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REVIEW ARTICLE

Progress in CFETR Power Stations Concept Study

Hua Li · Ge Li · Lu Qu · Peng Fu

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Abstract While EAST experiment was running in 2012, the project of the China fusion engineering test reactor (CFETR) concept design was started. This ITER-like tokamak system will be the second full superconducting tokamak in China based on EAST technology. In phase I, it has 50–200 MW heat output for demonstrating power generation. The fusion power stations contain complete structure of fusion power plant (FPP) which do not appear in the ITER and huge HV substation which receives power from the 500 kV transmission grid for powering its pulsed power electric network (PPEN) and steady-state electric power network. Furthermore, its structure of turbine generator of FPP is similar to that of a nuclear power station of the pressurized-water reactor. This paper describes the typical CFETR loads and put forward the requirements of short circuit capacity of HV grid. It analyzes different strategies of putting the generator power to the grid, i.e. on the 500 kV grid for future DEMO power structure or 66 kV medium-voltage local grid for self-use. In period between twice burning plasma, conceptual solutions are presented to maintain thermal circuit operation.

Keywords 500 kV · CFETR · EAST · Fusion power plant · ITER · Generator · Power grid structure

Introduction

Based on ITER and EAST technologies, the CFETR will be an advanced, steady-state, full superconducting tokamak fusion devise. It is intended to realize tritium self-sufficiency and utilize fusion power to product electrical energy [1]. About 80 % of the fusion power will be deposited in the blanket. Then these heat energy will be extracted through primary cooling circuit, and will heat water in a secondary circuit that will provide the steam to drive turbines.

As shown in Fig. 1, CFETR fusion power stations need to implement the following four functions:

(a) Convert the fusion thermal energy into electrical energy as much as possible;
(b) The electricity should link to distribution network;
(c) Ensure that the power factor of HV grid meet IEC/GB standards;
(d) Meet the power supply demand of tokamak device and accessory components.

According to the operation mode of tokamak device and accessory components, the distribution grid of fusion power stations can be divided into steady-state electric power network (SSEN) and pulsed power electric network (PPEN). Although the dimensions of CFETR is slightly smaller than ITER, its power demand is similar to ITER due to its steady-state operation and the electrical demand of tritium plant for self-sufficiency.

The design of SSEN is composed of switches, busbars, and step-down transformers, with reference to conventional substation design principles, while carefully considering the special requirements of tokamak experiment. In a large part, we refer the existing SSEN design of ITER [2–5].

The Coil Power Supply System (CPSS) and Heating and Current Drive (H & CD) system are similar to ITER as well [5–11]. Thyristor based technology will possibly be used for power converters consisted in CPSS. Thus 750 MVA reactive compensation equipment may be also needed for

H. Li (✉) · G. Li · L. Qu · P. Fu
Institute of Plasma Physics, Chinese Academy of Science, (ASIPP), P.O. Box 1126, Hefei 230031, Anhui Province, China
e-mail: lihua@ipp.ac.cn

