Compact Electric Power System for Fusion Reactor

Ge Li, *Member*, *IEEE*

***Abstract*— The issue of the Tokamak fusion reactor is its large area occupied by its power supply, which is about half of the total building area for the International Thermonuclear Experimental Reactor (ITER), together with the compatibility between the site grid and Tokamak loads during the plasma operation period. ITER is now implemented with Tokamak, which requires about 1 GVar reactive power to compensate its power system for superconducting magnets where about 0.2 GVar is transferred from France Electrical Power Network, the other 0.75 GVar is generated by the system of reactive power compensation and harmonic filtering, the standard VSC configuration. ITER can experimentally generate 500-MW fusion thermal power in 400 s long pulse mode. It could only generate about 500 MW/3 = 167 MWe active electric power if it is to be configured with pressured water reactor due to the fact that it is only about 1/3 conversion efficiency from thermal energy to electric energy. For such fusion machine, the requirement for reactive power is much larger than the active power it generates. Based on this requirement, one efficiency and compact pulsed synchronous generator is suggested for this purpose. It can generate not only the fundamental reactive power to compensate and stabilize the power network with low internal impedance but also the active power for outputting power to the network with exciting controller of the generator. Due to its two purposes in one device configuration, it becomes compact and reliable by being implemented in the design of future fusion power plant for demonstration. Some consideration has been done to the special low impedance synchronous generator, which is intended for the concept design of Chinese Fusion Engineering Testing Reactor, targeting the compact electric power system for superconducting Tokamak fusion reactor.**

***Index Terms*— Chinese fusion engineering testing reactor (CFETR), compact electric power system, compensated pulse alternator (compulsator), experimental advanced superconducting Tokamak (EAST), international thermonuclear experimental reactor (ITER), long pulse mode reliability availability maintainability and inspection (RAMI), reactive power compensation (RPC), passive compulsator, variable voltage variable frequency (VVVF).**

I. Introduction

THE MAGNETS of Tokamak have already realized its steady state operation by implementing superconducting windings in its toroidal field and poloidal field (PF) coils in EAST, ASIPP [1]. Chinese Fusion Engineering Testing Reactor (CFETR) is the essential step to validate fusion electric energy between ITER and DEMO power stations by implementing generator in its power train, which intends to put fusion power on the grid and attenuates requirements for its cooling system. The power plant is defined as 2000 s long pulse operation, its duty cycle is from 0.3 to 0.5, which means that about 50%–70% of its time could be used for remote handing maintenance/upgrade due to engineering reliability, availability, maintainability, and inspection (RAMI) requirements. The compensated pulsed alternator (compulsator) is considered to be inserted in the power system to eliminate its huge reactive power requirements occurred in present superconducting Tokamak power supplies [2].

Manuscript received December 14, 2012; accepted May 2, 2013. Date of publication June 7, 2013; date of current version July 3, 2013. This work was supported in part by the State Basic Research Development Program of China 973 Program under Grant 2011GB113005-1 and the National Magnetic Confinement Fusion Science Program of China under Grant 2010GB108003 and Grant 2011GB114003.

The author is with the Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China (e-mail: lige@ipp.ac.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2013.2262718

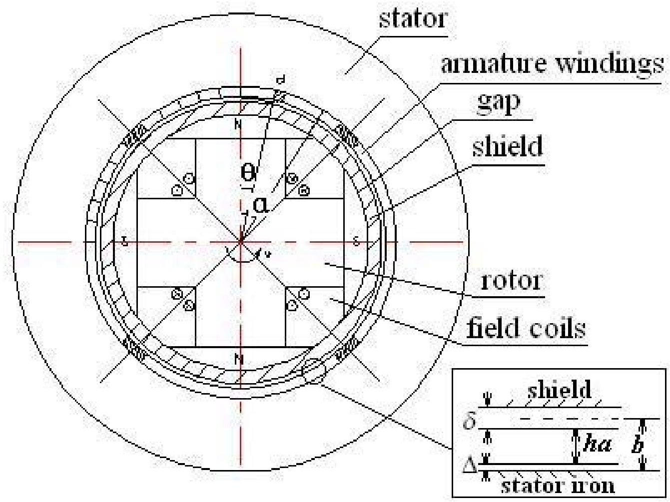


Fig. 1. Cross section of the passive compulsator.

