Giga-Joule Class Of Energy Storage By Large Flywheel Motor-Generator System

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Abstract - As a large energy storage equipment, the flywheel system is well-known one to store the energy by mechanical rotating action. The advantages of flywheel system are high density of stored energy, mechanical stiffness for long operation period, high energy storing efficiency in short cycle reputation and total system reliability based on sufficiently developed technology. The most attractive feature of flywheel system on engineering aspect is the possibility to construct the large flywheel for giga-joule class of energy storage with conventional materials and well experienced engineering. In this paper, three different type large flywheel motor-generator systems, which are constructed for the power supplies of JT-60 nuclear fusion plasma experimental facility, are described on their electrical and mechanical characteristics.

I. INTRODUCTION

The plasma operation of JT-60 is performed in about several seconds, and the electric power must be supplied in such a way to meet instantaneous power requirements of operations during this period. The power supply system of JT-60 has to control large pulsed electric power in a short time to meet various requirements of plasma operations of JT-60. Such a pulsed electric power having the peak value of about 1300 MVA cannot be received directly from the utility power network because of large electric disturbances to the local utility network. To limit the disturbances under allowable levels, a hybrid power supply system which consists of the utility power network system and motor generators system has been adopted. Fig. 1 shows a schematic diagram of overall JT-60 power supply and distribution system.[1]

Fig. 2 shows the total electric power pattern received from the utility power network for one cycle operation of JT-60. In period I, the toroidal field power supply begins to excite the toroidal field coils and the toroidal field strength reaches 4.5 Tesla in 30 seconds. In period II, the plasma experiment is performed, namely the plasma is built up, heated and terminated during this period. The rotating speed of three AC generators decreases from 100 % to 70 % in period I and II. In period III, the utility power network system of the toroidal field power supply is disconnected from the power network in four steps so as not to disturb the network voltage and frequency. Period IV is accelerating period of three generators. In this period, the speed of the generators is increased up to 100 % to prepare subsequent operations. In the fo1 1owings, more detailed descriptions of functions and characteristics of the toroidal and poloidal field power supplies and the power supply for additional heating systems are given.

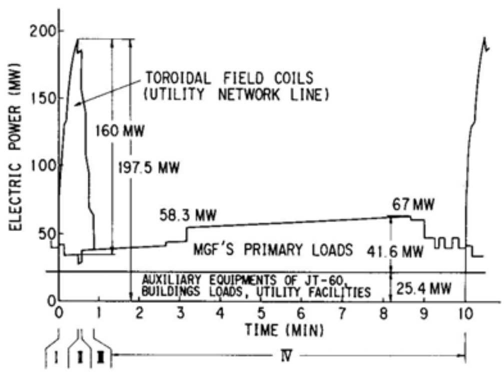

Fig. 1 Diagram of overall JT-60 electric power system

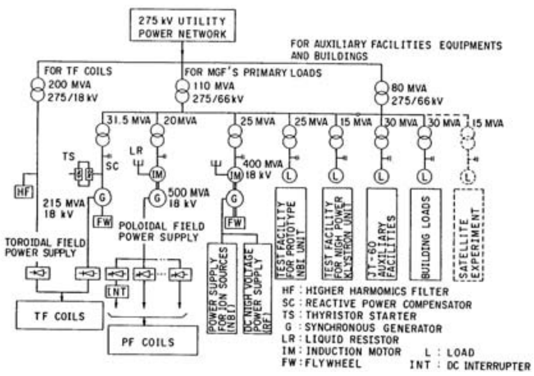

Fig. 2 Total electric power pattern for JT-60 operation

II. OUTLINE OF JT-60 POWER SUPPLY

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The toroidal field power supply (TFPS) is composed of the utility power network system and the motor generator (MG) system as shown in Fig. 3. Either both or each of them can supply the toroidal field coils with sufficient electric power according to various operational requirements. The utility power network system receives electric power directly from the 275 kV transmission network. On the other hand, the MG system has a 215 MVA AC generator with flywheel as the power source. The toroidal field power supply can generate as a whole the peak power of 400 MVA and deliver the energy of about 8 GJ to the toroidal field coils during one cycle of operation of JT-60.

