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SYSTEM ANALYSIS OF ELECTRICAL ENERGY STORAGE SYSTEMS

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INTRODUCTION

The storage capacity of superconducting coils can be employed to balance the fluctuations between generating capacity and connected load in an electric power grid. Electrical energy is stored in the coil when the generating capacity exceeds the connected load. Electrical energy is returned to the grid when the load exceeds the generating capacity.

The superconducting coil would be connected to the power grid through a multi-phase SCR power converter (rectifier-inverter) bridge. Depending on the firing angle of the individual SCR's in the bridge, the power converter would function either as a rectifier, storing energy in the coil; or as an inverter, feeding power into the grid.

SYSTEM

The basic system is represented in Figure 1. The superconducting coil, inductance L, interfaces to a 3Φ power network through a delta, wye, double-way 3-phase bridge. Basically a 6 pulse rectifier. The Y connected transformer has a number of voltage taps. The coil current is i, the coil voltage is v. For a 6 pulse rectifier with phase control

$$v = 2.34\, V_\varphi \cos\alpha$$
$$= 2.34\, \frac{V_L}{h} \cos\alpha$$

where α is the firing angle for the individual SCR's, 1/h is the turns ratio for the transformer. V_L is the system line-line voltage and V_φ is the secondary or transformer voltage to ground.

With the control angle between 0 and 90^o the voltage v is positive and the coil is charging or increasing in energy. With the control angle between 90^o and 180^o the voltage v is negative, the coil is discharging and feeding AC power into the grid.

From the DC side the power flow into the coil is given by vi, or

$$PDC = 2.34\ V\varphi i \cos \alpha.$$

From the AC side the power flow out of the grid is

$$PAC = \sqrt{3} V_L I_L \cos \alpha$$

where I_L is the AC line current, since $I_L = \frac{1.35i}{h}$, and $V_L = h\ V\varphi$ PAC reduces to

$$PAC = 2.34\ V_\varphi i \cos \alpha$$

establishing the power balance between the AC line and the bridge converter.

In addition to real power the AC side must support reactive volt-amperes due to the phase back of the SCR's.

$$Q = 2.34\ V_\varphi i \sin \alpha$$

Whether the converter is in the rectify or invert mode with P either positive or negative, the VAR's are always positive, or lagging. To correct for a lagging power factor load on the grid a capacitor bank is employed.

OPERATING CYCLE

An electrical energy system will be subject to a variety of charge/discharge cycles. For system analysis a constant power charge/discharge cycle is assumed. The coil energy is limited to values between fully charged w_o and one-half charged $0.5\ w_o$. Each cycle is normalized for 12 hours, as indicated in Figure 2. This figure also depicts the coil current i, and coil voltage v. These parameters are normalized and expressed as a ratio of the system parameters I_o and V_o, where

$$I_o = \sqrt{\frac{2w_o}{L}}$$

$$V_o = \frac{w_o}{86,400} \sqrt{\frac{L}{2w_o}}$$

The power flow is constant at

$$P_o = V_o I_o = \frac{W_o}{86{,}400}$$

During the coil charging period

$$i = I_o \sqrt{\frac{12 + h}{24}}$$

$$v = V_o \sqrt{\frac{24}{12 + h}}$$

and during the coil discharging period

$$i = I_o \sqrt{\frac{36 - h}{24}}$$

$$v = - V_o \sqrt{\frac{24}{36 - h}}$$

<u>POWER CONVERTERS</u>

The design of the power converters is limited by commutation failure. Fundamentally the commutation overlap angle u limits the maximum value of the firing angle α. Commutations overlap is a delay in switching conduction between SCR's due to line inductance. The subject is developed in appendix I, where it is shown that

$$\alpha + u < \pi$$

This limits the maximum voltage during the invert phase. For a 6 pulse rectify, the commutation angle should be less than 30^o. Therefore, α is limited to 135^o in this analysis.

