**The Interaction and Protection
of Superconducting Poloidal Field Coils
and Toroidal Field Coils in a Tokamak
Experimental Power Reactor**

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MASTER

OAK RIDGE NATIONAL LABORATORY

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COILS AND TOROIDAL FIELD COILS IN A TOKAMAK
EXPERIMENTAL POWER REACTOR

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Abstract

The protection problems of superconducting coils in a large tokamak device are delineated. Effects of the plasma discharge on the first wall, the induced voltage, and the temperature rise during the quench of a superconducting coil, as well as the mechanical load on coils due to their mutual interaction under normal or fault conditions, are discussed. Various design choices and protection schemes are used to ensure the integrity of the coils during quench. For the Oak Ridge EPR design, a scheme of connecting symmetrically-located toroidal field coils in groups and isolating and discharging the fault coil only gives satisfactory results.

^{*} Research sponsored by the Energy Research and Development Administration under contract with Union Carbide Corporation.

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Introduction

The magnet systems of a tokamak Experimental Power Reactor (EPR) store tens of gigajoules¹ of magnetic energy. It is vital to the successful operation of a reactor to be able to bring down this tremendous amount of energy safely and reliably so that neither the nuclear systems (blanket/shield) nor the magnets themselves are damaged. When a superconducting toroidal field (TF) or poloidal field (PF) coil quenches (i.e., goes normal in an uncontrollable way), the stored energy will be converted into heat by joule heating. A damaging temperature rise and associated thermal strain could result if this energy is not extracted quickly enough. On the other hand, a large terminal voltage may be developed if one tries to discharge a coil too quickly. In the multi-coil system of a tokamak reactor, the latter problem can be reduced by parallel connection of the coils or further segmentation of a coil.²

The pulsing PF coils induce a tipping out-of-plane load on the TF coils under normal operating conditions. The mutual inductive coupling between TF coils, if only one or a few of them are discharged, also induces out-of-plane loads that tend to push the coils out away from the faulty coils. Thus not to discharge all the TF coils introduces

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additional mechanical problems. On the other hand, if one can limit the number of coils to be discharged, the downtime will be shorter. One should also be mindful of the plasma when discharging the TF or PF coils. A sudden disruption of the plasma might deposit excess energy on the blanket first wall. The fewer the number of TF coils to be discharged, the less the chance that this incident could happen. Therefore, careful consideration of coil connection and the discharging scheme is warranted.

Compromises in limiting the temperature excursion, induced terminal voltage, induced current, mechanical fault loads, and complexity of circuitry should be evaluated for a given system. This paper considers the particular case of the Oak Ridge EPR design.³ Furthermore, initiation of the protection switching relies on a good detection mechanism. A fault detection scheme based on loss voltage measurement⁴ is also described.

System Parameters

The nuclear island of the Oak Ridge EPR reference design is illustrated in Fig. 1. There are 20 TF coils. Each has an oval shape with a vertical bore of 9.7 m and a horizontal bore of 7.4 m. It is designed for a maximum magnetic field at the winding of 11 T, to supply a field of 4.9 T at the plasma axis. The superconductors are multifilamentary Nb₃Sn for the high field layers and NbTi for the low field layers. The conductor cable is housed tight in an Al-alloy conduit and cooled by forced-flow supercritical helium. Four conductor conduits are layer-wound in parallel to form a 78 kA current path. Welded stainless steel honeycomb frames form a rigid structure for the conductors. The current density over the conductor conduit is 4030 A/cm^2 and that over

the whole coil case is 1790 A/cm^2 . The PF coil system consists of four groups of coils: ohmic heating (OH) primary coils, shield-vertical field (S-VF) coils, decoupling coils, and trim-vertical field (T-VF) coils. The S-VF and decoupling coils are normally run in series, but need to be disengaged with one another in the emergency shutdown as will be discussed later. The S-VF coils are located inside the TF coils⁵ and are wound with water-cooled copper conductors. The rest are all superconducting coils. Figure 2 shows the relative positions of the entire coil systems, both PF and TF. The plasma current is parallel to the toroidal magnetic field and opposite to the currents in the OH coils in the burn phase. The system parameters relevant to the present discussion are listed in Table I.

