FAULT ANALYSIS OF AN INTERNAL FAULT ON A SYNCHRONOUS GENERATOR

A DISSERTATION
submitted in partial fulfilment of
the requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power System Engineering)

By
V. N. PUDARUTH

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE (U.P.) INDIA
June, 1979

PANKAJ, SUCHIN, PYUS

CERTIFICATE

Certified that the dissertation entitled " FAULT ANALYSIS OF AN INTERNAL FAULT ON A SYNCHRONOUS GENERATOR" which is being submitted by Mr. V.N. PUDARUTH in partial fulfilment for the award of the degree of MASTER OF ENGINEERING in ELECTRICAL ENGINEERING (Power System Engineering) of the University of Roorkee, Roorkee is a record of the student's own work carried out by him under my guidance and supervision. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is further certified that he has worked for a period of about five and a half months from January to mid June 1979 for preparing this dissertation at this University.

(Dr. M.P. JAIN)
Reader,
Deptt. of Electrical Engineering
University of Roorkee
Roorkee.

Place: Roorkee

Date: 19 6 79

ACKNOWLEDGEMENT

The author wishes to express his deep sense of gratitude to Dr. M.P. JAIN, Reader in Electrical Engineering, for suggesting the problem and for his constant encouragement and guidance during the preparation of this dissertation.

The author is very grateful to Dr. V.K. VERMA, Professor in Electrical Engineering, and Dr. K. VENKATESSAN, Reader in Electrical Engineering, for their help and expert opinion.

The author is very much thankful to Dr. L.M. RAY, Professor and Head Electrical Engineering Department for his useful discussions and expert opinion.

His thanks also go to the Head of the Electrical Engineering Department, University of Roorkee for providing the necessary facilities in the department.

The author also wishes to thank the Management of Bharat Heavy Electricals Limited (BHEL), Ranipur, for providing the necessary data.

The author is indepted to the Council of the University of Mauritius for sponsoring him to persue the M.E.course.

Lastly, the author's thanks go to Punee for moral support throughout the course.

V.N. PUDARUTH

SYNOPSIS

This work consists essentially of two parts. In the first part the general principle of analysis of all types of internal faults in a synchronous generator is discussed. Although a salient pole synchronous generator is considered, it has been indicated how the equations should be modified when considering a cylindrical rotor synchronous generator. The analyses have been done using the symmetrical components.

The second part consists of a mathematical analysis of a short-circuit between one parallel path of phase A and another parallel path of phase B of a 141 MVA. 120MW, 0.85 pf turbo-generator having two parallel paths per phase. The object of the analysis is to predict the fault currents flowing in the various parts of the armature windings.

A detail analysis of an internal line-to-ground fault has been performed by V.A. Kinitsty in 1965 and the method of analysing a line-to-line fault has been suggested. In the case when the numbers of turns between the fault points and the neutral in the two faulted branches are not the same the suggested method becomes very cumbersome, and the application of Maxwells' Loop Equations have been found to be simpler.

<<<<<>>>>>

NOMENCLATURE

$A_a'', B_a'', C_a'', D_a''$	:	Coefficients of the mutual inductances between the 'f' and 'p' windings.
$A_b'', B_b'', C_b'', D_b''$	:	Coefficients of the mutual inductances between the 'f' winding and phase C or B.
a.	:	Number of parallel paths per phase.
E_f'', E_r'', E_p''	:	Substansient generated voltages in the 'f','r' and 'p' windings, respectively.
E_s''	:	Subtransient generated voltage of system.
E_{3f}	:	Third harmonic induced voltage in 'f' winding.
E_f''	:	Subtransient generated voltage per phase.
i_f	:	Total fault current in 'f' winding.
I_{f1}, I_{f3}	:	Amplitudes of the currents of the fundamental and third harmonic.
I_d, I_q	:	Armature currents in the Direct and quadrature axes, respectively.
I_{a1}, I_{b1}, I_{c1}	:	Positive-sequence currents in the A,B and C phases, respectively.
I_{apl}	:	Current in the 'p' winding.
I_1, I_2, I_o	:	Positive, negative and zero sequence currents in the entire armature winding.
I_{f2}	:	Negative-sequence current of fundamental frequency in the 'f' winding.
I_f	:	Field current
I_L	:	Line current
I_l	:	Line current prior to fault.
j	:	imaginary operator.
k_t	:	Effective turns ratio between the 'f' winding and the entire phase.

k_r : Effective turns ratio between the 'p' winding and the entire phase.

k_1, k_3 : Winding factors for the fundamental and third harmonic components, respectively.

k_{pr}, k_{pf}, k_{pd} : Winding factors of the 'r', 'f' and 'p' windings, respectively.