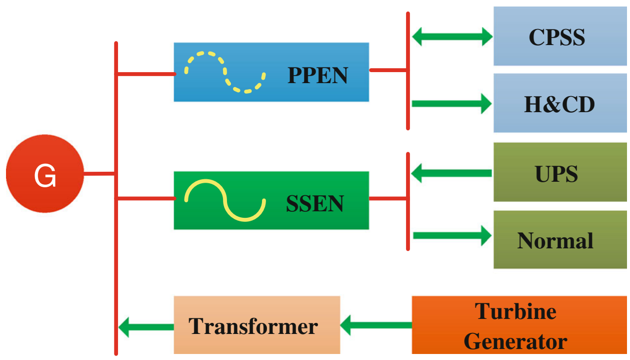

Fig. 1 Concept design of fusion power stations

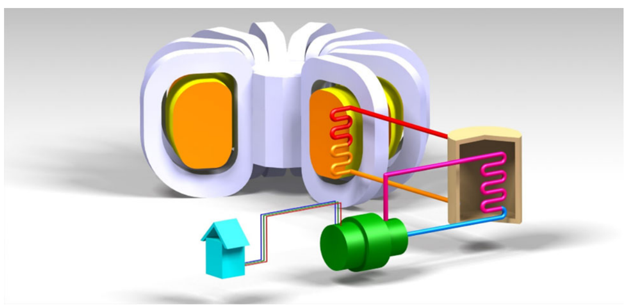

Fig. 2 Concept design of fusion power plant

voltage stabilization and compensation together with filters to eliminate harmonics generated by the power converters.

Tokamak magnet power supply is the largest load in PPEN, for it can be hundreds of megawatts. Thyristor-based AC/DC converters are first selected for coil power supply due to its high current nature. For example, Poloidal Field (PF) coil converter unit has four six-pulse bridges with four-quadrant and 12-pulse operation in TPX, EAST and ITER [5–11]. The solution based on thyristor technology can cause huge reactive power consuming and harmonic impact at AC supply grid, and affect not only the stability of 500 kV HV grid, but other tokamak subsystems. In order to ensure the reliable operation of the coil power supply and other loads, the reactive power compensator and harmonic filtering system (RPC&HF) must be installed, which can provides the dynamic reactive power compensation to minimize the voltage variation and eliminate the harmonic distortion. If we use full-controlled power semiconductor device (IGBT/IEGT/IGCT) with PWM operation, the large RPC&HF system can be omitted. But the technology maturity of this solution is worth discussion.

Eventually turbine generator produces electricity by using fusion thermal energy. The concept design of fusion power station is shown in Fig. 2. The choice of turbine generator depends on the cooling way of blankets. It is not decided which kind of blankets will be built for CFETR. However, the power plant will demonstrate the feasibility of electricity generation by fusion energy.

Steady-State Electric Power Network

The SSEN (Fig. 3) power to all CFETR plant electric loads except the CPSS and the H&CD. It receives AC power from the 500 kV HV grid, transforms it to appropriate voltage levels and distributes it to the CFETR components requiring steady state electric power. In the event of a loss of power accident, the SSEN use the emergency power sources (diesel generators, uninterruptible power supply systems and DC batteries) to supply the investment protection and safety relevant components as ITER-like structure [2, 4].

Most loads of SSEN always are online operation. On account of the demand of tritium self-sufficiency, the electrical capacity of CFETR tritium plant is a little more than ITER where we preserve total 60 MW for tritium plant. There may be a large discrepancy between estimated electric capacity and actual value of tritium plant, furthermore, there is no successfully project for reference due to that ITER has no tritium self-sufficiency requirement.

Cooling water system includes all cooling water equipment of Tokamak components. By numerical modeling analysis, the power demand of cooling water system is determined to 50 WM electricity power when using full superconducting coil.

Cryoplant is used to maintain the environment temperature of Liquid helium and liquid nitrogen. It contains 4.5 K helium cryogenic system and 80 K nitrogen cryogenic system. The cryoplant provides cooling for the superconducting magnet system, the thermal shields, the torus, and so on. By far the main load is the superconducting magnet system.

We combine the electrical demand of remote handling equipment, diagnostic, vacuum pumping, hot cell, waste processing, building and HVAC, and so on.

The active power consumption of SSEN loads can maximum up to 175 MW. In according with the power factor of 0.95, 120 % design margin, and 95 % efficiency, the power capacity of SSEN is equal to 232 MVA.

The loads and power capacity of SSEN are calculated. So 4 × 60 MW ITER SSEN capacity may be enough to accommodate all CFETR requirements. In order to meet the requirements of power factor, local reactive power compensation are needed with capacitors or more advanced technology. For Class I load and Class II load, DC batteries and diesel generators are used as uninterruptible power supply.

