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LA THÈSE A ÉTÉ
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TOWARDS DYNAMIC MODELING OF POWER SYSTEMS

by

Sandipan Roy

A thesis
presented to the School of Graduate Studies
in partial fulfillment of the
requirements for the degree of
Master of Applied Sciences (M.A.Sc.)
in
ELECTRICAL ENGINEERING

Ottawa, Ontario, CANADA, 1981

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ABSTRACT

Considering the continuous nature of power system operation, there may be voltage fluctuation as the system meets the variations in the daily demand. This fluctuation may be large enough leading to inefficient and unreliable operation of industrial plants with obvious economic impact. The fluctuation can be overcome by proper choice of control capacitors at suitable buses on the power networks. To maintain the voltages within tight admissible limits, it is necessary to have a complete dynamic model of the generation-transmission system.

In this thesis, the dynamic model of a power system consisting of synchronous generator, transmission lines containing four nodes and the control capacitors placed at the nodes, is developed and studied. This system model is simulated on University Of Ottawa's digital computer AMDAHL 470/V78. The mathematical model and the method used for numerical solution are presented in the thesis. Two types of (capacitor) controls are considered:

- i) synchronous capacitors (varied continuously), and
- ii) static capacitors (changed in steps)

The results indicate satisfactory regulation maintaining voltages within specified limits.

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INTRODUCTION

In power systems, the load varies widely over the period of twenty-four hours and consequently, the voltage may also change. Small deviation of voltages from a fixed reference is regulated by automatic voltage regulators located at the generating terminals. But, the voltages at the distant buses cannot necessarily be controlled by this process. However, the voltages at the distant buses can be controlled by proper application of capacitors placed at the nodes. The normal practice, in this respect, is to apply either,

(i) Synchronous capacitors (varied continuously)
or, (ii) Static capacitors (switched in steps).

In this thesis, a complete dynamic model for a generator, a transmission line and loads is presented. It is important to note here that in the dynamic model the controls (capacitors) are time-varying parameters. As a result, it is essential to consider the charge stored in the capacitor as the state variables rather than the voltages across the buses.

In this study, three separate cases of loads are simulated. In all the cases, the proposed controls are used to regulate the system voltages. These results indicate that

with the variation of loads, the desired voltage regulation can be achieved by proper choice of capacitors (controls) as functions of time.

In chapter I, the model for the synchronous generator is discussed and a generalized mathematical model is developed. (The Park's Transformation is also explained and applied into the model).

In Chapter II, the dynamic models for the transmission line and loads are presented. The transmission line model also includes the control capacitors.

In Chapter III, the generator model is coupled with the transmission line and loads. The complete set of non-linear differential equations representing the entire system in state-space form is also presented.

Chapter IV contains the control model and the numerical results on voltage regulation of the power system network. Under certain load impacts the capacitor is appropriate to regulate the system voltages.

Chapter I

SYNCHRONOUS GENERATOR MODEL

1.1 INTRODUCTION

In this chapter a mathematical model for synchronous generator in state-space form is developed. A synchronous machine can be modelled either in classical sense (which is rather approximate) or from coupled circuit point of view. The later method takes care of the details of the machine and is thus suitable for dynamic studies of power systems.

Two models can be developed, one using the currents as state variables and another using the flux linkages. Since under the study, the synchronous generator is connected to an external circuit in which currents are natural state variables, it will be rather desirable to express the currents as state variables.

The synchronous generator under the study is assumed to have three stator windings, one field winding and two damper windings. The six windings are magnetically coupled and the magnetic coupling between the windings is a function of the rotor position. Thus the flux linkage in each winding is also a function of rotor position. The instantaneous terminal voltage v of any winding is in the form [1],

$$v = r i + \dot{\lambda} \quad (1.1)$$

where λ is the flux linkage, r is the winding resistance and i is the current, with positive directions of stator currents flowing out of generator terminals. To develop the generator model the following assumptions are made :

- i) Distributed damper windings are represented by two lumped circuits on two axes of the rotor.
- ii) Hysteresis and eddy current losses are neglected.
- iii) Saturation and slot effect are neglected.
- iv) Distributed stator windings can be represented by three lumped coils on the axes in the stator.

1.2 FLUX LINKAGE EQUATIONS

The situation depicted in Figure 1.1 is that of a network consisting of six mutually coupled coils which represents a synchronous machine.

These are the three phase windings sa-fa, sb-fb and sc-fc; the field winding F-F; and the two damper windings D-D and Q-Q. (The damper windings are often designated by the symbols kd and kq. The shorter notation is preferred in this thesis. Phase-winding designations s and f refer to 'start' and 'finish' of the coils).

Hence the flux linkage equations for these circuits may

be written as,

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \\ \lambda_F \\ \lambda_D \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aQ} \\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bQ} \\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cQ} \\ L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & L_{FQ} \\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & L_{DQ} \\ L_{Qa} & L_{Qb} & L_{Qc} & L_{QF} & L_{QD} & L_{QQ} \end{bmatrix} \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \\ i_F \\ i_D \\ i_Q \end{bmatrix}$$

(1.2)

where

L_{jk} = self-inductance when $j = k$
 = mutual-inductance when $j \neq k$
 and $L_{jk} = L_{kj}$ in all cases.

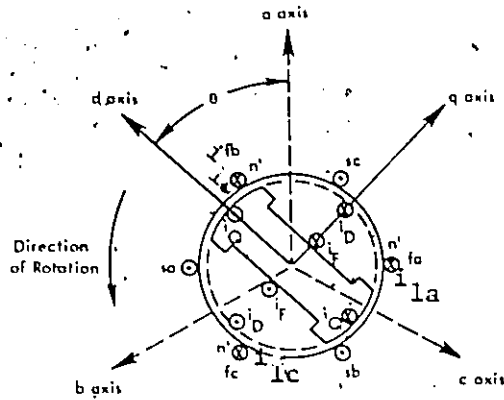


Fig. 1.1 : Pictorial Representation of a Synchronous Machine

It may be noted that the subscript convention in (1.2) where lowercase subscripts are used for stator quantities and uppercase subscripts are used for rotor quantities. Eddy currents and hysteresis losses are neglected here. Prentice [2] showed that most of the inductances in (1.2) are functions of the rotor position as shown in the next section.

1.3 FORMULATION OF INDUCTANCES

Each of the entries of the inductance matrix is given by a sum of two components, one of which is a function of θ , that is,

$$L_{kj} = a_{kj} + f_{kj}(\theta)$$

The details of all the inductances (in units of henry) are discussed below.

1.3.1 Stator self-inductances

The phase-winding self-inductances are given by,

$$L_{aa} = L_s + L_m \cos 2\theta$$

$$L_{bb} = L_s + L_m \cos 2(\theta - 2\pi/3) \quad (1.3)$$

$$L_{cc} = L_s + L_m \cos 2(\theta + 2\pi/3)$$

where $L_s > L_m$ and both L_s and L_m are positive constants and θ is the rotor position relative to axis of coils.

1.3.2 Rotor self-inductances

Since saturation and slot effect are neglected, all rotor self-inductances are constants and, according to our subscript convention, a single subscript notation may be used i.e.,

$$L_{FF} = L_F$$

$$L_{DD} = L_D \quad (1.4)$$

$$L_{QQ} = L_Q$$

1.3.3 Stator mutual inductances

The phase to phase mutual inductances are functions of angle but are symmetric.

$$L_{ab} = L_{ba} = -M_s - L_m \cos 2(\theta + \pi/\epsilon)$$

$$L_{bc} = L_{cb} = -M_s - L_m \cos 2(\theta - \pi/2) \quad (1.5)$$

$$L_{ca} = L_{ac} = -M_s - L_m \cos 2(\theta + \pi/\epsilon)$$

where $M_s > L_m$. It may be noted here that signs of mutual inductances terms depend upon assumed current directions and coil orientations.

1.3.4 Rotor mutual inductances

The mutual inductance between windings F and D is constant and does not vary with angle θ . The co-efficient of coupling between all pairs of windings with 90° displacement have zero mutual inductance. Thus,

$$L_{FD} = L_{DF} = M_R$$

$$L_{FQ} = L_{QF} = 0$$

$$L_{DQ} = L_{QD} = 0$$

(1.6)

1.3.5 Stator to rotor mutual inductances

Finally, the mutual inductances are considered between stator and rotor windings, all of which are functions of the rotor angle θ . From the phase windings to field winding, it may be written as follows,

$$L_{aF} = L_{Fa} = M_F \cos \theta$$

$$L_{bF} = L_{Fb} = M_F \cos(\theta - 2\pi/3)$$

(1.7)

$$L_{cF} = L_{Fc} = M_F \cos(\theta + 2\pi/3)$$

Similarly, from phase windings to damper winding D, it can be written,

$$L_{aD} = L_{Da} = M_D \cos \theta$$

$$L_{bD} = L_{Db} = M_D \cos(\theta - 2\pi/3) \quad (1.8)$$

$$L_{cD} = L_{Dc} = M_D \cos(\theta + 2\pi/3)$$

and finally, from phase windings to damper winding Q,

$$L_{aQ} = L_{Qa} = M_Q \sin \theta$$

$$L_{bQ} = L_{Qb} = M_Q \sin(\theta - 2\pi/3) \quad (1.9)$$

$$L_{cQ} = L_{Qc} = M_Q \sin(\theta + 2\pi/3)$$

The signs on mutual terms depend upon assumed current directions and coil directions.

1.4 PARK'S TRANSFORMATION

A great simplification in the mathematical description of the synchronous machine can be obtained if certain transformation of variables is performed. The transformation is commonly used in power systems problems and known as Park's Transformation or d-q Transformation. It defines a new set of stator variables such as d-q axis currents, voltages, or flux linkages in terms of actual winding variables. The new quantities are obtained from the projection of the actual variables on three axes; one along the polar axis of the rotor field winding, called the direct axis; a second along the neutral axis of the field winding, called the quadrature axis, where d-axis leads q-axis by 90°; and the third on a stationary axis.

The d axis of the rotor can be defined as being at some instant of time to be at an angle θ rad. with respect to a fixed reference position as shown in Figure 1.1. Let the stator phase currents i_{1a} , i_{1b} , i_{1c} be the currents leaving the generator terminals. If these currents are projected along the d and q axes of the rotor, we get the following relations.

$$\begin{aligned} i_{q\text{axis}} &= (\sqrt{2/3}) [i_{1a} \sin\theta + i_{1b} \sin(\theta - 2\pi/3) + i_{1c} \sin(\theta + 2\pi/3)] \\ i_{d\text{axis}} &= (\sqrt{2/3}) [i_{1a} \cos\theta + i_{1b} \cos(\theta - 2\pi/3) + i_{1c} \cos(\theta + 2\pi/3)] \end{aligned} \quad (1.10)$$

It may be noted that for convenience the axis of phase a was chosen to be the reference position, otherwise some angle of displacement between phase a and the arbitrary reference will appear in all the above terms.

The effect of Park's Transformation is simply to transform all stator quantities from phase a, b, and c into new variables, the frame of reference of which moves with the rotor. It should, however, be remembered that if there are three variables a, b, and c, then three new variables are needed to justify the transformation. Park's Transformation uses two of the new variables as the d and q axes components. The third variable is a stationary current, which is proportional to zero-sequence current. A multiplier is used to simplify the numerical calculations. Thus by definition,

$$i_{10dq} = P i_{1abc} \quad (1.11)$$

where the current vectors are defined as

$$i_{10dq} = \begin{bmatrix} i_{10} \\ i_{1d} \\ i_{1q} \end{bmatrix} \quad i_{1abc} = \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} \quad (1.12)$$

and where the Park's Transformation P is defined as

$$P = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos \theta & \cos (\theta - 2\pi/3) & \cos (\theta + 2\pi/3) \\ \sin \theta & \sin (\theta - 2\pi/3) & \sin (\theta + 2\pi/3) \end{bmatrix} \quad (1.13)$$

The main field-winding flux is along the direction of the d axis of the rotor. It produces an EMF that lags this flux by 90° . Therefore the machine EMF 'E' is primarily along the rotor q axis. Suppose a machine is considered having a constant terminal voltage V, for generator action the phasor E should be leading the phasor V. The angle between E and V is the machine torque angle δ .

At $t=0$ the phasor V is located at the axis of phase a, i.e., at the reference axis in Figure 1.1. The q axis is located at an angle δ , and the d axis is located at $\theta = \delta + \pi/2$. At $t > 0$, the reference axis is located at an angle $\omega_R t$ with respect to the axis of phase a. The d axis of the rotor is therefore located at

$$\theta = \omega_R t + \delta - \pi/2 \quad \text{rad.} \quad (1.14)$$

where ω_R is the rated (synchronous) angular frequency in rad./s and δ is the synchronous torque angle in electrical radians. Expression similar to (1.11) may also be written for voltages or flux linkages; e.g.,

$$v_{10dq} = P v_{labc}$$

(1.15)

$$\lambda_{10dq} = P \lambda_{labc}$$

Assuming

$$v_{labc} = \begin{bmatrix} \sqrt{2} v \sin(\theta + \alpha) \\ \sqrt{2} v \sin(\theta + \alpha - 120) \\ \sqrt{2} v \sin(\theta + \alpha + 120) \end{bmatrix}$$

and applying Park's Transformation, one can obtain,

$$v_{10dq} = \begin{bmatrix} 0 \\ \sqrt{3} v_1 \sin \alpha \\ \sqrt{3} v_1 \cos \alpha \end{bmatrix} \quad (1.15a)$$

Similarly it is easy to show that corresponding to

$$I_{labc} = \begin{bmatrix} \sqrt{2} I_1 \sin(\theta + \gamma) \\ \sqrt{2} I_1 \sin(\theta + \gamma - 120^\circ) \\ \sqrt{2} I_1 \sin(\theta + \gamma + 120^\circ) \end{bmatrix},$$

by applying the Park's Transformation,

$$\begin{aligned} I_{1d} &= \sqrt{3} I_1 \sin \gamma \\ I_{1q} &= \sqrt{3} I_1 \cos \gamma \end{aligned} \quad (1.15b)$$

If the transformation (1.13) is unique, an inverse transformation also exists wherein it may be written as

$$i_{labc} = P^{-1} i_{10dq} \quad (1.16)$$

The inverse of (1.13) may be computed to be

$$P^{-1} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1/\sqrt{2} & \cos \theta & \sin \theta \\ 1/\sqrt{2} & \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) \\ 1/\sqrt{2} & \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) \end{bmatrix} \quad (1.17)$$

and it may be noted here that $P^{-1} = P^t$, which means that the transformation P is orthogonal. Having P orthogonal also means that the transformation P is power invariant, and it is expected to use the same power expression in either the a-b-c or the 0-d-q frame reference. Thus

$$P(\text{power}) = v_{1a} i_{1a} + v_{1b} i_{1b} + v_{1c} i_{1c}$$

$$= v_{1abc}^t i_{1abc}$$

$$= (P^{-1} v_{10dq})^t (P^{-1} i_{10dq})$$

$$= v_{10dq}^t (P^{-1})^t P^{-1} i_{10dq}$$

$$= v_{10dq}^t P P^{-1} i_{10dq}$$

$$= v_{10dq}^t i_{10dq}$$

$$= v_{10} i_{10} + v_{1d} i_{1d} + v_{1q} i_{1q}$$

It is to be noted here that under balanced conditions v_{10} and i_{10} are zero.

1.5 TRANSFORMATION OF INDUCTANCES

It may be observed here that nearly all terms in the matrix (1.2) are time varying, since the angle is a function of time. Only four of the off-diagonal terms will be zero, as noted in (1.6). Thus

the λ term is not a simple L_i but must be computed as,

$$\dot{\lambda} = \dot{L}_{i1} + L_{i1} \dot{\theta} \quad (1.18)$$

It may be noted here that (1.2) with its time-varying inductances can be simplified by referring all quantities to a rotor frame of reference through a Park's Transformation (1.13) applied to the a-b-c partition. We thus compute,

$$\begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} \lambda_{labc} \\ \lambda_{FDQ} \end{bmatrix} = \begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} L_{aa} & L_{aR} \\ L_{Ra} & L_{RR} \end{bmatrix} \begin{bmatrix} P^{-1} & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} i_{labc} \\ i_{FDQ} \end{bmatrix} \quad (1.19)$$

L_{aa} = stator self-inductance

L_{aR}, L_{Ra} = stator-rotor mutual inductance

L_{RR} = rotor mutual inductance

Equation (1.19) is obtained by pre-multiplying (1.2) by

$$\begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix}$$

where P is the Park's Transformation and L_3 is the 3 x 3 unit matrix. Performing the operation indicated in (1.19), it may be computed as

$$\begin{bmatrix} \lambda_{10} \\ \lambda_{1d} \\ \lambda_{1q} \\ \lambda_F \\ \lambda_D \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & kM_F & kM_D & 0 \\ 0 & 0 & L_q & 0 & 0 & kM_Q \\ 0 & kM_F & 0 & L_F & M_R & 0 \\ 0 & kM_D & 0 & M_R & L_D & 0 \\ 0 & 0 & kM_Q & 0 & 0 & L_Q \end{bmatrix} \begin{bmatrix} i_{10} \\ i_{1d} \\ i_{1q} \\ i_F \\ i_D \\ i_Q \end{bmatrix} \quad (1.20)$$

where the following new constants may be defined as,

$$L_d = L_s + M_s + (3/2) L_m$$

$$L_q = L_s + M_s - (3/2) L_m$$

$$L_0 = L_s - 2M_s$$

$$k = \sqrt{3/2}$$

In (1.20) λ_d is the flux linkage in a circuit moving with the rotor and centered on the d axis. Similarly λ_q is centered on the q axis. Flux linkage λ_0 is completely uncoupled from the other circuits, as the first row and column have only a diagonal term.

1.6 TRANSFORMATION OF VOLTAGE EQUATIONS

The generator voltage equations are in the form of (1.1). Schematically, the circuits are shown in Figure 1.2, where coils are identified exactly the same as in Figure 1.1 and with coil terminations shown as well. Mutual inductances are omitted from the schematic for clarity but are assumed present with the values given in section 1.3. It may be noted that the stator currents are assumed to have a positive direction flowing out of machine terminals, since the machine is a generator.

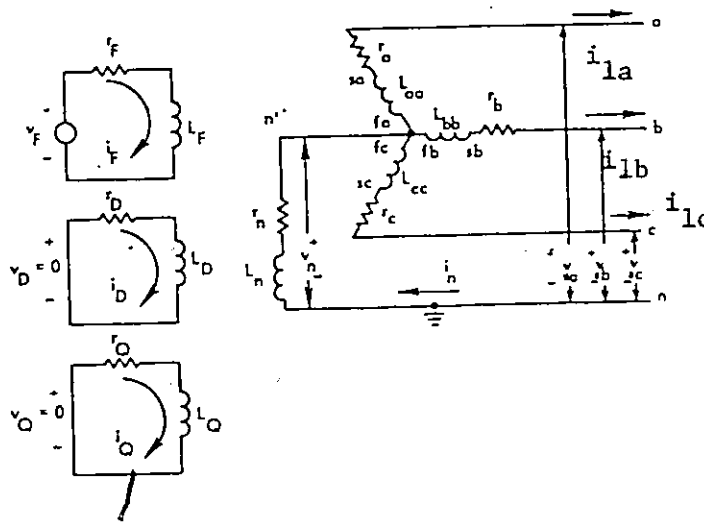


Fig. 1.2 : Schematic Diagram of a Synchronous Machine

For the conditions indicated above, the matrix equation may be written as follows

$$V_1 = -r i_1 - \dot{\lambda}_1 + V_n$$

or

$$\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \\ V_{1F} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_a & 0 & 0 & 0 & 0 & 0 \\ 0 & r_b & 0 & 0 & 0 & 0 \\ 0 & 0 & r_c & 0 & 0 & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 \\ 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \\ i_F \\ i_D \\ i_Q \end{bmatrix} - \begin{bmatrix} \dot{\lambda}_{1a} \\ \dot{\lambda}_{1b} \\ \dot{\lambda}_{1c} \\ \dot{\lambda}_F \\ \dot{\lambda}_D \\ \dot{\lambda}_Q \end{bmatrix} + \begin{bmatrix} V_n \\ \vdots \\ 0 \end{bmatrix} \quad (1.22)$$

where the neutral voltage contribution to V_n is defined as

$$\begin{aligned}
 V_n &= -r_n \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix} - L_n \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \dot{i}_{1a} \\ \dot{i}_{1b} \\ \dot{i}_{1c} \end{bmatrix} \\
 &= -R_n i_{1abc} - L_n \dot{i}_{1abc} \quad (1.23)
 \end{aligned}$$

If $r_a = r_b = r_c = r$, as is usually the case, then it may also be defined as

$$R_{abc} = rI_3$$

where I_3 is 3 X 3 unit matrix and (1.22) may be rewritten in partitioned form as follows:

$$\begin{bmatrix} v_{labc} \\ v_{FDQ} \end{bmatrix} = - \begin{bmatrix} R_{abc} & 0 \\ 0 & R_{FDQ} \end{bmatrix} \begin{bmatrix} i_{labc} \\ i_{FDQ} \end{bmatrix} - \begin{bmatrix} \dot{\lambda}_{labc} \\ \dot{\lambda}_{FDQ} \end{bmatrix} + \begin{bmatrix} v_n \\ \dots \\ 0 \end{bmatrix} \quad (1.25)$$

where,

$$v_{FDQ} = \begin{bmatrix} -v_F \\ 0 \\ 0 \end{bmatrix} \quad i_{FDQ} = \begin{bmatrix} i_F \\ i_D \\ i_Q \end{bmatrix} \quad \lambda_{FDQ} = \begin{bmatrix} \lambda_F \\ \lambda_D \\ \lambda_Q \end{bmatrix} \quad (1.26)$$

Thus (1.25) is complicated by the presence of time-varying coefficients in the $\dot{\lambda}$ term but these terms can be eliminated by applying a Park's Transformation to the stator partition. This requires that both sides of (1.25) be premultiplied by

$$\begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix}$$

By definition, $\begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} v_{labc} \\ v_{FDQ} \end{bmatrix} = \begin{bmatrix} v_{10dq} \\ v_{FDQ} \end{bmatrix} \quad (1.27)$

for the left side of (1.25). For the resistance voltage drop term we compute as

$$\begin{aligned}
 & \begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \cdot \begin{bmatrix} R_{abc} & 0 \\ 0 & R_{FDQ} \end{bmatrix} \begin{bmatrix} i_{1abc} \\ 0 \\ i_{FDQ} \end{bmatrix} \\
 &= \begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \cdot \begin{bmatrix} R_{abc} & 0 \\ 0 & R_{FDQ} \end{bmatrix} \begin{bmatrix} P^{-1} & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} i_{10dq} \\ i_{FDQ} \end{bmatrix} \\
 &= \begin{bmatrix} PR_{abc}P^{-1} & 0 \\ 0 & R_{FDQ} \end{bmatrix} \begin{bmatrix} i_{10dq} \\ i_{FDQ} \end{bmatrix} \\
 &= \begin{bmatrix} R_{abc} & 0 \\ 0 & R_{FDQ} \end{bmatrix} \begin{bmatrix} i_{10dq} \\ i_{FDQ} \end{bmatrix} \tag{1.28}
 \end{aligned}$$

The second term on the right side of (1.25) is transformed

$$\text{as } \begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} \dot{\lambda}_{1abc} \\ \dot{\lambda}_{FDQ} \end{bmatrix} = \begin{bmatrix} P \dot{\lambda}_{1abc} \\ \dot{\lambda}_{FDQ} \end{bmatrix} \tag{1.29}$$

We evaluate $P\dot{\lambda}_{1abc}$ by recalling the definition (1.15), $\lambda_{10dq} = P\lambda_{1abc}$ from which it is computed as $\dot{\lambda}_{10dq} = P\dot{\lambda}_{1abc} + \dot{P}\lambda_{1abc}$. Then

$$\begin{aligned} P\dot{\lambda}_{1abc} &= \dot{\lambda}_{10dq} - \dot{P}\lambda_{1abc} \\ &= \dot{\lambda}_{10dq} - \dot{P}P^{-1}\lambda_{10dq} \end{aligned} \quad (1.30)$$

It may be shown here that

$$\begin{aligned} \dot{P}P^{-1}\lambda_{10dq} &= \omega \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{10} \\ \lambda_{1d} \\ \lambda_{1q} \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ -\omega\lambda_{1d} \\ \omega\lambda_{1q} \end{bmatrix} \end{aligned} \quad (1.31)$$

which is the speed voltage term.

Finally, the third term on the right side of (1.25) is transformed as follows

$$\begin{bmatrix} P & 0 \\ 0 & I_3 \end{bmatrix} \begin{bmatrix} v_n \\ 0 \end{bmatrix} = \begin{bmatrix} Pv_n \\ 0 \end{bmatrix} = \begin{bmatrix} n_{0dq} \\ 0 \end{bmatrix} \quad (1.32)$$

where by definition n_{0dq} is the voltage drop from neutral to ground in the 0-d-q coordinate system. Using (1.23), it may

be defined as

$$\begin{aligned}
 n_{0dq} &= P v_n = -P R_n P^{-1} P i_{labc} - P L_n P^{-1} \dot{P} i_{labc} \\
 &= P R_n P^{-1} i_{10dq} - P L_n P^{-1} \dot{P} i_{10dq} \\
 &= - \begin{bmatrix} 3r_n i_{10} \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} 3L_n \dot{i}_{10} \\ 0 \\ 0 \end{bmatrix} \tag{1.33}
 \end{aligned}$$

and it may be observed that this voltage drop occurs only in the zero-sequence, as it should.

Summarising, (1.27) to (1.30) and (1.32) may be substituted into (1.25) to obtain

$$\begin{bmatrix} v_{10dq} \\ v_{FDQ} \end{bmatrix} = - \begin{bmatrix} R_{abc} & 0 \\ 0 & R_{FDQ} \end{bmatrix} \begin{bmatrix} i_{10dq} \\ i_{FDQ} \end{bmatrix} - \begin{bmatrix} \dot{\lambda}_{10dq} \\ \dot{\lambda}_{FDQ} \end{bmatrix} \begin{bmatrix} P P^{-1} \lambda_{10dq} \\ 0 \end{bmatrix} \begin{bmatrix} n_{0dq} \\ \dots \\ 0 \end{bmatrix} \tag{1.34}$$

It may be noted here that all terms in this equations are known. The resistance matrix is diagonal.

For balanced conditions the zero-sequence voltage is zero. To simplify the notation, it is written as

$$R = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix}$$

$$R_R = \begin{bmatrix} r_F & 0 & 0 \\ 0 & r_D & 0 \\ 0 & 0 & r_Q \end{bmatrix}$$

$$S = \begin{bmatrix} \omega \lambda_{1q} \\ \omega \lambda_{1d} \end{bmatrix}$$

Then for balanced conditions, (1.34) may be written without the zero-sequence equation as

$$\begin{bmatrix} v_{1dq} \\ v_{FDQ} \end{bmatrix} = - \begin{bmatrix} R & 0 \\ 0 & R_R \end{bmatrix} \begin{bmatrix} i_{1dq} \\ i_{FDQ} \end{bmatrix} + \begin{bmatrix} S \\ \dots \\ 0 \end{bmatrix} - \begin{bmatrix} \dot{\lambda}_{1dq} \\ \dot{\lambda}_{FDQ} \end{bmatrix} \quad (1.35)$$

1.7 CURRENT FORMULATION

Starting with (1.34), the terms in λ_1 and $\dot{\lambda}_1$ can be replaced by terms i_1 and \dot{i}_1 as follows. The $\dot{\lambda}_1$ term has been simplified so that its value from (1.20) can be calculated by arranging

$$\begin{bmatrix} \lambda_{10dq} \\ \lambda_{FDQ} \end{bmatrix} = \begin{bmatrix} L_{0dq} & L_m \\ L_m^t & L_{FDQ} \end{bmatrix} \begin{bmatrix} i_{10dq} \\ i_{FDQ} \end{bmatrix} \quad \text{wb. turns}$$

where L_m^t is the transpose of L_m . Put the inductance matrix here is a constant matrix, so it may be written as $\lambda_1 = Li_1$, and the term L behaves exactly like that of a passive inductance. Substituting the result into (1.34), expanding to full 6 X 6 notation, and rearranging,

$$\begin{bmatrix} v_0 \\ v_{ld} \\ -v_F \\ v_D \\ v_{lq} \\ v_Q \end{bmatrix} = \begin{bmatrix} r + 3r_n & 0 & 0 & 0 & 0 & 0 \\ 0 & r & 0 & 0 & \omega L_q & \omega kM_Q \\ 0 & 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & 0 & r_D & 0 & 0 \\ 0 & -\omega L_d & -\omega kM_F & -\omega kM_D & r & 0 \\ 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_{10} \\ i_{ld} \\ i_F \\ i_D \\ i_{lq} \\ i_Q \end{bmatrix}$$

$$\begin{array}{c}
 \left[\begin{array}{ccc|cc}
 L_0 + 3L_n & 0 & 0 & 0 & 0 \\
 \hline
 0 & L_d & kM_F & kM_D & 0 & 0 \\
 0 & kM_F & L_F & M_R & 0 & 0 \\
 0 & kM_D & M_R & L_d & 0 & 0 \\
 \hline
 0 & 0 & 0 & 0 & L_q & kM_Q \\
 0 & 0 & 0 & 0 & kM_Q & L_Q
 \end{array} \right] \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \end{array} \begin{array}{c} \dot{i}_{10} \\ \dot{i}_{1d} \\ \dot{i}_F \\ \dot{i}_D \\ \dot{i}_{1q} \\ \dot{i}_Q \end{array}
 \end{array}$$

(1.36)

where $k = \sqrt{3/2}$ as before.

