Design and Implementation of DC Pulsed Power Supply Employing Self-excited Induction Generators and Flywheels for Toroidal Field Coils of a tokamak device, PLATO

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1. Introduction

Tokamak devices using non-superconducting coils require large pulsed power consumption. When the device cannot receive electricity from power grid due to bad effects to power grid and electric load, energy storage system is needed.

Pulsed power supplies require some energy storage using capacitors, flywheels or batteries. Each energy storage has strong range of discharging time and peak power. Tokamak device also choose suitable energy storage depending on their scale. Generally Small tokamaks employs capacitors and middle or large tokamak employ flywheels.

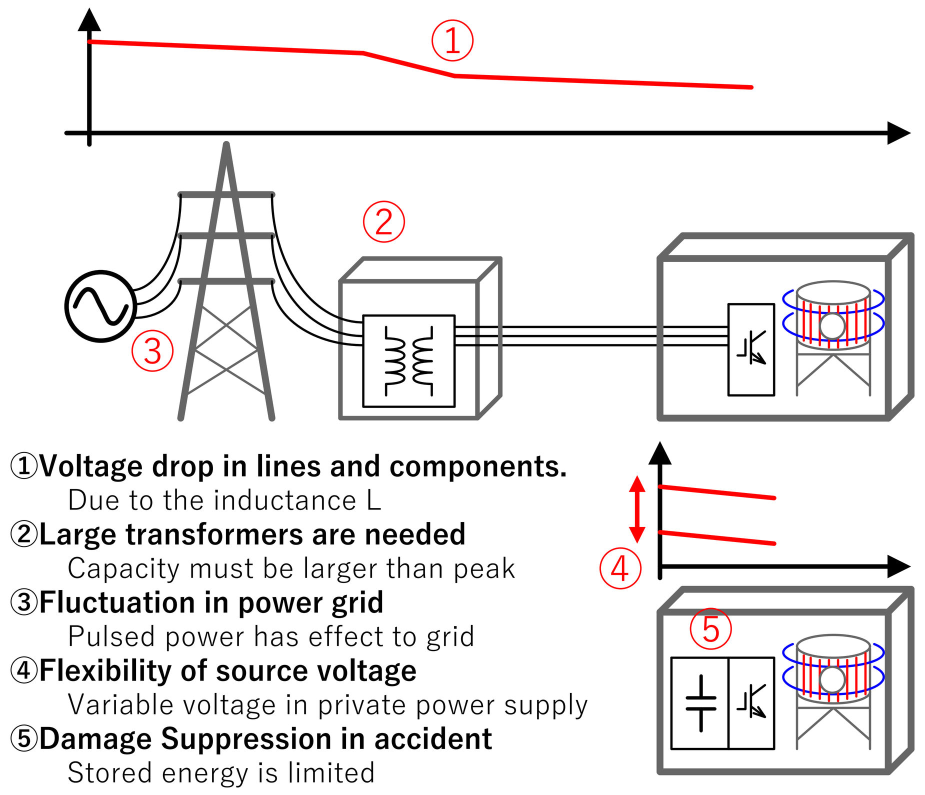

Fig.I Disadvantages of direct receiving and advantages of private power supplies

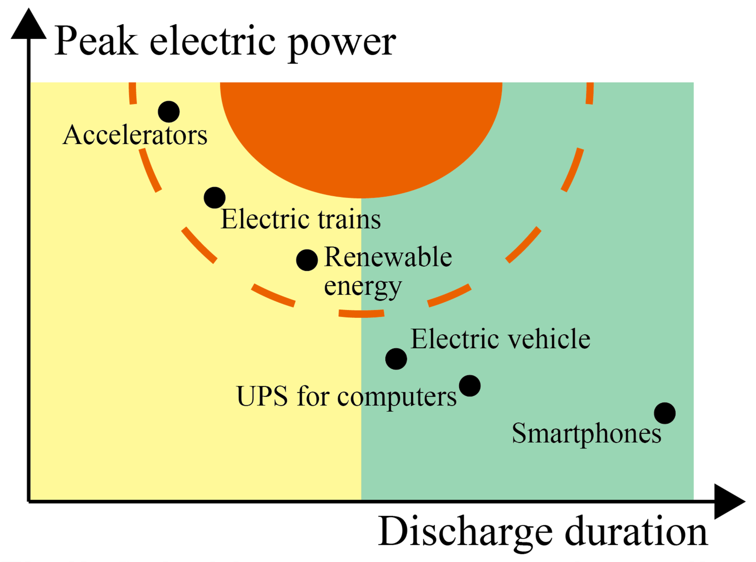

Fig.II Suitable energy storage depending on discharging time and peak power. Flywheels are suitable middle discharging term and large peak power consumption.

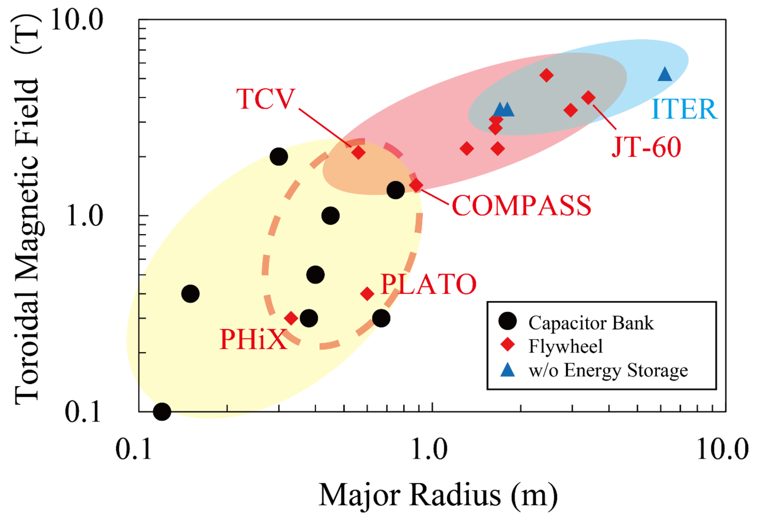

Fig.III Energy storage of tokamak in the world. We are developing flywheel energy storage for small tokamaks. (broken red circle area)