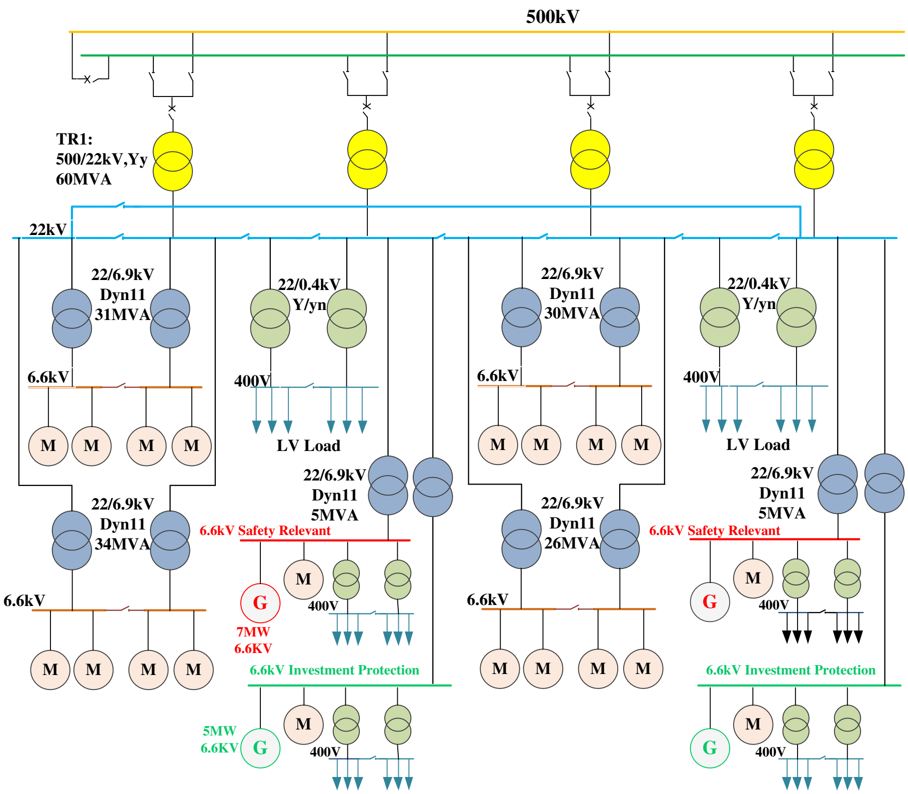

Fig. 3 SSEN configuration

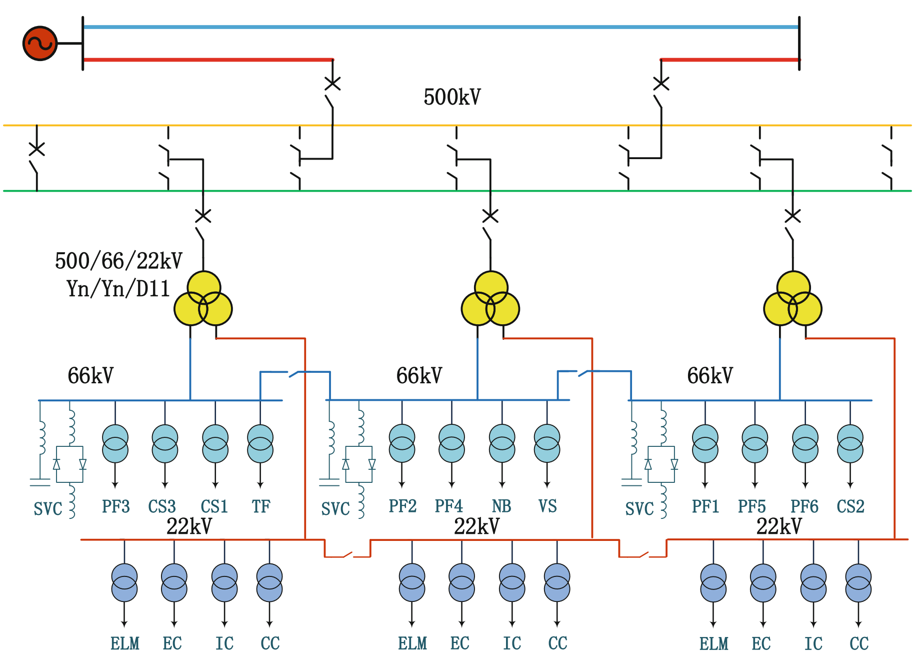

Fig. 4 PPEN configuration

Pulsed Power Electric Network

The PPEN (Fig. 4) will be connected to a powerful high-voltage (HV) grid capable of producing pulsed power to feed to the CFETR superconducting coils and the H&CD systems. The HV grid is assumed to provide large active and reactive power, and also the RPC&HF system is required as ITER [4, 8].

The major experimental power loads consist of the PF system. There are two designing schemes of PF power supply system. The basic ITER AC/DC converter is four six-pulse bridges with four-quadrant and 12-pulse operation [8, 9, 11]. In view of the obvious advantages of full-controlled semiconductor, we plan to design converter based on IGBT/IEGT or IGCT for comparison between the two schemes. This new scheme is now expensive and has higher risk than the thyristor converter. Its merit is that the RPC & HF system can be omitted, at same time the stability of power grid is enhanced. While the current scheme is still based on thyristor technology which may be powered by advanced motor-compulsator set to mitigate the inrush currents during the plasma pulse [12]. Full-controlled power semiconductor converter is also available option for further studies due to the rapid development of power electronic technology.

According to discussions in several CFETR meetings, the power demanded by CFETR PPEN is almost the same as that of ITER. The reactive power of PF is determined by converter configuration. When the thyristor converter is controlled by sequential method with suitable strategy, the reactive power demand of the units can be reduced by 25 % [6, 11].

The elongated plasma in D shape implemented in CFETR has intrinsic vertical instability and could disrupt in several milliseconds without control. The plasma discharge is then stopped which might damage the fusion devices. The magnetic field could stabilize the plasma vertical displacement, which is generated by the in-vessel active feedback