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IAEA INTOR WORKSHOP REPORT, GROUP 8
—— POWER SUPPLY AND TRANSFER ——

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IAEA INTOR Workshop Report, Group 8
— Power Supply and Transfer —

Fusion Research and Development Center,
Tokai Research Establishment, JAERI

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This report provides material for discussion in Group 8, Power Supply and Transfer, of the IAEA Workshop on INTOR.

A new system for the poloidal field power supply for INTOR is proposed and its overall system design is described. The results of simulation calculation of the system are also given.

Key words: Poloidal Field, Power Supply, Thyristor, Convertor,
INTOR, Tokamak Reactor, System Design

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IAEA INTOR ワークショップ検討報告書・グループ8
——電 源——

日本原子力研究所東海研究所核融合研究開発推進センター

（1979年9月27日受理）

本報告はIAEA INTORワークショップにおける検討資料として，原研が行ったINTORの電源に関する設計，検討の結果をまとめたものである。

主としてポロイダル磁場コイル電源システム設計に関するものであり，電源方式を提案し，これに基づき，発電機の運転特性を含めた電源システム全体の運転シミュレーション結果などが述べられている。

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1. Introduction

Among power supply systems of INTOR, that for poloidal field coils will be unconventional and occupy the largest part of power requirement. Therefore, the assessment of this time is concentrated on it. The power supply for superconducting toroidal field coils will be a conventional dc power supply for slow charging. Marks in parenthesis such as A-1 indicate the answer or the comment to the corresponding requirement in the questionary given at Session 1.

This is an interim report on the basic assessment of the poloidal field power supply for INTOR.

A composite type power system (utility power network plus motor generators) is proposed for the INTOR poloidal field power supply and a preliminary assessment has been made to outline an overall picture of the system and also to evaluate some important parameters (required peak electric power and energy etc.) which define the system size and its main characteristics.

Basic design conditions or requirements for the present study are summarized in section 2 and the outline of the system and its operation scenario are described in section 3. We also intend to answer partly the questions which were given as the working guideline to define INTOR power systems. In sections 2 and 3, the answers to some of the questions or related description (comments and/or data) are indicated by the corresponding numbers of questions such as (A-1) or (B-3). Answers or comments to those questions which are not convenient to be described in this way are summarized en bloc in section 4 together with some discussion of the results of the present study. Basic consideration of the proposed hybrid poloidal field system is briefly described in Appendix.

2. Basic design conditions

The following items are considered as design conditions or prerequisites for the INTOR poloidal field power supply. Basic machine and plasma parameters are assumed to be those given in Summary Report as the guideline parameters.

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(1) Superconductors are to be used for the poloidal field coils.

(2) The whole hybrid poloidal field coil system can provide the divertor field with some additional ampere-turns to the coils to form D-shape of the plasma. The analysis in this report is made for the case without divertors. However, the power requirement for divertors is anticipated not so much.

(3) The rate of rise of the plasma current should be reasonably small to be compatible with item (1) above. In connection with this, the maximum initial loop voltage at the plasma axis is assumed to be 100 V.(G-2)

(4) Two-step rise of the plasma current is envisaged; the first fast rise up to several hundreds kA is made by using dc circuit interrupters, which is followed by a slow rise up to prescribed flattop values using thyristor convertors.

(5) Both plasma position and shape are to be feedback-controlled throughout the plasma current build-up time.

(6) A hybrid system of the poloidal field coils is to be adopted. In this hybrid field system, the currents in the poloidal field coils are adjusted and controlled as a whole by separate dc power supplies to produce magnetic field configurations required for INTOR experiments.

3. System description

3.1 Arrangement of poloidal field coils

Figure 1 shows the arrangement of poloidal field coils which is taken as the design basis of the poloidal field power system. The coils are devided into six blocks. The function of each block of coils is assigned as shown in Fig.1 and the current in the coil of each block is energized and controlled by separate dc power supplies to produce poloidal magnetic field configurations which meet experimental requirements as a whole.

3.2 Description of proposed poloidal field power supply system

(1) system description

A simplified system configuration of the poloidal field power supply is shown in Fig.2. All the electric power and energy required for operation of the poloidal field system are supplied from two sets of motor generators(B-1) and utility power network: The utility power network supplies average electric power needed for operation of the entire poloidal field power

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The dc power system consists of two identical subsystems EOH,EI1,..,EI6 and EOH',EI1',.....,EI6', where EOH,EI1, etc are thyristor convertors connected in series with each block of coils. The dc power system also includes dc circuit interrupters S_1 and S_1'.

As shown in Fig.2, each block of coils (for example B1+B1') is sub-devided into two identical sub-blocks (B1 and B1')(since the arrangement of the coils is symmetric with respect to the median plane) and the coil of each sub-devided block has its own dc power supply (thyristor convertor) EI1 and EI1' respectively as described above (except blocks B2 and B2').

The thyristor convertors EOH and EOH' and the dc circuit interrupters S_1 and S_1' are used to build up the plasma current. The dc circuit interrupters are essential components to make a fast build-up of the plasma current in the first 0.1 sec or so. The second slow rise up to prescribed flattop values is made during a few seconds by using the thyristor convertors EOH and EOH'.

The thyristor convertors EI1 ~ EI6 (and also EI1' ~ EI6') are used to adjust and control the currents in the poloidal field coils to produce a required magnetic field configuration (see, for example, Fig.3) which equilibrates plasma positions and controls both plasma positions and shapes. Each block of coils is separately powered by these respective thyristor convertors and produces a magnetic field which has the ohmic heating (OH) field, the equilibrium field and the shaping field components simultaneously. By adjusting properly the current in each block of coils using respective thyristor convertors altogether, the required field configuration is realized as a resultant of these poloidal magnetic fields. The function of each block of coils is prescribed beforehand in connection with the spatial arrangement of the coils. A variety of plasma controls can also be made by fast computer-control of thyristor convertors (hybrid poloidal field system). More detailed description of the hybrid system (determination of the coil currents and the number of turns of each coil and circuit calculations) is given in Appendix.

(2) Operation sequence

i) Excitation of poloidal field coils

The poloidal field coils are initially charged with currents of proper values to store required magnetic field energy for initiation and fast build-up of the plasma current. The electric power is supplied from the power network. The motor generators are accelerated to their maximum available rotation and maintain that rotation and stand by the operation during this stage. Time required for this stage is about 30 sec in the present reference design.

ii) Fast rise phase

At t=0, the dc circuit interrupters operate to break the current in the poloidal field coils. The current in the coils then rapidly commutates to the resistor R producing a high voltage across it. The design value of the induction loop voltage at the plasma axis is 100 V and the plasma current build-up of up to several hundreds kA in about 0.1 sec is envisaged during this fast rise phase.

iii) Slow rise phase

When the above value of the plasma current is reached, the interrupter S_1 and S_1' are re-closed and the electric power from the generators are supplied, via thyristor convertors, to further increase the plasma current to flattop values. The maximum design value of the flattop current is 4.7 MA. This build-up is made relatively slowly during about 5 sec, but the peak electric power of the poloidal field power system is required during this slow rise phase. The peak capacity of the generators is thus determined from the system dynamics during this time.

iv) Flattop phase

After the flattop value is reached, it is maintained by compensating the resistive drop in the plasma. Also various plasma control is required during this time. If the plasma is quiet, the power required for this time is estimated about 40 MW(A-1)(A-2) in the present reference design and is taken directly from the power network. In case of any fast control of plasma is required, the generators can supply powers for this purpose.

v) Shutdown phase

At the end of each pulse (operation), the poloidal field energy is recovered to the generators to re-accelerate them for the subsequent operation. In the reference design calculation, the rotation of the generators almost reaches the maximum available rotation at the end of this phase.

(3) Circuit calculations and main results

Using the method described in Appendix, the necessary number of ampere-turns for each block of coils and hence the number of turns and the current of each coil are determined as summarized in Tables 1 to 3.

To evaluate the maximum capacity and operation performances of the poloidal field power system shown in Fig.2, a computer code developed for JT-60 to describe the overall system behavior of the poloidal field power system throughout a full one cycle of operation was used. The behavior of INTOR plasmas is assumed as the basis to perform circuit simulation calculations using the above computer code. Figure 4 shows the assumed wave forms of the plasma current and the plasma loop voltage given a priori for this calculation. These wave forms have been obtained from a plasma simulation calculation based on a zero-dimensional plasma model. The circuit calculation was made so as to realize the current behavior given in Fig.4, namely the currents and voltages of thyristor convertors, the interrupter capacity and so forth are determined to obtain the plasma current wave form shown in Fig.4 and the plasma position and shape as determined from equilibrium calculations (Fig.3). This is made automatically and consistently in the present calculation, and in that sense, an artificial plasma control is performed during the operation of this poloidal field power system.

Results of calculation are shown in Figs.5~13,(D-1,2,3) where variations of various quantities during one full cycle of operation (up to 207 sec) are summarized. They include plasma current, currents of each block of coils, voltages of thyristor convertors and some blocks of coils, total power and energy of the system and rotations of the generators. Table 4 shows the maximum and minimum voltages of thyristor convertors EI1,.....,EI6 and EOH (and also EI1',.....,EOH') required during the operation. These voltages define, in combination with the maximum current, the ratings of the thyristor convertors.

The peak electric power required for this operation is about 900 MW and comes at the end of the slow rise phase. The required energy for the plasma current build-up time (up to 5 sec) amounts to about 2.6 GJ. Since the plasma is assumed to be quiet during the flattop phase, the required power from the power network is approximately 40 MW, which is mostly dissipated in the normal conductor parts of the poloidal field coils.

Table 5 summarizes the ratings of major components of the poloidal field power system (Fig.2) determined on the basis of the calculation described here and outlines the present reference design for the INTOR poloidal field power supply system.

4. Notes on somepoints

A reference design calculation of the proposed INTOR poloidal field power supply was made to obtain an overall concept of the system. The design described in this report is quite preliminary and further studies are needed to define the system more definitely.

Judging from what is found in the present scope of design studies, the proposed hybrid power system for INTOR seems to be constructed relatively easily on the basis of rather conventional or familiar technologies, or at least of those within the reasonable extent of future extrapolation of present-day technologies both in hardware and software aspects.

The power system is a composite type of motor generators and power network. Two sets of motor generators supply the required peak power of the system, while the average power is supplied from the power network. The motor generators also act as a "filter" or "buffer" to prevent higher harmonic powers generated in the large capacity thyristor convertors from flowing out to the utility network. Since the peak power and the energy required for the system are supplied from the motor generators and are recovered to them at the end of each operation, the power network does not suffer any abrupt change of a large electric load and, owing to the recovery of energy, the motor generators can always prepare for the subsequent operation at the end of each pulse. This will contribute to minimize the dwell time of the system.

The required power from the network is calculated about 40 MW assuming that the overall resistive drops of the poloidal field system of 150 V including heat losses in the normal conductor parts of the coils and internal losses of dc power system (dc interrupters and thyristor convertors). As shown in Fig.12, the total energy required for one cycle of operation of the system is calculated to be about 17 GJ, which is mostly dissipated as resistive losses in the normal conductors.

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The most crucial point of the proposed power system comes from the restriction imposed on the time rate of change of magnetic fields in the superconductor coils. This is closely related to the build-up speed of the plasma current, and it is one of the major tasks of preceeding large tokamaks such as JT-60 etc. to make clear to what extent a controlled slow build-up of the plasma current is possible to be compatible with the use of superconductors. Discussion or evaluation of this point will not be made here since almost no technical data as to the allowable limit of $\dot{B}$ is available at present. To circumvent this, it may be possible to use partly normal conductor coils as a breakdown field generator at the initiation time of plasma currents.

Another point to be noted is the energy capacity of the commutation resistor R as a component of dc circuit interrupters (Table 5). A large amount of energy of about 40 MJ should be disposed of in the resistor during one operation (~10 MJ for JT-60), and this will need a developmental work. A large scale thyristor convertors (3,400 MW) form the central part of the dc power supply system (1,400 MW for JT-60). The computer control of thyristor convertors and other related engineering problems are anticipated to be developed and solved by the preceeding large tokamak experiments and may not be serious for this power system.

Appendix (1)

Hybrid operation matrix and its application to hybrid poloidal field system for INTOR

To analyze basic properties of the hybrid poloidal field system, it is useful to introduce a "hybrid operation matrix". In the hybrid system, the current of each poloidal field coil is a superposition of currents which produce the ohmic heating (OH) field component, the equilibrium field component and the shaping field component, and it should be a proper value so that the resultant magnetic field produced by the whole poloidal field coils has a required field property; the strength of the OH field should be minimized in the plasma region, while the equilibrium field should have a proper field strength and pattern in the same region and the shaping field should also have a required field strength and pattern to shape plasma cross-sections. To determine the magnitude of each coil current consistently in this system, the hybrid operation matrix is introduced as described below.

For the coil belonging to block k, the current I_k of the coil is expressed as,

$$I_k = F_{kOH} I_{OH} + F_{kE} I_E + F_{kS} I_S + \cdots\cdots\cdots\cdots$$

where I_{OH} is the OH field component of the current, I_E the equilibrium field component and I_S the shaping field component. The hybrid operation matrix can be used to define the currents of a system of n-blocks of coils;

$$\begin{bmatrix} I_p \\ I_1 \\ \vdots \\ I_k \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} \\ \\ \quad H \quad \\ \\ \\ \end{bmatrix} \left.\begin{bmatrix} I_p \\ I_{OH} \\ I_E \\ I_S \\ \vdots \end{bmatrix}\right\} m \qquad (1)$$

$$[\,H\,] = \left.\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & \cdots \\ 0 & F_{1OH} & F_{1E} & F_{1S} & \vdots & \\ 0 & F_{2OH} & F_{2E} & F_{2S} & \vdots & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \\ 0 & F_{nOH} & F_{nE} & F_{nS} & \vdots & \end{bmatrix}\right\} n+1$$

where [H] is the hybrid operation matrix having the dimension of $m \times (n+1)$, m is the order of the current vector of eq.(1) and I_p is the plasma current. The coefficients F_{kOH}, F_{kE} and F_{kS} are determined from the analyses of respective field geometries, namely F_{kOH}'s $(k=1,2,\cdots\cdots)$ are obtained from the ratios of coil currents which do not make stray magnetic fields in the plasma region and F_{kE}'s $(k=1,2,\cdots\cdots)$ are obtained from the ratios of coil currents which make a required field pattern in the plasma for a given arrangement of poloidal field coils. In the plasma current build-up phase, F_{kE}'s are determined approximately assuming that the necessary equilibrium (vertical) field is proportional to the plasma current $I_p(t)$. Table 1 shows F_{kOH} and F_{kE} $(k=1,\cdots\cdots6)$ for the arrangement of poloidal field coils given in Fig.1 (F_{kS} was not taken into account in the present reference design). Using eq.(1) and Table 1, the ampere-turns of each block of coils can be determined easily.

To determine the number of turns or the current of each coil, it is necessary to take the circuit equations of the system into consideration. The circuit equations are;

$$[\,V\,] = [\,M\,]\begin{bmatrix} \dot{I}_p \\ \dot{I}_1 \\ \vdots \\ \dot{I}_k \\ \vdots \\ \dot{I}_n \end{bmatrix} + [\,R\,][\,I\,] \qquad (2)$$

where [M] is the (n+1) × (n+1) square matrix of self and mutual inductances of the poloidal field coil system. The equation (2) becomes

$$[\ V\ ] = [\ M\ ][\ H\ ]\begin{bmatrix} \dot{I}_p \\ \dot{I}_{OH} \\ \dot{I}_E \\ \vdots \end{bmatrix} \tag{3}$$

Here the following assumptions are introduced; the resistance of the coils = 0, $\dot{I}_{OH} = -L_p \dot{I}_p / M_{pOH}$, where M_{pOH} is the mutual inductance between the OH field component and the plasma current, and $\dot{I}_E = F_E\ \dot{I}_p$.

The equation (3) now becomes

$$V_o \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = [\ M\ ][\ H\ ] \begin{bmatrix} 1 \\ -L_p/M_{pOH} \\ F_E \end{bmatrix} \dot{I}_p \tag{4}$$

where

$$[\ M\ ] = \begin{bmatrix} L_p & - & & \\ \vdots & & & \\ \vdots & n_1^2 L_1\ , & n_1 n_2 M_{12}\ , & - - - - - - - - - - \\ \vdots & - - - -, & n_2^2 L_2\ , & n_2 n_3 M_{23} - - - - - - \\ \vdots & - - - - - - - - -, & & n_3^2 L_3\ , - - - - - - \end{bmatrix} .$$

The equation (4) is the circuit equation of the system shown in Fig.2 (the poloidal field coils are connected in parallel and they are connected to the dc circuit interrupters in series) and here only the contribution of the OH field and the equilibrium (vertical) field are taken into consideration. The number of turns of the coil can be determined by solving eq.(4) under the condition to minimize the voltages of thyristor convertors EI1 to EI6 in the plasma current build-up phase. Table 2 shows the number of turns of each block of coils, and the currents of each block of coils obtained from the circuit calculation are tabulated as a function of time in Table 3.

Table 1

Necessary ampere-turns for each block of coils; F_{OH} denotes the ohmic heating field component and F_E the equilibrium field component.

Coil Block	F_{OH} (MAT)	F_E^*(MAT)
1	5.66 × 2	-1.34 × 2
2	5.023 × 3	0
3	1.159 × 4	5.0 × 4
4	0.329	0
5	0.203	-5.35
6	0.141	-1.67

* plasma current 4.68 MA
$\beta p=2.6$, $\ell_i=1.0$

Table 2

Number of turns of each coil

Block	1		2			3			4	5	6
coil	1	2	3	4	5	6	7	8	9	10	11
turns	86	86	120	120	120	-80	-40	-40	140	42	47

The (-) sign indicates the coils wound oppositely

Table 3

Currents of each block of coils
at typical times

	number of turns	t=0	t=0.2 sec	t=5.0 sec	t=200 sec
I_1	86 × 2	58.9 kA	51.7 kA	10 kA	- 15.2 kA
I_2	120 × 3	41.8 kA	38.0 kA	18.1 kA	0.13 kA
I_3	-40 × 3	-28.9 kA	-42.7 kA	-137 kA	-124 kA
I_4	140	2.35 kA	1.85 kA	0.96 kA	0 kA
I_5	42	4.8 kA	-12.9 kA	-125 kA	-126.9 kA
I_6	47	3.0 kA	- 0.8 kA	- 33 kA	- 35.4 kA

Table 4

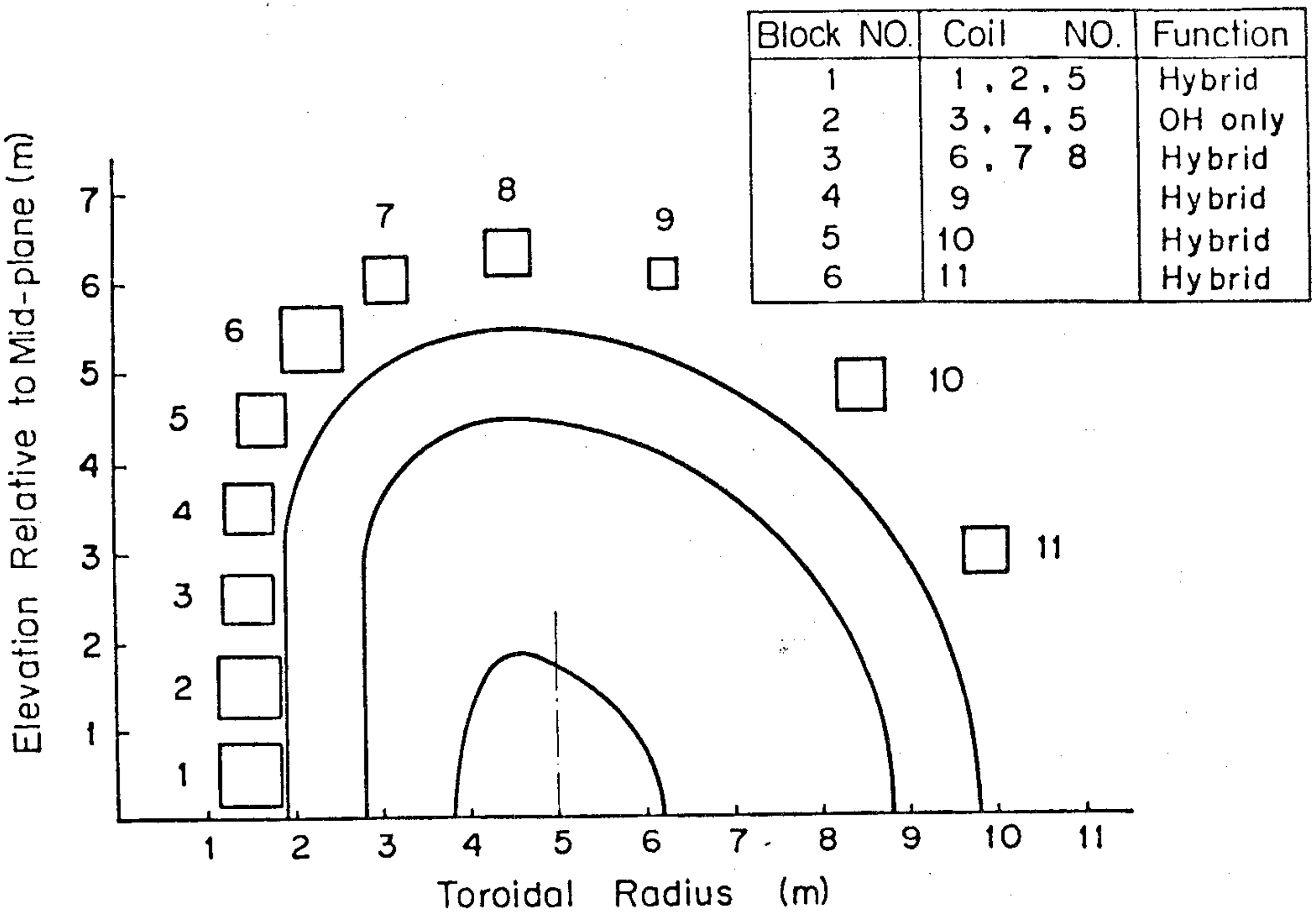
Required voltages of thyristor convertors

	maximum	minimum
E_1	364 V	- 686 V
E_3	0	-4300 V
E_4	875 V	0
E_5	0	-4900 V
E_6	0	-2600 V
E_{OH}	1000 V	- 50 V