2. Prototyping of a self-excited induction generator for smaller tokamak, PHiX

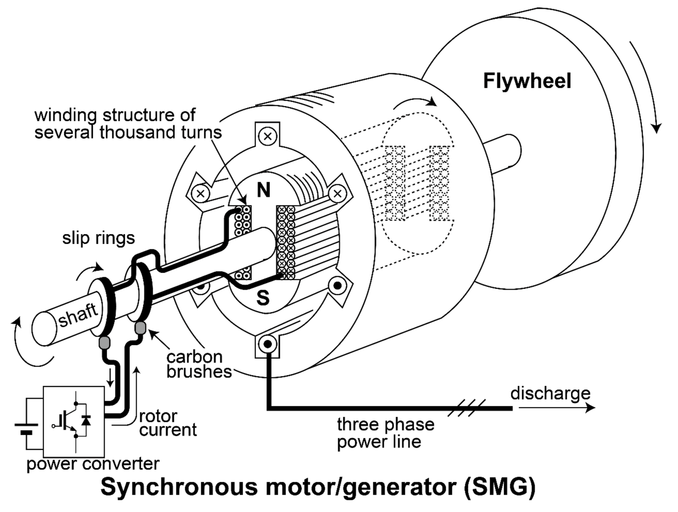

Fig.IV Construction of SMGs

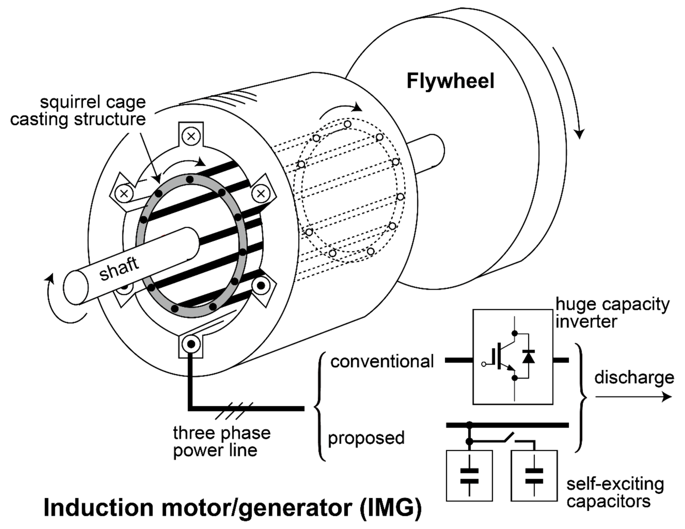

Fig.V Construction of IMGs

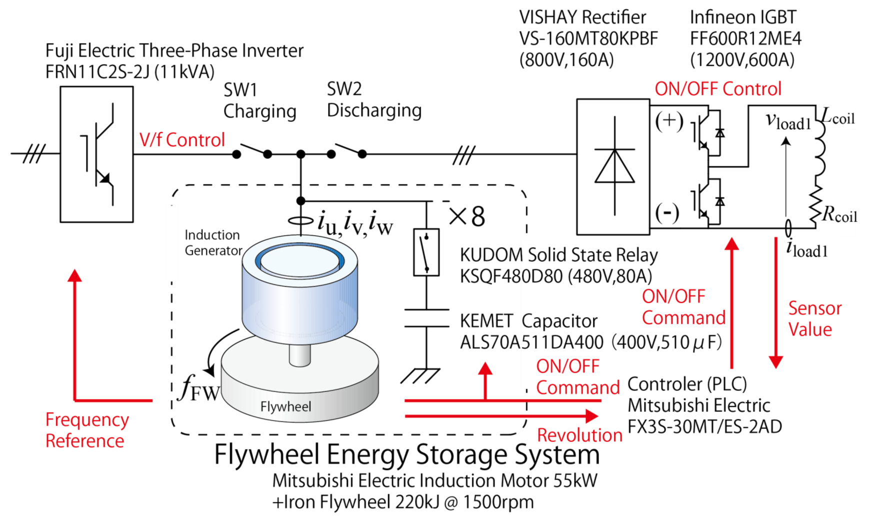

Fig.VI Circuit Configuration for PHiX

SMGs were used to perform energy conversion between electric energy and kinetic energy. One of the SMG problems is that they require frequent maintenance since the abrasion of mechanical parts cannot be avoided such as slip rings and carbon brushes that rotor current flows through as shown in Fig. IV. In contrast, IMGs have simple structure and we can use self-excitation phenomena of IMGs. Generally, for IMG operation, semiconductor power converters providing lag reactive power towards the IMGs are required. We propose a kind of electric generators called SEIGs, which does not require huge inverters. Mainly, SEIGs are adopted for wind power generation but the accuracy is not required in most cases. Furthermore, there is no precedent to employ choppers to obtain DC current since the load of wind turbine utilizes AC voltage. Therefore, SEIG have not been applied to tokamak devices.