The pulse covering range of the compulsator is from about 10 μs to tens of ms [3]–[7], which is nearly two to three orders now and being expected to be extended to about 2000 s or steady state operation for CFETR. As shown in Fig. 1, passively compensated pulsed alternator is considered for the application. Its basic idea is flux constant principle. It is implemented by mounting a nonmagnetic conductive shield on the rotor, which is inserted between the field winding and armature winding of the ac generator. When the armature winding is discharged, the magnetic flux of armature is compressed in the air gap between the compensated shield and armature windings by the induced eddy current on the shield. It makes the alternator keep extremely low internal inductance while working. Thus, the power density of this kind of pulsed alternator can be significantly enhanced and it has exceptional ac loading stability than conventional synchronous generator due to its extremely low impedance if suitable heat sink means are installed in the alternator for the extended 2000 s long pulse. It is intended to replace the generator in the conventional MG set for powering Tokamak magnets as shown in Fig. 2(a).

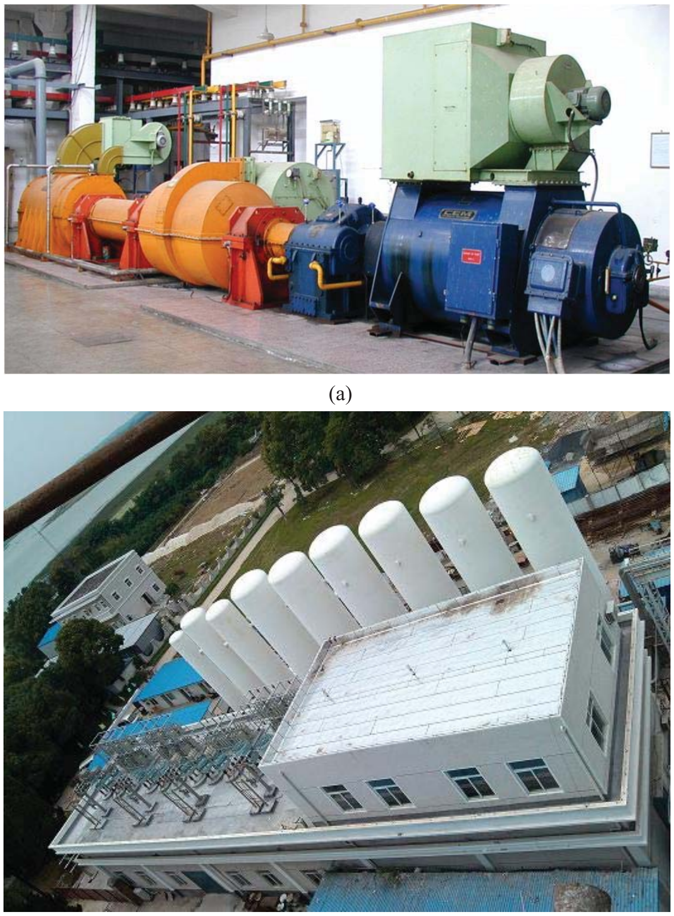


Fig. 2. (a) 100-MW MG set for powering Tokamak magnets (L14.8 m× W2.8 m× H2.7 m, 400 MJ@6000 r/min). (b) 50-MW RPC and harmonic filtering (HF) building for EAST (L60 m× W11 m× H12 m).

Based on previous investigations, this paper gives design formula of a compulsator, some of them are checked by experiments, which are within the range of engineering resolution. The performance of the passive compulsator is tested. Analysis as compact Tokamak power supply is suggested based on these results.

II. Requirement Analysis of Tokamak Power Supply

An earlier study [8] suggests that the large ITER requires only about 50–750 Mvar reactive power from the grid without considering the RPC system, But now the present scaled down ITER requires 950 Mvar for its plasma operation by further studying its reactive power requirement. ITER will be powered by 400-kV EHV Grid sited at Cadarache in southeast France. A dynamic study suggests that it could transfer about 180–200 Mvar to the ITER pulsed load within an acceptable range in terms of 3% voltage drops, and concerning electromechanical constraints on power generation units. Due to that ITER requires 950 Mvar reactive power, 3 × 250 Mvar additional VSC facilities will be installed there before its operation. The RPC&HF of the VSC will provide the following functions [2].

