Optimization of Tokamak Plasma Equilibrium Control in TOKASTAR-2[*)]

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(Received 9 December 2013 / Accepted 10 March 2014)

To improve capability of tokamak plasma equilibrium control in TOKASTAR-2, a pair of pulsed vertical field coils (PVF coils) was installed in 2012. Optimization of PVF coil current waveform was made with re-calculation using TOSCA code in varying the conditions of tokamak discharge. Then, simulation of the electric circuit of PVF coil system with LTspice code was done to find the optimum capacitance and charging voltage of capacitor for PVF coils consistent to the optimal current waveform. Eventually capacitor parameters for PVF coils to be used as base for experiment were obtained.

Keywords: TOKASTAR-2, tokamak, stellarator, hybrid configuration, TOSCA code, eddy current

DOI: 10.1585/pfr.9.3402059

1. Introduction

TOKASTAR-2 is a plasma confinement device, which has two coil systems, one for tokamak and the other for stellarator [1]. These two systems can be operated independently. The main purposes of this device are to evaluate the effect of helical field application on tokamak plasma confinement and to study the plasma current effect on compact stellarator configuration.

Tokamak coil system consists of eight toroidal field (TF) coils (N_{TF} = 50 turns each), three-block ohmic heating (OH) coils (central solenoid with N_{OH1} = 84 turns, and upper and lower coils with N_{OH2} = 22 turns each), and a pair of pulsed vertical field (PVF) coils (N_{PVF} = 20 turns each). The stellarator coil system consists of two outboard helical field (HF) coils (I_{HF} = 98 turns each), four upper or lower additional helical field (AHF) coils (N_{AHF} = 126 turns each), and a pair of vertical field coils (N_{VF} = 100 turns each). The coil configuration is shown in Fig. 1. VF coils are installed outside the vacuum vessel and the other coils are installed inside. For energization, capacitors are used in circuits of TF coils, OH coils and PVF coils, while DC power sources are used for VF coils, HF coils and AHF coils. The magnetic field strength in the plasma center is ∼0.1 T. For the pre-ionization, a radio frequency wave with the frequency of 2.45 GHz and the injection power of ∼2 kW is used. The working gas is helium. The plasma is generated inside the TF coils. The surface of the inner leg of TF coils is covered by stainless steel plate to allow contact of plasma.

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[*)] This article is based on the presentation at the 23rd International Toki Conference (ITC23).

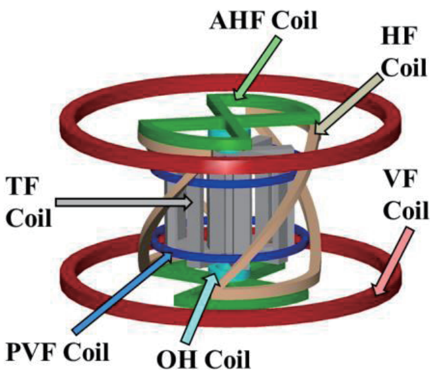

Fig. 1 Coil configuration of TOKASTAR-2.

Figure 2 shows the flowchart of experimental plan for TOKASTAR-2. This paper focuses on the topic, "optimization of tokamak operation" which is in progress now.

In this paper, optimization of tokamak equilibrium control in TOKASTAR-2 is reported. The key is the influence of the large eddy current induced in the vacuum vessel. This is one of common issues encountered in large scale tokamaks including ITER and JT-60SA.

2. Optimization of Equilibrium Control with PVF Coils

Before installation of PVF coils, the plasma current was limited less than 100 A and its duration was limited less than 15 µs in tokamak operation of TOKASTAR-2 with OH coils and VF coils [2]. Since the time constant of eddy current decay in the vacuum vessel is about 0.35 ms and was longer than the plasma duration of TOKASTAR-

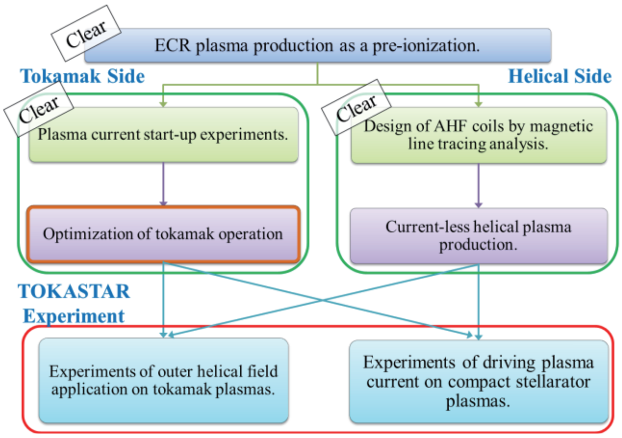

Fig. 2 TOKASTAR-2 experimental plans.

