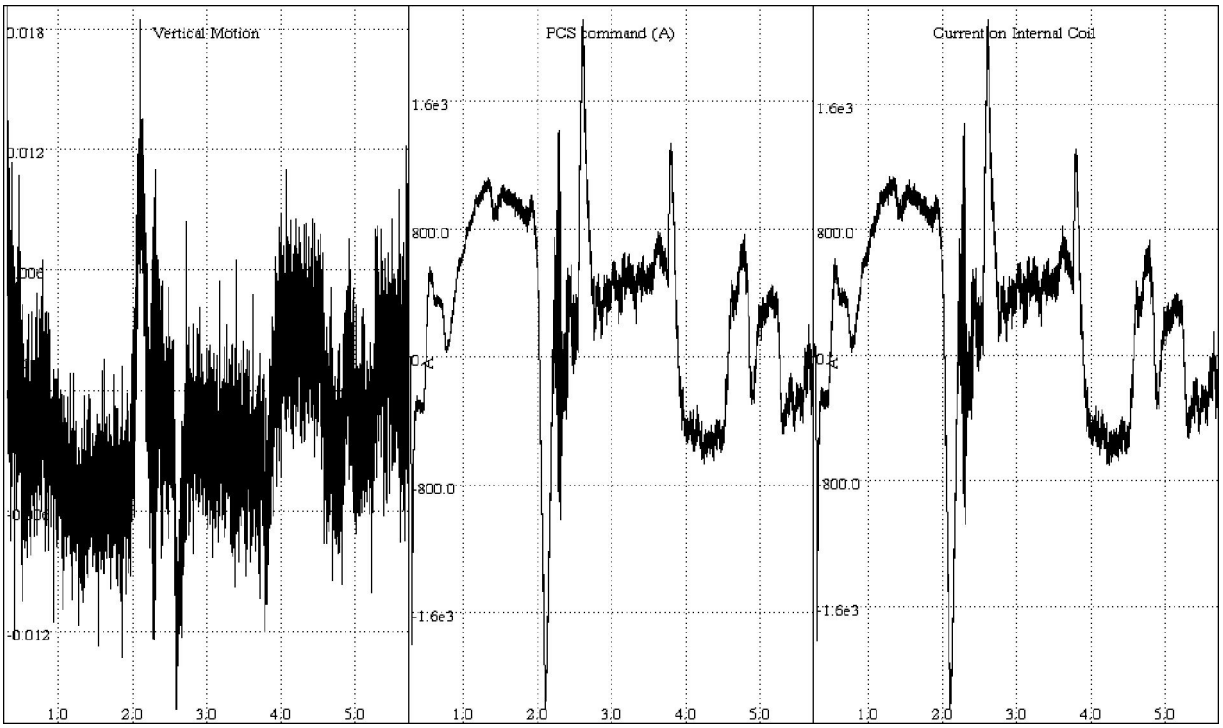


Fig.3. System principle of Power supply of vertical stability coil in EAST

There are two kinds of controller in power supply. One is system controller that controls the coil current according to the demand of plasma control and performs protection. The output of this controller is divided by 24 to controller in each inverter unit based on current feedback.
To get triangle carrier wave, a single chip computer in system controller emits six square waves with 30° phase shift. Then with RC charge-discharge and reverse circuit, twelve triangle waves with 30° phase shift are achieved. In inverter unit, control circuit detects triangle wave, produces two carrier waves by positive-negative offset circuit.
The monitoring system is done with industrial control configuration software to monitor the status of power supply including grid voltage, grid current, load voltage, load current, output voltage of each unit, output current and temperature of each module. In case of fault, this system will record the time, fault type and the wave. Also, this system can do some emergent protection.
All the current and voltage of each module as well as the load current and voltage are acquired and saved for later analysis.

4. Experimental result

The function of Power supply of vertical stability coil in EAST is to track the reference current signal in real time. Fig.4 shows an example in Tokamak operation.



(a) Vertical Motion (b) command from plasma control (C) Current on Internal coil

Fig.4.Experimental Result on EAST Tokamak

Input signal, output voltage wave and output current wave in experiment are shown in Fig.5. Current is detected by Rogowski current sensor, and output voltage is detected by high voltage difference probe. When input signal is sine wave with 100 Hz in frequency and 5V peak value as shown in channel 3, the peak value of output current is 2500A as shown in channel 2 with 1.823°lags input signal and the delay time is about 50 μ s. The corresponding output voltage wave is shown in channel 4.