Table 5

Specifications of main components

Generators	Vertical shaft synchronous motor-generator		2 sets
	Capacity	(B-2) 500 MVA	
	Revolution	600-420 RPM	
	Deliverable energy	(B-2) 1.3 GJ	
D.C Circuit interrupters S_1, S_1'	V.C.B. type		2 sets
	82 kA - 10 kV		
Resistors R,R'	Large scale resistors with minimum residual inductances		2 sets
	Resistance	0.114 Ω	
	Heat capacity	43 MJ	0.1 sec
Frequency convertor	50 Hz → 80~56 Hz		1 set
		40 MW(A-1)(A-2)	
Thyristor convertors	EI1	52 kA - 0.7 kV	2 sets
	EI3	137 kA - 4.5 kV	2 sets
	EI4	2 kA - 1 kV	2 sets
	EI5	127 kA - 5 kV	2 sets
	EI6	36 kA - 2.6 kV	2 sets
	EOH	306 kA - 1 kV	2 sets
	Total MW	3380 MW	



Block NO.	Coil NO.	Function
1	1 , 2 , 5	Hybrid
2	3 , 4 , 5	OH only
3	6 , 7 8	Hybrid
4	9	Hybrid
5	10	Hybrid
6	11	Hybrid

Fig.1 Arrangement of poloidal field coils

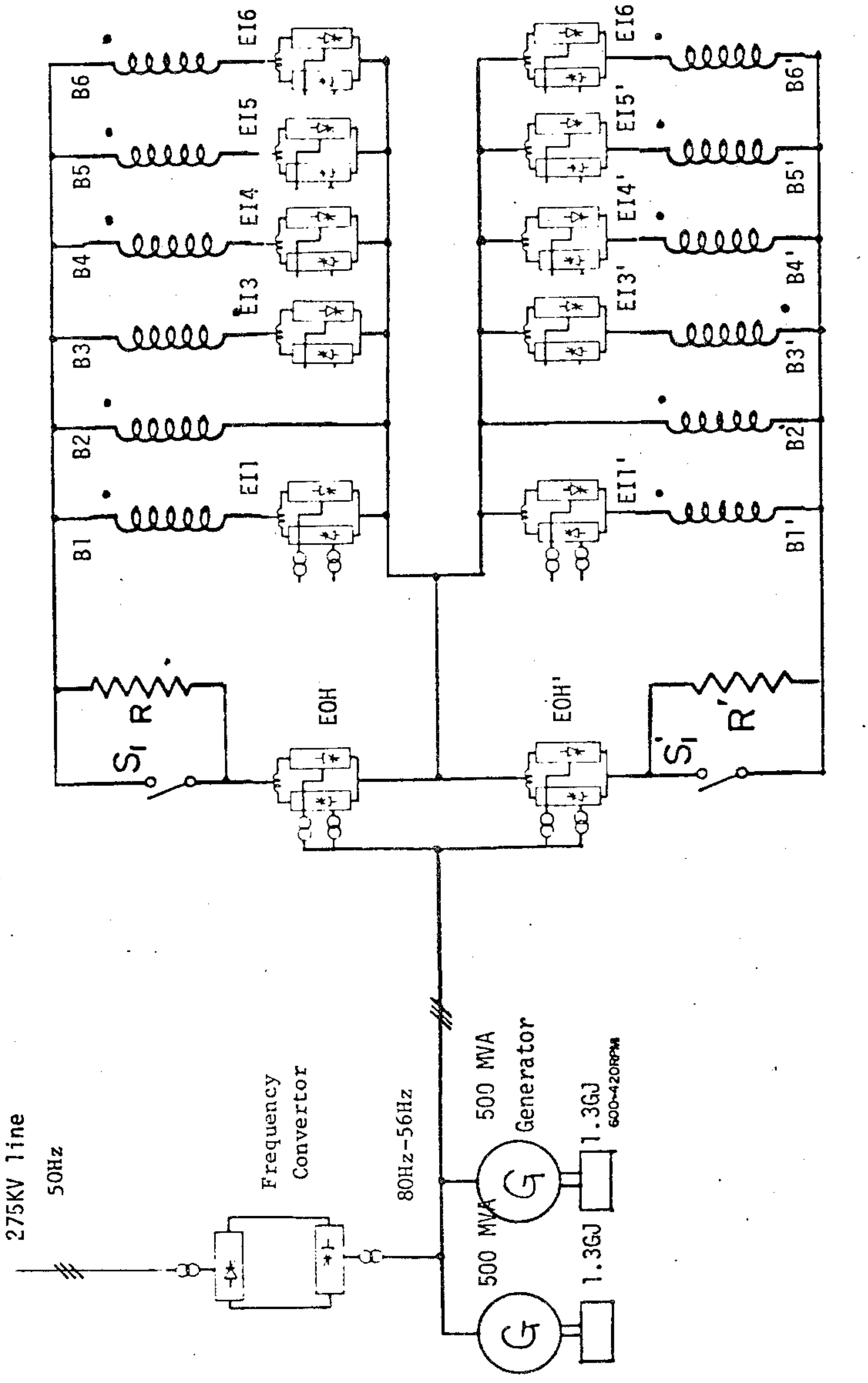


Fig.2 Schematic diagram of poloidal field power supply system

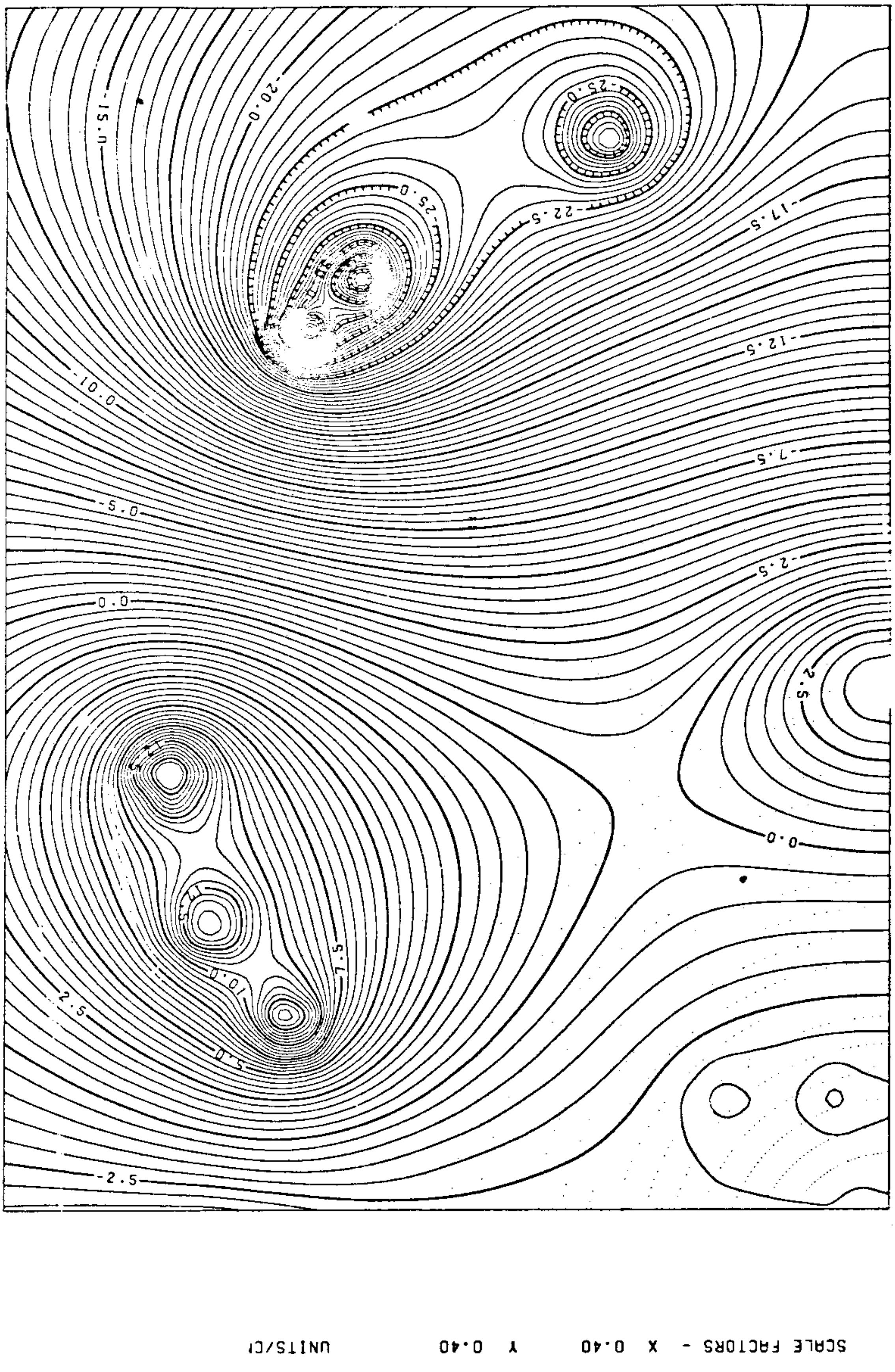
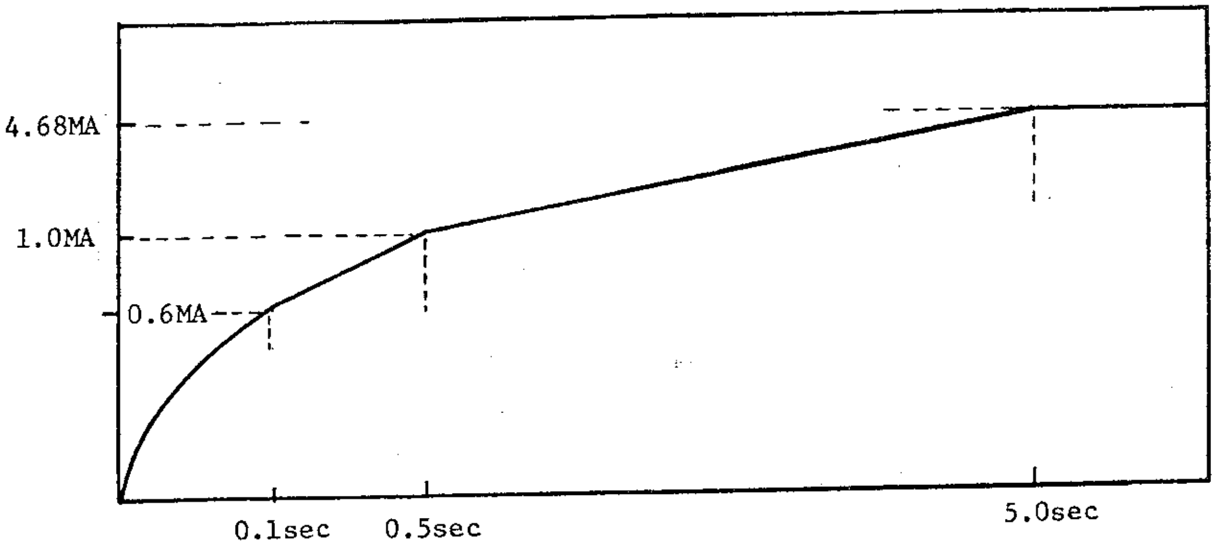


Fig.3 Equilibrium field configuration


Scheme of plasma current at the build-up phase

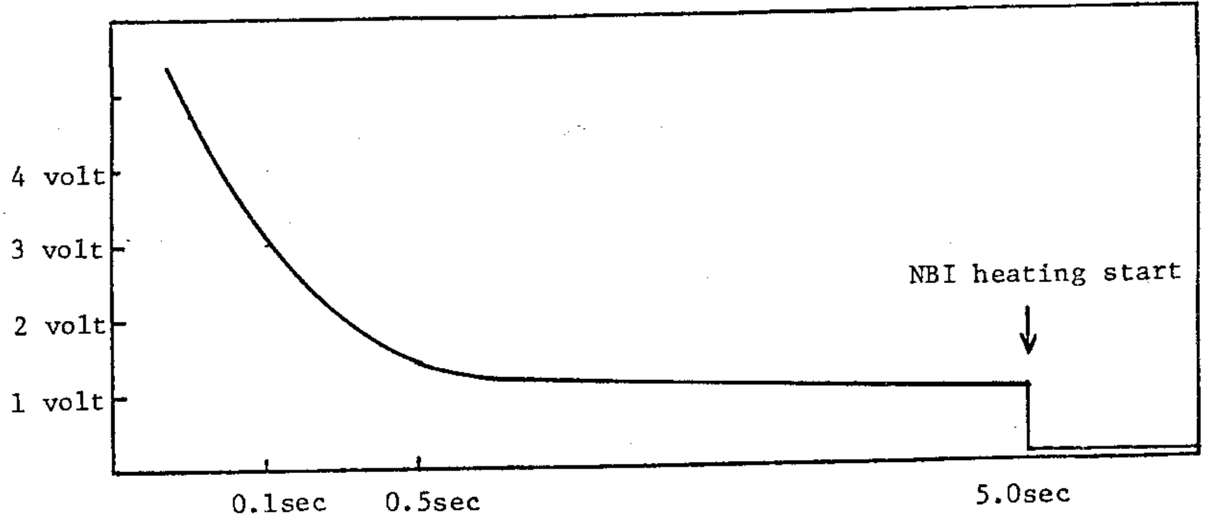
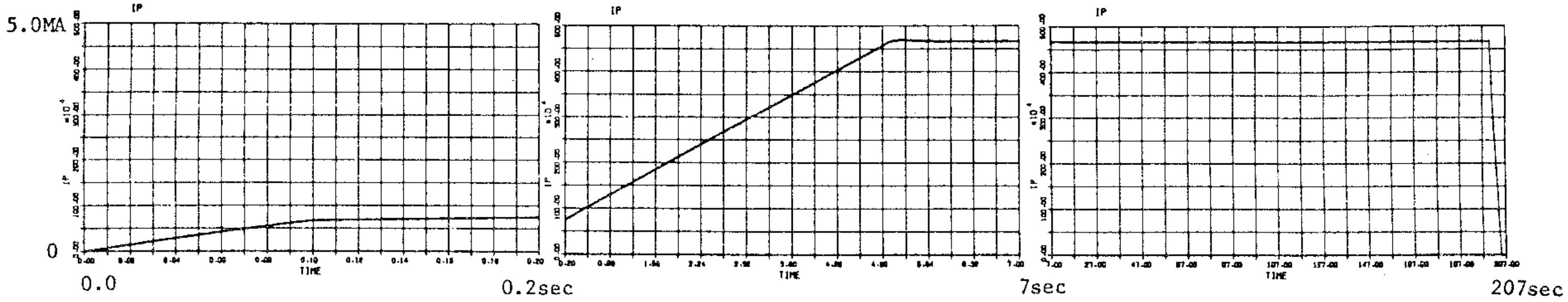

Resistive part of the one turn voltage

Fig.4 Plasma current and resistive loop voltage in the current build-up phase

Plasma current



Current of coil block-No.1

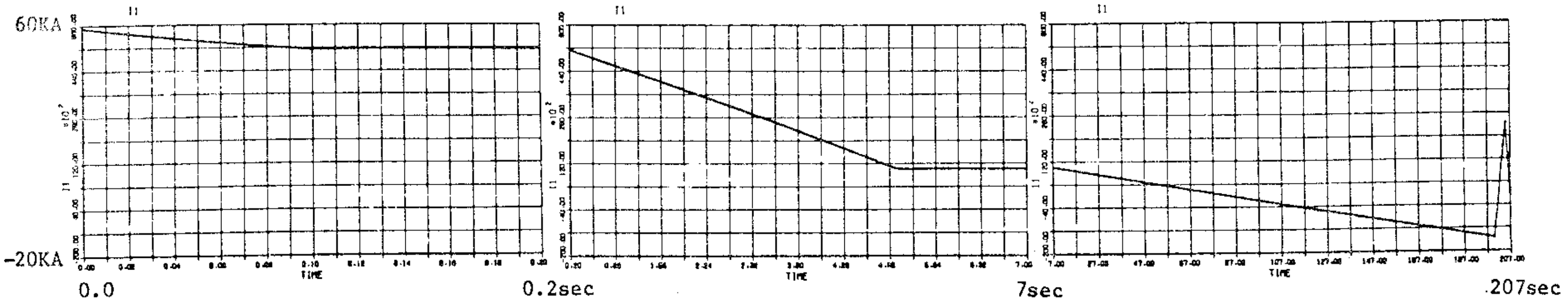
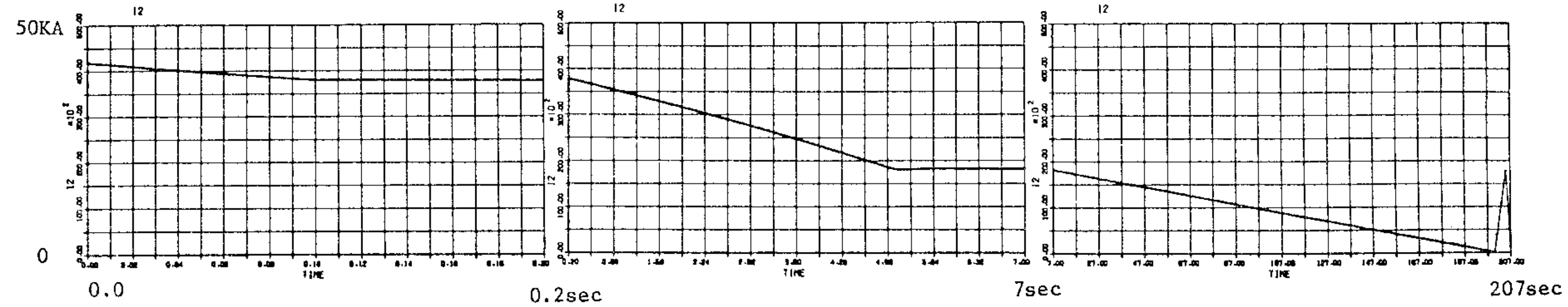