The other restraint in the system is the reactive volt-amperes generated by the phase back. Since the generated VAR's can be compensated by employing power factor correcting capacitors, only the swing of the generated VAR's need be limited. By employing voltage taps and phase back the coil voltage can be efficiently matched.

The results of using a two step voltage cycle is given in Figure 3. The results are normalized to the previously defined system parameters. The reactive power varies between $V_o I_o$ and 1.43 $V_o I_o$. The rating of the correcting capacitor bank is 1.215 $V_o I_o$. The net reactive volt amperes varies between .215 $V_o I_o$ lead and lag, and results in a corrected power factor that varies between 0.978 lead and lag.

As the number of steps in the phase voltage increases the phase back angle is decreased, increasing the corrected power factor. Table I gives the results of an increase in the number of transformer taps.

TABLE I

Number of Voltage Steps	VAR Rating of Capacitor Banks	Power Factor
1	0.933 $V_0 I_0$	$\pm$ 0.94
2	1.215 $V_0 I_0$	$\pm$ 0.978
4	1.096 $V_0 I_0$	$\pm$ 0.995

Though the analysis was performed for a period of 24 hours, the results are general. As the period varies, the normalizing voltage V_0 reflects the new period. In lieu of 86,400 use the number of seconds in the period to establish V_0 and the power P_0.

