JAERI-M
91-123

CONCEPTUAL DESIGN OF SC MAGNET SYSTEM FOR ITER (IV)

—— POWER SUPPLY AND CRYOGENIC SYSTEM ——

August 1991

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Japan Atomic Energy Research Institute

編集兼発行　日本原子力研究所
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Conceptual Design of SC Magnet System for ITER (IV)
- Power Supply and Cryogenic System -

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(Received July 8, 1991)

The International Thermonuclear Experimental Reactor (ITER) is an experimental thermonuclear tokamak reactor that will test some new technologies of physics. The conceptual design activity of ITER required the joint work at a technical site at the Max Plank Institute for Plasma Physics in the Garching Germany from 1988 to 1990. The proposals from Japan are summarized by the Fusion Experimental Reactor (FER) Team and the Superconducting Magnet Laboratory of the Japan Atomic Energy Research Institute (JAERI).

This paper describes the Japanese contributions to the utility (power supply and cryogenic system) for the magnet system of ITER. The concepts of a magnet utility design were based on the construction experiences of the domestic test facilities of the Large Coil Task and of the JAERI's Demo Poloidal Coil program. During the conceptual design phase, it is important to know what parts are critical for construction and what subjects need development. In the power supply system, the DC beakers shall be modified to compact size. Several cryogenic components also require scale-up development during the engineering design phase.

Keywords: Fusion, Superconducting, Magnet, Power Supply, Cryogenics

ITER 用超電導マグネット・システム概念設計（Ⅳ）
－ 電源と冷凍システム －

日本原子力研究所那珂研究所核融合工学部
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大川　慶直

（1991 年 7 月 8 日受理）

21 世紀初頭に完成が予定されている国際熱核融合実験炉（ITER）の概念設計活動の超電導マグネット・システムに対する日本の提案を示す。1988 年から 90 年まで，西ドイツのミュンヘン郊外ガルヒンにあるマックスプランク・プラズマ物理学研究所で，この ITER 概念設計活動は行われた。日本の設計案のまとめは原研那珂研究所の核融合実験炉特別チームが中心になり，コイル・システムに関しては，超電導磁石研究室が設計を担当した。

この設計書は超電導コイル・システムに使用する電源と冷凍機システムの設計案を示したものである。本設計案は LCT 国内試験装置や実証ポロイダル・コイル試験装置の製作経験を取り入れることによって技術的妥当性を高めた。概念設計活動においては，どの部品が設計上の問題点かを見いだすことを主題に検討を進めた。その結果，電源系では遮断器の信頼性向上と小型化が重要であることがわかり，冷凍機では大型化のための要素開発が重要であることが判明した。

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1. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is an experimental thermonuclear tokamak reactor that will test some technologies of physics. The conceptual design activity of ITER required the joint work at the Max Plank Institute for Plasma Physics in the Garching Germany from 1988 to 1990. The proposals from Japan are summarized by the Fusion Experimental Reactor (FER) Team and the Superconducting Magnet Laboratory, both from of the Japan Atomic Energy Research Institute (JAERI).

This paper describes the Japanese contributions to the utility for the magnet system of ITER. The concepts of a magnet utility design were based on the construction experiences at JAERI of the domestic test facilities of the Large Coil Task program facility and the Demo Poloidal Coil program facility. During the conceptual design phase, it is important to know which parts are critical for construction, and which subjects require additional for development. In power supply system, the DC beakers shall be compacted. Also, several cryogenic components need to be developed during this next engineering design phase.

2. POWER SUPPLY SYSTEM

2.1. Introduction

The electric power of the PF coil system is calculated to determine the capacity of the power supply system. The schematic circuit for power supply is designed. The quench detection method is designed from the experimental results of the Demo Poloidal Coil program[2].

2.2. Required power for PF coil system

(1) Scenario

The plasma scenario is referred from the reference [1].

(2) Inductance matrix

Number of turns for each PF coil is listed in Table 2.1. The PF coils' inductance matrices are calculated as shown in Table 2.2. All inductances and mutual inductances of the PF coils are calculated for the case of a single connection to power supply.

(3) Mutual inductance between plasma and coils

Mutual inductance between plasma and coils are calculated, with consideration of the major radius and the shape of plasma as shown in Table 2.3.

(4) Results

The calculated current, voltages and powers of each PF coil are shown in Fig. 2.1 (a) to (g). The voltages on PF coils are listed in Table 2.4. The power supply of the PF coil system requires the capacity of 3.9 MW as listed in Table 2.5 and 2.6,respectively.

2.3. Power supply system

(1) PF coil system

The power supply system of PF coil system is shown in Fig. 2.2. It has been decided that only one PF coil shall be connected to one power supply because of the over potential at a grand fault.

(2) TF coil system

The power supply system of the TF coil system is shown in

Fig. 2.3. The series and parallel pattern is selected by the fault analysis, as referred to session 3.

2.4. Quench Detection

The accuracy and the reliability of the quench detection method of the superconducting coils is vital for the safety of the superconducting coils, because the superconducting coil has high current density with large stored energy.

An improved potential method and a fluid dynamic method for the quench detection have been developed for the poloidal coil of the Demonstration Poloidal Coil(DPC)[2]. These methods have high accuracy and reliability when compared with experimental results.

(1) Potential Method

A schematic circuit of the potential method for quench detection is shown in Fig. 2.4. Instrumentation wires and compensation coils are installed for redundancy. The schematic circuit of the quench detection using the potential method is shown in Fig. 2.5.

(2) Fluid dynamic method

The schematic diagram of the quench detection system is shown in Fig. 2.6. Flow meters for the fluid dynamic method of quench detection are located at the inlet of coolant, which is a high field region as shown in Fig. 2.7.

2.5. Interpolation of Summary

(1) The power supply for the SC system is not challenging to design. However, coil protection circuitry presents a challenge.

(2) The coil protection technique is important to reduce energy dissipation during quench in the superconducting magnet. The two coil protection techniques advanced potential method and fluid dynamic method have been selected.

(3) The series and parallel pattern is selected for the TF coil power supply.

References

[1] ITER Poloidal Field System. ITER Document Series, No. 27, IAEA, Vienna, Austria, 1990
[2] K. Yoshida, "Quench Detection Methods of Superconducting Coils for the Fusion Reactor", Cryogenic Engineering of Japan, Vol. 24 (1989) 276

Table 2.1 Turns of PF coil

PF-1	550
PF-2	550
PF-3	550
PF-4	550
PF-5	400
PF-6	320
PF-7	200

Table 2.2 Inductance matrix of PF coils

(UNIT : H)

PF1U	PF2U	PF3U	PF4U	PF5U	PF6U	PF7U	PF1L	PF2L	PF3L	PF4L	PF5L	PF6L	PF7L
8.95D-01	2.94D-01	7.18D-02	2.59D-02	2.79D-02	7.21D-02	5.62D-02	4.98D-02	5.88D-02	1.65D-02	1.18D-02	2.59D-02	7.18D-02	2.94D-01
2.94D-01	8.95D-01	2.94D-01	7.18D-02	5.13D-02	8.45D-02	5.90D-02	4.16D-02	4.66D-02	1.04D-02	6.28D-03	1.18D-02	2.59D-02	7.18D-02
7.18D-02	2.94D-01	8.95D-01	2.94D-01	1.03D-01	9.26D-02	5.70D-02	3.34D-02	3.65D-02	6.96D-03	3.71D-03	6.28D-03	1.18D-02	2.59D-02
2.59D-02	7.18D-02	2.94D-01	8.95D-01	2.15D-01	9.38D-02	5.10D-02	2.63D-02	2.85D-02	4.85D-03	2.37D-03	3.71D-03	6.28D-03	1.18D-02
2.79D-02	5.13D-02	1.03D-01	2.15D-01	1.95D+00	3.12D-01	1.45D-01	6.71D-02	7.30D-02	1.11D-02	4.85D-03	6.96D-03	1.04D-02	1.65D-02
7.21D-02	8.45D-02	9.26D-02	9.38D-02	3.12D-01	4.95D+00	1.37D+00	5.07D-01	5.48D-01	7.30D-02	2.85D-02	3.65D-02	4.66D-02	5.88D-02
5.62D-02	5.90D-02	5.70D-02	5.10D-02	1.45D-01	1.37D+00	2.13D+00	4.93D-01	5.07D-01	6.71D-02	2.63D-02	3.34D-02	4.16D-02	4.98D-02
4.98D-02	4.16D-02	3.34D-02	2.63D-02	6.71D-02	5.07D-01	4.93D-01	2.13D+00	1.37D+00	1.45D-01	5.10D-02	5.70D-02	5.90D-02	5.62D-02
5.88D-02	4.66D-02	3.65D-02	2.85D-02	7.30D-02	5.48D-01	5.07D-01	1.37D+00	4.95D+00	3.12D-01	9.38D-02	9.26D-02	8.45D-02	7.21D-02
1.65D-02	1.04D-02	6.96D-03	4.85D-03	1.11D-02	7.30D-02	6.71D-02	1.45D-01	3.12D-01	1.95D+00	2.15D-01	1.03D-01	5.13D-02	2.79D-02
1.18D-02	6.28D-03	3.71D-03	2.37D-03	4.85D-03	2.85D-02	2.63D-02	5.10D-02	9.38D-02	2.15D-01	8.95D-01	2.94D-01	7.18D-02	2.59D-02
2.59D-02	1.18D-02	6.28D-03	3.71D-03	6.96D-03	3.65D-02	3.34D-02	5.70D-02	9.26D-02	1.03D-01	2.94D-01	8.95D-01	2.94D-01	7.18D-02
7.18D-02	2.59D-02	1.18D-02	6.28D-03	1.04D-02	4.66D-02	4.16D-02	5.90D-02	8.45D-02	5.13D-02	7.18D-02	2.94D-01	8.95D-01	2.94D-01
2.94D-01	7.18D-02	2.59D-02	1.18D-02	1.65D-02	5.88D-02	4.98D-02	5.62D-02	7.21D-02	2.79D-02	2.59D-02	7.18D-02	2.94D-01	8.95D-01

Table 2.3 Mutual inductance between plasma and PF coils (1/2)

TIME STEPS	I 0.0	1.00000D-01	6.00000D-01	3.00000D+00	1.00000D+01	2.00000D+01	2.80000D+01	3.50000D+02	3.60000D+02	3.80000D+02
PF1U	I 0.0	0.0	7.22000D-04	6.67000D-04	6.08000D-04	5.54000D-04	5.26000D-04	5.26000D-04	5.72000D-04	6.08000D-04
PF2U	I 0.0	0.0	4.47000D-04	4.42000D-04	4.31000D-04	4.19000D-04	4.14000D-04	4.14000D-04	4.26000D-04	4.31000D-04
PF3U	I 0.0	0.0	2.37000D-04	2.49000D-04	2.60000D-04	2.69000D-04	2.76000D-04	2.76000D-04	2.68000D-04	2.60000D-04
PF4U	I 0.0	0.0	1.28000D-04	1.40000D-04	1.54000D-04	1.66000D-04	1.73000D-04	1.73000D-04	1.62000D-04	1.54000D-04
PF5U	I 0.0	0.0	2.03000D-04	2.31000D-04	2.66000D-04	2.99000D-04	3.16000D-04	3.16000D-04	2.85000D-04	2.66000D-04
PF6U	I 0.0	0.0	7.72000D-04	9.16000D-04	1.11000D-03	1.31000D-03	1.38000D-03	1.38000D-03	1.20000D-03	1.11000D-03
PF7U	I 0.0	0.0	6.55000D-04	7.84000D-04	9.64000D-04	1.14000D-03	1.20000D-03	1.20000D-03	1.04000D-03	9.64000D-04
PF7L	I 0.0	0.0	6.55000D-04	7.84000D-04	9.64000D-04	1.14000D-03	1.20000D-03	1.20000D-03	1.04000D-03	9.64000D-04
PF6L	I 0.0	0.0	7.72000D-04	9.16000D-04	1.11000D-03	1.31000D-03	1.38000D-03	1.38000D-03	1.20000D-03	1.11000D-03
PF5L	I 0.0	0.0	2.03000D-04	2.31000D-04	2.66000D-04	2.99000D-04	3.16000D-04	3.16000D-04	2.85000D-04	2.66000D-04
PF4L	I 0.0	0.0	1.28000D-04	1.40000D-04	1.54000D-04	1.66000D-04	1.73000D-04	1.73000D-04	1.58000D-04	1.50000D-04
PF3L	I 0.0	0.0	2.37000D-04	2.49000D-04	2.60000D-04	2.69000D-04	2.76000D-04	2.76000D-04	2.68000D-04	2.60000D-04
PF2L	I 0.0	0.0	4.47000D-04	4.42000D-04	4.31000D-04	4.19000D-04	4.14000D-04	4.14000D-04	4.26000D-04	4.31000D-04
PF1L	I 0.0	0.0	7.22000D-04	6.67000D-04	6.08000D-04	5.54000D-04	5.26000D-04	5.26000D-04	5.72000D-04	6.08000D-04

(UNIT : H)

Table 2.3 Mutual inductance between plasma and PF coils (2/2)

TIME STEPS	3.90000D+02	4.00000D+02	5.00000D+02
PF1U	6.67000D-04	7.22000D-04	0.0
PF2U	4.42000D-04	4.47000D-04	0.0
PF3U	2.49000D-04	2.37000D-04	0.0
PF4U	1.40000D-04	1.28000D-04	0.0
PF5U	2.31000D-04	2.03000D-04	0.0
PF6U	9.16000D-04	7.72000D-04	0.0
PF7U	7.84000D-04	6.55000D-04	0.0
PF7L	7.84000D-04	6.55000D-04	0.0
PF6L	9.16000D-04	7.72000D-04	0.0
PF5L	2.31000D-04	2.03000D-04	0.0
PF4L	1.40000D-04	1.28000D-04	0.0
PF3L	2.49000D-04	2.37000D-04	0.0
PF2L	4.42000D-04	4.47000D-04	0.0
PF1L	6.67000D-04	7.22000D-04	0.0

(UNIT : H)

Table 2.4 Voltage on Coils (kV)

	Init	Lim	Lim	Lim	Lim	Lim	DN	DN	SOFT	SOB	EOB
Time(SEC)	0.00	0.10	0.60	3.00	10.00	20.00	28.00	44.00	70.00	90.00	290.00
Ip (MA)	0.00	0.00	0.50	2.00	5.00	10.00	10.00	15.00	22.00	22.00	22.00
PF-1		-10.056	-5.707	-2.602	-1.632	-2.181	-0.156	-1.455	-1.406	-0.179	-0.0763
PF-2		-10.041	-6.763	-3.013	-1.734	-1.720	0.057	-1.365	-1.306	-0.258	-0.0789
PF-3		-9.921	-10.197	-4.134	-2.093	-0.179	0.758	-0.985	-0.938	-0.474	-0.0819
PF-4		-8.856	-9.722	-4.050	-2.842	0.375	1.548	-0.654	-0.860	-0.197	-0.0389
PF-5		-13.706	-9.999	-6.681	-4.708	1.119	3.225	-0.344	-0.264	-0.647	-0.1314
PF-6		-5.172	-10.747	-4.748	-2.581	-3.072	-2.011	-2.529	-2.399	1.300	-0.0999
PF-7		-3.379	-7.431	-3.143	-1.644	-2.168	0.728	-1.282	-1.123	0.347	-0.1681

	EOB	EOC	DN	DN	Lim	Lim	Lim	Lim	Init
Time(SEC)	290.00	310.00	330.00	350.00	360.00	380.00	390.00	400.00	500.00
Ip (MA)	22.00	22.00	15.00	10.00	8.00	5.00	2.00	0.50	0.00
PF-1		-0.029	-0.084	0.475	0.178	0.641	0.431	0.088	0.962
PF-2		-0.012	-0.168	0.399	0.412	0.249	0.577	0.180	0.962
PF-3		0.024	-0.494	0.083	1.165	-1.071	1.002	0.432	0.955
PF-4		0.015	-0.549	-0.117	0.607	-1.482	1.032	0.463	0.855
PF-5		-0.251	-1.227	-0.498	-0.792	-2.092	1.727	0.790	1.341
PF-6		0.154	1.255	1.547	-1.743	2.541	1.438	0.844	0.625
PF-7		1.024	0.475	0.723	0.132	0.633	0.931	0.562	0.416

Table 2.5 Power supply requirement from PF system

	Umax(kV)	Umax(kV)	I max (kA)	
Time(s)	0.0 - 0.6	0.6 - 500.	+	-
PF1	-10.0652	2.6032	+37.11 /	-40.75
PF2	-10.0411	3.0139	+37.11 /	-40.75
PF3	-10.1975	4.1347	+37.11 /	-28.89
PF4	-9.7220	4.0509	+37.11 /	-28.89
PF5	-13.7065	6.6816	+36.32 /	-29.80
PF6	-10.7473	4.7485	+0.78 /	-27.97
PF7	-7.4311	3.1434	+1.25 /	-26.25