It may be observed from above that the zero-sequence voltage is dependent only upon i_0 and \dot{i}_0 . This equation can be solved separately from the others once the initial conditions on i_0 are given. The remaining five equations are

all coupled in a most interesting way. They are similar to those of a passive network except for the presence of the speed voltage terms. These terms, consisting of $\omega\lambda$ or ωLi products, appear unsymmetrically and distinguish this equation from that of a passive network. It may be noted here that the speed voltage terms in the d axis equations are due only to q axis currents, viz., i_q and i_Q . Similarly, the q axis speed voltages are due to d axis currents i_d, i_F, i_D .

It may also be observed that all the terms in the coefficient matrices are constants except , the angular velocity. This is a considerable improvement over the description given in (1.22) in the a-b-c frame of reference since nearly all inductances in that equation were time varying. Since ω is variable, this causes (1.36) to be non-linear.

1.8 PER UNIT CONVERSION

The equations of the preceding sections are not in a convenient form for engineering use. One difficulty is the numerically awkward values with stator voltages in kilovolt range and field voltage at a much lower level. This problem can be solved by normalizing the equations to a convenient base value and expressing all voltages in pu of base. Complete details of per unit conversion are explained in Appendix 1.

1.9 NORMALIZED VOLTAGE EQUATION

Having chosen appropriate base values, the voltage equations (1.36) may be normalized and therefore, the stator equations should be numerically easier to deal with.

Incorporating all normalized equations in a matrix expression, one can obtain,

$$\begin{bmatrix} V_{ld} \\ -V_F \\ 0 \\ \hline V_{lq} \\ 0 \end{bmatrix} = \begin{bmatrix} r & 0 & 0 & \omega L_q & -\omega kM_Q \\ 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & r_D & 0 & 0 \\ \hline -\omega L_d & -\omega kM_F & -\omega kM_D & r & 0 \\ 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_F \\ i_D \\ \hline i_{lq} \\ i_Q \end{bmatrix} \\
 - \begin{bmatrix} L_d & kM_F & kM_D & 0 & 0 \\ kM_F & L_F & M_R & 0 & 0 \\ kM_D & M_R & L_D & 0 & 0 \\ \hline 0 & 0 & 0 & L_q & kM_Q \\ 0 & 0 & 0 & kM_Q & L_Q \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_F \\ i_D \\ \hline i_{lq} \\ i_Q \end{bmatrix} \quad (1.37)$$

where the v_o equation is omitted, since under this voltage regulation studies the system is considered in balanced condition. It is important to notice that (1.37) is identical in notation to (1.36). This is always possible if base quantities are carefully chosen and is highly desirable, as the same equation symbolically serves both as pu and a "system quantity" equations. Using matrix notation, one can write (1.37) as

$$V = -(R + \omega N) i - \dot{L}i \quad (1.38)$$

where R is the resistance matrix and is a diagonal matrix of constants, N is the matrix of speed voltage inductance coefficients, and L is the matrix of constant inductances. If it is assumed that the inverse of the inductance matrix exists, it may be written as

$$\dot{i} = -L^{-1}(R + \omega N) i - L^{-1}V \quad (1.39)$$

However, equation (1.39) does not express the entire generator model. It simply describes the electrical behavior of the machine. On the other hand, the machine is nothing but a rotating mass. So for complete representation of the machine, the mechanical behavior of the generator known as swing equation should be considered here.

1.10 SWING EQUATION

The basic swing equation describing the mechanical oscillations of a generator can be given by,

$$2H\omega_B \frac{d^2\delta}{dt^2} + D \frac{d\delta}{dt} = T_a = T_m - T_{out} \quad (1.40)$$

If the equation (1.40) is split up into two first-order differential equations, then,

$$2H\omega_B \dot{\omega} = T_a = T_m - T_{out} - T_D \quad (1.41)$$

$$\dot{\delta} = \omega - 1$$

where T_m is the mechanical torque, T_{out} is the electrical torque, T_D is the damping torque and T_a is the acceleration torque.

Again electrical torque (T_{out}) can be described in terms of generator currents and voltages, which is shown below.

As the power output of a synchronous generator is invariant under the transformation P; i.e.,

$$P_{out} = v_{ld} i_{ld} + v_{lq} i_{lq} + v_{10} i_{10} \quad (1.42)$$

If the balanced condition is considered, then,

$$P_{out} = v_{ld} i_{ld} + v_{lq} i_{lq} \quad (1.43)$$

Substituting v_{ld} and v_{lq} from (1.35),

$$P_{out} = (i_{ld} \dot{\lambda}_{ld} + i_{lq} \dot{\lambda}_{lq}) + (i_{lq} \lambda_{ld} - i_{ld} \lambda_{lq}) \omega - r (i_{ld}^2 + i_{lq}^2) \quad (1.44)$$

Concordia [3] observed that the above three terms are identifiable as the rate of change of stator magnetic field energy, the power transferred across the air-gap, and the stator ohmic losses respectively. The electrical torque (T_{out}) may be obtained from the second term of (1.45).

By recalling (1.20) where flux linkages can be written in terms of currents, then,

$$\lambda_{ld} = L_d i_{ld} + kM_F i_F + kM_D i_D \quad (1.45)$$

$$\lambda_{lq} = L_q i_{lq} + kM_Q i_Q$$

Therefore, the expression for electrical torque (T_{out}) may be written as follows,

$$T_{out} = [L_d i_{lq} \quad kM_F i_{lq} \quad kM_D i_{lq} \quad -L_q i_{ld} \quad -kM_Q i_{ld}] \begin{bmatrix} i_{ld} \\ i_F \\ i_D \\ i_{lq} \\ i_Q \end{bmatrix} \quad (1.46)$$

The mechanical input (T_m) may be correctly simulated by considering the prime mover dynamics. Two major time constants in the turbine-governor system are turbine delay and governor delay, the effect of which is to delay the change in the prime mover input.

A good approximation can be made without including the detailed dynamics of the turbine-governor system. This can be done by considering a delay in the mechanical input (T_m) corresponding to the change in electrical load. Hence, in the simulation the mechanical input (T_m) equation can be written as

$$T_m(t) = T_{m0} + \Delta p (t - t_a) \quad (1.47)$$

where

T_{m0} = steady-state input.

Δp = the change in power demand.

t_a = the delay of mechanical input.

Finally, the following matrix equations can be obtained

Chapter II

TRANSMISSION LINE AND LOAD MODELS

2.1 INTRODUCTION

In this chapter the transmission line and loads are studied. The transmission line under this study is long and connected to an infinite bus. It is assumed to have four nodes from which the load currents may be drawn out. The one-line diagram of the transmission line along with loads is shown in Figure 2.1.

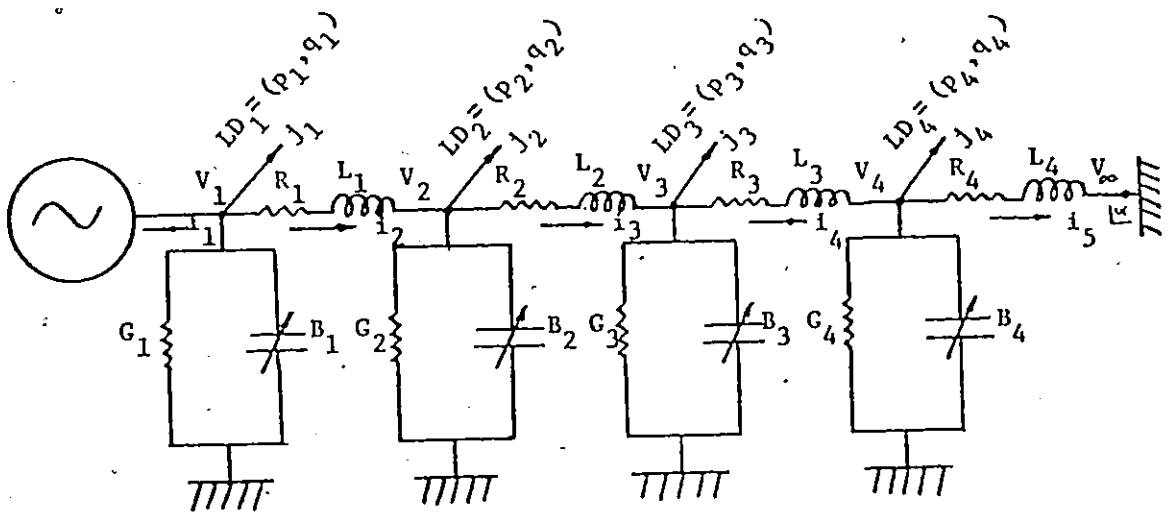


Fig. 2.1 : Single Machine Infinite Bus System

where,

v_i = the node voltages.
 i_i = the line currents.
 R_i = the line resistances.
 L_i = the line inductances.
 B_i = the capacitors.
 G_i = the leakage resistances.
 j_i = the load currents.
 LD_i = the loads on the nodes.

where, $i = 1, 2, 3, 4$

It may be noted from Figure 2.1 that the transmission line is a π -section connected to an infinite bus.

2.2 MODELING OF TRANSMISSION LINE AND LOADS

A variable load would cause varying currents and voltages in the transmission lines and at the nodes, respectively. This requires a dynamic representation of the transmission system.

By applying Kirchoff's Laws of currents and voltages and also considering the system parameters $B_1, G_1, R_1, L_1, G_2,$ and B_2 are constant, the following equations (in pu) can be developed for a section of the transmission line and loads.

$$i_{1abc} = i_{2abc} + G_1 v_{1abc} + B_1 \dot{v}_{1abc} + j_{1abc} \quad (2.1)$$

$$v_{1abc} = v_{2abc} + R_1 i_{12abc} + L_1 \dot{i}_{12abc} \quad (2.2)$$

As mentioned in Chapter 1, by applying Park's Transformation (2.1) can be written as,,

$$i_{10dq} = i_{20dq} + G_1 v_{10dq} + B_1 P \dot{v}_{1abc} + j_{10dq} \quad (2.3)$$

The term $P v_{1abc}$ on the right side of (2.3) may be computed as follows. From the definition of Park's Transformation $v_{10dq} = P v_{1abc}$, the derivatives $\dot{v}_{10dq} = P \dot{v}_{1abc} + \dot{P} v_{1abc}$. Thus,

$$P \dot{v}_{1abc} = \dot{v}_{10dq} - \dot{P} v_{1abc} = \dot{v}_{10dq} - \dot{P} P^{-1} v_{10dq} \quad (2.4)$$

where the quantity $P P^{-1}$ is known from Chapter 1. equation (1.31). Thus (2.3) may be written as

$$i_{10dq} = i_{20dq} + G_1 v_{10dq} + B_1 \dot{v}_{10dq} - \omega B_1 \begin{bmatrix} 0 \\ -v_{1q} \\ v_{1d} \end{bmatrix} + j_{10dq} \quad (2.5)$$

Similarly, by applying Park's Transformation in (2.2), one may obtain the following,

$$v_{10dq} = v_{20dq} + R_1 i_{20dq} + L_1 P \dot{i}_{2abc} \quad (2.6)$$

Thus the third term on the right side of (2.6) will be

$$P \dot{i}_{2abc} = \dot{i}_{20dq} - \dot{P} i_{2abc} = \dot{i}_{20dq} - \dot{P} P^{-1} i_{20dq} \quad (2.7)$$

Thus, (2.6) may be written as

$$v_{10dq} = v_{20dq} + R_1 i_{20dq} + L_1 \dot{i}_{20dq} - \omega L_1 \begin{bmatrix} 0 \\ -i_{1q} \\ i_{1d} \end{bmatrix} \quad (2.8)$$

By omitting the zero-sequence voltages and currents and rearranging the equations (2.5) and (2.8), the following equations could be obtained,

$$R_1 \dot{v}_{1d} = i_{1d} - i_{2d} - G_1 v_{1d} - \omega R_1 v_{1q} - j_{1d} \quad (2.9)$$

$$R_1 \dot{v}_{1q} = i_{1q} - i_{2q} - G_1 v_{1q} + \omega R_1 v_{1d} - j_{1q}$$

$$\dot{i}_{1d} = 1/L_1 (v_{1d} - v_{2d} - R_1 i_{2d} - \omega L_1 i_{1q}) \quad (2.10)$$

$$\dot{i}_{1q} = 1/L_1 (v_{1q} - v_{2q} - R_1 i_{2q} + \omega L_1 i_{1d})$$

The formulation of load currents j_{1d} and j_{1q} may be done as follows. Assuming the load LD1 on node 1 contains p_1 and q_1 as the active and reactive power, respectively, then the active power (p_1) can be expressed as

$$p_1 = 3v_1 j_1 \cos(\theta_{j1} - \theta_{v1})$$

$$p_1 = 3v_1 \sin\theta_{v1} j_1 \sin\theta_{j1} + 3v_1 \cos\theta_{v1} j_1 \cos\theta_{j1} \quad (2.11)$$

Using (1.15a) and (1.15b) in (2.11),

$$p_1 = v_{1d} j_{1d} + v_{1q} j_{1q} \quad (2.12)$$

and reactive power (q_1) may be expressed as,

$$\begin{aligned}
q_1 &= 3 v_1 j_1 \sin(\theta_{j1} - \theta_{v1}) \\
&= 3 v_1 \cos \theta_{v1} j_1 \sin \theta_{j1} \\
&\quad - 3 v_1 \sin \theta_{v1} j_1 \cos \theta_{j1}
\end{aligned} \tag{2.13}$$

By applying (1.15a) and (1.15b) in (2.13),

$$q_1 = v_{1q} j_{1d} - v_{1d} j_{1q} \tag{2.14}$$

Therefore from (2.12) and (2.14), the following load currents may be computed.

$$j_{1d} = (p_1 v_{1d} + q_1 v_{1q}) / (v_{1d}^2 + v_{1q}^2) \tag{2.15}$$

$$j_{1q} = (p_1 v_{1q} - q_1 v_{1d}) / (v_{1d}^2 + v_{1q}^2)$$

Equations (2.1) to (2.15) explain the fact that if any section of transmission line and load is considered, the Park's Transformation may also be applied. Therefore, if the same procedure is introduced to the rest of the transmission line and loads, then the following equations (in pu) may be obtained.

$$\begin{aligned}
B_2 \dot{v}_{2d} &= (i_{2d} - i_{3d} - G_2 v_{2d} - \omega B_2 v_{2q} - j_{2d}) \\
B_2 \dot{v}_{2q} &= (i_{2q} - i_{3q} - G_2 v_{2q} + \omega B_2 v_{2d} - j_{2q})
\end{aligned} \tag{2.16}$$

$$\begin{aligned}
\dot{i}_{3d} &= 1/L_2 (v_{2d} - v_{3d} - R_2 i_{3d} - \omega L_2 i_{2q}) \\
\dot{i}_{3q} &= 1/L_2 (v_{2q} - v_{3q} - R_2 i_{3q} + \omega L_2 i_{2d})
\end{aligned} \tag{2.17}$$

where,

$$j_{2d} = (P_2 v_{2d} + q_2 v_{2q}) / (v_{2d}^2 + v_{2q}^2)$$

(2.18)

and

$$j_{2q} = (P_2 v_{2q} - q_2 v_{2d}) / (v_{2d}^2 + v_{2q}^2)$$

$$B_3 \dot{v}_{3d} = (i_{3d} - i_{4d} - G_3 v_{3d} - \omega B_3 v_{3q} - j_{3d})$$

(2.19)

$$B_3 \dot{v}_{3q} = (i_{3q} - i_{4q} - G_3 v_{3q} + \omega B_3 v_{3d} - j_{3q})$$

$$i_{4d} = 1/L_3 (v_{3d} - v_{4d} - E_3 i_{4d} - \omega L_3 i_{3q})$$

(2.20)

$$i_{4q} = 1/L_3 (v_{3q} - v_{4q} - E_3 i_{4q} + \omega L_3 i_{3d})$$

where,

$$j_{3d} = (P_3 v_{3d} + q_3 v_{3q}) / (v_{3d}^2 + v_{3q}^2)$$

(2.21)

and,

$$j_{3q} = (P_3 v_{3q} - q_3 v_{3d}) / (v_{3d}^2 + v_{3q}^2)$$

$$B_4 \dot{v}_{4d} = (i_{4d} - i_{5d} - G_4 v_{4d} - \omega B_4 v_{4q} - j_{4d})$$

(2.22)

$$B_4 \dot{v}_{4q} = (i_{4q} - i_{5q} - G_4 v_{4q} + \omega B_4 v_{4d} - j_{4q})$$

where,

$$j_{4d} = (P_4 v_{4d} + q_4 v_{4q}) / (v_{4d}^2 + v_{4q}^2)$$

(2.23)

and,

$$j_{4q} = (P_4 v_{4q} - q_4 v_{4d}) / (v_{4d}^2 + v_{4q}^2)$$

Considering the system of Figure 2.1, the voltage of the infinite bus being $v_{\infty abc}$ which is a set of three phase balanced voltages and α is bus(infinite) voltage angle.

$$v_{\infty abc} = \sqrt{2} v_{\infty} \begin{bmatrix} \cos (\omega_R t + \alpha) \\ \cos (\omega_R t + \alpha - 120^\circ) \\ \cos (\omega_R t + \alpha + 120^\circ) \end{bmatrix} \quad (2.24)$$

By definition $v_{10dq} = P v_{abc}$, and hence, by applying Park's Transformation into (2.24),

$$v_{10dq} = \sqrt{3} v_{\infty} \begin{bmatrix} 0 \\ -\sin (\delta - \alpha) \\ \cos (\delta - \alpha) \end{bmatrix} \quad (2.25)$$

Neglecting the zero-sequence voltage and formulating the voltage similarly, the following expressions may be obtained for the last section of the transmission line.

$$\dot{i}_{5d} = 1/L_4 (v_{4d} + \sqrt{3} v_{\infty} \sin (\delta - \alpha) - R_4 i_{5d} - \omega L_4 i_{4q}) \quad (2.26)$$

$$\dot{i}_{5q} = 1/L_4 (v_{4q} - \sqrt{3} v_{\infty} \cos (\delta - \alpha) - R_4 i_{5q} - \omega L_4 i_{4d})$$

AS it is seen above that the transmission line and loads being represented by a dynamic model, it may be noted that in a similar way a dynamic model may be formulated in expressing any interconnected networks consisting of any number of branches. However, the number of variables in such a case will increase enormously.

Chapter III
COMPLETE SYSTEM MODEL

3.1 INTRODUCTION

In the preceding chapters, the model of the generators and the transmission lines with loads have been discussed separately. In this chapter a complete mathematical model is presented for the entire system by coupling transmission line and load equations with the generator model. Meanwhile, the control of the system will also be discussed here.

3.2 SYSTEM MODEL

As the objective is to regulate and maintain the voltages within the admissible limits, the capacitors have been chosen as the required control variables in the system.

But since the model for generator and transmission line with loads is developed, it is important to notice that if the system parameters are constant, then safely the models could be coupled. [As mentioned in equations (2.1) and (2.2)]. But since under the assumption of capacitors as control variables which will be varying with time, there is a need to modify the equations of the system model. Considering the capacitors as time-varying quantities, the equations (2.1) and (2.2) will be read as,

$$i_{lab\bar{c}} = i_{2abc} + G_1 v_{lab\bar{c}} + \frac{d}{dt} (B_1 v_{lab\bar{c}}) + j_{lab\bar{c}} \quad (3.1)$$

$$(1/B_1) Q_{lab\bar{c}} = (1/B_2) Q_{2abc} + R_1 i_{2abc} + L_1 \dot{i}_{2abc} \quad (3.2)$$

It is clear from (3.1) that if the time-varying capacitors are incorporated in the system, then one suitable way of handling the term $\frac{d}{dt} (B_1 v_{lab\bar{c}})$ is to express $B_1 v_{lab\bar{c}}$ as $\dot{Q}_{lab\bar{c}}$ which is the charge stored in the capacitor B_1 . Thus a new state variable $Q_{lab\bar{c}}$ may be defined and (3.1) & (3.2) can be expressed in terms of new state variable as follows.

$$i_{lab\bar{c}} = i_{2abc} + (G_1/B_1) Q_{lab\bar{c}} + \frac{d}{dt} (Q_{lab\bar{c}}) + j_{lab\bar{c}} \quad (3.1a)$$

$$1/B_1 Q_{lab\bar{c}} = 1/B_2 Q_{2abc} + R_1 i_{2abc} + L_1 \dot{i}_{2abc} \quad (3.2b)$$

Hence, by applying Park's Transformation in (3.1a) and (3.2b) and neglecting the zero-sequence charges and currents, the following expressions can be written as,

$$\dot{Q}_{1d} = (i_{1d} - i_{2d} - (G_1/B_1) Q_{1d} - \omega Q_{1q} - j_{1d}) \quad (3.3)$$

$$\dot{Q}_{1q} = (i_{1q} - i_{2q} - (G_1/B_1) Q_{1q} + \omega Q_{1d} - j_{1q})$$

$$i_{2d} = 1/L_1 ((Q_{1d}/B_1) - (Q_{2d}/B_2) - R_1 i_{2d} - \omega L_1 i_{1q}) \quad (3.4)$$

$$i_{2q} = 1/L_1 ((Q_{1q}/B_1) - (Q_{2q}/B_2) - R_1 i_{2q} + \omega L_1 i_{1d})$$

From above equations it is evident that some changes are required in the generator equations, too. So, when the principles of (3.3) and (3.4) are applied in the models of generator and transmission line with loads and by referring to Appendix 2 [where the inversion of matrix of (1.39) is developed], the complete system model of generator coupled with transmission lines and loads may be written as follows,

$$\begin{aligned} \dot{i}_{ld} = & A(11) i_{ld} + A(12) i_{fd} + A(13) i_D + A(14) \omega i_{lq} + A(15) \omega i_Q \\ & + (A(16)/B_1) Q_{ld} + A(17) E_{fd} \end{aligned} \quad (3.5)$$

$$\begin{aligned} \dot{i}_{fd} = & A(21) i_{ld} + A(22) i_{fd} + A(23) i_D + A(24) \omega i_{lq} + \\ & A(25) \omega i_Q + (A(26)/B_1) Q_{ld} + A(27) E_{fd} \end{aligned} \quad (3.6)$$

$$\begin{aligned} \dot{i}_D = & A(31) i_{ld} + A(32) i_{fd} + A(33) i_D + A(34) \omega i_{lq} + A(35) \\ & \omega i_Q + (A(36)/B_1) Q_{ld} + A(37) E_{fd} \end{aligned} \quad (3.7)$$

$$\begin{aligned} \dot{i}_{lq} = & A(41) \omega i_{ld} + A(42) \omega i_{fd} + A(43) \omega i_D + A(44) i_{lq} \\ & + A(45) i_Q + (A(46)/B_1) Q_{lq} \end{aligned} \quad (3.8)$$

$$\begin{aligned} \dot{i}_Q = & A(51) \omega i_{ld} + A(52) \omega i_{fd} + A(53) \omega i_D + A(54) i_{lq} \\ & + A(55) i_Q + (A(56)/B_1) Q_{lq} \end{aligned} \quad (3.9)$$

$$\begin{aligned} \dot{\omega} = & (A(61) + A(64)) i_{1q} i_{1d} + A(62) i_{1q} i_{fd} + A(63) i_{1q} i_{1d} \\ & + A(65) i_{1d} i_Q - 3.0 * D (\omega - 1) + T_m) / (3.0 * T_j) \end{aligned} \quad (3.10)$$

$$\delta = \omega - 1 \quad (3.11)$$

$$\dot{Q}_{1d} = i_{1d} - (G_1/B_1) Q_{1d} - \omega Q_{1q} - i_{2d} - j_{1d} \quad (3.12)$$

$$\dot{Q}_{1q} = i_{1q} - (G_1/B_1) Q_{1q} + \omega Q_{1d} - i_{2q} - j_{1q}$$

$$i_{2d} = 1/L_1 ((Q_{1d}/B_1) - R_{12d} i_{2d} - L_1 \omega i_{2q} - (Q_{2d}/B_2)) \quad (3.13)$$

$$i_{2q} = 1/L_1 ((Q_{1q}/B_1) - R_{12q} i_{2q} + L_1 \omega i_{2d} - (Q_{2q}/B_2))$$

$$\dot{Q}_{2d} = i_{2d} - (G_2/B_2) Q_{2d} - \omega Q_{2q} - i_{3d} - j_{2d} \quad (3.14)$$

$$\dot{Q}_{2q} = i_{2q} - (G_2/B_2) Q_{2q} + \omega Q_{2d} - i_{3q} - j_{2q}$$

$$i_{3d} = 1/L_2 ((Q_{2d}/B_2) - R_{23d} i_{3d} - L_2 \omega i_{3q} - (Q_{3d}/B_3)) \quad (3.15)$$

$$i_{3q} = 1/L_2 ((Q_{2q}/B_2) - R_{23q} i_{3q} + L_2 \omega i_{3d} - (Q_{3q}/B_3))$$

$$\dot{Q}_{3d} = i_{3d} - (G_3/B_3) Q_{3d} - \omega Q_{3q} - i_{4d} - j_{3d} \quad (3.16)$$

$$\dot{Q}_{3q} = i_{3q} - (G_3/B_3) Q_{3q} + \omega Q_{3d} - i_{4q} - j_{3d}$$

$$\dot{i}_{4d} = 1/L_3 ((Q_{3d}/B_3) - R_3 i_{4d} - L_3 \omega i_{4q} - (Q_{4d}/R_4)) \quad (3.17)$$

$$\dot{i}_{4q} = 1/L_3 ((Q_{3q}/B_3) - R_3 i_{4q} + L_3 \omega i_{4d} - (Q_{4q}/R_4))$$

$$\dot{Q}_{4d} = i_{4d} - (G_4/B_4) Q_{4d} - \omega Q_{4q} - i_{5d} - j_{4d} \quad (3.18)$$

$$\dot{Q}_{4q} = i_{4q} - (G_4/B_4) Q_{4q} + \omega Q_{4d} - i_{5q} - j_{4q}$$

$$\dot{i}_{5d} = 1/L_4 ((Q_{4d}/B_4) - F_4 i_{5d} - L_4 \omega i_{5q} + \sqrt{3} V_\infty \sin(\delta - \alpha)) \quad (3.19)$$

$$\dot{i}_{5q} = 1/L_4 ((Q_{4q}/B_4) - F_4 i_{5q} + L_4 \omega i_{5d} - \sqrt{3} V \cos(\delta - \alpha))$$

$$V_i = \sqrt{((Q_{id}^2 - Q_{iq}^2) / B_i^2)}$$

$$I_i = \sqrt{(i_{id}^2 - i_{iq}^2)} \quad (3.20)$$

$$J_i = \sqrt{(j_{id}^2 - j_{iq}^2)}$$

where,

$$i = 1, 2, 3, 4$$

3.3 STATE-SPACE MODEL OF THE SYSTEM

Using the equations (3.5) to (3.20), one can express the system dynamics in state-space form

$$\dot{X} = f(X, B, p, q, T_m, t) \quad (3.21)$$

where,

(i) X is the state vector given by

$$X = [i_{1d}, i_{1q}, i_{fd}, i_{D}, \dots, i_{2d}, \dots, i_{5d},$$

$$i_{2q}, \dots, i_{5q}, Q_{1d}, \dots, Q_{4d}, Q_{1q}, \dots, Q_{4q}]'$$

(ii) B is the control vector given by

$$B = [B_1, B_2, B_3, B_4]'$$

(iii) p is the vector of active loads at

nodes 1, 2, 3, 4 given by

$$p = [P_1, P_2, P_3, P_4]'$$

(iv) q is the vector of reactive loads

at nodes 1, 2, 3, 4 given by

$$q = [q_1, q_2, q_3, q_4]'$$

(v) T_m = mechanical input

(vi) t = time

The system (3.21) completely describes the system under study. The steady-state and transient behavior of the system can be obtained easily after solving it under appropriate initial conditions. Also by applying proper control B the system can be controlled for desired conditions.

