NEW DIGITAL SIMULATION TECHNIQUE FOR A CURRENT-SOURCE INVERTER FED SYNCHRONOUS MOTOR- PART II

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ABSTRACT

This paper presents a new accurate digital simulation technique that is capable of predicting both transient and steady-state performance for a synchronous motor fed from a naturally-commutated current-source inverter through a dc link fed from a controlled rectifier bridge. The commutation in the inverter bridge is achieved by using the induced back emf of the armature windings and therefore no forced commutation devices are required. This can be done if the machine is over excited so that a leading power factor or a lagging power factor is present at its input terminals for motoring or generating operation respectively. Analysis and simulation are based on tensor technique. Digital simulation results are studied including commutation failure at machine inverter side.

INTRODUCTION

The analysis of current -source inverter fed synchronous motor has received a great attention [1]-[7]. All these works have assumed constant link current which was achieved by assuming the presence of a large smoothing inductor and a dc supply voltage. However, in practical cases, the dc supply is normally a controlled rectifier bridge. Therefore the output voltage contains a dc average component beside fluctuations at sixth harmonic of the suuply frequency. Hence, toget an accurate representation the following items should be included for simulating the complete system:

1. Three-phase electrical power supply system.
2. Supply converter (rectifier mode).
3. A dc smoothing inductor (filter).
4. Machine naturally-commutated converter (inverter mode).
5. Three-phase salient-pole synchronous machine with damper windings.

Figure(1) shows this complete system.

Previous work described in references[1]-[7] for simulating the system are not capable of predicting the behaviour of the system during machine converter side commutation failure. This mode is the most common type of misoperation during inverter operation. In this paper the analysis and simulation are based on tensor technique. This simulation is capable of predicting both steady-state and transient performances for the complete system including commutation failure at the machine side. Digital simulation results are studied including commutation failure which was deliberately created.

Using this simulation technique, solutions for operation under unbalanced operating conditions of power supply will be the same without extra analysis. Also, closed-loop control can easily be incorporated to this analysis to give better system performance.

SYSTEM ANALYSIS

Inverter-Fed Synchronous Motor Analysis

The equivalent circuit representing a naturally-commutated current-source inverter-fed synchronous motor is shown in Figure(2). The parameters of this equivalent circuit was given in detail in PART I.

Rectifier Analysis

Figure(3) shows a modified circuit for the complete system. The oriented connected graph for this circuit is shown in Figure(4).

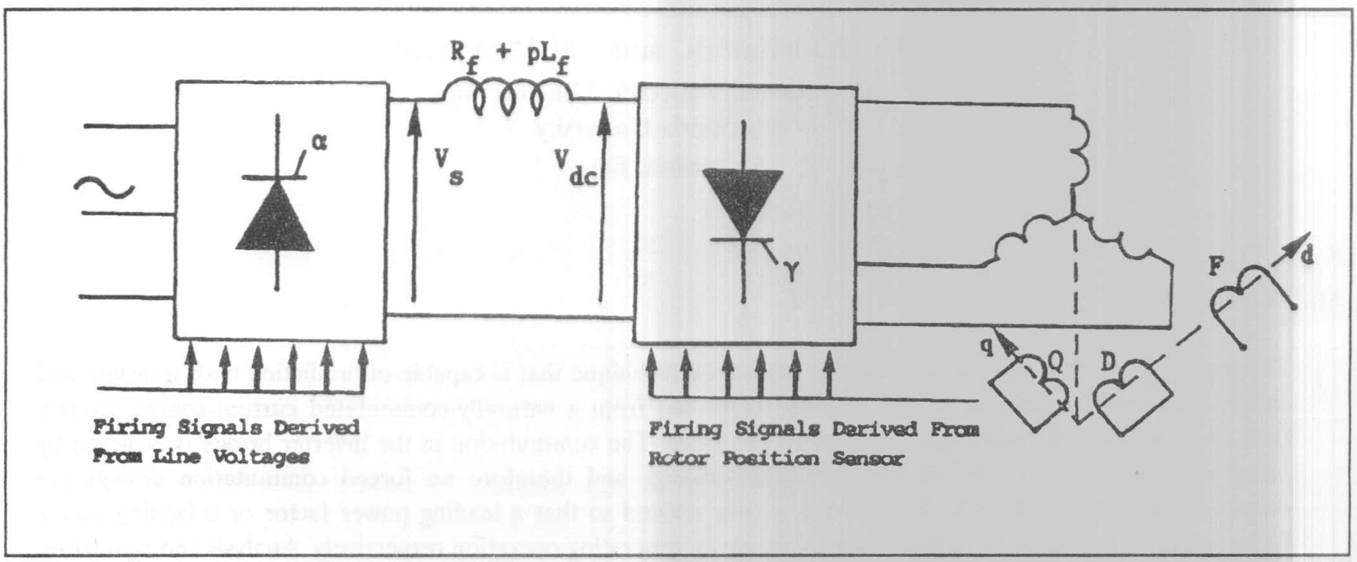

Figure 1. Complete naturally-commutated system.

