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# Simulation on Toroidal Field Power Supply of HL-2A Tokamak: Application of Dual DQ0 Transformation for Six-Phase Synchronous Generator Model

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The toroidal field power supply of HL-2A Tokamak operated in pulse mode is fed by two sets of motor generators with corresponding diode rectifiers. Each six-phase generator has two star stator windings with a phase difference of 30° between them. In this paper, the model of six-phase generator with rectifier load is built and toroidal field discharge operated in pulse mode is simulated based on dual DQ0 transformation.

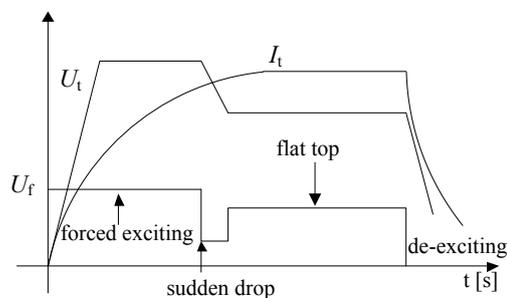
**Key words:** toroidal field, HL-2A, six-phase generator, dual DQ0 transformation

## 1. Introduction

HL-2A tokamak is a magnetic confinement fusion device which is operating at SWIP (Southwestern Institute of Physics), Chengdu, China, has approached its operational rated parameters with  $I_p = 480$  kA and  $B_t = 2.8$  T; based on the parameter  $B_t$ , the current of toroidal field coil ( $I_t$ ) must reach 45 kA at the flat top with voltage 3,510 V during pulse discharge<sup>1)</sup>. There are two types of power supplies for magnetic field of HL-2A tokamak: poloidal field power supplies and toroidal field power supply<sup>2,3)</sup>. The poloidal field power supplies include ohmic heating, radial field, multi-pole field and auxiliary heating power supplies; the toroidal field power supply must generate a stable, low-corrugation longitudinal magnetic field in the center of plasma during discharge. Three sets of flywheel motor generators with their corresponding transformers and rectifiers are equipped for the requirement of toroidal and poloidal field power supplies. The power of poloidal field coils (PFC) is supplied by one set of pulse motor generator; the power of toroidal field coil is supplied by two sets of flywheel motor generators through two groups

of diode rectifiers, the AC input sides of rectifiers are connected with the stator windings independently; DC output sides of rectifiers are connected with toroidal field coil in parallel directly<sup>4)</sup>.

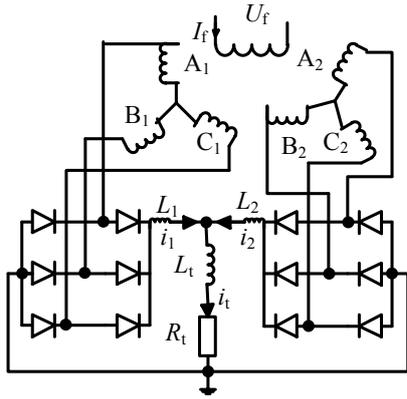
Three sets of motor generators are operated in the same way which is called “pulse mode”: The low power from the grid is accumulated in the flywheels by driving the motors for a long time, and then part of the energy from grid stored in the flywheels is released rapidly with a high power by the main synchronous generators connected to the magnetic field power supply units. The current of toroidal field coil is adjusted by controlling the exciter on the generator directly. According to the require-



**Fig.1** A typical adjustment process of excitation system during discharge.

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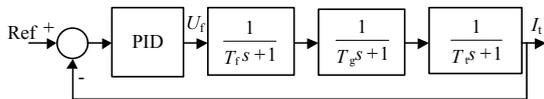
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**Fig.2** Simplified toroidal field power supply.

ment that current of toroidal field coil must reach 45 kA at the flat top and last for about 3 s, the control process of exciter is divided into four stages in time: forced exciting, sudden drop, flat top and de-exciting to generate toroidal field current during a pulse discharge. Figure 1 shows a typical adjustment process of excitation system during discharge, where  $U_t$  is the voltage of toroidal field coil,  $I_t$  is the toroidal field current, and  $U_f$  is the voltage of exciter.