Chapter IV

FEEDBACK CONTROL MODEL AND NUMERICAL SIMULATION

4.1 INTRODUCTION

In this chapter the system behavior is analyzed by simulation on digital computer under steady-state as well as under dynamic conditions. The dynamic conditions are created by variation of loads at the nodes. To regulate the voltages a feedback control is designed and explained in the following section.

4.2 STEADY-STATE LOAD FLOW TECHNIQUE

In order to simulate the dynamic system $\dot{X}=f(X, B, p, q, T_m, t)$, one has to know the initial conditions under steady-state by implementing a proper method of load-flow solution. There are several methods of load-flow studies [10] in existence, for example, Gauss-Seidel method, Newton-Raphson method and Minimisation method. In this thesis the Newton-Raphson method has been used to obtain the initial conditions. Briefly it may be mentioned here that under steady-state operations, the damper currents (i_D and i_Q) are zero and the angular velocity is unity.

Thus, from (3.4) to (3.18) mathematically at steady-state, the derivatives $\dot{X}=0$.

Hence, there will be nineteen non-linear algebraic equations in the system and are solved numerically on digital computer.

4.3 DYNAMIC STUDY OF THE SYSTEM

Once the initial conditions of the system are obtained with the help of load-flow studies, one can proceed to analyze the dynamic behavior of the system. One of the objectives of this thesis is to observe the effect of variation of loads which causes voltage drops across the nodes. The other objective is to present a feedback control scheme that will regulate the system voltages.

4.4 FEEDBACK CONTROL MODEL

Two kinds of controls are considered in this study.

- (i) Continuous variation of capacitor (synchronous)
- (ii) Step variation of capacitor (static)

In the former case, synchronous capacitor can be used to vary the capacitance, while in the latter case, step variation of capacitor can be realized by switching static capacitors.

Suppose the number of nodes in the system is n . In order to incorporate a continuous control model, the capacitor B at the node (s) is taken as a function of the integral of voltage deviation at all nodes. If the desired voltage at node (i) is V_{iD} and the actual voltage is V_{iA} , then the

feedback control (capacitor) at node 's' can be expressed as a function of the integral of voltage deviations at all the nodes in the following form

$$B_s(t) = B_s(t_0) + \sum_{i=1}^n K_{si} \int_{t_0}^t (V_{iD} - V_{iA}) dt \quad (4.1)$$

where

$B_s(t_0)$ = initial value of capacitor at node s,
and K_{si} (s, i = 1, 2, 3, n) = the required gains.

For a discrete control model (in the latter case), suppose the period of operation is given by the time interval $(t_0, T]$ and assume that for the purpose of regulation, this interval is partitioned into 'M' sub-intervals $(t_{m-1}, t_m]$, $m=1, 2, \dots, M$. At the end points t_1, t_2, \dots, t_{M-1} of each subinterval capacitors are switched to new values depending on the node voltages. The value of the capacitor at the node 's' at time t_m+0 is given by

$$B_s(t_m+0) = B_s(t_{m-1}+0) + \sum_{i=1}^n K_{si} \int_{t_{m-1}}^{t_m} (V_{iD}(t) - V_{iA}(t)) dt \quad (4.2)$$

where, as in the previous case, K_{si} is the weight given to the voltage deviation at the i^{th} node.

4.5 NUMERICAL SIMULATION

Simulation is done on University of Ottawa's digital computer AMDAHL 470/V78 by using Funge Kutta integration subroutine. In this simulation study it is considered that one generating source is connected to an infinite bus

through a transmission line having four nodes ($n=4$). Three separate cases are considered and these are described below.

Case I

- (i) The load (p_2 and q_2) are changed at node 2 only. At all the other nodes the loads are maintained at steady-values.
- (ii) Control is placed at node 2 only.

Case II

- (i) In this case, the loads (p_2, q_2 and p_3 and q_3) are changed at node 2 and node 3. The loads of node 1 and node 4 are maintained constant.
- (ii) Control is placed at node 2 only.

Case III

- (i) The loads (p_2, q_2 and p_3, q_3) at node 2 and node 3 are intensified compared to that of Case II.
- (ii) Control is placed at node 2 only.

In Case I and Case II, both the synchronous capacitor control and the static capacitor control are used. In Case III, only the synchronous capacitor control is applied.

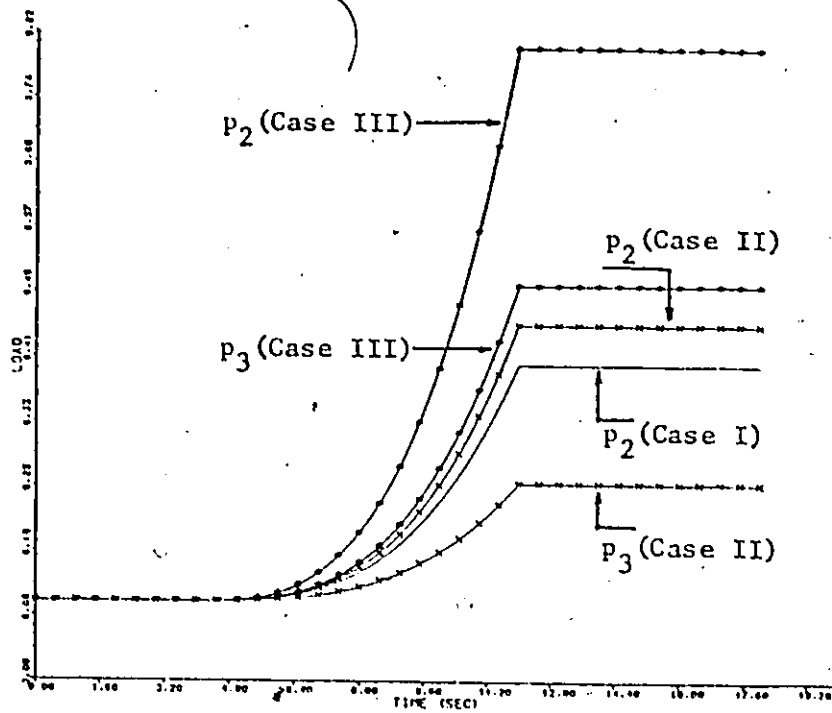


Fig. 4.1(a) - Variation of Active Loads

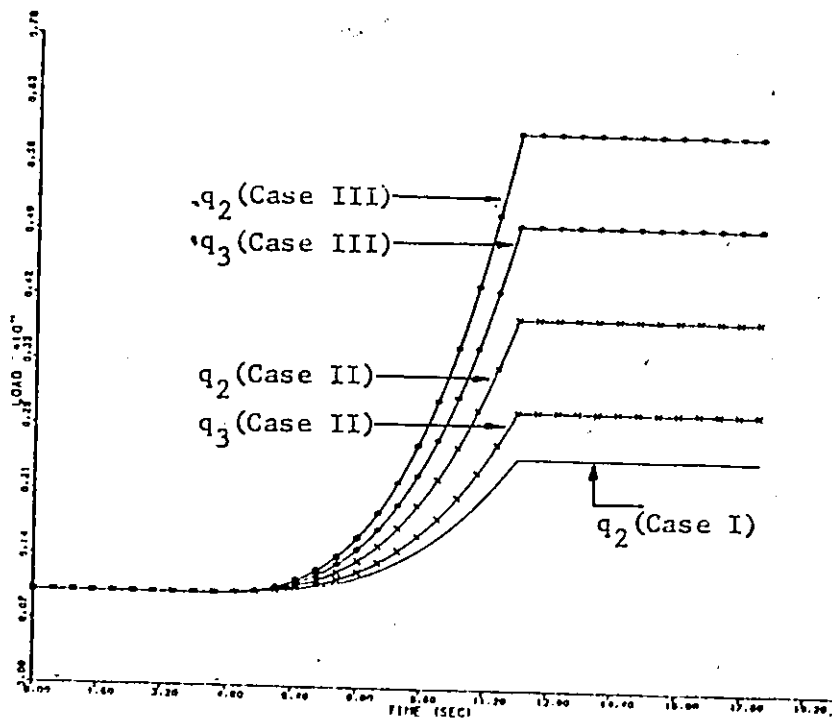


Fig. 4.1(b) - Variation of Reactive Loads

4.5.1 Case IA

Continuous Variation of Capacitor (Synchronous)

For the sake of simplicity, the control (B_2) at node 2 is assumed to be given by

$$B_2(t) = B_2(t_0) + K_{22} \int_{t_0}^t (V_{2D} - V_{2A}) dt \quad (4.3)$$

In other words the gains $K_{2i}, i=1,3,4$ are taken to be zero. The voltage regulation at node 2 for different values of the gain K_{22} is shown in Figure 4.2. The results show that the best value for K_{22} is $K_{22}^* = 0.002$. The voltage regulation at all the nodes corresponding to the gain K_{22}^* is shown in Figure 4IA(a)- Figure 4IA(d). The control profile B_2 is shown in Figure 4IA(e). These results indicate that even though the control is applied only at node 2 where the load (p_2 and q_2) had changed from steady-state values the regulation at other nodes are satisfactory.

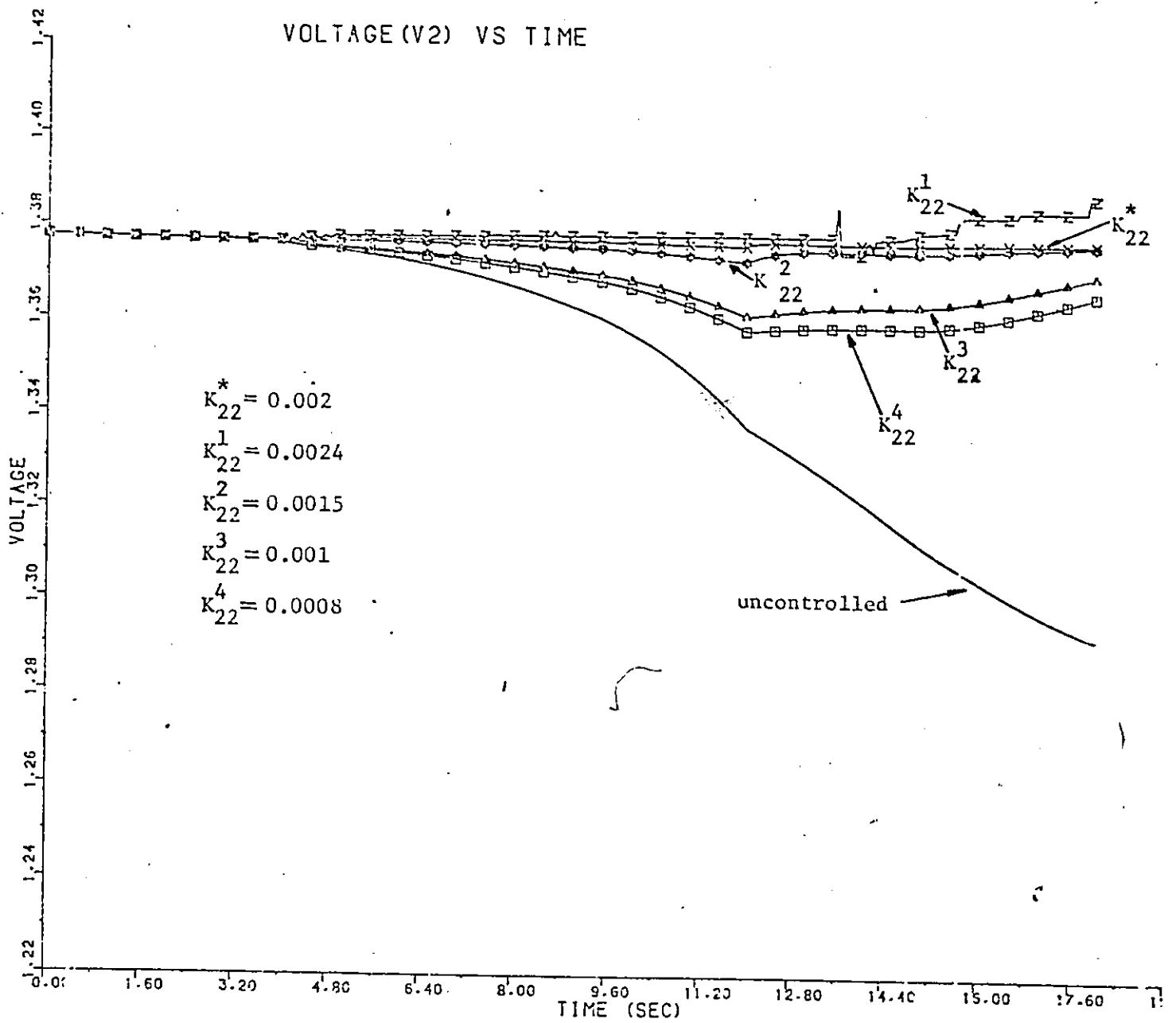


Fig. 4.2 : Regulation of Voltage (V_2) with different gains (K_{22})

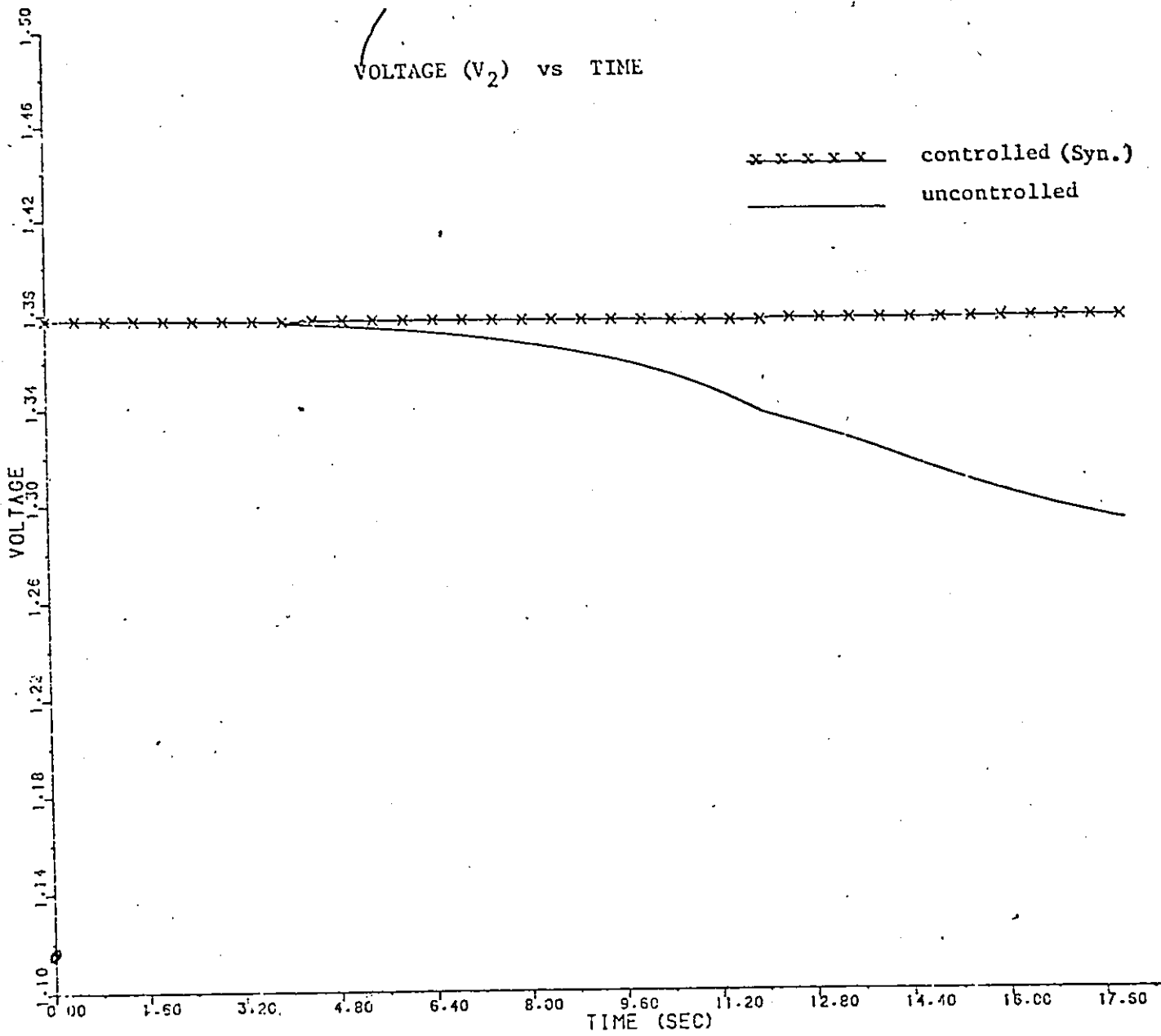


Fig. 4IA(a): Voltage (V_2) Profile - Case IA

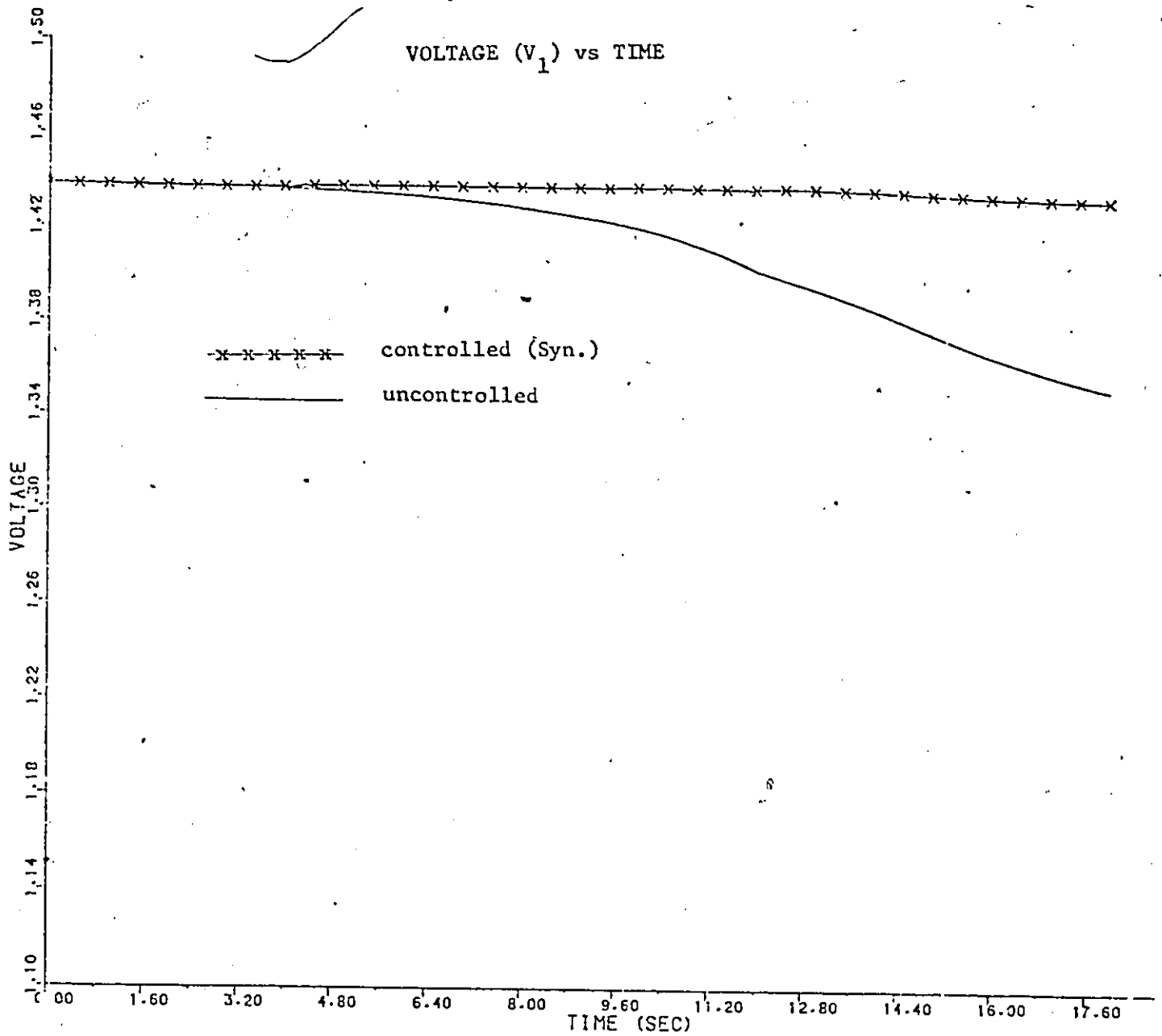


Fig. 4IA(b) : Voltage Profile (V_1) - Case IA

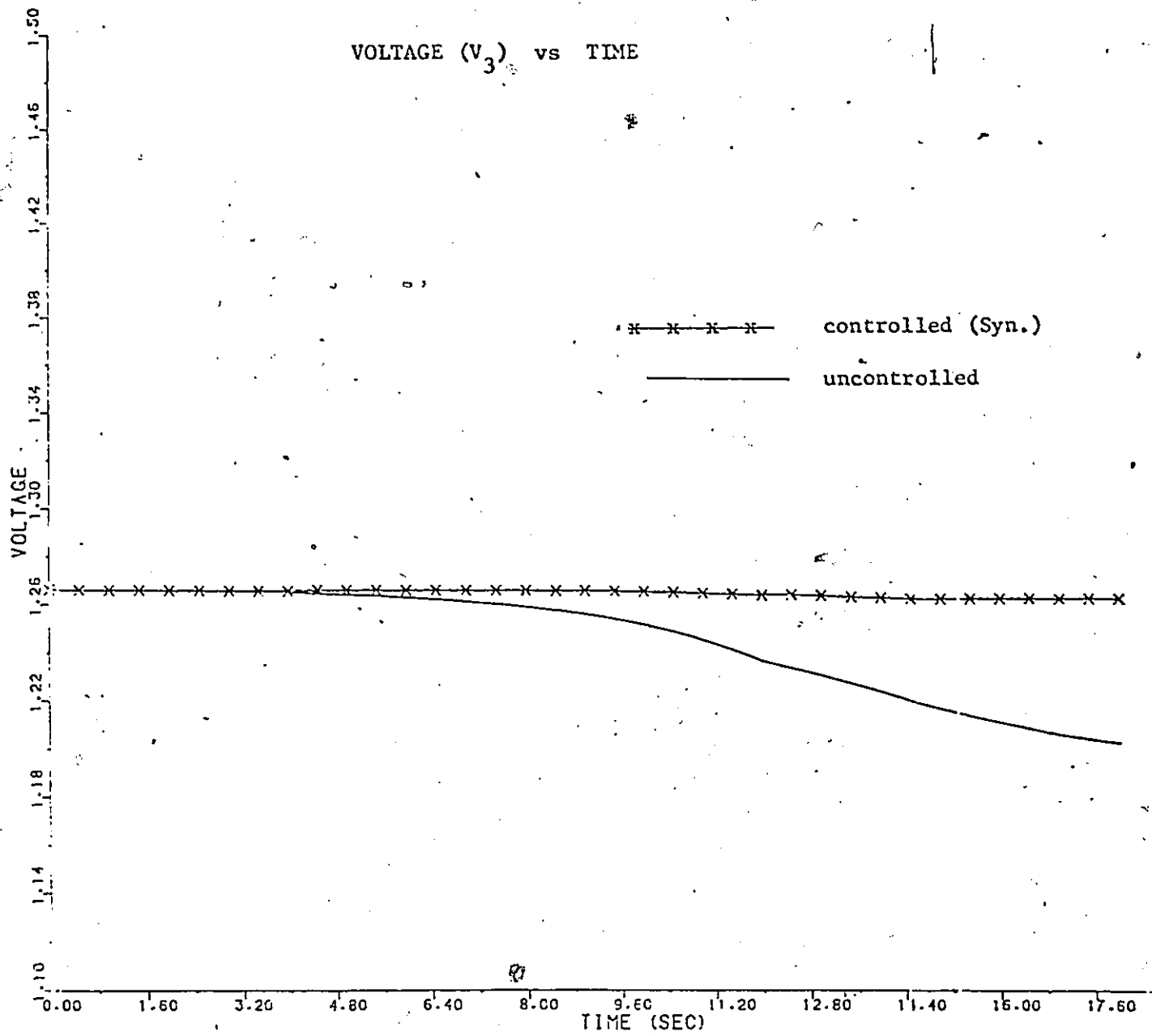


Fig. 4IA(c) : Voltage (V_3) Profile - Case IA

VOLTAGE (V_4) vs TIME

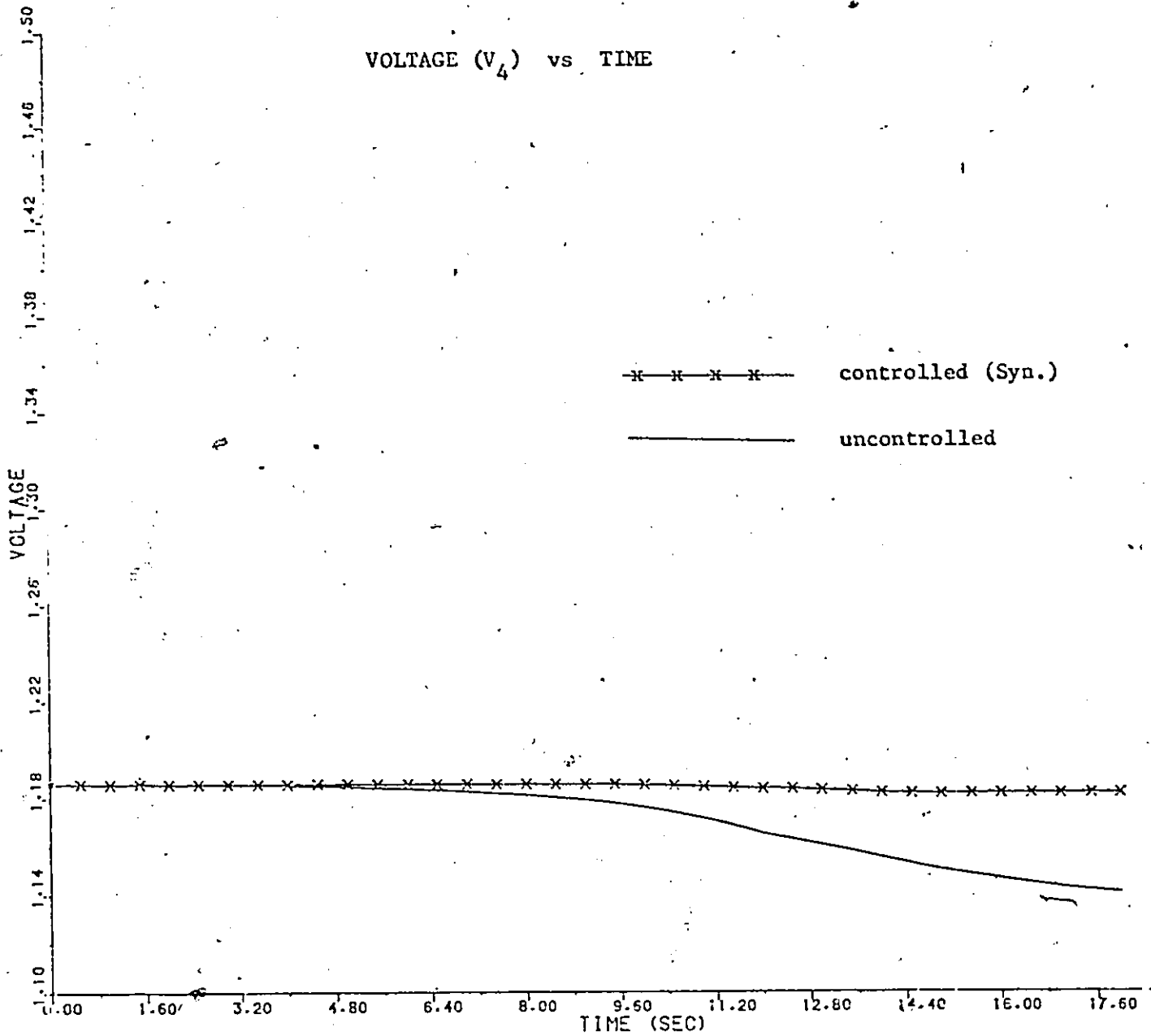


Fig. 4IA(d) : Voltage (V_4) Profile - Case IA

CONTROL (B₂) VS TIME

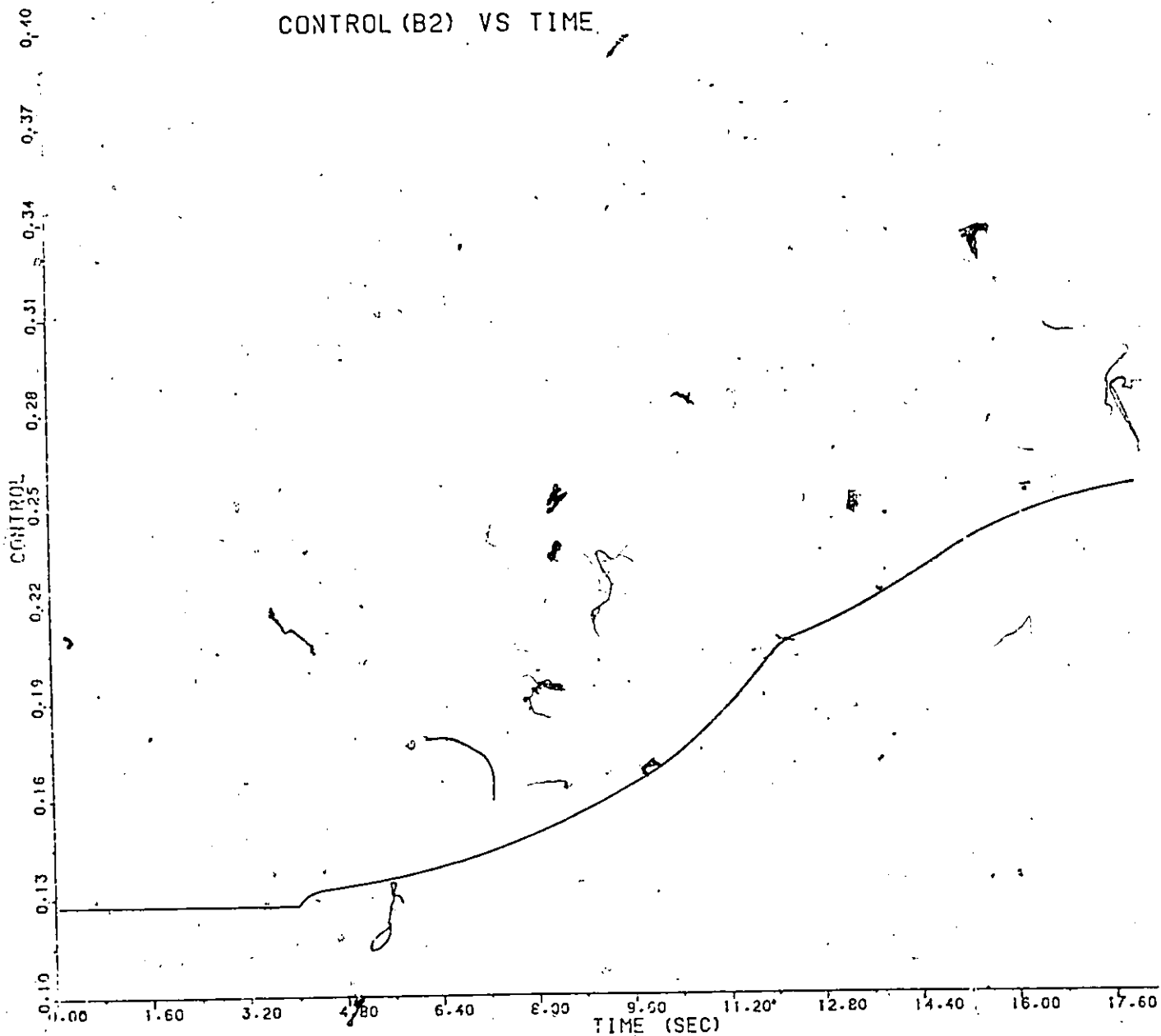


Fig. 4IA(e) : Control (Syn.) Profile (B₂) - Case IA

4.5.2 Case IB

Step Variation of Capacitor (Static)