Choosing elements 1,2,3,4, and 5 as links we obtain basic loops. Each basic loop contains only one link as shown in Figure (5).

The performance equation in the loop reference frame [8] can be written in the form

$$E_{loop} = Z_{loop}\, I_{loop} \qquad (1)$$

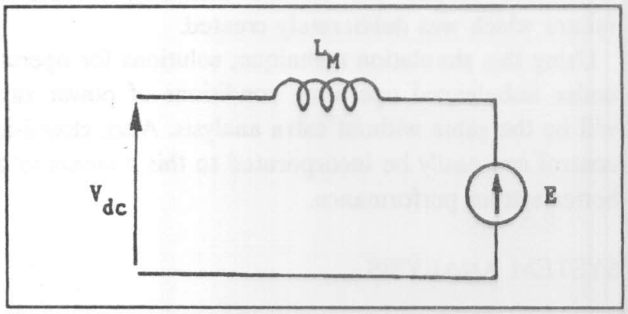

Figure 2. General equivalent circuit for a current-source inverter-fed synchronous machine.

from the previous choice of the basic loop shown in Figure(5), it can be seen that:

$$E_{loop} = \begin{bmatrix} -E + V_R - V_G \\ -E + V_Y - V_G \\ -E \\ V_R - V_G \\ V_Y - V_G \end{bmatrix} \qquad (2)$$

$$I_{loop} = \begin{bmatrix} I_A \\ I_B \\ I_C \\ I_D \\ I_E \end{bmatrix} \qquad (3)$$

$$Z_{loop} = \begin{bmatrix} Z_7+Z_R+Z_G & Z_7+Z_G & Z_7 & Z_R+Z_G & Z_G \\ Z_7+Z_G & Z_7+Z_Y+Z_G & Z_7 & Z_G & Z_Y+Z_G \\ Z_7 & Z_7 & Z_7 & 0 & 0 \\ Z_R+Z_G & Z_G & 0 & Z_R+Z_G & Z_G \\ Z_G & Z_Y+Z_G & 0 & Z_G & Z_Y+Z_G \end{bmatrix} \qquad (4)$$

where, $Z_7 = R_f + P\,(L_f + L_M)$

Equation (1) represents five independent equations if the six thyristors are conducting. However, if only two thyristors are conducting, these equations are reduced to one equation. If only three thyristors are conducting, these equations are reduced to two equations, etc. [9],[10]. The situation of the rectifier bridge can be defined in an array named rectifier state array S having six elements, the individual elements being 1 or 0 depending on whether the thyristor is conducting or not respectively [9]. The tensor connecting the existing loops with those if all thyristors are conducting is C_n . The construction of C_n is obtained from the previous knowledge of S [10]. The transformation process gives the voltages and currents vectors for the new network as:

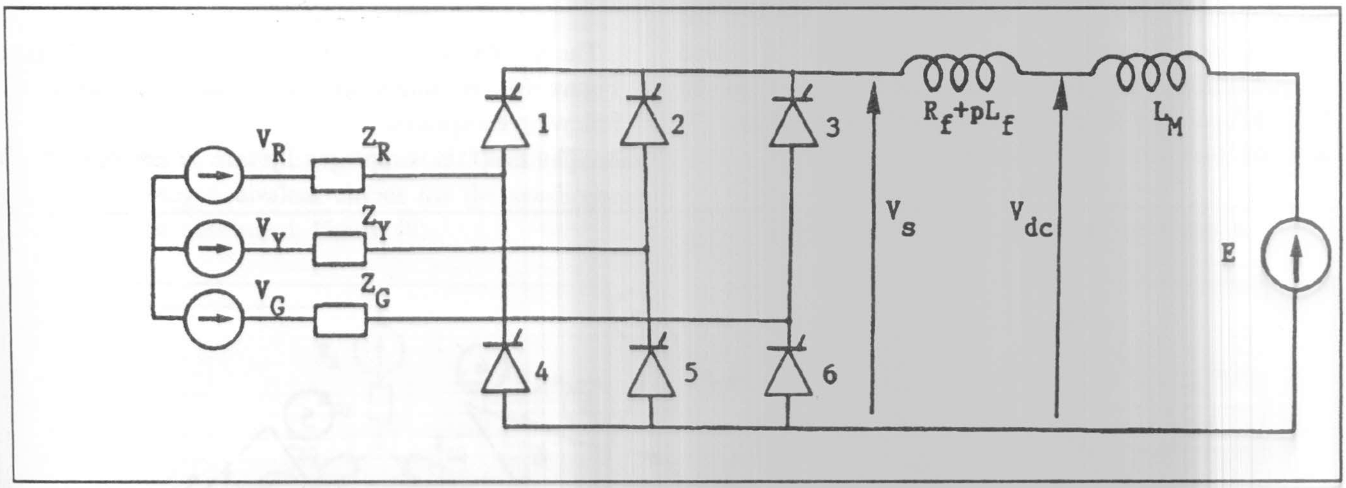

Figure 3. Modified circuit for the complete system.