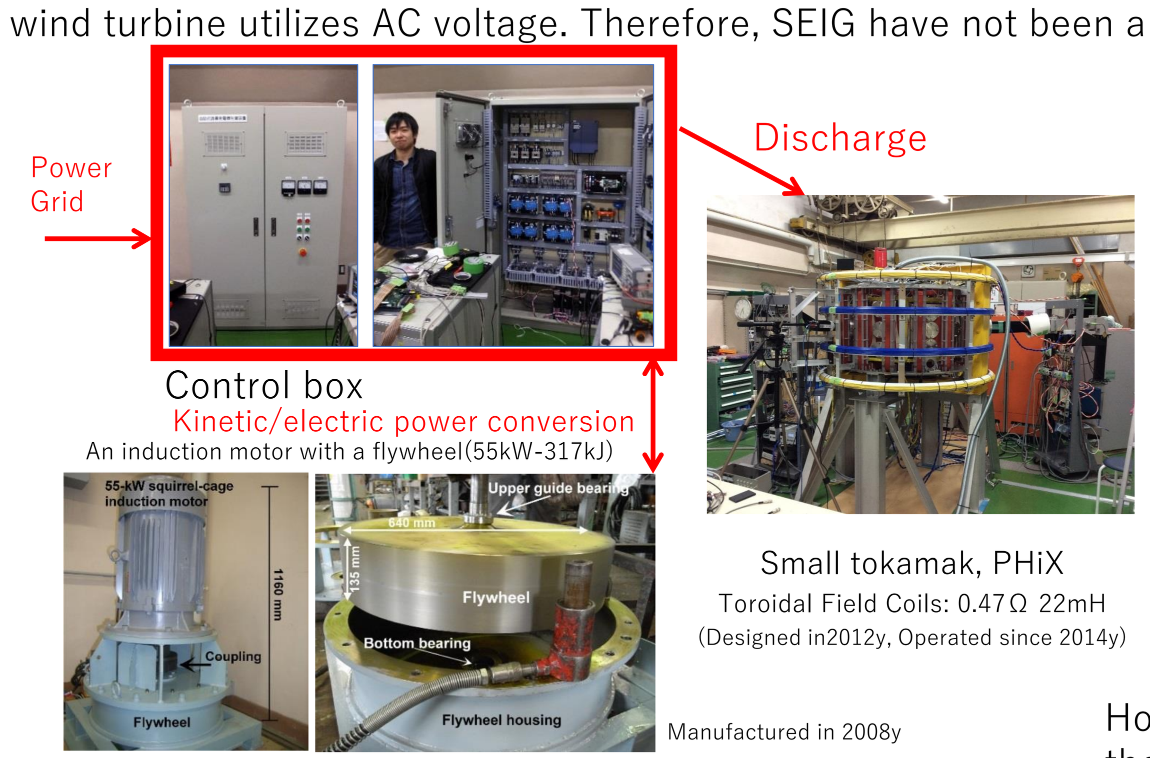

Fig.VII Experimental components of PHiX

Masamichi Murayama, et al "Magnet coil power supply by a self-excited induction generator with a flywheel for a small tokamak, PHiX", Fusion Engineering and Design, Volume 148, 2019.