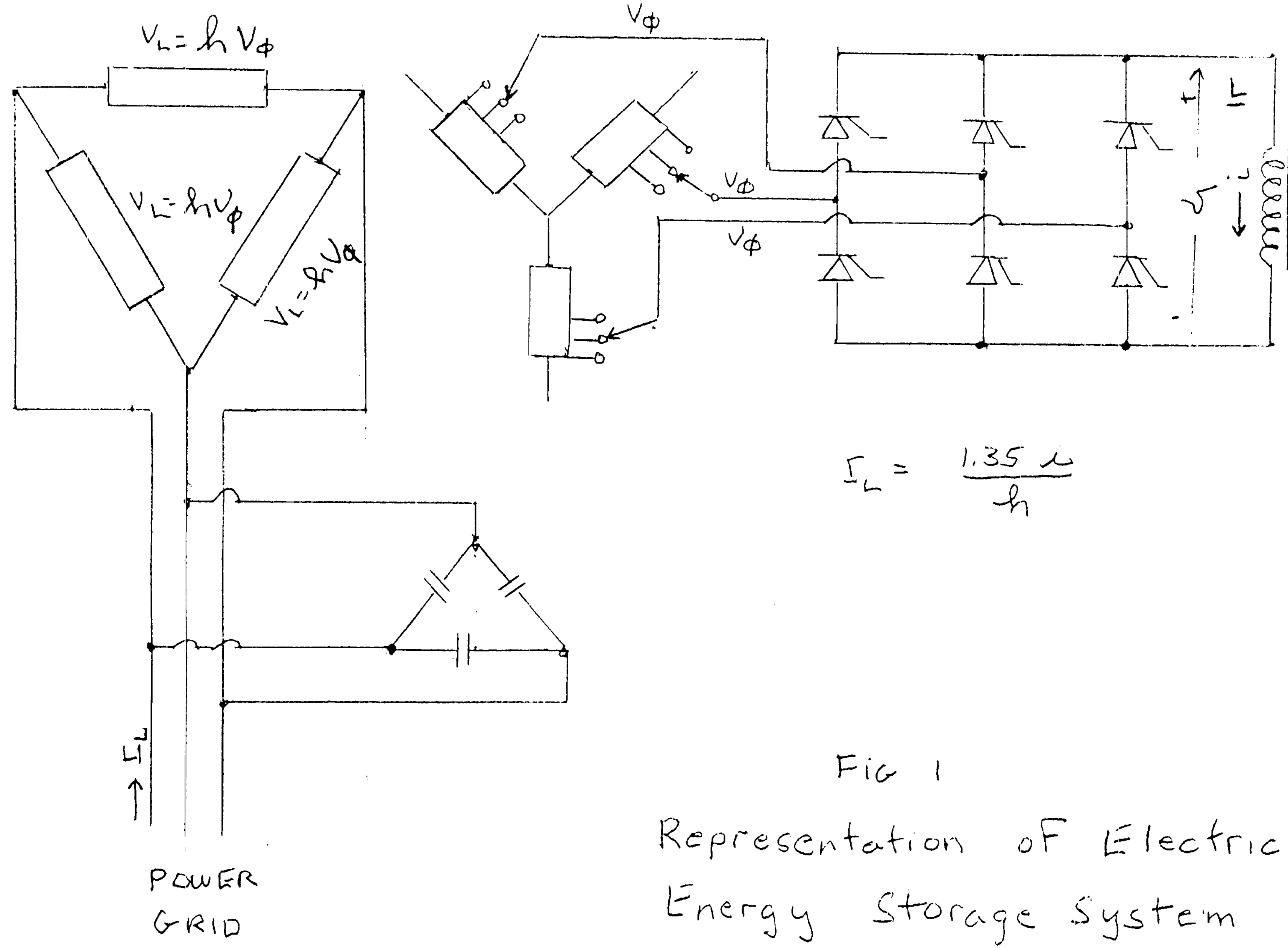


Fig 1

Representation of Electric Energy Storage System