TABLE I
Reactive Power Capacities of Tokamaks

	EAST	ITER	CFETR
Grid voltage	110 kV	400 kV	500 kV
Reactive power required	50 MW	950 MW	750 MW
Grid reactive power	N/A	200 MW	150 MW

1) Limit the net reactive power flow from the grid to around 200 Mvar by supplying a controlled source of leading reactive power, in order to limit voltage variation on the grid to maximum of ±3%.
2) Limit the voltage variation on 66-kV busbars between 62 kV to 72. 5 kV, i.e., (−6% to +10%) during normal plasma operation or load cycle.
3) Limit the voltage variation on 22-kV busbars to ±10% during normal plasma operation or load cycle.
4) Limit the individual harmonic (of 50 Hz) and total harmonic distortion to a level defined in IEC 61000-3-6 1996, in order to reduce voltage/current distortion on the grid and within PPEN.
5) Provide dynamic reactive power compensation during steady and transient state operation, required due to large amplitude and short rise time of the pulse power and for likely power step changes for a large varying reactive load.
6) Following a step change of the load (0%–100%), the RPC&HF susceptance will reach the theoretical reference value with a tolerance of ±10% within 20 ms. After 60 ms, the precision will be better than ±2%.
7) Limit the voltage rise on the busbars in the event of fast switch off of inductive load, e.g., during plasma disruption, magnet quench, etc.

Based on the above requirements, Table I lists the reactive power capacities of these typical superconducting Tokamak devices. Fig. 2(b) shows the EAST 50 MW RPC and harmonic filtering (HF) system accommodated in a building with dimensions of length 60 m × width 11 m × height 12 m, which is much larger than 100-MW MG set illustrated in Fig. 2(a).

III. Design and Test of the Compulsator Model

Based on Ampere's law, Maxwell equations, and the theory of the virtual displacement, an analyzed method for designing the compulsator is developed and checked by model tests.

A. Air Gap Armature Inductance

By Ampere's law, the conductor internal inductance, the air gap leakage inductance, and the end leakage inductance of the air gap armature windings can be derived. Integrating all inductance above, the total inductance of the compulsator air gap armature windings with p coils parallel connected can be derived as [7]

$$L = \frac{\mu_0 N(l + l_E)}{4\pi \cdot p} + \frac{\mu_0 N^2 \cdot l}{p} \cdot \left(1 + \frac{l_E}{l}\right) \times \left[\frac{1}{2} - \frac{b}{\alpha r} + \left(\frac{b}{\alpha r}\right)^2 \ln\left|1 + \frac{\alpha r}{b}\right| + \ln\left|\frac{b + \pi r/p}{b + \alpha r}\right|\right] \quad (1)$$

where N is the turns of the armature winding; l and l_E are, respectively, the effective length of the air gap winding and the end length of the generator, b is the thickness of the armature winding in radial direction, r is the inner radius of the generator stator, and 2α is the filled radian of one armature winding on one pole as illustrated in Fig. 1.

B. Mechanic Calculation of Air Gap Coils

Assuming that the flowing current of one air gap armature winding is I, the total stored energy of p coils is given by

$$W_m = \frac{1}{2}(pL) \cdot I^2.$$

According to the principle of the virtual displacement, the tangential shearing force can be derived as

$$F = \frac{\partial W_m}{\partial(r\alpha)} = \frac{I^2}{2r} \cdot \frac{\partial}{\partial \alpha}\left\{(\mu_0 N^2 \cdot l)\left(1 + \frac{l_E}{l}\right)\left[\frac{1}{2} - \frac{b}{\alpha r} + \left(\frac{b}{\alpha r}\right)^2 \ln\left|1 + \frac{\alpha r}{b}\right| + \ln\left|\frac{b + \pi r/p}{b + \alpha r}\right|\right] \Rightarrow F = \frac{I^2}{2}\mu_0 N^2 l\left(1 + \frac{l_E}{l}\right)\left[\frac{2b - \alpha r}{(\alpha r)^2} - \frac{b^2}{2(\alpha r)^3}\ln\left|1 + \frac{\alpha r}{b}\right|\right]\right\}. \tag{2}$$

While the armature coils are discharged, the average shear strength of the electromagnetic force on its bonding area in the inner surface of stator is derived as

$$P_t = \frac{F}{S} = \frac{I^2}{2S}\mu_0 N^2 l\left(1 + \frac{l_E}{l}\right)\left[\frac{2b - \alpha r}{(\alpha r)^2} - \frac{b^2}{2(\alpha r)^3}\ln\left|1 + \frac{\alpha r}{b}\right|\right] \tag{3}$$

where S is the total bonding area of the armature windings in the stator surface.