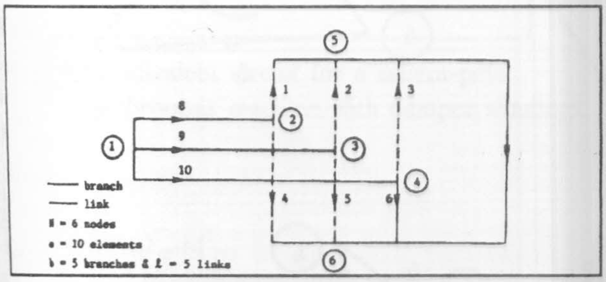

Figure 4. Tree and cotree for the circuit shown in Figure (3).

$$V_n = C^T{}_n E_{loop} \tag{5}$$

$$I_{loop} = C_n\ I_n \tag{6}$$

The new impedance matrix is given by:

$$Z_n = C^t{}_n\ Z_{loop}\ C_n \tag{7}$$

from which we can write the equation

$$V_n = Z_n\ I_n = (R_n + pL_n)\ I_n \tag{8}$$

and consequently,

$$pI_n = -\ L^{-1}{}_n\ R_n\ I_n + L^{-1}{}_n V_n \tag{9}$$

Equation (9) can be calculated at any time t giving the currents derivative at any instant.

When all six thyristors are conducting the voltage drop across each of them is zero, and equation (1) holds good. However, if any thyristor is open, then a voltage will appear across it. It is necessary to calculate this voltage to check whether a new thyristor is to be included in the conducting pattern or not. To calculate this voltage, equation (1) will modified to the following form:

$$V_x = E_{loop} - Z_{loop} I_{loop} \tag{10}$$

For the previously selected tree and cotree, thyristor 6 is the dependent one, then V_x can be expressed as:

$$V_x = \begin{bmatrix} V_1 + V_6 \\ V_2 + V_6 \\ V_3 + V_6 \\ -V_4 + V_6 \\ -V_5 + V_6 \end{bmatrix} \tag{11}$$

COMMUTATION FAILURE ANALYSIS

One important feature of synchronous machine is that it can be over-excited i.e. it can work with a leading power factor when motoring or it can work with a lagging power factor when generating. Therefore, the synchronous machine stator windings emf's can commutate the converter bridge (naturally commutated). The commutation may not be completed before the alternating commutation emf reverses. This may be due to increased direct link current, low alternating machine voltage, low machine speed, excessive firing angle, or a combination of these. A short circuit will be established across the dc link through any two devices on the same leg. This short circuit effectively separates the machine from the rest the power circuit. Therefore, both converters can be solved independently. The analysis described before can be applied separately to both converters. Figures (6) and (7) show the two parts after separation.

Converter 1. Analysis

The simulation of converter 1 under this circumstances, Figure (6), is similar to that described before with the following exceptions:

a. The e.m.f. E is replaced by zero in equation (2).