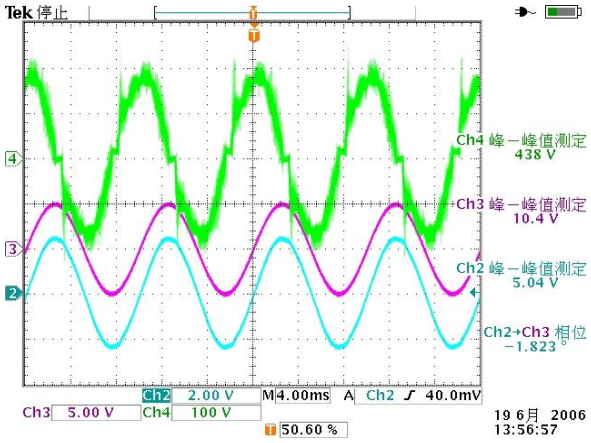


Fig.5. Comparison with input signal and output wave

To detect current-sharing coefficient, current RMS of each inverter unit is detected when input signal is sine wave with 100 Hz in frequency and 5V peak value as shown in table.1. The sum of current is 1830.3A, current-sharing coefficient is:

$$k = \frac{\sum i}{n \bullet i_{\max}} = 0.97$$

Table 1 Current of each inverter unit

Unit	Current(A)	Unit	Current(A)	Unit	Current(A)	Unit	Current(A)
1	76.5	7	76.0	13	76.5	19	79.0
2	76.4	8	75.2	14	78.5	20	78.2
3	77.2	9	76.0	15	73.0	21	76.2
4	76.6	10	76.0	16	75.5	22	77.2
5	73.5	11	76.1	17	74.4	23	74.9
6	78.0	12	75.8	18	75.3	24	77.6

Local computer of data collection detects the status of power supply in real time. Fig.6 is Current wave of 12 inverter unit, which shows that effect of current-sharing is well.

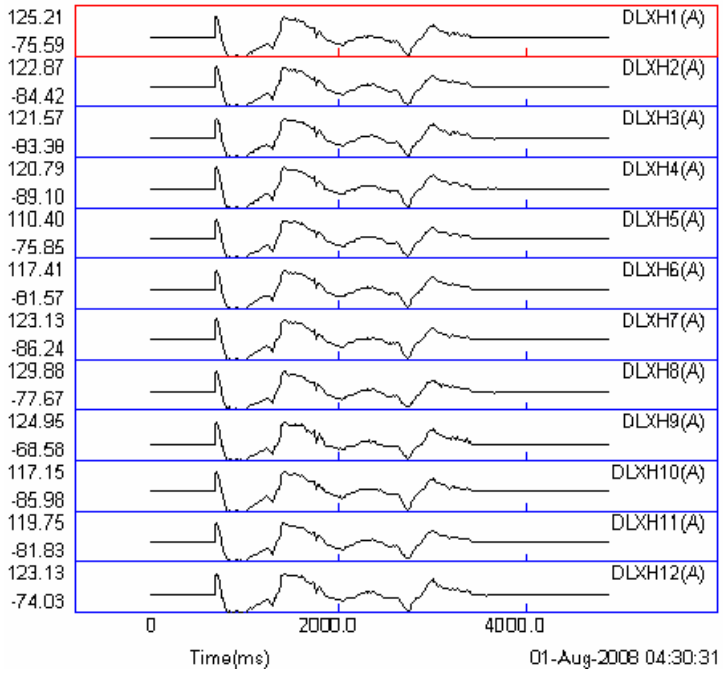


Fig.6.Current wave of 12 inverter unit detected by local data collection computer

5. Conclusions

The method of paralleling inverters and control principle used in power supply of vertical stability coil in EAST are introduced. The main parameters including ability of output current and responding time can meet requirement of EAST vertical stability coil power supply.

6. References

[1] Y.D. Li, et al. “Development of PWM control technology in multi-level converters”, Power Electronics, Vol. 39, No. 5, 2005

[2] X. Zhang, et al. “Design of HT-7U plasma displacement fast control power supply”, Nuclear Fusion and Plasma Physics, Vol. 24, No. 4, 2004