Fig.5 Variations of plasma and coil currents

Current of coil block-No.2



Current of coil block-No.3

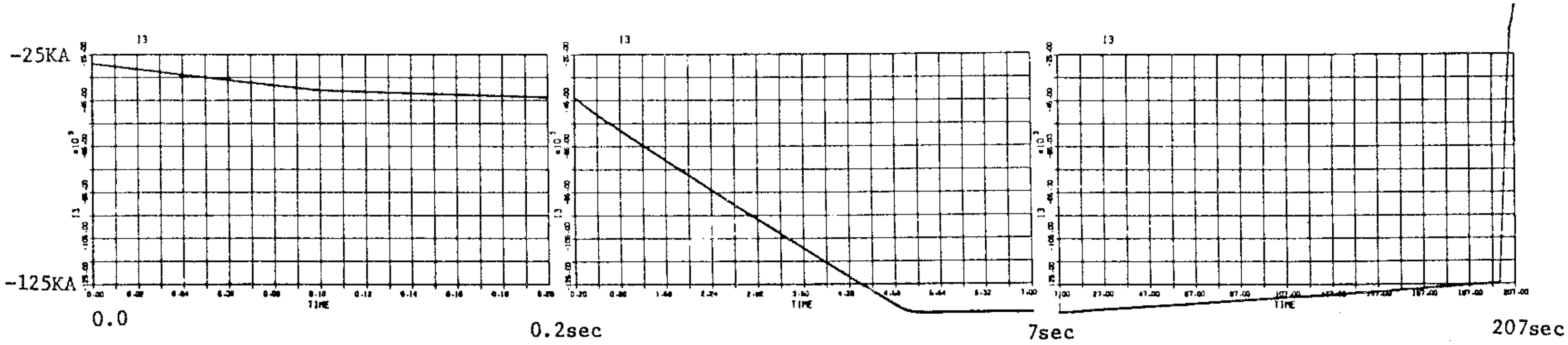


Fig.6 Variations of coil currents

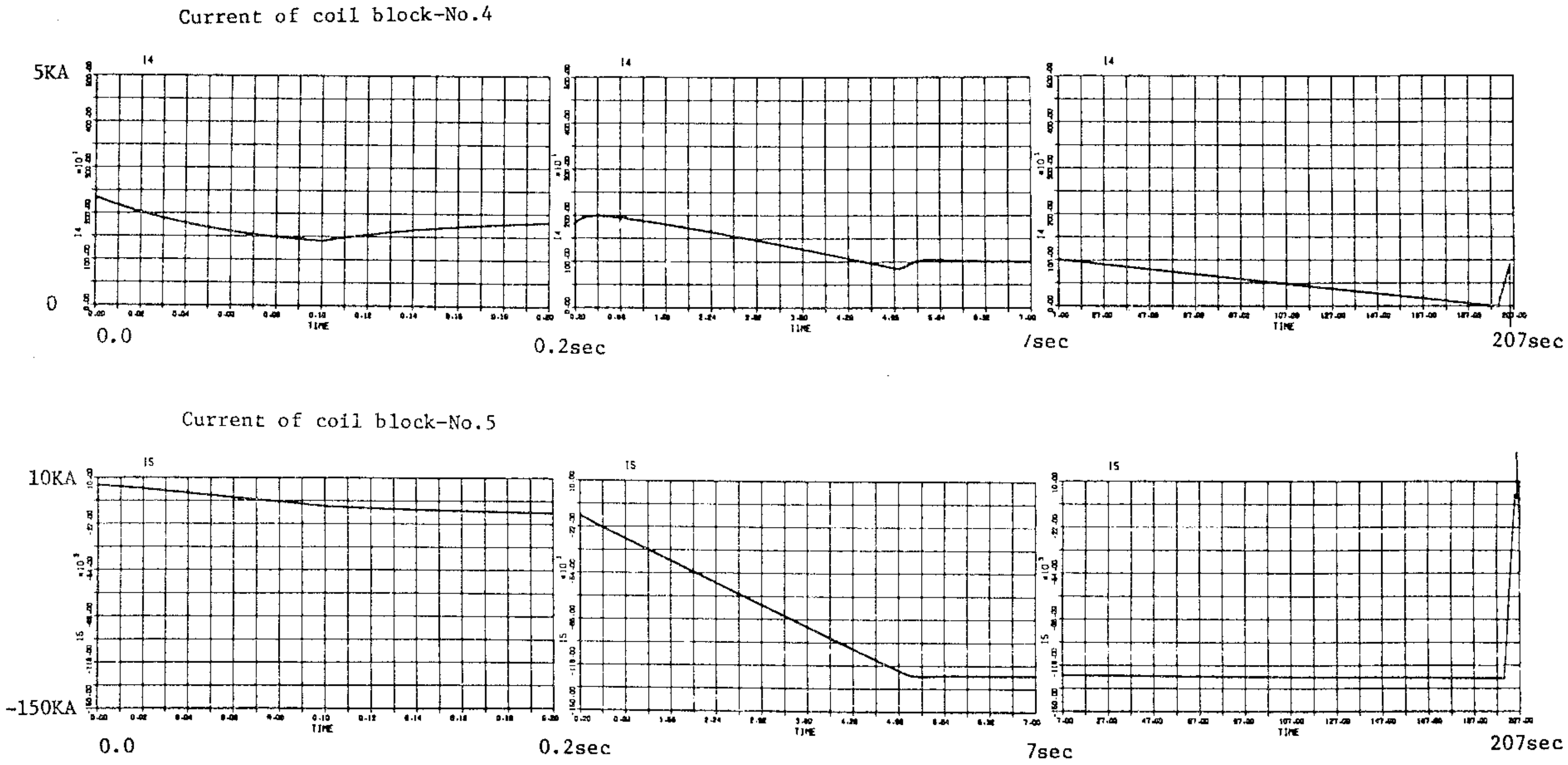


Fig.7 Variations of coil currents

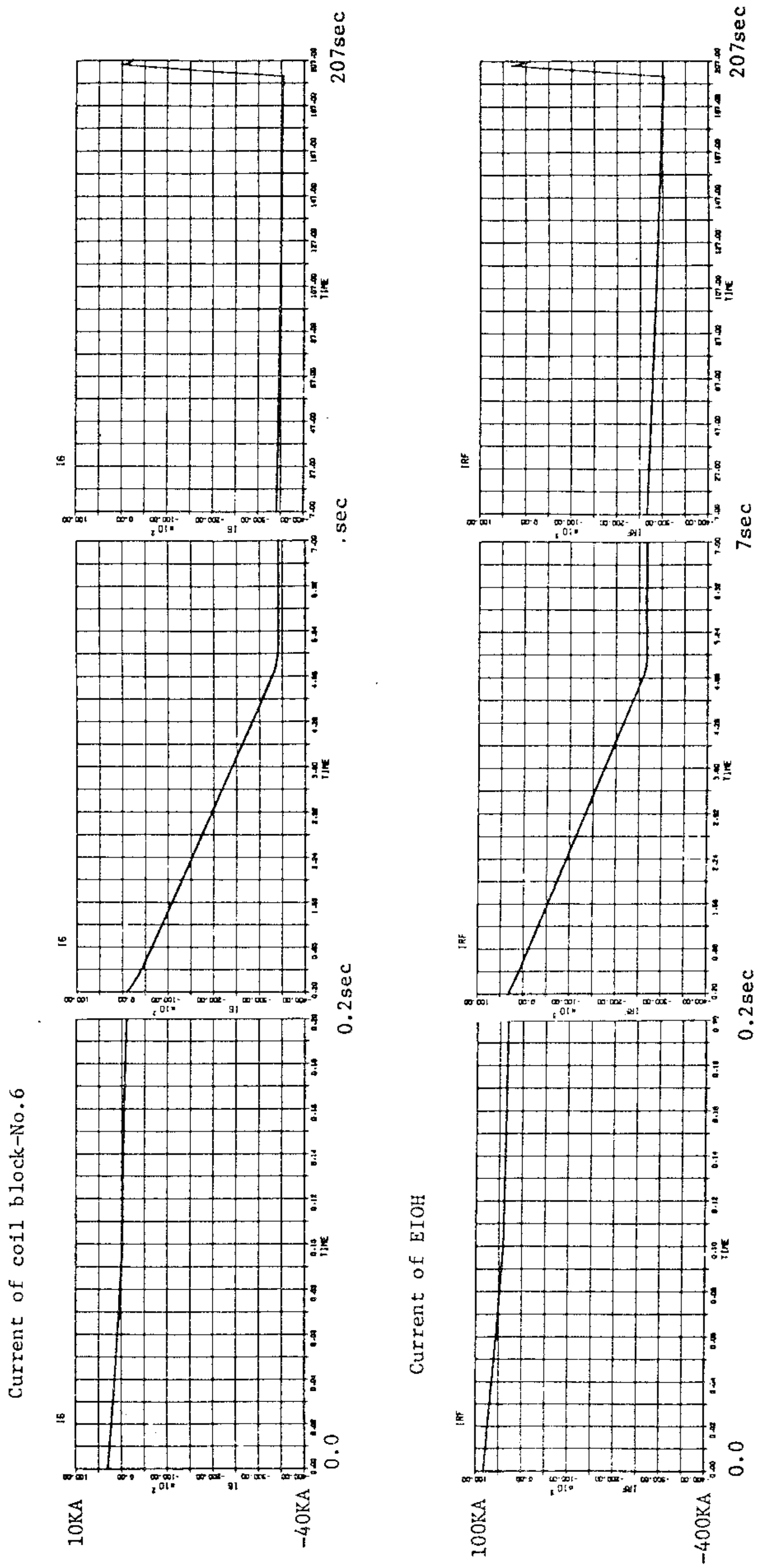


Fig.8 Variations of coil current and thyristor convertor current

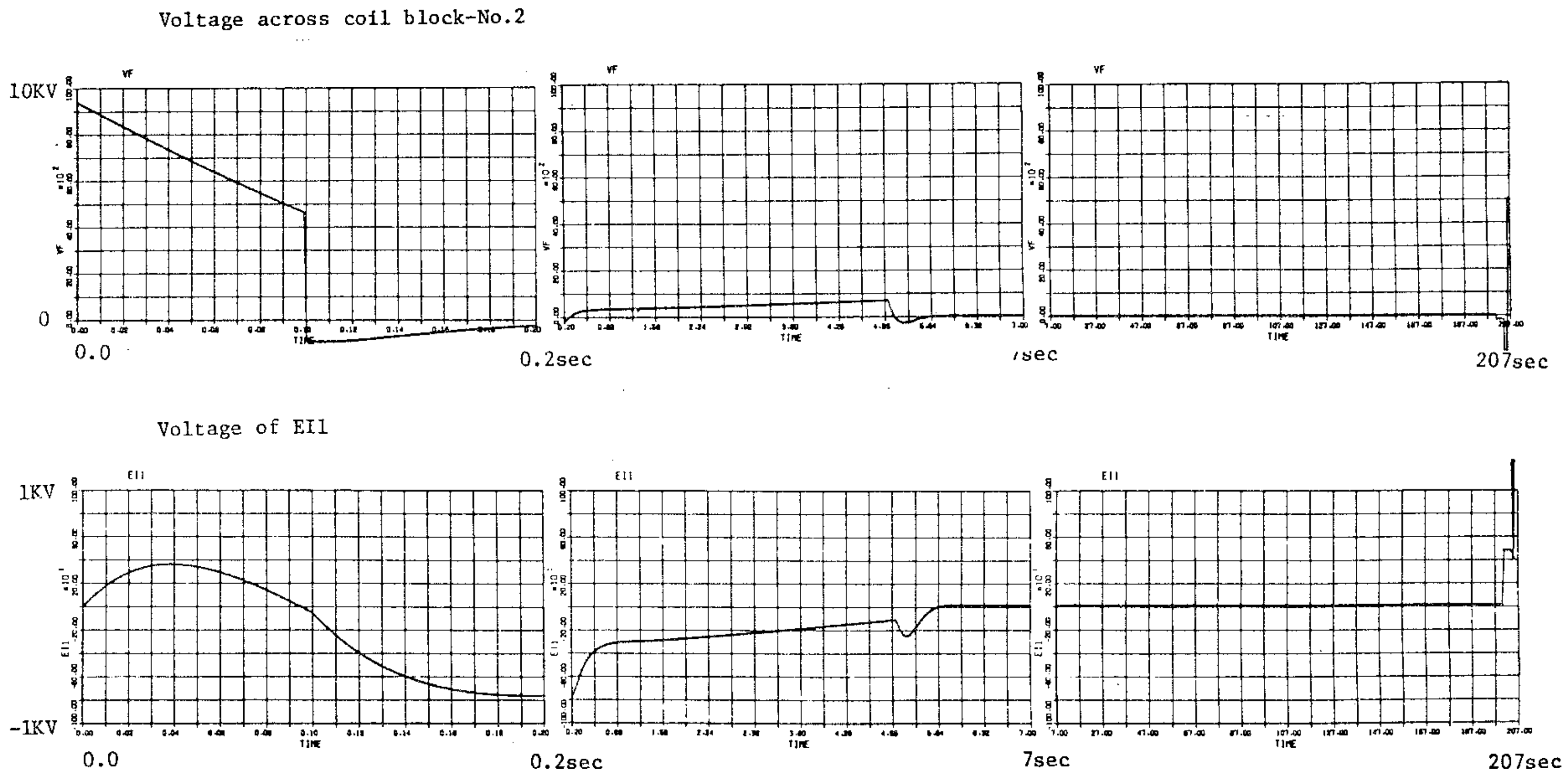


Fig.9 Variations of voltages across the coil block NO.2 and of thyristor convertor

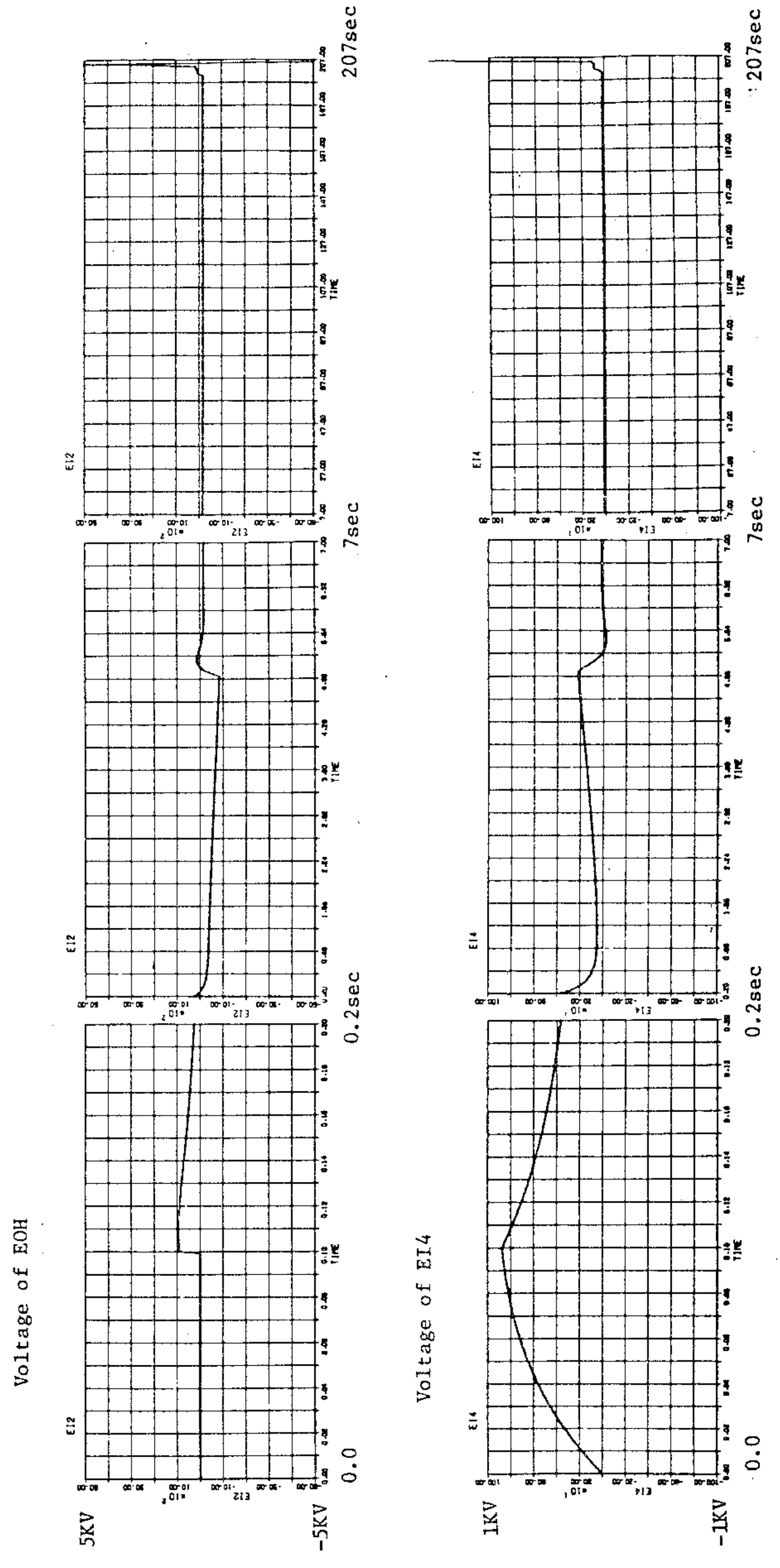
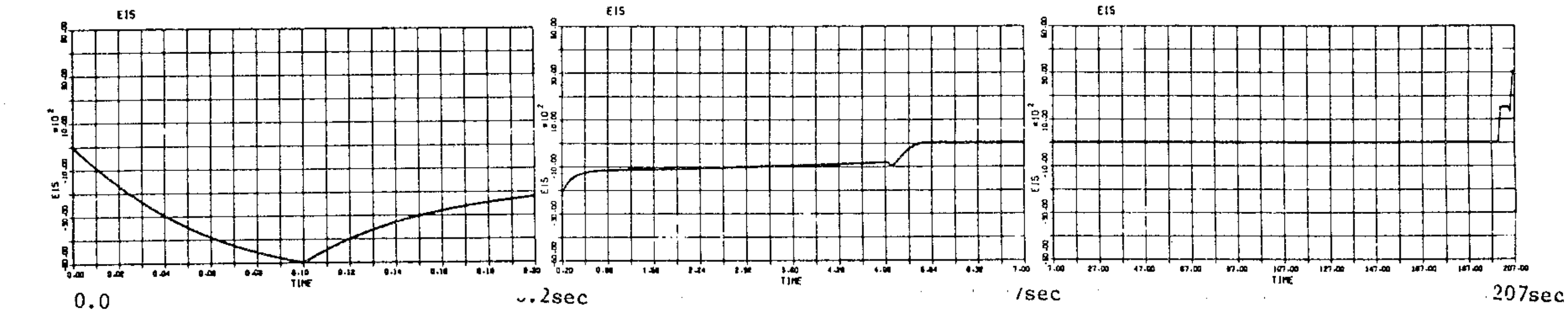


Fig.10 Variations of voltages of thyristor convertors

Voltage of EI5



Voltage of EI6

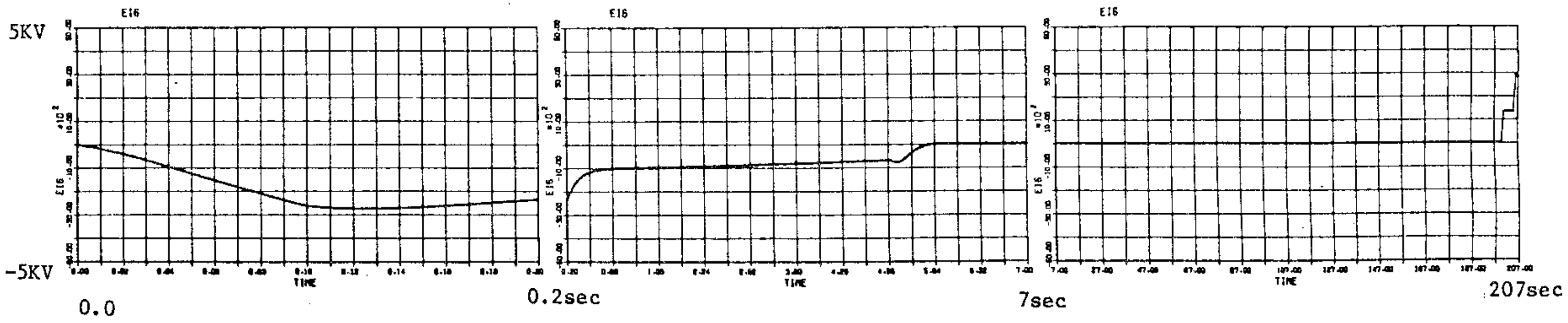


Fig.11 Variations of voltages of thyristor convertors

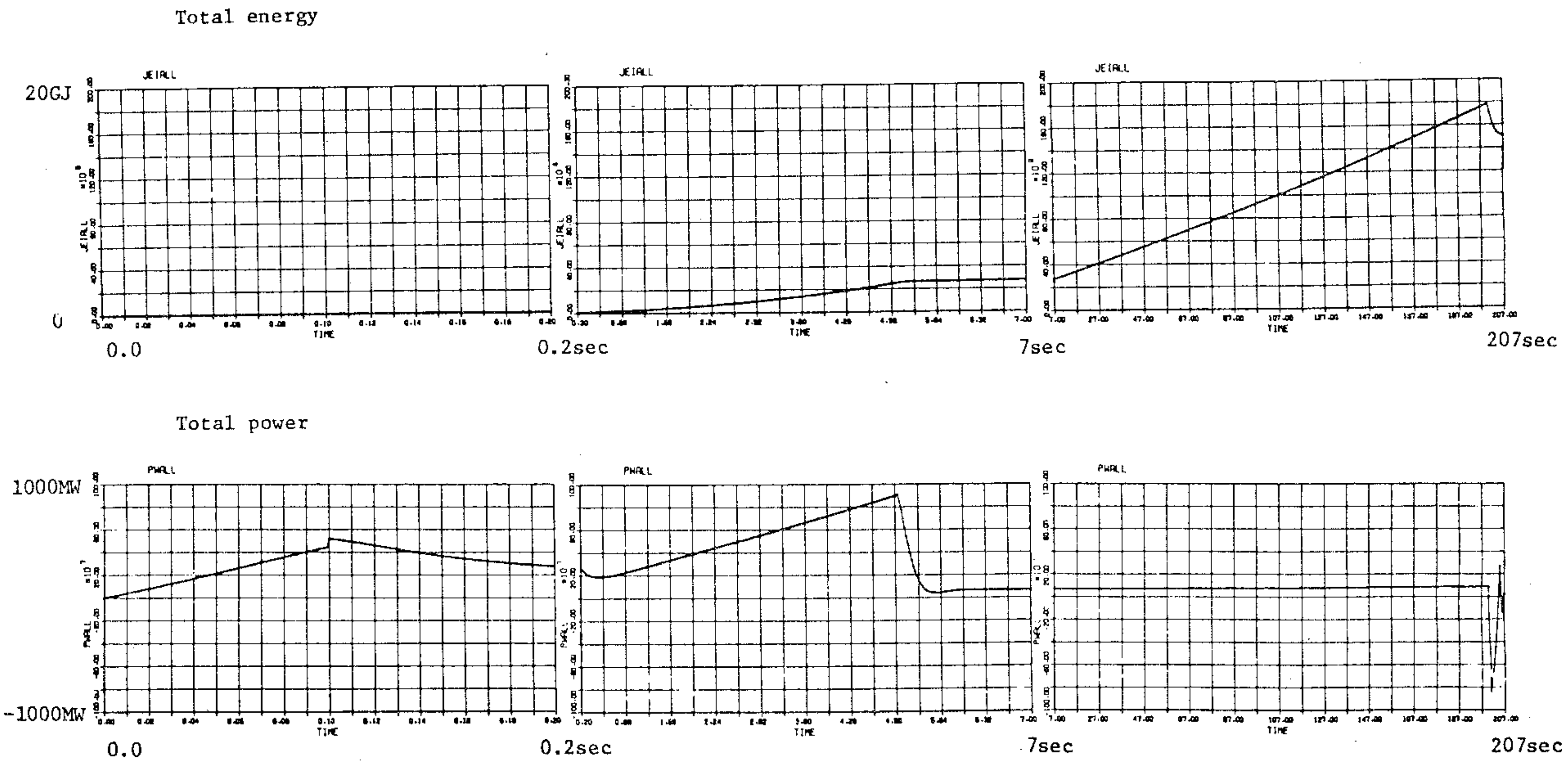


Fig.12 Variations of total required energy and power

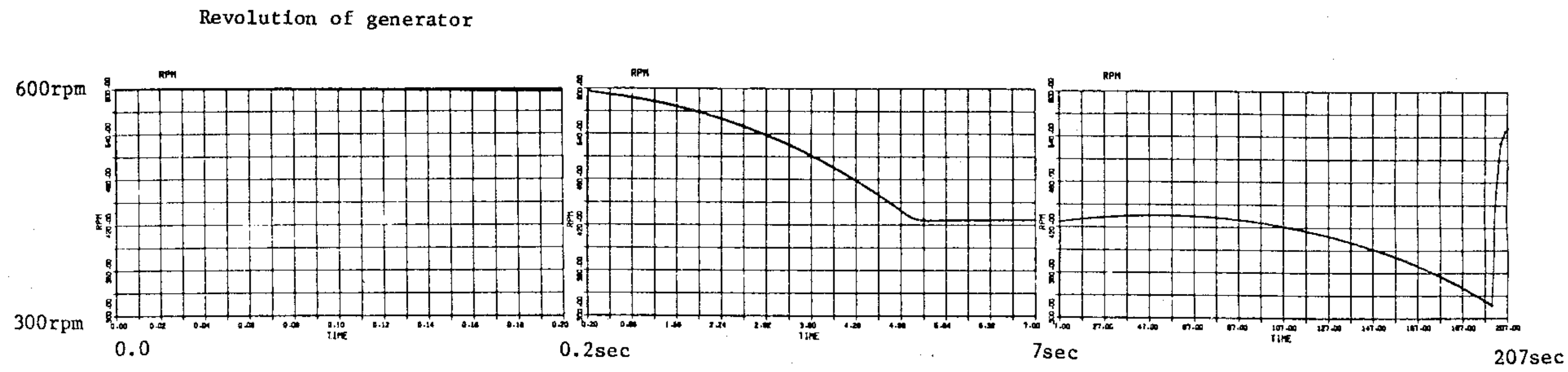


Fig.13 Variation of generator rotation

Appendix (2)

HOME WORKS BETWEEN SESSIONS 2 AND 3

Preface

At Session 2 of Workshop, the following requirements were give as home tasks betwenn Sessions 2 and 3.