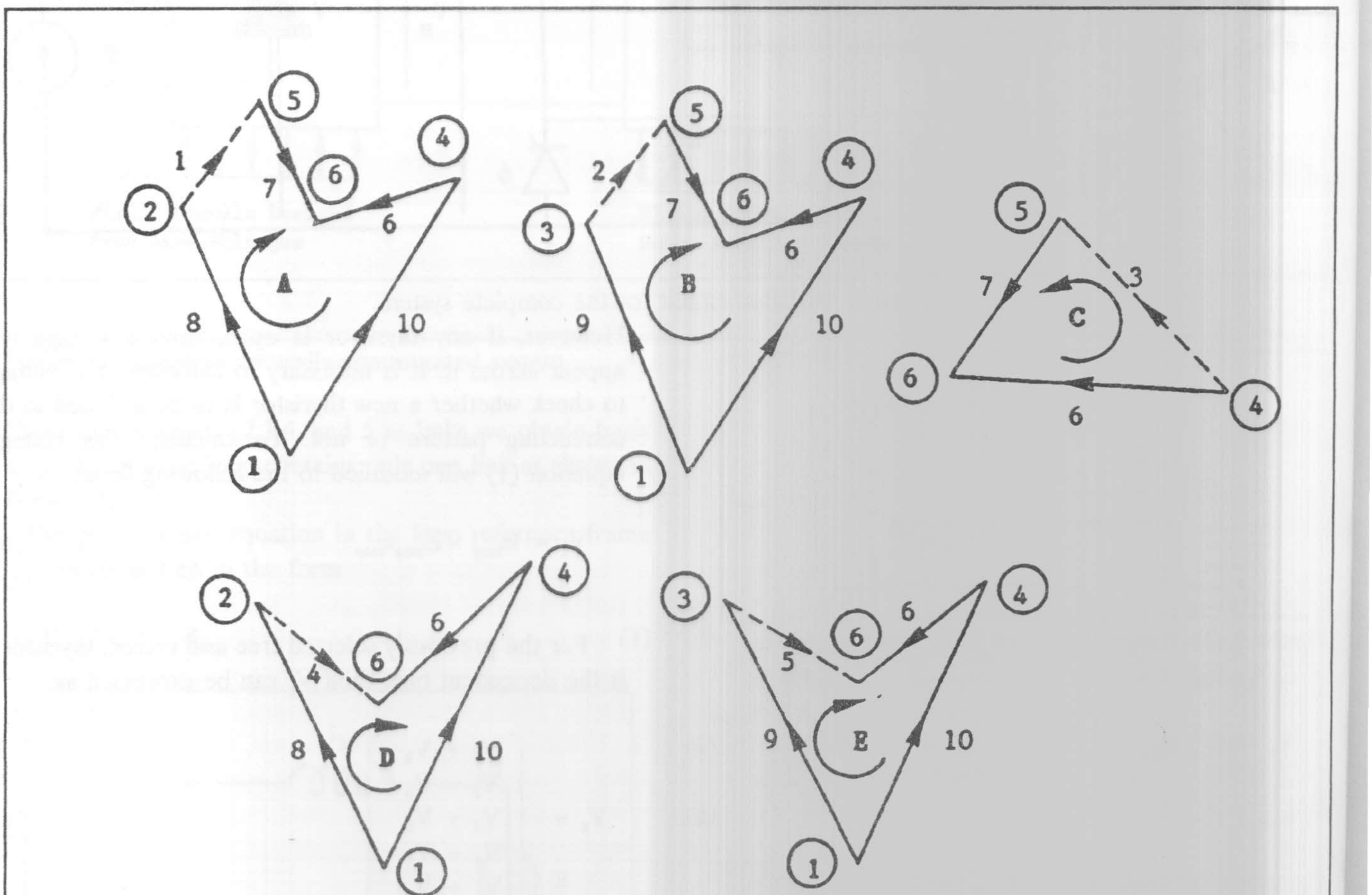

Figure 5. Basic Loops for the tree and cotree shown in Figure (4).

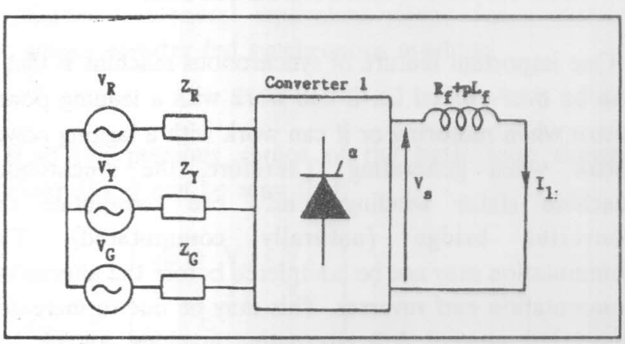

Figure 6. Converter 1 after a short circuit across machine converter.

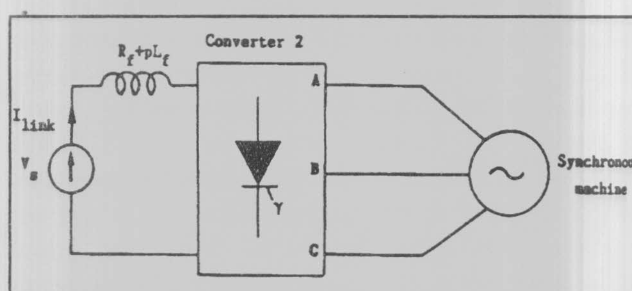

Figure 7. Converter 2 after being disconnected from converter 1 due to short circuit across converter 2.

b. The impedance Z_7 in equation (4) will be: $Z_7 = R_7 + pL_f$; since $L_M = 0$.

Converter 2. Analysis

From PART I, substituting equation (1) into equation (4), the following equivalent circuit for the synchronous machine can be concluded, Figure (8).

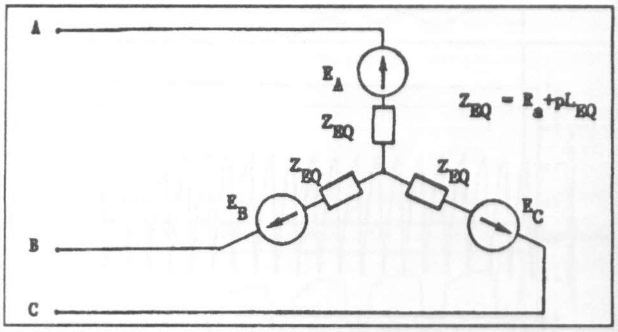

Figure 8. Equivalent circuit for a salient-pole synchronous machine with damper windings.

where,

$$L_{EQ} = D_1/(L_D L_F - M^2_{FD} \quad (12)$$

$$E_A = \sqrt{2/3}\, L_{EQ}(\, C_1 \cos\theta + C_2 \sin\theta) \quad (13)$$

$$C_1 = [M_d/D_1][M_{FD} - L_D][R_F i_F + V_F] + \omega_r\, i_q[(L_q/L_{EQ})-1]$$

$$+[M_d/D_1][M_{FD} - L_F]\, R_D i_D + [M_q/L_{EQ}]\, i_Q \omega_r$$

$$C_2 = [1-(L_Q/D_2)L_d] i_d \omega_r - [L_Q/D_2] M_d [i_F + i_D]\, \omega_r$$

$$-[M_q/D_2] R_Q i_Q - [(L_Q/D_2)-(1/L_{EQ})][V_q - R_A i_q]$$

V_q can be determined from equation (7) PART I since V_{AN}, V_{BN}, and V_{CN} are known from conduction pattern, with v_{dc} =0.$E_B$and E_C are calculated using equation (13) with θ replaced by (θ-120°) and (θ+120°) respectively.