C. Temperature Rise of the Shield Under Pulse Load

Assuming that the energy of the eddy current loss caused by eight current pulses are all used to heat the aluminium cylinder with constant rotor speed, the adiabatic temperature rise of the aluminium cylinder is then derived as [8]

$$\Delta t = \frac{8PT}{\mathrm{cm}} = \frac{8Tl}{\mathrm{cm}}\sqrt{\frac{\omega\mu}{2\sigma}}\frac{(pNI)^2}{\pi D f} \tag{4}$$

where $T = 1.9$ ms is the period of the short electric pulse; $c = 0.211 \times 4.2 \times 1000 = 886$ J (kg c) is the specific heat of the aluminum shield; and $m = 19.54$ kg is the shield mass.

Inserting the most rough operation parameters of the 25-MW compulsator into (4), i.e., $I = 52$ kA, $\omega = 900$ (4298 r/min), $l = 0.59$ m, $f = 0.72$, $p = 4$, $N = 5$, $D = 0.302$ m, $\sigma = 3.82 \times 10^7/(\Omega \cdot \mathrm{m})$ the adiabatic temperature rise is calculated as: $\Delta T = 11.3$ °C.

For 2000 s long pulse case, the designed current density in the shield must be decreased to the suitable level.

TABLE II(A)
TYPICAL PARAMETERS OF THE COMPULSATOR STATOR

Poles	4
Air gaps (mm)	0.5
Stator effective length	570
Stator outer diameter (mm)	462
Stator inner diameter (mm)	315
Open circuit voltage (V) at 4298 r/min	250
Short circuit current kA at 4298 r/min	68.365
Skin depth of armature windings (mm@200 Hz)	4.5
Total armature resistance (mΩ)	0.39
Total armature inductance (μH)	4.04
Maximum flux density of stator yoke (T)	1.01
Armature tangential stress (kg/mm^2)	0.153
Turns of each armature coil	5
Lead wire of each armature coil	16
Lead wire dimensions (mm^2)	1 × 5

TABLE II(B)
PARAMETERS OF THE COMPULSATOR ROTOR

Maximum induction field in rotor yoke (T)	2.5
Rated power (MW)	17.1
Weight (kg)	270
Rotor effective length	500
Rotor outer diameter (mm)	298
Shield thickness (mm)	14
Poles	4
Inertia moment: (kg·m^2)	2.0
Stored energy: (MJ) at 4298 r/min	0.2
Unilateral magnetic pulling force (1 mm off center) (kg)	56
Exciter resistance (mΩ)	140
Exciter inductance (mH)	11.2
Time constant of the exciting coil (ms)	80
Exciting current: (A)	600
Turns of each exciter coil on one pole	16
Rotor designed exciter A–T	86 400
Exciting power: (kW)	40
Maximum temperature rise of the aluminum shield (°C) with 8 pulses	11.3

D. Electromagnetic Design Sheet of the Compulsator

Pulsed excitation is used to replace the dc excitation system for optimizing the performance of the compulsator while it is fired. Its magnetic circuit is computed in [9]. According to above (1)–(4), the main parameters of the stator and the rotor of the passive compulsator are calculated and, respectively, listed in Tables II(A) and II(B).

The armature current density at 2000 s long pulse mode is decreased to about 6 A/mm^2, which is nearly the same as conventional middle sized electric machines. So, it can work in steady state.

The shield current density at 2000 s long pulse mode should be decreased to about 4 A/mm^2, which is not too large to find suitable heat sink in conventional electric machine technology for steady state operation.

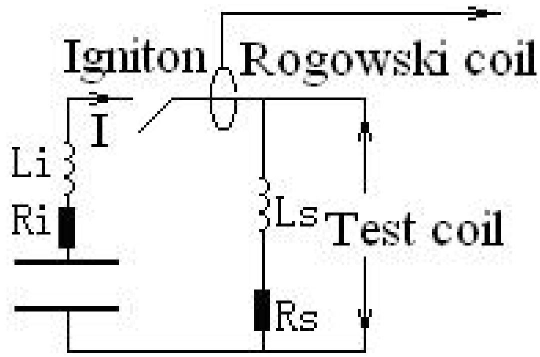


Fig. 3. Discharged circuit of capacitor banks to test model.