TFPS excites the toroidal field coils to produce the toroidal magnetic field of up to 4.5 Tesla for 5 seconds. To generate the magnetic field of 4.5 Tesla, the toroidal coil current of 52.1 kA is needed in JT-60. The utility power network system and the MG system are connected in series by 24-pulse diode converters. The utility power network system supplies pulsed power of 160 MW which is the maximum allowable value to limit the disturbances to the local utility network. The AC generator has a large flywheel and is driven by a thyristor accelerating equipment. The total GD^2 value of the generator is 16,000 ton-m^2. Each 24-pulse diode converter is composed of 6-pulse diode converters connected in series and parallel. The phase shift of the secondary voltage between each converter transformer is 15 degrees in each 24-pulse diode bank. By using 24-pulse diode converters, harmonic currents and reactive power are decreased. The DC output power is controlled by the two means; which are (i) connecting or disconnecting each 24 pulse diode converter bank and (ii) controlling the generator output voltage.

The peak DC output voltage and current of TFPS are 7 kV and 52.1 kA respectively. The DC output voltage of 7 kV is applied to the toroidal coil and the coil current begins to rise exponentially. The coil current continues to increase and reaches 52.1 kA in about 30 sec, while the DC output voltage is almost same or gradually decreased. During the flat top period of 5 seconds, the DC output voltage is controlled by AVR of the generator to keep the coil current constant at 52.1 kA. By the end of the flat top period, the rotating speed of the generator decays from 600 rpm to 420 rpm. At the end of the flat top period, the output of the generator is switched off, and, at the same time, one of the four 24-pulse diode converter banks of the utility power network system is also disconnected from the network. Other three banks are disconnected one after the other at intervals of 7 seconds not to disturb the utility network voltage.

As shown in Fig. 4, the poloidal field power supply (PFPS) consists of the AC generator, the ohmic heating (OH) power supply (thyristor converters and other equipment), the vertical field (VF) power supply, the magnetic limiter (ML) power supply, the quadrupole field (QF) power supply and the horizontal field (HF) power supply. The OH power supply includes inductive energy storage (IES) coil to build up plasma current stepwise. An induction motor with a thyristor scherbius equipment accelerates the AC generator up to 582 rpm, which then delivers AC power and energy to AC/DC power conversion thyristor converters with decreasing the rotating speed to 406.5 rpm. Each poloidal coil is independently excited by respective thyristor converters to meet particular functions required for each coil.