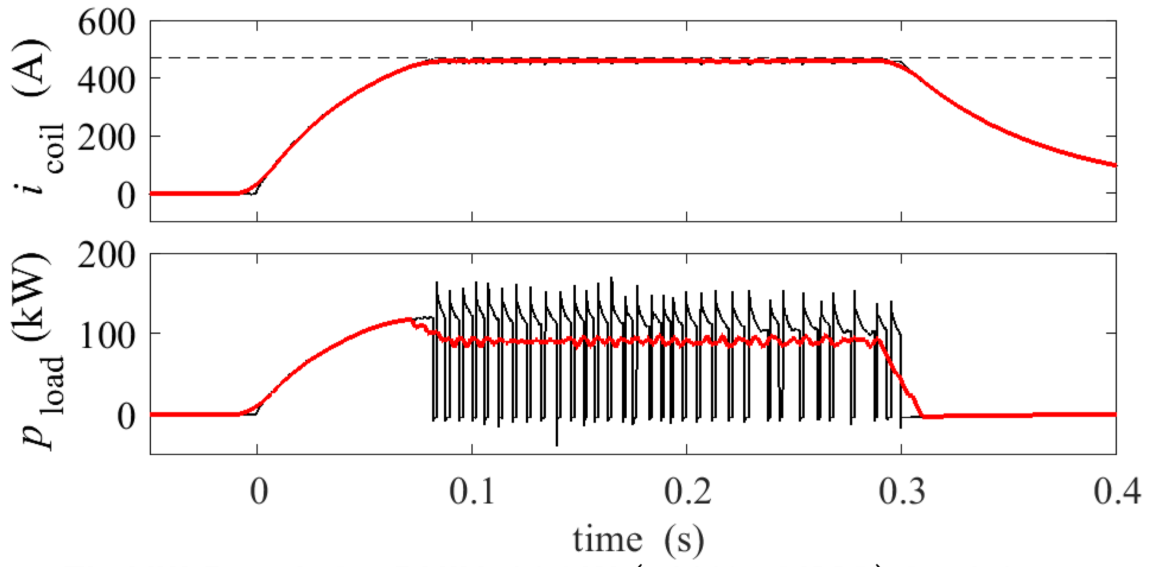

Fig.VIII Result for PHiX, 90 kW (160% of IMG) for 0.25 s

Due to digital control of self-exciting capacitors, IMG voltage Is stepwise. However, the continuous voltage control by the SEIG is not required since the IMG voltage is converted to DC voltage through a diode rectifier and finally to a precisely controlled magnet coil current with a DC/DC converter. Finally, we succeeded in current flattop for 0.25 s at PHiX

3. Fabrication & experimental test of power supply for PLATO

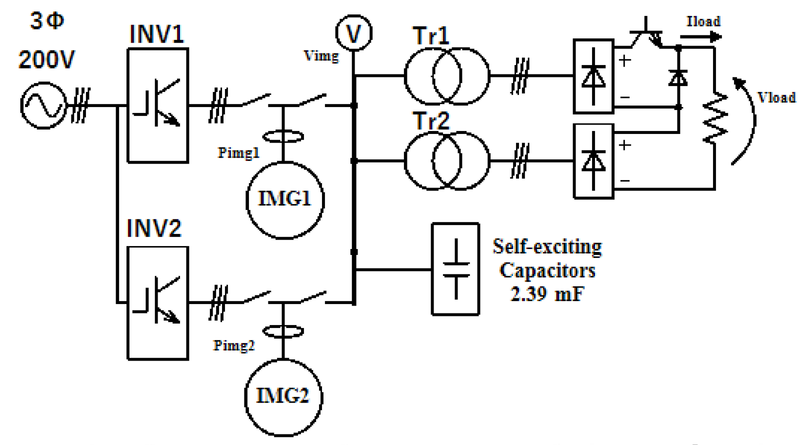

Fig.IX Circuit configuration of the pulsed power supply for PLATO's toroidal filed coils.

Pulsed power supplies require some energy storage using capacitors, flywheels or batteries. Each energy storage has strong range of discharging time and peak power. Tokamak device also choose suitable energy storage depending on their scale. Generally Small tokamaks employs capacitors and middle or large tokamak employ flywheels.

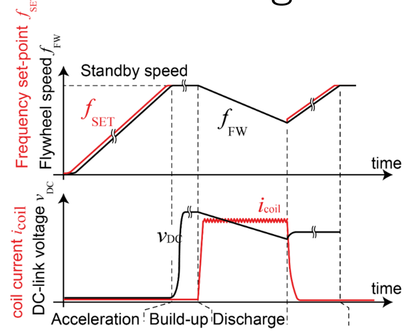

Fig.X Operation sequence of the power supply