FIG 2

ENERGY CYCLE OF COIL INCLUDING CURRENT AND VOLTAGE

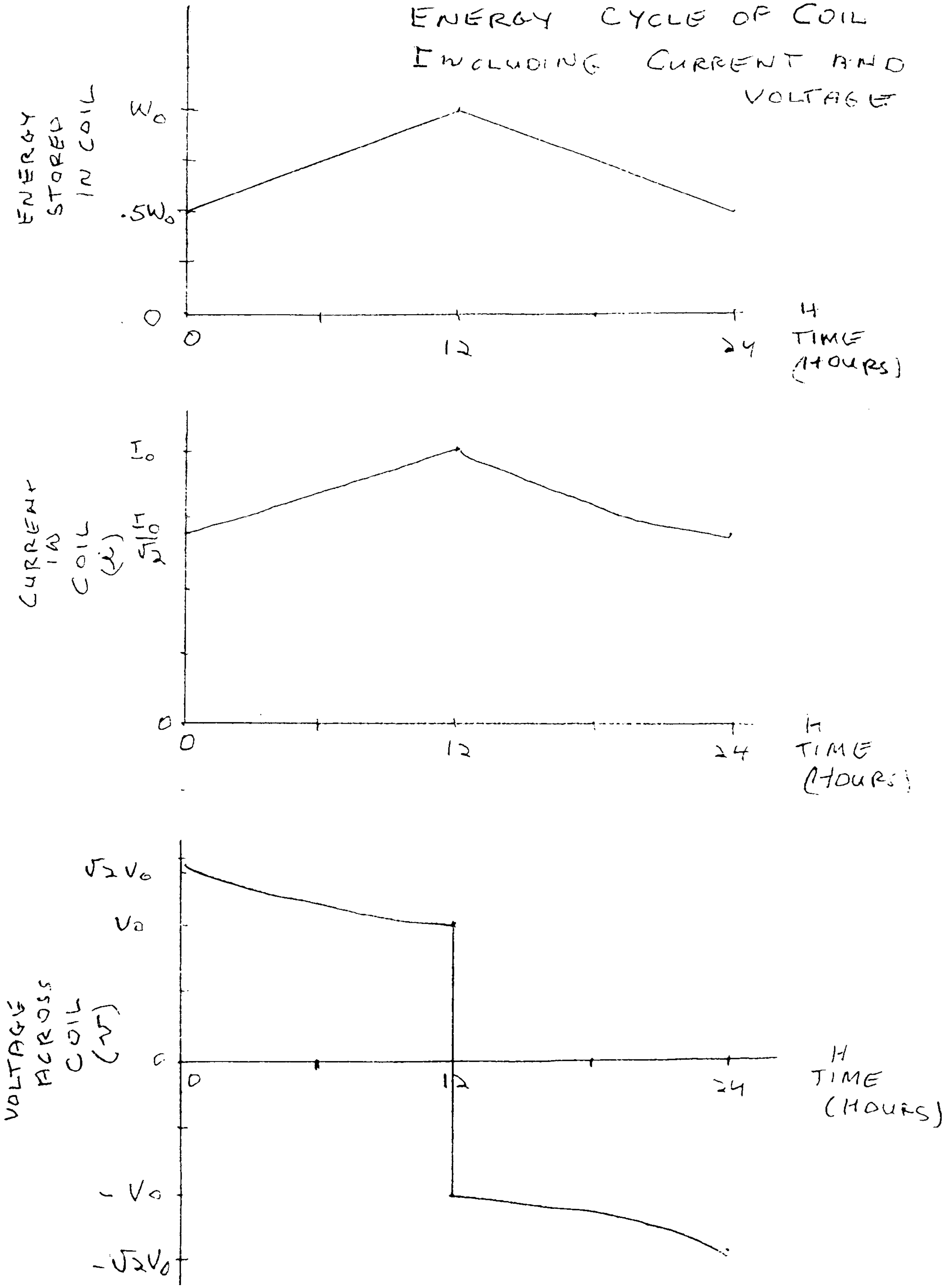