Figure (9) shows a modified circuit for converter 2 shown in Figure (7). The oriented connected graph for this circuit is shown in Figure (10). This oriented connected graph is similar to that shown in Figure (4). The same analysis described previously can be reapplied with the following exceptions:

a. The e.m.f.E is replaced by-V_s.

b. The emf's V_R, V_Y, and V_G are replaced by E_A, E_B, and

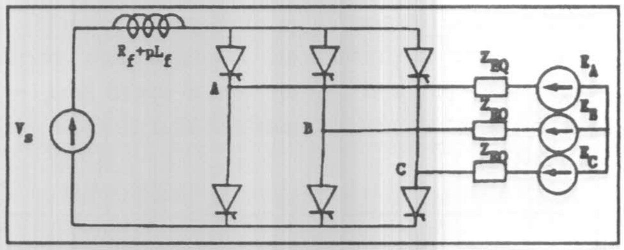

Figure 9. Modified circuit for converter 2.

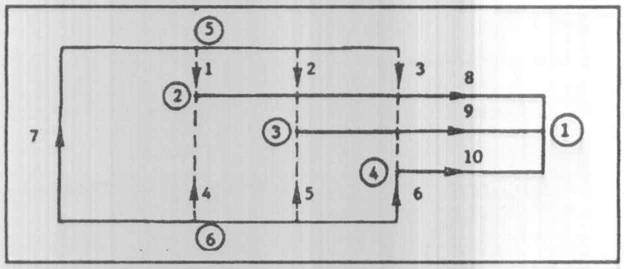

Figure 10. Tree and cotree for Figure (9).

E_C respectively.

c. The impedance Z_7 will be : $Z_7 = R_f + pL_f$.

d. The impedances z_R, z_Y,and z_G are replaced by Z_{EQ}.

NUMERICAL RESULTS

The ac supply is assumed to have the following form:

$$V_R = A \sin \omega t$$

$$V_Y = A \sin (\omega t - 120°)$$

$$V_G = A \sin (\omega t + 120°)$$

In per unit: $A = 0.5$ & $\omega = 1.0$

$$Z_R = Z_Y = Z_G = 0.01 + J0.03 \text{ p.u.}$$

Therefore rectifier firing angle $\alpha = 66°$ will give an average rectifier output voltage V_s = 0.3222p.u. for an average link current I_{Link} =0.49p.u.

Using the simulation technique described in the preceding sections, steady state and dynamic performances for the complete system are predicted. The machine used in **PART I** has been chosen for this prediction. Simulation results are executed with firing angles for converter 1 "α" and converter 2 "γ" chosen to be 66° and 80° respectively. This choice will allow the synchronous machine to run as a motor.

For steady state prediction, the machine is loaded with constant load torque T_L = 0.28 p.u. Figure(11) shows steady state performances. Average link current is I_{Link} = 0.49 p.u. and average motor speed is ω_r = 0.238 p.u. All other shapes are nearly similar to those obtained in PART I.

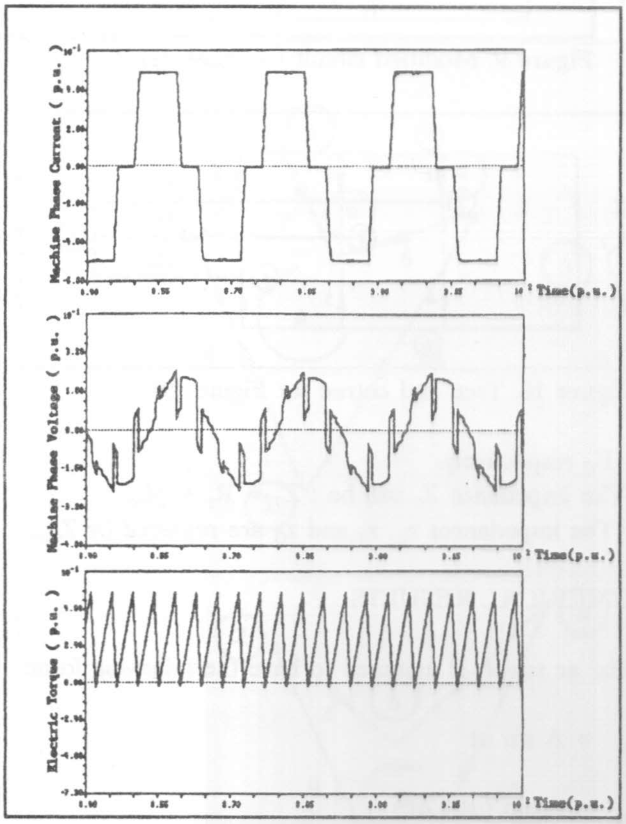

Figure 11. Steady-state performance.