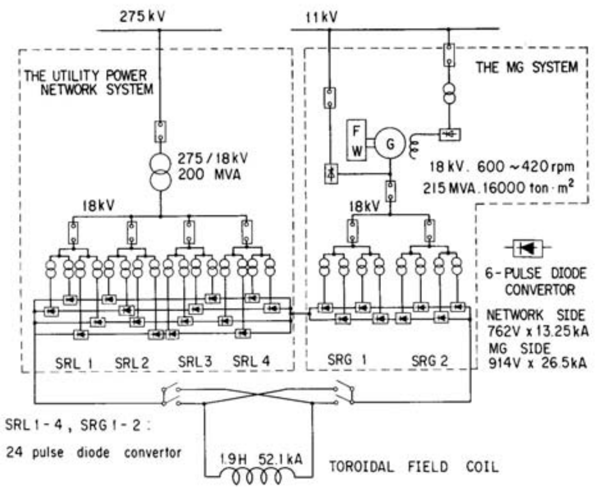

Fig. 3 Schematic diagram of TFPS

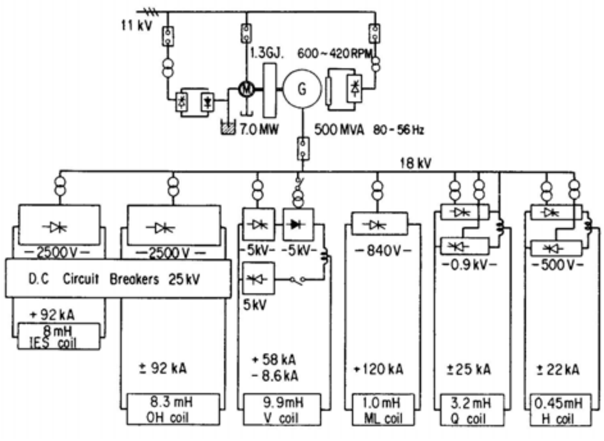

Fig. 4 Schematic diagram of PFPS

Thyristor converters are used to make fast and accurate control of DC output power by direct digital control method. In premagnetization period, each coil current is set at the initial value. In build up period, the OH coil current and the IES coil current are interrupted sequentially by DC interrupters (VCB's). Immediately the plasma current is induced and built up by transformer action of the OH coil. The VF coil current is controlled in proportion to the plasma current to prevent the plasma from going outward. In flat-top period, the plasma current is maintained at 2.7 MA by OH power supply, and the plasma position and shape are also controlled by operating the VF, HF, QF and ML power supplies. In this period, both the NBI and the RF heating systems are operated to raise the plasma temperature. Fast and accurate control of coil currents is required to maintain plasma positional stability, shape and current. All the power and energy required for the poloidal field system are supplied from an AC generator of the peak capacity of 500 MVA.

To make the plasma temperature much higher, two additional heating systems are used. One is the neutral beam injection heating system (NBI), which is to inject the high energy neutral particle beam into the plasma and to transfer the high energy to the plasma by neutral-ion particle interaction. The other one is the radio frequency heating system (RF), which is to inject several types of high frequency radio wave to the plasma by corresponding antennae and to propagate the wave energy with plasma-wave resonance interaction. Both the NBI and the RF plasma heating systems are also powered by a flywheel AC generator with the peak capacity of 400 MVA, 2.65 GJ as shown in Fig. 5. On design consideration of feeding the two heating systems by one generator, the stability of the AC voltage on the common bus bar is important, which is just the output voltage of generator. Newly developed Auto Voltage Regulator (AVR) was applied for the controller, in which the thyristor exciter for field coil is directly driven by the mini-computer.

III. MOTOR-GENERATOR SYSTEMS

The energy stored in flywheel, which is coupled directly with a motor-generator's rotor shaft, is controlled by motor-generator operation, i.e. acceleration by motor mode operation increases the stored energy and deceleration by generator mode operation decreases it. The total required energy for JT-60 plasma experiment is about 1300 MVA and 12 GJ per one cycle operation, a part of which, about 200 MVA and 4 GJ, is directly received from the high voltage utility power network. The other power is generated by three flywheel motor-generator systems. To accelerate the motor-generator and flywheel, the two systems have the corresponding pony motor respectively, which is a winding type induction motor. On the other hand, such a pony motor is not prepared for the remaining one because of design consideration on the critical rotating speed, and a static thyristor starter with power electronics circuit is applied.

A. MOTOR-GENERATOR WITH FLYWHEEL FOR TFPS

The first one is 215 MVA motor-generator with a large flywheel of 6.6 m in diameter and 645 ton in weight, which yields 4 GJ energy in rotating speed between 600 rpm and 420 rpm. It is clear that the required energy cannot be obtained by the rotor of the motor-generator itself, because it is about eight times as large as the energy yielded with the usual GD^2 value. As a result, a large flywheel is directly coupled to the motor-generator. Fig. 6 shows the full cross-section