L_f'', L_{f2}, L_{fo} : Positive, negative and zero sequence self-inductances, respectively, of the 'f' winding.

L_r'', L_{r2}, L_{ro} : Positive, negative and zero sequence self-inductances, respectively, of the 'r' winding.

L_{p1}'', L_{p2}, L_{po} : Positive, negative and zero sequence self-inductances, respectively, of the 'p' winding.

L_{fd}'', L_{fq}'' : Subtransient inductances of the 'f' winding in the direct and quadrature axes, respectively.

L'' : Subtransient inductance per phase.

L_d'', L_q'' : Subtransient inductances per phase in the direct and quadrature axes, respectively.

L_o : Zero-sequence inductance of the entire phase.

L_f : Inductance of field winding.

L_D, L_Q : Inductances of direct axis damper winding and quadrature axis damper winding, respectively.

L_{mt} : Amplitude of the variable part of the mutual inductance between the 'f' winding and the remaining part of the phase to which the 'f' winding belongs.

L_{mf}, L_{mr} : Main inductances of the 'f' and 'r' windings respectively.

L_m	:	Amplitude of the variable part of mutual inductance between the entire phases.
n	:	Number of phases.
M_{frd}, M_{frq}	:	Mutual inductances between the 'f' and 'r' windings, in the direct and quadrature axes, respectively.
$M_{pf}'', M_{pf2}, M_{pfo}$	:	Positive, negative and zero sequence mutual inductances, respectively, between the 'p' and 'f' windings.
$M_{pr}'', M_{pr2}, M_{pro}$	:	Positive, negative and zero sequence mutual inductances, respectively, between the 'p' and 'r' windings.
$M_{fr}'', M_{fr2}, M_{fro}$	:	Positive, negative and zero sequence mutual inductances, respectively, between the 'f' and 'r' windings.
$\bar{M}_{ap}'', \bar{M}_{ab}', \bar{M}_{ac}'$	:	Mutual inductances between the 'f' winding and the 'p' winding, and phase B and C, respectively.
$M_{apo}, M_{abo}, M_{aco}$	:	Zero-sequence mutual inductances between the 'f' winding and the 'p' winding and phase B and C, respectively.
M_{ad}, M_{aq}	:	Mutual inductances between the single phase armature winding and the rotor winding in the direct and quadrature axes, respectively.
M_{pfd}'', M_{pfq}'	:	Mutual inductances between the 'p' and the 'f' windings in the direct and quadrature axes, respectively.
$\bar{M}_{afr}$	:	Mutual inductance between 'f' and 'r' windings considered in isolation.
$\bar{M}_{apf}$	:	Mutual inductance between the 'f' and the 'p' windings considered in isolation.
$\bar{M}_{bf}, \bar{M}_{cf}$	:	Mutual inductances between the 'f' winding and phase B and C, respectively.

M_{st}	:	Constant part of the mutual inductance between the 'f' winding and the remaining part of the phase to which the 'f' winding belongs.
M_s	:	Constant part of the mutual inductance between the entire phases.
N_f, N_r, N_p	:	Numbers of turns of the 'f','r' and 'p' windings, respectively.
P	:	Rated power.
R_{f1}, R_{f2}, R_{fo}	:	Positive, negative and zero sequence resistances, respectively, of the 'f' winding.
R_{r1}, R_{r2}, R_{ro}	:	Positive, negative and zero sequence resistances, respectively, of the 'r' winding.
R_{p1}, R_{p2}, R_{po}	:	Positive, negative and zero sequence resistances, respectively, of the 'p' winding.
R_D, R_Q	:	Resistance of the damper windings in the quadrature and direct axes, respectively.
R_f	:	Resistance of the field winding.
$R_F + jX_F$	:	Fault impedance.
$R_L + jX_L$	:	Load impedance.
r_a	:	Resistance of armature winding per phase.
$R_s + jX_s''$, $R_{s2} + jX_{s2}$, $R_{so} + jX_{so}$	:	Positive, negative and zero sequence impedances of the parallel system.
S_b, V_b	:	Base capacity and base voltage, respectively.
V_t, V_L	:	Phase terminal and Line voltages, respectively.
X_f, X_r, X_p	:	Reactances of the 'f','r' and 'p' windings, respectively.