In this case, the control B_2 at node 2 is taken as

$$B_2(t_m+0) = B_2(t_{m-1}+0) + K_{22} \int_{t_{m-1}}^{t_m} (V_{2D} - V_{2A}) dt \quad (4.4)$$

assuming again that $K_{2i} = 0, i=1,3,4$.

The corresponding voltage regulations are shown in Figures 4IB(a)-4IB(d). The control profile (B_2) is shown in Figure 4IB(e).

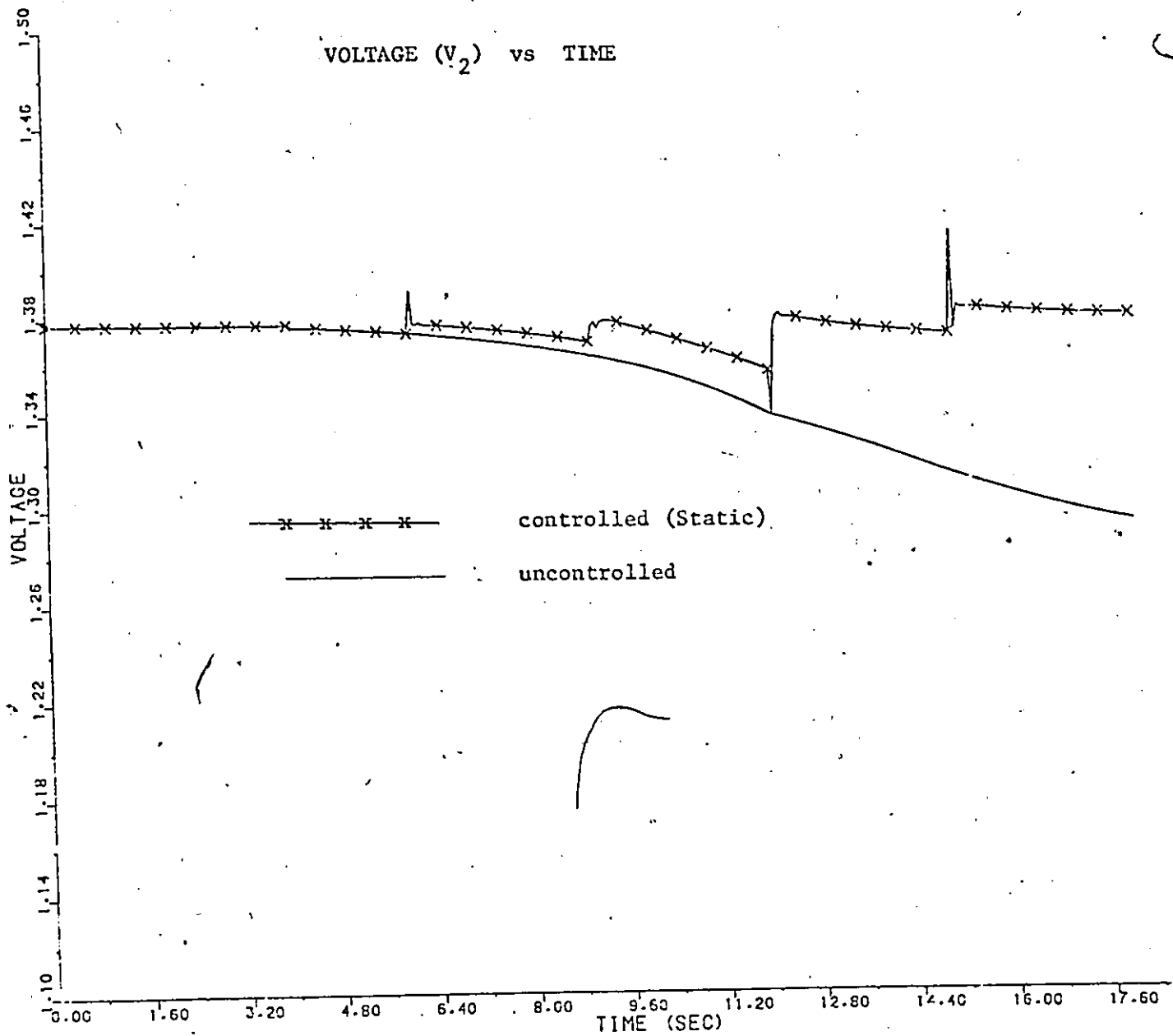


Fig. 4IB(a): Voltage (V_2) Profile - Case IB

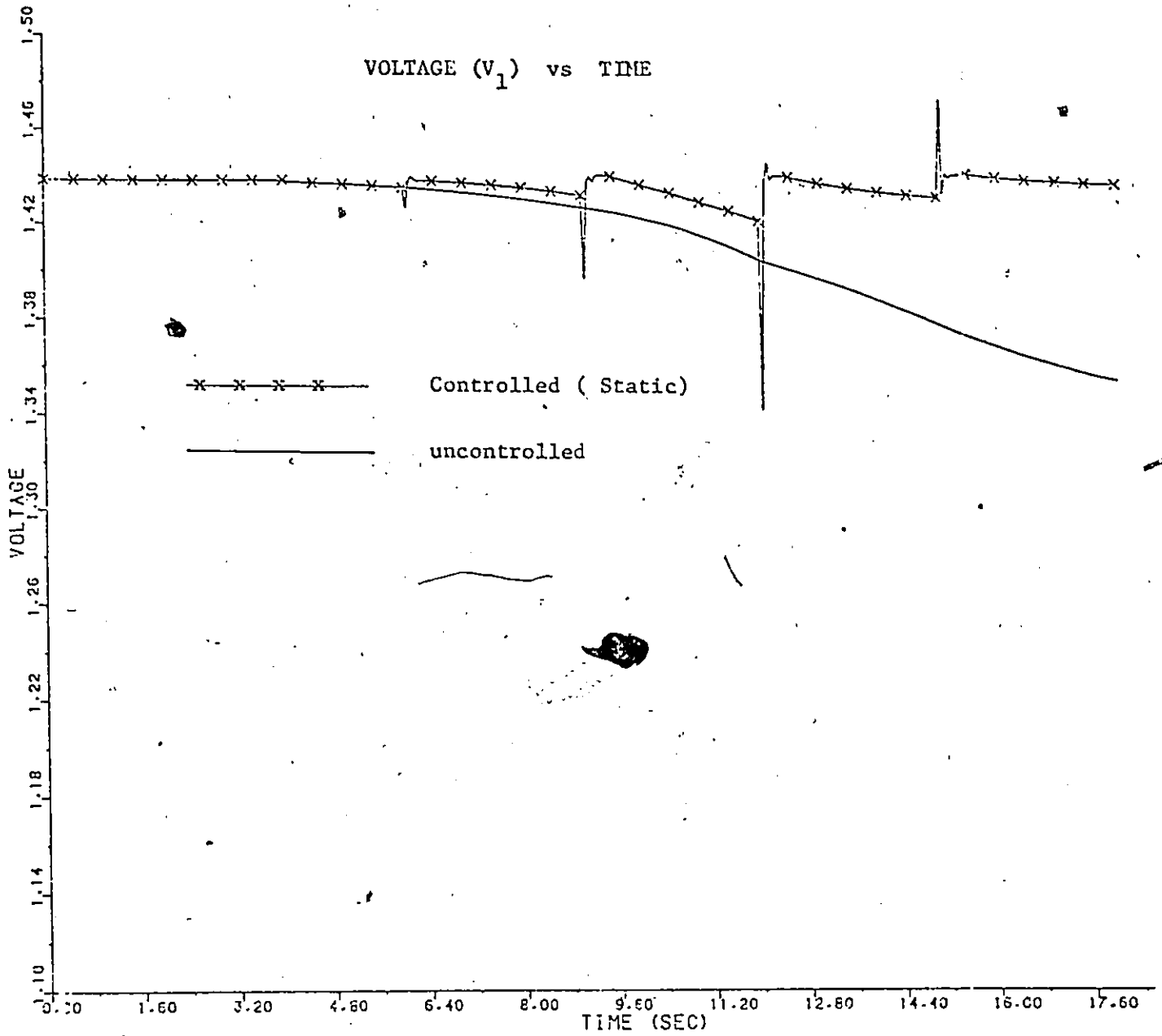


Fig. 4IB(b) : Voltage (V_1) Profile - Case IB

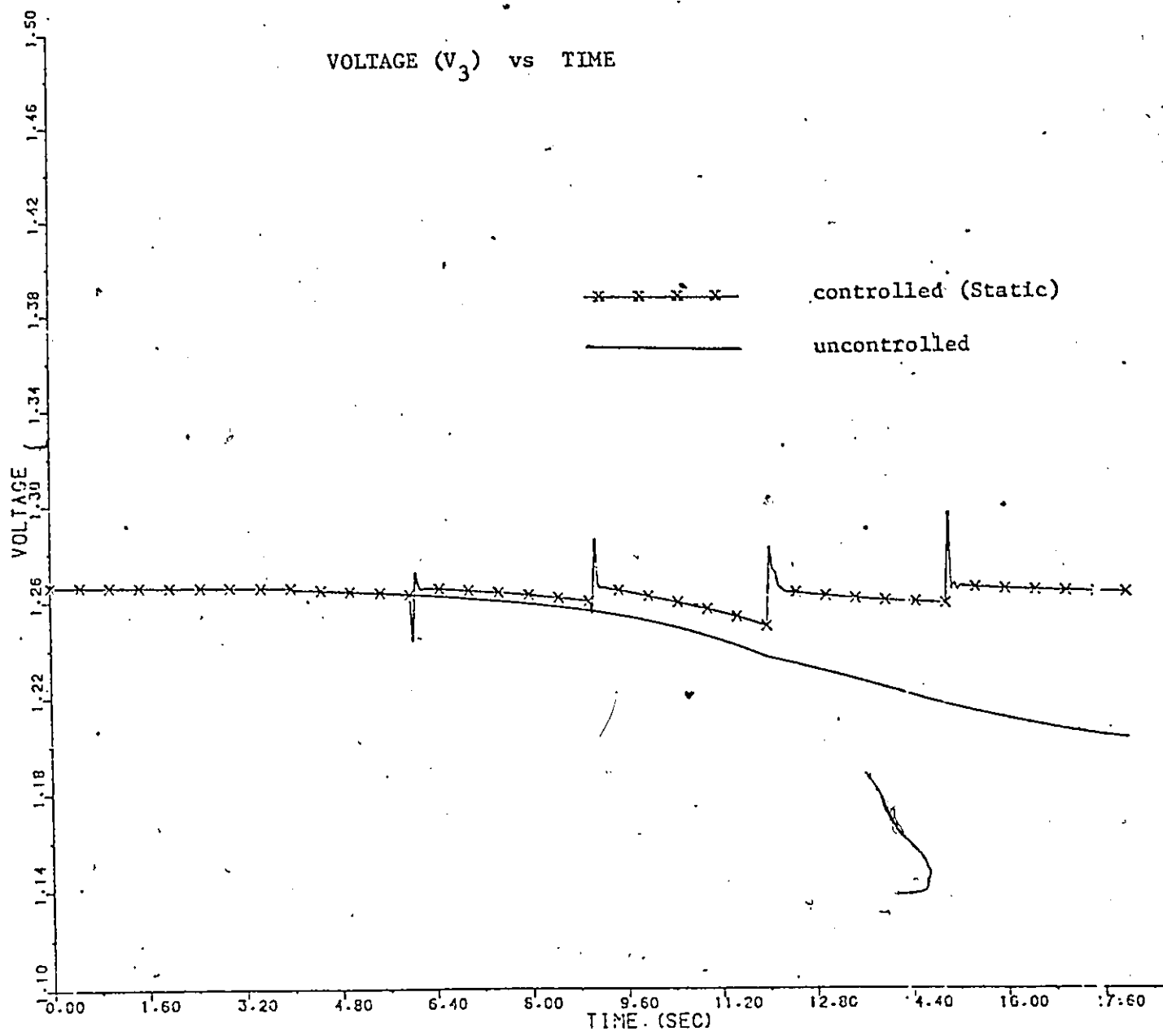


Fig. 4IB(c) : Voltage (V_3) Profile - Case IB

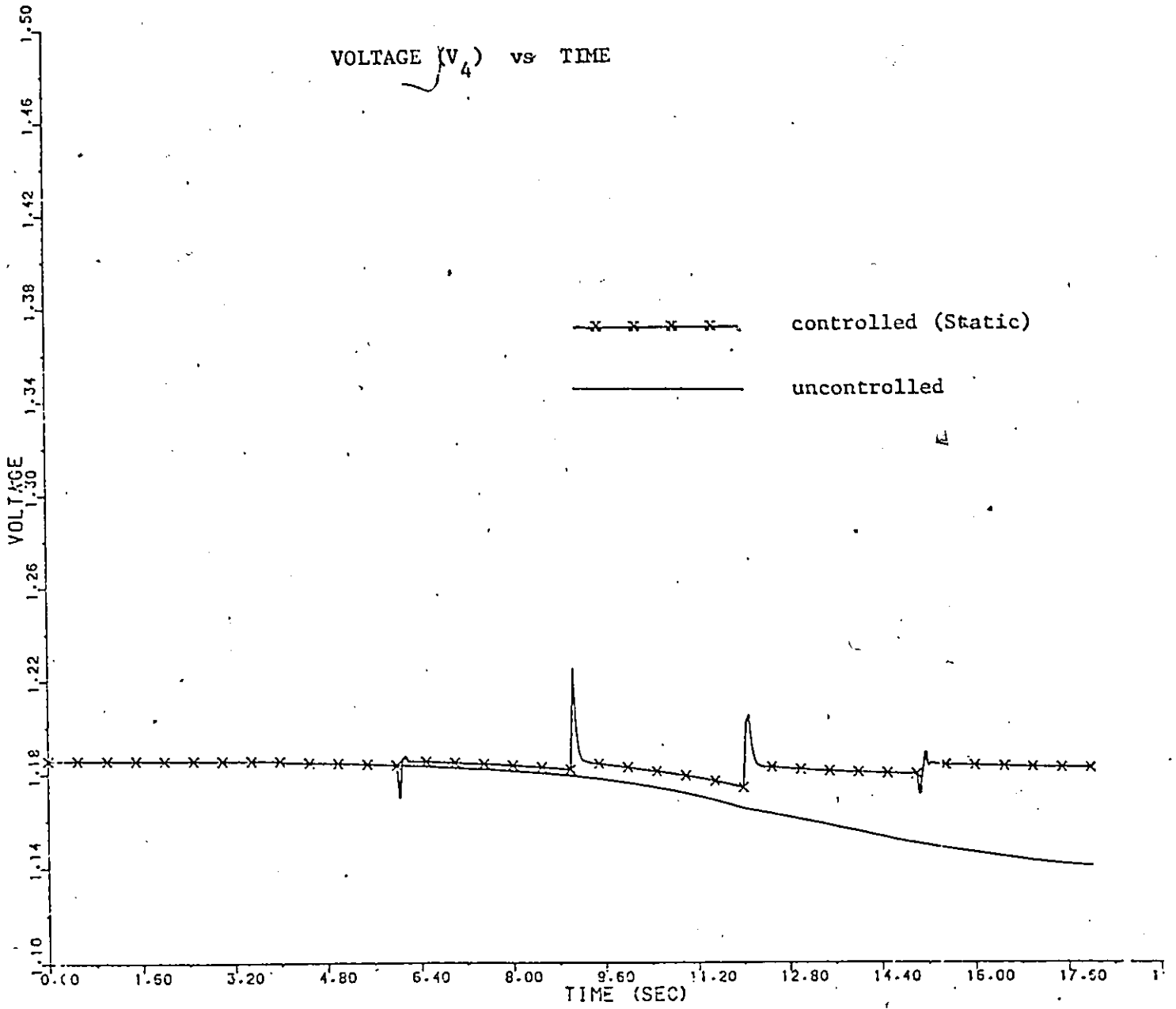


Fig. 4IB(d) : Voltage (V_4) Profile - Case IB

CONTROL (B_2) vs TIME

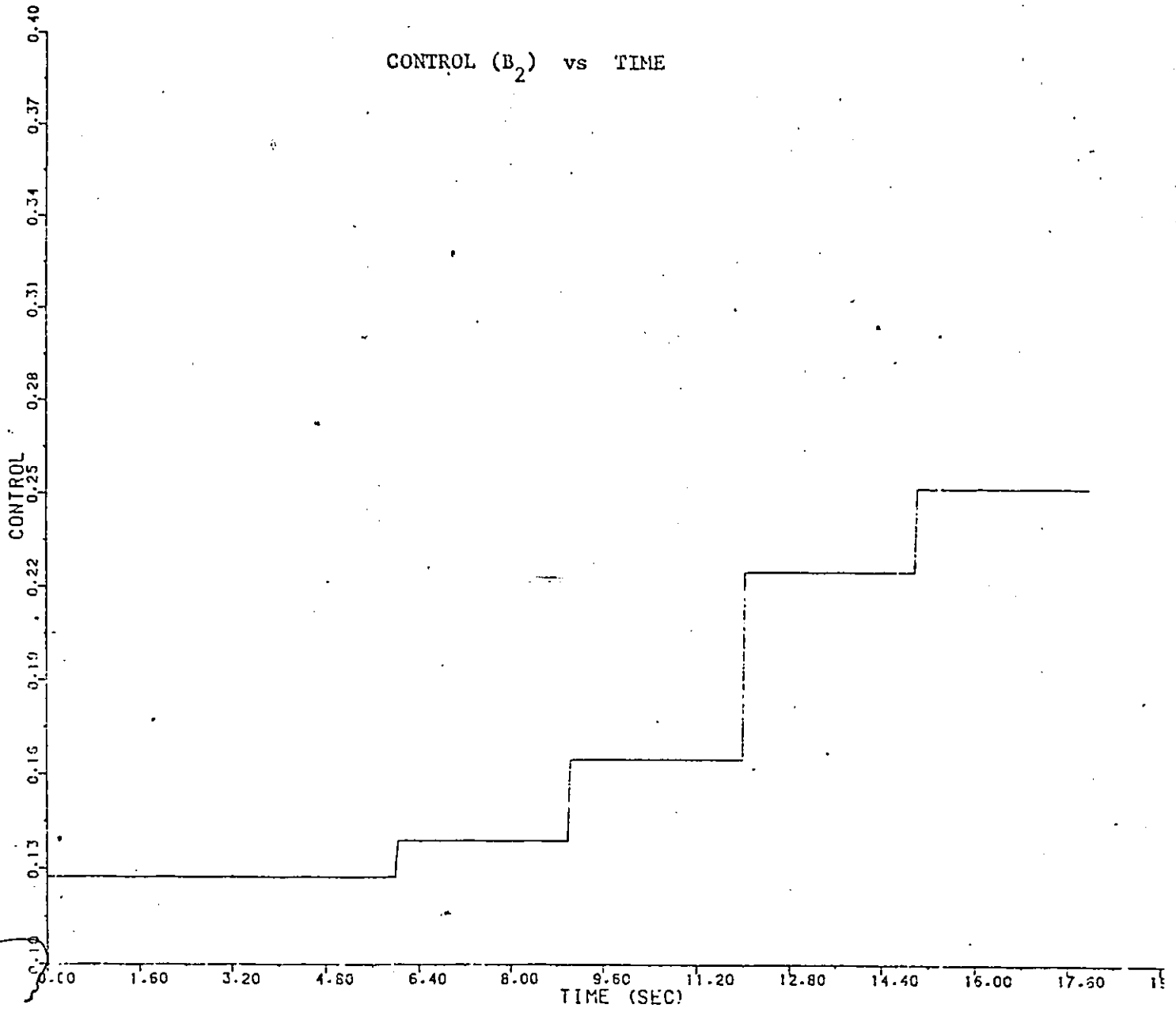


Fig. 4IB(e) : Control (Static) Profile (B_2) - Case IB

4.5.3 Case IIA

Continuous Variation of Capacitor (Synchronous)

In this case, as indicated earlier, the loads are changed at two nodes (node 2 and node 3). Once again, the control law given by (4.3) is applied at node 2 and the voltage regulations are shown in Figures 4IIA(a)-4IIA(d). Identical regulations are obtained as observed in Case IA, even though there are two loads at node 2 and node 3. The control profile is shown in Figure 4IIA(e).