2, it was difficult to control the radial position by VF coils located outside the vacuum vessel. Therefore, a pair of pulsed vertical field (PVF) coils was designed in 2011, and installed in January 2012, to be used in place of or in addition to the VF coils to improve plasma equilibrium controllability in TOKASTAR-2. In its design, equilibrium calculation was done with the tokamak operation scenario and circuit analysis code (TOSCA) code, and the optimal PVF coil current waveform was obtained, whose peak value was 5 kA turns for each coil and duration was 0.88 ms. In this analysis, it was assumed that the capacitance of OH coil circuit capacitor was 800 µF and the pulse duration of plasma current (0.67 ms) was equal to the duration that a positive loop voltage would be supplied by the increase in the OH coil current. Based on the results, the number of turns of PVF coils was decided to be 20 each, considering rough consistency with the available switch (current limit 1.6 kA) and capacitors (200 µF).

The PVF coil current waveform can be adjusted to the optimum one by varying capacitance and charging voltage of the capacitor. The capacitance is varied to adjust the rise time, the duration from the start of discharge to the current peak, while the charging voltage is varied to adjust the value of the peak current. The rise time is roughly given by $\pi\sqrt{LC}/2$ since the PVF coil circuit is regarded as an LCR circuit with a damped oscillation condition as shown in Fig. 8. Of course, the optimum values of capacitance and charging voltage for PVF coils depend on capacitance and charging voltage for OH coils. Therefore, it is needed to do analysis for various values of capacitance of OH circuit capacitor that will be used in the experiment, though it was done for only one case (800 µF) in the previous analysis in the design phase.

Optimization of PVF coil current waveform was made in a two-step process. First, the optimal PVF coil current waveform was evaluated by calculating plasma equilibrium using TOSCA code, with input of OH coil current waveform for various values of capacitance of OH circuit capacitor. And secondly, based on the results, the capacitance and the charging voltage of capacitors for PVF coils were scanned to fit the optimal coil current waveform in a circuit simulator, LTspice.

3. Equilibrium Analysis with TOSCA Code

For PVF coil current optimization, the vertical fields produced by the OH coil current and by the eddy current in the vacuum vessel should be taken into account. The TOSCA code is used for PVF coil current optimization, including these effects.

The TOSCA code is a free-boundary equilibrium analysis code [3], which evaluates target poloidal coil current to achieve target plasma equilibrium parameters including the plasma current, the plasma major radius, the plasma minor radius, the elongation, the poloidal beta and the plasma internal inductance, given by input. The target coils are PVF coils in the present analysis. According to input data, TOSCA code analyzes the time evolution of plasma equilibrium, where the Grad-Shafranov equation is solved with a discrete mesh at each time step. The eddy current induced in the conductors such as the vacuum vessel is calculated by time derivative of the flux linked to each conductor evaluated by successive equilibria. The vertical fields produced by PVF coils, OH coils and eddy current are separately calculated and added. Finally, the optimal PVF coil current waveform for keeping the plasma equilibrium is obtained.

The capacitance of capacitor for the OH coil circuit can be varied by four steps, 200, 400, 600 and 800 µF, by changing the number of capacitors to be connected. The OH coil current waveform was obtained for each capacitance in the circuit test without plasma, and it was used in the TOSCA analysis. The discharge duration of OH coil current depended on capacitance of capacitor for OH coils. The maximum of OH coil current was set ~ 2200 A in each case, considering the present operation limit. The plasma current waveform was assumed to be a sine wave with its maximum of 1 kA, whose duration is equal to the duration of positive slope of the OH coil current. Figure 3 shows an example of the time evolution of the plasma current and the OH coil current used in the TOSCA analysis.

In the analysis, the vacuum vessel was modeled by 62 conductor ring blocks, with the resistivity of 7.2×10^{-7} Ωm. The plasma internal inductance was 1.0, and the poloidal beta was almost zero. The toroidal magnetic field strength was 0.1 T at $R = 0.1$ m. The plasma major radius was varied from 0.071 m to 0.092 m, and the minor radius was varied from 0.005 m to 0.026 m during the plasma current ramp-up phase, to increase the plasma volume with the increase in the plasma current while keeping the high field side edge of the plasma at $R = 0.066$ m that is determined by the stainless steel plates on the TF coils.