X_d, X_q	:	Reactance per phase in the direct and quadrature axes, respectively.
W	:	Angular frequency.
δ_f, δ_r	:	Rotor displacement angle corresponding to the 'f' and 'r' windings, respectively, when these windings are considered as polyphase ones.
θ_f''	:	Phase angle of the subtransient impedance difference between the direct and quadrature axes of the 'f' winding.
θ	:	Angle between the axis of the magnetic systems of the rotor and stator.
ϕ	:	Power factor.
ϕ_{f1}, ϕ_{f3}	:	Phase angle of fundamental and third harmonic currents, respectively, in respect to the chosen reference.
ϕ_{f2}	:	Phase angle of the negative-sequence current in the 'f' winding.
γ_{fr}	:	Angle between the 'f' and 'r' windings.
α_f	:	Shift angle between the 'f' winding and phase A.
$\bar{\psi}_{ap1}, \bar{\psi}_{ap2}$ ψ_{apo}	:	Positive, negative and zero sequence flux linkages, respectively, in the separated branch.
ψ_{rf}''	:	Mutual-flux Linkages between the 'f' and 'r' windings.

C O N T E N T S

.....ii

<<<<<<>>>>>>

CHAPTER-I

INTRODUCTION AND REVIEW OF THE EXISTING LITERATURE

1.1 INTRODUCTION:

Although much work has been done on fault currents calculations due to faults occuring external to the machine, very little has been done on faults occuring internal to the machine. This could be due to, inter-alia, three reasons. Firstly, the probability of occu-rence of an internal fault is much less than that of an external fault. Secondly, the analyses are very involved due to mutual inductances between all windings, including damper and field windings. Thirdly, external faults stress the machine more severely than internal faults.

It is, however, important to be familiar with the method of calculation of fault currents due to the occurence of an internal fault. This will give an insi-ght in the magnitude of fault currents flowing in the various parts of the armature windings. With this know-ledge a suitable scheme of protection against internal faults can be designed. This analysis also shows that when a synchronous generator connected to another system develops an internal fault, current will flow into the generator. So the protection scheme should be devised to prevent this as well.

Two types of internal faults, namely, the line-to-ground and the turn-to-turn which can occur more often than other types of faults, can be simply analysed by the use of symmetrical components. The mathematical analysis of fault currents, in a machine, having several parallel paths per phase, and which has developed an internal fault in one or more of the parallel paths, is very involved.

A 141 MVA, 120 MVA, 0.85 pf, turbo-generator having two parallel paths per phase has developed an uncommon type of fault, that of a short circuit between one parallel path of one phase and another parallel path of another phase. No previous work has been done on such type of fault. So the management of BHEL, Ranipur, has approached the Electrical Engineering Department, University of Roorkee, Roorkee to carry out a mathematical analysis of this fault in order to predict the fault currents flowing in the various circuits.

1.2 REVIEW OF EXISTING LITERATURE:

As it has been mentioned earlier there is extremely little work done on internal fault current calculations.

In 1941 R.A. Galbraith presented a method for the calculation of fault currents in one or a series of short circuited turns. The fault currents calculated by Galbraith refer to the direct and quadrature axes of the faulty machine. Further, the parallel operation of the faulty machine with an active network has not been taken into account.

The main work has been done by V.A. Kinitsky in 1965 |1| . He showed that a synchronous machine with an internal fault in its armature winding can be represented by an equivalent circuit in each sequence network. The interconnection of the sequence network is dictated by the type of fault. The fault current in each winding of the faulty machine can be calculated from the obtained interconnected network in accordance with the method of symmetrical components. However detailed analysis was done for only a line-to-ground fault.