A further somewhat more detailed analysis of the power requirements of INTOR would be desirable in order to obtain a more accurate estimate of the peak and average powers required to be taken from the supply network.

Furthermore, the power supply for poloidal field coils were investigated in more details and revised.

1. Introduction
2. The poloidal field power supply
3. The total power system for INTOR
4. Plasma controllability of INTOR poloidal field power supply

1. Introduction

This report together with the previous one presented at Session 2 will complete the basic assessment of the power supply system for INTOR.

To evaluate the feasibility of the new operation scheme of the poloidal field divertor, i.e. "swinging" the current in the divertor field coil, the operation scenario and the power requirement for the equilibrium field system were studied. Reexamination and optimization of the overall poloidal field power system described in the previous report were also made, and the specifications of the system have been partly modified. To set up as a design basis the total power requirements for INTOR, the power requirements other than the poloidal field system were also estimated.

2. The poloidal field power supply

The basic concept of the poloidal field power supply system is as proposed from JAERI in the report of Group 8 at Session 2. We have re-examined the overall system in some detail and attempted to optimize the design and the related specifications of some important components.

Major considerations and the results are summarized below.

1) According to the operation scenario of the divertor system of INTOR (as described in the report of design options, "Impurity control"), the operation of swinging the divertor coil current was analyzed. The swinging of the divertor field lines is achieved mainly by swinging the current in the block 4 coils (see Fig. 1 of the previous report). The speed of swinging is required as about 1 Hz. The maximum peak-to-peak amplitude is limited by the peak capacity of the generators and was found to be about 400 kAT at 1 Hz, if we assume the maximum deliverable power of the poloidal field supply of 1000 MVA. The physical considerations about this point (what is the necessary flux swing at the divertor? etc.) will be found elsewhere.

The results of calculations are shown as the necessary currents of each block of coils in Table 3'* for following three cases: case (1) ... divertor operated with current swinging of 392 kAT (peak to peak) at 1 Hz; case (2) ... divertor operated but no current swinging; case (3) ... divertor not operated.

2) The maximum ampere-turns related to the ohmic heating field components of each block of coils have been reduced as compared with the previous design. This was made by optimizing the operational patterns of the coil currents so as to balance the initial ampere-turns with those required at the end of each operation, while the amount of flux change during operation was kept constant. As to the equilibrium field components, the operation of divertor field described above was taken into consideration. The results are summarized in Table 1'.

3) To obtain a more accurate estimation of the required energy per one operation, the energy dissipation in the normal conductor parts of the poloidal field coils and in the dc power system (the internal losses of dc interrupters and thyristor convertors) was recalculated. The length of dc feeders between the superconductor coils and the dc power system was assumed to be 100 m and the current density in the copper part of the dc feeders 4 A/mm^2. Under these assumptions, the resistive drop of the dc feeders amounts to about 6 V. The interval resistive drop of one thyristor bridge (for example, the thyristor convertor EI3) was assumed to be 4 V.

4) In the present calculation, the initial loop voltage for breakdown was lowered and assumed to be 50 V. This was simply made with the intention to design a poloidal field power supply compatible with the superconductor coils, but we have still no available technical data to judge whether this assumption is allowable with respect to the time rate of change of magnetic fields ($\dot{B}$) in the superconductor coils. Quantitative discussion should wait for the earliest possible information.

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* The Tables and the Figures contained in the previous report will be partly revised in this report, and those revised will be labelled the same numbers as the previous ones but with primes like Table 3'. Those Tables and Figures which appear first in this report will be labelled numbers of two figures beginning from 31.

5) The build up wave form of plasma current has been slightly modified as shown in Fig. 4'; the build up rate of the current is somewhat slowed down after t = 3.6 sec and the flattop is reached at t = 6.0 sec (in the previous design, t = 5.0 sec). This modification was made to eliminate an extra peak in required power in the current build up phase.

6) The minimization of reactive power associated with the operation of thyristor convertor systems is essential to improve the power factors of generators to restrict their peak capacity and other related electrical and mechanical performances within a reasonable limit. Based on this consideration, the control of reactive power was intended in the present design. To perform the reactive power control, the thyristor convertors are devided into several separate and identical banks with bypass switches as shown in Fig. 31 . These banks are connected in series and operated by the combination of on-off control of bypass switches and thyristor gate control according to the operation sequence. This control method by separate banks has been applied to three large thyristor convertors EI3, EI5 and EOH. For example, the thyristor convertor EOH which has the maximum voltage of ± 1,500 V is devided into three identical banks of ± 500 V. According to the required voltage ranges, they are operated separately or simultaneously as shown in Table 31.

The simulation calculations of the system operation were made in the same way as described in the previous report. The calculations were performed for a complete one cycle of operation including the dwell time. The results are shown in Figs. 32 ∿ 34 for three different operations; (i) without divertor, (ii) with divertor, (iii) with "swinging" divertor. In Table 4', the required currents and voltages for the thyristor convertors are summarized, and the specifications of main components of the INTOR poloidal field power supply are tabulated in Table 5'. The system configuration is shown in Fig. 2'.

3. The total power system for INTOR

The total power requirements for INTOR were estimated as shown in Table 32 . They are also shown schematically in Fig. 35 as a function of time . A possible scheme of the power supply and distribution system for INTOR is shown in Fig. 36 .

4. Plasma controllability of INTOR poloidal field power supply

The capability of plasma position control of the INTOR poloidal field power supply may be evaluated in the following way.

If we assume a situation where the equilibrium field is varied to control plasma positions while keeping the plasma current constant, the voltage required to control the plasma positions can be calculated by using the hybrid operation matrix described in the previous report;

$$\begin{pmatrix} V \end{pmatrix} = \begin{pmatrix} M \end{pmatrix} \begin{pmatrix} \dot{I}_p \\ I_1 \\ I_2 \\ \vdots \end{pmatrix} = \begin{pmatrix} M \end{pmatrix} \begin{pmatrix} H \end{pmatrix} \begin{pmatrix} \dot{I}_p \\ I_{OH} \\ I_E \end{pmatrix}$$

$$\text{and } \dot{I}_p = 0,\ \dot{I}_{OH} = 0,\ \dot{I}_E = \frac{1}{\nu}\dot{B}_\perp,$$

where I_p is the plasma current, I_{OH} is the component of coil current corresponding to the ohmic heating field, I_E that of the equilibrium field, ν the proportionality constant, and $B_\perp$ the equilibrium (vertical) field.

The result of calculation is shown in Fig. 37 , where the equilibrium field is varied from 4.13 kG to 4.66 kG in one second or with a time rate of 0.53 kG/sec. Assuming an approximate relation $R_p \propto 1/B_\perp$, this time rate of change of the equilibrium field is found to correspond to the motion of the plasma axis with a speed of $|\dot{R}_p| = 0.64$ m/sec, where R_p is the plasma major radius. As shown in the figure, the required voltages of the thyristor conventors (EI1, ..., EOH) are all within the maximum ratings given in Table 4' . This operation requires a peak power of about 960 MW, and this is also within the maximum ratings. From this simple analysis, it may be said that the present INTOR poloidal field power supply can afford to control the plasma horizontal displacement with a velocity of up to 0.6 m/sec and this may give a measure of plasma controllability of INTOR (That for JT-60 is also about 0.6 m/sec).

Table 1'

Coil Block	F_{OH} (MAT)	F_E *(MA)		
		1)	2)	3)
1	3.68 × 2	-2.34 × 2	-2.34 × 2	-1.95 × 2
2	3.60 × 3	0	0	0
3	0.86 × 4	5.0 × 4	5.0 × 4	4.0 × 4
4	0.15	±2.0	0	0
5	0.10	-5.17	-5.17	-3.29
6	0.15	-1.98	-1.98	-2.87

* plasma current 4.68 MA
β_p=2.6, ℓ_i=1.0

Necessary ampere-turns for each block of coils; F_{OH} denotes the ohmic heating field component and F_E the equilibrium field component.

1) divertor operated with current swinging
2) divertor operated
3) divertor not operated

Table 3' Currents of each block of coils at typical times. The maximum and the minimum currents are also shown.

Case (1) divertor operated with current swinging

	Number of turns	t=0	t=205 sec	max.	min.
I_1	86 × 2	42.8 KA	-41.0 KA	42.8 KA	-43.0 KA
I_2	120 × 3	30.0 KV	-10.0 KA	30.0 KA	-11.1 KA
I_3	-40 × 3	-21.5 KA	-115.3 KA	-21.5 KA	-131.5 KA
I_4	140	1.1 KA	-0.8 KA	1.2 KA	-1.6 KA
I_5	42	2.4 KA	-121.3 KA	2.4 KA	-124.7 KA
I_6	47	3.2 KA	-42.7 KA	3.2 KA	-43.6 KA

Case (2) divertor operated

	Number of turns	t=0	t=205 sec	max.	min.
I_1	86 × 2	42.8 KA	-40.4 KA	42.8 KA	-40.4 KA
I_2	120 × 3	30.0 KA	-9.2 KA	30.0 KA	-9.2 KA
I_3	-40 × 3	-21.5 KA	-116 KA	-21.5 KA	-131.5 KA
I_4	140	1.1 KA	-0.3 KA	1.2 KA	-0.3 KA
I_5	42	2.4 KA	-123.6 KA	2.4 KA	-123.6 KA
I_6	47	3.2 KA	-43.0 KA	3.2 KA	-43.0 KA

Case (3) divertor not operated

	Number of turns	t=0	t=205 sec	max.	min.
I_1	86 × 2	42.8 KA	-42.8 KA	42.8 KA	-42.8 KA
I_2	120 × 3	30.0 KA	-14.1 KA	30.0 KA	-14.1 KA
I_3	-40 × 3	-21.5 KA	-88.3 KA	-21.5 KA	-103.0 KA
I_4	140	1.1 KA	-0.4 KA	1.1 KA	-0.8 KA
I_5	42	2.4 KA	-79.3 KA	2.4 KA	-79.3 KA
I_6	47	3.2 KA	-62.5 KA	3.2 KA	-62.5 KA

Table 4' Required currents and voltages of thyristor convertors

	max. positive direction current	max. negative direction current	voltage
EI1	42.7 KA	-40.8 KA	± 1.1 KV
EI3	0	-131 KA	± 3.5 KV
EI4	1.2 KA	-1.6 KA	± 4.0 KV
EI5	2.4 KA	-124.5 KA	± 3.0 KV
EI6	3.2 KA	-43.0 KA	± 2.5 KV
EIOH	57.3 KA	-337 KA	± 1.5 KV

Table 5' Specifications of main components

Generators	Vertical shaft synchronous motor-generator				2 sets
	Capacity			500 MVA	
	Revolution			650 - 420 RPM	
	Power factor			0.5	
	GD^2			5,500 ton-m^2	
D.C. circuit interrupters S_1, S_1'	V.C.B type				2 sets
				45 KA - 5 KV	
Resistors R_1, R_1'	Large scale resistors with minimum residual inductances				2 sets
	Resistance				0.1 Ω
	Heat capacity		20 MJ	0.1 sec	
Frequency convertors	Thyristor startor				
		50 Hz ⟶ 86 Hz ~ 56 Hz			
		20 MW			2 sets
Thyristor convertors	EI1	E1F	1.1 KV	43 KA	2 sets
		E1R		41 KA	2 sets
	EI3	E3R	3.5 KV	132 KA	2 sets
	EI4	E4F	4.0 KV	2 KA	2 sets
		E4R		2 KA	2 sets
	EI5	E5F	3.0 KV	3 KA	2 sets
		E5R		125 KA	2 sets
	EI6	E6F	2.5 KV	4 KA	2 sets
		E6R		45 KA	2 sets
	EOH	EOHF	1.5 KV	58 KA	2 sets
		EOHR		337 KA	2 sets
	Total MW			3340 MW	

Modified scheme of plasma current in the build-up phase

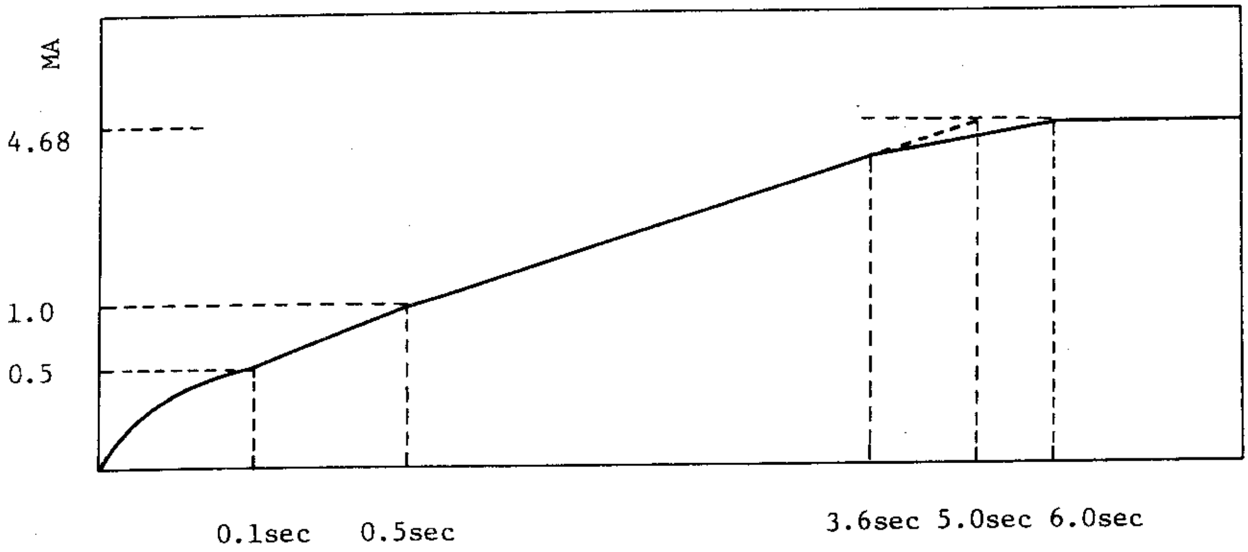

Fig. 4' Plasma current in the build-up phase

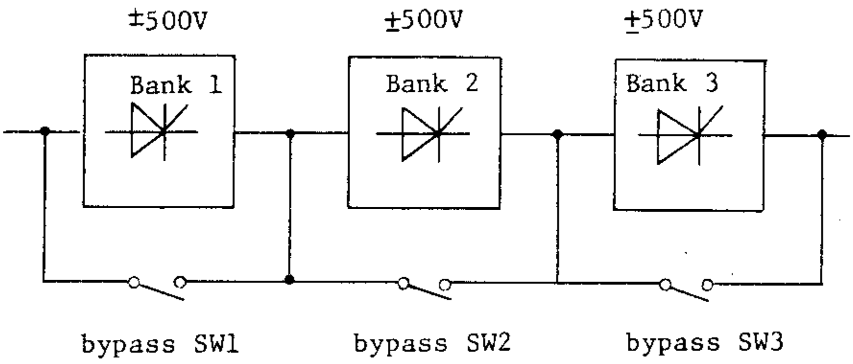

Fig. 31 Separate bank system of thyristor convertors

Table 31 Operation scheme of thyristor banks

required voltage (V)	SW1	SW2	SW3
0 ∿ ±500	OFF	ON	ON
±500 ∿ ±1000	OFF	OFF	ON
±1000 ∿ ±1500	OFF	OFF	OFF

Table 32 Summary of power requirements for INTOR

		Peak	Mean
(i)	Poloidal magnetic field coil (superconducting coils)		
	(a) without divertor	435 MW	26 MW
	(b) with divertor	688 MW	34 MW
	(c) with divertor and current swinging	688 MW	34 MW
(ii)	Toroidal Magnetic field coil	1 ∿ 2 MW	1 ∿ 2 MW
(iii)	N.B.I. heating	330 MW	23 MW
(iv)	R.F. heating	Efficiency not sufficiently known	
(v)	Cryogenic system and pumping	55∿85 MW	55∿85 MW
(vi)	Pumping power for shield and blanket	25 MW	25 MW
(vii)	Vacuum pumps	2 ∿ 3 MW	2 ∿ 3 MW
(xi)	Miscellaneous power and building auxiliary loads	60 MW	60 MW
	Total power	1193 MW	232 MW
	Total energy for one cycle (sum of figures underlined)		55 GJ