The validity of the TOSCA analysis was confirmed by

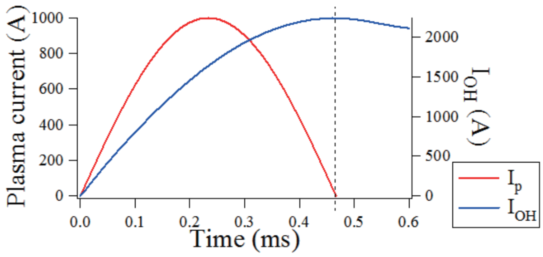

Fig. 3 Relation between plasma current and OH coil current. The capacitance of OH coil circuit capacitor is 400 µF.

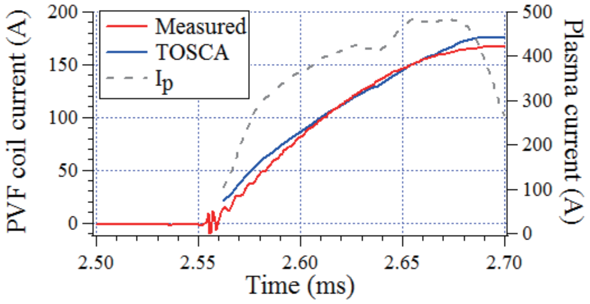

Fig. 4 Comparison of PVF coil current, measured and TOSCA output.

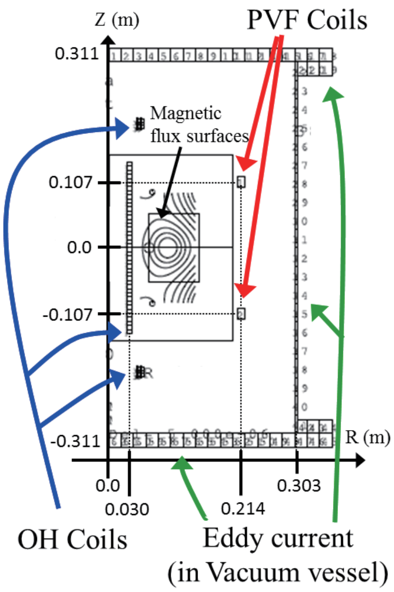

Fig. 5 Magnetic flux surfaces and current components.

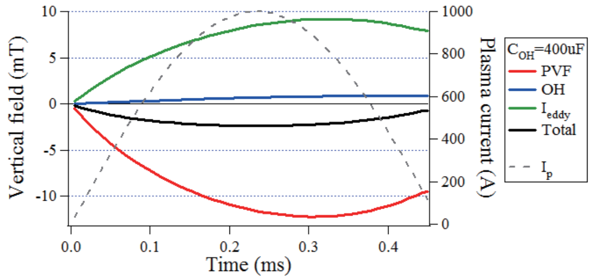

Fig. 6 Vertical fields produced by each current and the plasma current. The vertical fields by the PVF coil current, the OH coil current, and the eddy current are shown by red, blue and green curves, respectively.

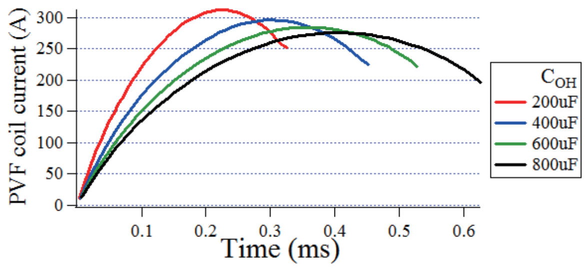

Fig. 7 Optimal PVF coil current waveforms for four values of capacitance of capacitor for OH coils.

analyzing the tokamak experiment data. Figure 4 shows the two PVF coil current waveforms, one is measured, and the other is output of TOSCA. We have relatively good agreement between the output results of analysis with TOSCA and the measured current.