In 1968 V.A. Kinitsky |2| developed a computer programme for the calculation of internal fault currents in synchronous machines operated individually or connected to a system. The applied method boiled down to a straight-forward solution of a network with several loops and sources. Deviations between calculated and measured currents were found and were attributed to the parameters used rather than to the method itself. Here also, only a line-to-ground fault was considered.

In 1960 V.A. Kinitsky | Bib.5 | devised a certain relay scheme which could protect generators against all internal faults. In 1964 he presented a very useful paper on the calculation of mutual inductances between a part of armature windings and all the other windings.

The last work mentioned, although not dealing directly with internal fault calculation, is instrumental in the calculation of internal fault currents.

1.3 FORMATION OF DISSERTATION WORK:

In the preparation of the work the arrangement given below has been followed.

In the first chapter a brief introduction is given about the dissertation work. A review of existing literature has been done. The literature reviewed deals mainly with the work of V.A. Kinitsky. It seems that he is the only one who has done most work on internal fault calculations.

In the second chapter it has been shown that a synchronous machine, which has developed an internal fault can be represented by an equivalent circuit in each sequence network. Cases for a generator on no-load, load and operating in parallel with another system have been discussed. The calculations of third harmonic fault currents also have been discussed.

In the third chapter the fault currents in various parts of the armature winding of a turbo-generator are calculated. Since the short circuit is between one parallel path of one phase and another parallel path of another phase and the number of turns involved between fault points and neutral are not the same in the two faulted branches, the Maxwell's Loops Equations were prefered and hence used.

In the final chapter, the calculated values of fault currents are summerised and commented on and suggestion is given for further investigation.

CHAPTER - 2

EQUIVALENT CIRCUIT OF A SYNCHRONOUS MACHINE DUE TO AN INTERNAL FAULT AND CALCULATION OF FAULT CURRENTS

2.1 INTRODUCTION

It is shown that a synchronous generator with any number of parallel paths per phase can be represented, for the sake of analysis, by only two parallel paths per phase. A synchronous machine with an internal fault can be represented by an equivalent circuit in each sequence network. The networks are connected according to the type of fault and the sequence currents calculated by Kirchhoffs' Laws. In case the synchronous generator is operated in parallel with another system, the latter is represented by its sequence network and its line and neutral terminals are connected to the corresponding sequence networks of the faulted generator. The three sequence currents are calculated by Kirchhoff's laws and the fault currents in each branch is given by the sum of the three sequence currents flowing through it. In case of a salient pole generator the third harmonic fault current is not negligible and should be calculated and included in the total fault current.

2.2 SYNCHRONOUS MACHINE OPERATING SINGLY AND ON NO LOAD

As a general case, let us assume that each phase of the generator has 'a' parallel paths and that a fault has occured within one of them. The faulted branch is separated from the rest of the windings. The (a-1) unfaulted paths are represented by an equivalent circuit denoted by 'p'.Suppose the fault occurs somewhere within the faulted branch, say at point 'c', dividing it into two parts: one adjacent to the neutral and referred to as the 'f' winding and the second adjacent to the machine terminal and referred to as the 'r' winding. The number of turns of the 'f' winding is N_f and consequently the number of turns of the 'r' winding is N_r and that of the 'p' winding N_p (Fig. 2.1).

At the breakdown of the minor insulation in the separated path, a turn-to-turn fault occurs which can also be represented by two parts of the separated branch, the first adjacent to the neutral having say one turn and the second part adjacent to the terminal having (N_p-1) turns where'N_p' is the number of turns per parallel path. Consequently , the equivalent circuits of the synchronous machine during a single phase-to-ground fault and a turn-to-turn fault shall be similar.