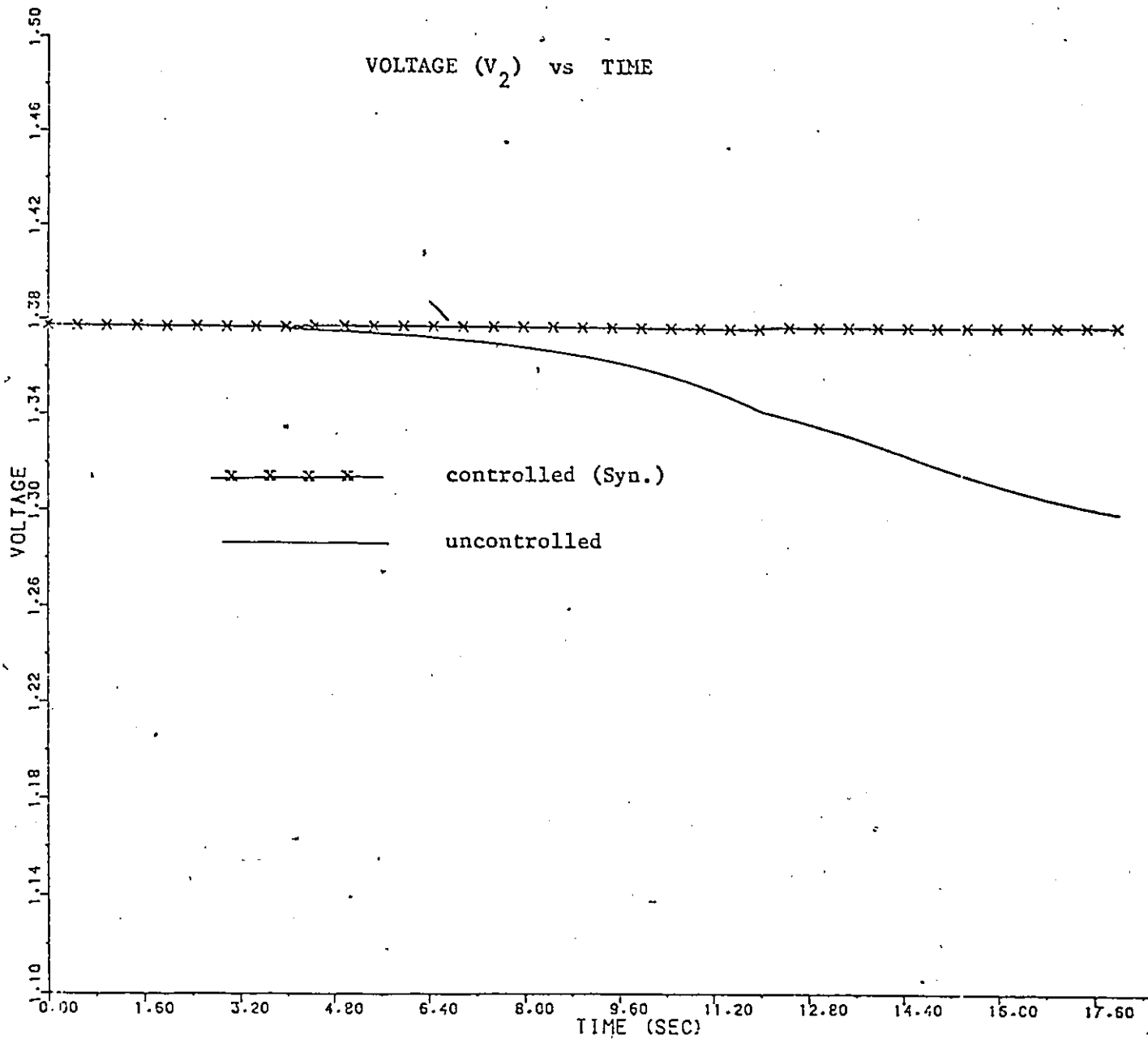


Fig. 4IIA(a) : Voltage (V_2) Profile - Case IIA

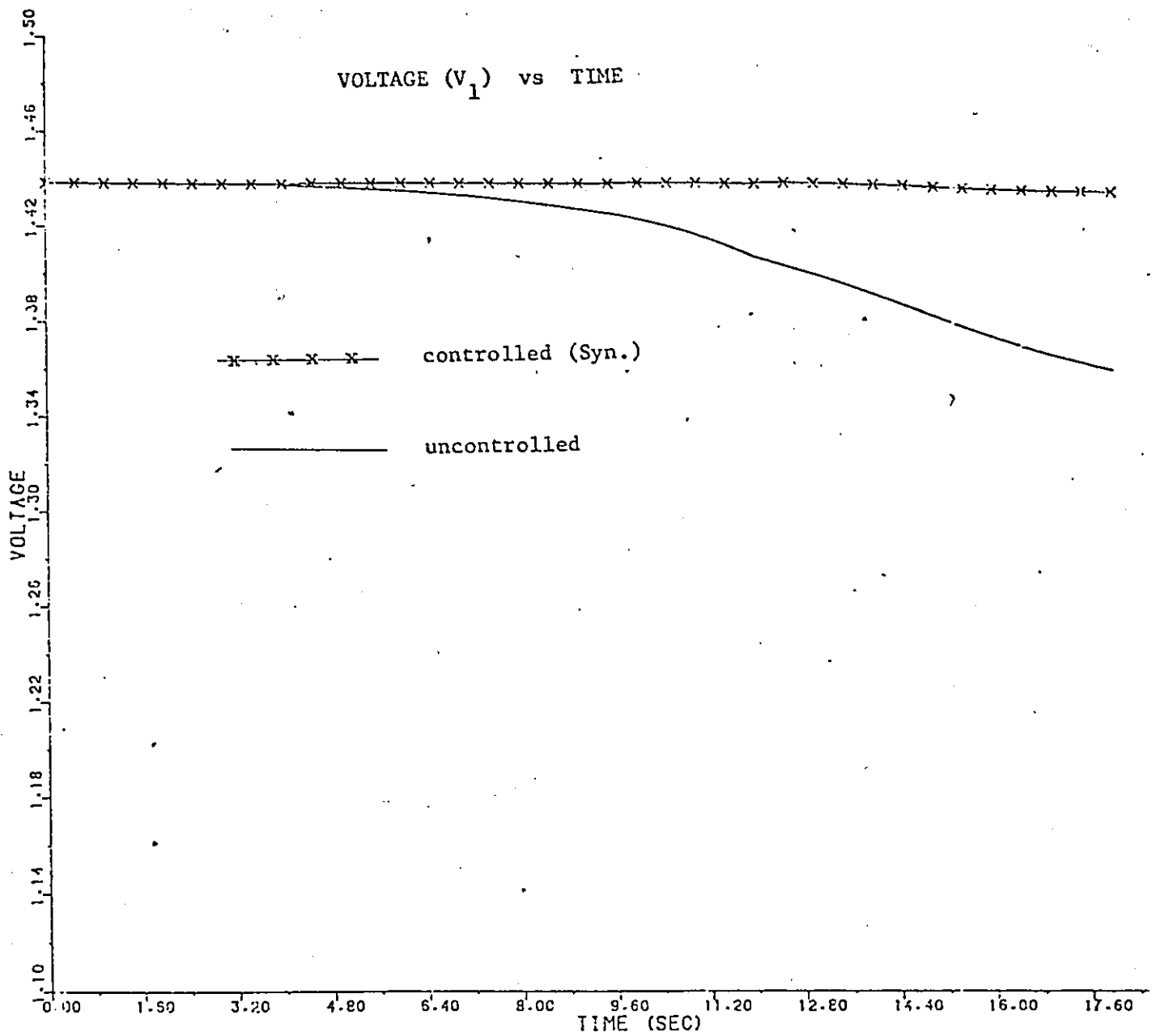


Fig. 4IIA(b) : Voltage (V_1) Profile - Case IIA

VOLTAGE (V_3) vs TIME

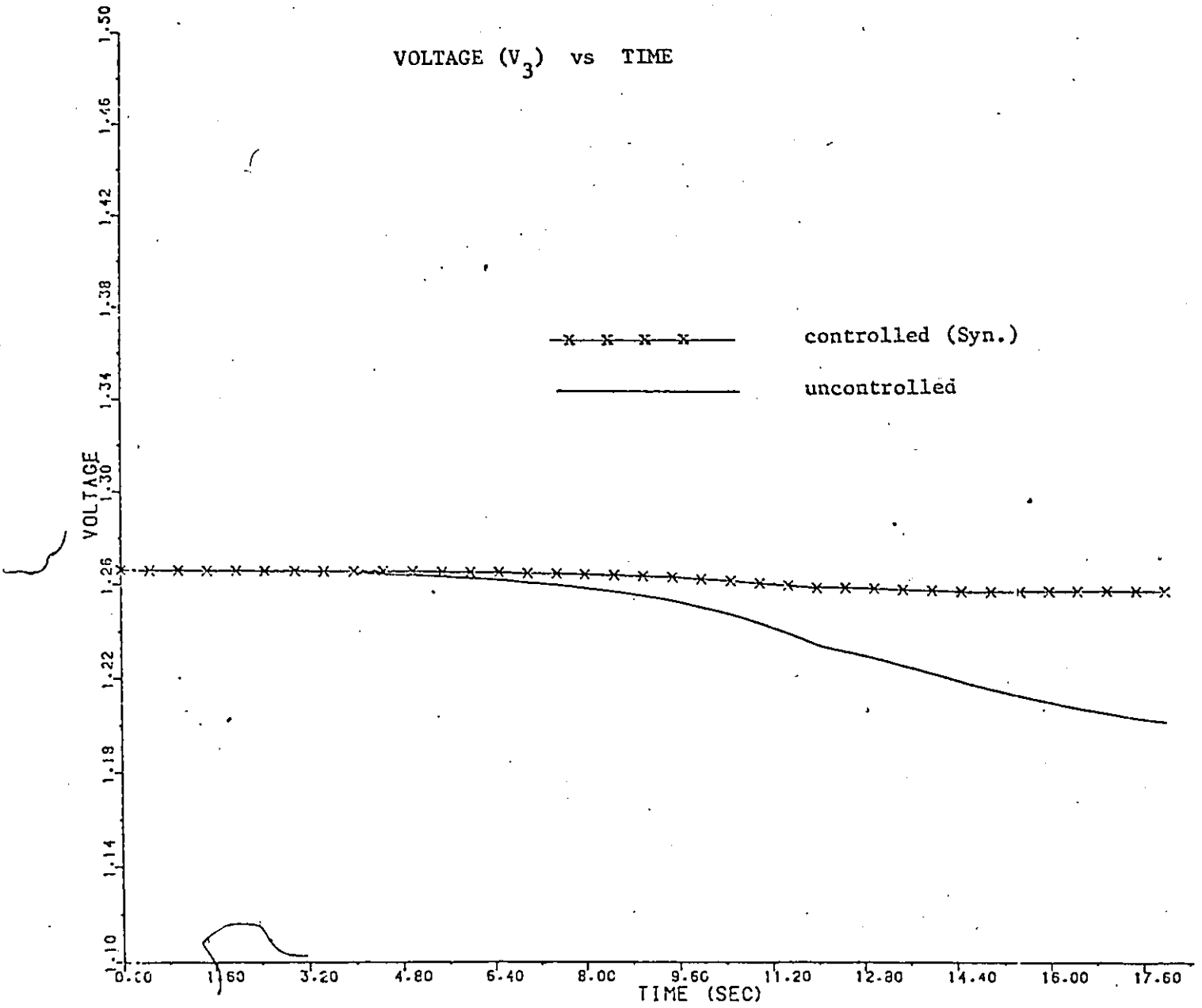


Fig. 4IIA(c) : Voltage (V_3) Profile - Case IIA

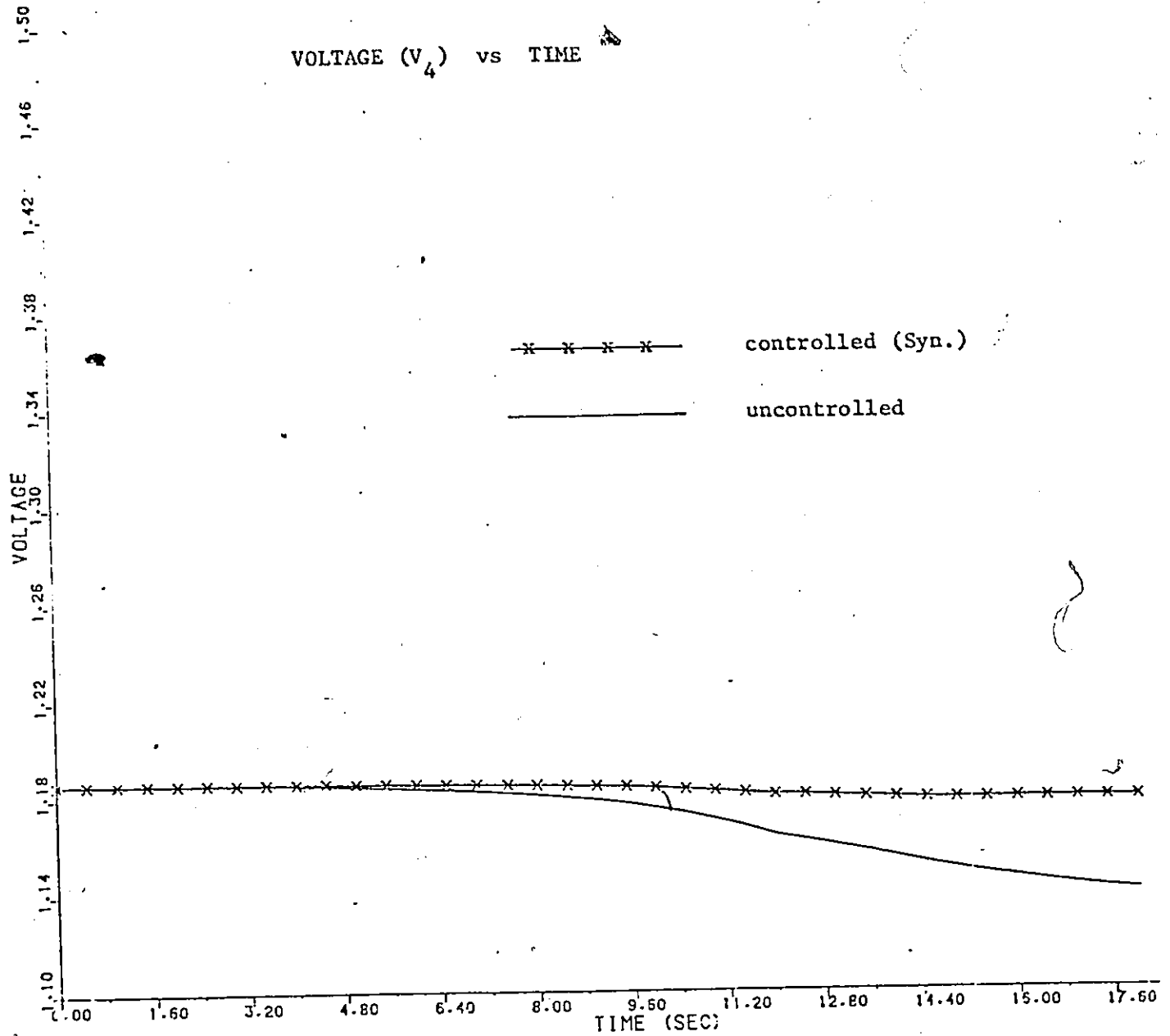


Fig. 4IIA(d) : Voltage (V_4) Profile - Case IIA

CONTROL (B2) VS TIME

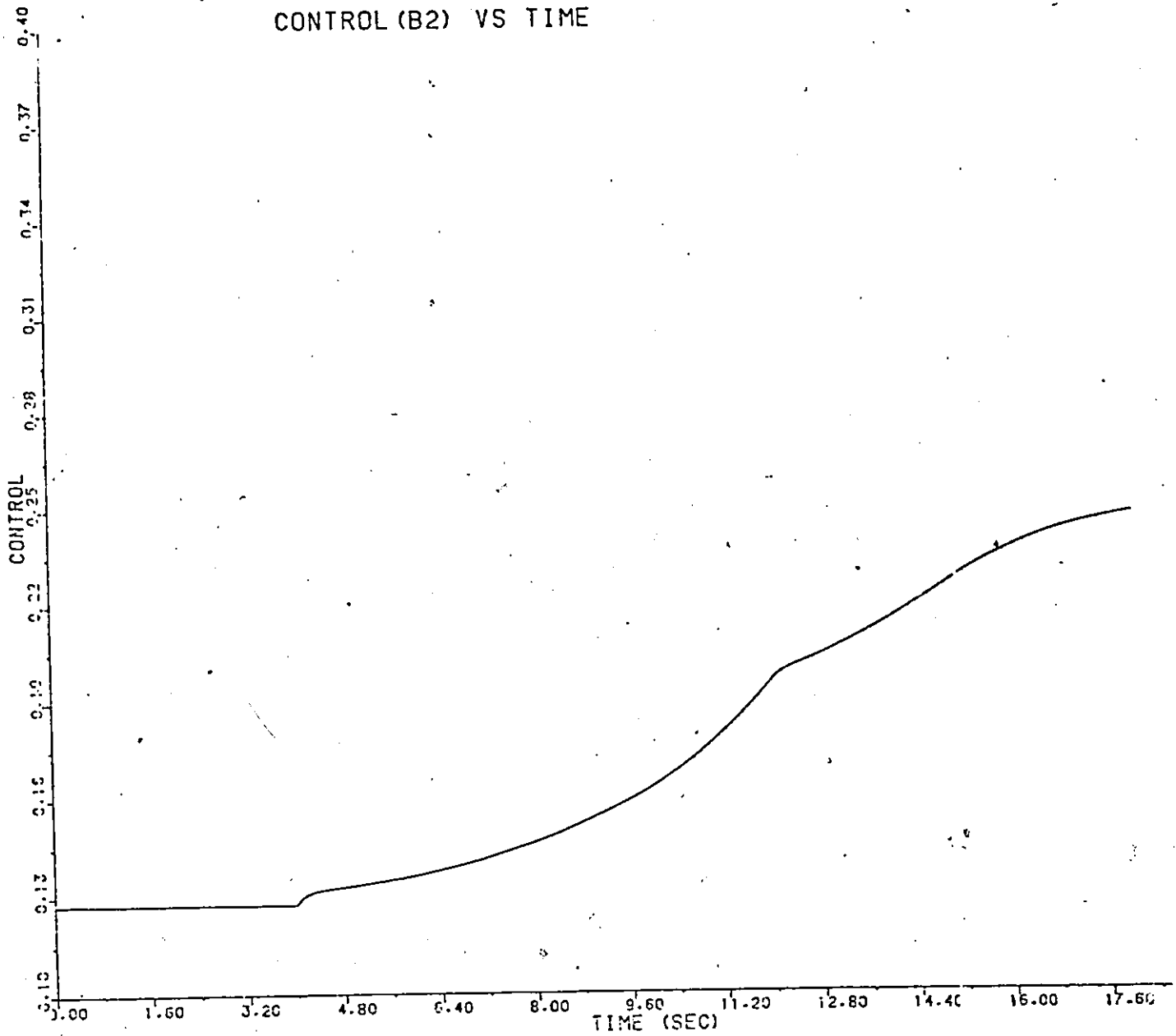


Fig. 4IIA(e) : Control Profile (Syn.) -- Case IIA

4.5.4 Case IIB

Step Variation of Capacitor (Static)

As depicted in Case IIA, similar characteristics of loads are taken in this case. The proposed control law given by (4.4) is used to regulate the voltages. Figures 4IIB(a)-4IIB(d) show the regulations. Figure 4IIB(e) will indicate the control profile (B_2).