The power supply require flywheel acceleration and voltage build-up sequence before discharge sequence. In second or later discharge, acceleration time is shorter since flywheel can be accelerated from middle speed.

① Flywheel acceleration test : 5 min 20 sec from stop state to standby state

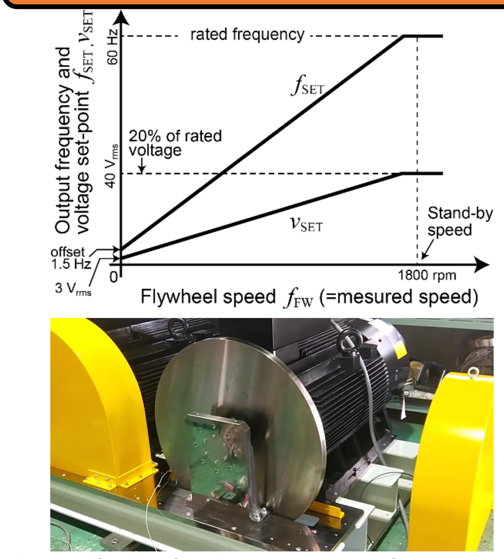

Fig.XI Flywheel and setting of acceleration inverters

General-purpose three-phase inverters are assigned to each IMG for the acceleration and operate V/f control with pulse generators. The ouput voltage is set as 80 V at commanded frequency of 60 Hz. The offset frequency that determines the slip of IMGs and accelerating power is set as 0.3 Hz. Fig. shows the acceleration test result when we accelerated the two IMGs at the same time. We can accelerate the flywheels from stop state to waiting speed in 320 s with the control method in the test. The peak power consumption of the power supply for acceleration is 34 kW, only 4.3% of rated peak output power of the power supply. Waiting power consumption is 12 kW in total at steady state.