Table 2.6 Total power requirements

Time (s)	Power (MW)	
0.0 - 0.6	0.0	-3897.5
0.6 - 500	+376.6	-1391.0

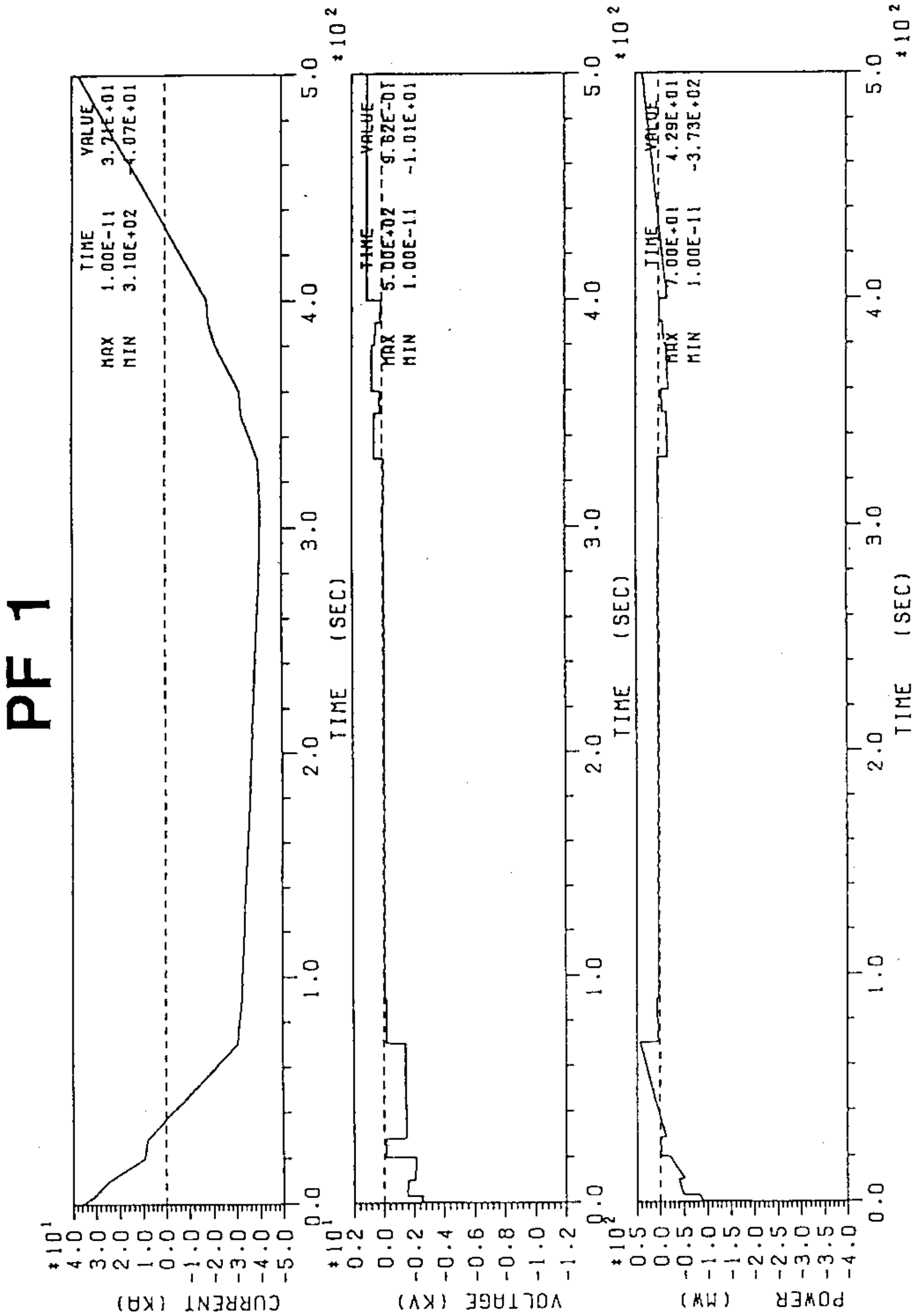


Fig. 2.1 (a) Pattern of current, voltage and power of PF coils -PF 1

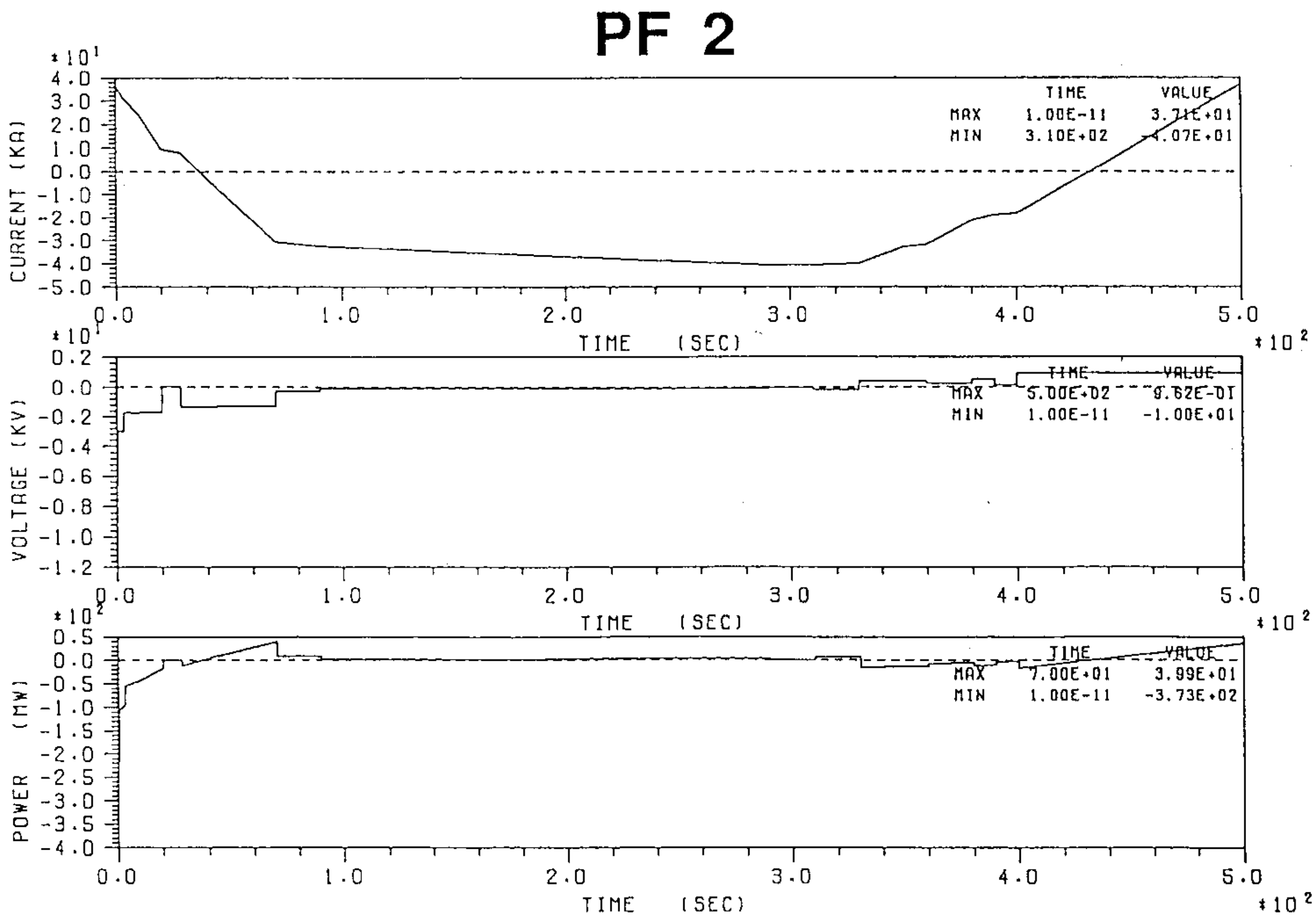


Fig. 2.1 (b) Pattern of current, voltage and power of PF coils
-PF 2

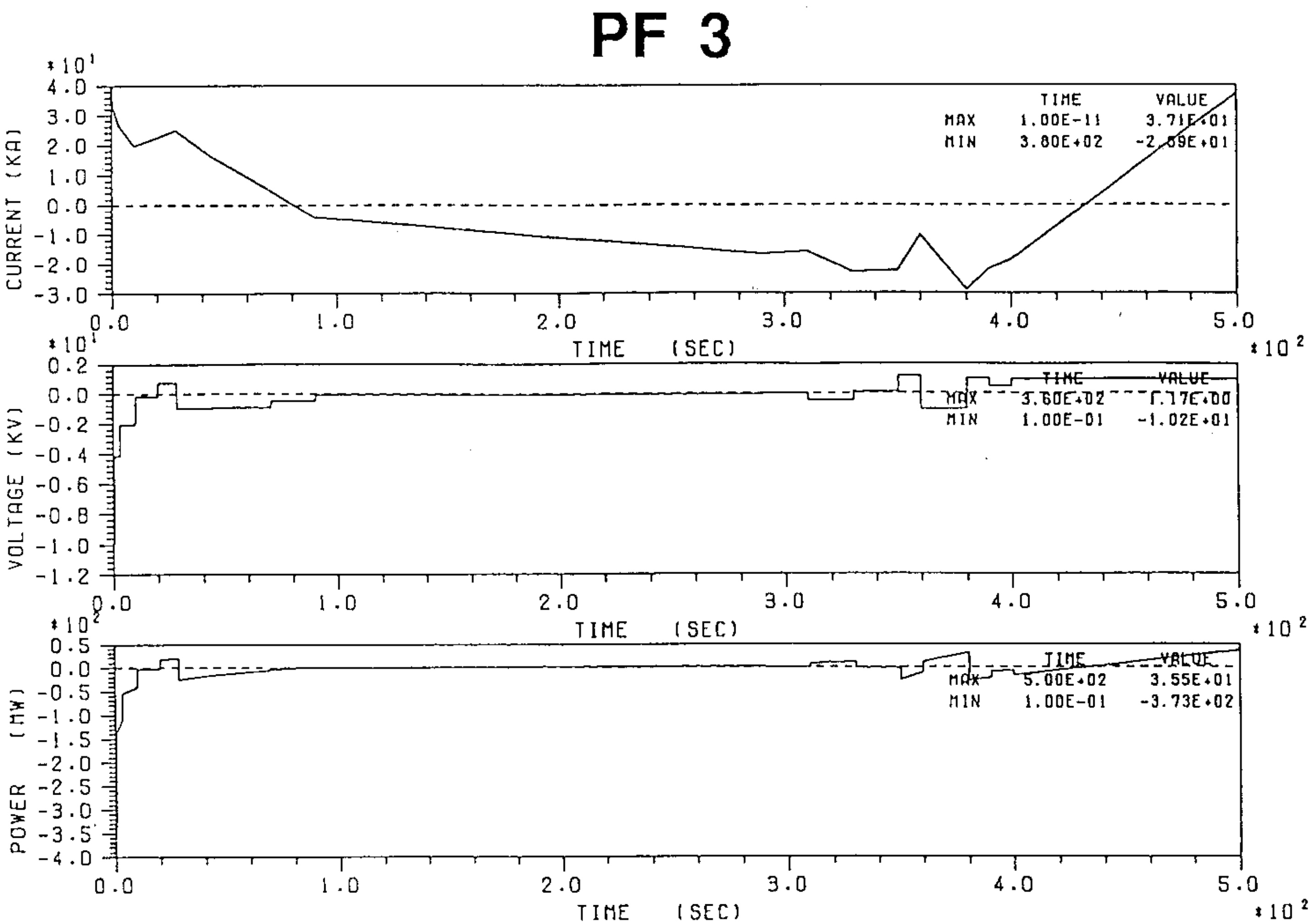


Fig. 2.1 (c) Pattern of current, voltage and power of PF coils
-PF 3

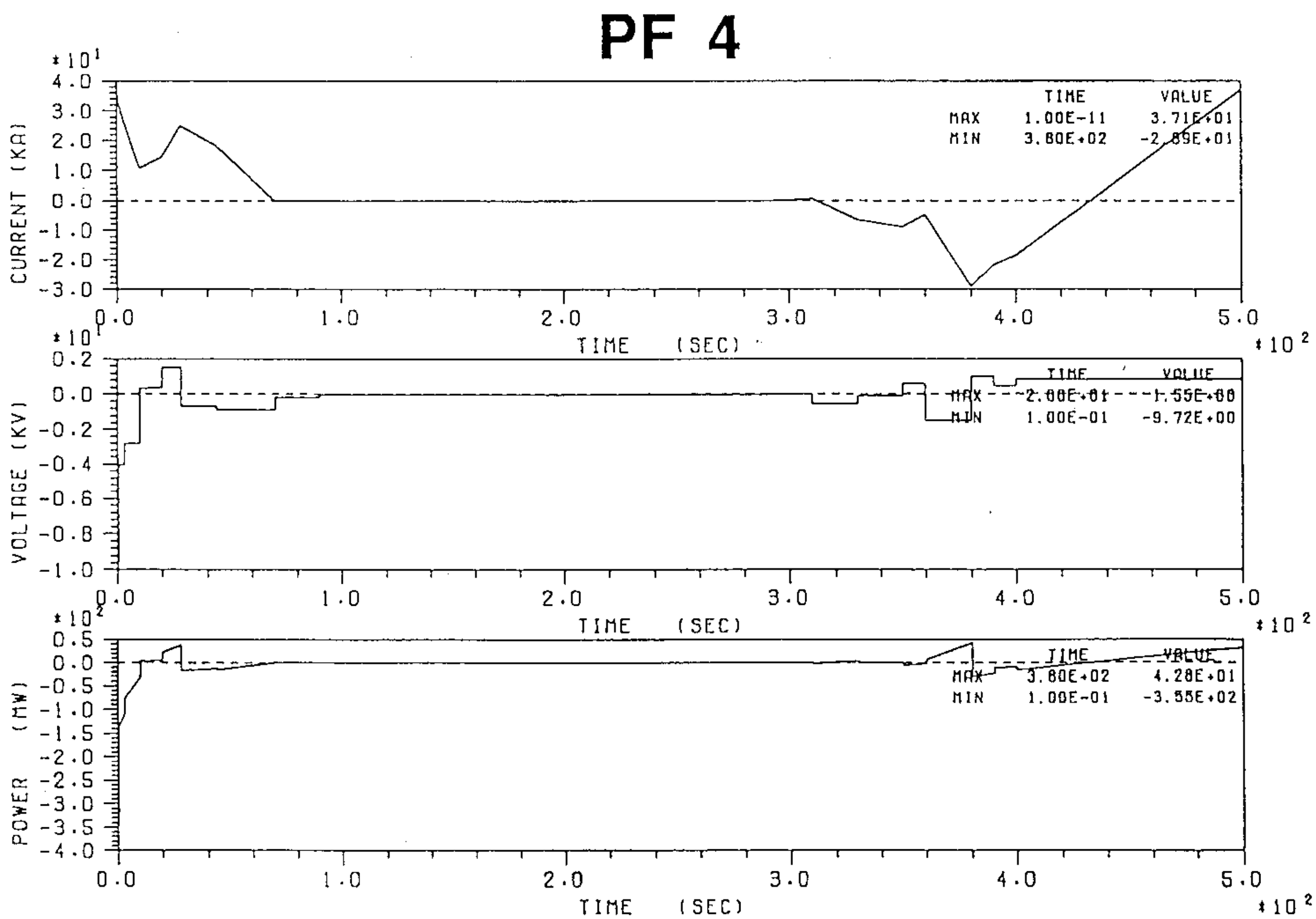


Fig. 2.1 (d) Pattern of current, voltage and power of PF coils
-PF 4

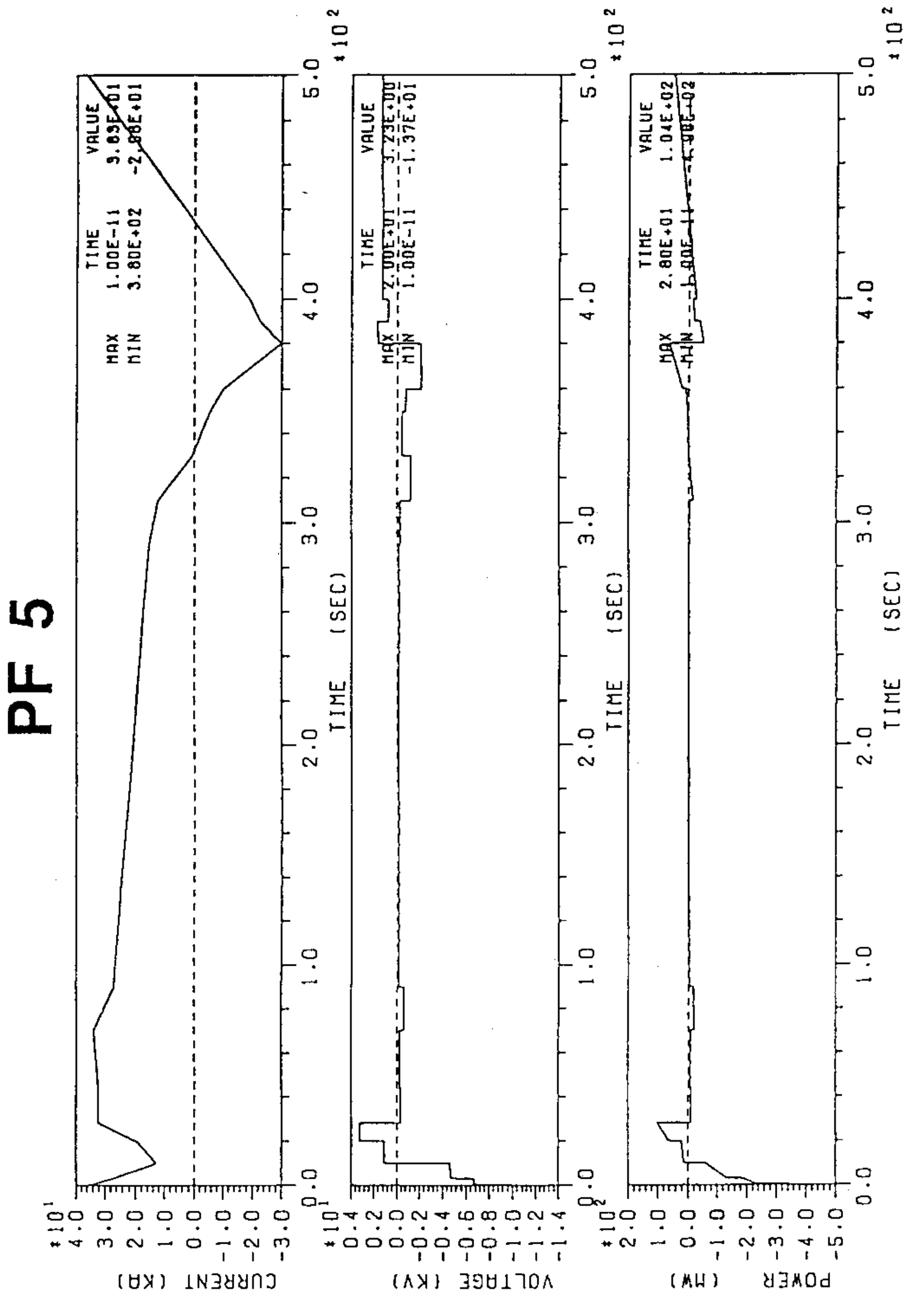


Fig. 2.1 (e) Pattern of current, voltage and power of PF coils
-PF 5

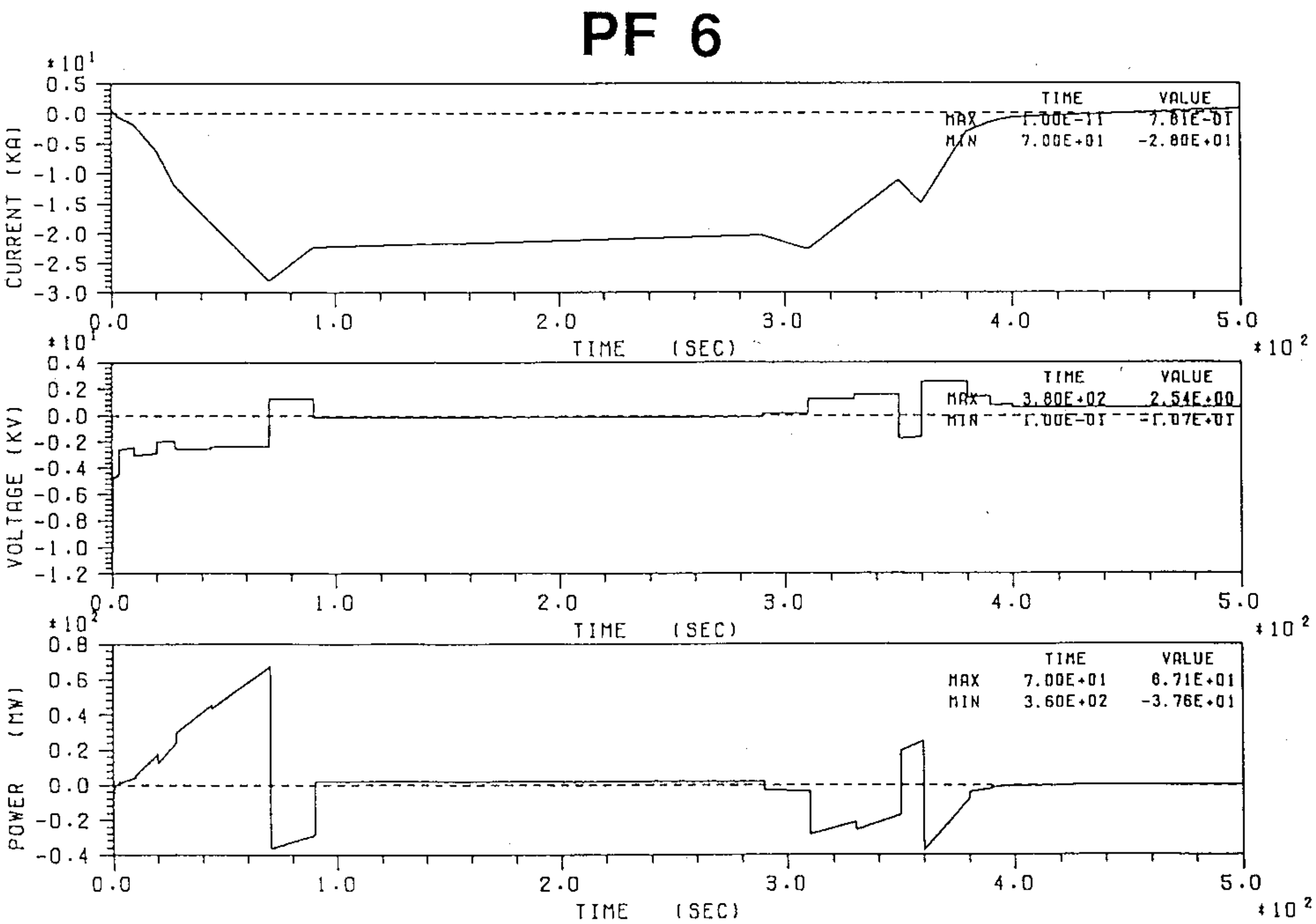


Fig. 2.1 (f) Pattern of current, voltage and power of PF coils
-PF 6

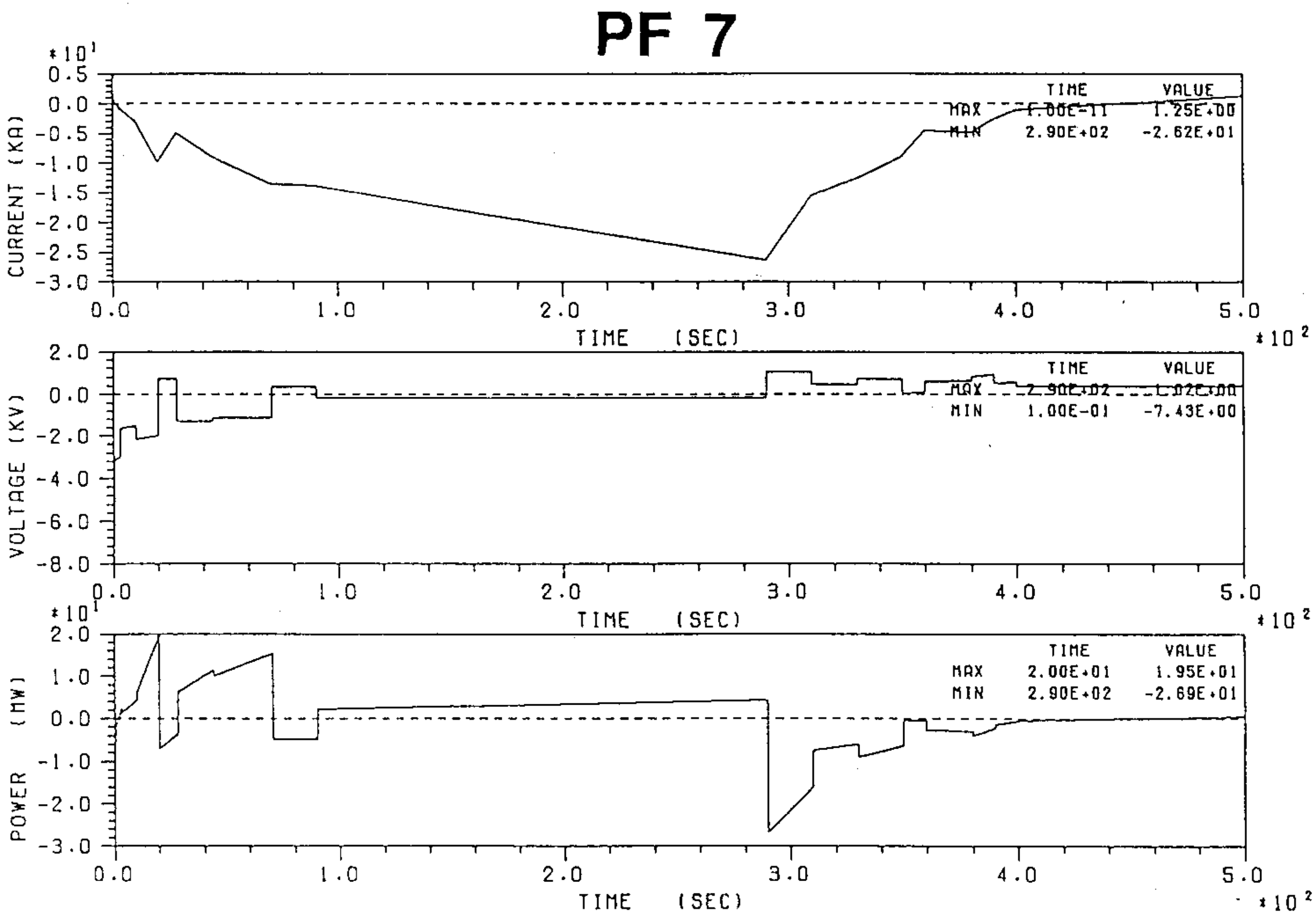


Fig. 2.1 (g) Pattern of current, voltage and power of PF coils
-PF 7

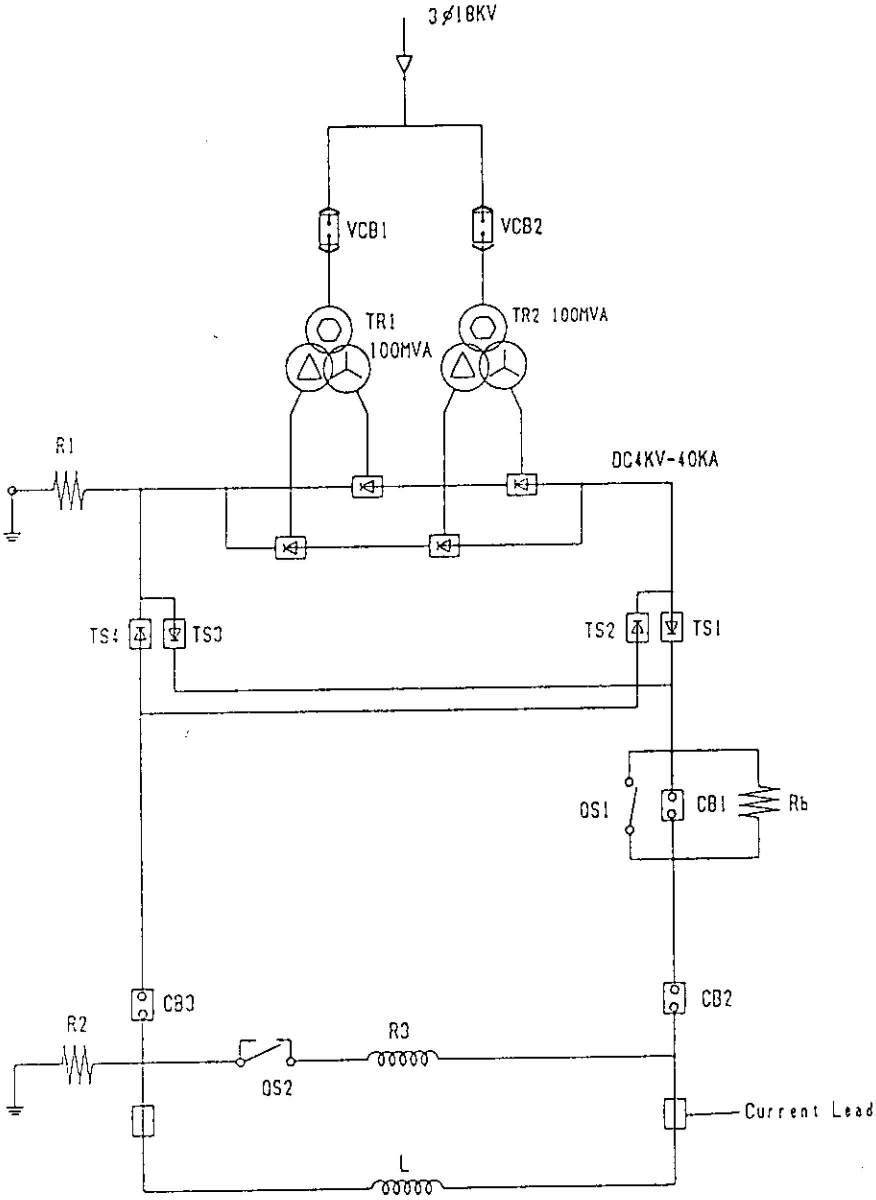


Fig. 2.2 The power supply system of PF coil system