Consideration of Shielding Shells for the TF Coils

Consideration of shielding and protecting the TF coils against the normal operating pulsed field and plasma current disrupting transients with a conductor shell has been performed. The conductor shell can be in the form of double donuts, one inside and the other outside of the TF coils, electrically connected through a vertical cut. In order to shield the poloidal field completely out of the TF coils, it is found that the shell thickness would be prohibitively high. For example, 40 cm of copper operated at nitrogen temperature would be required for each shell, if it is used alone.

Instability in the plasma could cause a current disruption in a matter of micro-seconds. The S-VF coil cannot shield this transient field effectively enough. With a copper shell of 1.3 cm, it is found that the transient can be reduced to 0.2 T/sec or below. However,

its presence may degrade the normal shielding capability of the S-VF coils and interfere with the vertical field trimming function of the T-VF coils. This is because in the copper shell the pure vertical field has a diffusion time constant about seven times longer than the plasma current produced poloidal field. A normal conductor shielding shell for the TF coils is thus not recommended for the present machine. Although the disrupting transient field would be high, the total ac loss induced in the TF coils is not expected to be large enough to quench the coils.

Fault Detection

A previous study⁶ has concluded that a passive self-protection scheme for a superconducting coil such as a secondary inductive coil, a resistor permanently connected in parallel, or an insulator of high thermal conductivity, suffers from low energy extraction efficiency or longer downtime after discharge. The most promising protection scheme which is also the most common scheme in use provides a standby external resistor that can be switched into the coil circuit for discharge. The success of this scheme depends heavily on reliable detection of the fault condition in the magnet. Very many non-electrical fault-detection devices might be required in order to cover the whole winding region. They might also suffer from slow response time or their sensitivities may be degraded by the strong magnetic field⁷ and/or very low temperature environment. Electrical measurements, on the other hand, are subject to interferences from the charging/discharging of the magnet itself or the pulsing of other magnets. These inductive signals often overwhelm the fault signal. For example, a normal zone 1 m long in the TF coil produces a voltage of about 70 mV, while the inductive voltage for a

neighboring coil quench is as high as 180 V. Thus the main problem here is to compensate the inductive signals. A simple scheme with measurement of loss voltage can accomplish this. The terminal voltage of a coil in a multiply-coupled magnet system can be expressed by

$$V_i = I_i R_i + \frac{d\phi_i}{dt} + L_i \frac{dI_i}{dt} + \sum_{i \neq j} M_{ij} \frac{dI_j}{dt},$$

where $I_i R_i$ represents normal-zone voltage and $d\phi_i/dt$ represents voltage induced by the flux motion inside the superconductor. Thus the loss voltage to be measured is

$$V_i^{\text{loss}} = I_i R_i + \frac{d\phi_i}{dt}.$$

The self- and mutual-inductive voltages are proportional to dI_j/dt . This can be picked up by a Rogowski coil at the power supply bus-bar (away from the magnets) of each coil or group of coils. Differential amplifiers on line with each pick-up coil make the M_{ij} compensations. A schematic diagram of this approach with two coupled magnets is shown in Fig. 3. Compensation down to 0.1% of the inductive voltage was demonstrated in a recent ac loss experiment.⁴ The compensation factors so obtained are independent of the charging/discharging rate of the coils and can be predetermined by charging one coil and monitoring the voltage in the second coil with all other coils in open circuit. It is desirable to automate this checking system in a tokamak reactor because of the large number of checks required. One might note further that the loss voltage ($d\phi/dt$) induced by flux motion appears before the normal zone voltage ($I_i R_i$). Valuable information may thus be obtained even before a quench occurs.

Plasma Consideration and General Strategy

Before shutdown of the magnet systems, it is prudent to consider what will happen in the plasma, blanket, and shield. In particular, the thermal loading on the first wall should not be taken lightly. One estimate⁸ indicates that when a plasma of 2 keV mean particle energy deposits its thermal energy uniformly on the first wall in half a millisecond, the temperature rise of the surface will exceed 300°C. The magnetic energy of the 7.2 MA plasma current is about fifteen times the 2 keV plasma thermal energy. The first wall is very probably unable to bear an abnormal discharge of the plasma. A sudden discharge of all the TF coils is likely to lead to an immediate quench of the plasma. Therefore, it is recommended that only the quenched TF coil be discharged and that all the other coils and plasma be kept (if possible) in operation.