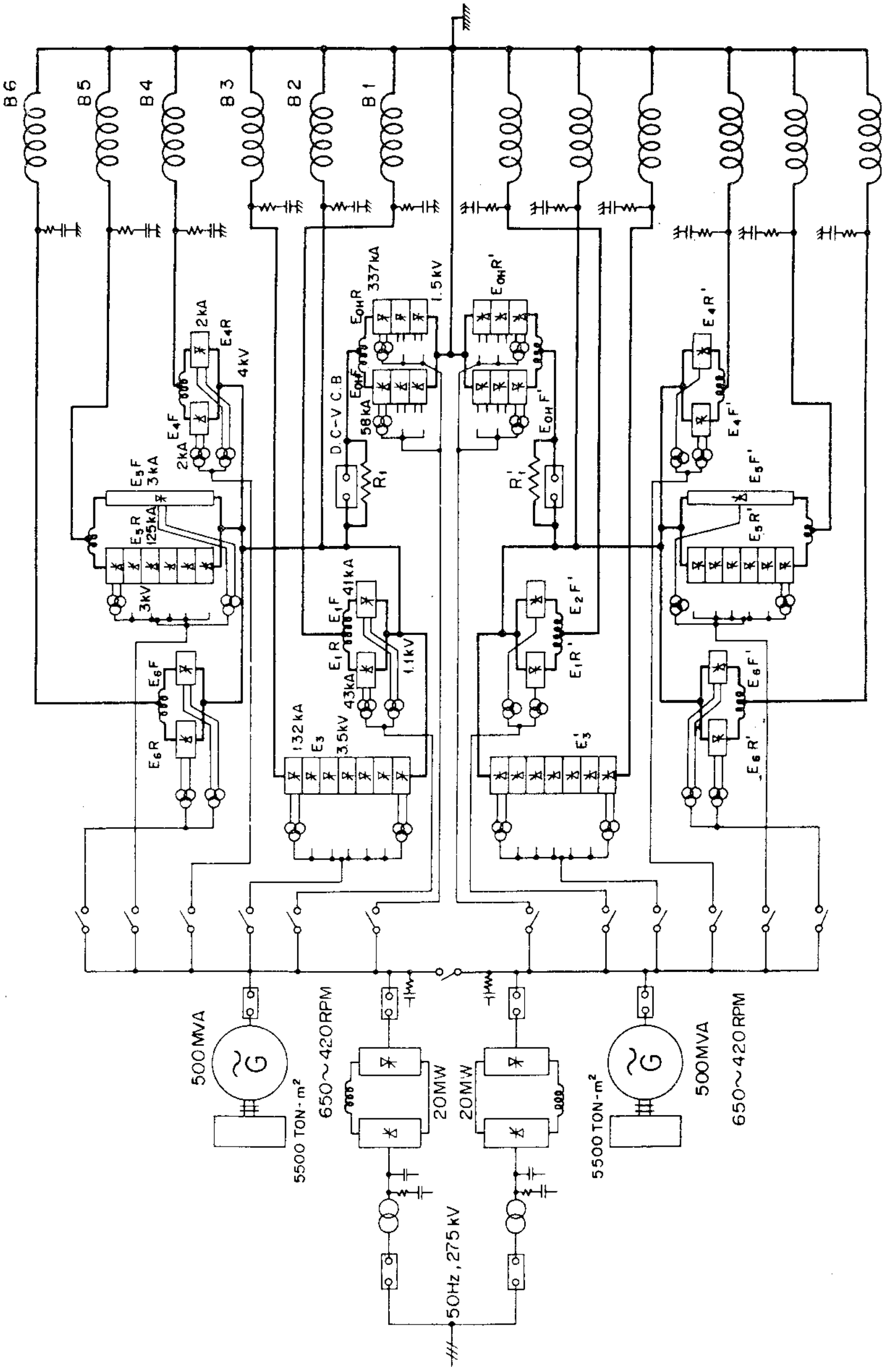

Fig. 2' Schematic diagram of poloidal field power supply system

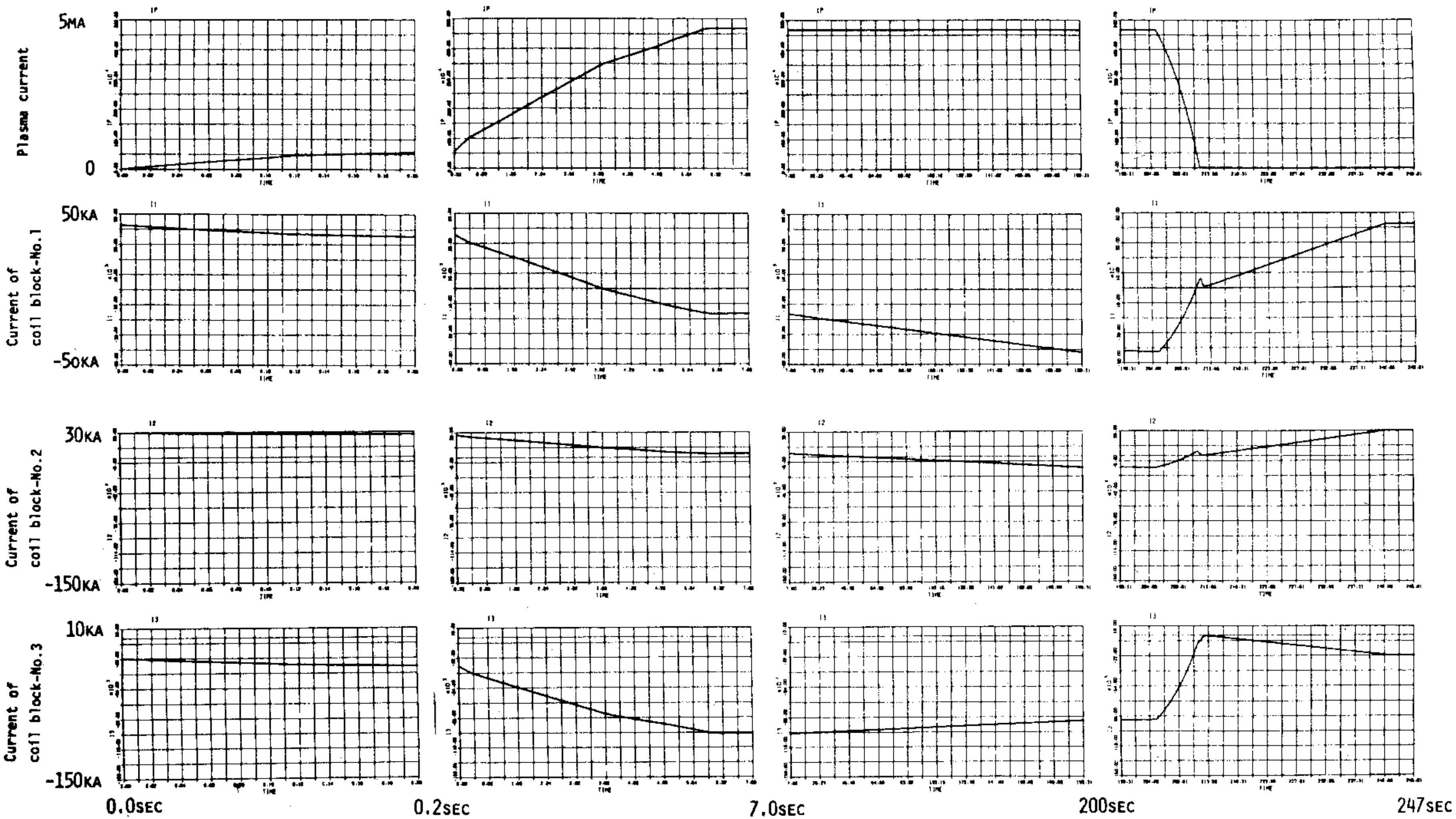

Fig. 32 Simulation calculation of INTOR poloidal field power supply (divertor not operated) A

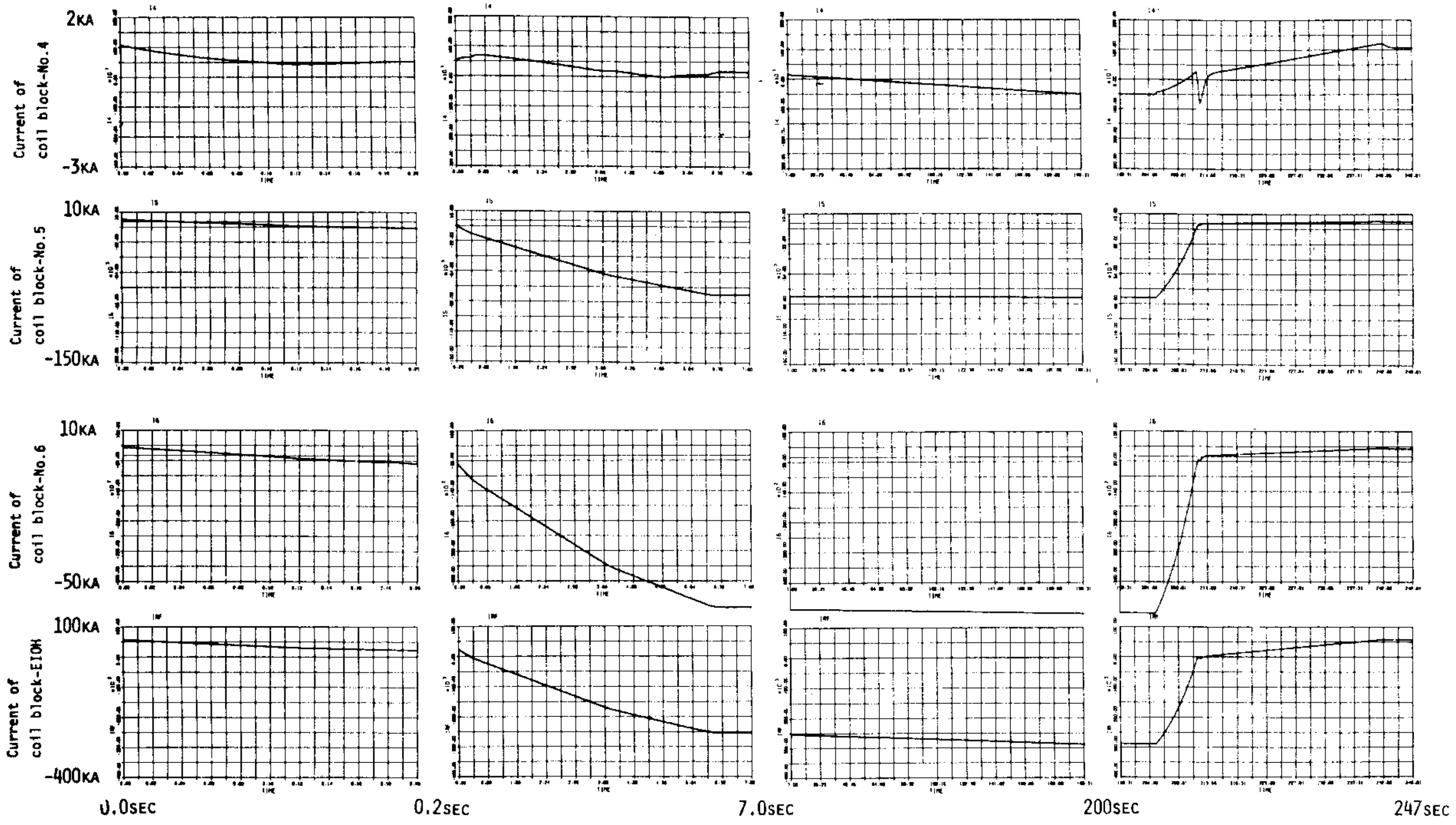

Fig. 32 Simulation calculation of INTOR poloidal field power supply (divertor not operated) B

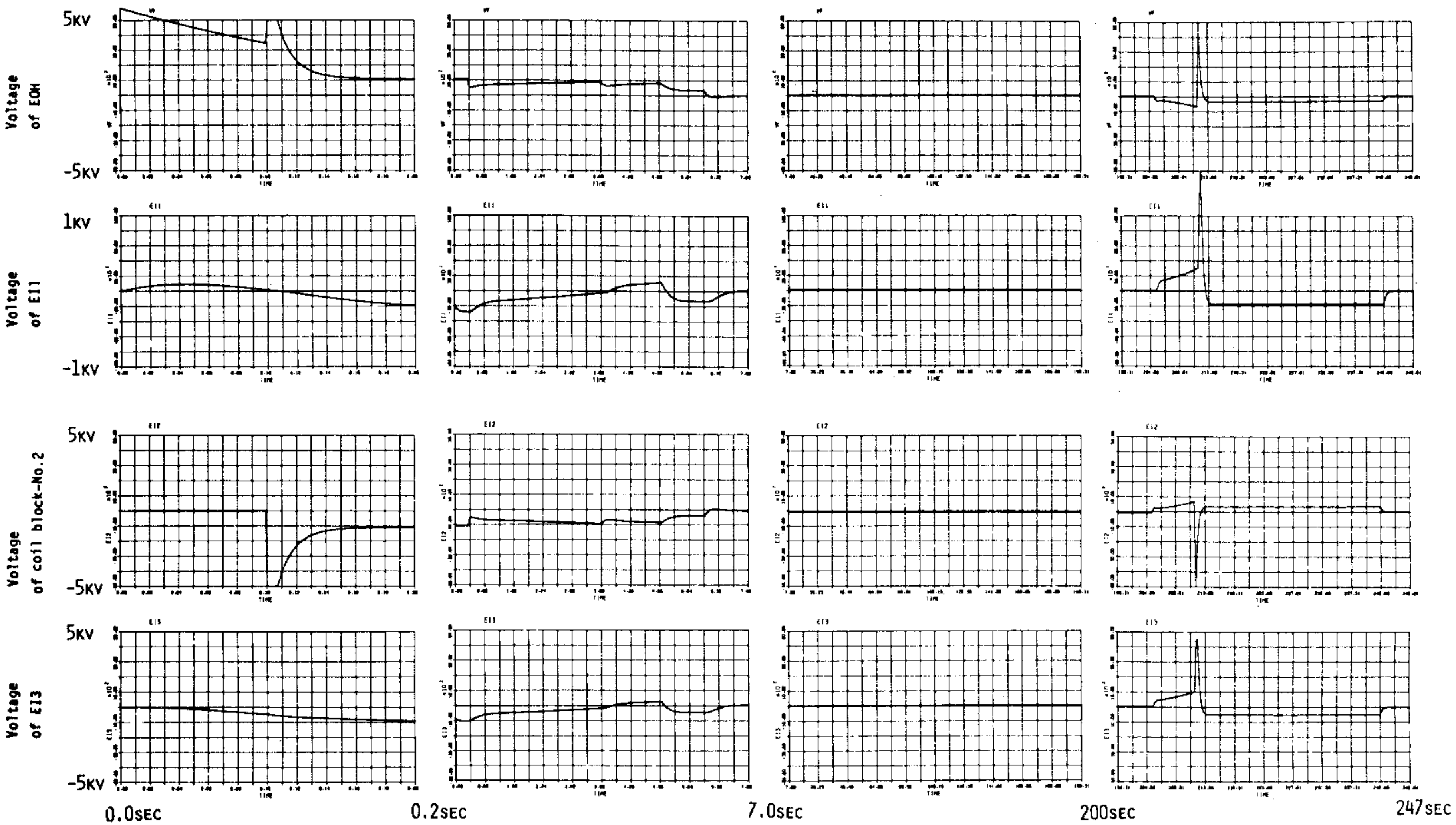

Fig. 32 Simulation calculation of INTOR poloidal field power supply (divertor not operated) C

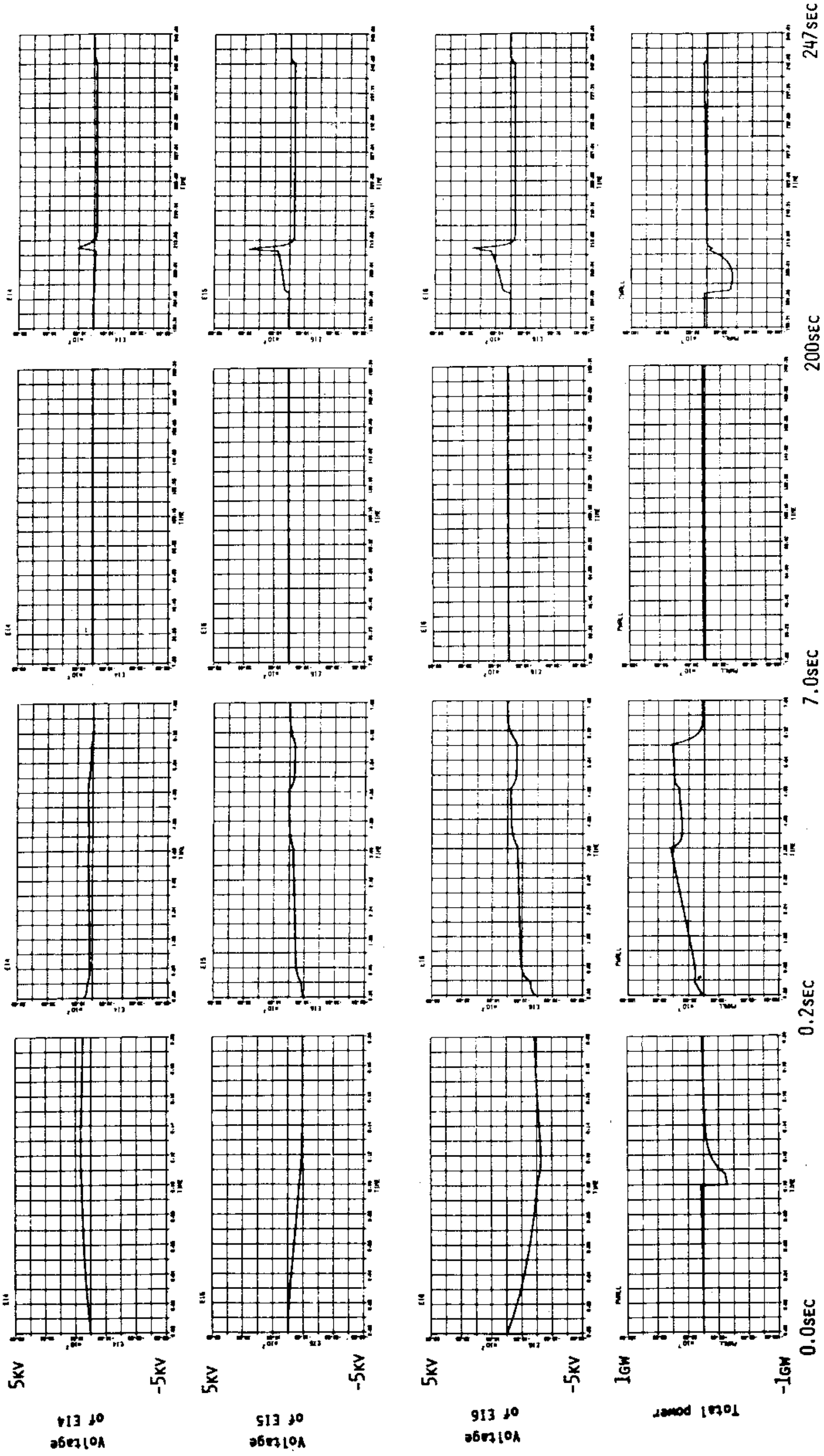

Fig. 32 Simulation calculation of INTOR poloidal field power supply (divertor not operated) D

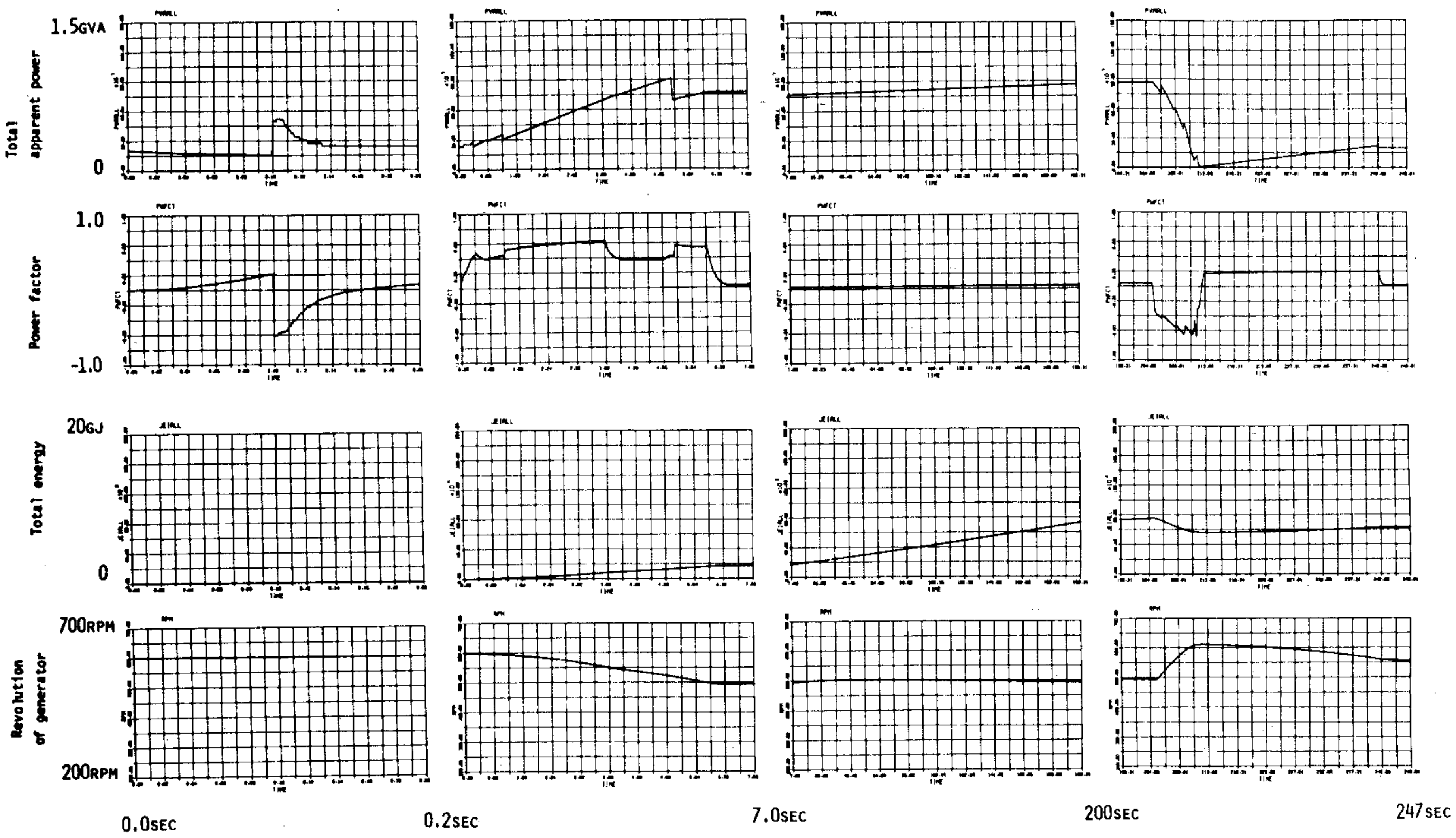

Fig. 32 Simulation calculation of INTOR poloidal field power supply (divertor not operated) E