coils driven by the pulse power supply. This is one of the most effective methods to cure this vertical instability which is verified primarily in the EAST. The fast control power supply of EAST comprises IGBT converter, which is developing to 10 MW within one millisecond responding time. On this basis, the fast control power supply of CFETR could be designed.

The demand power of PPEN is needed to calculate. Due to the site of CFETR has not yet been determined, the HV grid parameters of ITER is used for calculation. And there will be no discrepancy with order of magnitude between the calculation and the actual value.

The maximum active power of H&CD and CPSS system can reach 390 and 230 MW respectively. And the real power consumption of PPEN loads could up to 600 MW. Considering the PPEN impact on HV power grid, the design margin is raised to 130 %. As in Eq. (1), the power capacity of PPEN is calculated by the same calculation method,

$$\frac{600}{0.95 \times 95\,\%} \times 130\,\% = 864\ \text{MVA} \tag{1}$$

In order to determine the impedance voltage of main step-down transformers, we have done a lot of calculation and analysis. Finally according to reasonable selection methods by economy study, the impedance voltage of 3 × 300 MVA transformers is set to 12 %.

The maximum reactive power of PPEN depend on the plasma operation scenario. However, the PPEN is capable to compensate 750 MVar of reactive power just as ITER-like [2].

Fusion Power Plant

At present the most likely solution may be efficiency nuclear steam turbine generator with 4 poles at half synchronous speed. The steam generator connects tokamak reactor with the primary cooling loop. The coolant in the primary loop flows into the steam generator, where it exchange heat with the secondary heat loop through heat pipes. Due to the transferred heat to the cooling water in secondary loop, the liquid water transform into high temperature and high pressure steam, which is used for driving steam turbines to generate electricity. The power generation process is shown in Fig. 5.