If one of the PF magnets has quenched, it is then unlikely to hold the plasma. In this case, we propose to discharge the plasma first, then all the PF coils. The TF coils can remain in operation. To discharge the plasma, irrespectively of whichever PF coil has quenched, the first step is to reconnect the decoupling coils and the S-VF coils into parallel circuits, as shown in Fig. 4. Then the S-VF coils can be discharged quickly (in 2 sec) through an external dump resistor. The S-VF coils are now acting as a discrete conducting shell to the plasma because of their very close mutual coupling, and the plasma current will be driven down together with the current in the S-VF coils. Minor changes in the T-VF and OH coils may be necessary to keep the plasma centered and to supplement the flux swing. After the plasma has been discharged, one can proceed to discharge the remaining PF coils.

Thermal and Electrical Considerations

The temperature excursion of a normal zone in a superconducting magnet depends on the current density, the magnetic field, and the heat transfer characteristics. The circulating helium, which is vital to the stability of the magnet, plays a minor role in protection. Even in our forced-flow scheme the helium flow velocity (approximately 0.25 m/sec) is still slower than the normal-zone propagation velocity^{9,10} (approximately 1 m/sec); i.e., the helium can be treated as essentially stationary. As the temperature of the normal zone goes up, the density and the available enthalpy of the helium goes down rapidly. For a temperature rise of 100 K in the TF coil, the enthalpy contribution of helium is less than 10% of that of the stabilizing normal conductor. Because of the high current density involved (see Table I), a normal zone in a TF coil will raise its temperature to 300 K in about 30 sec, if the current is unchanged. It is thus advisable to be able to discharge the magnet in this time frame, if needed. An external dump resistor of 17 m Ω is required for each TF coil if all 20 coils are to be discharged in parallel. The temperature excursion inside the coil is then limited to 100 K with an associated thermal strain $\sim 5 \times 10^{-4}$, and a terminal voltage of 1.3 kV will be developed across each coil. Reduction of this voltage can be achieved by segmenting the coil. For example, dividing a coil into two segments (such as that shown in Fig. 4) will reduce the required dump resistance and the resulting terminal voltage on each segment by half. Because of the magnetic coupling, if the quenched coil alone is discharged, the energy dissipated is less than 1/20 of the total stored energy. However, in the case of the remaining coils

connected in parallel, the nearest neighbor can have an asymptotic induced current increase as high as 30%.⁶ This in turn leads to a large out-of-plane load, lateral displacement,¹¹ and possible magnetoelastic instability.¹² In the case of the remaining coils connected in series, induced voltages of the same order of magnitude as the quenched coil will be developed.⁶ The maximum voltage may occur at any point in the toroid, depending on which coil is quenched, and this makes electrical protection more difficult. As a compromise between induced current and voltage, we propose to divide the 20 TF coils into four parallel groups. The symmetrically-located coils in each group are connected in series and charged by a common power supply. If one coil quenches, it is isolated from the group it belongs to and discharged by its own dump resistor. This is necessary because even higher currents would be induced in the nearest neighbor groups if all five coils in a group were to be discharged. An illustration of this arrangement is shown in Fig. 5. With coil #1 quenched, the two groups with coils next to #1 could increase their current by 7%, the other group could increase by 2%, and the coils originally in series with #1 could decrease by 4%. The induced voltages in the undischarged coils are no more than ± 300 V. The discharge time constant for #1 is now 10 sec, and the temperature rise is about 50 K. Thus this active switching scheme produces manageable numbers.