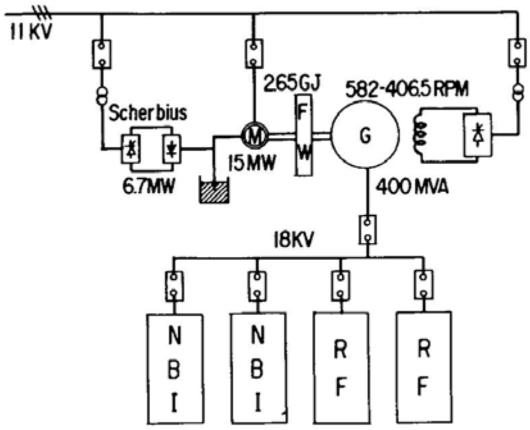

Fig. 5 Schematic diagram of the power supply for additional heating systems

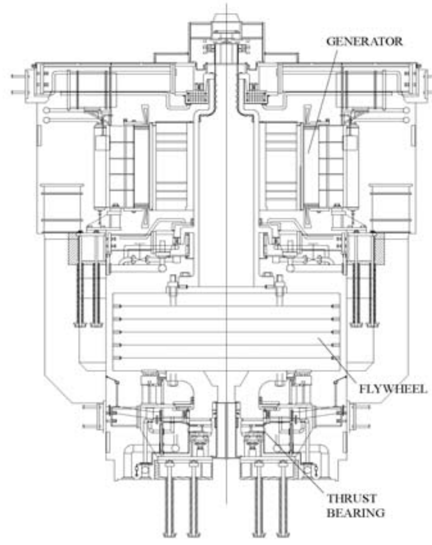

Fig. 6 Cross section of TFPS motor-generator with flywheel

of the flywheel motor-generator for TFPS. As shown in Fig. 6, the motor-generator is a vertical type salient-pole synchronous one supported by the three guide bearings, that is, upper, middle and lower guide bearings. The flywheel consists of six disks and they are fastened firmly by through-bolts. Cooling air is provided by cooling blowers. A part of the cooling air is conducted into the ventilation ducts in the concrete and flowed down to the lower area of pit to cool the flywheel. Then the cooling air flows upward into the motor-generator together with the other remaining cooling air. After cooling the motor-generator, the air is cooled by heat exchangers mounted on the periphery of the stator frame of the motor-generator. Main parameters of the motor-generator with flywheel for TFPS are summarized in Table 1.[2]

A thrust bearing is located at the bottom of the flywheel. The thrust bearing is of design load of 1,100 tons, mean bearing pressure of 45 kgf/cm^2 and maximum peripheral speed of 67.5 m/s. Copper plate pads are adopted in order to reduce the thermal distortion to be half of the value which is estimated when steel pads are adopted. The result is that the copper plate pads ensure an oil film of minimum 60 micro-meter for the minimum rotating speed 420 rpm during operations. The lubricating oil is cooled by external oil coolers and circulated by a self-pumping system, that is, the pumping action of pump holes provided in the thrust collar drives the lubricating oil to external oil coolers.

A thyristor static starter is applied for acceleration of the motor-generator because it has the following merits compared to a directly coupled induction motor start-up system, namely increase of the critical speed by 30% with a shorter shaft length, energy regeneration during electrical braking action and easier maintenance because of having no moving parts. The rating power of the thyristor static starter was determined to be 19 MW taking the acceleration time and the losses of the motor-generator into consideration. The motor-generator is accelerated to 600 rpm by the thyristor static starter before the commencement of operation, and outputs the stored energy in accordance with the load pattern during the operation. The motor-generator which is decelerated to 420 rpm is accelerated to 600 rpm again by the thyristor static starter. The output of generator is controlled by the field current control with thyristor exciter in order to satisfy the DC output current pattern of TFPS, which is required current pattern to energize the toroidal coil. The capacity of the thyristor exciter is determined to be 797 kW considering the high ceiling voltage and the maximum field current which are required just before the flat top period.

Concerning the flywheel, Fig. 7 shows the relation between the diameter, weight, thickness, peripheral velocity, windage loss and maximum stress of the flywheel under constant GD^2 condition. When the diameter increases, the weight can be reduced and it is advantageous to reduce the thrust bearing load, however the windage loss and the maximum stress increase. Considering that the windage loss and the maximum stress are kept well below the values of their allowable levels, the diameter of the flywheel is set at 6.6 m. As the result, the weight of the flywheel becomes 645 ton, and it is impossible to adopt a single forging construction because of limitations of fabrication, transportation and assembly.

Table 1 Specifications of the TFPS motor-generator

Output	215 MVA
Voltage	18 kV
Current	6,896 A
Power factor	0.85
Frequency	80 – 56 Hz
Rotating speed	600 – 420 rpm
Total flywheel effect: GD^2	16,000 ton-m^2
Discharge energy	4.02 GJ
Total weight of rotating part	1,100 ton
Thrust bearing	Mitchell type (1,100ton,45kgf/cm^2)
Operating frequency	Once every 10 minutes
Thyristor exciter	797 kW
Thyristor starter	19 MW