Commutation failure was created deliberately during normal operation by changing converter 2 firing angle while keeping converter 1 firing angle unchanged. The load connected to the machine is assumed to have very large inertia so that the speed is kept constant during predication. The machine speed is taken as ω_r= 0.246 p.u. and firing angles α= 66° and γ = 80°.

Commutation failure was created deliberately during normal operation by two different ways:

1. After steady state was achieved the firing angle γ of converter 2 was suddenly changed from 80° to 30° while keeping converter 1 working with α = 66°. Figure (12) shows the digital simulation response in this case.
2. After steady state was achieved, commutation failure was initiated by suddenly firing all six thyristors in converter 2 all the time while leaving the firing angle of converter 1 unchanged. This will allow converter 2 to act as a rectifier so that the machine will be running as a generator with constant speed ω_r = 0.246 p.u. Figure (13) shows the digital simulation response for this case.

In the first case, Figure(12) , a series of commutation failures occur. The voltage at the dc terminals of converter 2 is reversed for approximately one-half cycle. During this time converter 2 works as a rectifier and aids the rectifier

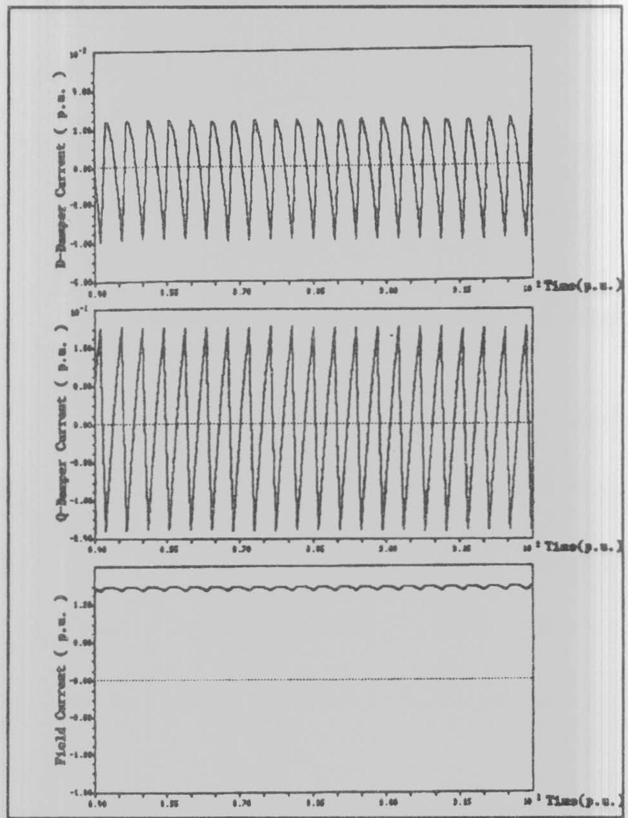

Figure 11. Stead-state performance continued.

at the other end in circulating more current in the line. This causes the dc link current to increase. The damper windings start acting to damp the oscillations caused by this transient. In the second case, Figure (13), the dc voltage of converter 2 reverses polarity. During this period converter 2 works as a rectifier and aids the rectifier at the other end in circulating extra current in the link. As can be seen from Figure (13) after the reversal of V_{dc} periods of short circuit start to occur. These periods are increasing in duration as the link current increases. In both cases, eventually, a continuous short circuit will be established across both dc and ac sides of converter 2. When this happens the ac supply will be feeding the

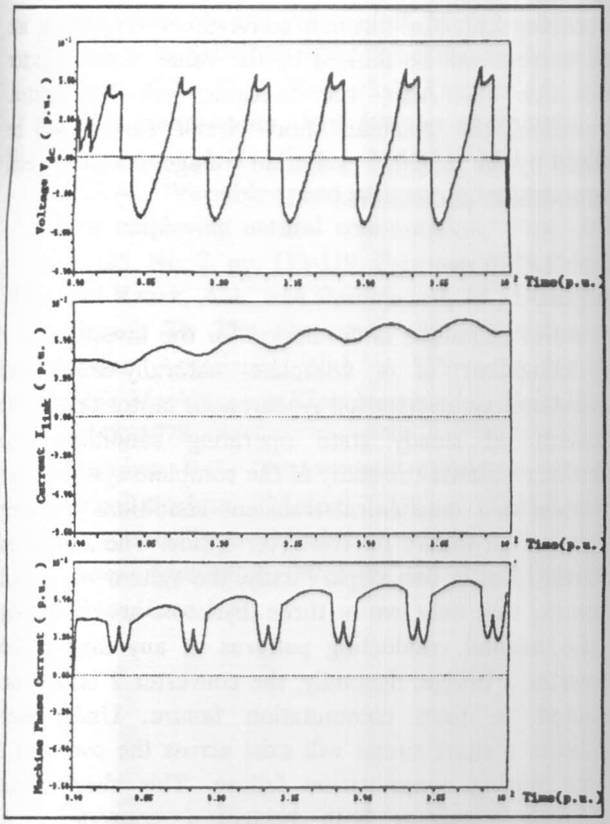

Figure 12. Transient performance due to sudden change in converter 2 firing angle γ.