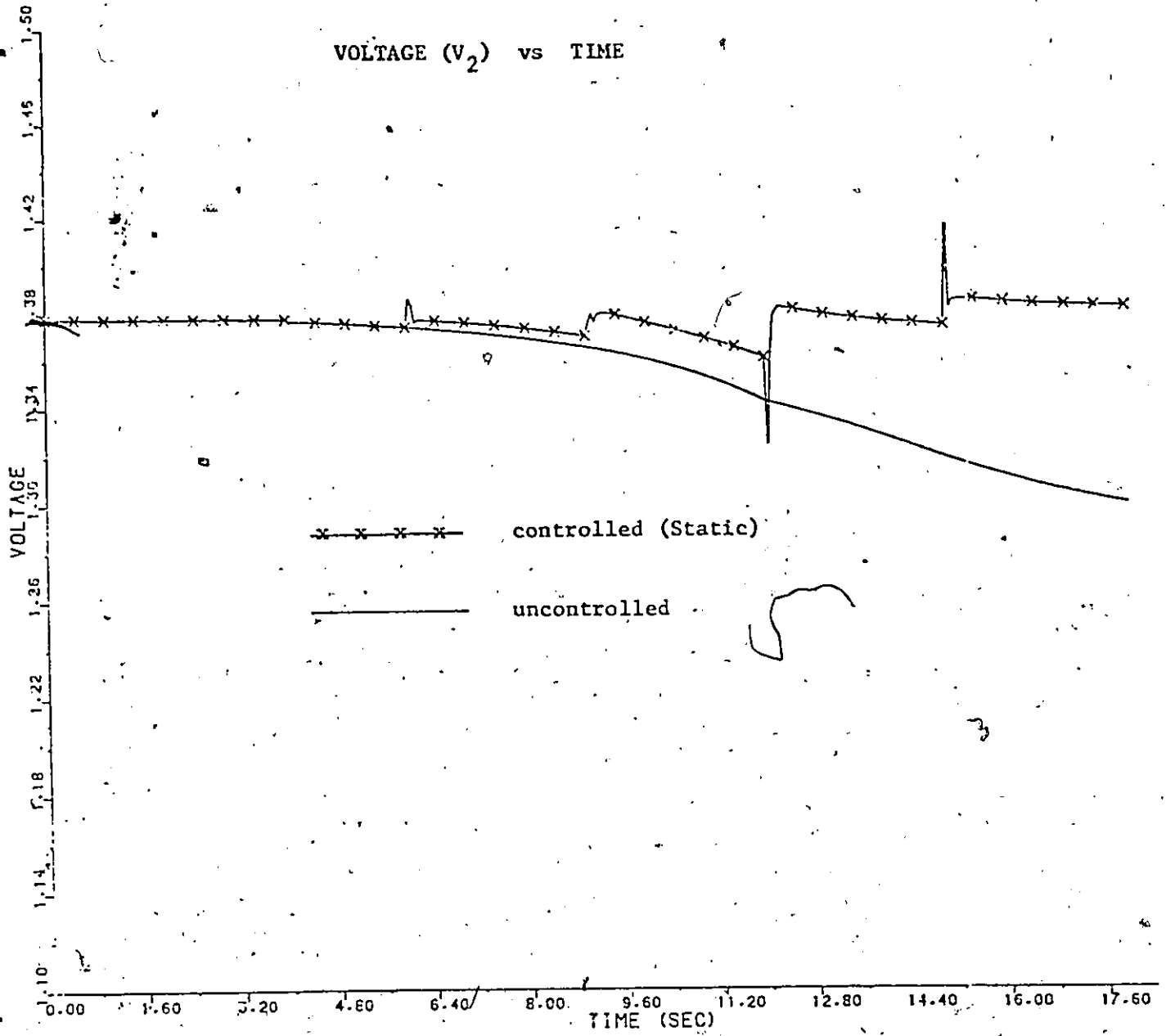


Fig. 4IIB(a) : Voltage (V_2) Profile - Case IIB

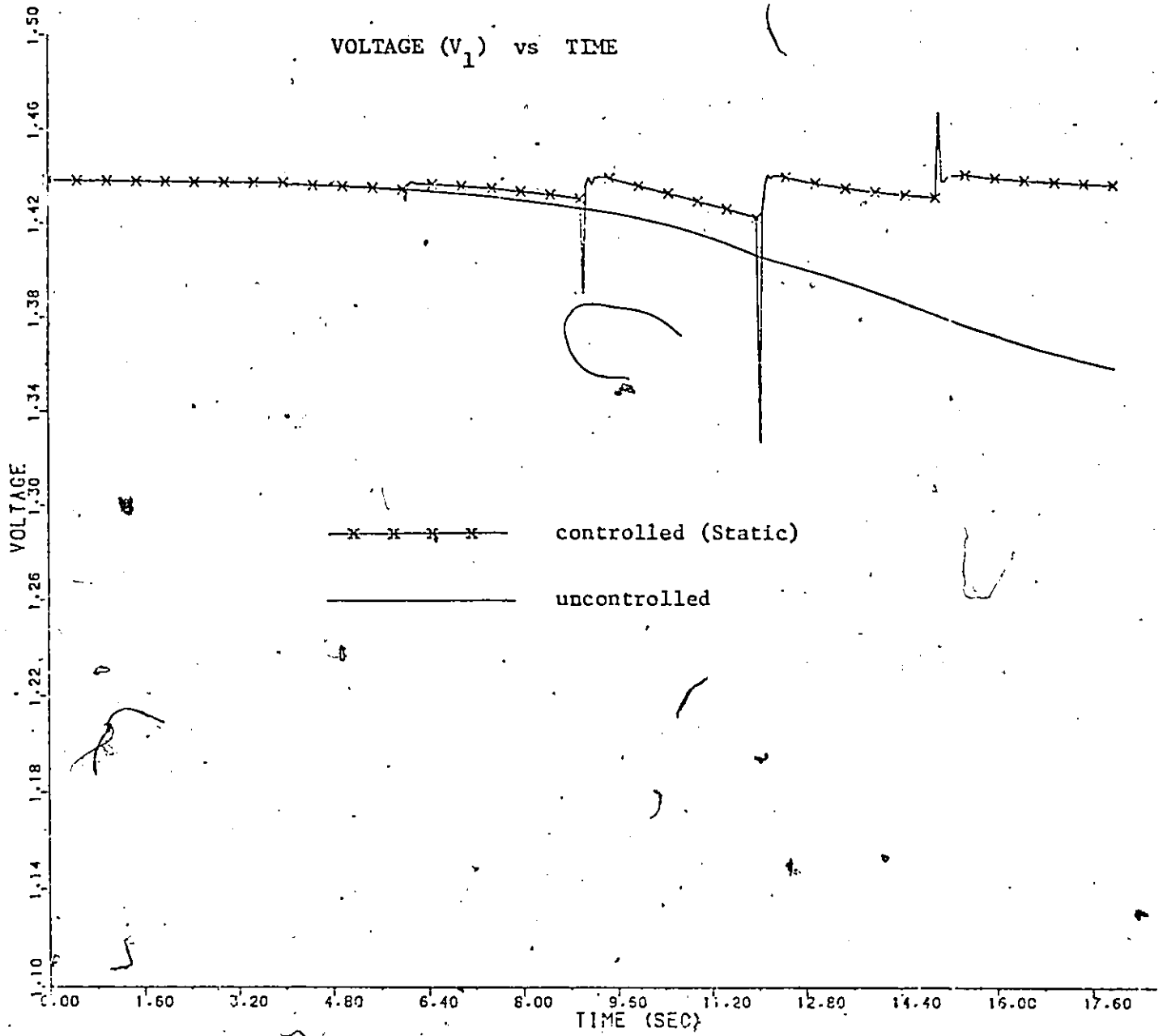


Fig. 4IIB(b) : Voltage (V_1) Profile - Case IIB

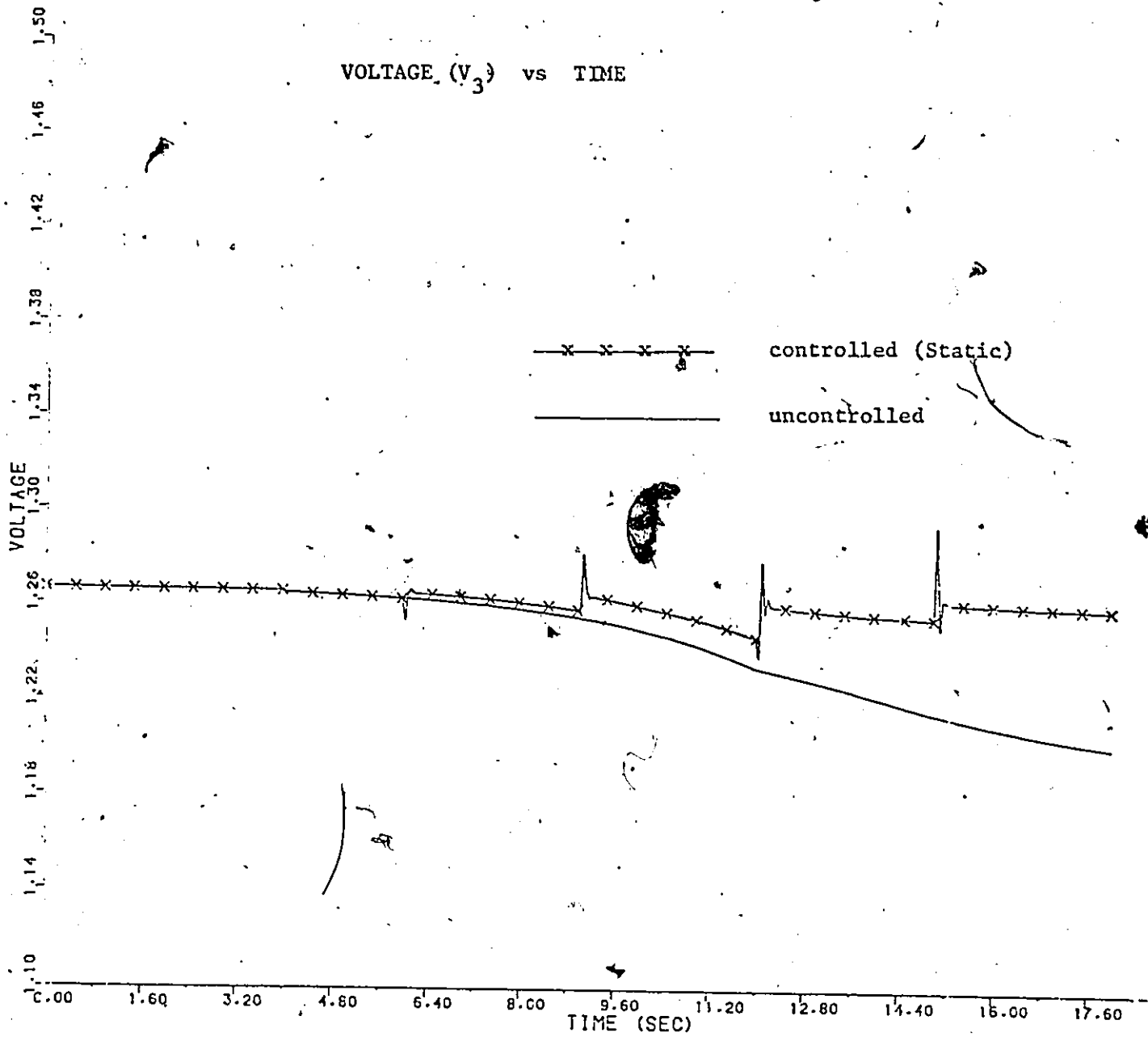


Fig. 4IIB(c) : Voltage (V_3) Profile - Case IIB

VOLTAGE (V_4) vs TIME

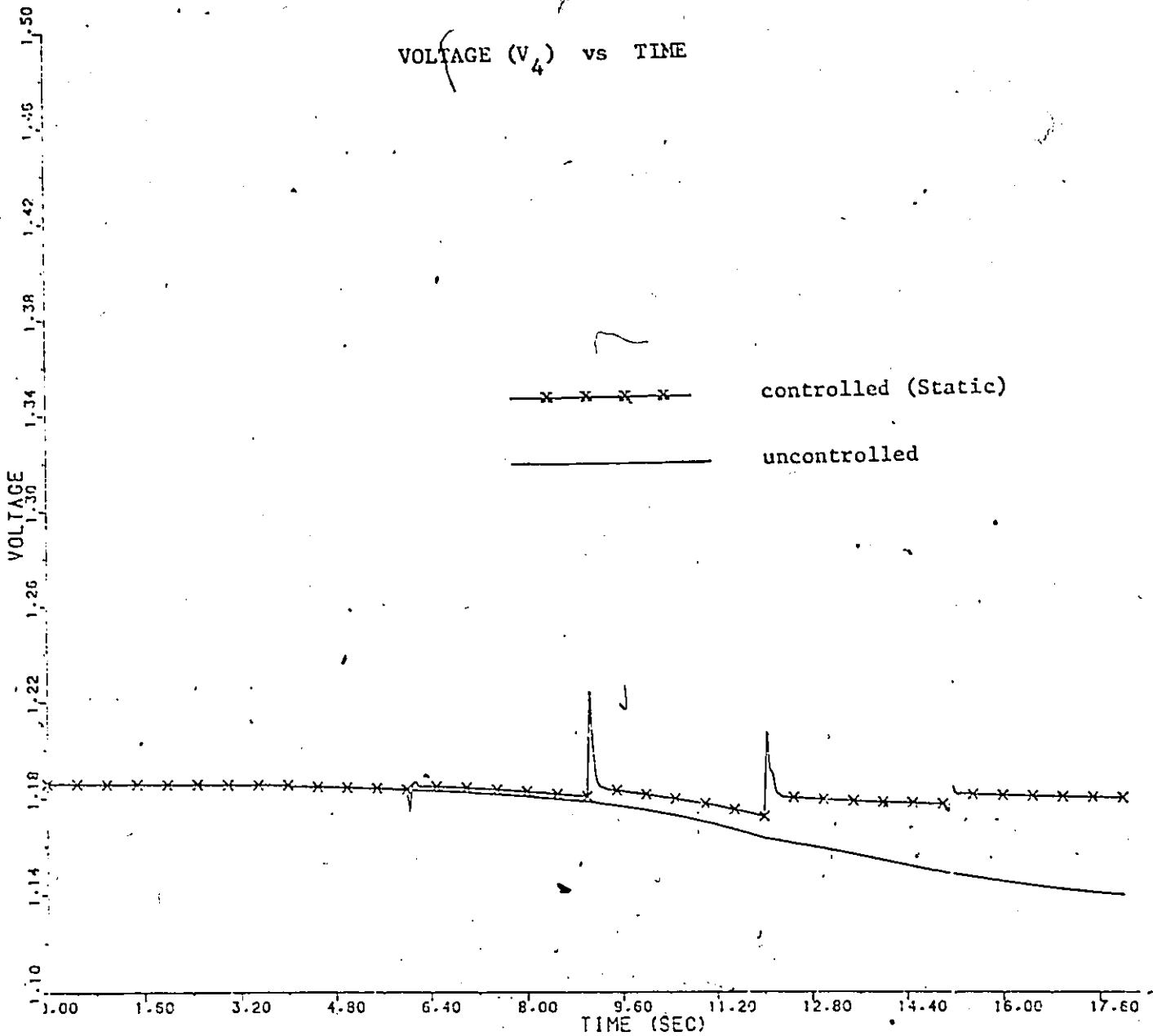


Fig. 4IIB(d) : Voltage (V_4) Profile - Case IIB

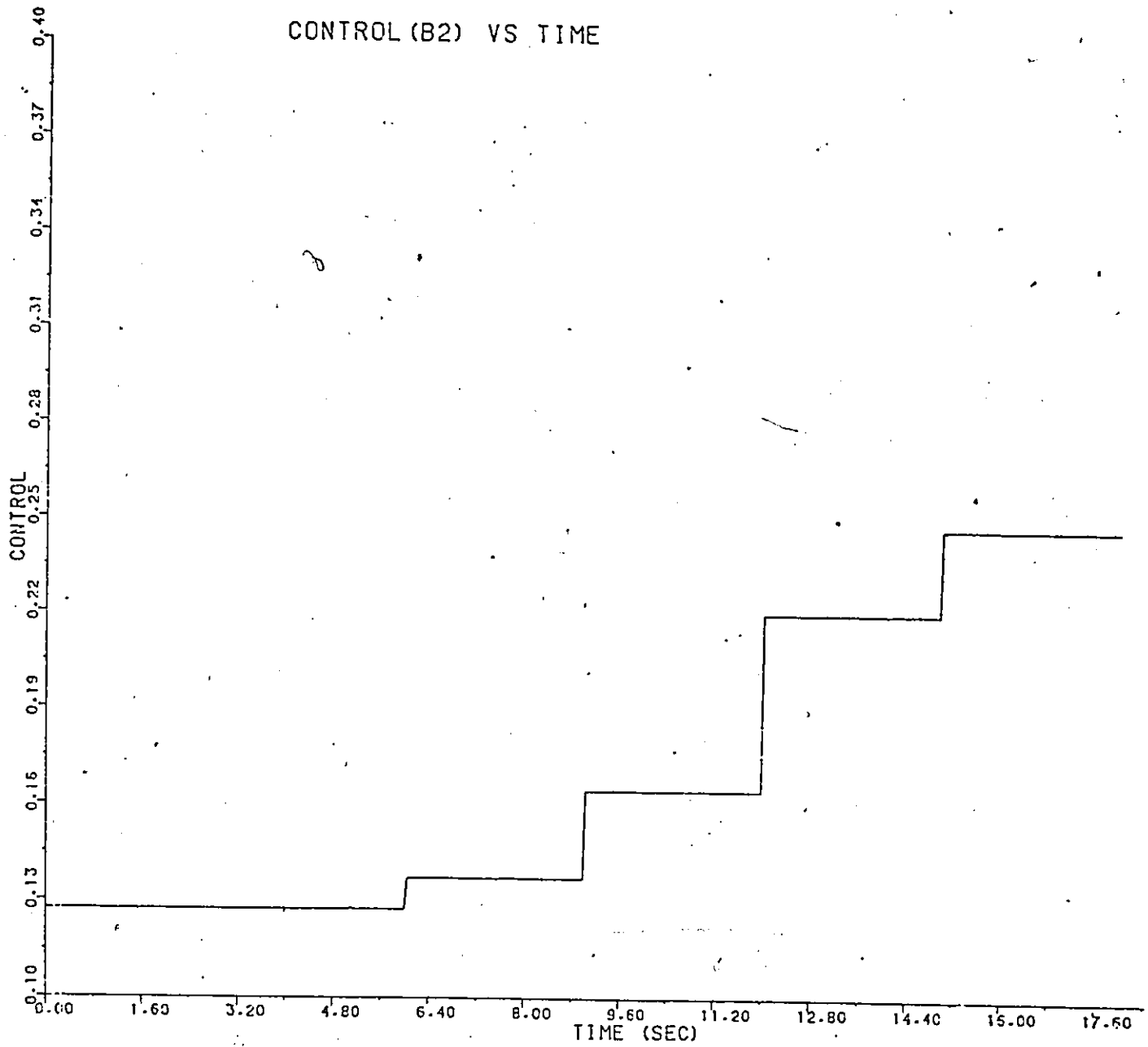


Fig. 4IIB(e) : Control (B₂) Profile (Static) - Case IIB

4.5.5 Case IIIA

Continuous Variation of Capacitors (Synchronous)

In this case, the loads are intensified heavily at two nodes (node 2 and node 3). In other words, the real and reactive components (p_2, q_2 and p_3, q_3) are changed from steady-state to very high magnitudes. The uncontrolled voltage profiles (in "thick lines") are shown in Figures 4IIIA(a)-4IIIA(d). In order to regulate these voltages, the same proposed control law given by (4.3) is applied at node 2.

Although the voltage (V_2) at node 2 is regulated, but a refined regulation for other voltages is not obtained in this case. The profile of control (B_2) will indicate the higher value of capacitance as shown in Figure 4IIIA(e).

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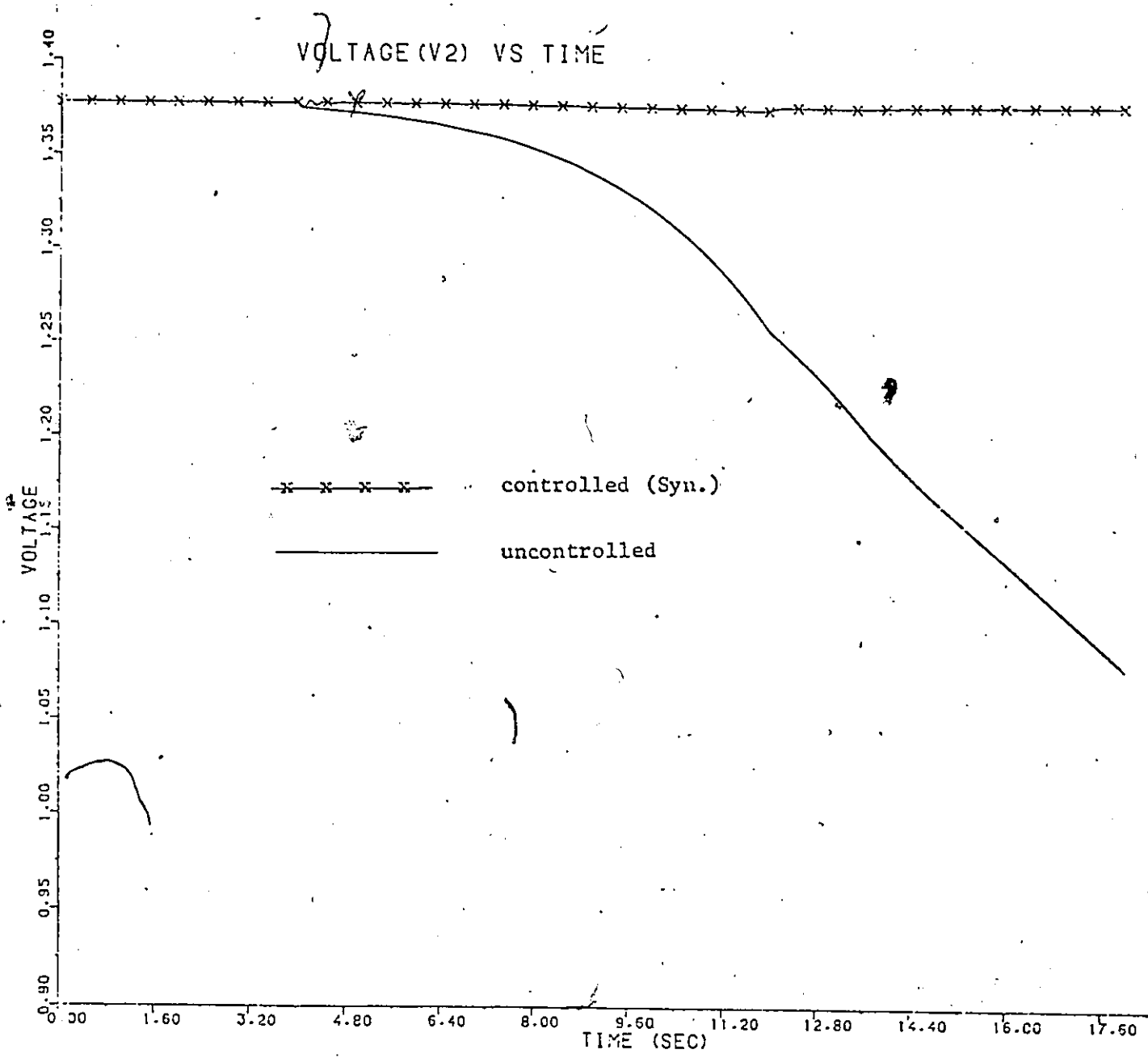


Fig. 4III(a) : Voltage (V₂) Profile - Case IIIA

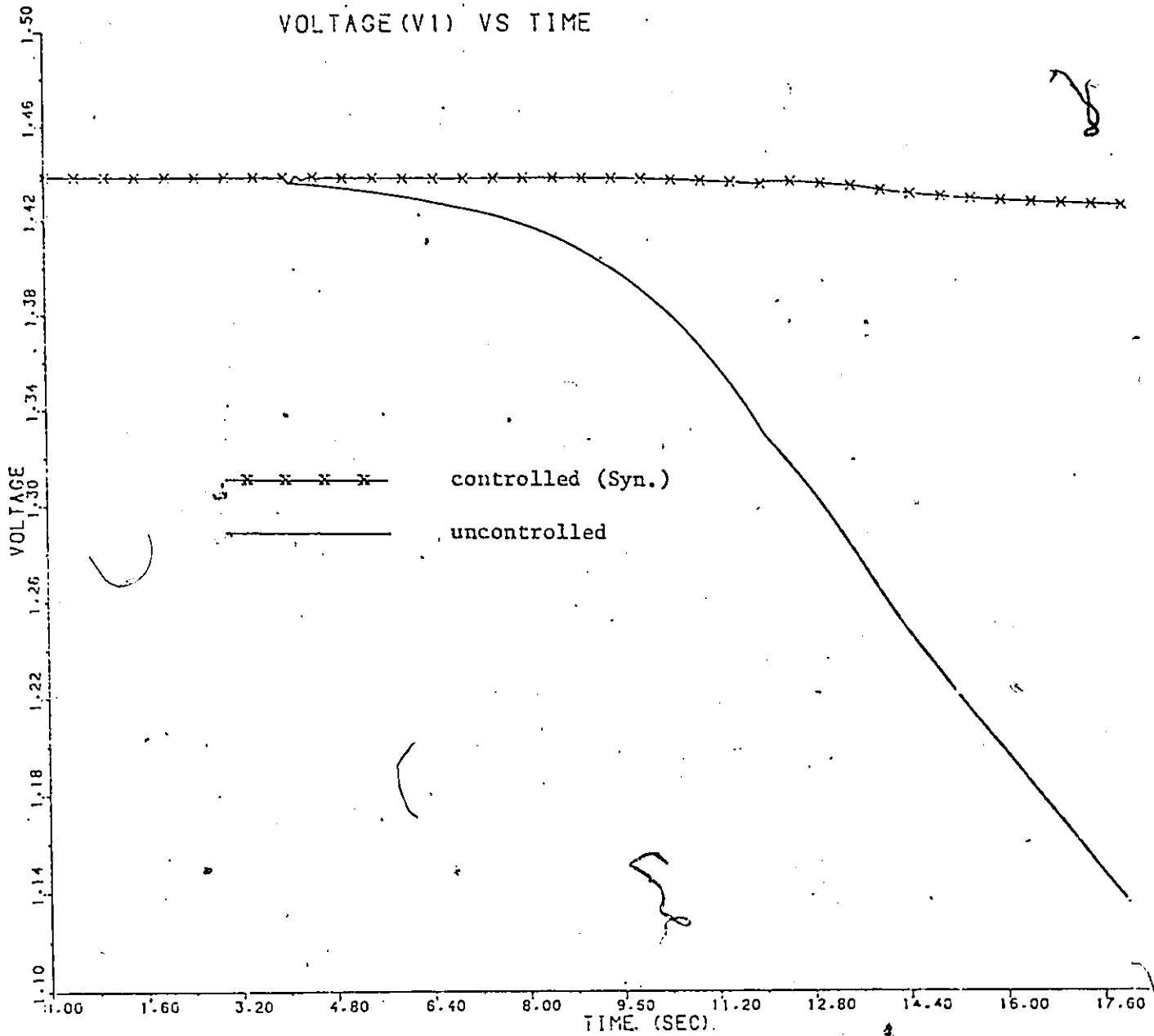


Fig. 4IIIA(b) : Voltage (V₁) Profile - Case IIIA

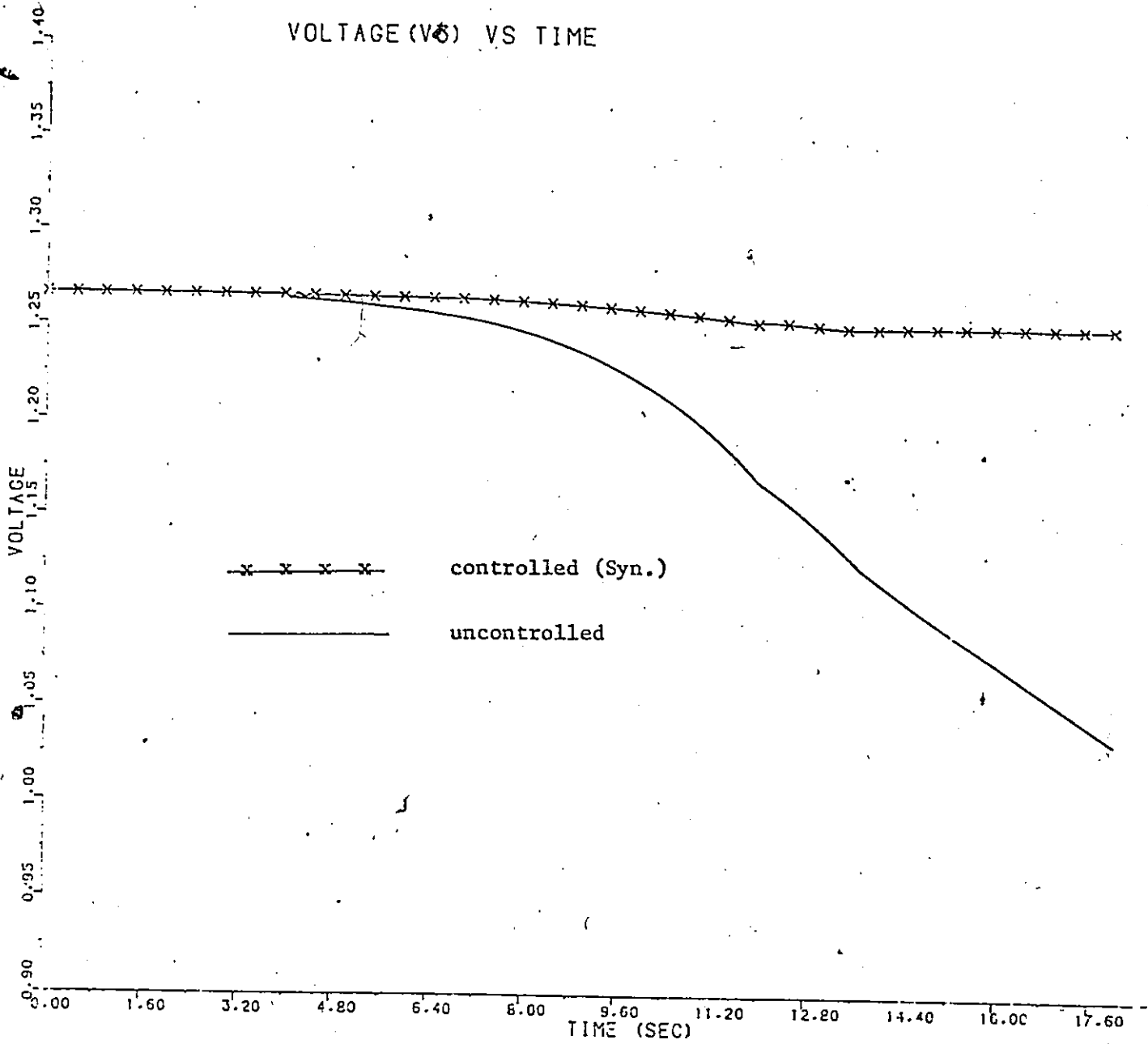


Fig. 4IIIA(c) : Voltage (V) Profile - Case IIIA

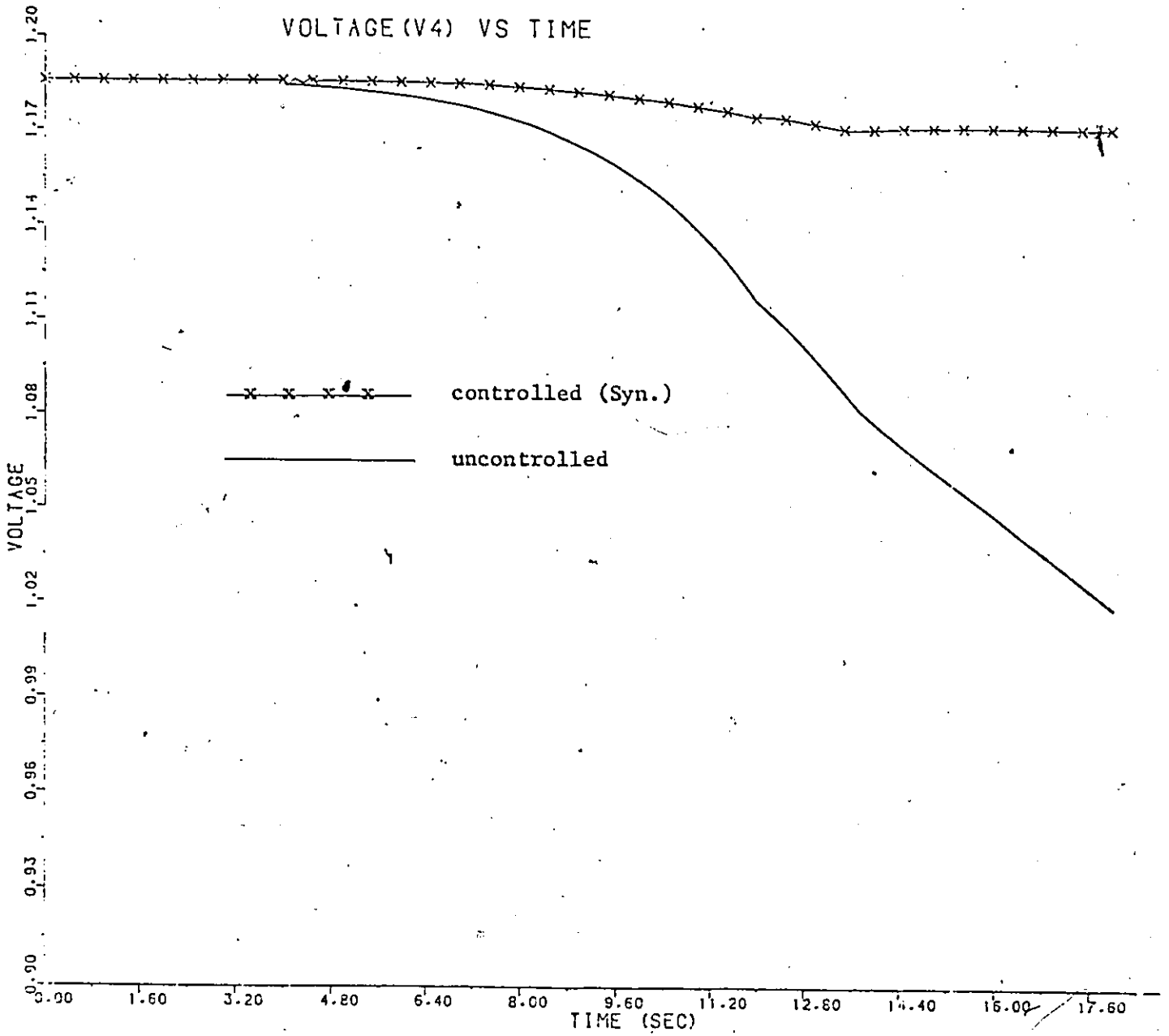


Fig. 4IIIA(d) : Voltage (V₄) Profile - Case IIIA

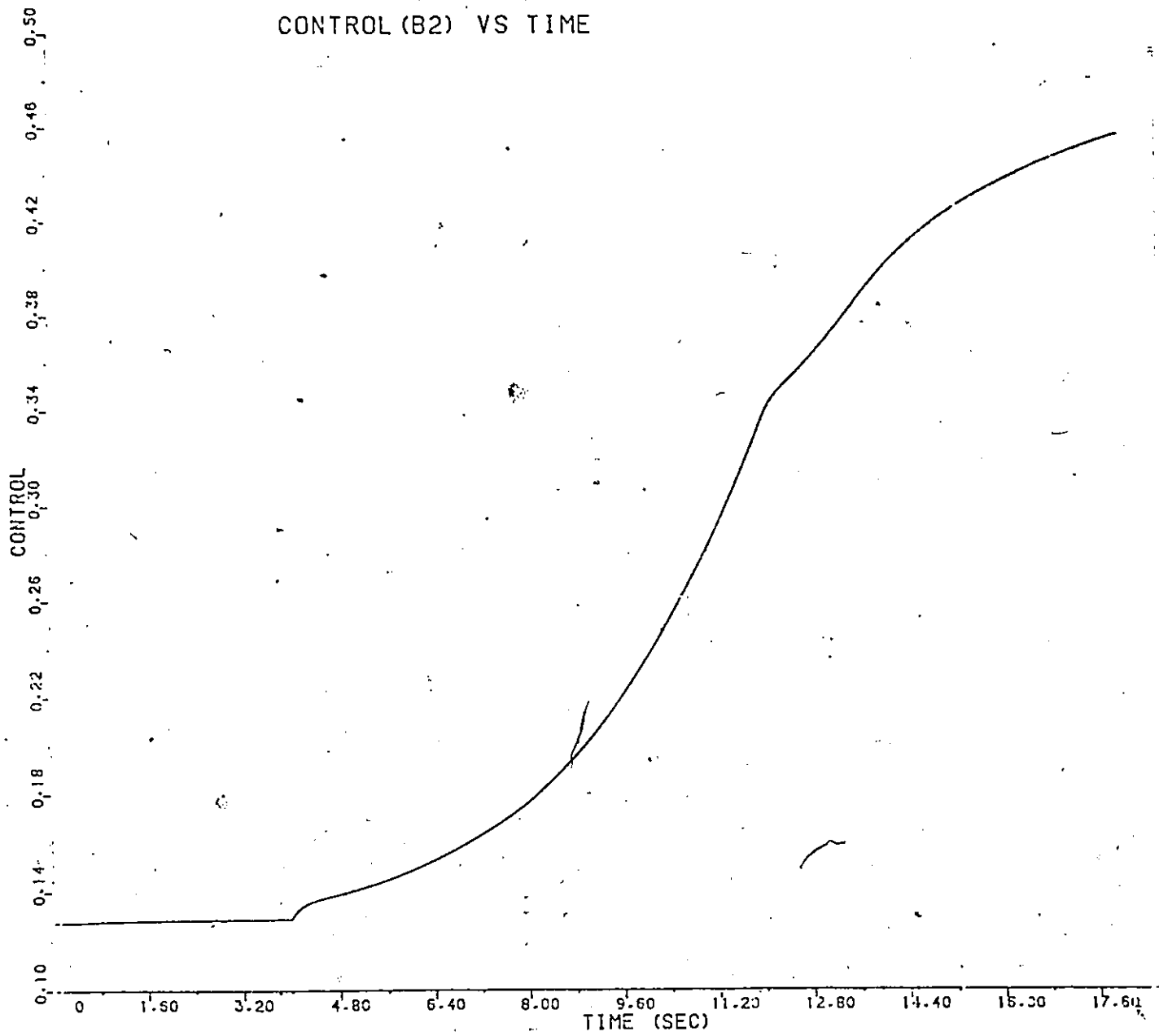


Fig. 4IIIA(e) : Control (Syn.) Profile - Case IIIA

4.6 PERFORMANCE ANALYSIS

Based on this dynamic study, it is evident that the voltages at all the buses can be regulated by suitable use of control (capacitors). Smoother regulation of voltages may be obtained by synchronous condenser in comparison with the static capacitors.

It follows from the results of Case I where the load is changed at one node (node 2), the voltage regulation is smooth at all the nodes even though the control is placed only at one position (node 2)

Studying the results of Case II (Fig. 4IIA(a)-4IIA(e)) in which the load has been changed from steady-state at node 2 and node 3 and the control is placed at node 2, it is observed that the voltages are maintained close to the desired values at all the nodes. This shows that the control law (4.3) as used in Case I (at node 2) continues to perform satisfactorily even though the the load has been changed at two different nodes (node 2 and node 3). This is due to the fact that the transmission line is short and the load changes are not very large.

Comparing the results of Case III (Fig. 4IIIA(a)-4IIIA(e)) with those of Case II (Fig. 4IIA(a)-4IIA(e)), it is observed that in Case III, the voltage regulation at node 1,3,4 is poorer compared to that of Case II. This is due to the intensification of loads at

some nodes (node 2 and node 3) and having control only at node 2.

This shows that even though the transmission line is considered short, controls may have to be applied at the other nodes if the distribution of loads is not uniform. In other words, the general control as given by (4.1) should be used. An optimal set of gains (K_{si}) can be obtained by the method of parameter optimization as suggested in [4]. It is extremely encouraging to see that the voltages can be maintained within any specified limits by simple integral feedback control located at suitable nodes, provided the gains (K_{si}) are chosen appropriately.

Chapter V

CONCLUSION

The main objective of this thesis is to investigate the control in regulating the voltages at the distap buses. Based on a dynamic model a method is proposed to control the node voltages by the use of control capacitors. The feasibility of the method has been clearly demcnstrated by three examples (Case I, Case II, and Case III).

It is evident from the results of Chapter IV that disturbances in the power systems due to the impact of loads cause the dip of the bus voltages quite considerably. One of the efficient methods, in regulating the system voltages clearly implies that control (capacitor) may be suitably placed at the buses to supply the reactive power into the system.

If the transmission line is long and the distribution of loads is not uniform, then it is necessary to use control (capacitor) at other nodes also, provided the gains (K_{si}) are found out appropriately by parameter optimization [4].

From the results of Chapter IV, it can be observed that synchronous capacitor is superior to static capacitor in regulating the voltage. However, because of economic

considerations static capacitor may be more suitable for application in power systems. But switching of static capacitor can present some potentially dangerous situation such as overvoltage surge etc. as seen in the results of Cases IA, and IIB in Chapter IV.