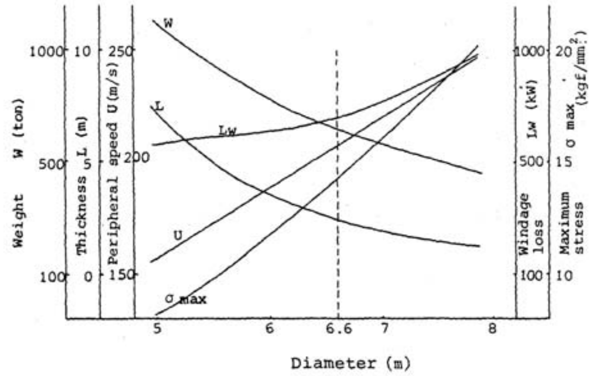

Fig. 7 Dependence of flywheel

Therefore the flywheel is split into six carbon steel disks and they are fastened by through-bolts. Bolts are located at the inner position of the disk in order to minimize the bending stress caused by the centrifugal force of the bolts themselves. The bolts are so tightened that any slip between the disks does not occur under the torsional force induced at short circuit condition of the motor-generator. In order to reduce the bending stress of the bolts caused by the different radial deformation of each disk and the centrifugal force of the bolts themselves, special bolts are adopted which make smaller moments of inertia in the radial direction compared with that in the circumferential direction.

B. MOTOR-GENERATOR FOR PFPS

The second motor-generator doesn't have a flywheel, but has the sufficient flywheel effect of the motor-generator itself to output 1.3 GJ and large peak power of 500 MVA, the rotating speed being in the range of 582 rpm to 406.5 rpm. The required energy can be obtained by the rotor of the motor-generator, and the generator rotor has the dimensions of 4.7 m in diameter and 4.2 m in length. Fig. 8 shows the full cross-sectional view of the motor-generator for PFPS. As shown in Fig. 8, the motor-generator consists of generator part and pony motor part. The pony motor is an induction motor which is connected directly to the generator shaft. The generator is a vertical type salient-pole synchronous one supported by the upper and lower guide bearings. Main parameters of the motor-generator for PFPS are summarized in Table 2.

The thrust bearing in bottom is to support the total weight of 500 ton approximately, which means bearing pressure of 30 kgf/cm^2. The thrust pads are mechanically sustained by several metallic spiral springs to allow the flexible action for high speed rotating motion. The thin oil film on pad is kept naturally in range of 582 rpm to 406.5 rpm, while a oil pressurizing lift pump is to work under 406.5 rpm. The lubricating oil is cooled by external oil coolers and circulated by a circulation pumping system. Cooling air is provided by upper and lower cooling blowers. They circulate the cooling air to flow into the motor-generator, and, after cooling the motor-generator, the air is cooled by heat exchangers mounted on the periphery of the stator frame of the motor-generator.

The induction motor as pony motor is a three phase winding type one of 7 MW. To accelerate the motor-generator by pony motor, the induction motor should be energized proportional to its rotating speed. For this purpose, well known scherbius method is employed for speed control. The secondary winding of induction motor is connected to the rectifier circuit of scherbius equipment, and the output DC power of rectifier circuit is converted to AC power by the inverter circuit of scherbius equipment to supply the power back to AC line. As the result, the scherbius equipment can control the secondary side power of induction motor, which means that the accelerating torque of induction motor corresponding to the secondary side power is controlled instantaneously according to the rotating speed and the accelerating schedule.

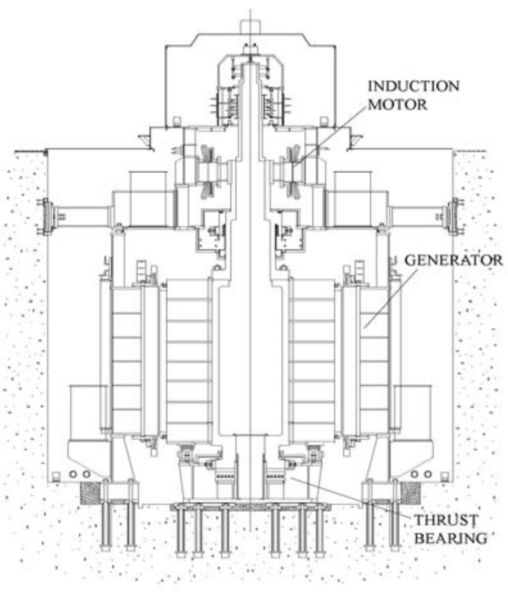

Fig. 8 Cross section of PFPS motor-generator

Output	500 MVA
Voltage	18 kV
Current	16,038 A
Power factor	0.45
Frequency	77.6 – 54.2 Hz
Rotating speed	582 – 406.5 rpm
Total flywheel effect: GD^2	5,500 ton-m^2
Discharge energy	1.3 GJ
Weight of generator rotor	460 ton
Thrust bearing	Spring type (500 ton,30 kgf/cm^2)
Operating frequency	Once every 10 minutes
Thyristor exciter	4.9 MW
Induction motor	7 MW
Scherbius equipment	2.9 MW