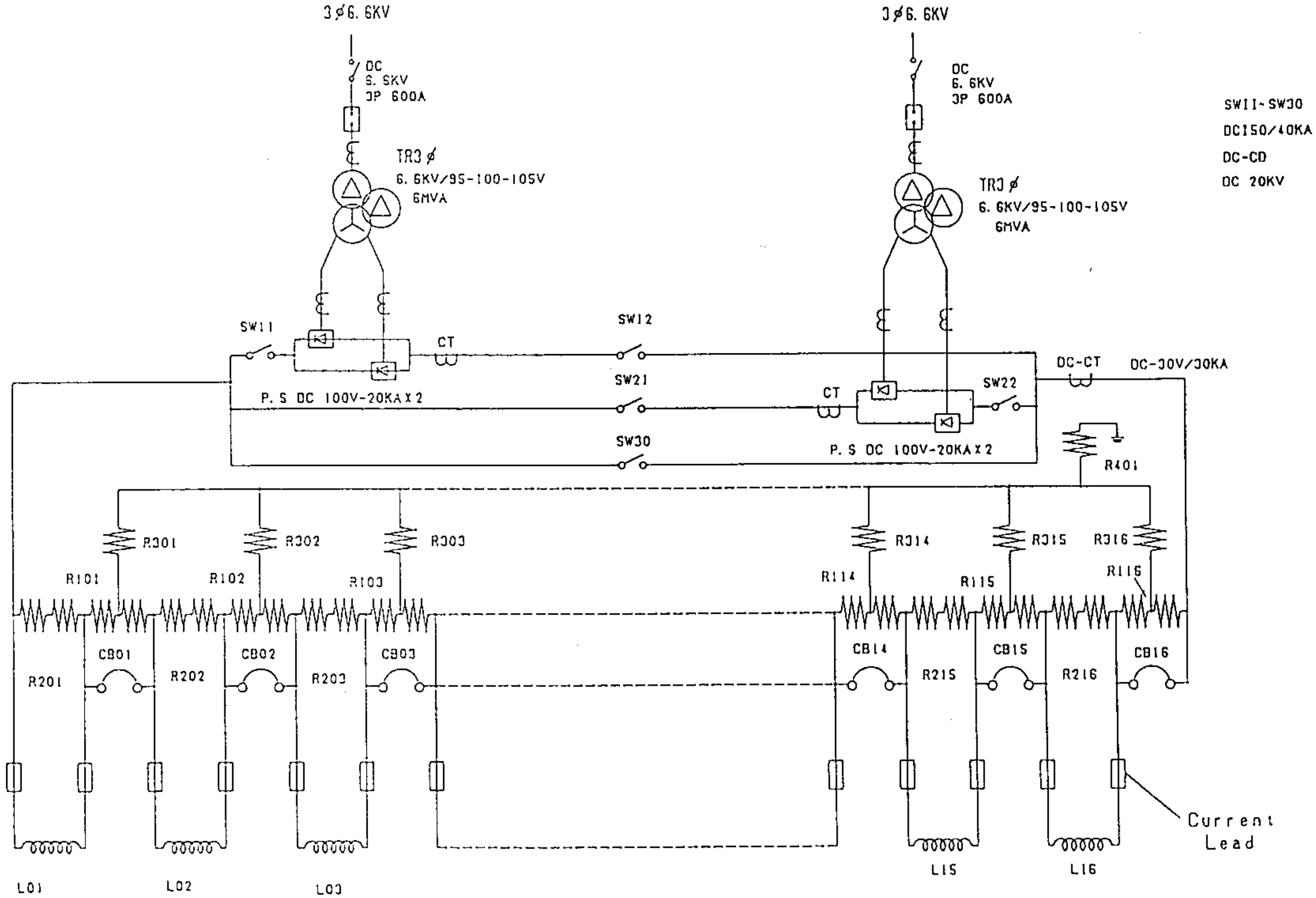


Fig. 2.3 The power supply system of TF coil system

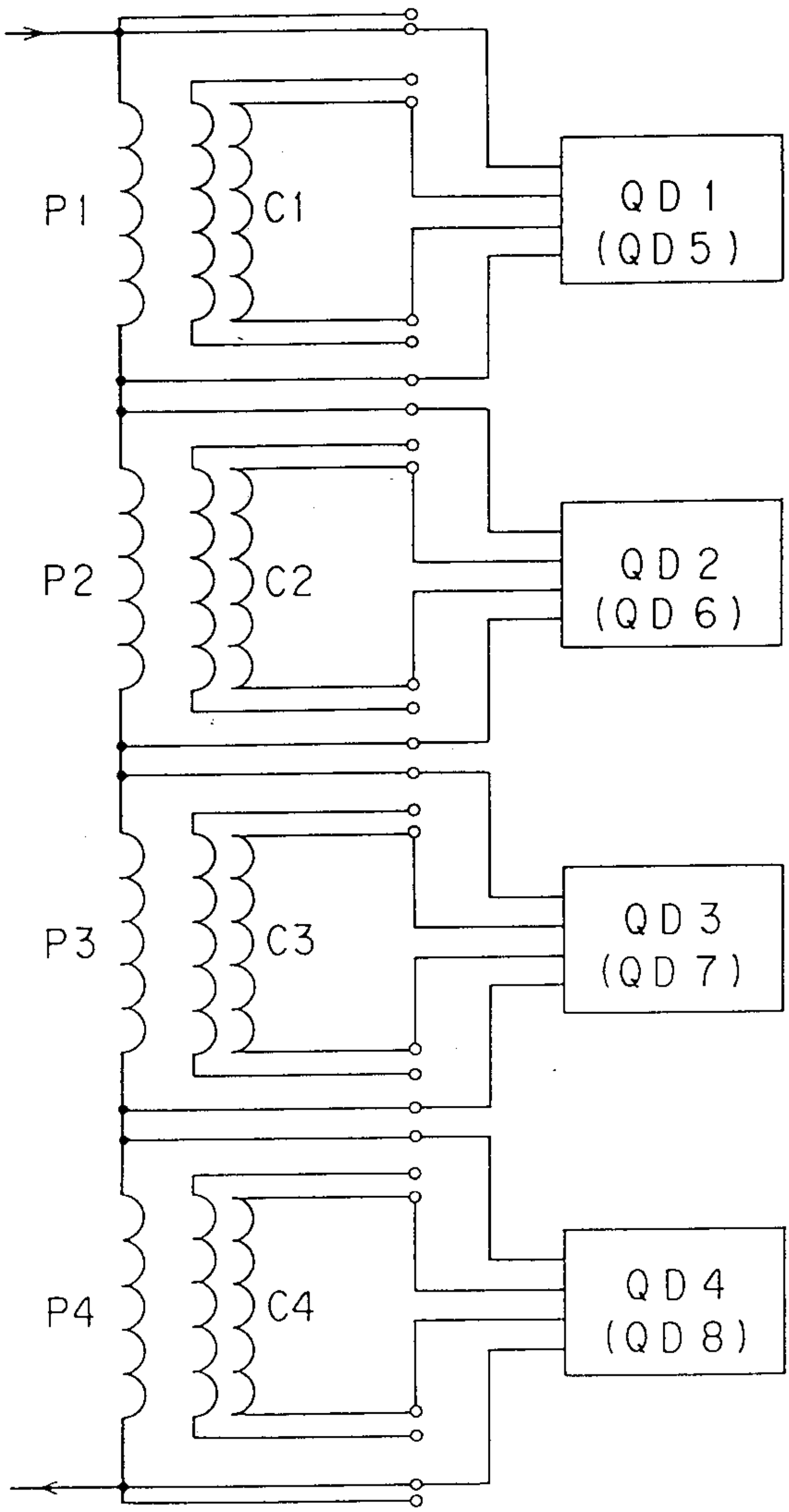


Fig. 2.4 Protection circuit based on the potential method. Instrumentation wires and compensation coils are installed for redundancy.

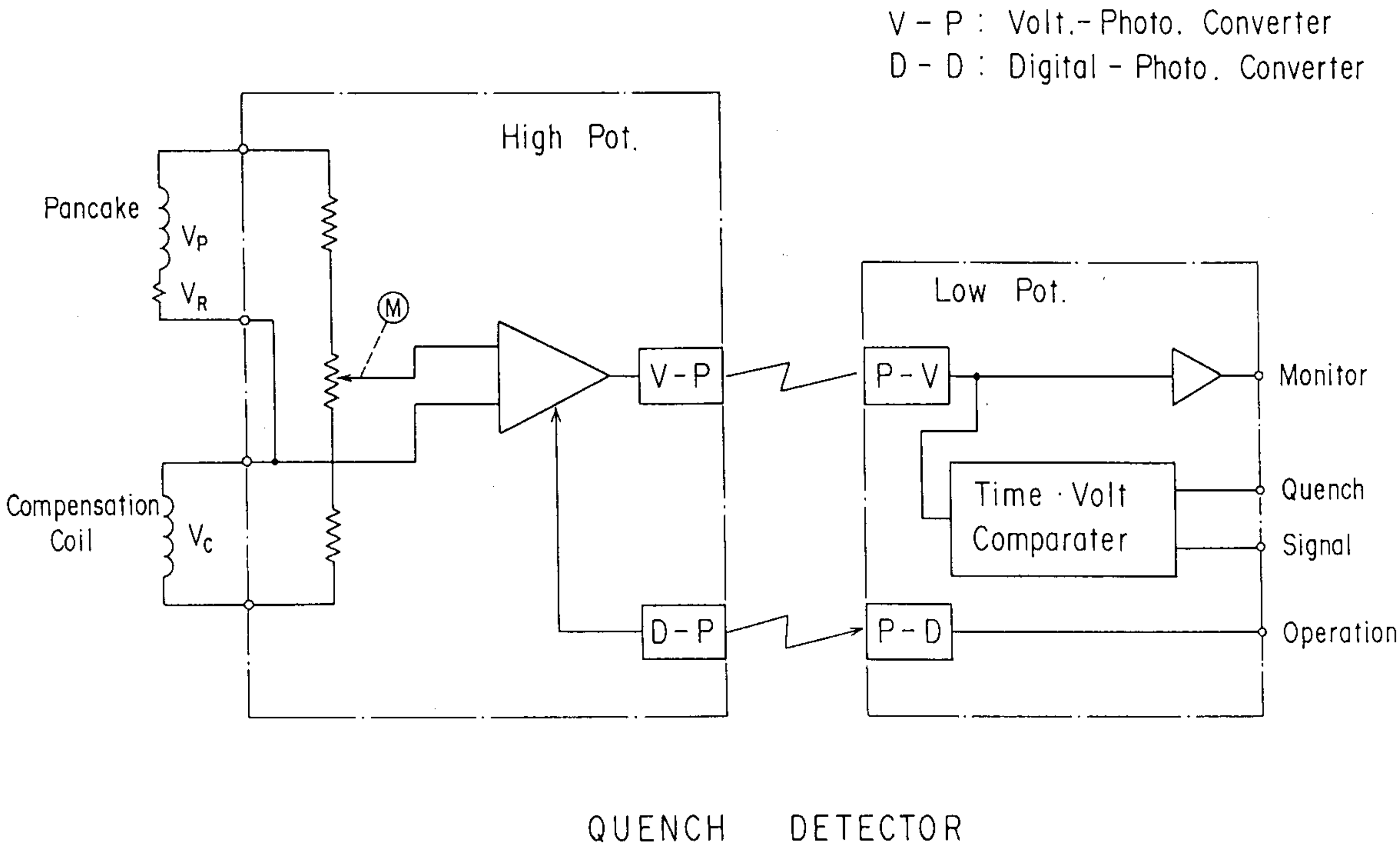


Fig. 2.5 The schematic circuit of the quench detecting potential method

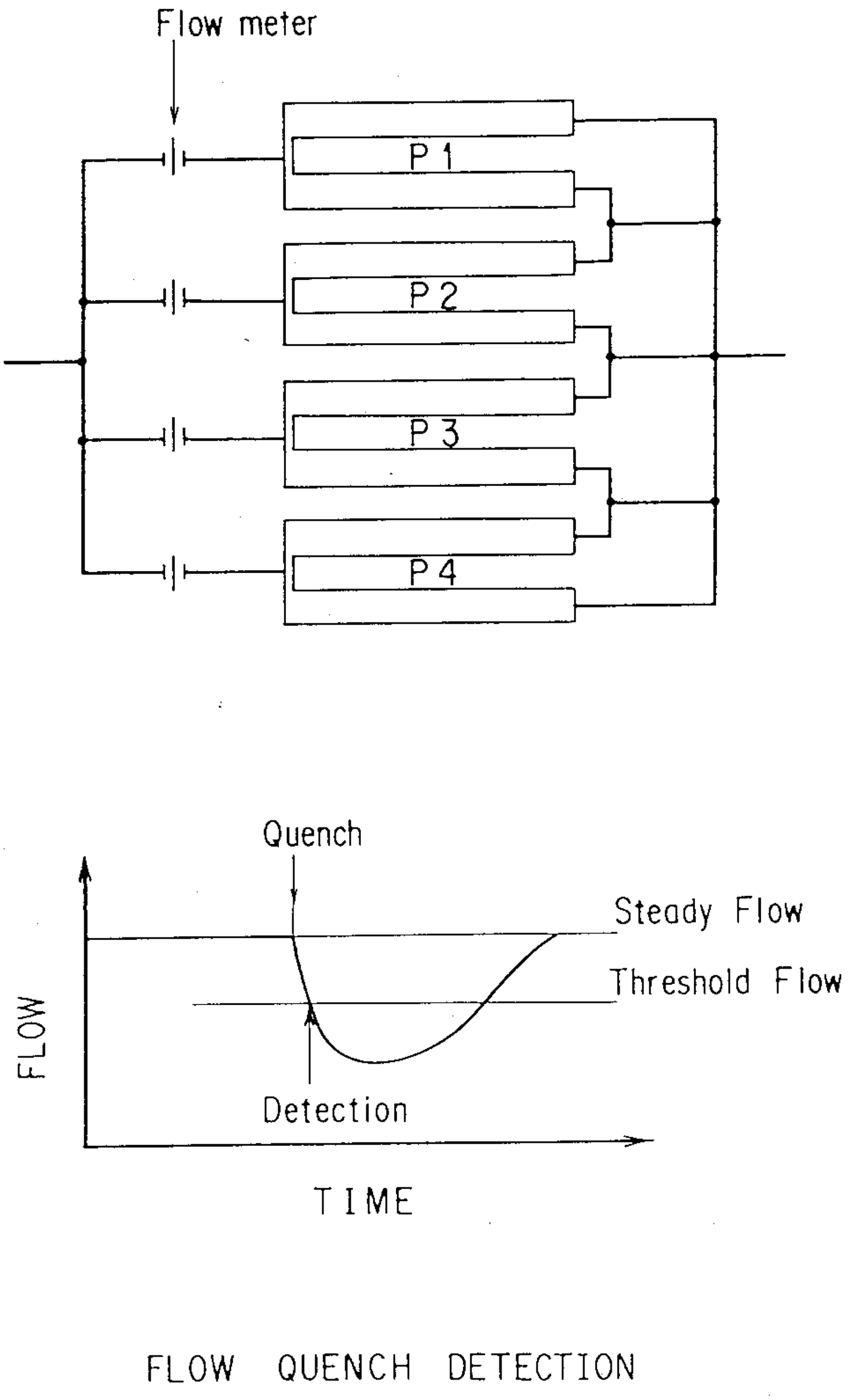


Fig. 2.6 The schematic diagram of the quench detection system.

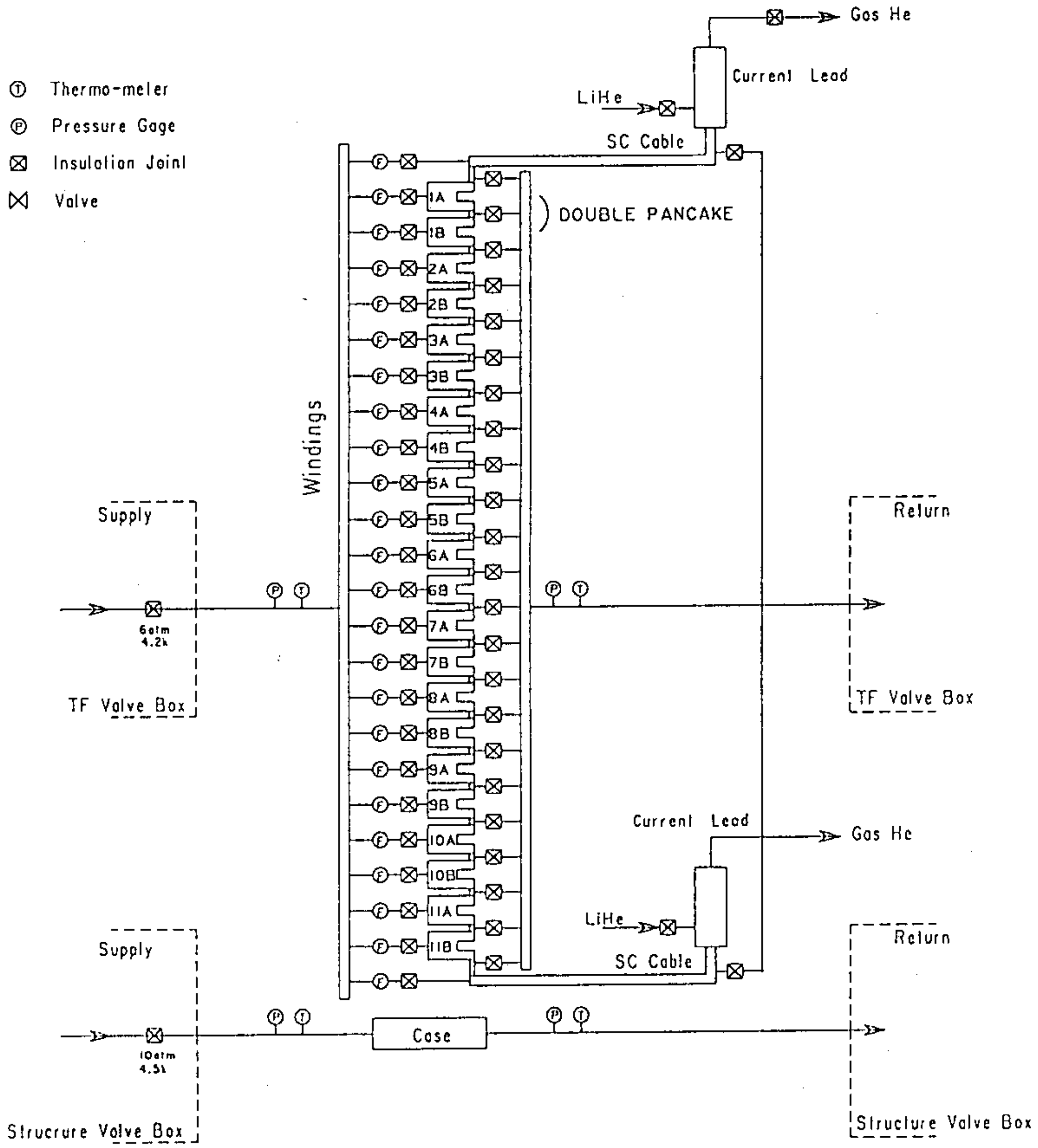


Fig. 2.7 Location of flow meter for the fluid dynamic method of quench detection

3. FAULT ANALYSIS OF TF POWER SUPPLY SYSTEM

3.1 Introduction

The toroidal field (TF) coils are one of the essential components in tokamak fusion reactor. If a fault occurs, the TF coils must be protected from damage caused by current unbalance and overvoltage. This report describes the differences of circuit pattern, effect of ground resistance and several fault modes with computer circuit analysis.