The parameters of two sets of motor generators with their corresponding rectifiers equipped for toroidal field power supply are recognized the same. The unbalance between the outputs of the two groups of rectifiers is solved by the series connection of exciter coils, so the toroidal field power supply can be simplified for simulation as one generator with its corresponding rectifiers because of the same operational mode. Figure 2 shows that the power of toroidal field coil is supplied by only one generator with rectifiers.



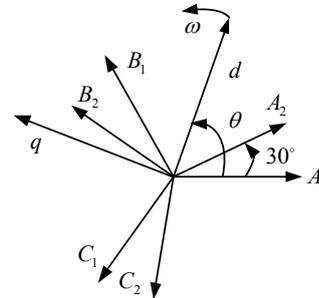
**Fig.3** Control block diagram of toroidal field power supply.

The feedback control diagram of toroidal field power supply is shown in Fig. 3, where  $T_f$  is the time constant of excitation system,  $T_g$  is the time constant of generator,  $T_t$  is the time constant of toroidal field coil. Based on the parameters of the whole system where the excitation inductance is 600 mH, excitation re-

sistance is 161 m $\Omega$ , the inductance of toroidal field coils is 230 mH and the resistance of toroidal field coils is 60 m $\Omega$ , so  $T_f$  is 3.727 s,  $T_t$  is 3.833 s, the toroidal coil current is difficult to be controlled quickly because of the long time constants, a control mode including feedback gain and stability can be analyzed from the control diagram and verified by simulation.

## 2. Mathematical Model of Six-Phase Generator with Rectifier Load

The stator windings of each six-phase non-salient synchronous generator are grouped into two sets of Y-connected windings that are geometrically displaced from each other by 30°. Compared with three-phase generator, higher harmonic of magneto motive force in air gap is weakened; the pulsation coefficient of the DC outputs of rectifiers is smaller than that in three-phase condition also. The inductance coefficients in generator differential equations under ABC coordinate system are time-variant and changing with rotator position angle ( $\theta$ ). Three-phase generator has 3 $\times$ 3 time-variant inductance coefficients in stator, but for six-phase generator,



**Fig.4** Dual DQ0 transformation.

there are 6 $\times$ 6 time-variant inductance coefficients for stator windings, the dimension of differential equations significantly increases. The rotational speed is declining irregular in pulse operational mode; the load of generator is rectifier with RL circuit, the six-phase stator windings are running alternately in the asymmetric mode. Based on the previous reasons, dual DQ0 transformation is introduced to build the upgraded model of generator, the coordinate system is built on the rotator, the eddy effect, harmonic distortion and magnetic saturation are taken for granted, so that the

time-varying coefficients of generator differential equations are transferred into constant. By inverting dual DQ0 transformation, the components under dual DQ0 coordinate system are transformed to components of ABC coordinate system, the work condition of rectifiers can be analyzed, and Fig. 4 shows the geometrical relationship between dual DQ0 and ABC coordinate system.

Similar to DQ0 transformation in three phase condition, dual DQ0 transformation matrix is built from Fig. 4, it is shown as follows:

$$P = \frac{2}{3} \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}$$

The sub matrix  $P_1$  and  $P_2$  describe the situation that the ABC components on the two groups of stator windings are projected on rotor winding, and  $P_1$  and  $P_2$  are shown in the following matrix,  $n$  is sequence number of stator windings.