E. Tests to the Passive Compulsator

1) Bond Strength Test for Air Gap Armature: In order to check the bond strength of the fabrication process and simulate the shear stress of armature windings attached in the stator inner surface, one turn coil is bonded to an iron plate, with the same surface treating process as that of the stator assembly. The shear stress distribution of the test model is almost the same as that of the real situation. Then, the test model is discharged by capacitor banks with high current generation circuit as shown in Fig. 3. By increasing the charging voltage of the capacitor banks step by step, the discharged current, which is measured by Rogowski coil, is enhanced step by step until the bonding layer of the test model is broken down by electromagnetic force. The former step current is used for safe evaluations of the air gap armature windings of the compulsator. When the discharge current reaches 105 kA, the epoxy based adhesive is not destroyed and the test model is still safe. At this time, the computed electromagnetic shear force on the coil is 1.98 Ton and the shear stress on bond surface is 0.83 kg/mm^2 [8]. This value is far beyond requirement, for the maximum average operation value of the compulsator is 0.15 kg/mm^2 [8]. Although large area bonding of the air gap armature windings could decrease the shear strength a little, its RAMI margin of safe operation is still high.

F. Dynamic Balance Tests to the Rotor

The static and dynamic balance test was completed on the dynamic balance machine after assembling the rotor. The final dynamic balance results reach Chinese standard rank as 2.5. Its first critical speed is 20 000 r/min, which is far beyond the designed maximum speed at 6000 r/min. The rotor maximum stress is 110 MPa (excluding discharge stress). The peak oscillation magnitudes of the alternator bearing are less than 5 and 1 μm, respectively, in axial and radial directions. The test results show that the compulsator has a high stiffness shaft as well as high precision processing and assembly.

G. Measurements to the Winding Parameters

The stator air gap armature winding and rotor exciting winding are measured by accuracy electric bridge. Their inductance and resistance parameters are listed in Table III.

TABLE III
MEASURED PARAMETERS OF THE COMPULSATOR

Designed exciter resistance (mΩ)	140
Measured exciter resistance (mΩ)	116
Designed exciter inductance (mH)	11.2
Measured exciter inductance (mH)	10.2
Designed armature resistance (mΩ)	0.39
Measured armature resistance (mΩ)	<1
Designed armature inductance (μH)	4.04
Measured armature inductance after inserting the aluminum shielded rotor (μH)	4.05
Measured armature inductance without the aluminum shielded rotor (μH)	6.33

TABLE IV
MEASURED OPEN CIRCUIT VOLTAGE OF THE COMPULSATOR

n/(r/min)	V_f (V)	I_f/(A)	*U* (V)
1842	10	75	24.5
1842	20	150	45.5
1842	30	230	60
1842	40	310	73.5
1842	50	385	87.5
1842	60	460	98
3070	70	520	175
3070	80	600	178.5
3070	90	700	182
4280	90	700	253

TABLE V
MEASURED VALUE VERSUS THE DESIGN VALUE

	n/(r/min)	I_f (A)	*U* (V)
Designed Value	3070	600	178.5
Measured Value	3070	600	179.1