This analysis is calculated by EMTP(Electro Magnetic Transients Program)[1].

3.2. Breaker Faults Mode : Circuit Pattern

3.2.1. Condition

Three circuit patterns are calculated to compare between current unbalance and overvoltage as follows:

(1) Series & Parallel (S&P) : Fig. 3.1,
(2) Series (S)[2] : Fig. 3.2,
(3) Parallel (P) : Fig. 3.3,

All self inductances and mutual inductances are considered in all analysis cases (refer to Table 3.1). The ground resistances are assumed to be 12 (Ohm).

The following two calculation cases are selected to compare the effect:

(1) One breaker fault : one breaker (CB01) is closed when other breakers are opened,
(2) Two breaker fault : neighboring two breakers (CB01 and CB02) are closed.

3.2.2. Analysis

The maximum value for the terminal voltages and coil potentials, and the maximum/ minimum value for the time constants are shown in Table 3.2.

The coil currents of L01-L03,L16 are shown in Fig. 3.4 at 'SP2F'(when CB01 and CB02 are faults).

The coil potential of L01-L03,L16 are shown in Fig. 3.5 at 'P2F'(when CB01 and CB02 are faults).

3.2.3. Results

The difference of the time constant and the terminal voltage of the coils during one breaker fault are smaller than those of a two breaker fault. The series pattern has the following features in comparison with S&P pattern:

(1) The difference of the time constant and the terminal voltage is larger.
(2) The maximum coil potential is smaller.
(3) The maximum coil potential appears after a few seconds after the breakers are operated.
(4) The current differences of neighboring coils are larger.

The Parallel pattern has the following features:

(1) The maximum terminal voltage is larger and the time constant is smaller.
(2) Coil potential (maximum voltage: 26.163 kV.) is much higher than the nominal voltage.
(3) The current differences with the neighboring coils are smaller.

Parallel pattern is difficult to be adapted since this pattern's coil potential is high.

3.3. **Breaker Faults Mode : Effect of Ground Resistances**

3.3.1. Condition

Three circuit patterns are calculated to compare between current unbalance and overvoltage as follows:

(1) Series & Parallel pattern of 1.2 (Ohm) ground resistance
(2) Series & Parallel pattern of 12 (Ohm) ground resistance
(3) Series & Parallel pattern of 120 (Ohm) ground resistance

The following two calculation cases are selected to compare the effect:

(1) One breaker fault : one breaker (CB01) is closed while the other breakers are kept opened,
(2) Two breaker fault : neighboring two breakers (CB01 and CB02) are closed.

3.3.2. Analysis

The maximum/minimum value for terminal voltages and coil potentials, and the maximum/minimum value for the time constants are shown on Table 3.3.

Coil currents of L01-L03,L16 are shown on Fig. 3.6 at 'SP2FS' (CB01 and CB02 are faults).

Coil potential of L01-L03,L16 are shown on Fig. 3.7 at 'SP2FL' (CB01 and CB02 are faults).

3.3.3. Results

The ground resistance(Rg) = 1.2(Ohm) type has the following features in comparison with Rg = 12 (Ohm):
(1) The differences of the time constant and the terminal voltage is larger.
(2) The maximum coil potential is smaller.
(3) The current difference of neighbor coil is larger.

The Rg = 120 (Ohm) type has the following features in comparison with Rg = 12 (Ohm).
(1) The terminal voltage and the time constant are smaller.
(2) Coil potential is larger.
(3) The current difference of neighbor coil is smaller.

Considering the difference of the time constant and the terminal voltage,it is suitable that the ground resistance is from ten to one hundred times as large as the dump resistance.

3.4. Serious Fault Modes

Because the 'parallel pattern' has high potential at the faults of the breaker(see 3.2), only the circuits of 'series pattern' and 'series & parallel pattern' are considered.

3.4.1. Condition

(1) Ground-fault

To simulate a ground fault, one side terminal of the coil 'L01' is grounded with the 10^{-6} Ohm resistance. The CB01-16 is then reopened. (refer to Fig. 3.8)

(2) Short

To simulate a short, both sides of the coil 'L01' are connected with the 10^{-6} Ohm resistance. The CB01-16 is then opened. (refer to Fig. 3.8)

(3) Melt-down

To simulate energy of the coil suddenly disappearing, both sides of the coil ('L16') are connected with the resistance 'RD'(120 Ohm), which is then separated by a breaker. The other breakers (CB01-16) are not changed. (refer to Fig. 3.8)

And to study the effect of 'RD', the patterns, which has the corresponded 'RD' are calculated.

3.4.2. Analysis

The maximum value for the terminal voltages and the coil potentials, and the maximum/minimum value for the time constants are shown in Table 3.4. The maximum value of the coil currents and the coil potentials, and the maximum/minimum value of time constants at 'SPMD' (RD = 12, 1.2 Ohm) are shown in Table 3.5.

Coil currents of L01-L03,L16 are shown in (1) Fig. 3.9 at 'SGF', (2) Fig. 3.10 at 'SPS', and (3) Fig. 3.11 at 'SPMD'. Potential of L01-L03,L16 are shown on (1) Fig. 3.12 at 'SGF', (2) Fig. 3.13 at 'SS', and (3) Fig. 3.14 at 'SMD'.

3.4.3. Results

(1) Ground-fault

The current difference, terminal voltage,and coil potential between 'L02' and 'L03' of 'series pattern' are larger than that of 'series & parallel pattern'.

(2) Short

The current through 'L01' in the 'series pattern' is 68.3kA, and in the 'series & parallel pattern' is 68.2kA. The terminal voltage and coil potential of 'series pattern' are larger than those of 'series & parallel pattern'.

(3) Melt-down

When 'RD' is 120 Ohm, the maximum coil potential of 'series pattern' at adjacent coil is 386.069kV. If a melt-down happens, the adjacent coil will be broken by the high potential. Except for the melt-down coil, the maximum potential of 'series & parallel pattern' is 16.456kV. There fore, neighboring coils are not damaged in this pattern.

If the value of 'RD' can be smaller, then the 'series & parallel' is safer.

3.5. Interpolation of Summary

(1) 'Series pattern' and 'series & parallel pattern' are both suitable for the 'breaker faults' mode since they keep the coil potential in the acceptable value.

(2) It is suitable that the ground resistance is from ten to one hundred times as large as the dump resistance. The large resistance will reduce the difference of the time constants and the terminal voltage.

(3) Considering the influence to neighboring coils and their coil potential in a fault situation, the 'series & parallel pattern' is the best selection for ground-fault and melt-down modes.

References

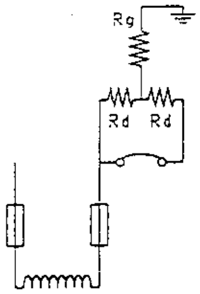
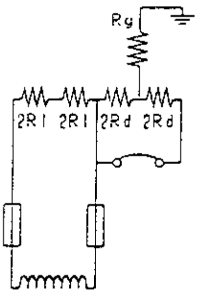
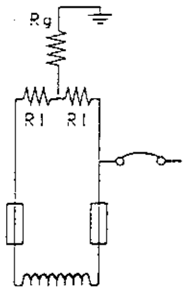
[1] "ELECTRO MAGNETIC TRANSIENTS PROGRAM (EMTP) Rule Book Mode 31," Methods Analysis Unit, Route EOGA Branch of System Engineering Bonneville Power Administration, Apr 1982.

[2] B.TURCK, "TORE SUPRA : A TOKAMAK WITH SUPERCONDUCTING TOROIDAL FIELD COILS STATUS REPORT AFTER THE FIRST PLASMAS," IEEE TRNSACTIONS ON MAGNETICS, VOL.25, NO.2, (1989.) 1473

Table 3.1 TF coil specifications

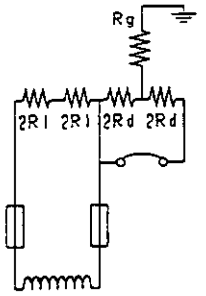
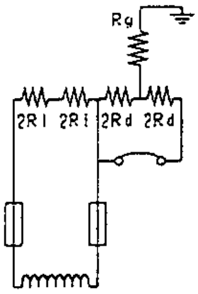
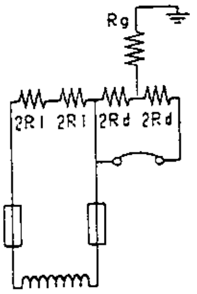
Self Inductance		2.6 (H)
Mutual Inductance	L01vsL02	0.76 (H)
	L01vsL03	0.37 (H)
	L01vsL04	0.21 (H)
	L01vsL05	0.13 (H)
	L01vsL06	0.087(H)
	L01vsL07	0.065(H)
	L01vsL08	0.054(H)
	L01vsL09	0.051(H)
Rated Current		30.3 (kA)

Table 3.2 Comparison of the basic circuit pattern

Circuit		Normal	CB01 Fault	CB01&CB02 Fault
	Pattern	SN	S1F	S2F
	Terminal voltage(max) kV	18.005	18.091	18.159
	Coil potential (max) kV	9.002	14.260	18.408
	Time constant (max) sec	10.2	11.4	13.0
Series pattern	Time constant (min) sec	————	10.5	11.0
	Pattern	SPN	SP1F	SP2F
	Terminal voltage(max) kV	18.005	17.873	17.717
	Coil potential (max) kV	9.002	16.266	21.988
	Time constant (max) sec	10.2	11.1	12.3
Series & Parallel pattern	Time constant (min) sec	————	10.3	10.4
	Pattern	PN	P1F	P2F
	Terminal voltage(max) kV	18.005	18.005	18.005
	Coil potential (max) kV	9.002	17.790	26.163
	Time constant (max) sec	10.2	10.3	10.8
Parallel pattern	Time constant (min) sec	————	10.2	10.1

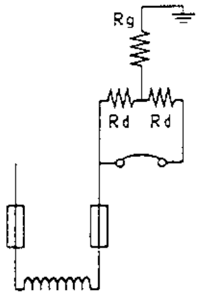
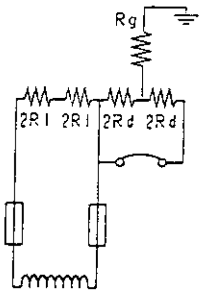
Rd = Rl = 0.3 (Ohm)
Rg = 12 (Ohm)

Table 3.3 Comparison of grand resistances

Circuit		Normal	CB01 Fault	CB01&CB02 Fault
	Pattern		SP1FS	SP2FS
	Terminal voltage(max) kV	———	18.004	18.002
	Coil potential (max) kV	———	14.051	16.482
	Time constant (max) sec	———	12.8	17.5
Rg = 1.2(Ohm)	Time constant (min) sec	———	10.1	10.1
	Pattern	SPN	SP1F	SP2F
	Terminal voltage(max) kV	18.005	17.873	17.717
	Coil potential (max) kV	9.002	16.266	21.988
	Time constant (max) sec	10.2	11.1	12.3
Rg = 12(Ohm)	Time constant (min) sec	———	10.3	10.4
	Pattern		SP1FL	SP2FL
	Terminal voltage(max) kV	———	17.528	17.010
	Coil potential (max) kV	———	17.242	24.700
	Time constant (max) sec	———	10.6	11.1
Rg = 120(Ohm)	Time constant (min) sec	———	10.5	10.8

Rd = Rl = 0.3 (Ohm)

Table 3.4 Comparison of the fault modes

Circuit		Grand fault	Short	Melt down
	Pattern	SGF	SS	SMD
	Terminal voltage(max) kV	22.940	26.401	386.548
	Coil potential (max) kV	17.591	17.917	386.069 (Except L16 Coil)
	Time constant (max) sec	11.4	9.2	16.0
	Time constant (min) sec	9.1	8.1	1.0 (Except L16 Coil)
	Pattern	SPGF	SPS	SPMD
	Terminal voltage(max) kV	19.352	19.214	9.785
	Coil potential (max) kV	16.306	16.139	16.456
	Time constant (max) sec	11.1	9.8	100
	Time constant (min) sec	9.5	7.1	87 (Except L16 Coil)

Rd = Rl = 0.3 (Ohm)
Rg = 12 (Ohm)

Table 3.5 Effect of RD in melt-down

Pattern	SPMD	
RD(Ohm)	12	1.2
Coil current (max) kA	35.48	31.62
Coil potential (max) kV	16.223	15.492
Time constant (max) sec	100	100
Time conatant (min) sec	86	86

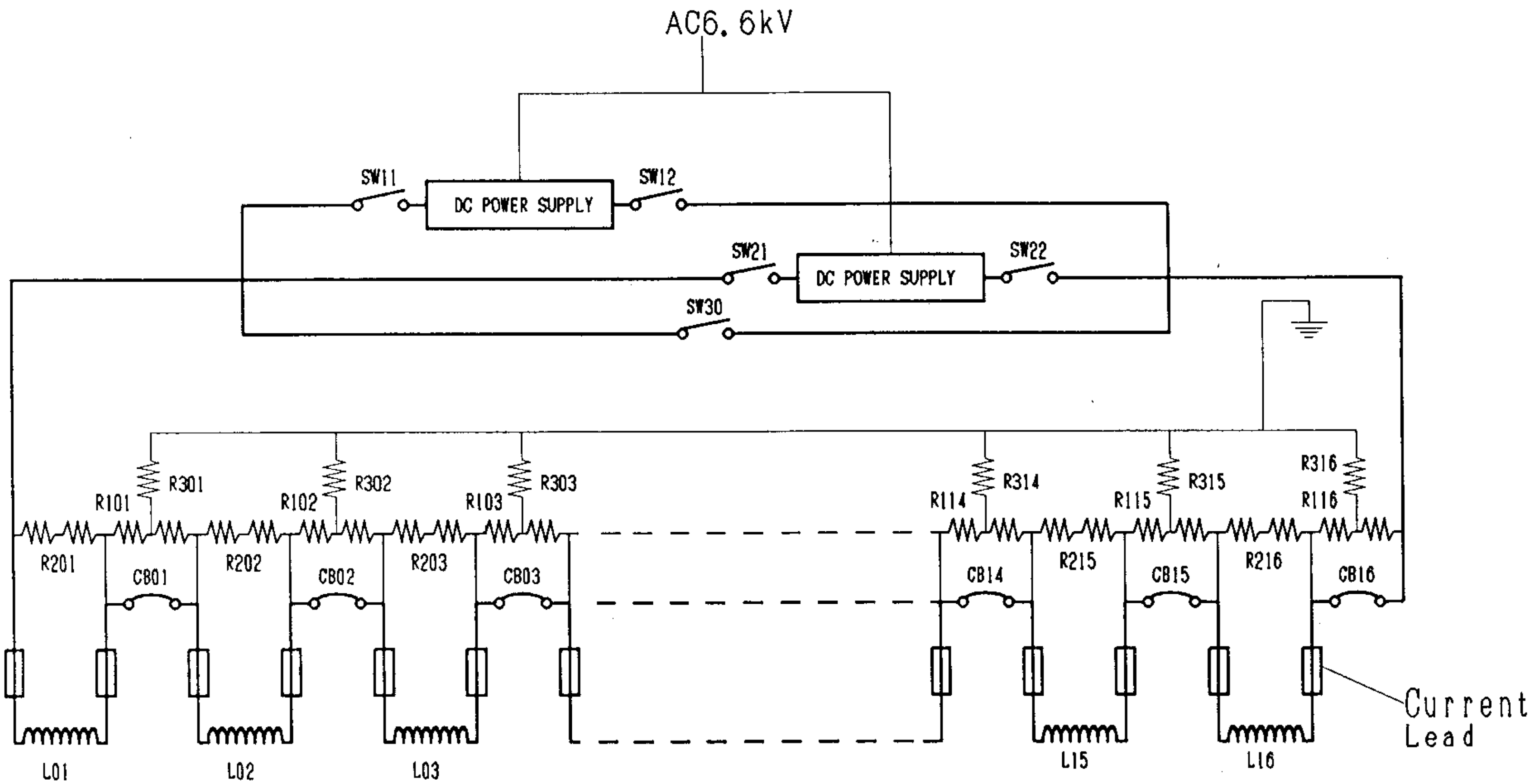


Fig. 3.1 TF power supply and protection (Series & Parallel pattern)

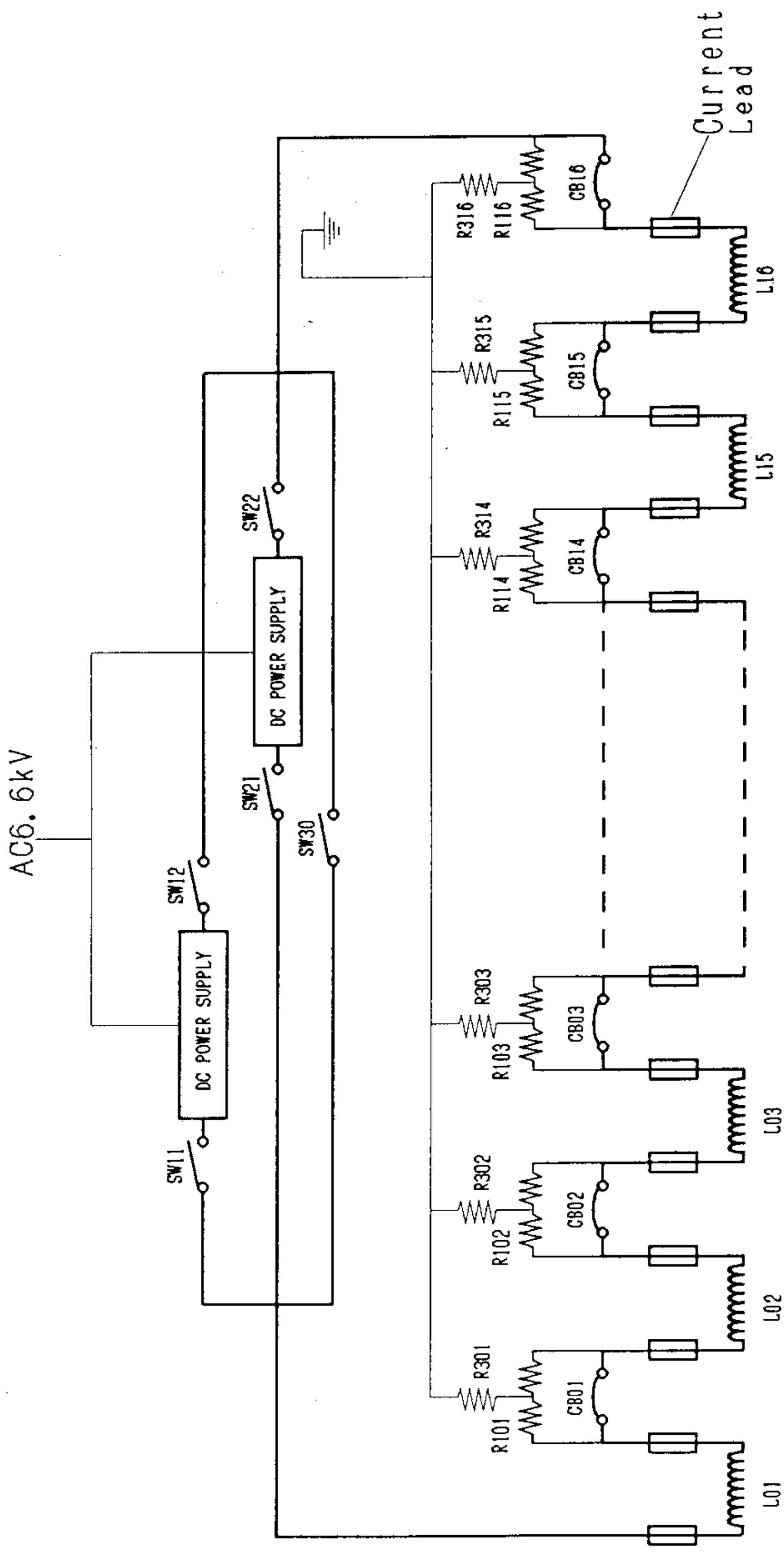


Fig. 3.2 TF power supply and protection (Series pattern)