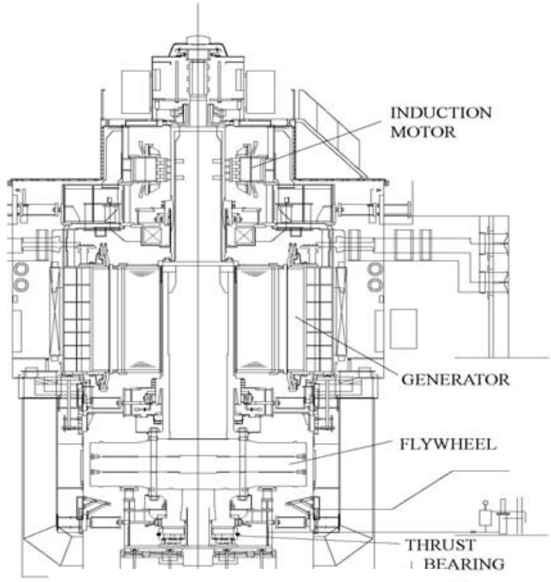

Fig. 9 Cross section of the motor-generator with flywheel

Table 3 Specifications of the motor-generator for additional heating systems

Output	400 MVA
Voltage	18 kV
Current	12,830 A
Power factor	0.62
Frequency	77.6 – 54.2 Hz
Rotating speed	582 – 406.5 rpm
Total flywheel effect: GD^2	11,600 ton-m^2
Discharge energy	2.65 GJ
Weight of generator rotor	460 ton
Weight of flywheel	330 ton
Thrust bearing	Mitchell type (895 ton,45 kgf/cm^2)
Operating frequency	Once every 10 minutes
Thyristor exciter	2.2 MW
Induction motor	15 MW
Scherbius equipment	6.7 MW

C. MOTOR-GENERATOR WITH FLYWHEEL FOR ADDITIONAL HEATING SYSTEMS

The third one is 400 MVA and 2.65 GJ motor-generator with a flywheel of 330 ton in weight, the rotating speed being as same as that of the motor-generator for PFPS. The generator rotor has the dimensions of 5.0 m in diameter and 3.3 m in length, and the flywheel has 6.1 m and 1.35 m respectively. Fig. 9 shows the full cross-section of the motor-generator with flywheel for additional heating systems. As shown in Fig. 9, the motor-generator consists of generator part and pony motor part. The pony motor is an induction motor which is connected directly to the generator shaft. The generator is a vertical type salient-pole synchronous one. The flywheel consists of three disks, which are fastened together and coupled with the rotor shaft by the through bolts. Main parameters of the motor-generator with flywheel for additional heating systems are summarized in Table 3. The thrust bearing in bottom is Mitchell type one to support the total weight of 895 tons approximately, which means the bearing pressure is 45 kgf/cm^2. The lubricating oil is cooled by external oil coolers and circulated by a circulation pumping system. Cooling air is provided by upper and lower cooling blowers. They circulate the cooling air to flow into the motor-generator and the bottom area. After cooling the motor-generator and flywheel, the air is cooled by heat exchangers mounted on the periphery of the stator frame of the motor-generator. The induction motor as pony motor is a three phase winding type one of 15 MW. scherbius method is also employed for speed control of the motor-generator as same as that of PFPS. The secondary side power of induction motor is controlled by scherbius equipment, and the accelerating torque of induction motor corresponding to the secondary side power is changed instantaneously according to the rotating speed and the accelerating schedule. For decelerating the motor-generator, liquid rheostat equipment is prepared, which is connected to the secondary side of induction motor. In decelerating period, the stored energy in the motor-generator with flywheel is consumed in the liquid rheostat by generator mode operation of the induction motor.

IV. CONCLUSION

The main features of three different type motor-generator systems for giga-joule energy storage are described. Two of them have the respective large flywheel to satisfy the sufficient GD^2 value. From the first plasma experiment of JT-60 in 1985, All of the motor-generator systems have been operated successfully. Many experiences have been also obtained for energy storage by motor-generator with flywheel, which will be good references for the design of this type of energy storage system in the future.

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