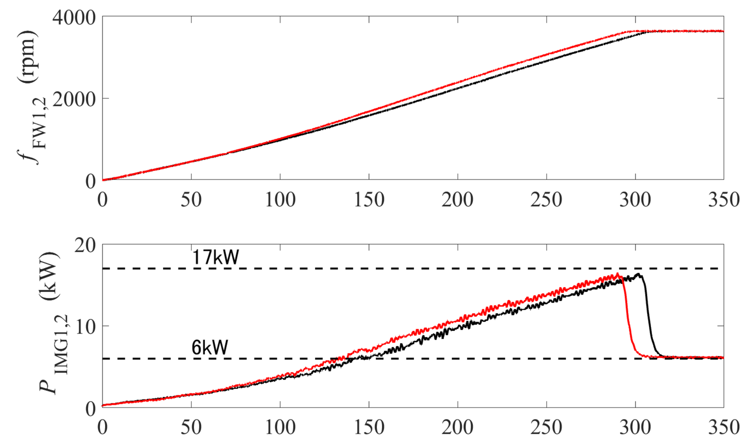

Fig.XIV Flywheel speed and power consumption in acceleration test

② Voltage build-up test : success in spite of transformer connection to generators

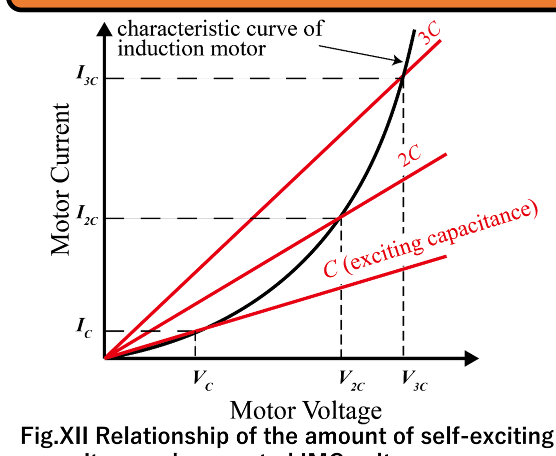

Fig.XII Relationship of the amount of self-exciting capacitors and generated IMG voltage

SEIGs are ready for discharge after the voltage build-up. It is caused by self-exciting phenomena when the IMGs are connected to self-exciting capacitors in parallel. Reactive power supply to the IMGs are 145 kVar at 400 V of IMG voltage. In the test, transformer Tr1 and Tr2 are connected to the bus. IMG voltage increase in exponential curve at first and become steady due to the iron magnetic flux saturation In the test, IMG voltage became steady in 23 s from standby state.

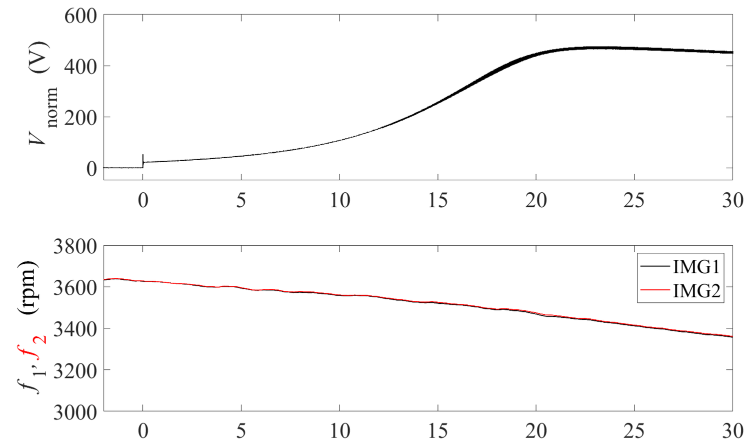

Fig.XV IMG phase voltage and flywheel speed in build-up test

③ Discharge test with resistive dummy load : peak power of 766 kW

Fig.XIII Salt water dummy load for discharge test.