The two parts of the defective branch, the 'f' and the 'r' windings and the equivalent parallel branch form a

mutual

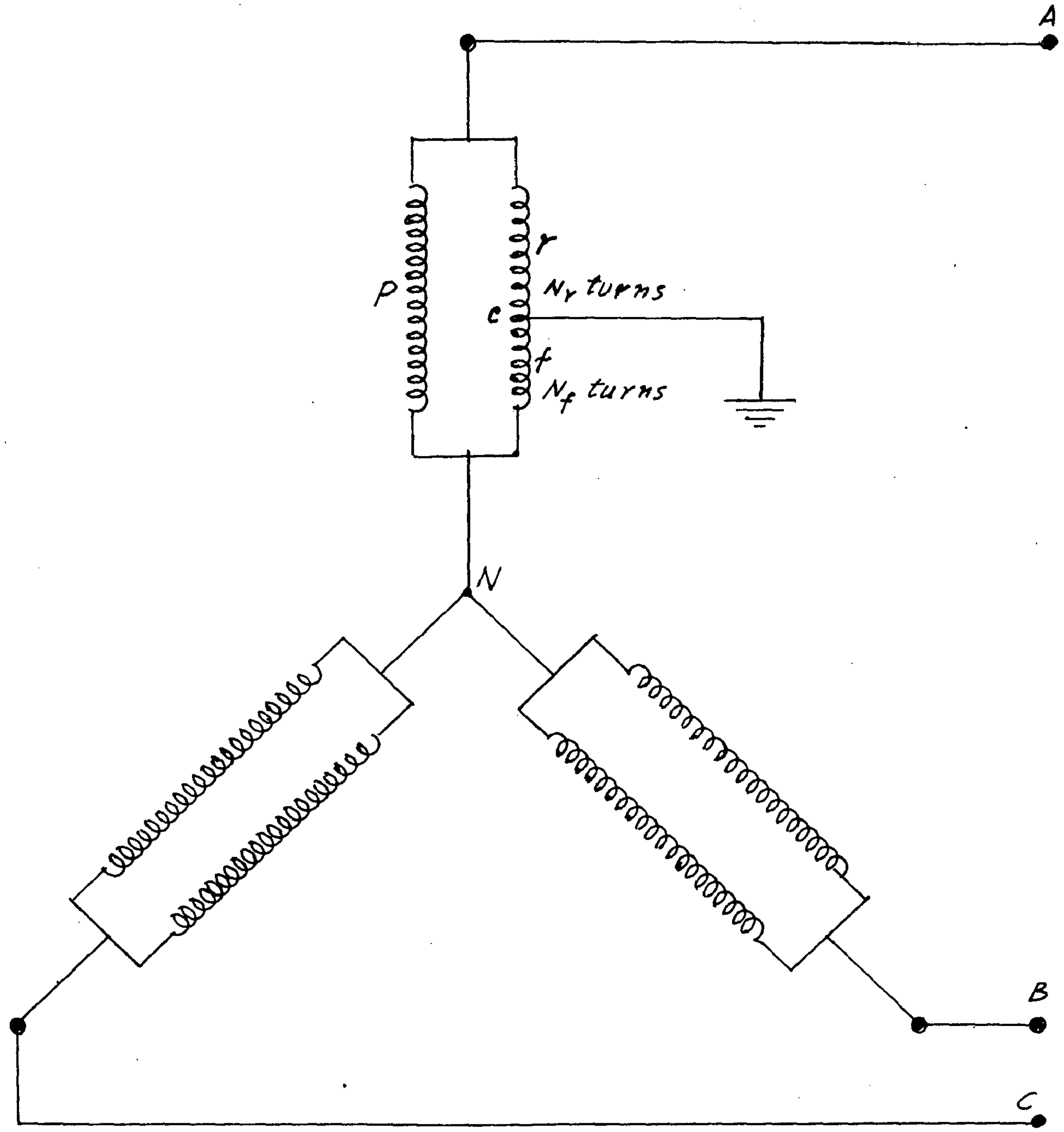
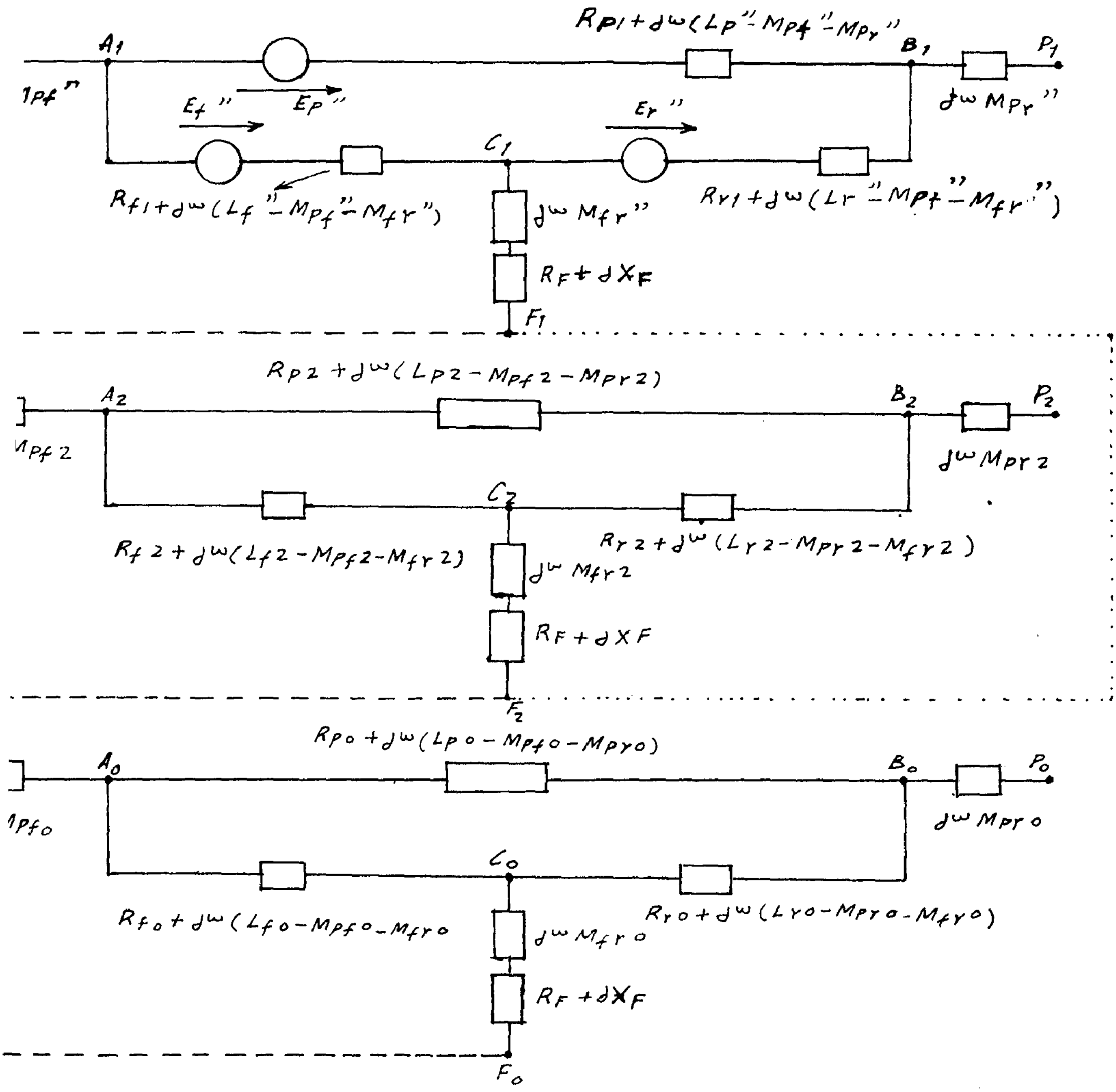