$$P_n = \begin{bmatrix} \cos(\theta + \frac{(n-1)\pi}{6}) & \cos(\theta + \frac{(n-1)\pi}{6} - \frac{2\pi}{3}) & \cos(\theta + \frac{(n-1)\pi}{6} + \frac{2\pi}{3}) \\ \cos(\theta + \frac{(n-1)\pi}{6}) & \sin(\theta + \frac{(n-1)\pi}{6} - \frac{2\pi}{3}) & \sin(\theta + \frac{(n-1)\pi}{6} + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Based on the dual DQ0 transformation, the model of six-phase generator under DQ0 coordinate system is shown in the following matrix equation:

$$U_{DQ0f} = A \frac{dI_{DQ0f}}{dt} + BI_{DQ0f} \quad (1)$$

Where  $A$  and  $B$  are the constant coefficient matrices and

$$U_{DQ0f} = [u_{D1} \ u_{Q1} \ u_{01} \ u_{D2} \ u_{Q2} \ u_{02} \ u_f]^T$$

$$I_{DQ0f} = [i_{D1} \ i_{Q1} \ i_{01} \ i_{D2} \ i_{Q2} \ i_{02} \ i_f]^T$$

Where the superscript "T" means transpose of matrix.

The load circuit is described by the following equations:

$$L_1 \frac{di_1}{dt} = u_1 - L_1 \frac{d(i_1 + i_2)}{dt} - R_1(i_1 + i_2) \quad (2)$$

$$L_2 \frac{di_2}{dt} = u_2 - L_2 \frac{d(i_1 + i_2)}{dt} - R_2(i_1 + i_2) \quad (3)$$

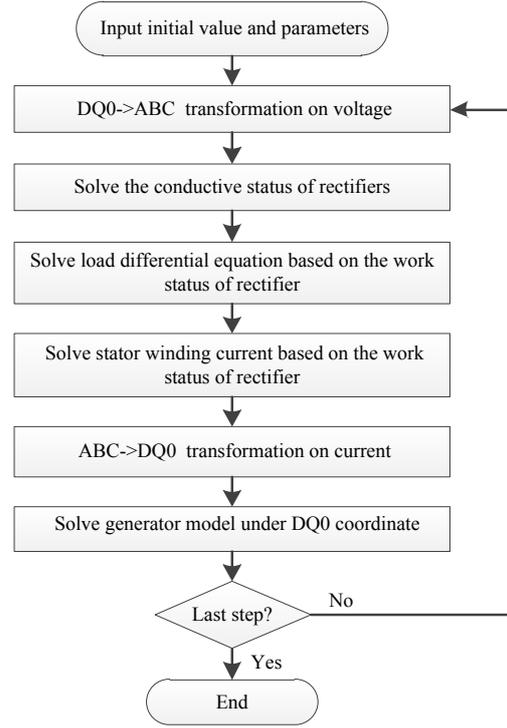


Fig.5 Flow chart of simulation.

The toroidal field current  $I_t$  is considered as sum of the output current of the rectifiers during simulation.

### 3. Simulation on Toroidal Field Power Supply on the Basis of Dual DQ0 Transformation

There are super-transient processes during discharge, such as short-circuit of generator during commutation process; the rectifiers are operated in sundry states, generator terminal voltage waveform is seriously distorted; the rotational speed and frequency of AC output are changing during discharge. In order to design and verify reasonable operational mode of toroidal field power supply of HL-2A devices, simulation is necessary.

The basic parameters (per unit) of six-phase generator under DQ0 coordinate system is shown in the following:  $X_{ad}$  is 1.158,  $X_{dm}$  and  $X_{qm}$  (the mutual inductance between the two stator windings) are 1.2138,  $X_{d1}$ ,  $X_{d2}$ ,  $X_{q1}$  and  $X_{q2}$  are 1.3958, where the basic value of voltage is 5,660 V, the basic value of current is 14,100 A, basic value of rotational speed is 1,320 rpm.  $L_1$  and  $L_2$  are the inductance for keeping balance between the DC outputs of rectifiers, which is 10 mH. In order to get the numerical value of toroidal field current di-

rectly, all the parameters in per unit are transferred to actual value during simulation.