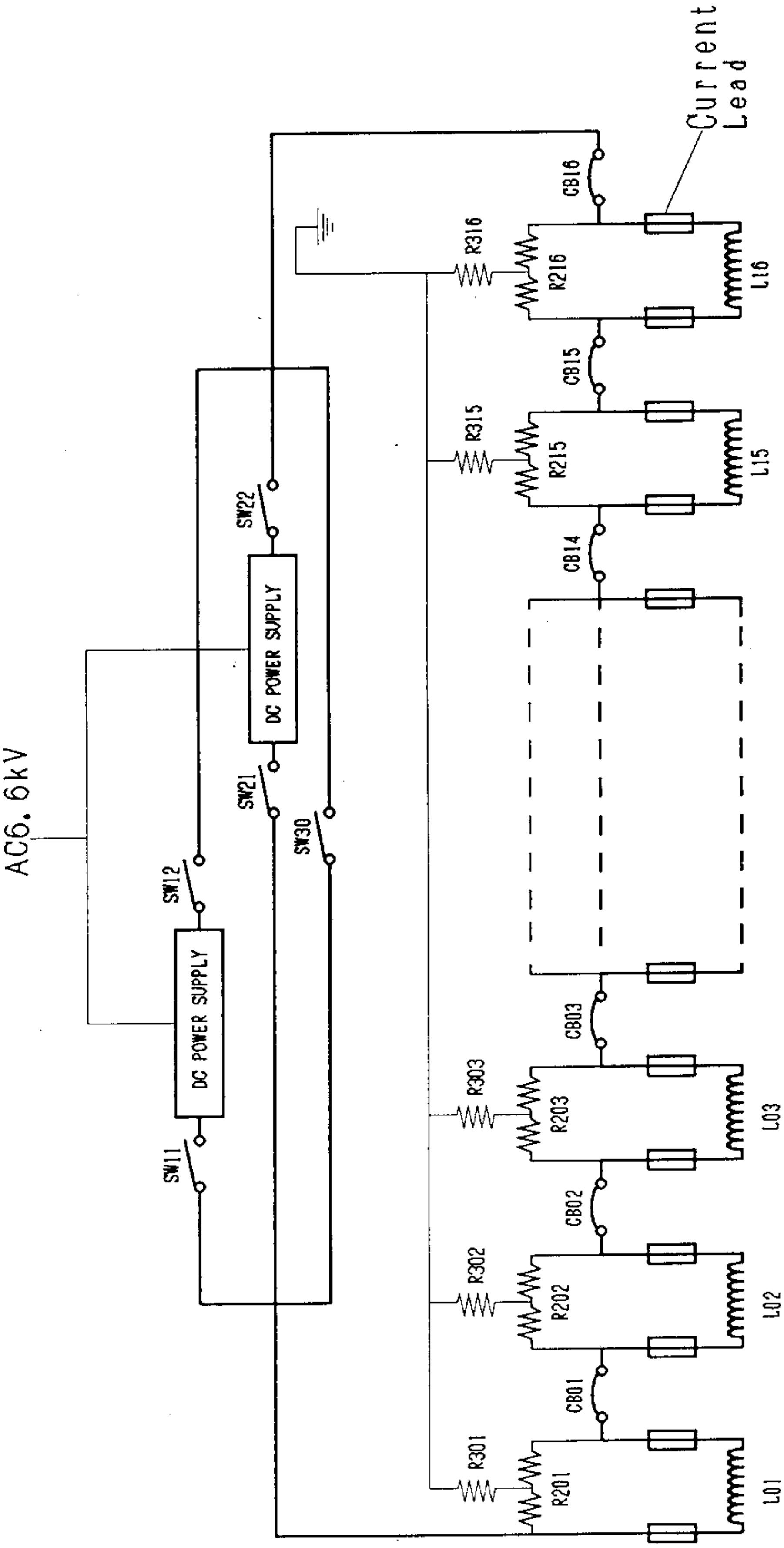


Fig. 3.3　TF power supply and protection (Parallel pattern)

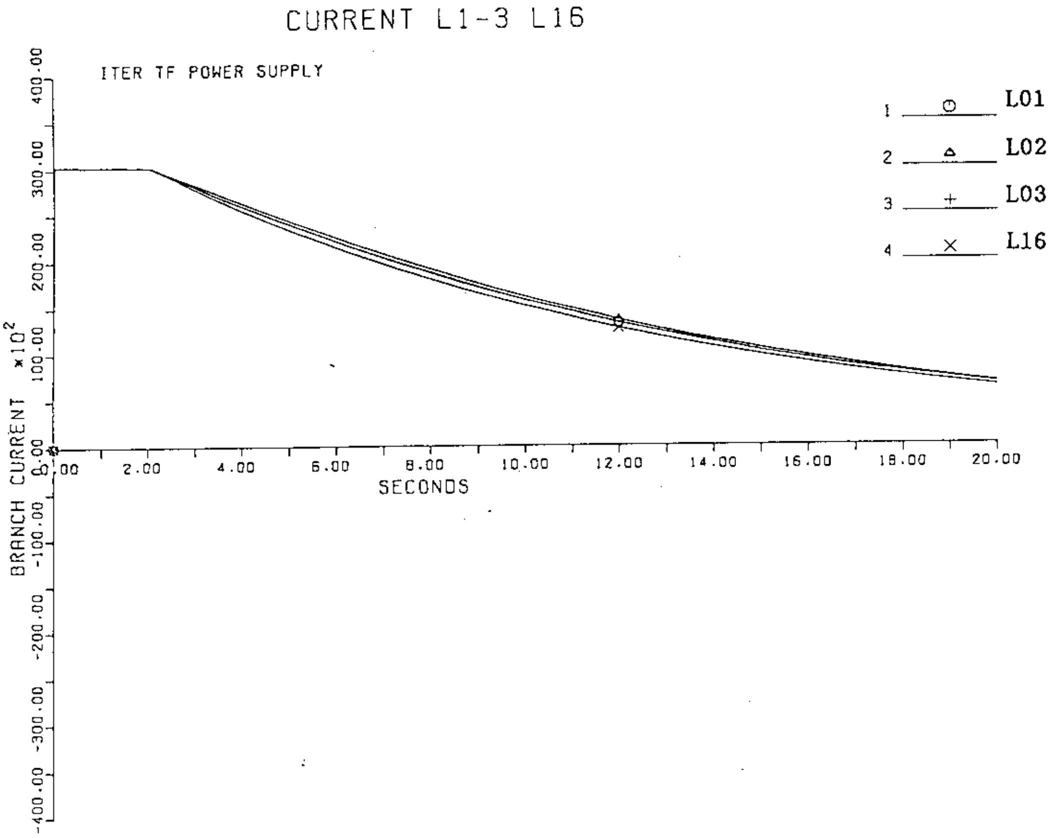
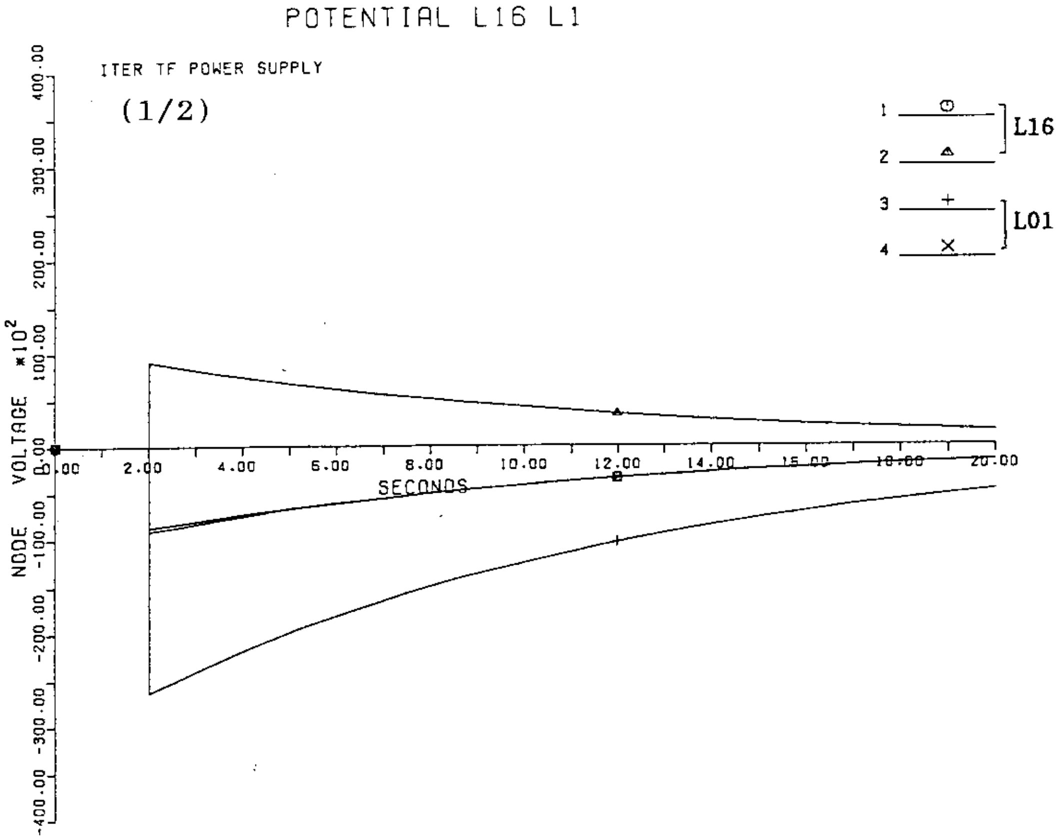


Fig. 3.4 Coil current of circuit pattern 'SP2F'



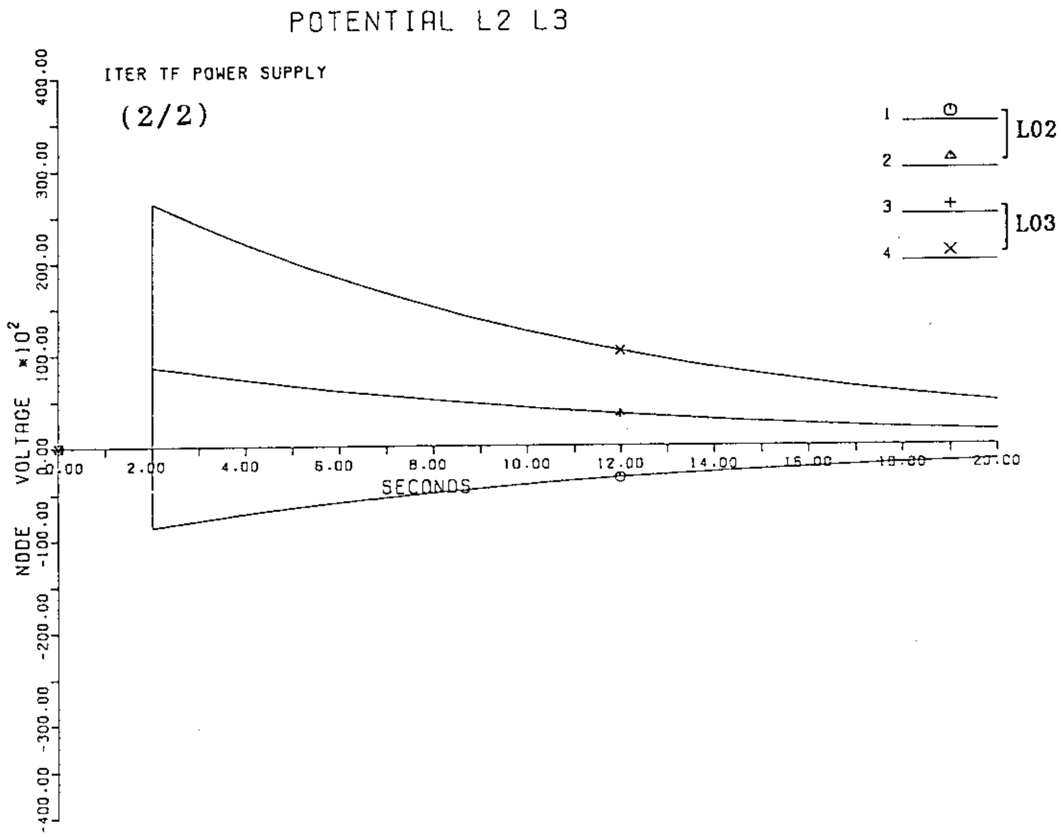


Fig. 3.5 Coil potential of circuit pattern 'P2F'

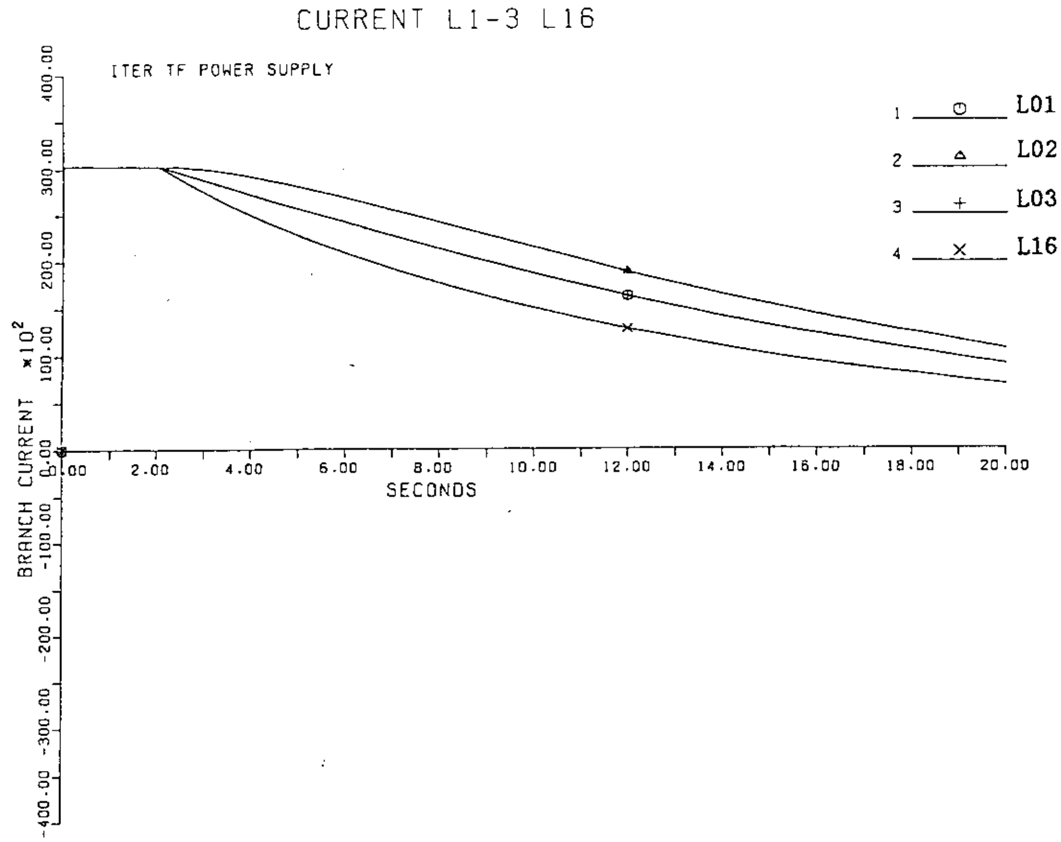
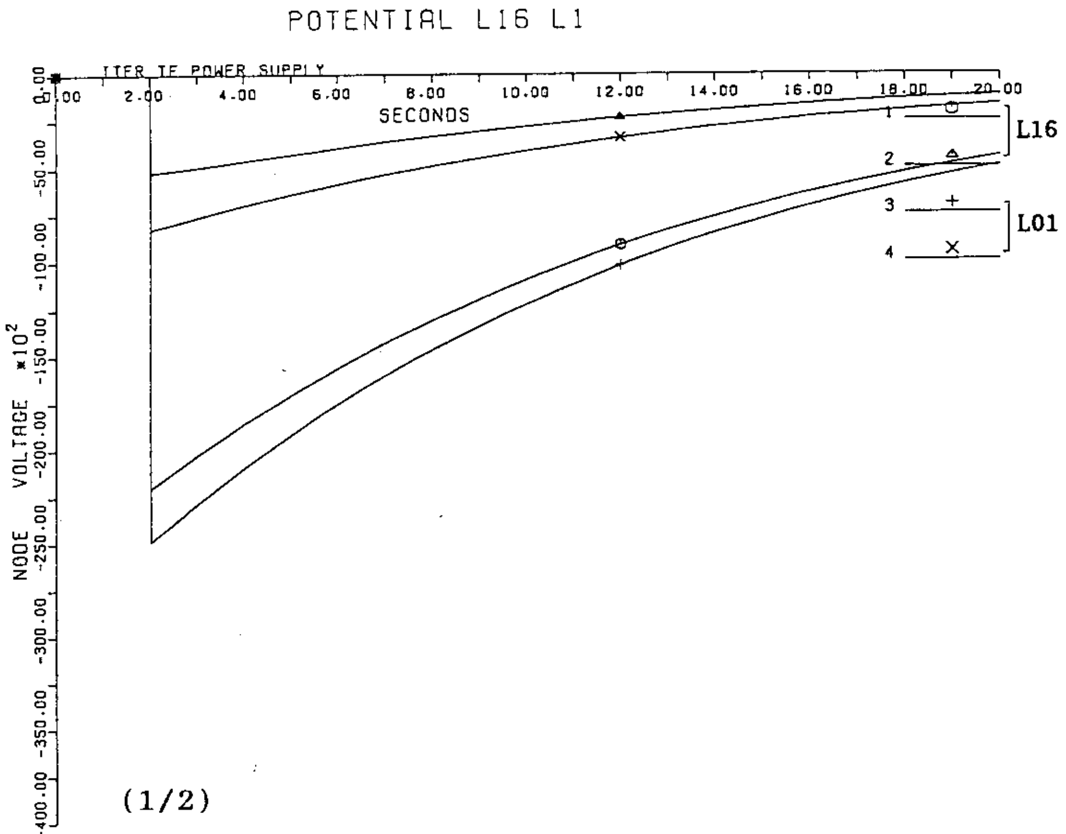


Fig. 3.6 Coil current of circuit pattern 'SP2FS'
(ground resistance = 1.2 Ohm)



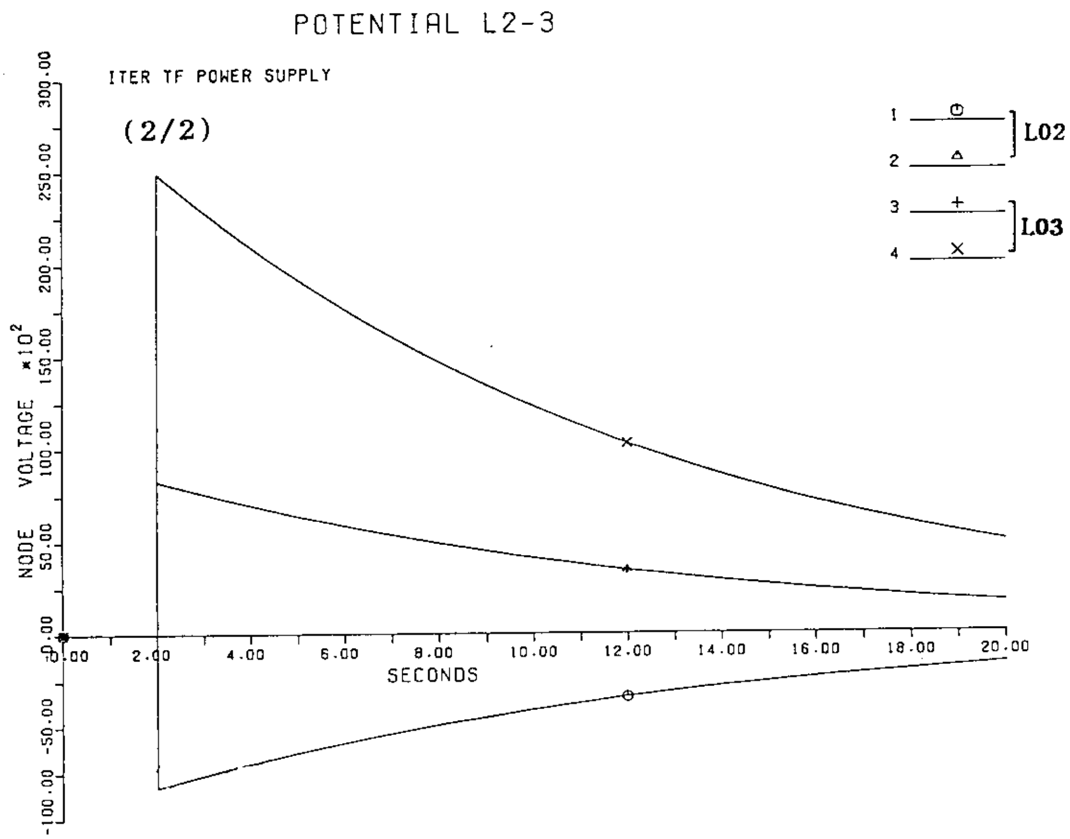


Fig. 3.7 Coil potential of circuit pattern 'SP2FL' (ground resistance = 120 Ohm)