Fig.2.1 Representation of parts of armature windings due to a fault in one parallel path.

delta. The mutual inductances between the adjacent windings are connected at the corners of the delta. The inductance of individual windings will be its original value minus the mutual inductance associated with it (Fig. 2.2). The three end points P, N and F of the equivalent circuit in each sequence represent the terminal of the machine, the neutral and the fault point, respectively. If there is a fault impedance (R_F + j X_F) then the latter should be introduced into the fault path of each sequence network. The sequence networks should be connected in accordance with the type of fault as in the case of an external fault. In the case of a line-to-ground or a turn-to-turn fault the three sequence networks should be connected in series, thus the point F_1 is connected to N_2, F_2 is connected to No and Fo is connected to N_1 as shown by the dashed lines (Fig. 2.2). In the case of a line-to-line fault involving equal numbers of turns from the neutral in both faulted phases, the positive and negative sequence networks are connected in parallel as shown by the dotted lines. (Fig. 2.2). The electromotive forces of fundamental frequency behind the corresponding substransient impedances at the instant of fault are inserted in each active branch of the positive sequence network.

2.3 CALCULATION OF FAULT CURRENTS

Considering a line-to-ground fault; the total current flowing in the circuit can be simply obtained by



g.2.2 Equivalent circuit of a synchronous generator on no-load and with an internal fault.

R,L,M	=	Resistance, self-inductance and mutual-inductance, respectively.
E''	=	Subtransient generated voltage
W	=	angular frequency

Suffix

f,r,p	=	f-winding, r-winding, p-winding, respectively.
1,2,0	=	Positive, negative and zero sequences, respectively.
F	=	Fault.

replacing the positive sequence network by its Thevenin equivalent, the negative and zero sequence networks by their equivalent impedances and then applying Kirchhoffs' Laws. The current flowing in the various branches are then obtained by the current division principle. The fault current in any branch will be equal to the sum of the positive, negative and zero sequence components of currents.

2.4 SYNCHRONOUS MACHINE ON LOAD

Suppose now that a 3-phase load of (R_L + j X_L) per phase is connected to the synchronous generator. The load must be connected between the terminal and neutral point of each sequence network and for a line-to-ground fault the sequence networks are connected in series as shown in Fig.2.3 by the dashed lines. For a line-to-line-to-ground fault, with the numbers of turns between fault points and the neutral in each faulted phase being equal, the equivalent circuit will be as shown by the dotted lines in Fig. 2.3.

2.5 CALCULATION OF FAULT CURRENTS

First of all the negative and zero sequence networks are replaced by their equivalent impedance. The application of Maxwells' loop Equations then, gives the positive-sequence currents in the 'f' 'r' and 'p' windings and the positive - sequence fault current. The negative-sequence