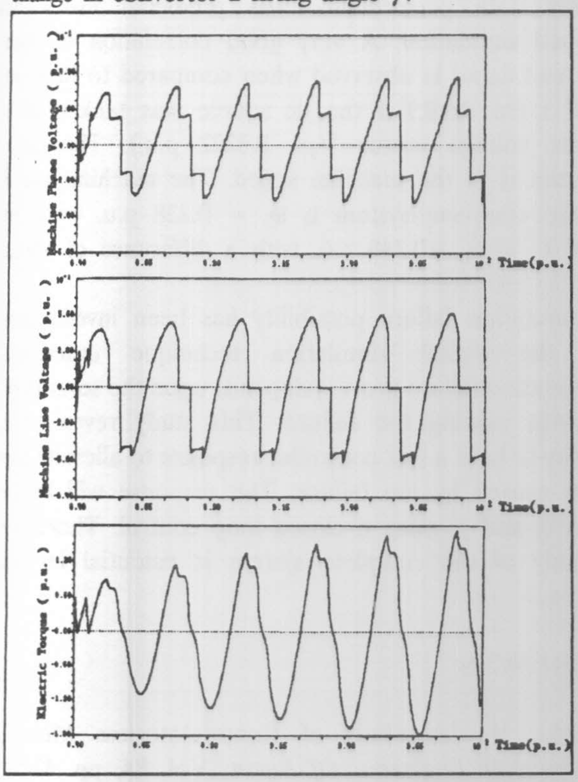

Figure 12. Continue.

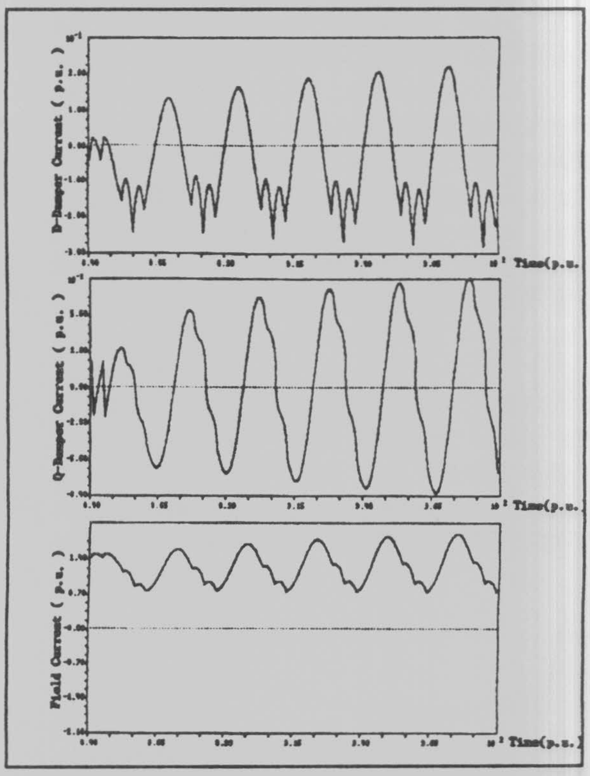

Figure 12. Continue.

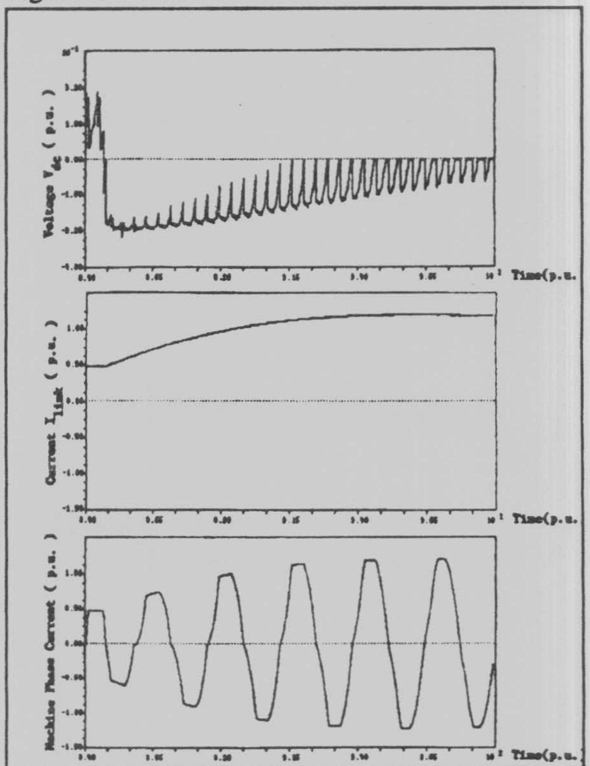

Figure 13. Transient performance due to suddenly firing all six thyristors in converter 2.