Because of the relative phase of current and voltage (current leads the voltage by approximately 90°) the capacitor is fully charged to maximum voltage when the switch interrupts. The capacitor, when isolated from the source, retains its charge. As a consequence of this trapping of the charge, after half a cycle the current becomes zero and the voltage across the switch reaches the peak value of $2V$, which may cause the circuit breaker to restrike [13].

5.1 SCOPE OF FURTHER RESEARCH

In order to represent the model in a more generalized fashion, one can include governor and exciter dynamics into the system.

Since this study is based on single machine system, it may be worthwhile to investigate a multi-machine system model.

In this thesis the gain in the control model has been chosen by trial and error, but in order to have a more refined regulation of system voltages, this gain could be found out by implementing a proper optimization method.

Under this study, system voltages have been regulated during a slow variation of loads by proper choice of capacitor control at different places. Other type of large scale disturbances has not been considered in this simulation. However, to obtain a complete regulation of the system owing to short circuit as well as the load variation, one has to, aside from the capacitor control, incorporate the exciter and governor controls into the system model.

APPENDIX I

A.1 CHOOSING A BASE FOR STATOR QUANTITIES

The variables v_d , v_q , i_d , i_q , λ_d , and λ_q are stator quantities because they relate directly to the a-b-c phase quantities through Park's Transformation. Using the subscript B to indicate "base" and R to indicate "rated", the following stator base quantities may be chosen.

$$\begin{aligned} \text{Let } S_B &= S_R = \text{stator rated VA/phase, VA rms} \\ V_B &= V_R = \text{stator rated line to neutral voltage,} \\ &\quad V \text{ rms} \\ \omega_B &= \omega_R = \text{generator rated speed, elec rad/s} \end{aligned} \quad (A1.1)$$

First note that the three-phase power in pu is three times the pu power per phase (for balanced conditions). To prove this, let the rms phase quantities be $V \angle \alpha$ and $I \angle \gamma$. The three-phase power is

$$3 VI \cos (\alpha - \gamma)$$

The pu power $P_{3\phi}$ is given by

$$\begin{aligned} P_{3\phi} &= (3VI/V_B I_B) \cos (\alpha - \gamma) \\ &= 3 V_u I_u \cos (\alpha - \gamma) \end{aligned} \quad (A1.2)$$

where the subscript u is used to indicate pu quantities. To obtain the d and q axis quantities, the instantaneous

voltage and currents may be written. To simplify the expression without any loss of generality, let $v_a(t)$ is in the form,

$$\begin{aligned} v_a &= V_m \sin(\theta + \alpha) = \sqrt{2} V \sin(\theta + \alpha) \\ v_b &= \sqrt{2} V \sin(\theta + \alpha - 2\pi/3) \\ v_c &= \sqrt{2} V \sin(\theta + \alpha + 2\pi/3) \end{aligned} \quad (A1.3)$$

Then from (1.13), $v_{10dq} = P v_{labc}$ or

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{3} V \sin \alpha \\ \sqrt{3} V \cos \alpha \end{bmatrix} \quad (A1.4)$$

In pu

$$v_{du} = v_d / V_B = \sqrt{3} (V/V_B) \sin \alpha = \sqrt{3} V_u \sin \alpha \quad (A1.5)$$

Similarly,

$$v_{qu} = \sqrt{3} V_u \cos \alpha \quad (A1.6)$$

Obviously, then

$$v_{du}^2 + v_{qu}^2 = 3 V_u^2 \quad (A1.7)$$

The above results are significant. They indicate that with this particular choice of the base voltage, the pu d and q axis voltage are numerically equal to $\sqrt{3}$ times the pu phase voltages.

Similarly, it can be shown that if the rms phase current is $I \angle \gamma$, the corresponding d and q axis currents are given by,

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{3} I \sin \gamma \\ \sqrt{3} I \cos \gamma \end{bmatrix} \quad (\text{A1.8})$$

and the pu currents are given by

$$i_{du} = \sqrt{3} I_u \sin \gamma \quad (\text{A1.9})$$

$$i_{qu} = \sqrt{3} I_u \cos \gamma$$

To check the validity of the above, the power in the d and q axis circuits must be the same as the power in three stator phases, since P is a power invariant transformation.

$$\begin{aligned} P_{3\phi} &= i_{du} v_{du} + i_{qu} v_{qu} \\ &= 3 I_u V_u (\sin \alpha \sin \gamma + \cos \alpha \cos \gamma) \\ &= 3 I_u V_u \cos (\alpha - \gamma) \quad \text{pu} \end{aligned} \quad (\text{A.10})$$

Now the relations can be developed for the various base quantities. From (A1.1) the following may be computed:

$$\begin{aligned} I_B &= S_B / V_B = S_R / V_R \quad \text{A rms} \\ \lambda_B &= V_B t_B = V_R / \omega_R = L_B I_B \quad \text{Wb turn} \\ F_B &= V_B / I_B = V_R / I_R \quad \Omega \\ t_B &= 1 / \omega_B = 1 / \omega_R \quad \text{s} \\ L_B &= V_B t_B / I_B = V_R / I_R \omega_R \quad \text{H} \end{aligned} \quad (\text{A1.11})$$

Thus by choosing the three base quantities S_B , V_B , and t_B , the base values can be computed for all quantities of interest.

To normalize any quantity, it is divided by the base quantity of the same dimension. For example, for currents it may be written

$$i_u = i(A) / I_B(A) \quad \text{pu} \quad (A1.12)$$

where the subscript u is used to indicate pu.

A.2 CHOOSING A BASE FOR ROTOR QUANTITIES

Lewis [11] showed that in circuits coupled magnetically, which are to be normalized, it is essential to select the same voltampere and time base in each part of the circuit. The choice of equal time base throughout all parts of a circuit with mutual coupling is the important constraint. It can be shown that the choice of a common time base t_B forces the VA base to be equal in all circuit parts and also forces the base mutual inductance to be the geometric mean of the base self-inductances if equal pu mutuals are to result, i.e.,

$$M_{12B} = (L_{1B} L_{2B})^{1/2}$$

For the synchronous machine the choice of S_B is based on the rating of the stator, and the time base is fixed by the rated frequency. These base quantities must be the same for the rotor circuits as well. It should be remembered, however, that the stator VA base is much larger than the VA rating of the rotor (field) circuits. Hence some rotor base quantities are bound to be very large, making the

corresponding pu rotor quantities appear numerically small. Therefore, care should be taken in the choice of the remaining free rotor base term, since all other rotor base quantities will then be automatically determined.

To illustrate the above, consider a machine having a stator rating of 100×10^6 VA/phase. Assume that its exciter has a rating of 250 V and, 1000 A. If, for example, it is chosen $I_{RB} = 1000$ A, $V_{RB} = 100,000$ V; and if it is chosen $V_{RB} = 250$ V, then I_{RB} will be 400,000 A.

Therefore, it seems desirable to choose some base quantity in the rotor to give the correct base quantity in the stator. For example, the base rotor current may be chosen to give, through the magnetic coupling, the correct base stator flux linkage or open circuit voltage. Even then there is some latitude in the choice of the base rotor current, depending on the condition of the magnetic circuit.

The choice made here for the free rotor base quantity is based on the concept of equal mutual flux linkages. This means that base field current or base d-axis damper current will produce the same space fundamental of air gap flux as produced by base stator current acting in the fictitious d winding.

Referring to the flux linkage equations (1.20) let

$$i_{ld} = I_B, \quad i_F = I_{FB}, \quad \text{and} \quad i_D = I_{DB}$$

be applied one by one with other currents set to zero.

To equate the mutual flux linkages in each winding,

$$\begin{aligned} \lambda_{md} &= L_{md} I_B = kM_F I_{FB} = kM_D I_{DB} & \text{Wb} \\ \lambda_{mF} &= kM_F I_B = L_{mF} I_{FB} = M_R I_{DB} & \text{Wb} \\ \lambda_{mD} &= kM_D I_B = M_R I_{FB} = L_{mD} I_{DB} & \text{Wb} \end{aligned} \quad (A1.13)$$

$$\begin{aligned} \lambda_{mq} &= L_{mq} I_B = kM_Q I_{QB} & \text{Wb} \\ \lambda_{mQ} &= kM_Q I_B = L_{mQ} I_{QB} & \text{Wb} \\ L_{md} I_B^2 &= L_{mF} I_{FB}^2 = L_{mD} I_{DB}^2 = kM_F I_B I_{FB} \\ &= kM_D I_B I_{DB} = M_R I_{FB} I_{DB} \end{aligned} \quad (A1.14)$$

$$L_{mq} I_B^2 = kM_Q I_B I_{QB} = L_{mQ} I_{QB}^2$$

and this is the fundamental constraint among base currents.

From (A1.14) and the requirement for equal S_B , it may be computed

$$\begin{aligned} V_{FB}/V_B &= I_B/I_{FB} = (L_{mF}/L_{md})^{1/2} kM_F/L_{md} \triangleq k_F \\ &= L_{mF}/kM_F = M_R/kM_D \\ V_{DB}/V_B &= I_B/I_{DB} = (L_{mD}/L_{md})^{1/2} = kM_D/L_{mD} \triangleq k_D \\ &= L_{mD}/kM_D = M_R/kM_F \\ V_{QB}/V_B &= I_B/I_{QB} = (L_{mq}/L_{mQ}) = kM_Q/L_{mQ} \triangleq k_Q \\ &= L_{mQ}/kM_Q \end{aligned} \quad (A1.15)$$

These basic constraints permit one to compute

$$\begin{aligned} P_{FB} &= k_F^2 R_B \Omega \\ R_{DB} &= k_D^2 R_B \Omega \\ R_{QB} &= k_Q^2 R_B \Omega \\ L_{FB} &= k_F^2 L_B H \\ L_{DB} &= k_D^2 L_B H \\ L_{QB} &= k_Q^2 L_B H \end{aligned} \quad (A1.16)$$

and since the base mutuals must be the geometric mean of the base self-inductances,

$$\begin{aligned}
 M_{FB} &= k_F L_B & H \\
 M_{DB} &= k_D L_B & H \\
 M_{QB} &= k_Q L_B & H \\
 M_{RB} &= k_{FD} L_B & H
 \end{aligned}
 \tag{A1.17}$$

A.3 COMPUTATION OF PU VALUES

The following data of the generator under study are given, from the pu values will be calculated.

Rated MVA = 160 MVA

Rated voltage = 15 KV

Excitation voltage = 375 V

Stator current = 6158.40 A

Field current = 926 A

Power factor = 0.85

$$\begin{aligned}
 L_d &= 6.341 \times 10^{-3} & H \\
 L_F &= 2.189 & H \\
 L_D &= 5.989 \times 10^{-3} & H \\
 L_q &= 6.118 \times 10^{-3} & H \\
 L_Q &= 1.423 \times 10^{-3} & H \\
 kM_D &= 5.782 \times 10^{-3} & H \\
 kM_Q &= 2.779 \times 10^{-3} & H \\
 r &= .18.421 \times 10^{-3} & \Omega \\
 r_F &= 18.969 \times 10^{-3} & \Omega
 \end{aligned}$$

Inertia constant = 1.765 KW.s/hp

A.3.1 Solution

Stator Base Quantities :

$$S_B = 160/3 = 53.33 \text{ MVA/phase}$$

$$V_B = 15000/\sqrt{3} = 8660.25 \text{ V}$$

$$I_B = 6158.40 \text{ A}$$

$$t_B = 2.6526 \times 10^{-3} \text{ s}$$

$$\lambda_B = 8660 \times 2.65 \times 10^{-3} = 22.972 \text{ Wb turn/phase}$$

$$R_B = 8660.25/6158.40 = 1.406 \text{ } \Omega$$

$$L_B = 8660/(377 \times 6158) = 3.730 \times 10^{-3} \text{ H}$$

$$\begin{aligned} L_{md} &= L_d - l_d = (6.341 - 0.5595) \times 10^{-3} \\ &= 5.79 \times 10^{-3} \text{ H} \end{aligned}$$

At open circuit the mutual inductance L_{aF} and the flux linkage in phase a are given by

$$L_{aF} = M_F \cos \theta$$

$$\lambda_a = i_F M_F \cos \theta$$

the instantaneous voltage of phase a is

$$v_a = i_F \omega_R M_F \sin \theta$$

where ω_R is the rated synchronous speed. Thus the peak voltage corresponds to the product $i_F \omega_R M_F$. From the air gap line of the no-load saturation curve, the value of field current at rated voltage is 365 A. Therefore,

$$M_F = 8660 \sqrt{2} / (377 \times 365) = 89.006 \times 10^{-3} \text{ H}$$

$$kM_F = \sqrt{3/2} \times 89.006 \times 10^{-3} = 109.01 \times 10^{-3} \text{ H}$$

$$\text{Then } k_F = kM_F / L_{md} = 18.854.$$

Then it can be computed from (A1.15) - (A1.17),

$$I_{FB} = 6158.4 / 18.854 = 326.64 \text{ A}$$

$$M_{FB} = 18.854 \times 3.73 \times 10^{-3} = 70.329 \times 10^{-3} \text{ H}$$

$$V_{FB} = (53.33 \times 10^6) / 326.64$$

$$= 163280.68 \text{ V}$$

$$P_{FB} = 163280.68 / 326.64$$

$$= 499.89 \text{ } \Omega$$

$$L_{FB} = (18.845) \times 3.73 \times 10^{-3}$$

$$= 1.326 \text{ H}$$

Amortisseur Base Quantities :

$$kM_D / L_{md} = 5.781 / 5.781 = 1.0$$

$$M_{DB} = L_B \text{ H}$$

$$kM_Q / L_{mq} = 2.779 / 5.782 = 0.5$$

$$L_{QB} = L_B / 4 = 0.933 \times 10^{-3} \text{ H}$$

$$L_{DB} = L_B \text{ H}$$

$$R_{DB} = R_B$$

$$R_{QB} = R_B / 4 = 0.352 \text{ } \Omega$$

Inertia Constant :

$$H = 1.765 (1.0 / 0.746) = 2.37 \text{ kW.s/KVA}$$

The pu parameters are thus given by :

$$L_d = 6.34 / 3.73 = 1.70$$

$$L_F = 2.189/1.326 = 1.651$$

$$L_D = 5.989/3.730 = 1.605$$

$$L_q = 6.118/3.73 = 1.64$$

$$L_Q = 1.423/0.933 = 1.526$$

$$L_{AD} = kM_D = kM_F = M_R = 1.70 - 0.15 \\ = 1.55$$

$$L_{AQ} = kM_Q = 1.64 - 0.15 = 1.49$$

$$r = 0.001542/1.406 = 0.001096$$

$$r_F = 0.371/499.9 = 0.000742$$

$$r_D = 0.018/1.406 = 0.0131$$

$$r_Q = 18.969 \times 10^{-3} / 0.351 = 0.0540$$

APPENDIX II

Considering a 60-Hz synchronous generator [1] with the following pu parameters as mentioned below, the matrix L (1.39) is inverted and multiplied by $(R + \omega N)$.

$L_d = 1.70$	$kM_Q = 1.49$
$L_q = 1.64$	$r = 0.001096$
$L_F = 1.65$	$r_F = 0.000742$
$L_D = 1.605$	$r_D = 0.0131$
$L_Q = 1.526$	$r_Q = 0.0540$
$kM_F = kM_D = M_R = 1.55$	$H = 2.37 \text{ s}$

From (1.39) one can obtain numerically,

$$(R + \omega N) = \begin{bmatrix} 0.0011 & 0 & 0 & 1.64 & 1.49 \\ 0 & 0.00074 & 0 & 0 & 0 \\ 0 & 0 & 0.0131 & 0 & 0 \\ -1.70 & -1.55 & -1.55 & 0.0011 & 0 \\ 0 & 0 & 0 & 0 & 0.0540 \end{bmatrix} \quad (A2.1)$$

$$L = \begin{bmatrix} 1.70 & 1.55 & 1.55 & 0 & 0 \\ 1.55 & 1.65 & 1.55 & 0 & 0 \\ 1.55 & 1.55 & 1.605 & 0 & 0 \\ 0 & 0 & 0 & 1.64 & 1.49 \\ 0 & 0 & 0 & 1.49 & 1.526 \end{bmatrix} \quad (A2.2)$$

By the help of digital computer, (A2.1) and (A2.2) may be computed as follows,

$$-L^{-1}(R - \omega N) = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \omega & A_{15} \omega \\ A_{21} & A_{22} & A_{23} & A_{24} \omega & A_{25} \omega \\ A_{31} & A_{32} & A_{33} & A_{34} \omega & A_{35} \omega \\ A_{41} \omega & A_{42} \omega & A_{43} \omega & A_{44} & A_{45} \\ A_{51} \omega & A_{52} \omega & A_{53} \omega & A_{54} & A_{55} \end{bmatrix}$$

and,

$$L^{-1} = \begin{bmatrix} A_{16} & A_{17} & A_{18} & A_{19} & A_{20} \\ A_{26} & A_{27} & A_{28} & A_{29} & A_{30} \\ A_{36} & A_{37} & A_{38} & A_{39} & A_{40} \\ A_{46} & A_{47} & A_{48} & A_{49} & A_{50} \\ A_{56} & A_{57} & A_{58} & A_{59} & A_{60} \end{bmatrix}$$

where,

$$\begin{aligned} A_{11} &= 0.005930 \\ A_{12} &= -0.00138 \\ A_{13} &= -0.04486 \\ A_{14} &= 8.874 \\ A_{15} &= 8.0623 \\ A_{16} &= 5.4109 \\ A_{17} &= 1.8648 \\ A_{18} &= -3.4245 \\ A_{19} &= 0.0 \\ A_{20} &= 0.0 \end{aligned}$$

$$\begin{aligned} A_{21} &= -0.002043 \\ A_{22} &= 0.00529 \\ A_{23} &= -0.0666 \\ A_{24} &= -3.0583 \\ A_{25} &= -2.7786 \\ A_{26} &= -1.8648 \\ A_{27} &= 7.1313 \\ A_{28} &= -5.0860 \\ A_{29} &= 0.0 \\ A_{30} &= 0.0 \end{aligned}$$

$$\begin{aligned} A_{31} &= -0.00375 \\ A_{32} &= -0.00377 \\ A_{33} &= 0.11583 \\ A_{34} &= -5.6163 \\ A_{35} &= -5.1026 \\ A_{36} &= -3.4245 \\ A_{37} &= -5.0860 \\ A_{38} &= 8.8450 \\ A_{39} &= 0.0 \\ A_{40} &= 0.0 \end{aligned}$$

$A_{41} = -9.1817$
 $A_{42} = -8.3715$
 $A_{43} = -8.3715$
 $A_{44} = 0.005919$
 $A_{45} = -0.28477$
 $A_{46} = 0.0$
 $A_{47} = 0.0$
 $A_{48} = 0.0$
 $A_{49} = 5.4010$
 $A_{50} = -5.2735$

$A_{51} = 8.9651$
 $A_{52} = 8.1740$
 $A_{53} = 8.174$
 $A_{54} = -0.005779$
 $A_{55} = 0.31344$
 $A_{56} = 0.0$
 $A_{57} = 0.0$
 $A_{58} = 0.0$
 $A_{59} = -5.2735$
 $A_{60} = 5.8044$

TRANSMISSION LINE DATA

$L_1 = 0.10$	$L_2 = 0.15$	$L_3 = 0.10$	$L_4 = 0.20$
$R_1 = 0.01$	$R_2 = 0.015$	$R_3 = 0.015$	$R_4 = 0.02$
$B_1 = 0.085$	$B_2 = 0.1275$	$B_3 = 0.085$	$B_4 = 0.17$
$G_1 = 0.0$	$G_2 = 0.0$	$G_3 = 0.0$	$G_4 = 0.0$

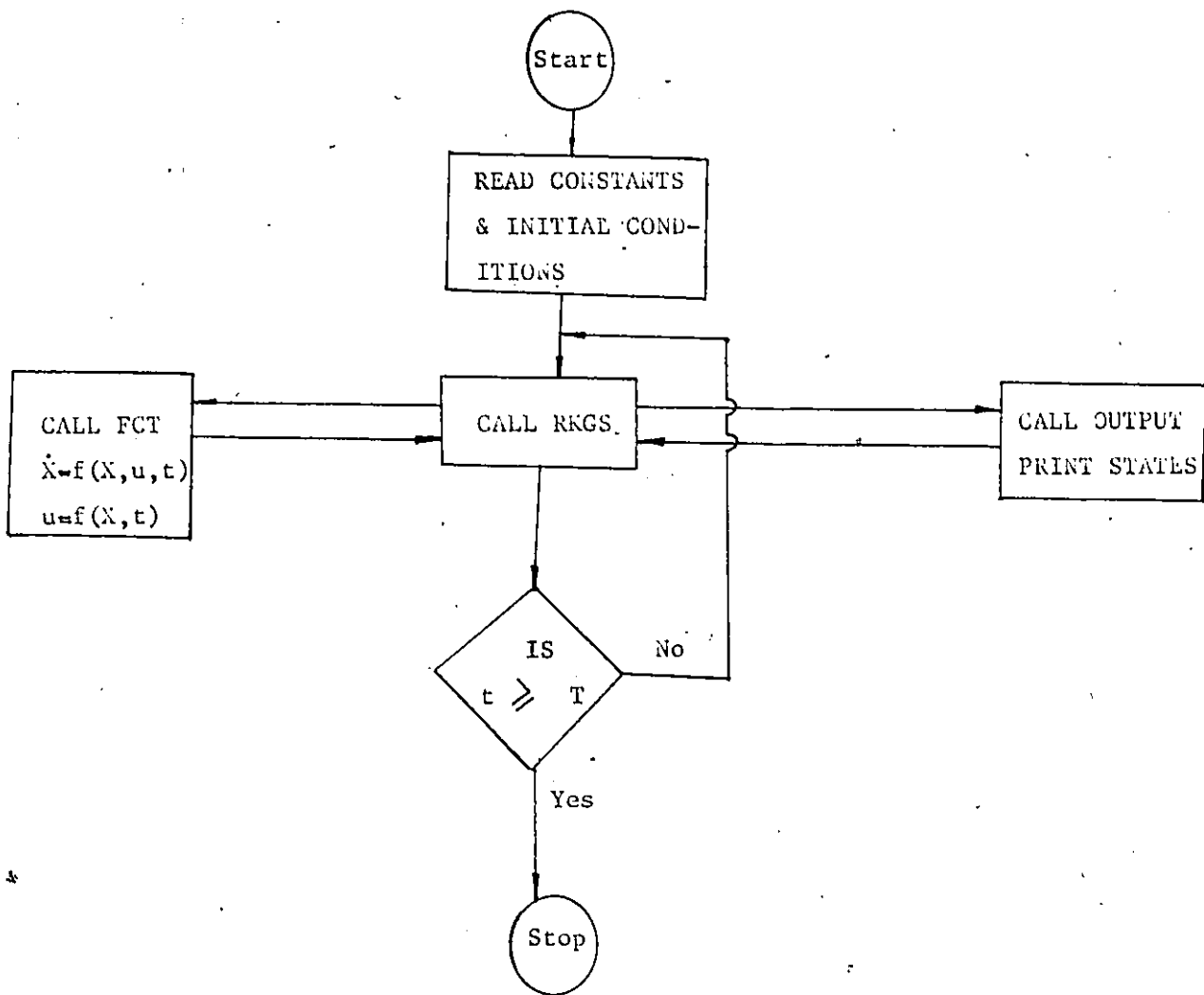


Fig. 5 : Flow Chart For Simulation (Main Program)

```

C      MATRIX INVERSION
C      AND MULTIPLICATION PROGRAM
      DIMENSION A(5,5),B(5,5),R(5,5),L(5),L(5)
      DOUBLE PRECISION A,D,B,R
      READ(5,11) ((A(I,J),J=1,5),I=1,5)
      WRITE(6,12) ((A(I,J),J=1,5),I=1,5)
      CALL MINV(A,5,D,L,M)
      READ(5,11) ((B(I,J),J=1,5),I=1,5)
      DO 30 I=1,5
      DO 30 J=1,5
      R(I,J)=0.0
      DO K=1,5
30     R(I,J)=R(I,J)*A(I,K)*B(K,J)
      WRITE (6,12) ((A(I,J),J=1,5),I=1,5)
      WRITE (6,12) ((B(I,J),J=1,5),I=1,5)
      WRITE (6,12) ((R(I,J),J=1,5),I=1,5)
11     FORMAT(5D15.6)
12     FORMAT(5X,5D25.16/)
      STOP
      END
      SUBROUTINE MINV(A,N,D,L,M)
      DIMENSION A(1),L(1),M(1)
      DOUBLE PRECISION A,D,EIGA,HOLD
      D=1.0
      NK=-N
      DO 30 K=1,N
      NK=NK+N
      L(K)=K
      M(K)=K
      KK=NK+K
      BIGA=A(KK)
      DO 20 J=K,N
      IZ=N*(J-1)
      DO 20 I=K,N
      IJ=IZ+I
20     IF(DABS(BIGA)-DABS(A(IJ))) 15,20,20
25     BIGA=A(IJ)
      L(K)=I
      M(K)=J
20     CCNTINUE
      J=L(K)
      IF(J-K) 35,35,25
25     KI=K-N
      DO 30 I=1,N
      KI=KI+N
      HCLD=-A(KI)
      JI=KI-K+J
30     A(KI)=A(JI)
35     A(JI)=HCLD
      I=M(K)
      IF(I-K) 45,45,33
38     JP=N*(I-1)
      DO 40 J=1,N
      JK=NK+J
      JJ=JP+J
      HCLD=-A(JK)
      A(JK)=A(JI)
40     A(JI)=HCLD
45     IF(BIGA) 48,46,48
46     D=0.0
      RETURN
48     DC 55 I=1,N
      IF(I-K) 50,55,50
50     IK=NK+I

```

```

55  A(IK)=A(IK)/(-BIGA)
    CCNTINUE
    DC 65 I=1,N
    IK=NK+I
    HCLD=A(IK)
    IJ=I-N
    DC 65 J=1,N
    IJ=IJ+N
    IF(I-K) 60,65,60
60  IF(J-K) 62,65,62
62  KJ=IJ-I+K
    A(IJ)=HOLD*A(KJ)+A(IJ)
65  CCNTINUE
    KJ=K-N
    DC 75 J=1,N
    KJ=KJ+N
    IF(J-K) 70,75,70
70  A(KJ)=A(KJ)/BIGA
75  CCNTINUE
    D=D*BIGA
    A(KK)=1.0/BIGA
90  CCNTINUE
    K=N
100 K=(K-1)
    IF(K) 150,150,105
105 I=L(K)
    IF(I-K) 120,120,108
108 JQ=N*(K-1)
    JR=N*(I-1)
    DC 110 J=1,N
    JK=JQ+J
    HCLD=A(JK)
    JI=JR+J
    A(JK)=A(JI)
110 A(JI)=HCLD
120 J=M(K)
    IF(J-K) 100,100,125
125 KI=K-N
    DC 130 I=1,N
    KI=KI+N
    HCLD=A(KI)
    JI=KI-K+J
    A(KI)=-A(JI)
130 A(JI)=HCLD
    GC TC 100
150 RETURN
    END

```

C

STEADY STATE SOLUTION

REAL *8 A(20,20),C(20),DD(20,20),ERR(20),Y(20)

REAL IM,IL1,IL2,IL3,IL4

REAL *8 AA1,AA2,AA4,AA6,AA7,AA22,AA25,AA27,AA23

REAL *8 IFD,TIN,PCUT,QCUTP

REAL L1,L2,L3,L4,LAD

DATA C/ -0.13D+01,0.9D+00,-0.13D+01,0.12D+01,-0.17D+01,

X 0.8D+00,-0.13D+01,0.12D+01,-0.16D+01,0.7D+00,-0.12D+01.

X 0.11D+01,-0.15D+01,0.7D+00,-0.12D+01,0.11D+01,-0.15D+01.