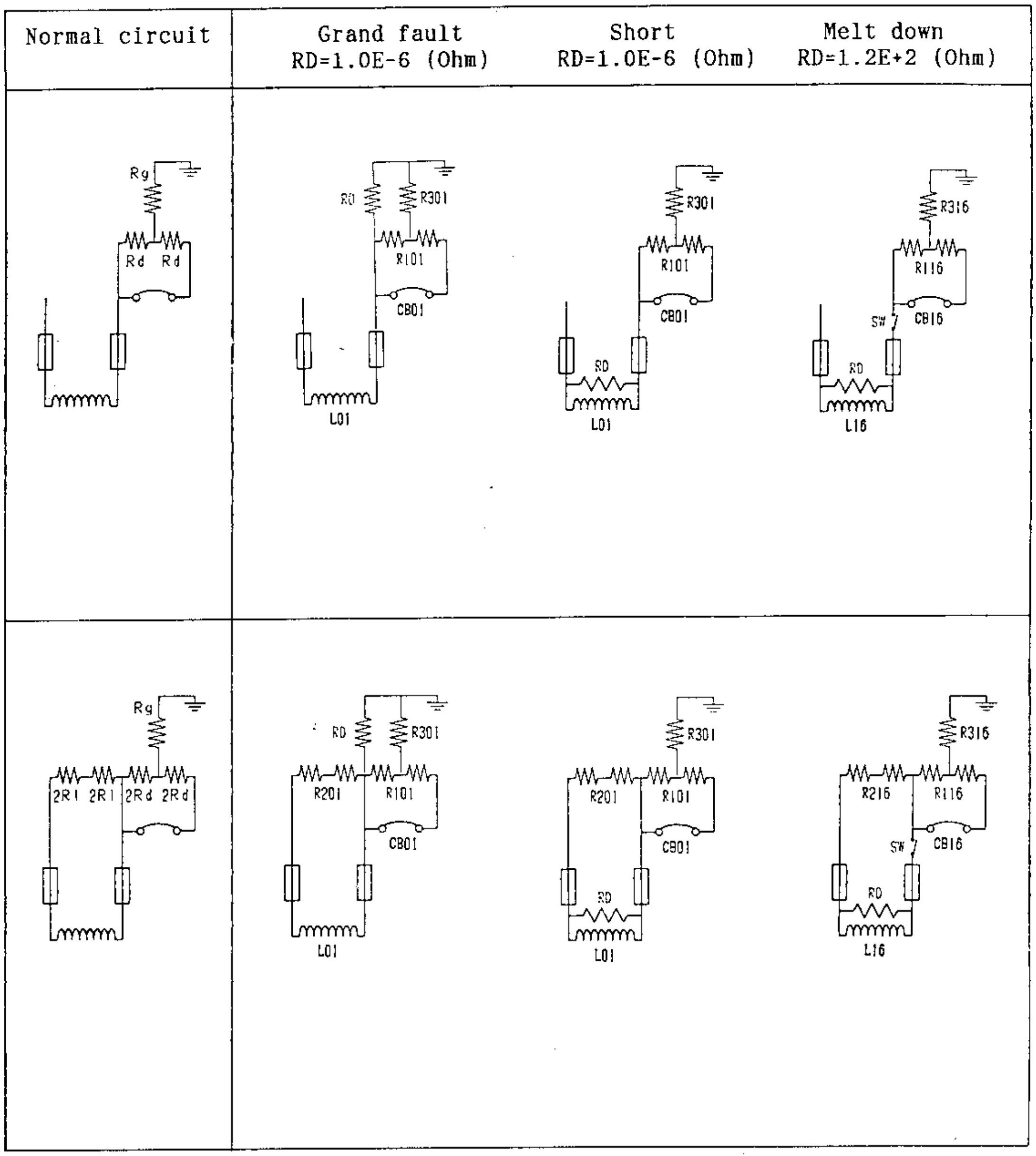


Fig. 3.8　　Modified circuits of the fault modes

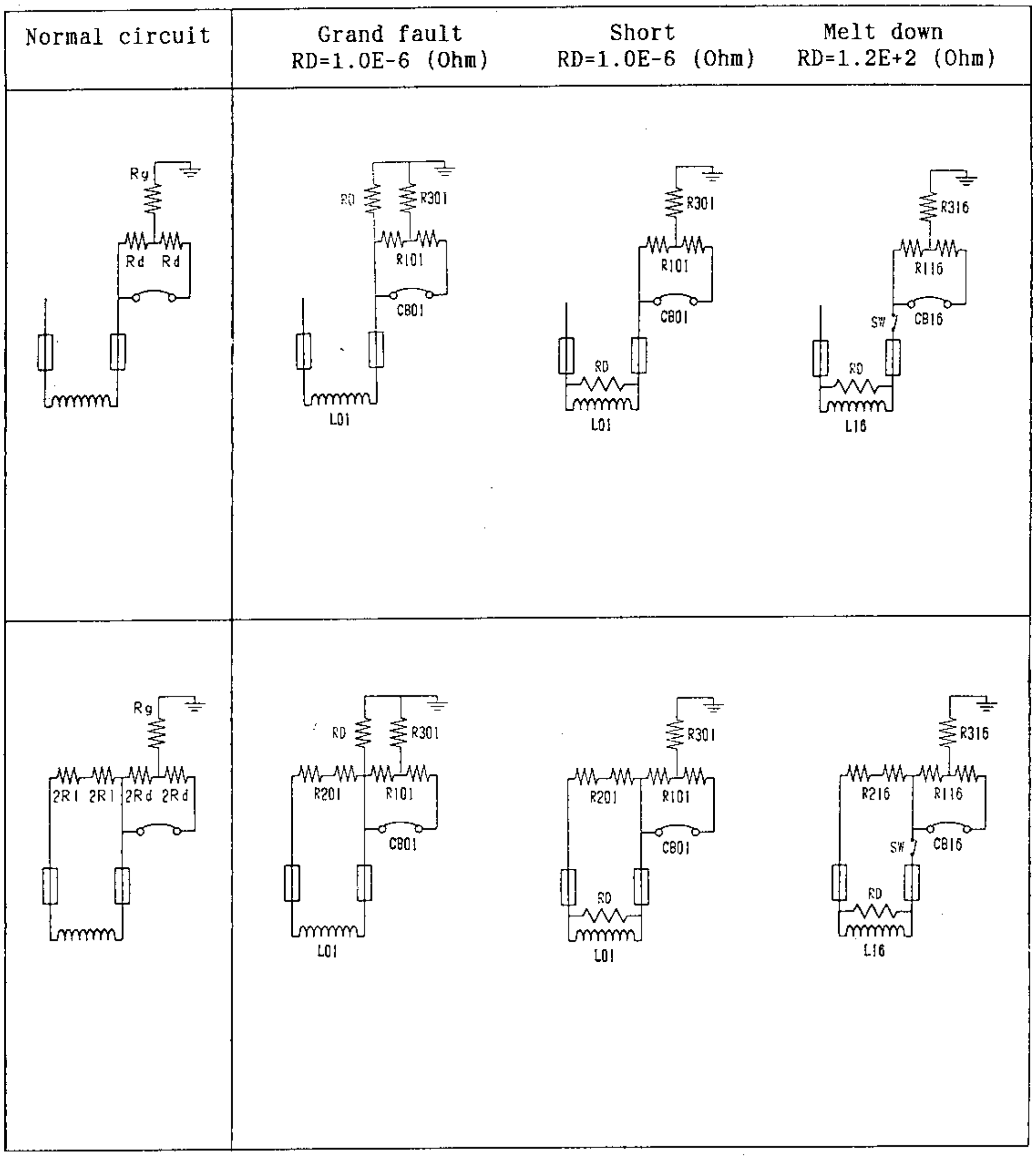


Fig. 3.8 Modified circuits of the fault modes

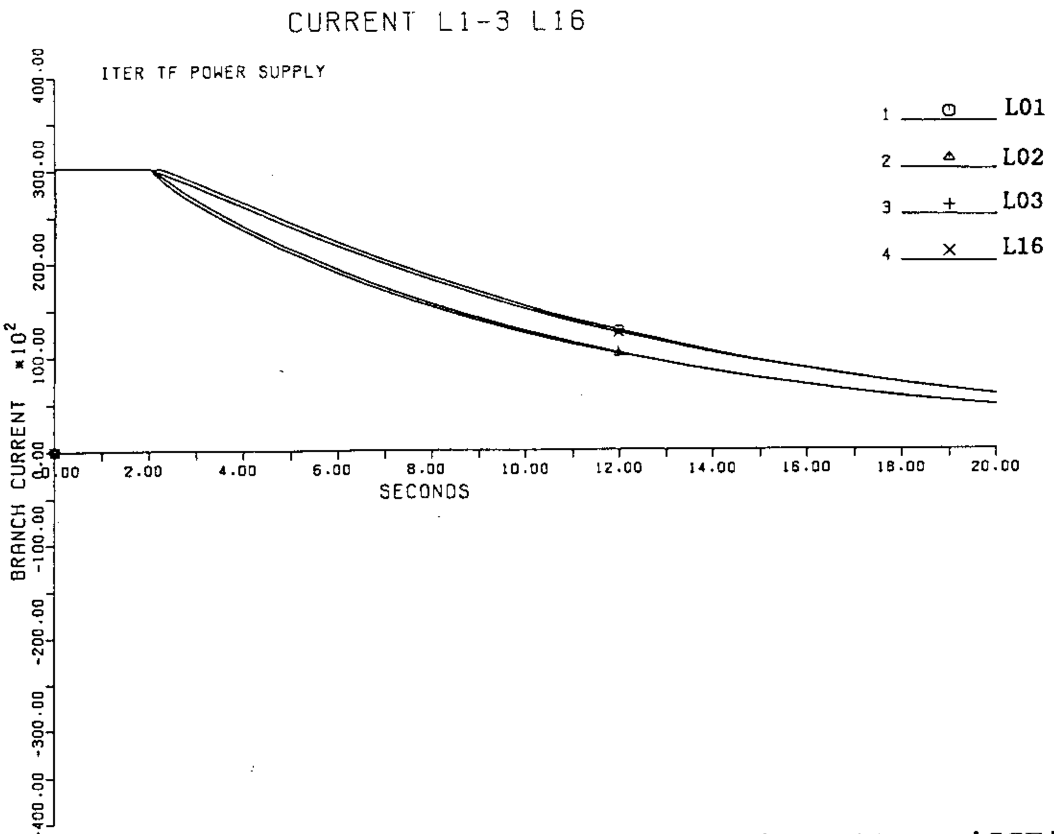


Fig. 3.9 Coil current of circuit pattern 'SGF' (ground-fault)

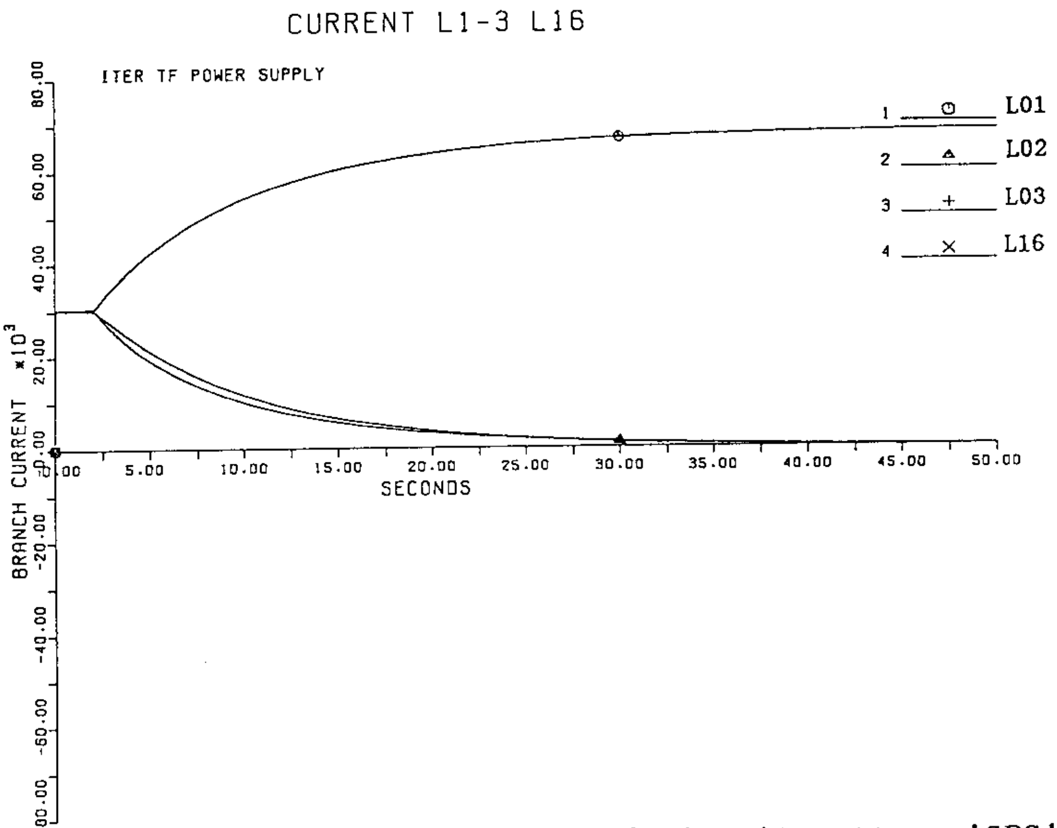


Fig. 3.10 Coil current of circuit pattern 'SPS' (short)

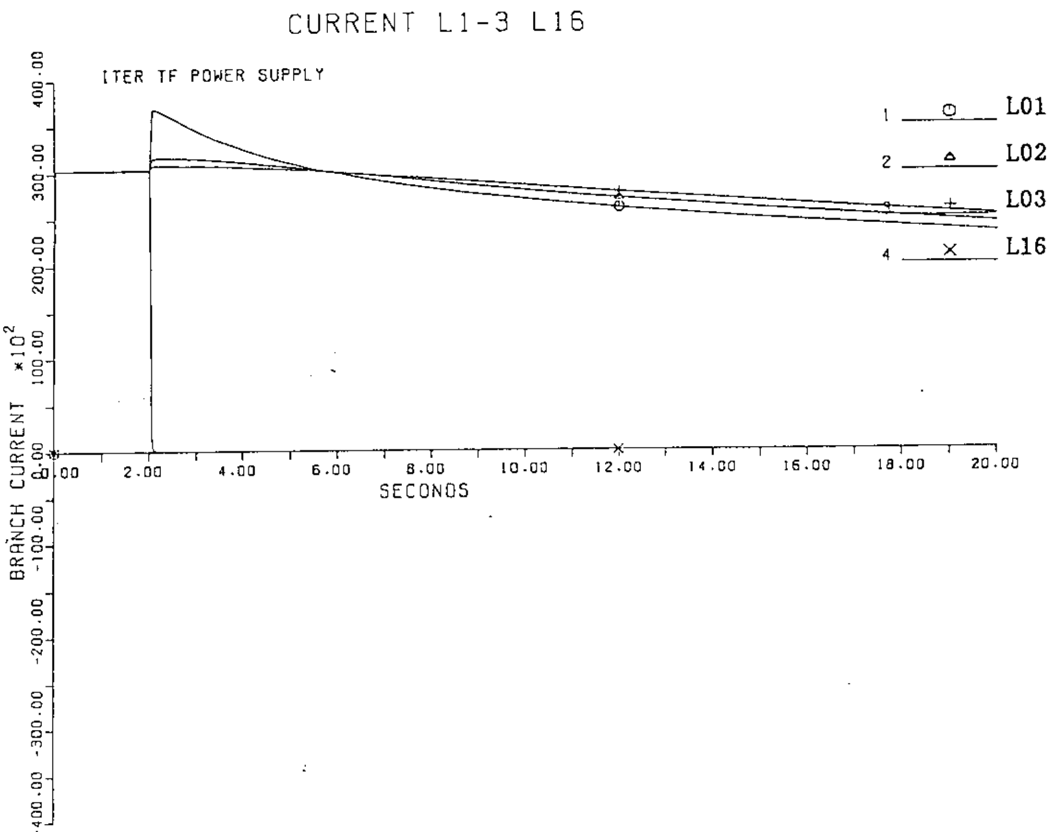
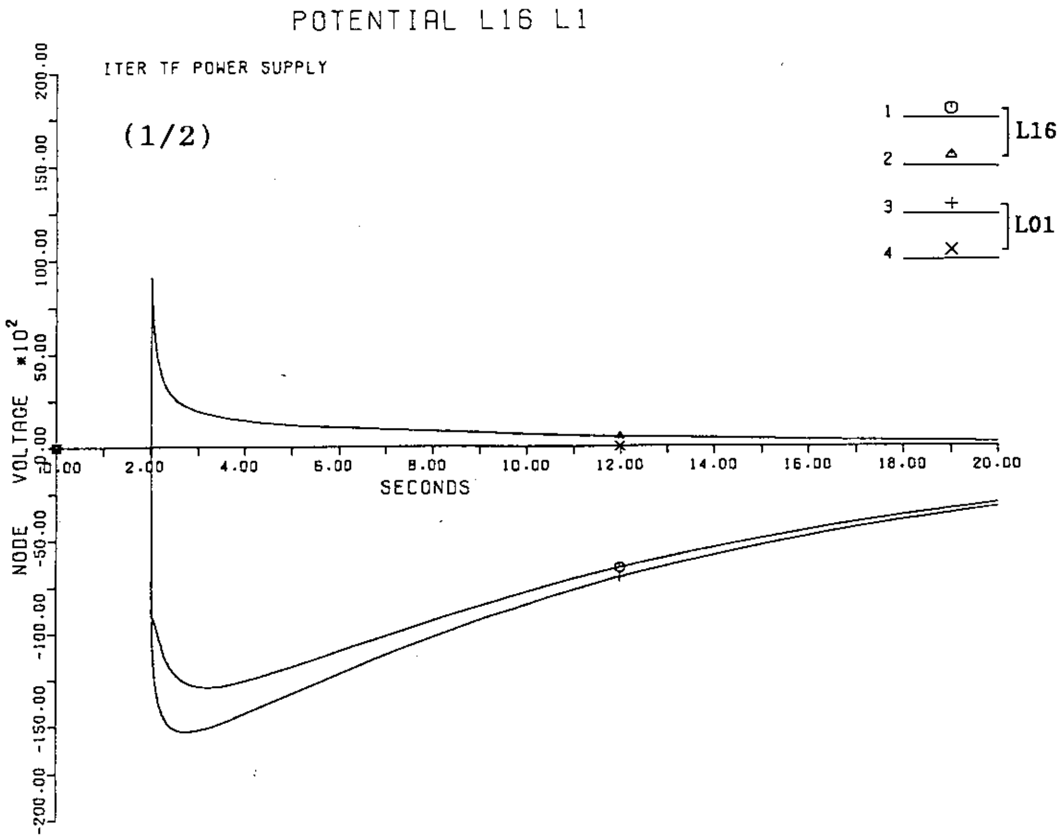


Fig. 3.11 Coil current of circuit pattern 'SPMD' (melt-down)



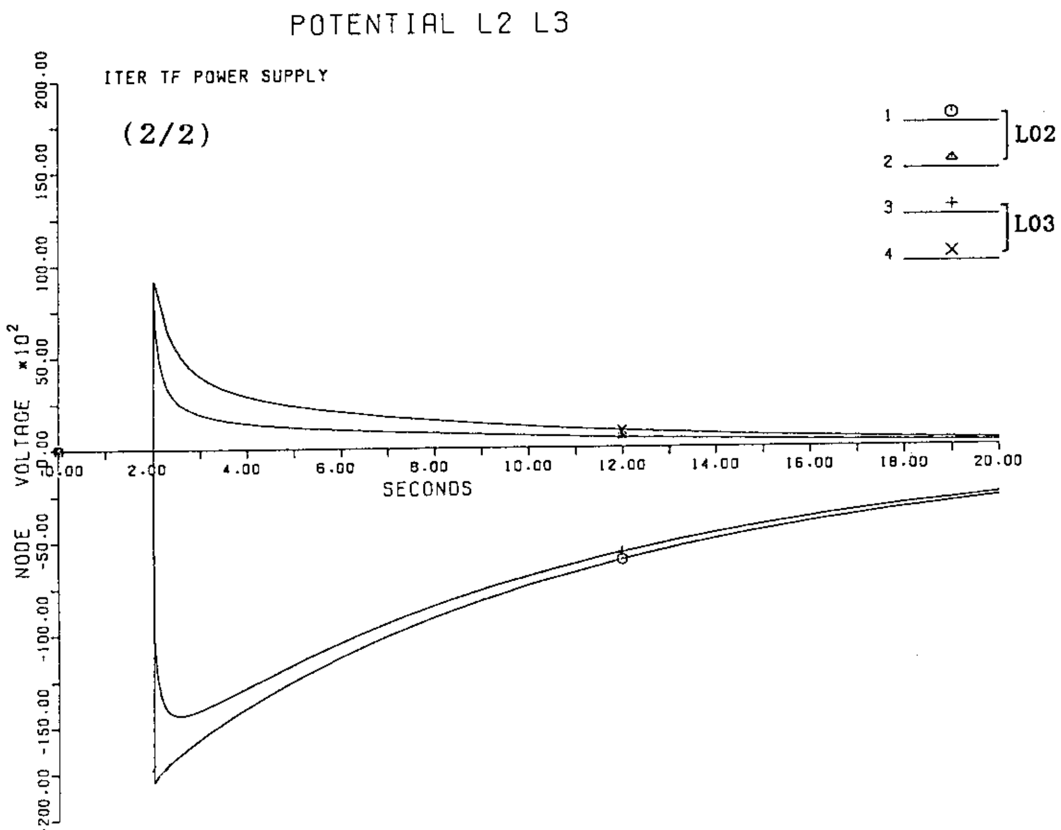
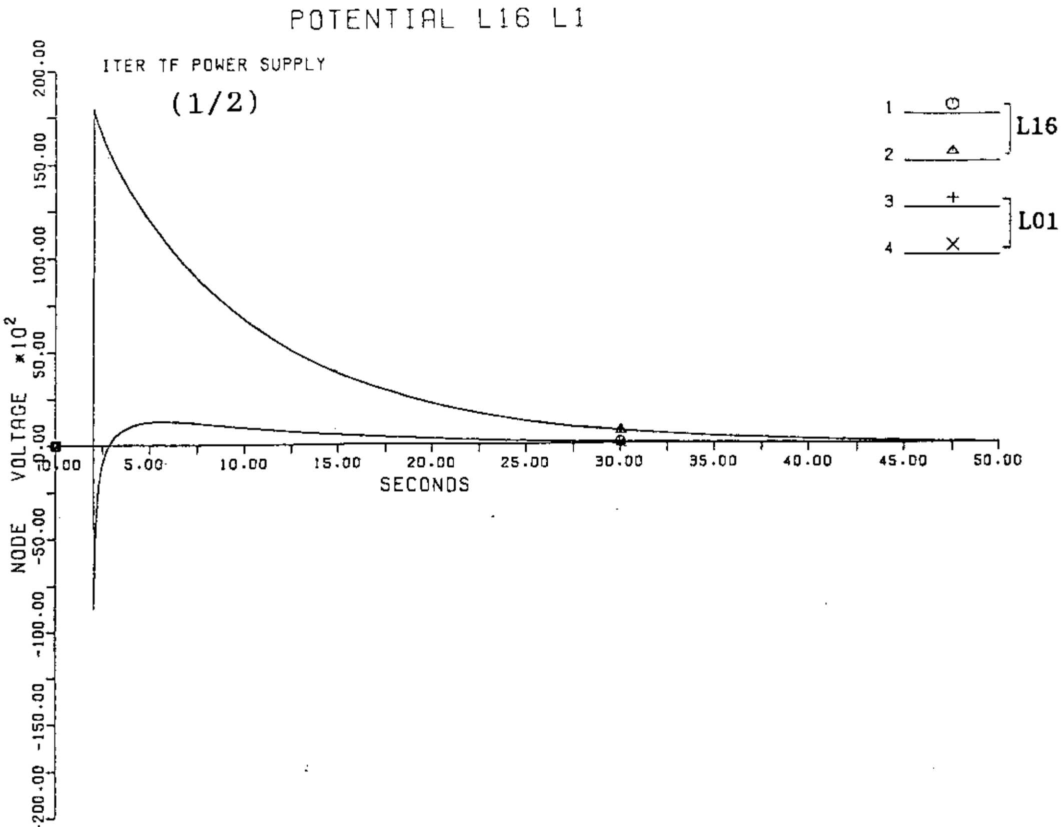