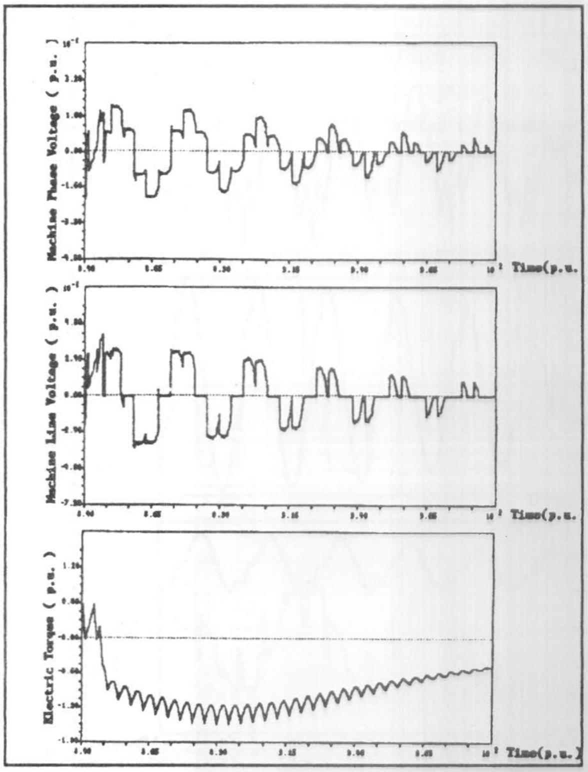

Figure 13. Continue.

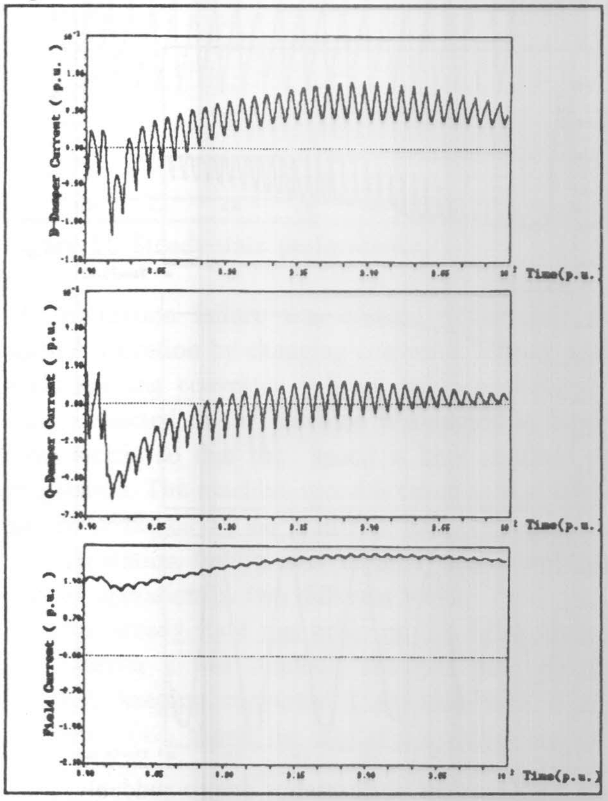

Figure 13. Continue.

smoothing inductor through converter 1. Therefore, the link current will be limited by the value of the inductor resistance R_f. Also, the machine will be shorted. Therefore, the machine short circuit current will be limited by the machine excitation voltage, machine speed, and machine parameters.

CONCLUSIONS

A novel technique is developed for the investigation of the behaviour of a complete naturally-commutated current-source inverter fed synchronous motor under both transient ad steady state operating conditions. The technique permits the study of the complete system under electrical and mechanical transient conditions including commutation failure on converter 2 side. The simulation is carried out in two steps. Firstly, the system was solved assuming that only two or three thyristors are conducting in the normal conducting patterns at any time in the converter 2 bridge. Secondly, the converter 2 bridge was assumed to have commutation failure. Under such condition a short circuit will exist across the converter 2 bridge during commutation failure. This short circuit effectively separates both bridges (converter 1 & converter 2). Therefore each can be solved independently.

Steady state performance was predicted using the described simulation. A very good correlation in both shape and detail is observed when compared to those in **PART I** (In **PART I** the dc source was tanken as a constant voltage source V_s = 0.3222 p.u.). The clear difference is in the machine speed. The machine speed with the complete system is ω_r = 0.238 p.u. while in **PART I** is ω_r =0.246 p.u. with a difference of about 3.5%.

Commutation failure possibility has been investigated using the digital simulation technique described. Commutation failure process depends upon the severity of conditions causing the failure. This study reveals the necessity to have a fast controller response to alleviate the burden caused by the failure. The response will be to change α and γ using a closed loop control. Therefore the study of the complete system is essential in this situation.

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