X 0.7D+00,0.25D+01,0.1D+01/

AA1=-0.593048054404063D-02

AA2=0.1383757845494219D-02

AA4=-0.887401314710097D+01

AA6=-0.5410963626281079D+01

AA7=-0.186437580255D+01*0.17320508D+01*0.742D-03/0.155D+01

AA22=0.9181708784596858D+01

AA23=0.8371558009485371D+01

AA25=-0.591950166348127D-02

AA27=-0.5401005167409917D+01

LAD=1.55

AA34=-0.170D+01

AA35=-0.15D+01

AA37=0.164D+01

RF=0.742D-03

B1=0.085

B2=0.1275

B3=0.335

B4=0.17

L1=0.1

L2=0.15

L3=0.1

L4=0.2

R1=0.01

R2=0.315

R3=0.01

R4=0.02

G1=0.0

G2=0.0

G3=0.0

G4=0.0

VIN=1.0

DD 1 I=1.20

DC 1 J=1.20

1

A(1,J)=0.0

A(1,1)=AA1

A(1,2)=AA4

A(1,3)=AA6

A(1,19)=AA7+0.17320508D+01*AA2/LAD

A(2,1)=AA22

A(2,2)=AA25

A(2,4)=AA27

A(2,19)=0.17320508D+01*AA23/LAD

A(3,1)=1.0

A(3,3)=-G1

A(3,4)=-B1

A(3,5)=-1.0

A(4,2)=1.0

A(4,3)=B1

A(4,4)=-G1

A(4,6)=-1.0

A(5,3)=1.0

A(5,5)=-R1

A(5,6)=-L1

A(5,7)=-1.0

```

A(6.4)=1.0
A(6.5)=L1
A(6.6)=-R1
A(6.8)=-F.0
A(7.5)=1.0
A(7.7)=-G2
A(7.8)=-B2
A(7.9)=-1.0
A(8.6)=1.0
A(8.7)=B2
A(8.8)=-G2
A(8.10)=-1.0
A(9.7)=1.0
A(9.9)=-R2
A(9.10)=-L2
A(9.11)=-1.0
A(10.8)=1.0
A(10.9)=L2
A(10.10)=-R2
A(10.12)=-1.0
A(11.9)=1.0
A(11.11)=-G3
A(11.12)=-B3
A(11.13)=-1.0
A(12.10)=1.0
A(12.11)=E3
A(12.12)=-G3
A(12.14)=-1.0
A(13.11)=1.0
A(13.13)=-R3
A(13.14)=-L3
A(13.15)=-1.0
A(14.12)=1.0
A(14.13)=L3
A(14.14)=-R3
A(14.16)=-1.0
A(15.13)=1.0
A(15.15)=-G4
A(15.16)=-B4
A(15.17)=-1.0
A(16.14)=1.0
A(16.15)=B4
A(16.16)=-G4
A(16.18)=-1.0
A(17.15)=1.0
A(17.17)=-R4
A(17.18)=-L4
A(18.16)=1.0
A(18.17)=L4
A(18.18)=-R4
ITER=0
12 A(17.20)=0.17320508D+01*VIN*DCOS(C(20))
A(18.20)=0.17320508D+01*VIN*DSIN(C(20))
A(19.1)=C(3)
A(19.2)=C(4)
A(19.3)=C(1)
A(19.4)=C(2)
A(20.1)=-C(4)
A(20.2)=C(3)
A(20.3)=C(2)
A(20.4)=-C(1)
CALL DEQTN(X,C,ERR)
10 DC 10 I=1,20
Y(I)=-ERR(I)
WRITE (6,51) (ERR(I),I=1,20)
51 FORMAT(5E16.5)
DC 11 I=1,20
DC 11 J=1,20

```

```

11  DB(I,J)=A(I,J)
    CALL DT51S(DD,Y,20)
    DC 13 I=1,20
13  C(I)=C(I)+Y(I)
    ITER=ITER+1
    SUM=0.0
    DC 14 I=1,20
14  SUM=SUM+DABS(Y(I))
    IF(ITER .GT. 20) GO TO 15
    IF(SUM-0.1E-13) 15,12,12
15  EFD=C(19)
    IFD=C(19)*0.17320559D+01/LAD
    DEL=C(20)
    DELTA=DEL*180.0/3.141592D+01
    TIN=0.60D-01*C(1)*C(2)+C(2)*IFD*0.155D+01
    WRITE(6,7) DELTA,TIN
7   FORMAT(/10X,'DELTA=',F6.2,5X,'TIN=',D25.16//)
    WRITE(6,50) (C(I),I=1,20)
50  FORMAT(5D25.16)
    ET=DSQRT((C(3)*C(3)+C(4)*C(4))/3.)
    E2=DSQRT((C(7)*C(7)+C(8)*C(8))/3.)
    E3=DSQRT((C(11)*C(11)+C(12)*C(12))/3.)
    E4=DSQRT((C(15)*C(15)+C(16)*C(16))/3.)
    IM=DSQRT((C(1)*C(1)+C(2)*C(2))/3.)
    IL1=DSQRT((C(5)*C(5)+C(6)*C(6))/3.)
    IL2=DSQRT((C(9)*C(9)+C(10)*C(10))/3.)
    IL3=DSQRT((C(13)*C(13)+C(14)*C(14))/3.)
    IL4=DSQRT((C(17)*C(17)+C(18)*C(18))/3.)
    DEL1=DEL-DATAN(-C(3)/C(4))
    DEL2=DEL-DATAN(-C(7)/C(8))
    DEL3=DEL-DATAN(-C(11)/C(12))
    DEL4=DEL-DATAN(-C(15)/C(16))
    DELI=DEL-DATAN(-C(1)/C(2))
    ANG=180.0/3.141592
    DELTA1=DELI*ANG
    DELTA2=DEL2*ANG
    DELTA3=DEL3*ANG
    DELTA4=DEL4*ANG
    DELTAI=DELI*ANG
    PF=CCS(DELI-DELI)
    PCUT=C(1)*C(3)+C(2)*C(4)
    QJUTP=C(2)*C(3)-C(1)*C(4)
    *WRITE(6,4) IFD,ET,E2,E3,E4,VIN
    WRITE(6,4) DELTA1,DELTA2,DELTA3,DELTA4
    WRITE(6,4) IM,IFD,IL1,IL2,IL3,IL4
4   FORMAT(8F15.7/)
    WRITE(6,4) IM,DELTAI,PCUT,QJUTP,PF
    WRITE(6,50) IFD
    STOP
    END
C   STEADY STATE EQUATIONS
    SUBFCUTINE DEQTN(X,Y,ERR)
    REAL *8 Y(20),ERR(20),PCUT,QJUTP,IFD
    REAL *8 AA1,AA2,AA3,AA4,AA5,AA6,AA7,AA22,AA25,AA27,AA23
    REAL L1,L2,L3,L4,LAD
    B1=0.085
    B2=0.1275
    B3=0.085
    B4=0.17
    L1=0.1
    L2=0.15
    L3=0.1
    L4=0.2
    P1=0.01
    R2=0.015
    R3=0.01
    R4=0.02
    G1=0.0

```

```

G2=0.0
G3=0.0
G4=0.0
VIN=1.0
PCUT=0.3D+01
QOUTP=0.1859233D+01
AA1=-0.593048054404063D-02
AA2=0.1363737845494219D-02
AA4=-0.887401314710057D+01
AA6=-0.5410983626281079D+01
AA7=-0.186487580255D+01*0.17320508D+01*0.742D-03/0.155D+01
AA22=0.9181708784596855D+01
AA25=-0.591950166348127D-02
AA27=-0.5401005167409917D+01
AA23=0.8371558009485371D+01
RF=0.742E-03
LAD=1.55
IFD=Y(19)*0.17320508D+01/LAD
ERR(1)=AA1*Y(1)+AA4*Y(2)+AA6*Y(3)+AA2*IFD+AA7*Y(19)
ERR(2)=AA22*Y(1)+AA25*Y(2)+AA27*Y(4)+AA23*IFD
ERR(3)=Y(1)-G1*Y(3)-B1*Y(4)-Y(5)
ERR(4)=Y(2)+B1*Y(3)-G1*Y(4)-Y(6)
ERR(5)=Y(3)-R1*Y(5)-L1*Y(6)-Y(7)
ERR(6)=Y(4)+L1*Y(5)-R1*Y(6)-Y(8)
ERR(7)=Y(5)-G2*Y(7)-B2*Y(8)-Y(9)
ERR(8)=Y(6)+B2*Y(7)-G2*Y(8)-Y(10)
ERR(9)=Y(7)-R2*Y(9)-L2*Y(10)-Y(11)
ERR(10)=Y(8)+L2*Y(9)-R2*Y(10)-Y(12)
ERR(11)=Y(9)-G3*Y(11)-B3*Y(12)-Y(13)
ERR(12)=Y(10)+B3*Y(11)-G3*Y(12)-Y(14)
ERR(13)=Y(11)-R3*Y(13)-L3*Y(14)-Y(15)
ERR(14)=Y(12)+L3*Y(13)-R3*Y(14)-Y(16)
ERR(15)=Y(13)-G4*Y(15)-B4*Y(16)-Y(17)
ERR(16)=Y(14)+B4*Y(15)-G4*Y(16)-Y(18)
ERR(17)=Y(15)-R4*Y(17)-L4*Y(18)+0.17320508D+01*VIN*DSIN(Y(20))
ERR(18)=Y(16)+L4*Y(17)-R4*Y(18)-0.17320508D+01*VIN*DCOS(Y(20))
ERR(19)=Y(1)*Y(3)+Y(2)*Y(4)-PCUT
ERR(20)=-Y(1)*Y(4)+Y(2)*Y(3)-QOUTP
RETURN
END

```

C SOLUTION OF MATRIX EQUATION

SUBROUTINE DTSIS(A,B,N)

REAL *8 A(20,20),d(20)

REAL *8 BA,D,H

NM1=N-1

D=L.0

DO 7 K=1,NM1

BA=A(K,K)

J=K

KP1=K+1

DO 1 I=KP1,N

IF(ABS(BA).GE.DABS(A(I,K))) GO TO 1

BA=A(I,K)

J=I

1 CONTINUE

D=D+BA

IF(J.LE.K) GO TO 3

IF(DABS(D).EQ.0.0) GO TO 3

DO 2 I=K,N

H=A(K,I)

A(K,I)=A(J,I)/BA

2 A(J,I)=H

H=B(K)

B(K)=B(J)/BA

B(J)=H

GO TO 5

3 DO 4 I=KP1,N

4 A(K,I)=A(K,I)/BA

```

      B(K)=B(K)/DA
5     DO 7 I=KP1,N
      DC 6 J=KP1,N
-----
6     A(I,J)=A(I,J)-A(I,K)*A(K,J)
7     B(I)=B(I)-A(I,K)*B(K)
      D=D*A(N,N)
      IF(DABS(D) .EQ. 0.0) GO TO 9
      B(N)=B(N)/A(N,N)
      DO 8 I=1,NM1
      K=N-I
-----
      KP1=K+1
      DO 8 J=KP1,N
8     B(K)=B(K)-A(K,J)*B(J)
      RETURN
9     WRITE (6,10)
10    FORMAT('          SINGULAR SOLUTION')
      RETURN
      END
-----

```

PROGRAM FOR LOAD VARIATION AND CONTROL

BLOCK DATA

DIMENSION AY(365),BY(365),CY(365),DY(365),EY(365),FY(365)

REAL A(38)

REAL L1,L2,L3,L4,LAD

COMMON /RCY/A,NA,AY,BY,ET1,ET2,PP4,ET3

COMMON/SANDY/ AIT1,AIT2,DLC,QLC,QLC1,QLC1,QLC2,QLC2

COMMON/NAND/CH1,CH2,CH3,CH4,TT,TIN,VIN,D,AA39

COMMON/RGN/WO,H,RF,LAD,P2,Q2,P3,Q3,P4,Q4,TJ,EFD,PP3

COMMON/NCR/B1,B2,B3,B4,R1,R2,R3,R4,CY,DY,EY,FY

COMMON/DRN/L1,L2,L3,L4,G1,G2,G3,G4,ET4

DATA A/-0.5930438054404063E-02,0.1383737845494219E-02,

X 0.4486213044286703E-01,-0.887401314710097E+01,

X -0.8062365603158806E+01,-0.5410983626281079E+01,

X -0.1864875802552856E+01,0.2043903879597931E-02,

X -0.5291478447285815E-02,0.6662692640029753E-01,

X 0.3058396316186684E+01,0.2773664945803756E+01,

X 0.1864875802552856E+01,0.7131372570466057E+01,

X 0.3753350760716203E-02,0.3773830437711510E-02,

X -0.115830533376356E+00,0.5616327780633734E+01,

X 0.5102639264112356E+01,0.3424590110142521E+01,

X -0.5086024916053248E+01,0.9181708784596858E+01,

X 0.8371558009485371E+01,0.8371558009485371E+01,

X -0.5919501663481270E-02,0.2847738373327667E+00,

X -0.5401005167409917E+01,-0.8965102286401912E+01,

X -0.8174063849366450E+01,-0.8174063849366450E+01,

X 0.5779854179939117E-02,-0.3134423444468036E+00,

X 0.5273589580236420E+01,

X -0.170E+01,-0.155E+01,-0.155E+01,0.164E+01,0.149E+01/

DATA B1,B2,B3,B4/0.085,0.1275,0.085,0.17/

DATA R1,R2,R3,R4/0.01,0.015,0.01,0.02/

DATA L1,L2,L3,L4/0.10,0.15,0.10,0.20/

DATA G1,G2,G3,G4/0.0,0.0,0.0,0.0/

DATA WO,H,RF,LAD/376.59116,2.5,0.000742,1.55/

DATA P2,Q2,P3,Q3,P4,Q4/0.1,0.01,0.1,0.01,0.1,0.01/

DATA TJ,EFD,VIN/0/1834.9558,2.472045378,1.0,2.0/

DATA AA39,TIN/0.0008291494,3.002199645396/

DATA NA/0/

END

DIMENSION Y(23),DERY(23),PRMT(5),AUX(4,23)

DIMENSION AY(365),BY(365),CY(365),DY(365),EY(365),FY(365)

REAL L1,L2,L3,L4,LAD

COMMON/SANDY/ AIT1,AIT2,DLC,QLC,QLC1,QLC1,QLC2,QLC2

COMMON/NAND/CH1,CH2,CH3,CH4,TT,TIN,VIN,D,AA39

COMMON/RGN/WO,H,RF,LAD,P2,Q2,P3,Q3,P4,Q4,TJ,EFD,PP3

COMMON/NCR/B1,B2,B3,B4,R1,R2,R3,R4,CY,DY,EY,FY

COMMON/DRN/L1,L2,L3,L4,G1,G2,G3,G4,ET4

EXTERNAL FCT

EXTERNAL COTP,CRKS

REAL A(38)

COMMON /RCY/A,NA,AY,BY,ET1,ET2,PP4,ET3

DATA Y/-0.1223935800515844E+01,0.2762392452067018E+01,

X 0.0E+00,0.7134043466009036E+00,0.0E+00,0.1E+01,

X 0.61600970780501E+00,-0.993345431E-01,

X 0.1870200216E+00,-0.1410955774942271E+01,

X 0.6140098264667290E+00,-0.155032234E+00,

X 0.2617574138E+00,-0.1672713183935244E+01,

X 0.4590375972748078E+00,-0.1070748423E+00,

X 0.15259258E+00,-0.1825305725487668E+01,

X 0.3519027820074389E+00,-0.2170300306E+00,

X 0.2735566373E+00,-0.2098802293736306E+01,

X 0.1349328001315060E+00/

X=0.0

CALL FCT(X,Y,DERY)

```

2      WRITE (6,2) (DERY(I),I=1,23)
      FORMAT(5D16.5)
      PRMT(1)=0.0
      PRMT(2)=18.0
      PRMT(3)=0.0001
      PRMT(4)=0.000001
      NDIM=23
      DC 1 I=1,NDIM
1      DERY(1)=1.0/23.0
      CALL CRKS(PRMT,Y,DERY,NDIM,IHLF,FCT,OUTP,AUX)
      WRITE (6,20) IHLF
20     FORMAT(I20)
      WRITE (6,100)
100    FORMAT(//,' VOLTAGE NCDE 1')
      DC 101 I=1,NA
      WRITE(6,102) BY(I)
102    FORMAT(5E16.7)
101    CCNTINUE
      WRITE(6,103)
103    FORMAT(//,' VOLTAGE NCDE 2')
      DO 104 I=1,NA
      WRITE(6,102) CY(I)
104    CCNTINUE
      WRITE (6,105)
105    FORMAT(//,' VOLTAGE NCDE 3')
      DC 106 I=1,NA
      WRITE (6,102) DY(I)
106    CCNTINUE
      WRITE (6,107)
107    FORMAT(//,' VOLTAGE NCDE 4')
      DC 108 I=1,NA
      WRITE (6,102) EY(I)
108    CCNTINUE
      WRITE (6,109)
109    FORMAT(//,' CONTROL')
      DC 110 I=1,NA
      WRITE (6,102) FY(I)
110    CCNTINUE
      STOP
      END
C      OUTPUT SUBROUTINE
      SUBROUTINE OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
      REAL A(38)
      DIMENSION Y(23),DERY(23),PRMT(5)
      DIMENSION AY(365),BY(365),CY(365),DY(365),EY(365),FY(365)
      REAL L1,L2,L3,L4,LAD
      COMMON /ROY/A,NA,AY,BY,ET1,ET2,PP4,ET3
      COMMON/SANDY/AIT1,AIT2,DLC,JLC,DLC1,QLC1,QLC2,QLC3
      COMMON/NAND/CH1,CH2,CH3,CH4,TT,TIN,VIN,D,AA39
      COMMON/RCN/W0,H,RF,LAD,P2,Q2,P3,Q3,P4,Q4,TJ,EFD,PP3
      COMMON/NJR/B1,B2,B3,B4,R1,R2,R3,R4,CY,DY,EY,FY
      COMMON/JRN/L1,L2,L3,L4,G1,G2,G3,G4,ET4
      ET22=SQRT(((Y(12)/B2)*(Y(12)/B2)+(Y(13)/B2)*(Y(13)/B2))/3.0)
      BB2=B2+0.002*(1.377595-ET22)
      BB2=0.137
      BB3=0.1645
      BB4=0.22
      BB5=0.247
      IF(X .GE. 0.0) B2=BB2
      IF(X .GE. 9.0) B2=BB3
      IF(X .GE. 12.0) B2=BB4
      IF(X .GE. 15.0) B2=BB5
      IF(X .GE. 4.0) B2=BB2
      TIN2=3.002199645396+0.4
      TIN1=3.002199645396+(0.2*(X-1)*(X-1)*(X-1)/(12.0*12.0*12.0)
      X)*2.0
      TIN1=3.002199645396+(0.4*(X-1)*(X-1)*(X-1)/(12.0*12.0*12.0))
      IF(X .GT. 4.0) TIN=TIN1

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IF(X .GT. 13.0) TIN=TIN2
PP3=0.1+(0.7*(X-4)*Y(X-4)*Y(X-4)/(8.0*8.0*8.0))
IF(X .GE. 4.0) P3=PP3
IF(X .GT. 12.0) P3=0.80
PP4=0.01+(0.05*(X-4)*Y(X-4)*Y(X-4)/(8.0*8.0*8.0))
IF(X .GE. 4.0) Q3=PP4
IF(X .GT. 12.0) Q3=0.06
PP5=0.1+(0.4*(X-4)*Y(X-4)*Y(X-4)/(8.0*8.0*8.0))
IF(X .GE. 4.0) P4=PP5
IF(X .GT. 12.0) P4=0.5
PP6=0.01+(0.04*(X-4)*Y(X-4)*Y(X-4)/(8.0*8.0*8.0))
IF(X .GE. 4.0) Q4=PP6
IF(X .GT. 12.0) Q4=0.05
C   DLC IS LOAD CURRENT ON NODE- ONE OF THE
C   SYSTEM(CONSUMER LOAD- DIRECT AXIS)
C   QLC IS LOAD CURRENT ON NODE- ONE OF THE
C   SYSTEM(CONSUMER LOAD- QUADRATURE AXIS)
DLC=(P2*Y(8)-Q2*Y(9))/(Y(8)*Y(8)+Y(9)*Y(9))
QLC=(P2*Y(9)+Q2*Y(8))/(Y(8)*Y(8)+Y(9)*Y(9))
DLC1=(P3*(Y(12)/B2)-Q3*(Y(13)/B2))/(Y(12)/B2*(Y(12)/B2)
X+(Y(13)/B2)*(Y(13)/B2))
QLC1=(P3*(Y(13)/B2)+Q3*(Y(12)/B2))/(Y(12)/B2*(Y(12)/B2)
X+(Y(13)/B2)*(Y(13)/B2))
DLC2=(P4*(Y(16)/B3)-Q4*(Y(17)/B3))/(Y(16)/B3*(Y(16)/B3)
X+(Y(17)/B3)*(Y(17)/B3))
QLC2=(P4*(Y(17)/B3)+Q4*(Y(16)/B3))/(Y(16)/B3*(Y(16)/B3)
X+(Y(17)/B3)*(Y(17)/B3))
DLC3=(P5*(Y(20)/B4)-Q5*(Y(21)/B4))/(Y(20)/B4*(Y(20)/B4)
X+(Y(21)/B4)*(Y(21)/B4))
QLC3=(P5*(Y(21)/B4)+Q5*(Y(20)/B4))/(Y(20)/B4*(Y(20)/B4)
X+(Y(21)/B4)*(Y(21)/B4))
IF(X .LE. 0.0) XNEW=0.0
IF(X-XNEW) 14,20,20
XNEW=XNEW+0.050
DELTA=Y(7)+190.0/3.141592
IT=SQRT((DLC1*QLC1)+(QLC1*QLC1)/3.0)
CH1=SQRT((Y(8)+Y(8)+Y(9)*Y(9))/3.0)
CH2=SQRT((Y(12)*Y(12)+Y(13)*Y(13))/3.0)
CH3=SQRT((Y(16)*Y(16)+Y(17)*Y(17))/3.0)
CH4=SQRT((Y(20)*Y(20)+Y(21)*Y(21))/3.0)
ET1=SQRT(((Y(8)/B1)*(Y(8)/B1)+(Y(9)/B1)*(Y(9)/B1))/3.0)
AIT1=SQRT((Y(1)*Y(1)+Y(4)*Y(4))/3.0)
ET2=SQRT(((Y(12)/B2)*(Y(12)/B2)+(Y(13)/B2)*(Y(13)/B2))/3.0)
ET3=SQRT(((Y(16)/B3)*(Y(16)/B3)+(Y(17)/B3)*(Y(17)/B3))/3.0)
ET4=SQRT(((Y(20)/B4)*(Y(20)/B4)+(Y(21)/B4)*(Y(21)/B4))/3.0)
AIT2=SQRT((Y(10)*Y(10)+Y(11)*Y(11))/3.0)
13  FORMAT(10X,6E16.6)
C 15  WRITE(6,12) X
C   WRITE(6,13) (Y(I),I=8,23)
C   WRITE(6,17)
17  FORMAT(10X,'DERIVATIVE')
12  FORMAT(F10.5)
C   WRITE(6,1000) Q3,ET1,ET2,ET3,TIN,B2
1000 FORMAT(6E16.7,5E16.7)
NA=NA+1
AY(NA)=X
BY(NA)=ET1
CY(NA)=ET2
DY(NA)=ET3
EY(NA)=ET4
FY(NA)=B2
14  RETURN
END
SUBROUTINE FCT(X,Y,DERY)
DIMENSION Y(23),DERY(23)
DIMENSION AY(365),BY(365),CY(365),DY(365),EY(365),FY(365)
REAL A(38)
COMMON /RCY/A,NA,AY,BY,ET1,ET2,PP4,ET3

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REAL L1,L2,L3,L4,LAD
COMMON/SANDY/AIT1,AIT2,DLC,OLC,DLC1,OLC1,DLC2,OLC2
COMMON/NAND/CH1,CH2,CH3,CH4,TT,TIN,VIN,D,AA39
COMMON/RDN/WO,H,RF,LAD,P2,Q2,P3,Q3,P4,Q4,TJ,EFD,PP3
COMMON/NCR/B1,B2,B3,B4,R1,R2,R3,R4,CY,DY,EY,FY
COMMON/ORN/L1,L2,L3,L4,G1,G2,G3,G4,ET4
DERY(1)=A(1)*Y(1)+A(2)*Y(2)+A(3)*Y(3)+A(4)*Y(6)*Y(4)
X +A(5)*Y(6)+Y(5)+A(6)*(Y(8)/B1)+A(7)*AA39*EFD
DERY(2)=A(8)*Y(1)+A(9)*Y(2)+A(10)*Y(3)+A(11)*Y(6)
X *Y(4)+A(12)*Y(6)*Y(5)+A(13)*(Y(8)/B1)+A(14)*AA39*EFD
DERY(3)=A(15)*Y(1)+A(16)*Y(2)+A(17)*Y(3)+A(18)*Y(6)*Y(4)
X +A(19)*Y(6)*Y(5)+A(20)*(Y(8)/B1)+A(21)*AA39*EFD
DERY(4)=A(22)*Y(6)*Y(1)+A(23)*Y(6)*Y(2)+A(24)*Y(6)*Y(3)
X +A(25)*Y(4)+A(26)*Y(5)+A(27)*(Y(9)/B1)
DERY(5)=A(28)*Y(6)*Y(1)+A(29)*Y(6)*Y(2)+A(30)*Y(6)*Y(3)
X +A(31)*Y(4)+A(32)*Y(5)+A(33)*(Y(9)/B1)
DERY(6)=((A(34)+A(37))*Y(1)*Y(4)+A(35)*Y(4)*Y(2)+A(36)*
X Y(4)*Y(3)+A(38)*Y(1)*Y(5)-3.0*D*(Y(6)-1)+TIN)/(3.0*TJ)
DERY(7)=Y(6)-1
DERY(8)=(Y(1)-(G1/B1)*Y(8)-Y(6)*Y(9)-Y(10)-DLC)
DERY(9)=(Y(4)-(G1/B1)*Y(9)+Y(6)*Y(8)-Y(11)-OLC)
DEPY(10)=((Y(8)/B1)-R1*Y(10)-L1*Y(6)*Y(11)-(Y(12)/B2))/L1
DERY(11)=((Y(9)/B1)-R1*Y(11)+L1*Y(6)*Y(10)-(Y(13)/B2))/L1
DERY(12)=(Y(10)-(G2/B2)*Y(12)-Y(6)*Y(13)-Y(14)-DLC1)
DERY(13)=(Y(11)-(G2/B2)*Y(13)+Y(6)*Y(12)-Y(15)-OLC1)
DERY(14)=((Y(12)/B2)-R2*Y(14)-L2*Y(6)*Y(15)-(Y(16)/B3))/L2
DERY(15)=((Y(13)/B2)-R2*Y(15)+L2*Y(6)*Y(14)-(Y(17)/B3))/L2
DERY(16)=(Y(14)-(G3/B3)*Y(16)-Y(6)*Y(17)-Y(18)-DLC2)
DEPY(17)=(Y(15)-(G3/B3)*Y(17)+Y(6)*Y(16)-Y(19)-OLC2)
DERY(18)=((Y(16)/B3)-R3*Y(18)-L3*Y(6)*Y(19)-(Y(20)/B4))/L3
DERY(19)=((Y(17)/B3)-R3*Y(19)+L3*Y(6)*Y(18)-(Y(21)/B4))/L3
DERY(20)=(Y(18)-(G4/B4)*Y(20)-Y(6)*Y(21)-Y(22))
DERY(21)=(Y(19)-(G4/B4)*Y(21)+Y(6)*Y(20)-Y(23))
DERY(22)=((Y(20)/B4)-R4*Y(22)-L4*Y(6)*Y(23)
X +1.7320508*VIN* SIN(Y(7)))/L4
DERY(23)=((Y(21)/B4)-R4*Y(23)+L4*Y(6)*Y(22)
X -1.7320508*VIN* COS(Y(7)))/L4
DC 1 I=1,23
DERY(I)=DERY(I)*WO
RETURN
END
RUNGE KUTTA GILL CLASSICAL SUBROUTINE
SUBROUTINE CRKS(PRMT,Y,DERY,NDIM,IHLF,FACT,CUTP,AUX)
DIMENSION Y(23),DERY(23),PRMT(5),AUX(4,23),YY(23)
COMMON/SANDY/AIT1,AIT2
X=PRMT(1)
XEND=PRMT(2)
H=PRMT(3)
IHLF=0
1 IF(X-XEND) 2,2.9
2 CALL FCI(X,Y,DERY)
CALL CUTP(X,Y,DERY,IHLF,NDIM,PRMT)
DC 7 K=1,4
DC 6 I=1,NDIM
GC TO (3,4,4.5).K
3 YY(I)=Y(I)
GC TO 0
4 YY(I)=Y(I)+AUX(K-1,I)*0.5
GC TO 0
5 YY(I)=Y(I)+AUX(K-1,I)
6 CCNTINUE
CALL FCT(X,YY,DERY)
DC 7 I=1,NDIM
7 AUX(K,I)=H*DERY(I)
DC 8 I=1,NDIM
DY=(AUX(1,I)+2.0*AUX(2,I)+2.0*AUX(3,I)+AUX(4,I))/6.0
8 Y(I)=Y(I)+DY
X=X+H
GC TO 1
9 RETURN
END

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