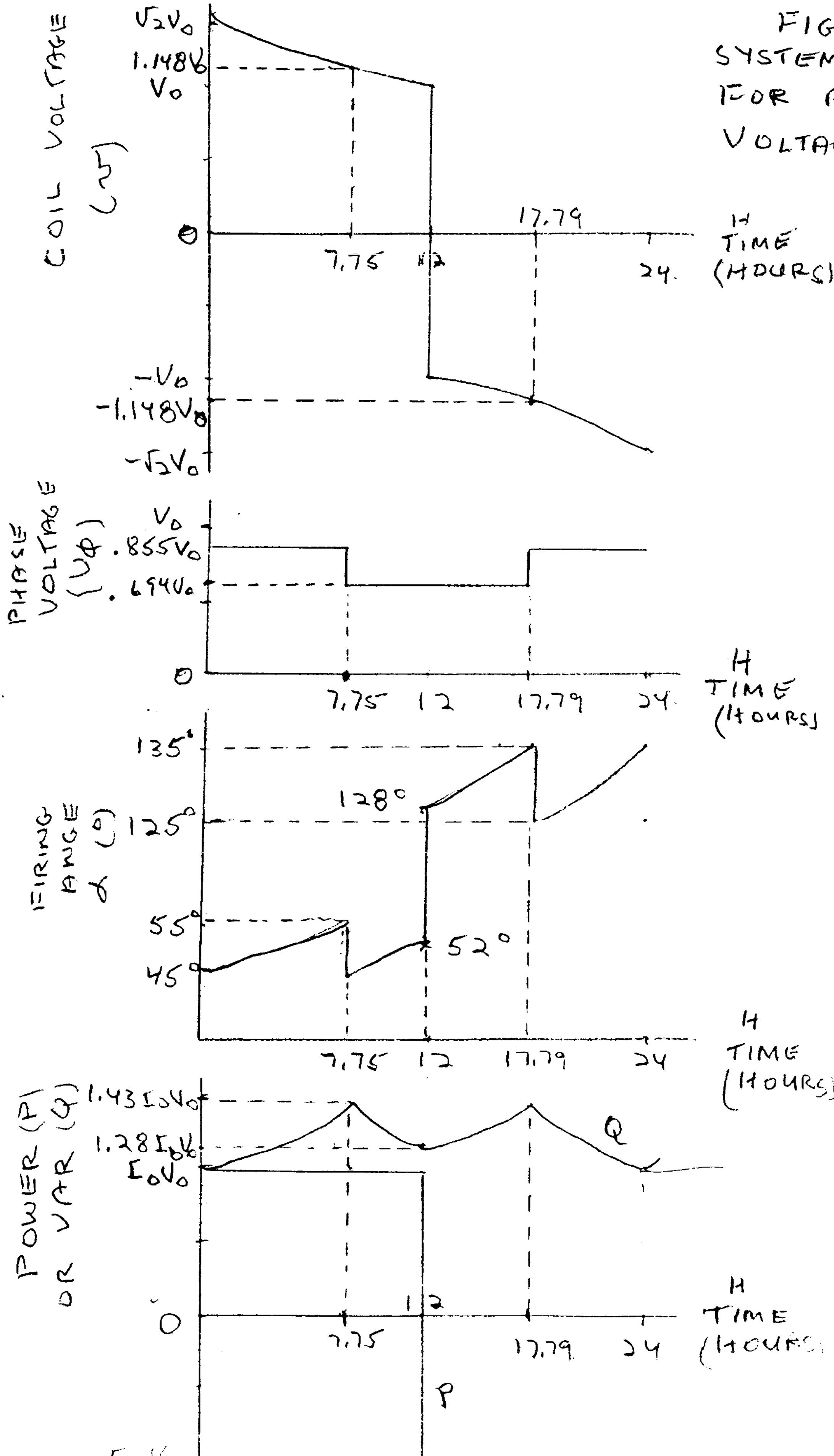
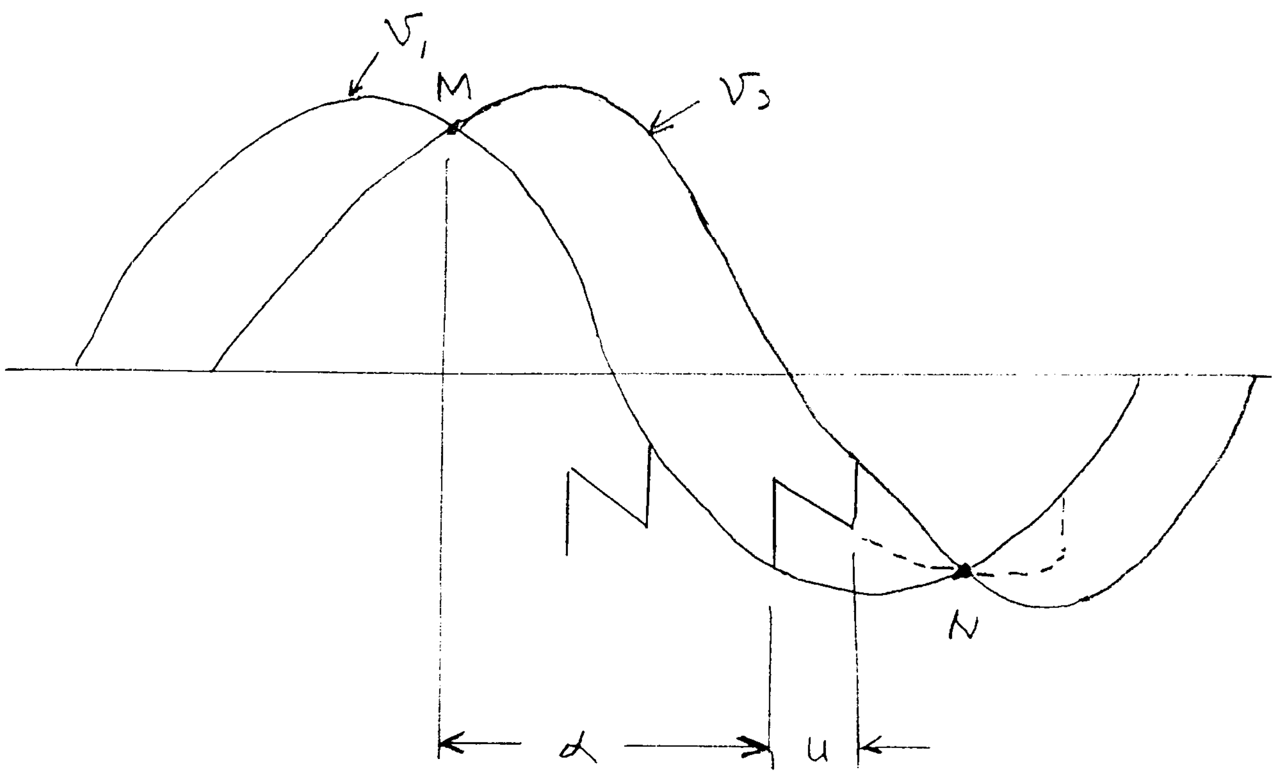