The OH coils are designed to withstand high terminal voltage (up to 70 kV for the two-group option) for the charge-up phase. With a 7 m Ω dump resistor, they can be discharged in 30 sec with a terminal voltage of 1.3 kV. Similarly, with dump resistors of 0.05 m Ω for the decoupling

coils and $0.1 \text{ m}\Omega$ for the T-VF coils, the terminal voltages are 24 V and 40 V, respectively. The temperature excursions are all limited to 100 K. The S-VF coil needs to be discharged quicker (2 sec). Using four parallel segments with $6.4 \text{ m}\Omega$ dump resistors, the voltages can be limited to 700 V.

Mechanical Loading

The magnetic fields due to the normally operating and abnormal current distributions introduce mechanical loadings on each coil. For simplicity, we divide them into two categories, in-plane and out-of-plane loads. The in-plane hoop tensions on a TF coil under normal and fault conditions are given in Fig. 6. The fault loads are on the coil nearest to a quenched coil due to the redistributed currents discussed in the previous section. It shows that the tensions are decreased slightly when the outer portion of the coil remains near constant tension. Figure 7 shows the out-of-plane loads under the same conditions. The normal operation loads are due to the pulsed PF coils and plasma current. These produce a torque which tends to flip the coil. The fault loads are, on the other hand, symmetric with respect to the midplane. They are acting in the direction of pushing the coils away from the quenched coil. Even with our distributed scheme, these fault loads are about an order of magnitude higher than that under normal conditions. The results of all other coils connected in parallel are about 20% higher. Since the PF coils are expected to be discharged in groups, their induced loads on the TF coil will not be worse than those of the normal operating conditions. Therefore a lateral support structure designed for the TF coil in fault should be sufficient.

The loading on a PF coil depends on its location, current, and current direction. We shall use the first and the last T-VF coil to illustrate the problems. Assume the TF coil on the toroidal angle $\Theta=0$ is at fault. The in-plane and out-of-plane loads on $R = 1.7$ m T-VF coil are shown in Figs. 8 and 9. This coil is very close to the OH solenoid and its current is opposite to that of the OH coils. Under normal conditions its in-plane load is a constant compression and the out-of-plane load is a pure lifting force. When the TF coil at $\Theta=0$ is quenched and the currents redistributed, the compressive loads decrease on the quenched coil side and increase on the far side up to $\pm 3\%$. This results in a bending moment and a net translation force of 0.21×10^6 N toward the quenched coil. The out-of-plane loads change even more significantly (up to $\pm 25\%$) resulting in a torque flipping up away from the quenched coil. For the $R = 11.7$ m T-VF coil the field components in the winding due to the PF coils and the TF coils are of the same order of magnitude. This results in a rather complex loading pattern under both normal and fault conditions. However, since the field strengths are weaker, the level of loading is small compared with those on the inner PF coils. The loads shown in Figs. 10 and 11 indicate that local bending moments would be present even under normal conditions. Again a net translation force (now toward $\Theta=\pi$ direction) and flipping torques are developed under fault conditions. Because of the unpredictable location of the TF coil at fault, the support structures of the PF coils should be designed for the translation and bending fault loads.

Summary

The protection problems of the magnet systems of the Oak Ridge EPR were discussed. A simple yet very informative voltage measurement scheme serves to detect the fault signal of the coils. Protection of the blanket first wall is provided by controlled discharging of the plasma current. Active switching and external dump resistors are used to discharge the coils. The TF coils are divided into symmetrically located groups. A quenched coil can be isolated from the group it belongs to and can be discharged separately. This scheme keeps temperature excursion, terminal voltage, and induced currents on adjacent coils all within easily manageable ranges. There is also significant reduction in out-of-plane loads. The PF coils, which pose no problem in containing the temperature excursion and terminal voltages, require a closer look into the support of their complex fault mechanical loads.