H. Open Circuit and Load Test

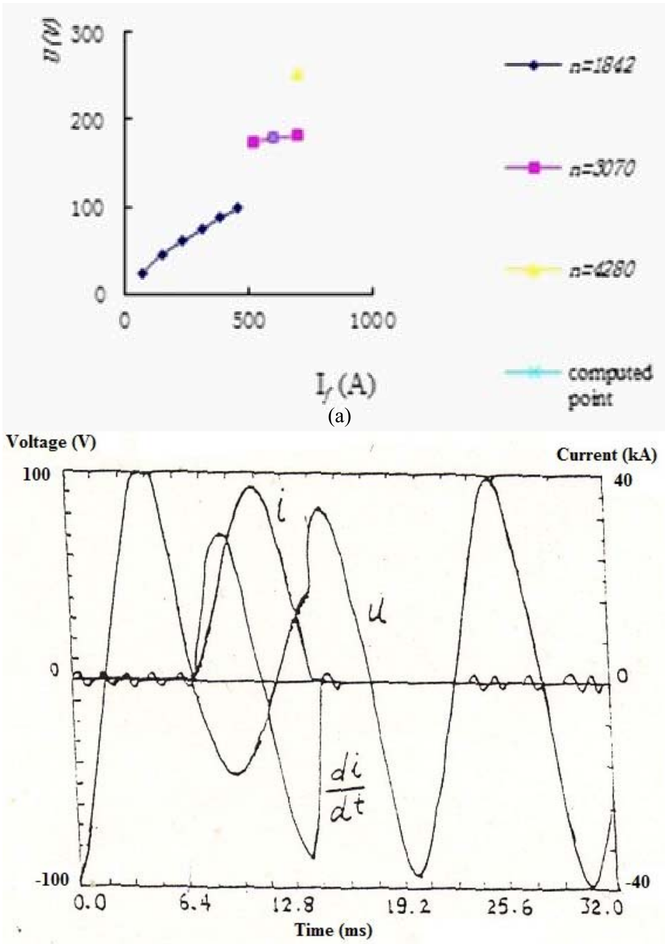
The compulsator's speed n is increased step by step after measuring all its winding parameters. Its output voltage is measured with different excitation voltage V_f and current I_f. The results are listed in Table IV. Fig. 4 shows its excitation curve [9].

According to the test shown in Fig. 4, the open circuit voltage increases linearly with the excitation current along curve $n = 1842$ r/min. When the rotational speed arrives at $n = 3070$ r/min, the designed point of open circuit voltage is just on the measured curve. Table V lists the calculated value versus the measured value at the speed $n = 3070$ r/min, which shows that the magnetic circuit design agrees well with the test. The working point shown in Fig. 4(a) is at the point $n = 3070$ r/min, $I_f = 600$ A.

I. Short Circuit and Loaded Tests

According to the measured parameters at the working point, the maximum short-circuit current is derived as

$$I = U/\sqrt{R_i^2 + (\omega L_i)^2} = 68 \text{ kA}$$



(b)

Fig. 4. (a) Open circuit voltage of the compulsator versus its exciting current. (b) Output voltage and current of the compulsator at $V_f = 30$ V.

where the open circuit voltage $U = 179.1$ V is measured at the rotation speed of $n = 3070$ r/min.

The values of internal resistance $R_i = 0.39$ mΩ and the internal inductance $L_i = 4.05$ μH are from Table III.

At 30-V exciting voltage of the compulsator, the measured output voltage and current of its armature are shown in Fig. 4(b). The shorting current is over 35 kA. Such shorting current can overcome the friction force of a little piston in a small EML for demonstration purpose, which was proved by the following EML and ETL tests [9]–[11]. In the ETL experiments driven by the compulsator, its peak current reached 80 kA by enhancing its rotating speed to improve its output voltage to about 400 V with initially triggering and discharging energy in high voltage capacitor to an ETL capillary [11]. The test verified that compulsator has exceptional ability to withstand the pulsed shocks due to the loads of Tokamak magnets for the functions listed from 2.1 to 2.7.

With suitable heat sink means to its armatures and shield, it could output 344 kW for 2000 s which trebles the output power of the generator with the same 90 kW frame by the installed shield at normal speed of 3070 r/min. It could be scaled up to over 100 MW for powering Tokamak magnets by cooling its rotor shield and stator armature suitably.

IV. Analysis to Motor Compulsator Set for Fusion Reactor

Fig. 4(a) shows the open circuit voltage of the compulsator versus its exciting current, which is similar to the conventional MG system for powering Tokamak magnets [12], [13]. The unique difference of the compensator to the conventional synchronous machine is that a conductive compensating shield is established that fully encases the rotor body of the conventional synchronous machine, the force on that body can be shown to be the integral of force density in the shield, or traction over that shield surface. The shield not only has the function of "damper" windings in synchronous machine, but also let the compensator working at much low subtransient inductance [12]–[14], which has much low voltage drop than that of conventional synchronous machine working at synchronous inductance at the same load current. From (2), the loaded electromagnetic torque can be computed as

$$T_{em} = F \cdot r = \frac{I^2}{2}\mu_0 N^2 l r \left(1 + \frac{l_E}{l}\right) \times \left[\frac{2b - \alpha r}{(\alpha r)^2} - \frac{b^2}{2(\alpha r)^3} \ln\left|1 + \frac{\alpha r}{b}\right|\right]. \quad (5)$$

The loaded electromagnetic power is then derived as

$$P_{em} = \Omega \cdot T_{em} \propto I^2 \quad (6)$$

where Ω is the synchronous shaft speed of MG set. Due to that compulsator could offer much large current than that of conventional synchronous generator at the same frame, it could output much large active and reactive power than the later, which could scale down the power supply system for Tokamak reactor.