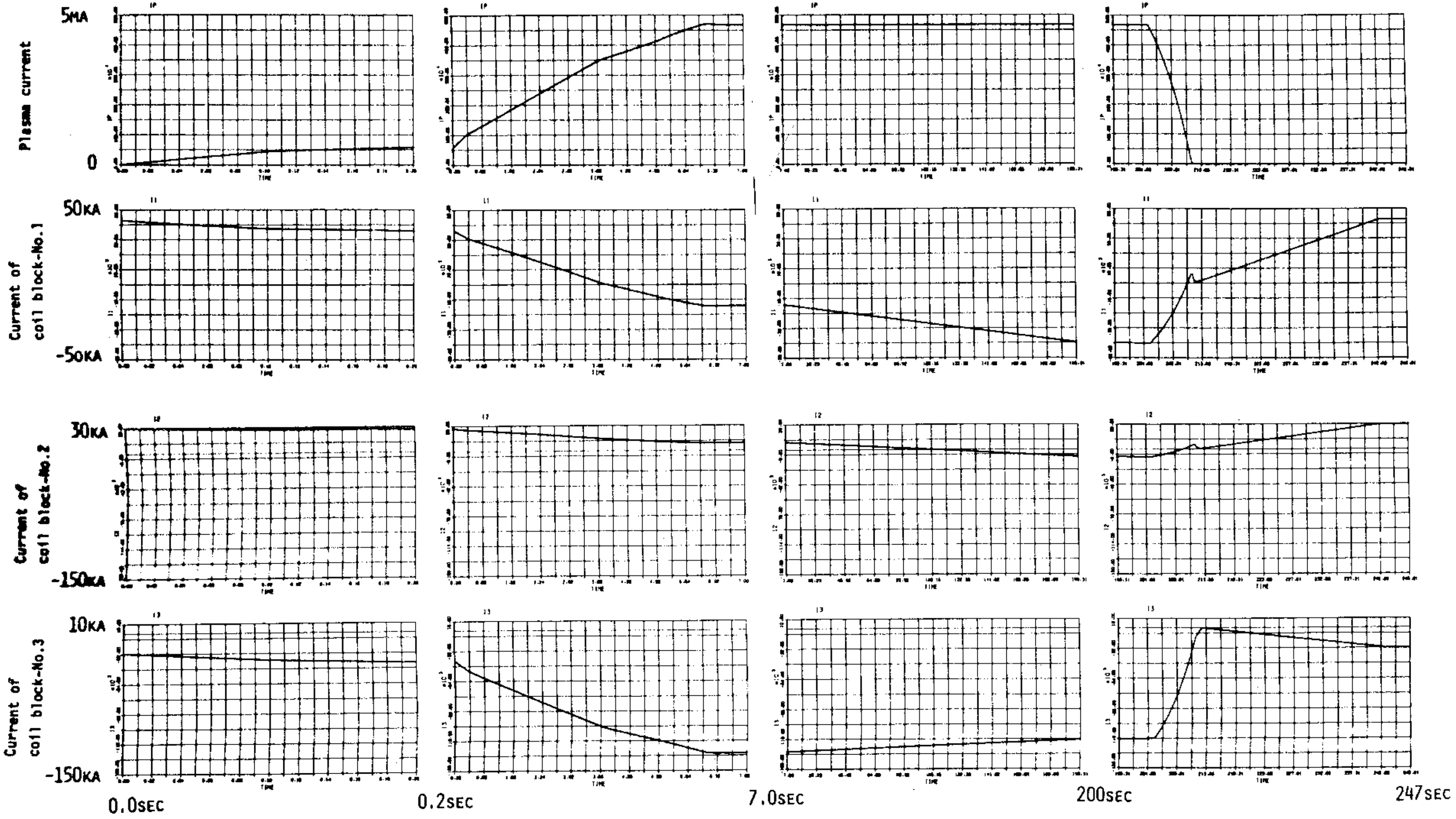

Fig. 33 Simulation calculation of INTOR poloidal field power supply (divertor operated) A

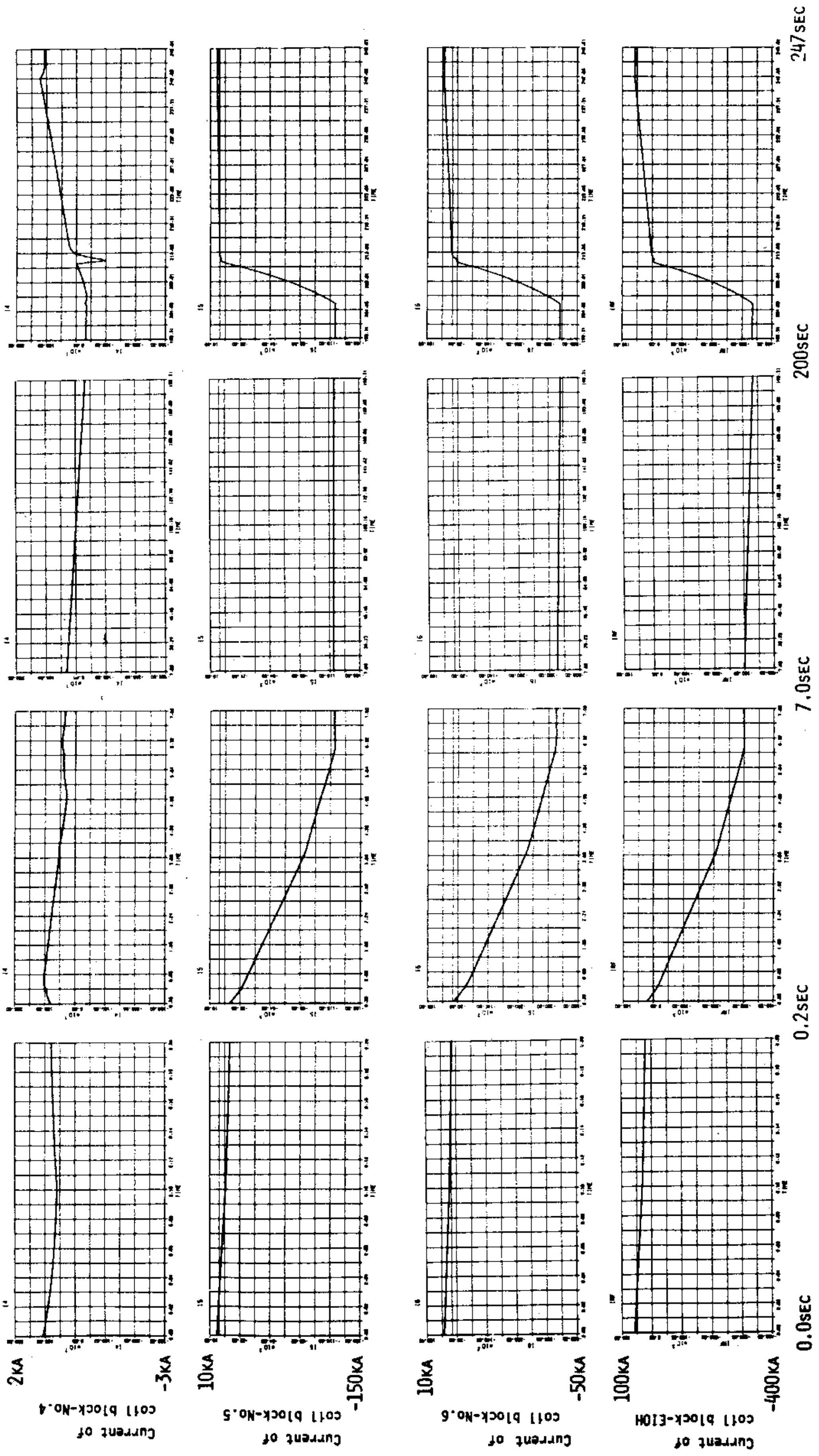

Fig. 33 Simulation calculation of INTOR poloidal field power supply (divertor operated) B

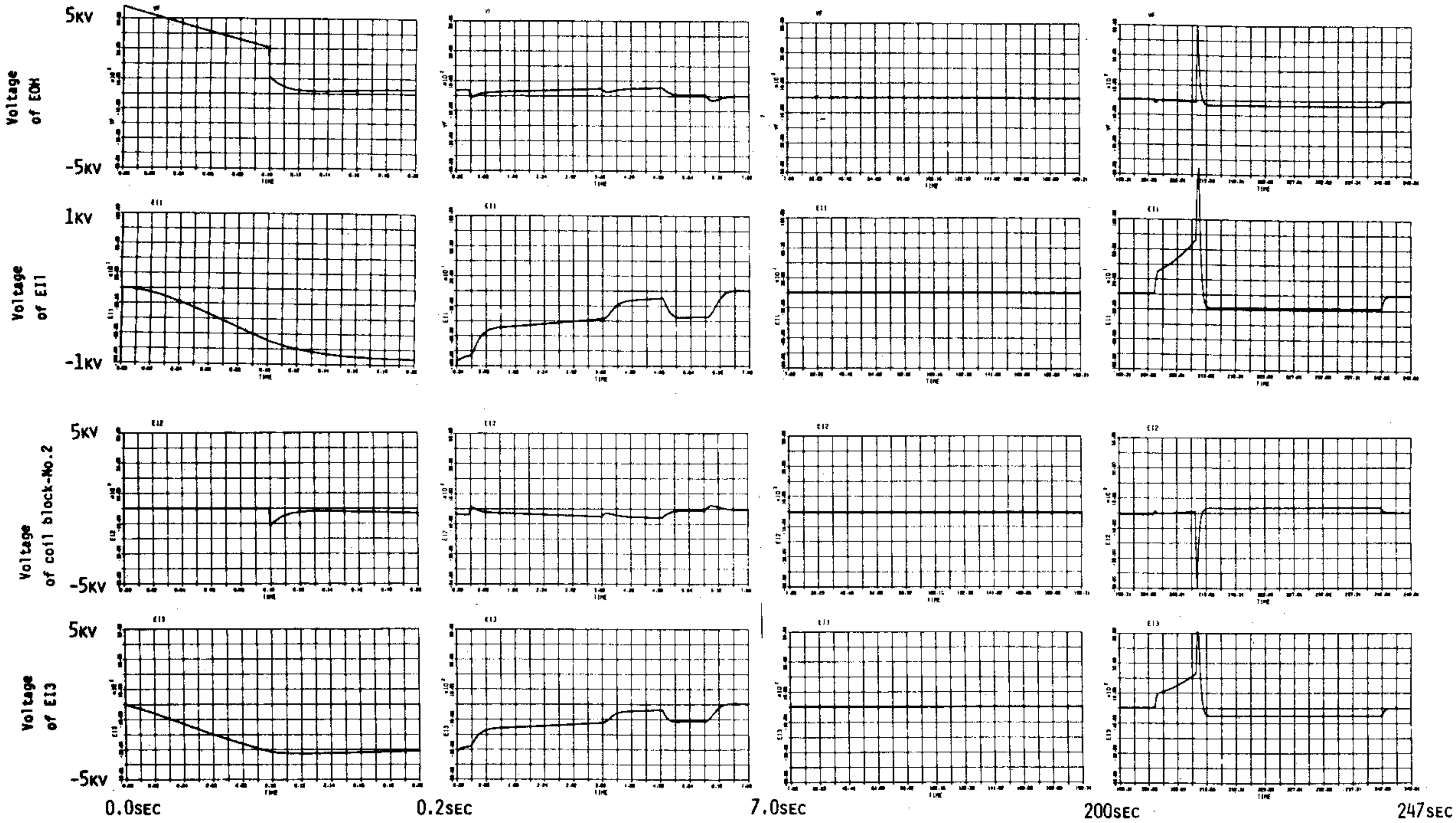

Fig. 33 Simulation calculation of INTOR poloidal field power supply (divertor operated) C

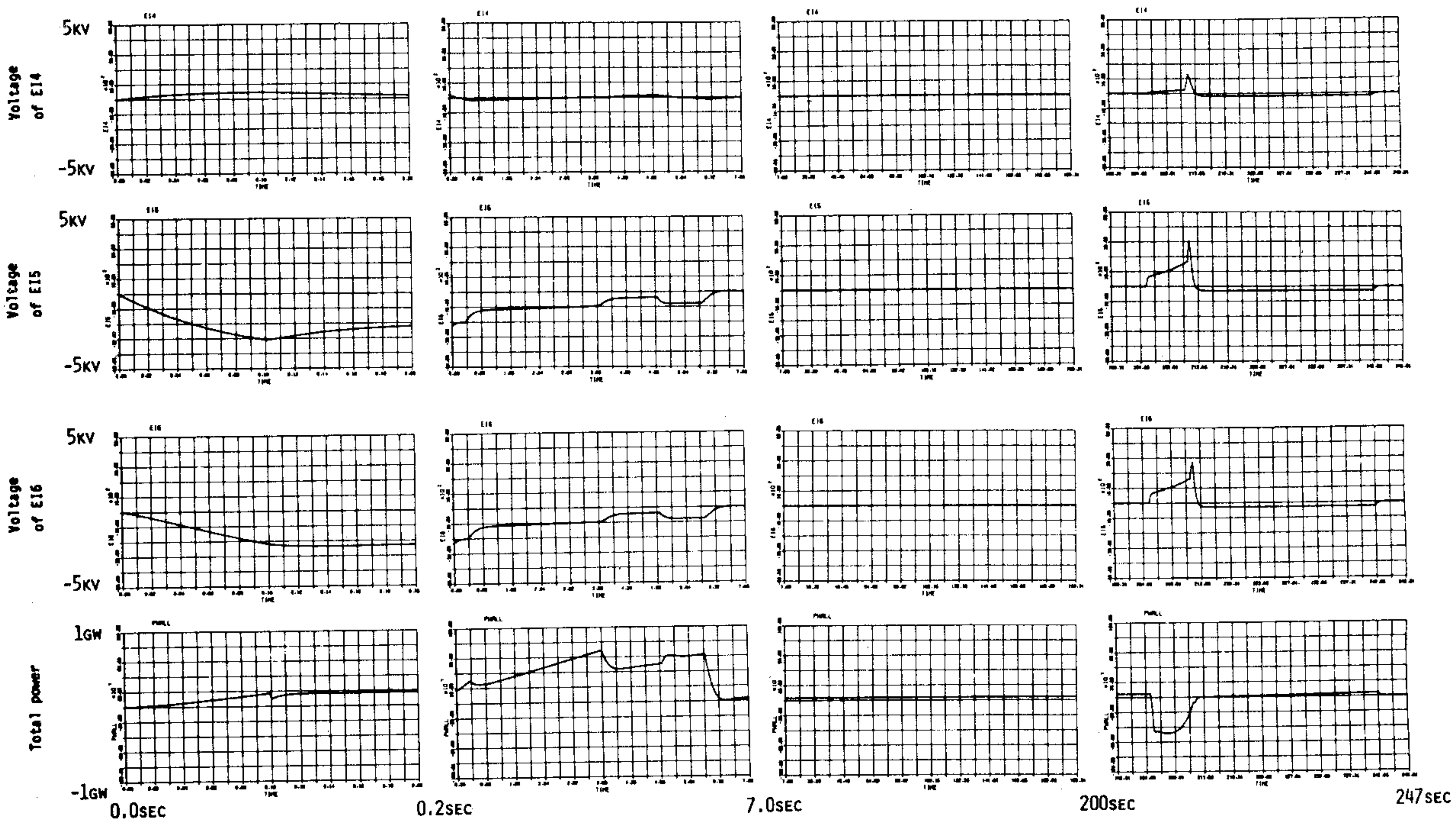

Fig. 33 Simulation calculation of INTOR poloidal field power supply (divertor operated) D

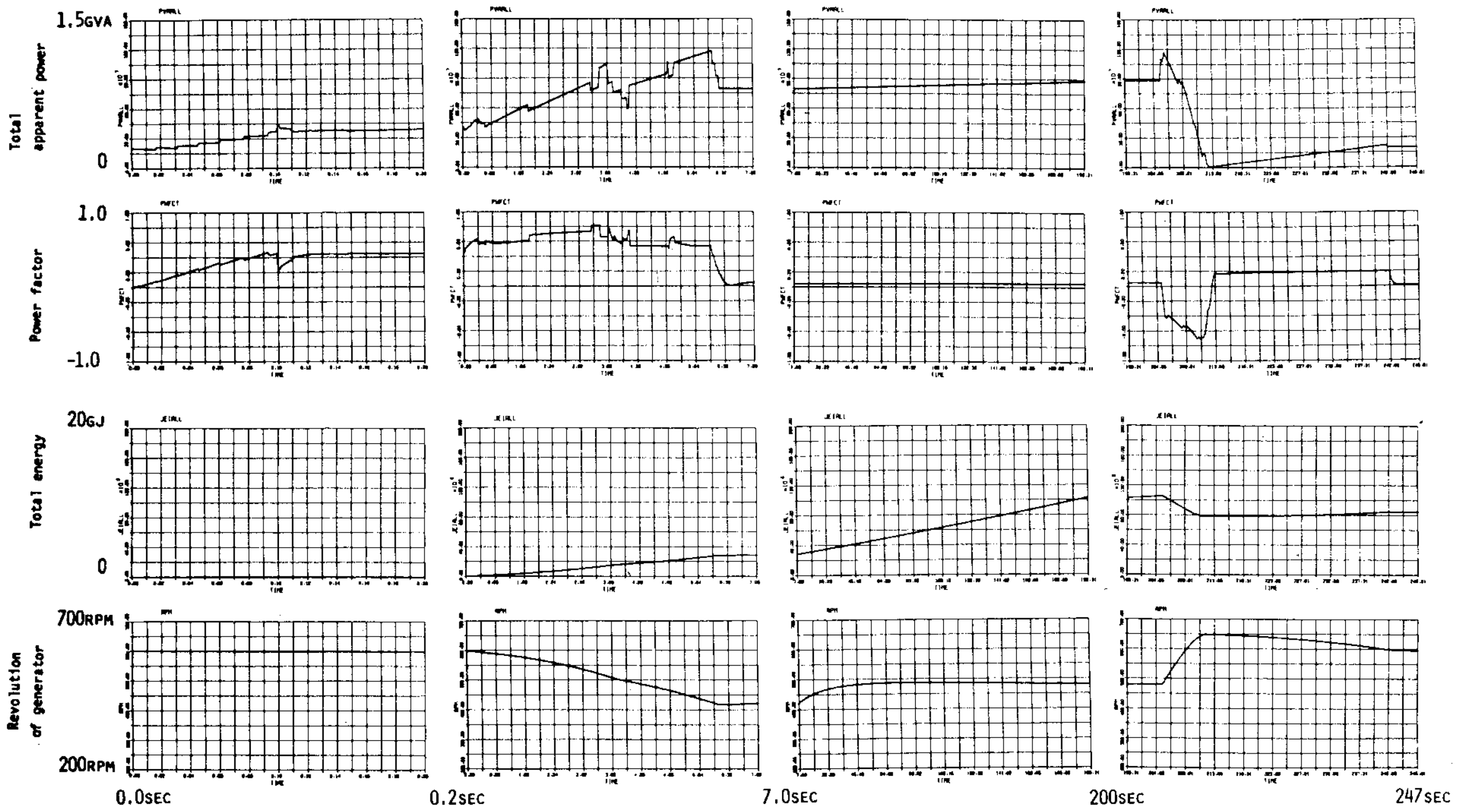

Fig. 33 Simulation calculation of INTOR poloidal field power supply (divertor operated) E