We conduct discharge test to drive load current with rectifier after the build-up sequence. We used resistive dummy load since toroidal field coils are under construction. Salt water with mass fraction of 4.3% are filled between the electrodes. The power supply output 766 kW of peak electric power at load resistance R_{load} = 1.4 Ω.

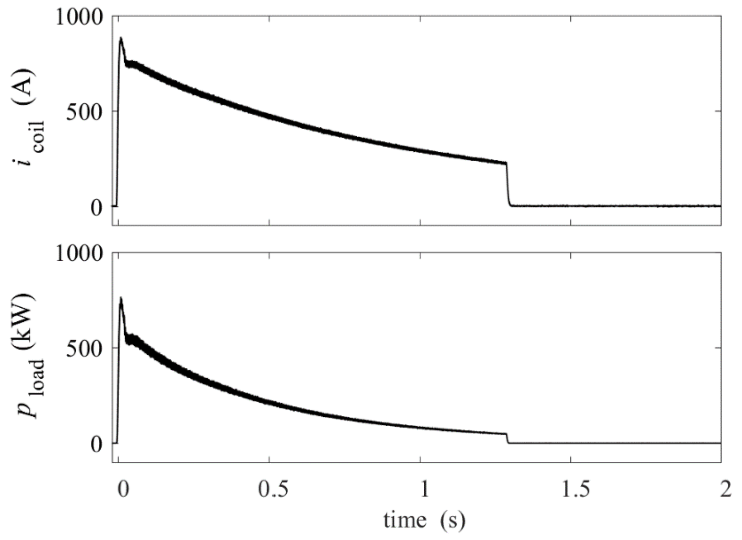

Fig.XVI Current and load power in discharge test

4. Conclusion and future works

In this paper, we developed **1-MW class pulsed power supply** employing IMGs with flywheels for a tokamak device, PLATO. The proposed design in this presentation have following **two novelty** to our conventional design. First one is the **adoptation of multiple IMGs**. Second one is the **adoptation of transformers** to reduce electromagnetic noise and voltage class adjustment.

We conducted **acceleration, build-up and discharge tests**. From the experiments, we pointed out **possibility to adopt modular multiple IMGs and transformers** in the design of pulsed power supply with SEIGs and flywheels.

In 2020, we plan to conduct a **commissioning test for first plasma of PLATO** with actual load to adjust the amount of self-exciting capacitors and to expand discharging period.

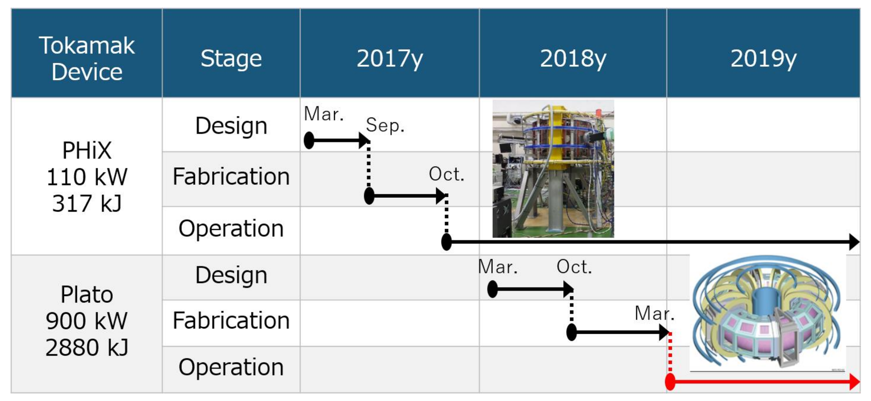

Fig.XVII Development schedule of the power supplies. In 2020, PLATO's first plasma (the first experiment) is planned