Acknowledgement

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Table I

System Parameters of the Oak Ridge EPR Reference Design

Plasma

Shape	Circular
Radius (m)	2.25
Current (MA)	7.2
Burn time (sec)	100
Self-inductance (μH)	12
Particle density (cm^{-3})	7.5×10^{13}
Field at center line (Tesla)	4.9

First Structural Wall

Neutron wall loading [$\text{MW(th)}/\text{m}^2$]	0.55
Material	Type 316 stainless steel
Safe-operation temperature limit ($^{\circ}\text{C}$)	550
Coolant (helium) outlet temperature ($^{\circ}\text{C}$)	370

Toroidal Field Coils

Shape	Oval
Number	20
Horizontal opening (m)	7.4
Vertical opening (m)	9.7
Total stored energy (GJ)	29
Major radius (m)	6.75
Coil dimension (cm)	69 x 62
Number of layers/coil	16
Number of turns/layer	6.5

Table I

(continued)

Toroidal Field Coil Conductor

Configuration	Composite cable in a square, aluminum-alloy conduit cooled with supercritical forced-flow helium
Conduit dimensions (cm)	2.2 x 2.2
Cable diameter (cm)	2
Helium/conductor ratio	0.48/0.52
Conductor current (kA)	19.5 (four in parallel)
Conductor composition Cu/SC	0.86/0.14

Poloidal Field Coils

Configuration	Air core with minimum field at the toroidal field coils
Conductor:	
in the ohmic heating decoupling, and trim-vertical field coils	NbTi in Cu and CuNi mixed-matrix conductor
in the shield-vertical field coils	Normal copper

Number of Coils

T-VF	12
Decoupling	Central solenoid plus 6
S-VF	16
OH	Central solenoid plus 16

Poloidal Field Coil Conductor

Configuration	Bundled strands in stainless steel conduit cooled with forced-flow supercritical helium
Current (kA)	25
Helium/conductor ratio	1 : 1
Conductor composition: NbTi:Cu:CuNi	0.2 : 0.7 : 0.1

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Figure Captions

- Fig. 1. Oak Ridge EPR reference design.
- Fig. 2. Coil systems for the Oak Ridge EPR reference design.
- Fig. 3. Fault detection by loss voltage measurement. In the equations shown, the left-hand side represents the measurement and the right-hand side represents its physical content. The coefficients are related to the inductances as: $f_i \propto L_i$,
 $f_{ij} \propto M_{ij}$.
- Fig. 4. Coil disengagement and discharging scheme.
- Fig. 5. TF coils protection circuitry. Only one of the four groups is shown. The switching sequence for discharge is also indicated.
- Fig. 6. In-plane mechanical loading for a TF coil under normal and fault conditions. The hoop tension is calculated by the average field on the coil disregarding effects of external supports. The poloidal angle shown is counted from the outermost point with origin at plasma center of $R = 6.75$ m.
- Fig. 7. Out-of-plane mechanical loading for a TF coil under normal and fault conditions.
- Fig. 8. In-plane mechanical loading for the PF coil at radius = 1.7 m under normal and fault conditions. The toroidal angle shown is counted from the quenched coil. Negative tension represents coil in compression.
- Fig. 9. Out-of-plane mechanical loading for PF coil at radius = 1.7 m under normal and fault conditions. Positive forces point upward.
- Fig. 10. In-plane mechanical loading for the PF coil at radius = 11.7 m under normal and fault conditions.
- Fig. 11. Out-of-plane mechanical loading for the PF coil at radius = 11.7 m under normal and fault conditions.

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Fig. 1

Fig. 2

ORNL-DWG 76-9875

Fig. 3

ORNL-DWG 76-9874

NORMAL OPERATION: AS SHOWN

SEGMENT DISCHARGE: (a) CLOSE S_1 AND S_2

(b) OPEN S_3 TO ISOLATE FROM POWER SUPPLY

(c) CLOSE S_4, S_5, S_6

(d) OPEN S_2 AND S_7

(e) OPEN S_5 AND/OR S_6 TO DISCHARGE

Fig. 4

1. FOUR SYMMETRIC GROUPS

2. NORMAL OPERATION :

S_1 AND S_1' CLOSED ; S_2 , S_2' , S_3 AND S_3' OPEN

3. DISCHARGE :

(A) CLOSE S_2' AND S_3' , THEN OPEN S_1' FOR THE QUENCHED COIL

(B) OPEN S_3' TO DISCHARGE THE QUENCHED COIL THROUGH ITS R_D

(C) THE POWER SUPPLY CAN BE ISOLATED THROUGH S_1 , S_2 , AND S_3 , IF DESIRED

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

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