The thermal efficiency of steam turbine generator is closely related to the output coolant temperature of the primary loop. As it has been proved both in theory and practice, the main steam temperature and reheat steam temperature are raised by every 20°, the cycle efficiency can be increased by 1 %. If we use water as coolant, the outlet water temperature is about 320° centigrade with 15.5 MPa. And then the heat efficiency can be up to 34 %. Moreover, when the primary loop using helium as coolant and outlet temperature is about 500° centigrade with 8 MPa, the heat efficiency can be up to 40 %. In addition, there is a similar scheme to the advanced boiling water reactor (ABWR), in which the secondary loop and steam generator can be removed. But it is difficult to control tritium leaks in fusion case.

The turbine generator is designed rated at 150 MW in phase I. There are two kinds of schemes to connect generator and HV grid. The first plan is directly connecting the generator and 500 kV HV grid with a step-up transformer. The other project is the generator connected to the 66 kV busbar (PPEN) through a transformer.

In order to inhibit short-circuit current, the step-down transformer in HV grid usually has high short-circuit impedance. But for the purpose of cost reduction and efficiency improvement, the transformer should use small short-circuit impedance as far as possible. In this paper, the short-circuit impedance of the step-up transformer which the generator is connected to the 66 kV busbar with is 12 %. And it is 15 % in another case. The 66 kV local grid should be regarded as three separate grids, since the auxiliary busbar bus is not used when the grid operate normally. The generator is connected to one of the three 66 kV busbar. It can provide part of the reactive power that coils power supply need.

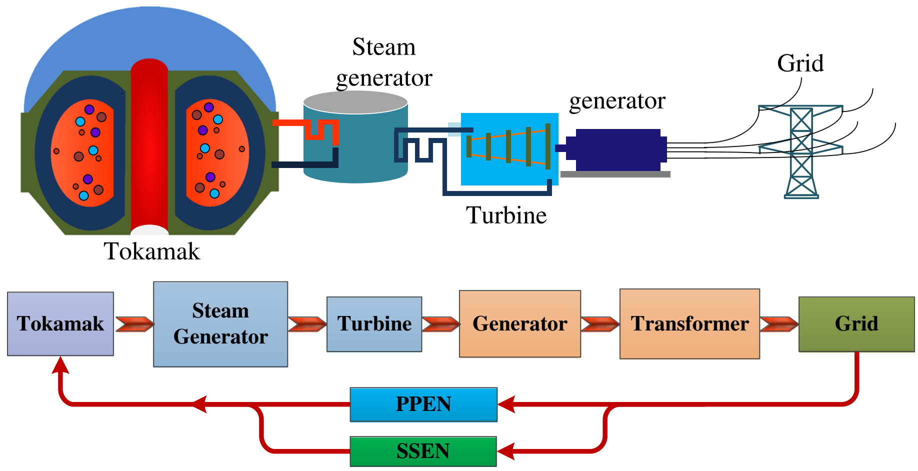

Fig. 5 Schematic diagram of power generation process

Table 1 The reactive power flow from the grid

Case	a (Mvar)	b (Mvar)	c (Mvar)	d (Mvar)
500 kV Grid	253.7	186.3	252.6	246.9
PPEN	214.1	215.9	282.4	207.2

The loads of CFETR includes a static component, a dynamic component with a duration of about a thousand seconds, a random component corresponding to fast plasma repositioning pulses. To take into account the reactive compensation, we use a static load modelling, in which total active and reactive load are defined at the maximum value. The PSCAD model includes infinity voltage sources, impedance of HV transmission line, step-down transformers, and fixed loads. By this modelling, we contrast the following four conditions.

(a) The generator is not connected to the electricity grid. And a 750 MVar RPC unit connected on 66 kV busbar of PPEN.
(b) The generator is connected to 500 kV HV grid. And a 750 MVar RPC unit connected on 66 kV busbar of PPEN.
(c) The generator is connected to 500 kV HV grid. And a 680 MVar RPC unit connected on 66 kV busbar of PPEN.
(d) The generator is connected to 66 kV grid. And a 680 MVar RPC unit connected on 66 kV busbar of PPEN.