For the value subtransient reactance of conventional large synchronous generator, the usual range is 0.1–0.4 per unit. The time constant in subtransient region is relatively short (0.01 to 0.05 s) due to that the resistance of damper windings is generally much greater than that of its exciting winding [12]. The subtransient component is significant in determining maximum short-circuit currents and in determining the current to be interrupted by fast-acting circuit breakers.

The compulsator changes above subtransient fault state of synchronous machine into working state by replacing damper windings with the fully encased shield on the rotor. The power and voltage stability could be enhanced significantly while discharged to the magnet load due to its extremely low internal impedance of compulsator. The equivalent circuit of the loaded compulsator is shown in Fig. 5, where Z is the impedance of the load.

The active power of the passive compulsator could be then derived as

$$P = \frac{mUE_0}{x_a''} \sin\delta \quad (7a)$$

where m is the polyphase number of the synchronous machine, U is its terminal voltage of this generator, E_0 is the internal voltage of the armature, the subtransient reactance x_a'' of the synchronous machine becomes the normal internal reactance of the compulsator, and the power angle δ represents rotor phase angle with respect to the synchronous reference in

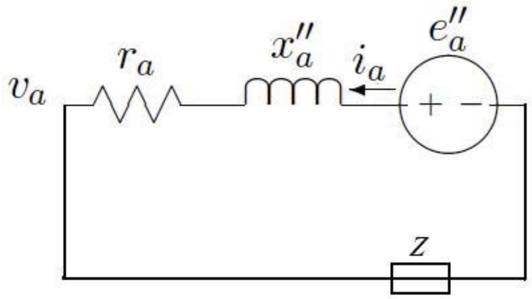


Fig. 5. Equivalent circuit of the loaded compulsator.

Park's Equations [14]. By changing it with tuning exciting system of the machine, it can be operated in the mode of motor, synchronous condenser, and generator, respectively, at the electrical degree of $-35°$ to $0°$, $0°$ and $0°$ to $35°$ for stable operation. The reactive power of the passive compulsator could be derived as

$$Q = \frac{mUE_0}{x_a''}\cos\delta. \tag{7b}$$

Due to that the subtransient reactance x_a'' of the compulsator with the shield is much low than that of the synchronous machine in the same frame, its power density can be significantly enhanced.

V. Conclusion

1) Except that the fusion power plant and steady state electric network were required to interchange energy with the grid continually, the other Tokamak power supply is essentially the pulsed power. All power supplies for Tokamak magnets are naturally the pulsed power owing to that they only have functions of charging and discharging current to the superconductor magnets, together with quench protection [13].
2) The conventional MG set for powering Tokamak magnets eliminated its effects to the grid, which saves the installed grid capacity. As in KSTAR case, one 200-MW MG set driven by a 12-MW VVVF was economically implemented in its grid to power its PF magnets with the required reactive power [13].
3) One new compact electric power system for Tokamak was mapped out by implementing passive compulsator in MG set to power its magnets, which has extremely low internal impedance and economically avoids the massive reactive power compensation system. The compulsator option insulated the connection between the power supply of Tokamak magnets with the site grid by its air gap where its excitation system could be tuned up to support its output voltage in the stator armature while required. The massive RPC and HF system for Tokamak power supply could then be attenuated economically. For CFETR or ITER [15] cases, one 600-MW motor–compulsator set could not only omits the huge RPC system by tuning the exciting system of the compulsator, but also avoid the pulse shocks to the electric grid, which is not benign to the grid as in [2], [15] due to the repetition spikes during the plasma pulse period.