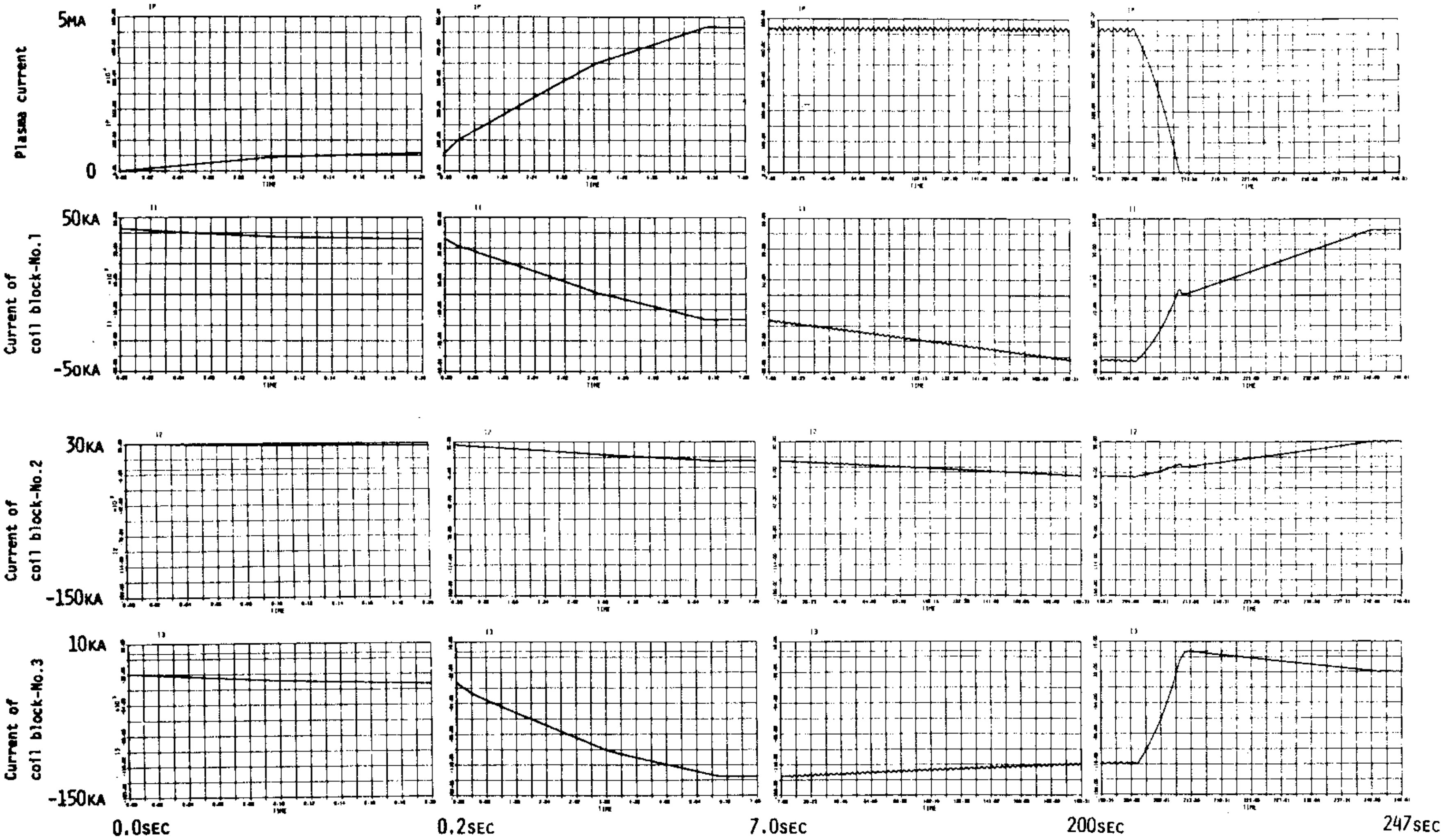

Fig. 34 Simulation calculation of INTOR poloidal field power supply (divertor operated with current swinging) A

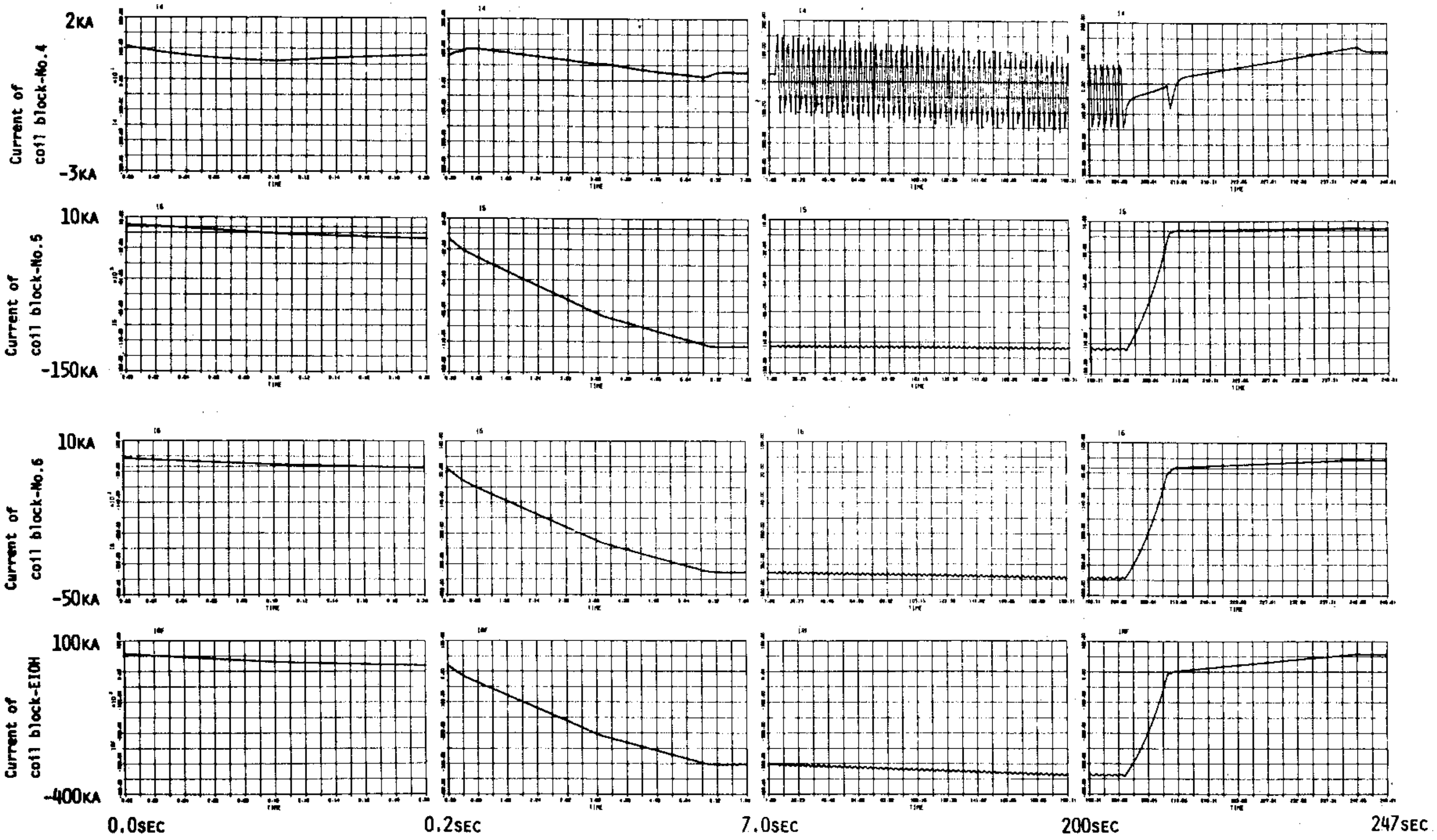

Fig. 34 Simulation calculation of INTOR poloidal field power supply (divertor operated with current swinging) B

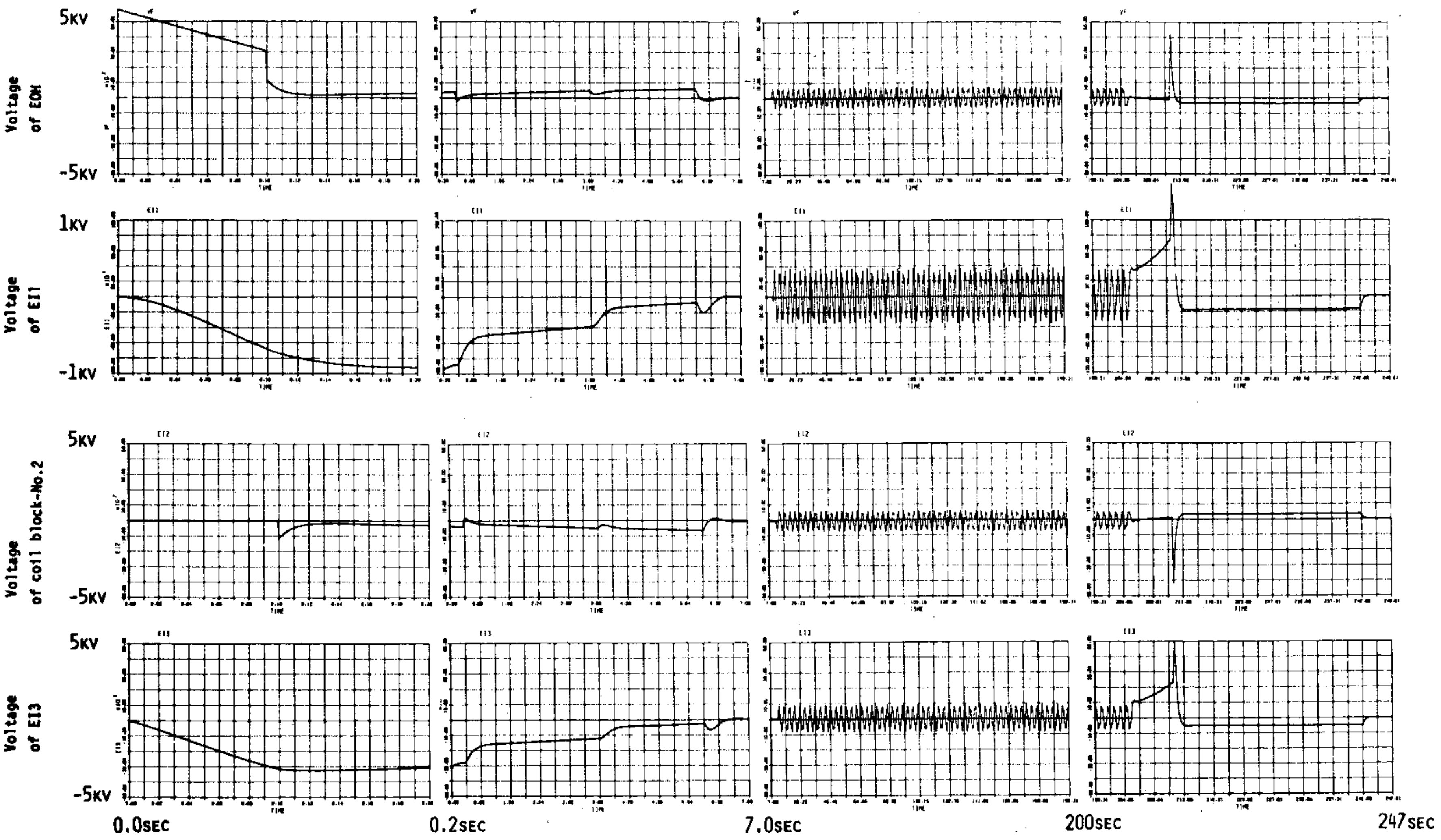

Fig. 34 Simulation calculation of INTOR poloidal field power supply (divertor operated with current swinging) C

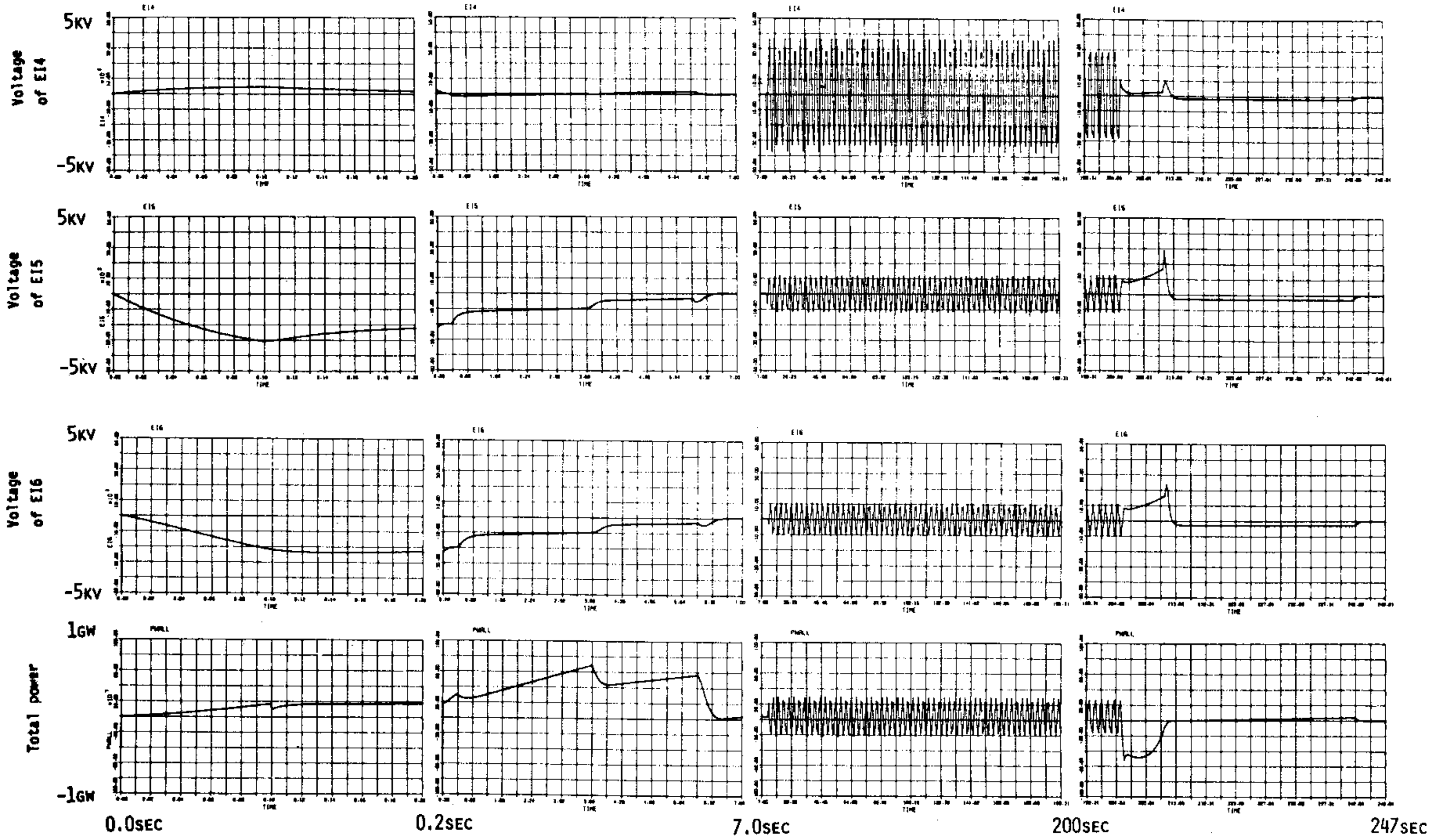

Fig. 34 Simulation calculation of INTOR poloidal field power supply (divertor operated with current swinging) D

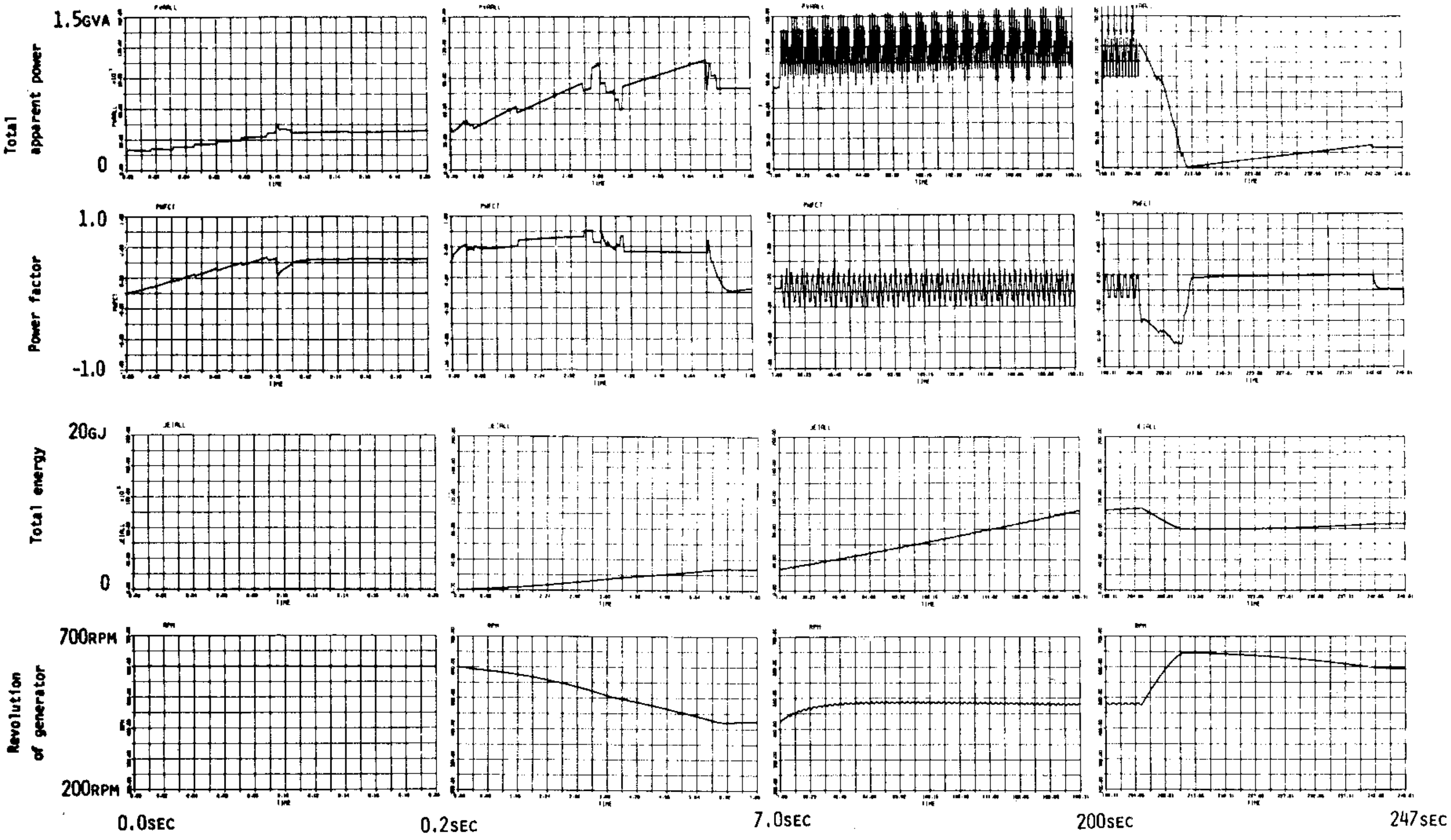

Fig. 34 Simulation calculation of INTOR poloidal field power supply (divertor operated with current swinging) E