The conductive status of the diodes in the two rectifiers is decided by the six-phase AC voltage of generator; commutation is operated not only among the different diodes in the same rectifier, but also could be operated between the different rectifiers. The phase of AC output voltage is calculated from the rotator position angle, so that the commutation point is determined by the rotator position angle, there are totally 12 commutation points in a period, the load circuit can be solved from the different commutation situations. The two rectifiers are set to be operated in 4-5-4 (4 diodes conduction – 5 diodes conduction – 4 diodes conduction) mode during discharge during simulation, that means that the two rectifiers are operate in 2-3-2 (2 diodes conduction – 3 diodes conduction – 2 diodes conduction) mode and alternately. The simulation step is set to be 0.01 ms, the whole simulation time is 7.5 s and de-exciting operation is not simulated. In order to approach the actual experimental status of toroidal field discharge, the exciting voltage and rotational speed of generator are set to be the same as the actual experimental condition; the initial position angle of rotator is set to be 0. Simulation is carried out from the model of generator under DQ0 coordinate system, work status of rectifiers and load equations; Figure 5 shows the flow chart of simulation, in which dual DQ0 transformation is operated twice in one simulation period.

The simulation result is presented in Fig. 6, where  $\omega$  is the rotational speed,  $I_f$  is exciting current,  $U_{AB1}$  is the line voltage between phase A and phase B and  $i_{A1}$  is the current in phase A winding of the first stator. The simulation result shows that the DC output current  $i_1$  and  $i_2$  are balanced; the adjustment to exciting voltage is effective for the toroidal field current control. The result is under the condition that only one motor generator set for toroidal field power supply, it is about 20 kA at flat top and last for about 2.5 s.

#### 4. Summary and Conclusion

According to the requirements of plasma discharge, the motor generator sets on toroidal field power supply of HL-2A tokamak must be operated in pulse mode. The outputs of the two groups of rectifiers is balanced by the same exciting coil; the model of six-phase generator

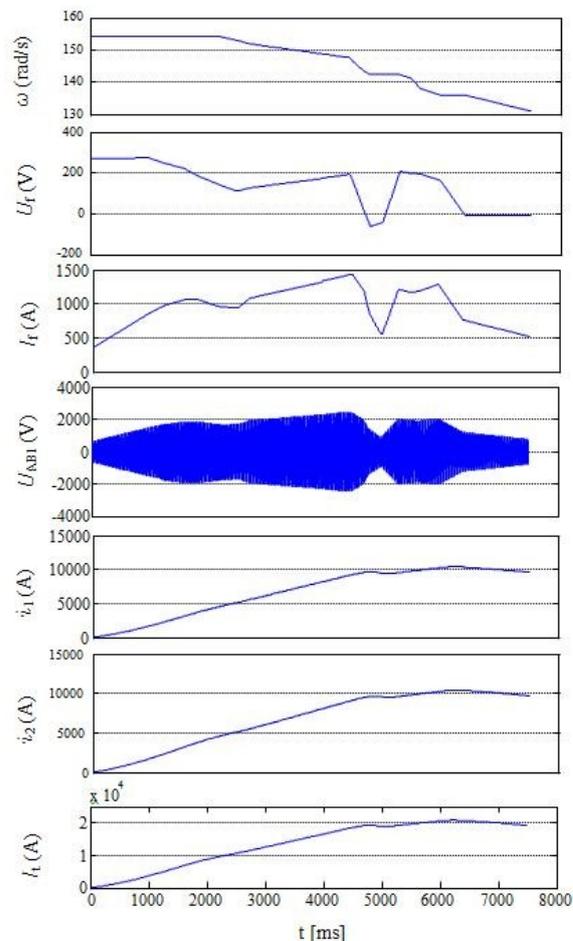


Fig.6 Simulation result of toroidal field discharge.

with rectifiers and RL load circuit is built on dual DQ0 transformation, the procedure of pulse discharge is simulated. The simulation result shows that dual DQ0 transformation is effective for the six-phase generator model; verifying discharge process and designing new operational order; and the model can be applied to the PFC system simulation because of their similar structure. The simulation could be upgraded and applied to real-time simulation for whole discharge in future. The power of toroidal field supplied by two motor generators can also be simulated based on different rotator position angle.

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