References

[1] P. Weng, Q. Wang, P. Yuan, Q. Zhou, and Z. Zhu, "Recent development of magnet technology in China: Large devices for fusion and other applications," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 731–738, Jun. 2006.
[2] A. D. Mankani, I. Benfatto, J. Tao, J. K. Goff. J. Hourtoule, J. Gascon, D. Cardoso-Rodrigues, and B. Gadeau, "The ITER reactive power compensation and harmonic filtering (RPC & HF) system: Stability & performance," in *Proc. IEEE/NPSS 24th Symp. Fusion Eng.*, Jun. 2011, pp. 1–6.
[3] I. R. McNab, "Pulsed power for electric guns," *IEEE Trans. Mag.*, vol. 33, no. 1, pp. 453–460, Jan. 1997.
[4] M. L. Spann, S. B. Pratap, M. D. Werst, W. A. Walls, and C. W. Fulcher, "Compulsator research at The University of Texas at Austin—An overview," *IEEE Trans. Mag.*, vol. 25, no. 1, pp. 529–537, Jan. 1989.
[5] S. K. Murthy and W. L. Weldon, "A single element multiphase compulsator powered railgun system," *IEEE Trans. Mag.*, vol. 30, no. 1, pp. 145–154, Jan. 1994.
[6] H. P. Liu and J. J. Hahne, "High-speed compulsator stator thermal management," *IEEE Trans. Mag.*, vol. 39, no. 1, pp. 357–361, Jan. 2003.
[7] L. Ge, "The inductance computation for the passive compulsator," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 4, pp. 1033–1036, Aug. 2007.
[8] A. Maschio, E. Bertolini, J. M. Bottereau, D. Crisford, G. D'Andrea, A. DeLorenzi, S. Geeves, H. Lefebvre, G. Murphy, and P. Scarpellini, "Assessment of the suitability of the European 400 kV grid to supply the ITER load," in *Proc. IEEE/NPSS 16th Symp. Fusion Eng.*, Oct. 1995, pp. 178–181.
[9] G. Li, "Investigation on compusator," Ph.D. dissertation, Dept. Inst. Plasma Phys., Univ. The Chin. Sci. Acad., Hefei, Anhui, China, Dec. 1990.
[10] G. Li, "Theory and experimental investigation of compusators," Ph.D. dissertation, Dept. Inst. Plasma Phys., Univ. The Chin. Sci. Acad., Hefei, Anhui, China, Dec. 1993.
[11] Y. Pan, K.-F. Liu, and B.-H. Liu, "System simulations and experiments for ETL powered by compulsators," *IEEE Trans. Mag.*, vol. 39, no. 1, pp. 427–431, Jan. 2003.
[12] G. R. Slemon, *Magnetoelectric Devices*. New York, NY, USA: Wesley, 1966.
[13] C. H. Kim, J. D. Kong, D. Y. Eom, N. Y. Joung, W. J. Lee, Y. S. Kim, M. Kwon, F. J. Parker, D. Hopkinson, and G. D. L. Flem, "Conceptual design of the KSTAR motor generator," in *Proc. IEEE/NPSS 24th Symp. Fusion Eng.*, Jun. 2011, pp. 1–5.
[14] J. L. Kirtley, *Electric Machinery*. Cambridge, MA, USA: MIT Press, Feb. 2004.
[15] J. Tao, I. Benfatto, J. K. Goff, A. Mankani, F. Milani, I. Song, H. Tan, and J. Thomsen, "ITER coil power supply and distribution system," in *Proc. IEEE/NPSS 24th Symp. Fusion Eng.*, Jun. 2011, pp. 1–8.

Ge Li (M'08) was born in Shandong, China, in 1966. He received the B.Eng. degree in electrical engineering from the Hefei University of Technology, Hefei, China, in 1987, and the Ph.D. degree in electric machines from the Institute of Plasma Physics, The Chinese Academy of Sciences (ASIPP), Beijing, China, in 1994.

He was a Post-Doctoral Fellow with the National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China (USTC), Hefei, and an Associate Professor in 1996. He became a Full Professor with the Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China. He held this post for a period of four years until he was finally tempted back into more basic academic life for green energy investigation. He is currently a Professor with ASIPP and he is currently working on power supplies and their control as well as electric machines, together with remote handing. He has worked with Prof. D. He with NSRL and USTC on accelerators and free electron lasers, with Prof. Menzies with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada, on electric machines, and with Prof. P. Acarnley with the Department of Electrical and Electronic Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne, U.K., on induction energy transfer.