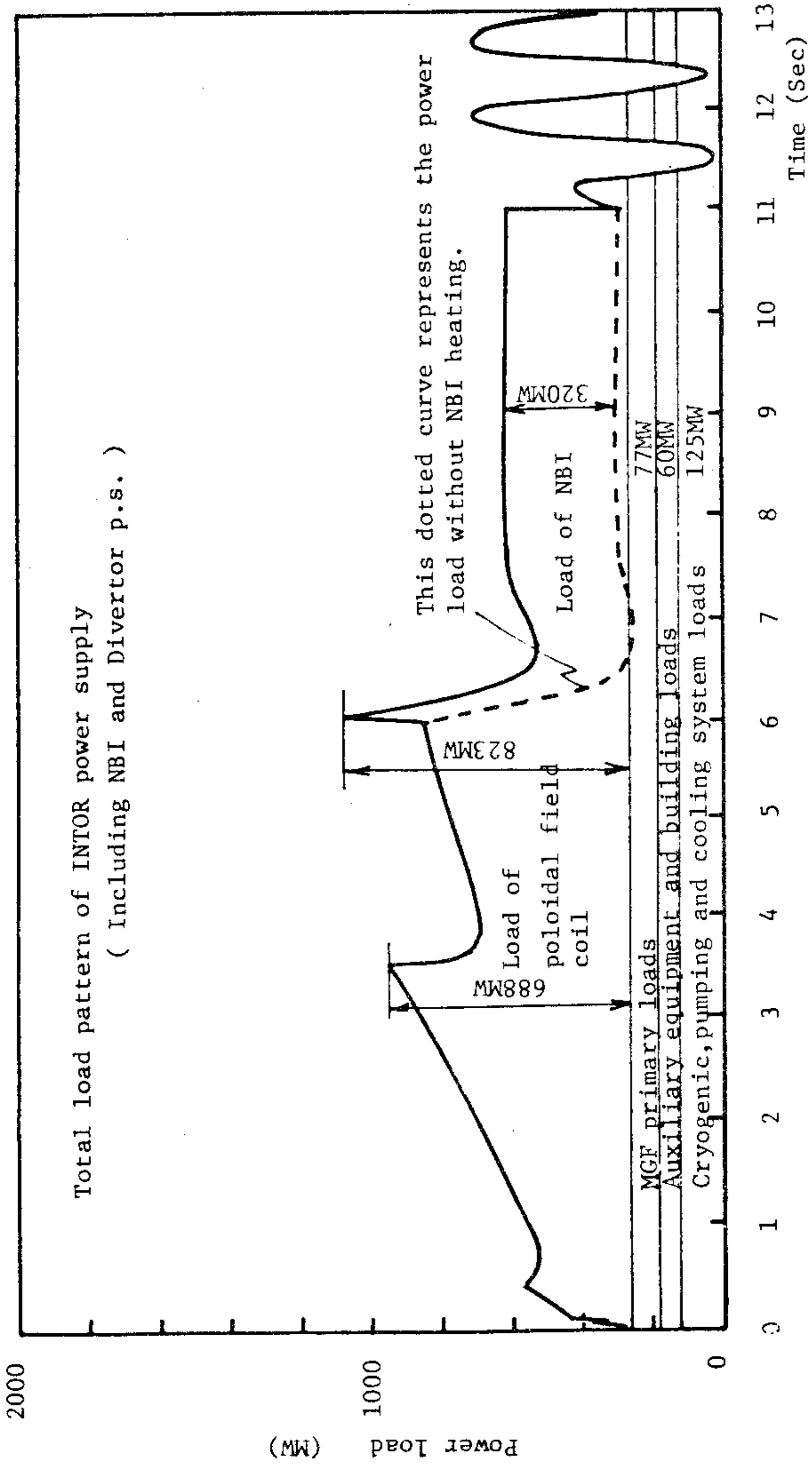

Fig. 35 Total load pattern of INTOR

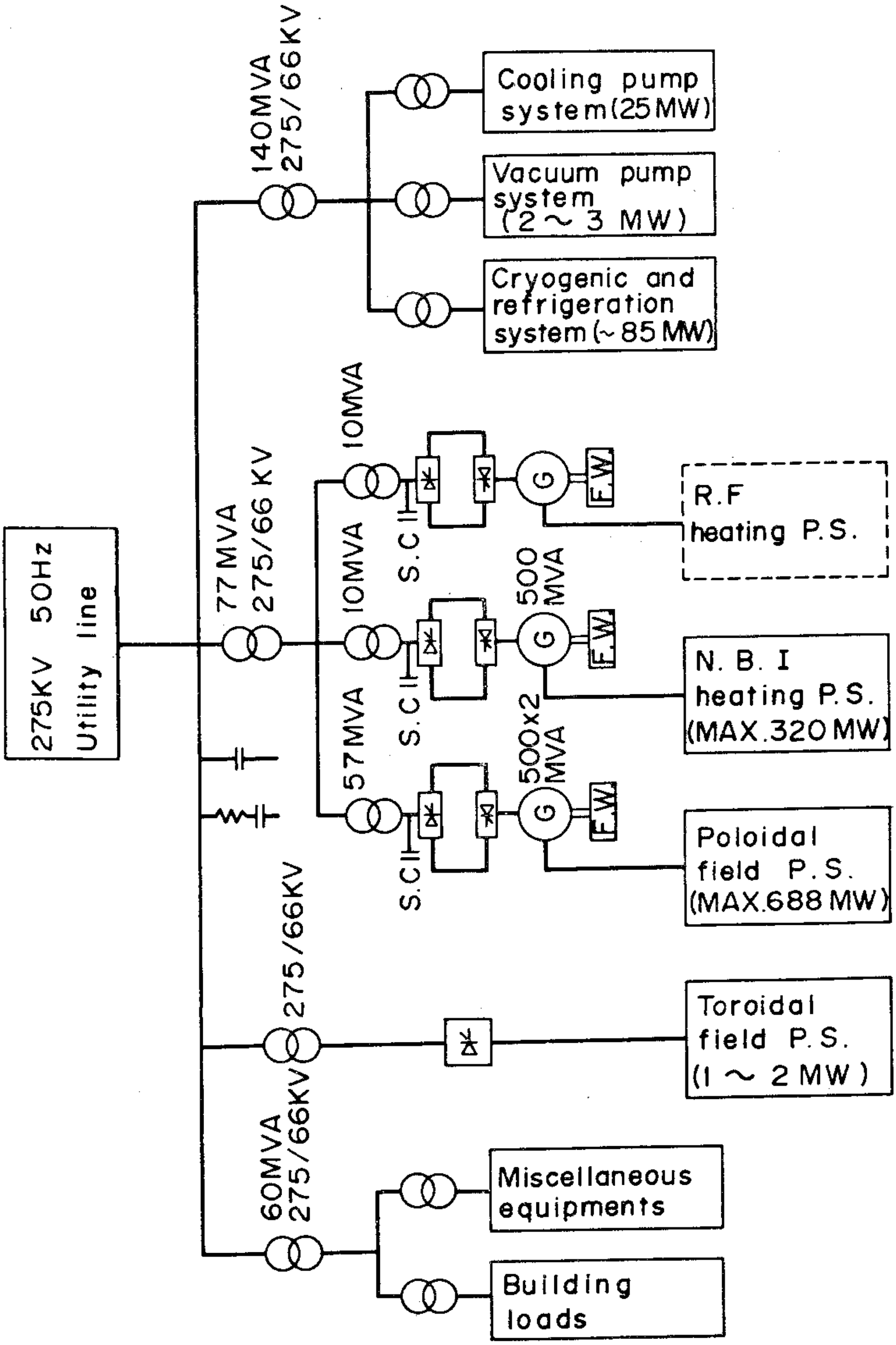

Fig. 36 INTOR power supply and distribution system

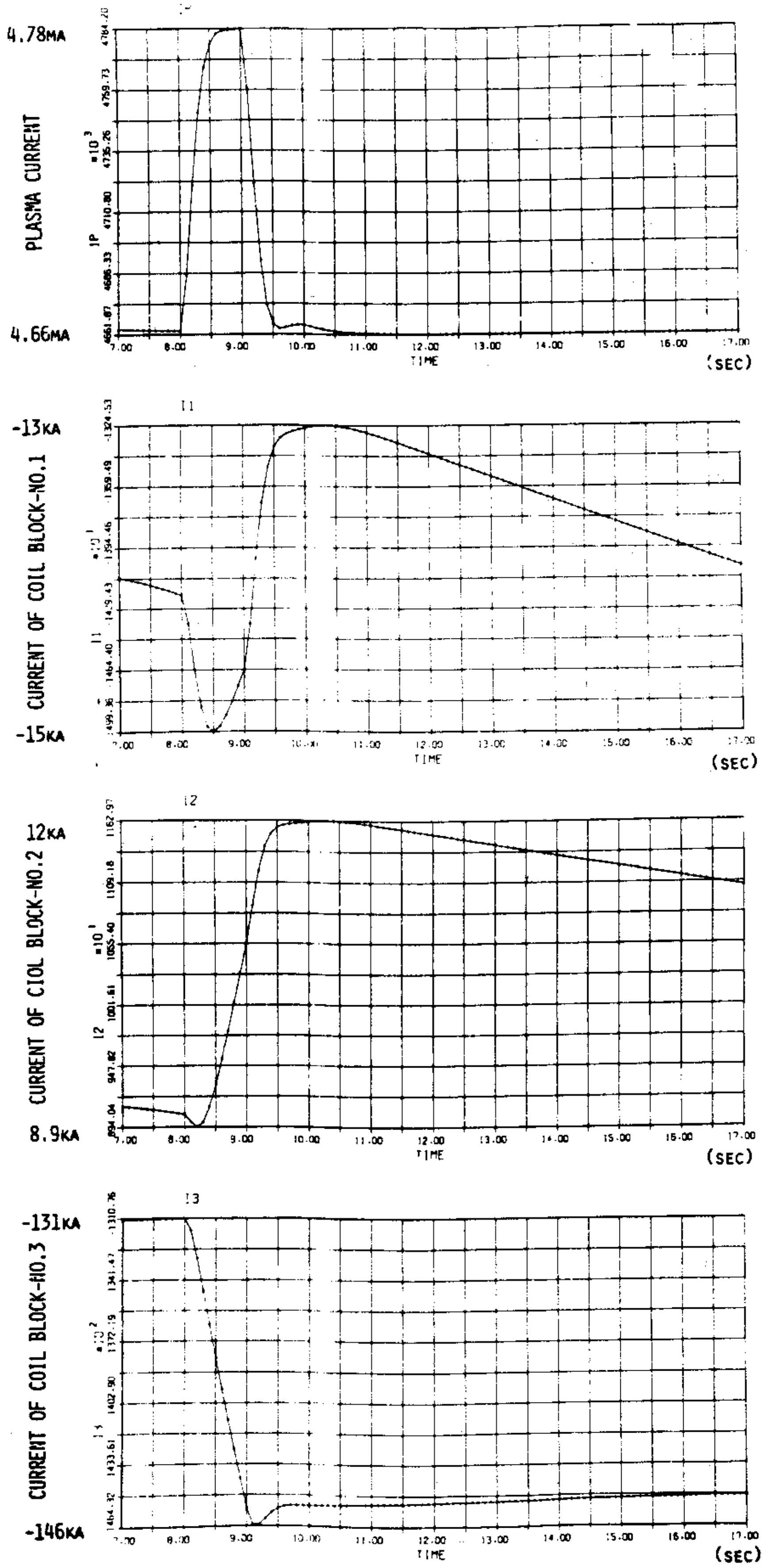

Fig. 37 System simulation of operation for plasma control A

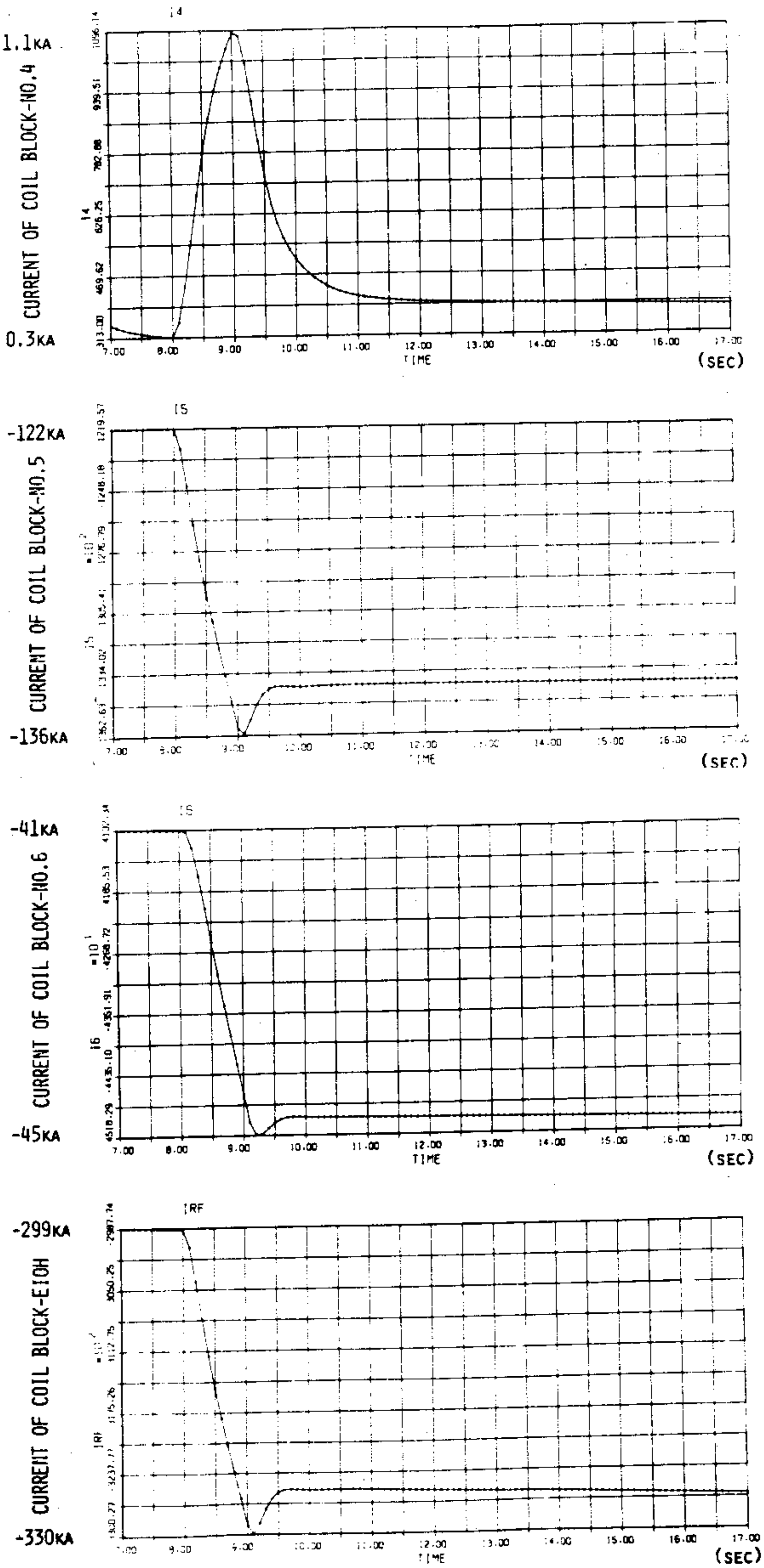

Fig. 37 System simulation of operation for plasma control B

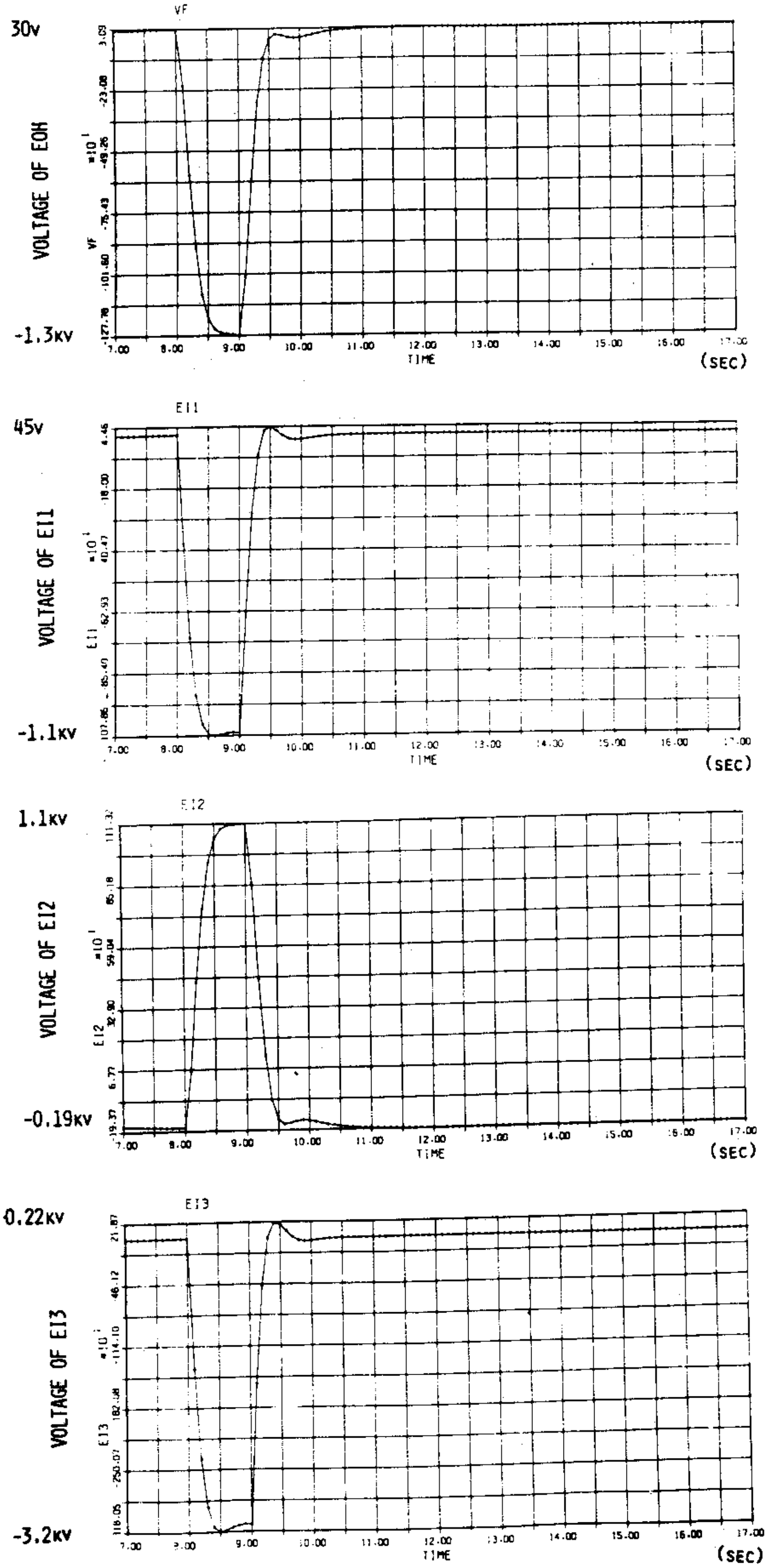

Fig. 37 System simulation of operation for plasma control C

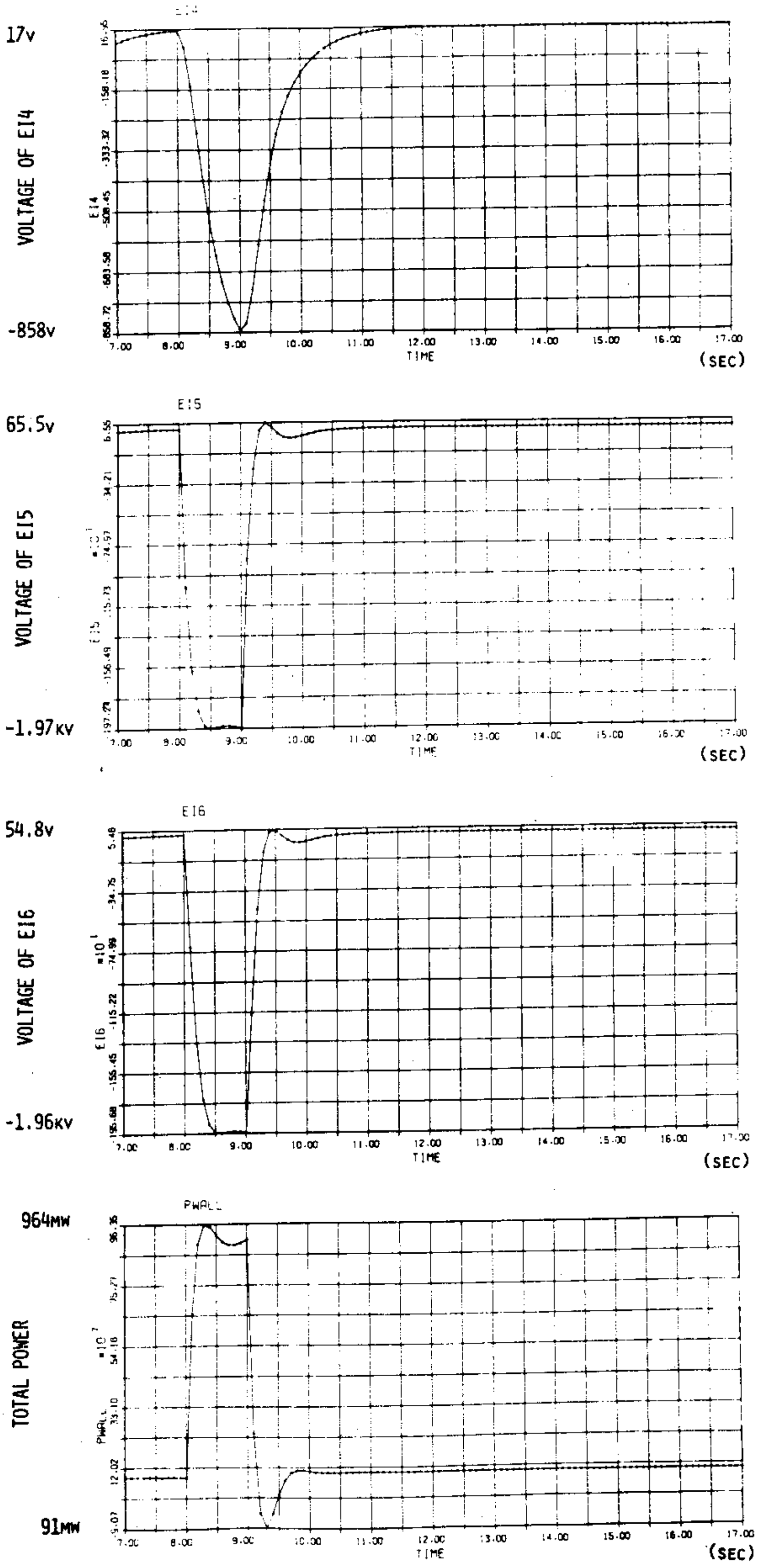

Fig. 37 System simulation of operation for plasma control D

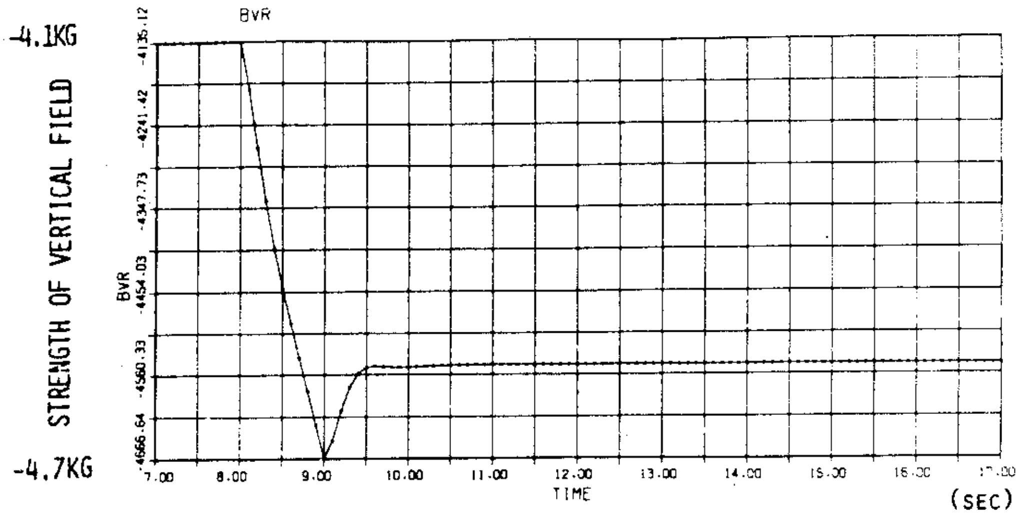

Fig. 37 System simulation of operation for plasma control E