Fig. 3.12 Coil potential of circuit pattern 'SGF' (ground-fault)



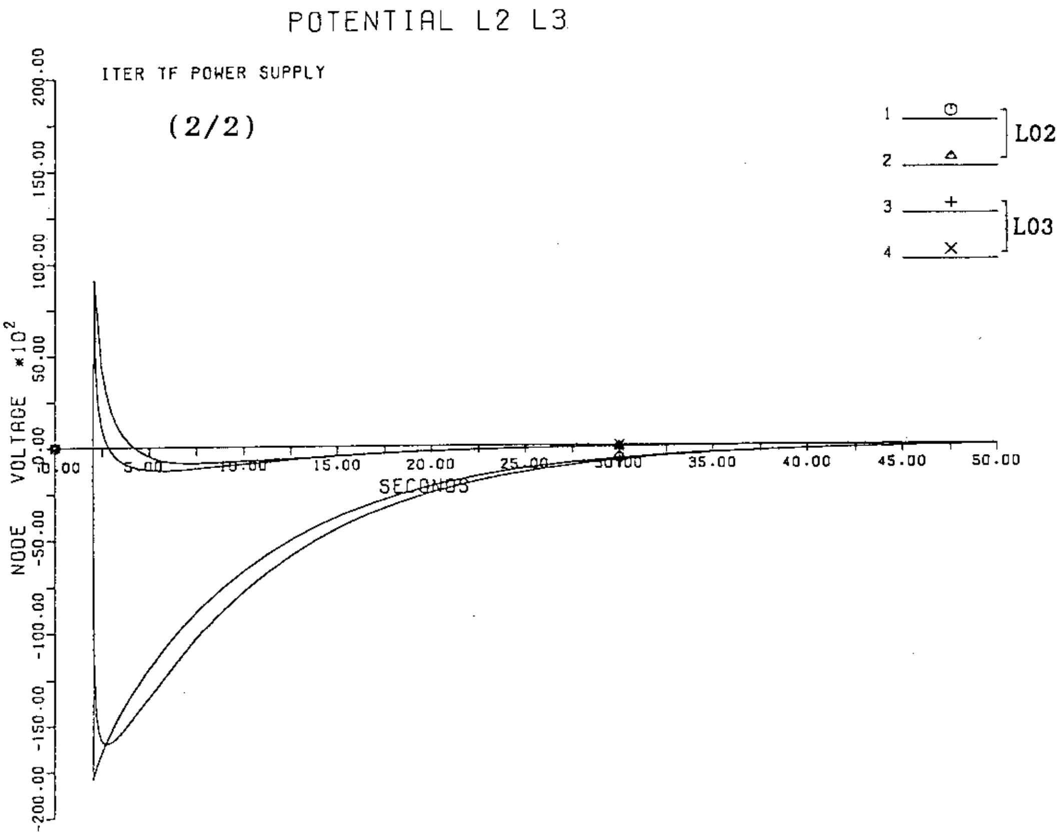


Fig. 3.13　Coil potential of circuit pattern 'SS' (short)

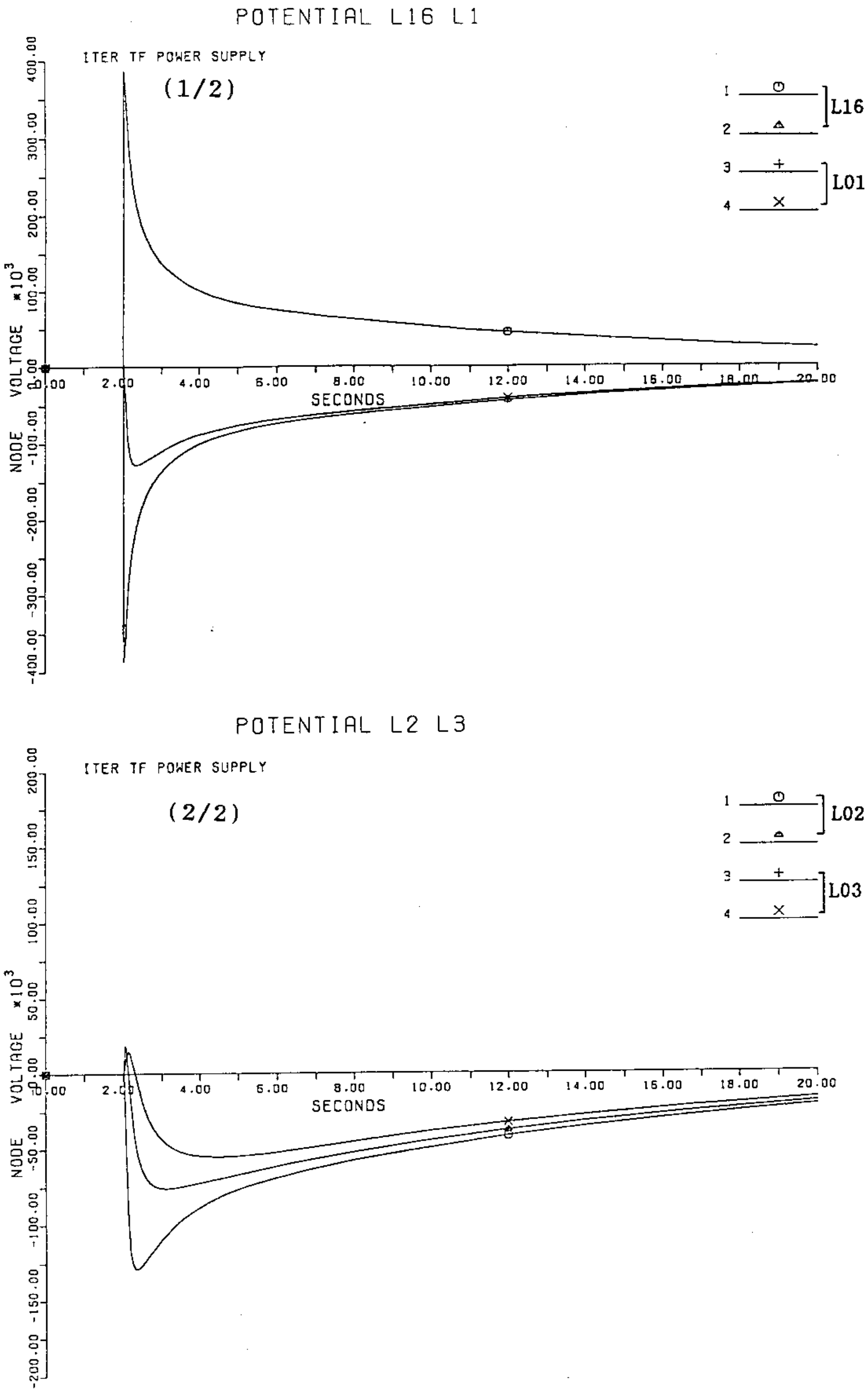


Fig. 3.14 Coil potential of circuit pattern 'SMD' (melt-down)

4. CRYOGENIC SYSTEM

4.1 Design Requirements

4.1.1 General requirements

The cryogenic system of ITER is required to satisfy following conditions:

(1) Large refrigeration power

(2) Reliability for long term operation (Specification: continuous operation for 3 years)

(3) Controllability for different operating scenarios

(4) Effective for less than 300W/W in cold-box

(5) Safety in case of a magnet quench or radioactive contamination

4.1.2 Cooldown weight

Tentative cooldown weight of the total magnet system is around 12,000 tons. (The weight for each component is listed in Table 4.1)

4.1.3 Heat load requirements at 4 K

The cryogenic system should have enough capacity for the expected magnet heat load. This heat load is based on the Physics Phase Operation Scenario.

(1) Heat loads for the magnet system

The TF magnet and the PF magnet heat loads are listed in Table 4.2 and 4.3, respectively. And the total heat loads in the operation mode are listed in Table 4.4. Accordingly, the head loads for the magnet system are as follows:

(a) Standby	10 kW + 2000 l/h
(b) Operation	
- Ramp-up	103 kW + 3400 l/h
- Burn	78 kW + 3400 l/h
- Shut-down	103 kW + 3400 l/h

Therefore, the maximum required heat load for the magnet system is 103 kW + 3400 l/h (approximately 115 kW).

(2) Other heat loads

The cryogenic system provides coolant to cool the following devices, which have a total heat load of about 20 kW at 4 K.

(a) Cryogenic pumps for plasma exhaust, NBI, pellet injection
(b) Fuel processing device
(c) RF heating device

(3) Total required heat load at 4 K

As mentioned above, the total required heat load for the cryogenic system is summed up to be:

123 kW + 3400 l/h (approximately 135 kW)

4.1.4 Heat load requirement at 80 K

The cryogenic system provides helium coolant to cool the radiation shield at the 80-K regime to avoid the possibility of radioactive Nitrogen. The total heat load of this shield is currently estimated to be around 200 kW at 80 K.

4.1.5 Cooldown requirement

A mass flow rate of around 4 kg/s will be necessary to cool the magnet system to 4 K within 300 hours.

It is assumed that a cooldown from 300 K to 100 K and 100 K to 4 K should take 200 hours and 100 hours, respectively. As such, the cooldown capacity is calculated to be 1000 kW at 100 K. This capacity roughly corresponds to the refrigeration capacity of 100 kW at 4 K. Therefore the refrigeration capacity of more than 100 kW at 4 K can cool the magnet system to 4 K within 300 hours[1].

4.2 System Design

4.2.1 Refrigeration capacity

As mentioned in 4.1, the required refrigeration capacity for the cryogenic system is as follows:

(a) 135 kW at 4 k regime
(b) 200 kW at 80 K regime
(c) 1000 kW at 100 K regime

In addition, other heat loads such as cryogenic piping and valves, should be taken into account in the required refrigeration capacity. If a cryogenic pump system will be used for circulating supercritical helium to the magnet system, this pump load should add to the refrigeration capacity. As a whole, a cryogenic system should have a capacity of at least 150 kW at 4 K regime.

4.2.2 System structure

In order to achieve the above general requirements and heat load requirements, a cryogenic system should be composed of a several unit refrigerator/liquefier system. Basic system structure is shown in Fig. 4.1. From the view point of the heat load requirements, a refrigeration capacity of 30 kW at the 4 K regime will be effective as a unit. Accordingly, a 5 unit refrigeration system will be installed. The typical operation sequences are assumed as follows;

4 - 5 units operation for cooldown
4 - 5 units operation for operation mode
2 - 3 units operation for standby mode and 2 - 3 unit for redundancy

4.2.3 Thermodynamic cycle

Based on technical experience, reliability, and controllability, a separate and double JT cycle[2] is expected to be used for the ITER cryogenic system. Figure 4.2 shows the typical flow scheme of an unit refrigerator/liquefier system. Typical features for the system follows:

(a) Separated cycle can:
- protect turbines from the back pressure cased by a magnet quench,
- protect a turbine circuit from impurities in the magnet circuit (JT circuit),

- optimize the pressure of JT valves regardless of the operating pressure of turbine circuit, and
- achieve high controllability for heat load fluctuation

(b) Double JT valve system has the advantage of achieving 20% higher thermodynamic efficiency than the single JT valve system. This increase is due to non-linear helium enthalpy profile.

(c) Quadruple turbine arrangement (T1 - T4) is effective for the following operation modes:

- operating 4 turbines for the cooldown and liquefaction mode, and
- operating 2 turbines (T1 or T2 with T3 or T4) for the operation mode. The 2 remaining turbines can serve as backups.

Preliminary mass and heat balance calculations have been carried out. The result of the 30-kW unit refrigerator is shown in Fig. 4.3. Optimum mass flow rates of the JT circuit and the turbine circuit are around 1.9 kg/s and 1.6 kg/s, respectively. In case of the 150-kW system, corresponding to 5-unit system, mass flow rates are around 9.5 kg/s and 8 kg/s, respectively. Both circuits thermodynamic efficiencies are calculated to be about 270 W/W.

4.3. Coolant circulation

4.3.1. Cooldown

As described in 4.1.5, a total mass flow rate of around 4 kg/s is required to cool the magnet system in 300 hours. Also, the cryogenic system can supply a mass flow rate of 9.5 kg/s for the magnet circuit(as mentioned in 4.2.). Accordingly, the cryogenic system has enough capacity for cooldown mass flow circulation.

4.3.2 Operation mode

To cool the magnet system with the heat load of 103 kW may require supercrical helium flow of around 17 kg/s. This flow rate is much higher than the optimum mass flow (9.5 kg/s) of a 150-kW refrigerator system. Accordingly, a cryogenic pump is necessary for circulating such supercritical helium effectively[3][4]. Use of such pump produces an additional heat load to the cryogenic system. Taking in to account the required mass flow rate and assuming a pump head loss associated with a pumping efficiency of 70%, the heat load is calculated to be 18 kW.

A cryogenic pump system has the other merits as described below:

(a) Suitable pump sizes are available for different magnet systems.
(b) An independent pump circuit can be established for different magnet systems.
(c) The system should have good controllability.
(d) A transient phenomenon or radioactive contamination can be prevented from affecting the refrigerator system.

Typical layout of the pump system is shown in Fig. 4.4. Two circulation pumps (P1 and P2) are installed for both redundancy and effective operation in each operation mode. If necessary, A cold compressor can be installed to decrease the supply temperature to the magnet system.

Figure 4.5 shows the overall flow scheme of the magnet system in the cryostat. There are 6 circuits, (1) the center solenoid circuit, (2) the TF magnet circuit, (3) the PF magnet circuit, (4) the TF magnet structure, (5) the case circuit, and (6) the radiation shield circuit. A typical TF magnet cooling scheme is shown in Fig. 4.6.

4.4 **Interpolation of Summary**

The conceptual design of the cryogenic system has been developed from the preliminary thermal analysis. Notable conclusions are as follow:

(1) The ITER cryogenic system has a refrigeration capacity of 150 kW at 4K. It is composed of a 5 unit refrigerator/liquefier system, which possesses a refrigeration capacity of 30 kW at 4 K.

(2) A separated double JT cycle is studied for use in the thermodynamic cycle of the ITER cryogenic system. This cycles thermodynamic efficiency is calculated to be 270 W/W.

(3) A cryogenic pump, to supply supercritical helium to the magnet system, should be installed in the cryogenic system.

Reference

[1] T. Kato, et al.,"Design Concept of Cryogenic System for The Proto Toroidal Coil Program", Proc. of Fusion Technol., (1988) 1603.

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[3] E. Tada, et al.,Performance Test Results of Cryogenic System for Demonstration Poloidal Coil, IEEE Trans. Magn., MAG-24 No. 2 (1988)1003

[4] T. Kato, et al.,Operation Performance of DPCF in The Test of The Nb-Ti Demo Poloidal Coils (DPC-U1,U2), Proc. of MT-11,(1989) to be published.

Table 4.1 Cooldown weight for the magnet system

Items		No. of magnet	Total mass
TF magnet winding		16	1,120 tons
TF magnet case		16	6,400 tons
Intercoil structure		32	1,140 tons
Gravity support		16	320 tons
Center Solenoid		8	720 tons
PF magnets	PF5	2	240 tons
	PF6	2	700 tons
	PF7	2	420 tons
PF magnet support		16	300 tons
Total			11,700 tons

Table 4.2 Heat loads for TF magnet system

Items		Stand-by	Operation		
			Ramp-up	Burn	Shut-down
Conduction & Radiation		6 kW	6 kW	6 kW	6 kW
Current Leads		1000 l/h	1700 l/h	1700 l/h	1700 l/h
Joint Loss		0	1 kW	1 kW	1 kW
AC Losses	winding	0	7 kW	0	7 kW
	case	0	30 kW	0	30 kW
Nuclear Heating	winding	0	0	23 kW	0
	case	0	0	42 kW	0
(Swing	winding)	(0)	(0)	(41 kW)	(0)
(	case)	(0)	(0)	(95 kW)	(0)
Total		6 kW + 1000 l/h	44kW + 1700 l/h	72 kW + 1700 l/h	44 kW + 1700 l/h

* : The value dose not include swing mode

Table 4.3 Heat loads for PF magnet system

Items	Stand-by	Operation		
		Ramp-up	Burn	Shut-down
Conduction & Radiation Current Leads Joint Loss	4 kW 1000 l/h 0	4 kW 1700 l/h 2 kW	4 kW 1700 l/h 2 kW	4 KW 1700 l/h 2 kW
AC Losses (Swing)	0 (0)	53 kW (0)	0 (42 kW)	53 kW (0)
Total	4 kW + 1000 l/h	59 kW + 1700 l/h	6 kW + 1700 l/h	59 kW + 1700 l/h

* : The value dose not include swing mode

Table 4.4 Magnet system heat loads in the operation mode

	0 90 sec Ramp-up	90 290 sec Burn	290 500 sec Shut-down	0 500 sec Average
TF magnet (Including case)	44 kW + 1700 l/h	72 kW + 1700 l/h	44 kW + 1700 l/h	44 kW + 1700 l/h
PF magnet	59 kW + 1700 l/h	6 kW + 1700 l/h	59 kW + 1700 l/h	59 kW + 1700 l/h
Total	103 kW + 3400 l/h	78 kW + 3400 l/h	103 kW + 3400 l/h	103 kW + 3400 l/h