Figure 5 is an example of tokamak equilibrium obtained by the TOSCA code where the magnetic flux surfaces and poloidal field coils and eddy current elements (vacuum vessel) are shown. Figure 6 shows time evolution of vertical fields at $R = 0.096$ m and $Z = 0$ m produced by each current and of plasma current, in the case of capacitance of capacitor for OH of 400 µF. Figure 6 indicates that the eddy current has a very large contribution to the vertical field in the plasma region. This is because the vacuum vessel of TOKASTAR-2 has no breaks in the toroidal direction. The eddy current is large and has longer duration than the plasma current. Namely the eddy current has a peak later than the plasma current, so that the optimal vertical field produced by PVF coil, and hence the PVF coil current waveform, also should have a longer duration.

Figure 7 shows the optimal PVF coil current waveforms for four values of capacitance of capacitor for OH coils. The required current decreases and the duration becomes longer gradually with the increase of capacitance.

4. Scanning Parameter of the Capacitor for PVF Coils by Circuit Simulator

Based on previous results, capacitance and charging voltage of capacitors for PVF coils was determined to realize the optimal PVF coil current waveform by the analysis using the circuit simulator, LTspice. Figure 8 shows the simplified circuit of PVF coil system and OH coil system on LTspice. The value of self-inductance and resistance of coil circuits and the mutual-inductance between the OH coils and the PVF coils were determined based on the measured waveform at the vacuum discharge. The

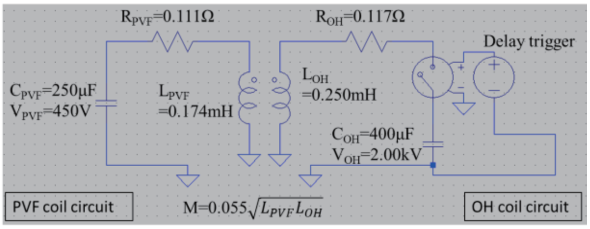

Fig. 8 Simplified circuit of PVF coil system (left) and OH coil system (right) on LTspice. M denotes the mutual inductance between the PVF coils and the OH coils. The delay trigger denotes the time delay of OH coil circuit discharge from the PVF coil circuit discharge.

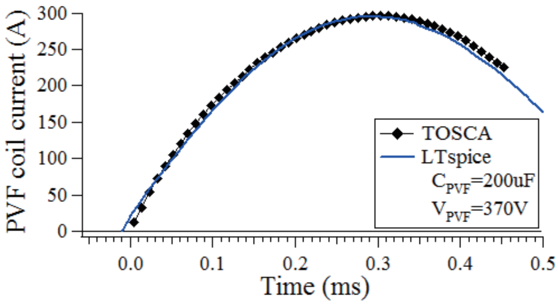

Fig. 9 PVF coil current waveforms evaluated by analysis using TOSCA code and obtained by LTspice.

optimum value was determined by running the calculation while gradually varying capacitance and charging voltage of capacitor for PVF coils to fit the optimal coil current waveform, and while adjusting the discharge starting timing. Figure 9 shows two PVF coil current waveforms, one is the optimal waveform evaluated by analysis using TOSCA code, the other is the waveform obtained by LTspice which is most aligned with the optimal waveform determined by TOSCA code.

Table 1 shows the capacitor parameters for OH coils and PVF coils. The capacitance for PVF coils increases roughly in proportion to the capacitance for OH coils.

However, these results are just indication; there may be a slight difference in practice. In particular the waveform of the plasma current would be varied depending on the device and experimental conditions. So, in the future experiments, capacitance and charging voltage for PVF coils will be scanned based on these results to find the optimum conditions.

Table 1 Capacitor parameters for OH coils and PVF coils.

Capacitors			
For OH coils		For PVF coils	
Capacitance	Voltage	Capacitance	Voltage
200μF	2.73kV	120μF	500V
400μF	2.00kV	200μF	370V
600μF	1.68kV	290μF	300V
800μF	1.46kV	380μF	260V

5. Conclusions and Future Plans

The optimal PVF coil current waveform for keeping the plasma equilibrium in TOKASTAR-2 was obtained by calculation using a free-boundary equilibrium analysis code, TOSCA code, and then the capacitance and charging voltage of capacitors for PVF coils were determined to realize the optimal PVF coil current waveform by analysis using the circuit simulator, LTspice. Based on these results, optimization of tokamak plasma equilibrium control in the actual device will be carried on.

After that, tokamak plasma properties including the radial profile of the poloidal magnetic field will be investigated. In parallel, the helical field produced by HF coils and AHF coils will be applied to tokamak plasma to study the effect of helical field to the tokamak plasma.

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