FIG 3
SYSTEM RESPONSE FOR A TWO-STEP VOLTAGE CYCLE



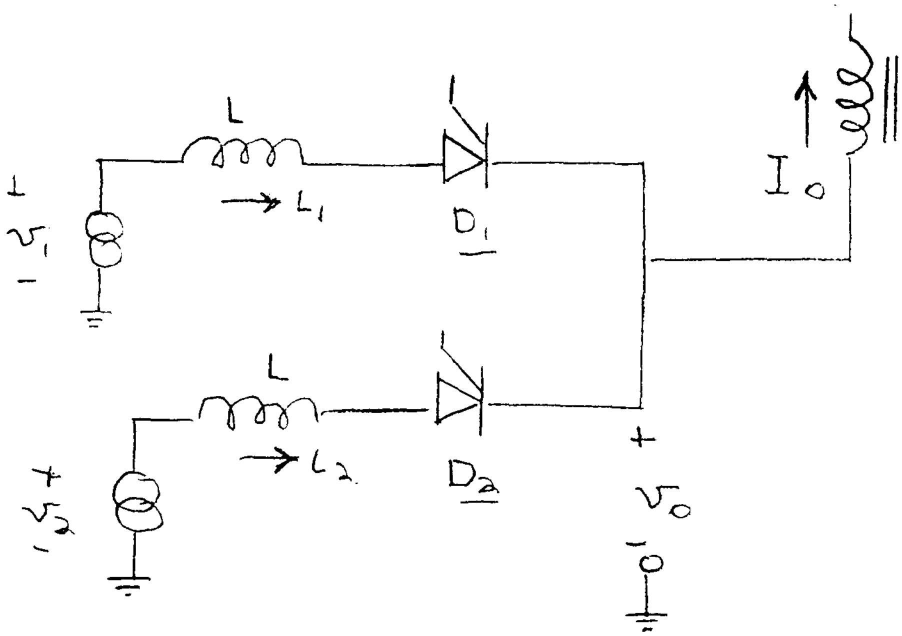
APPENDIX I

COMMUTATION FAILURE



Consider the mechanism of transferring conduction from phase 1 to phase 2. At the angle α diode D_2 is gated ow. Diode D_1 does not turn off immediately, but is held in conduction through the energy storage of its line inductance.

The equivalent circuit involving diodes D_1 and D_2 is given below, L represents the line-neutral commutating inductance for each phase.



In addition,

i_1 and i_2 are the line currents

I_o is the current in the energy storage ring, considered a constant.

v_1 and v_2 are the phase voltages

During commutation

$$v_1 - L\frac{di_1}{dt} + L\frac{di_2}{dt} - v_2 = 0$$

$$i_1 + i_2 = I_o$$

$$\frac{di_1}{dt} + \frac{di_2}{dt} = 0$$

therefore

$$(v_1 - v_2) - 2L\frac{di_1}{dt} = 0$$

$$\frac{di_1}{dt} = \left[\frac{v_1 - v_2}{2}\right]$$

$$\frac{di_2}{dt} = -\left[\frac{v_1 - v_2}{2}\right]$$

$$vo = \frac{v_1 + v_2}{2}$$

For a successful transition v_2 must be larger than v_1, causing i_1 to go through zero and turn diode D_1 off.

If the commutation is not completed before point N, v_1 becomes larger than v_2 and current i_2 is forced to go through zero and turn diode D_2 off. Resulting in a fault.

Thus, the successful transition must be initiated and terminated between the points M and N, i.e. in the region where $v_2 \geq v_1$. Thus,

$$\alpha + u < \pi$$