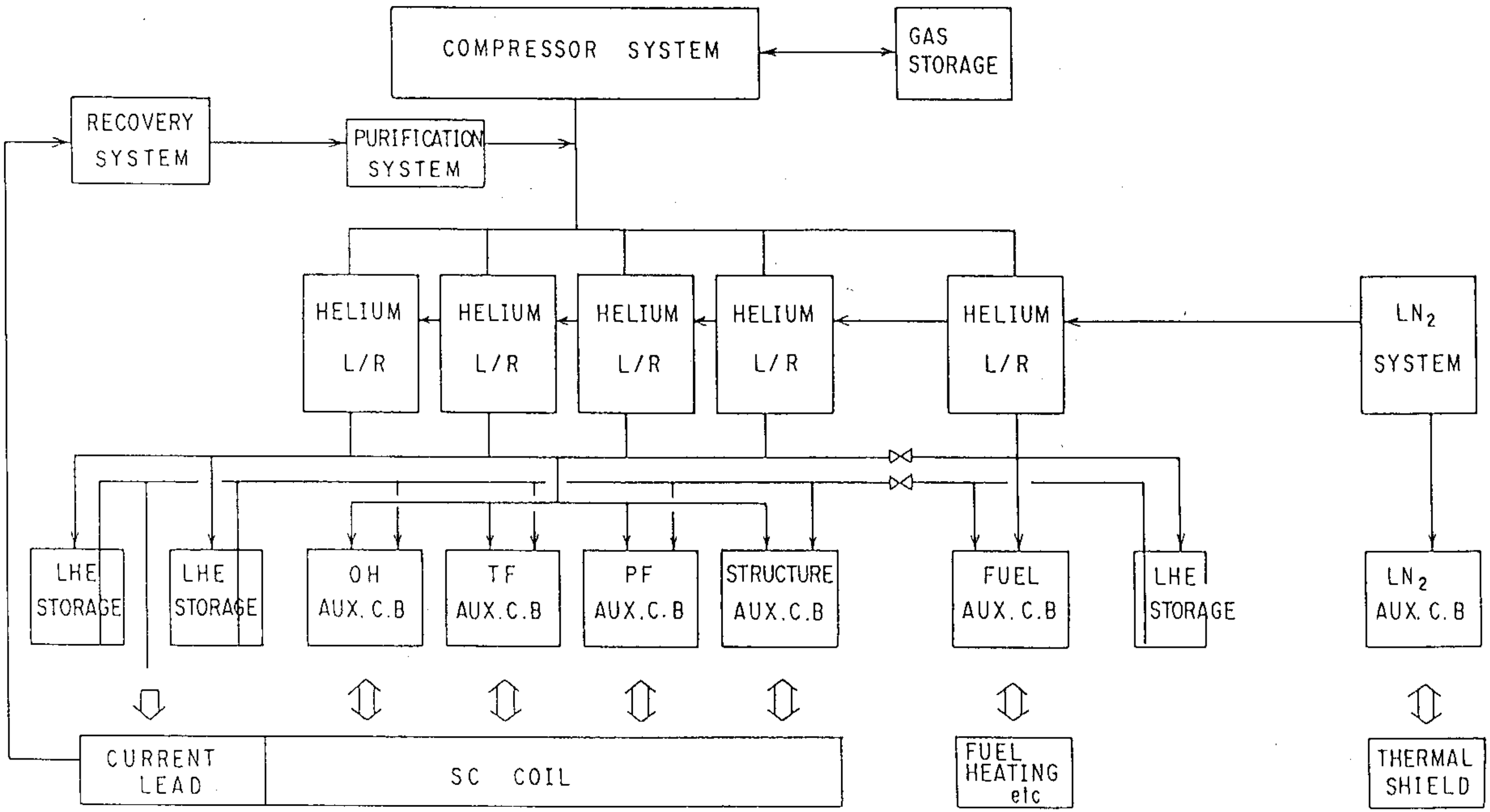

Fig. 4.1 Basic structure of the ITER cryogenic system

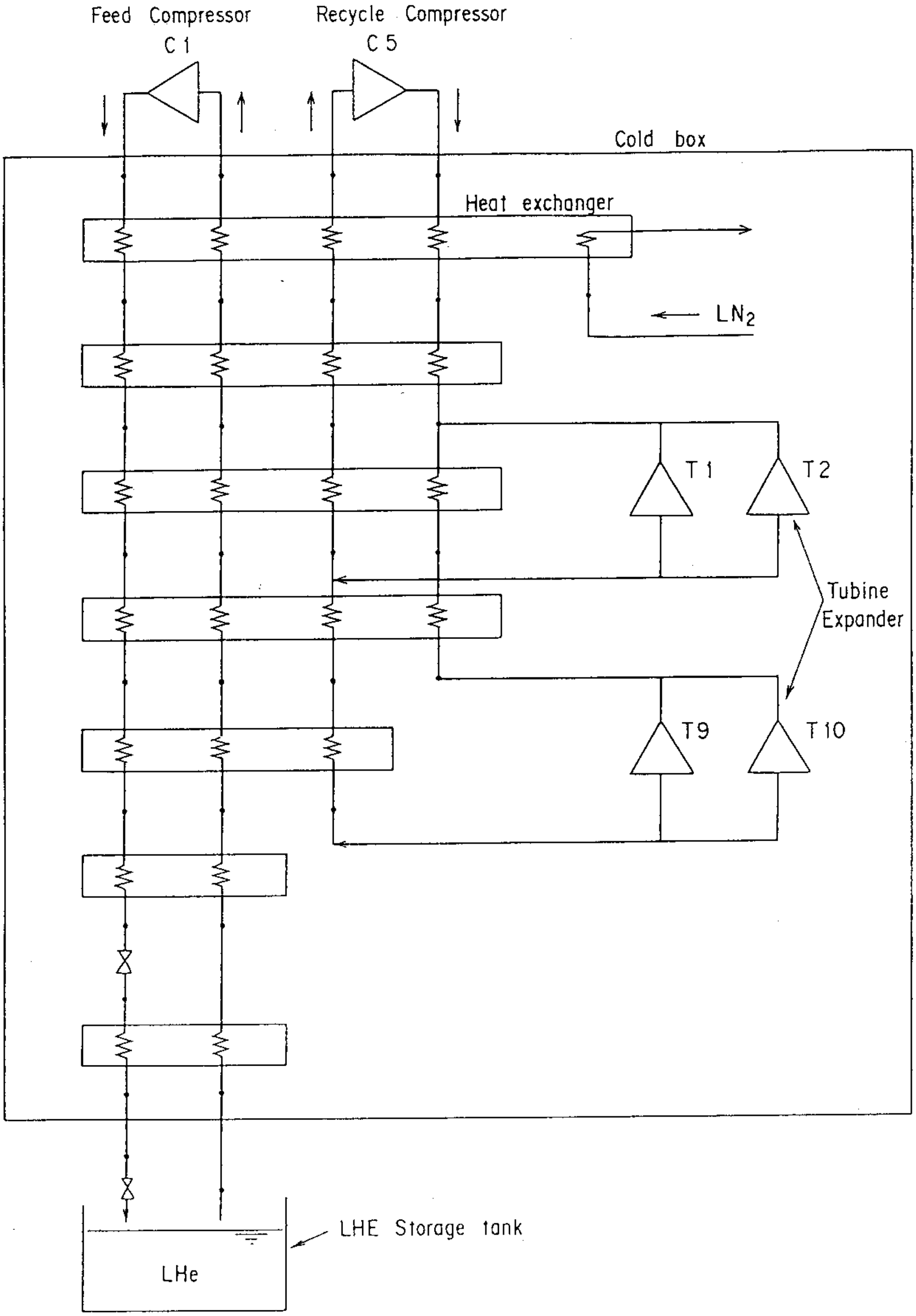

Fig. 4.2 Typical flow scheme of an unit refrigerator/liquefier

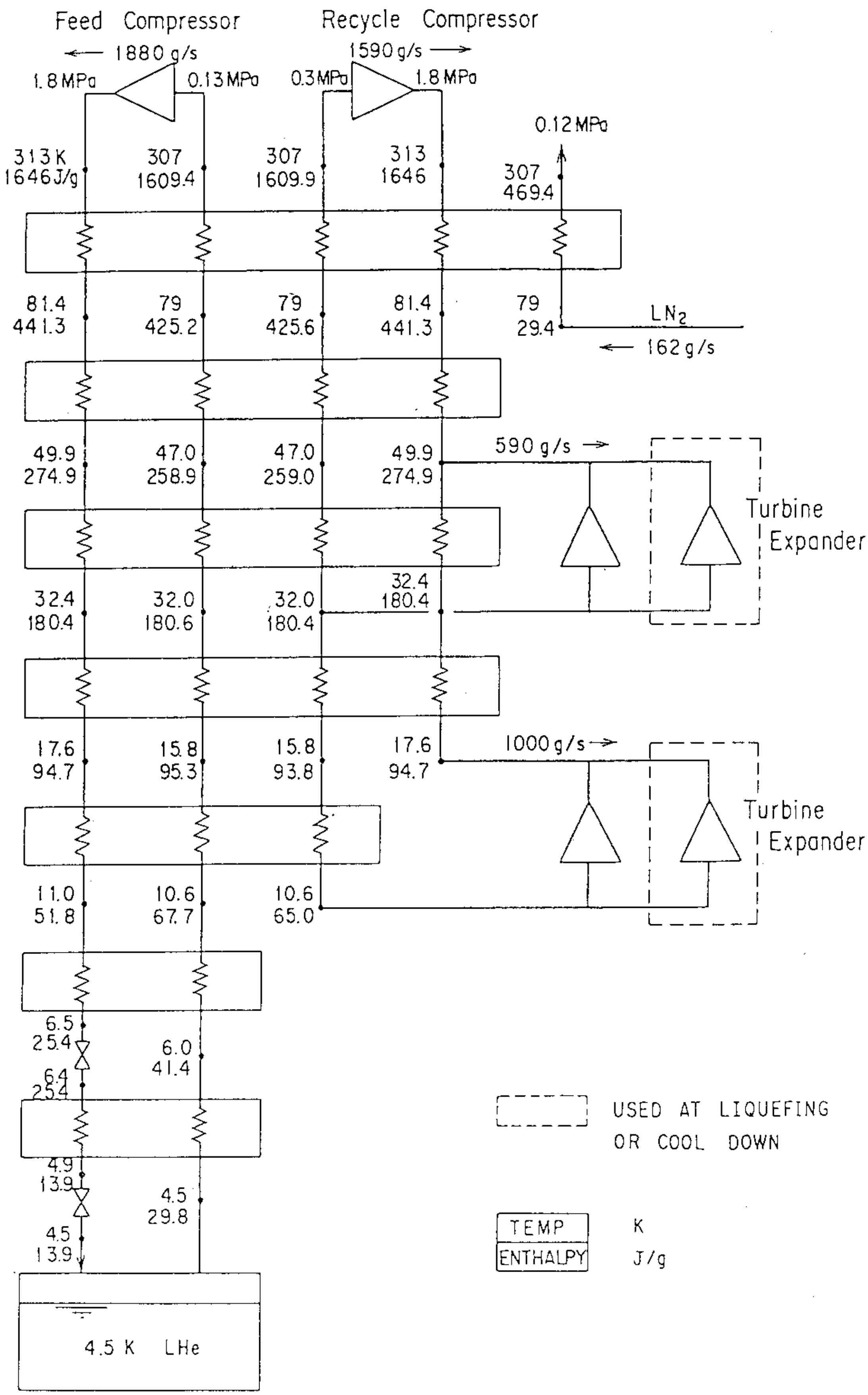

Fig. 4.3 Mass and heat balance of a 30-kW refrigerator

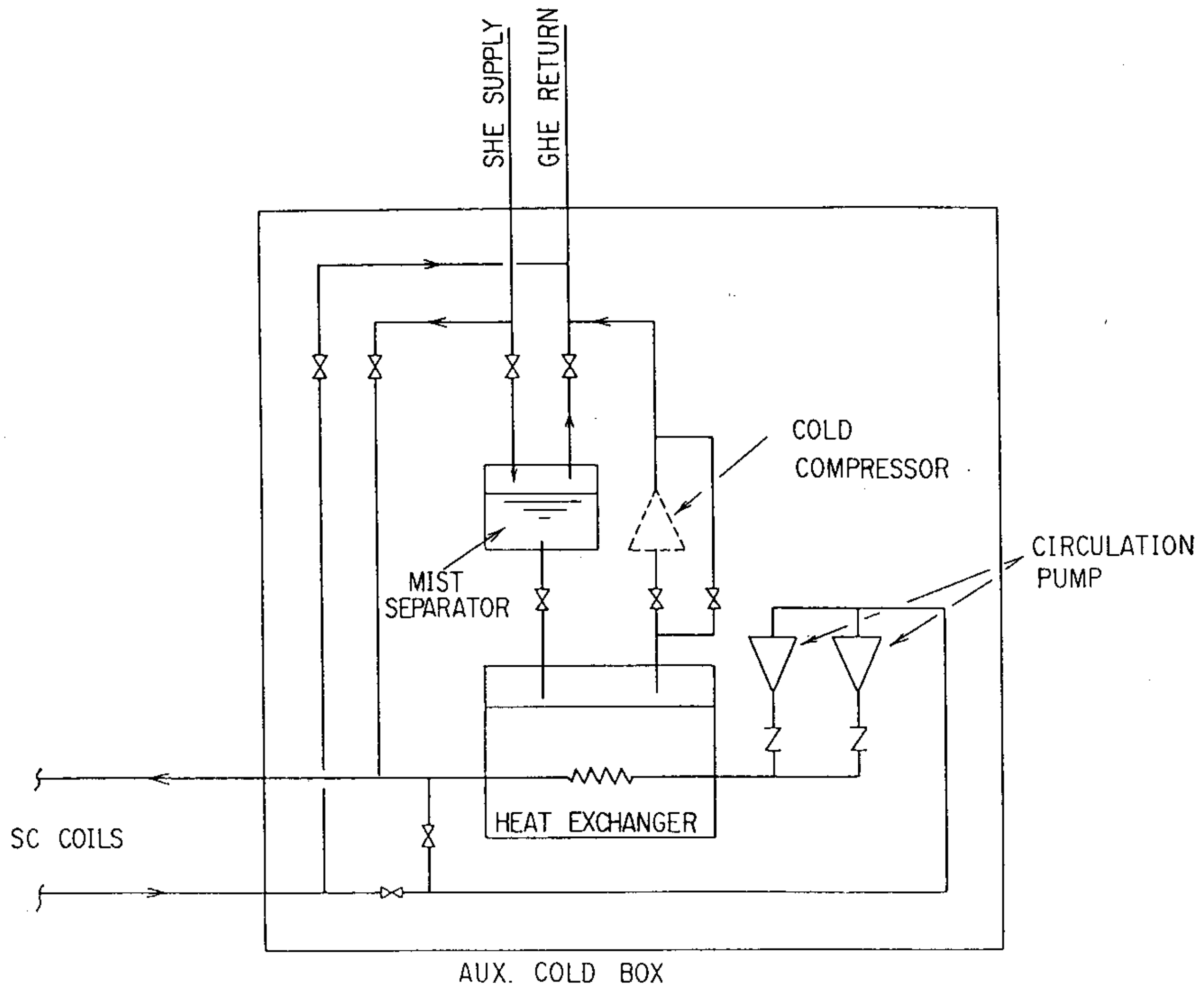

Fig. 4.4 Typical layout of the cryogenic pump system

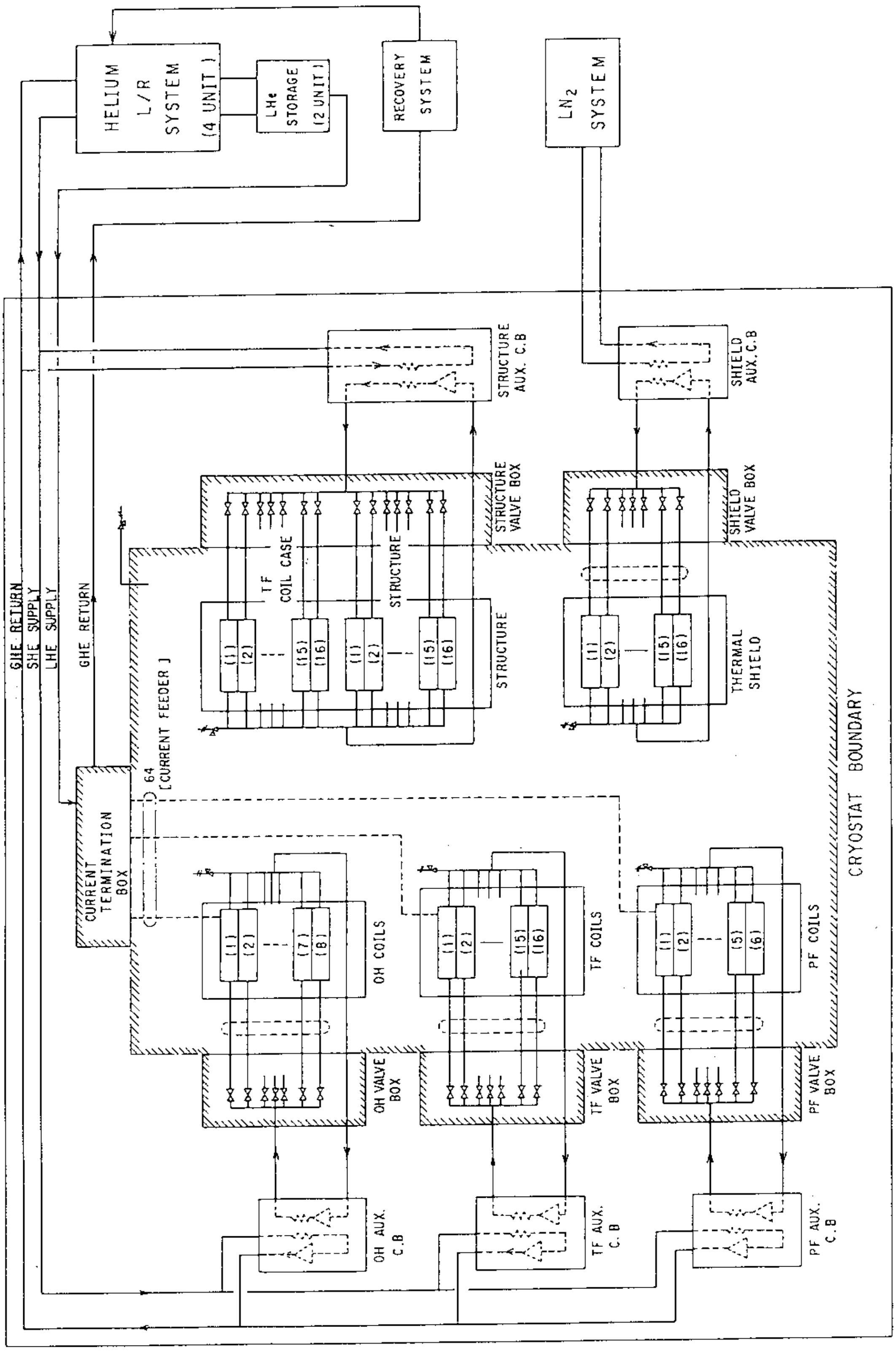

Fig. 4.5 Typical overall flow scheme of the magnet system

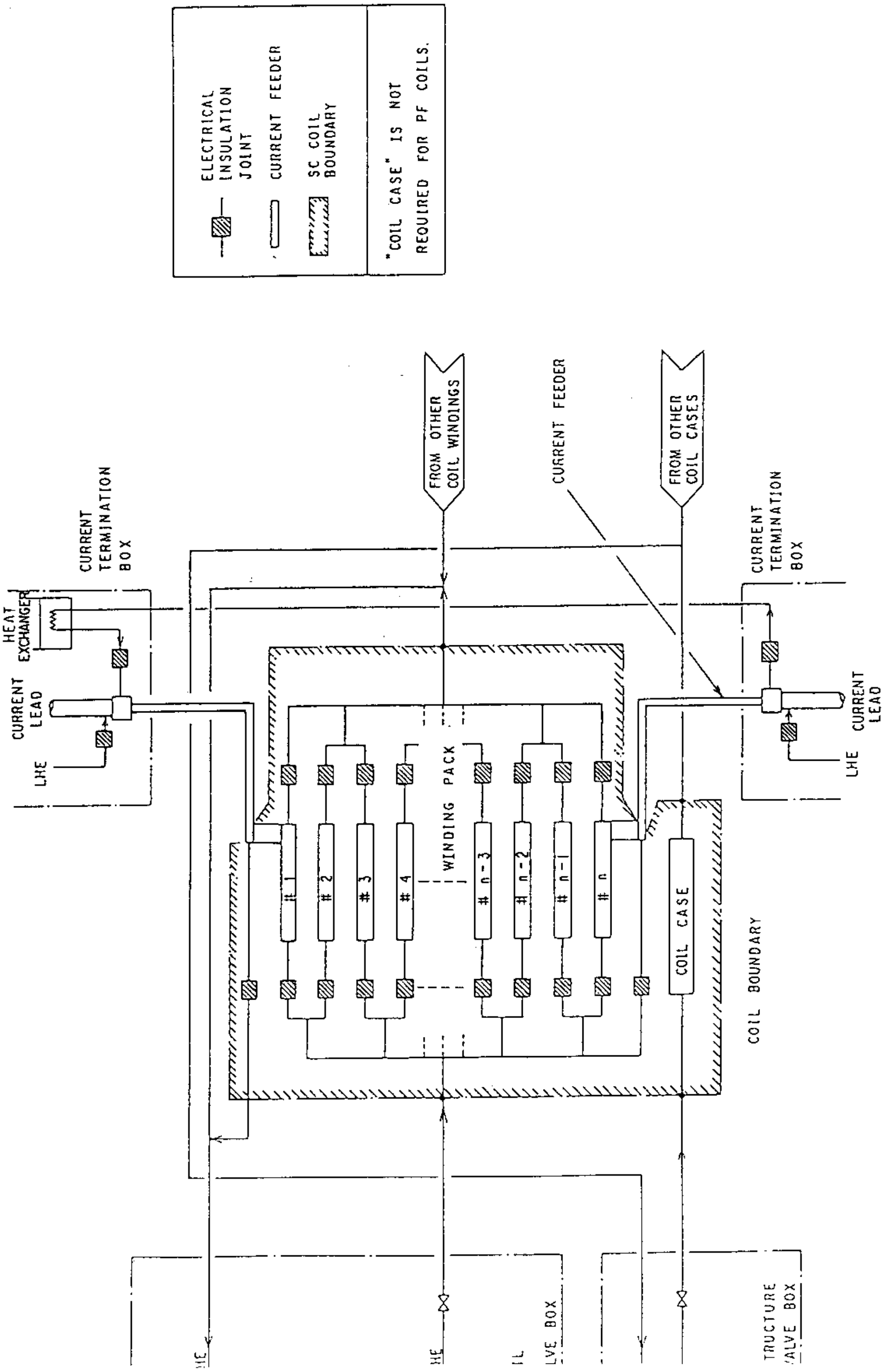

Fig. 4.6 Typical TF magnet cooling scheme

5. SUMMARY

The power supply of magnet system is not challenging to design, except for the coil protection circuit. The coil protection technique is important to reduce high voltage in the superconducting magnet during a quench. The advanced potential method and fluid dynamic method are both selected for the quench detection system. From fault analysis, it is suitable that the ground resistance is from ten times to one hundred times larger than the dump resistance, This large ground resistance will compact the difference of the time constants and terminal voltages. The series and parallel pattern is selected for the TF coil power supply.

The ITER cryogenic system has a refrigeration capacity of 150 kW at 4K. It is composed of a 5 unit refrigerator/liquefier system that possesses a refrigeration capacity of 30 kW at 4 K. A separated, double JT cycle was studied as a thermodynamic cycle of the ITER cryogenic system. This cycle has a calculated thermodynamic efficiency of about 270 W/W. A cryogenic pump should be installed in the cryogenic system to supply supercritical helium to the magnet system.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. S. Shimamoto and Dr. S. Matsuda for their strong support and kind encouragement of our design activities during the past three years. Also, the authors wish to thank the staff of the Superconducting Laboratory and the Fusion Experimental Reactor Design Team for their consultation. And authors would also like to thank Mr. T. Shimizu, Mr. Y. Nakane, Mr. H. Shimane, Mr. T. Nishino, and Mr. E. Yaguti from Kanazawa Computer Service Co Ltd for their computer analysis. Also thanks to Miss Y. Iida, Miss Y. Hasegawa, Mr. K.Hirano, and Miss H.Nagahori for the CAD operations, and Miss A. Miwa of Gensiryoku Shiryo Service Co Ltd for the publishing.