In order to limit voltage variation on the grid to maximum of 2.5 %, the reactive power flow from the 500 kV HV grid should be limited to around 250 MVar. We want to reduce the power capacity of line to put down expenditure as possible. Hence, the smaller the reactive power flow from the PPEN is the better. The results of four cases are shown in Table 1.

We can decrease the capacity of the reactive power compensation without increasing the power capacity of PPEN by connecting the generator to 66 kV grid.

In order to make the output power of synchronous generator achieve fast response, we need to design an excitation system with high precision and high response speed. The design of control operation about the generator should include optimization and impact of dynamic loads. This work is based on the optimal control theory of transmission system [13].

To improve the thermal cycle efficiency of steam turbine generator has been a tireless pursuit for power plants. Hence, the 4 pole steam turbine generator is considered. When the total enthalpy drop keep constant, power of turbine satisfy the following formula

$$P_i \propto A_0 \propto \frac{1}{n^2} \quad (2)$$

A_0 is the steam circulation area, and n is the turbine speed.

It can be seen that reducing the turbine speed can improve the steam circulation area, by which the output power increase with the same thermal parameter. On the other hand, slower speed turbine has higher relative internal efficiency [14]. As comparing typical 1 GW steam turbines, the relative internal efficiency of half speed turbine can be improved by 2 %. With the same rated power, the cost of half speed turbine generator is about 1.2–1.3 time of full speed turbine generator.

Parameters of 500 kV HV Grid

The 500 kV HV transmission grid of China could meet the power consumption of CFETR. However, due to special operation properties of PPEN, we request that the short-circuit capacity range of power grid for candidate sites evaluated and selected.

In HV transmission line, the resistance can be ignored in calculation,because X/R is greater than 10. The impedance of transmission line is 0.2 Ω/km with ignoring R, and the length of line is assumed to be 50 km. The maximum breaking current of 500 kV circuit breaker that will be used is 50 kA, that is, the maximum breaking capacity is 43 GVA. And the reference capacity is 100 MVA. The reference voltage is 1.05 times more than Rated voltage (about 525 kV). On this condition, the maximum breaking capacity of power grid is

$$S_{\max} = \frac{S_j}{X^*_{\Sigma \min}} = \frac{100}{\frac{100}{43 \times 10^3} + \frac{0.2 \times 50 \times 100}{525^2}} \approx 16.8 \text{ GVA} \quad (3)$$

The d is voltage flicker factor,

$$d = \frac{R_L \Delta P_i + X_L \Delta Q_i}{U_N^2} \times 100\,\% \quad (4)$$

Ignoring R_L,

$$d \approx \Delta Q_i / S_{sc} \times 100\,\% \quad (5)$$

As defined in IEC 61000-3-7 2008 and GB/T 12326-2008, the d is equal to 0.025. The reactive power that HV grid supplying to PPEN is 254 MVar (Table 1), so the maximum breaking capacity of HV grid is

$$S_{\max} \geq \frac{\Delta Q}{2.5\,\%} = \frac{254 \text{ MVA}}{2.5\,\%} = 10 \text{ GVA} \quad (6)$$

The reactive power loss of step-down transformers is

$$Q \approx 11\,\% \times 3 \times 250 \text{ MVA} + 12.5\,\% \times 4 \times 60 \text{ MVA} = 112.5 \text{ MVA} \quad (7)$$

The minimum breaking capacity of HV grid is

$$S_{\min} > \frac{Q}{2.5\,\%} = 4.5 \text{ GVA} \quad (8)$$

Conclusion

The fusion power station of CFETR consist of the SSEN, PPEN, and FPP. The power plant is implemented with efficiency nuclear turbine generator with 4 poles at half synchronous speed. This paper expounds the concept design of high voltage distribution network, describes the process of power generating system, and suggest the short-circuit capacity requirements of HV transmission grid for candidate sites.

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