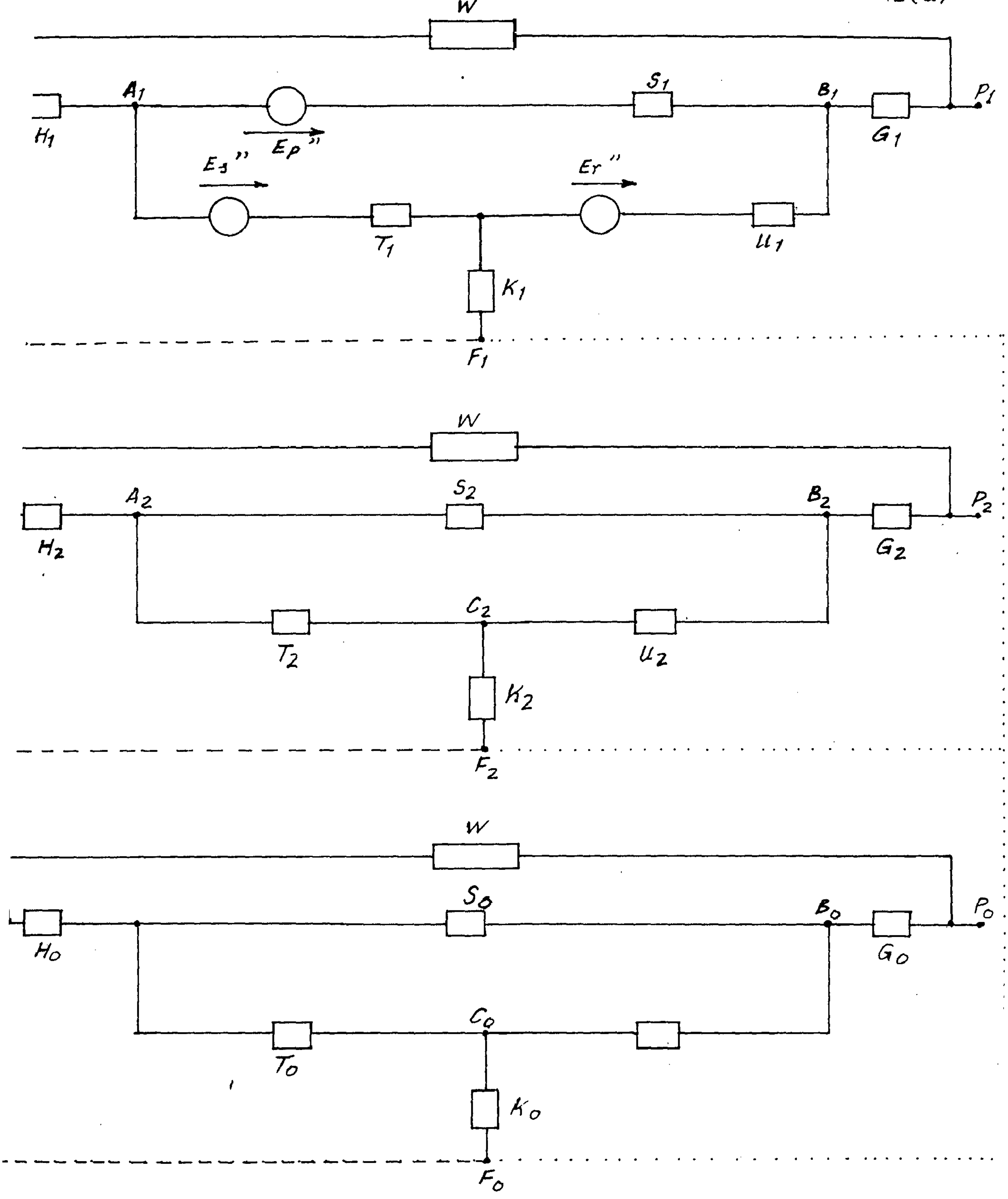


Fig. 2.3 Equivalent circuit of a synchronous generator on load and with an internal fault.

W	=	$R_L + jX_L$
H_1, H_2, H_0	=	jWM_{pf}'' , jWM_{pf2}, jWM_{pf0}, respectively
G_1, G_2, G_0	=	jWM_{pr}'', jWM_{pr2}, jWM_{pro}, respectively
K_1, K_2, K_0	=	$jWM_{fr}'' + (R_F + jX_F)$; $jWM_{fr2} + (R_F + jX_F)$, $jWM_{fro} + (R_F + jX_F)$
T_1, T_2, T_0	=	$R_{f1} + jW(L_f'' - M_{pf}'' - M_{fr}'')$; $R_{f2} + jW(L_{f2} - M_{pf2} - M_{fr2})$; $R_{fo} + jW(L_{fo} - M_{pfo} - M_{fro})$, respectively.
U_1, U_2, U_0	=	$R_{r1} + jW(L_r'' - M_{pr}'' - M_{fr}'')$, $R_{r2} + jW(L_{r2} - M_{pr2} - M_{fr2})$, $R_{ro} + jW(L_{ro} - M_{pro} - M_{fro})$, respectively.

currents are obtained by replacing the positive-sequence network by its Thevenin equivalent, the zero-sequence network by its equivalent impedance and then applying Maxwells' loop Equations. The zero-sequence currents are found in the same way. The total fault current will be given by the sum of the three sequence components of currents.

$$S_1, S_2, S_0 = R_{p1} + jW(L_p'' - M_{pf}'' - M_{pr}''); \; R_{p2} + jW(L_{p2} - M_{pf2} - M_{pr2}); \; R_{po} + jW(L_{po} - M_{pfo} - M_{pro}) \text{ respectively.}$$

2.6 SYNCHRONOUS MACHINE OPERATING IN PARALLEL WITH ANOTHER SYSTEM

The system is represented by its sequence networks. The line and neutral terminals are connected to the faulted generator networks in each sequence. The resulting sequence networks should then be connected according to the type of fault. For a line-to-ground fault the sequence networks are connected in series as shown by the dashed lines in Fig. 2.4. For a line-to-line fault, provided the same number of turns between fault points and neutral are involved in both phases, the sequence networks are connected in parallel as shown by the dotted lines in fig. 2.4

The fault currents in the various branches and in the short circuit loop are calculated in exactly the same way as in the case of a loaded machine. In case of a line-

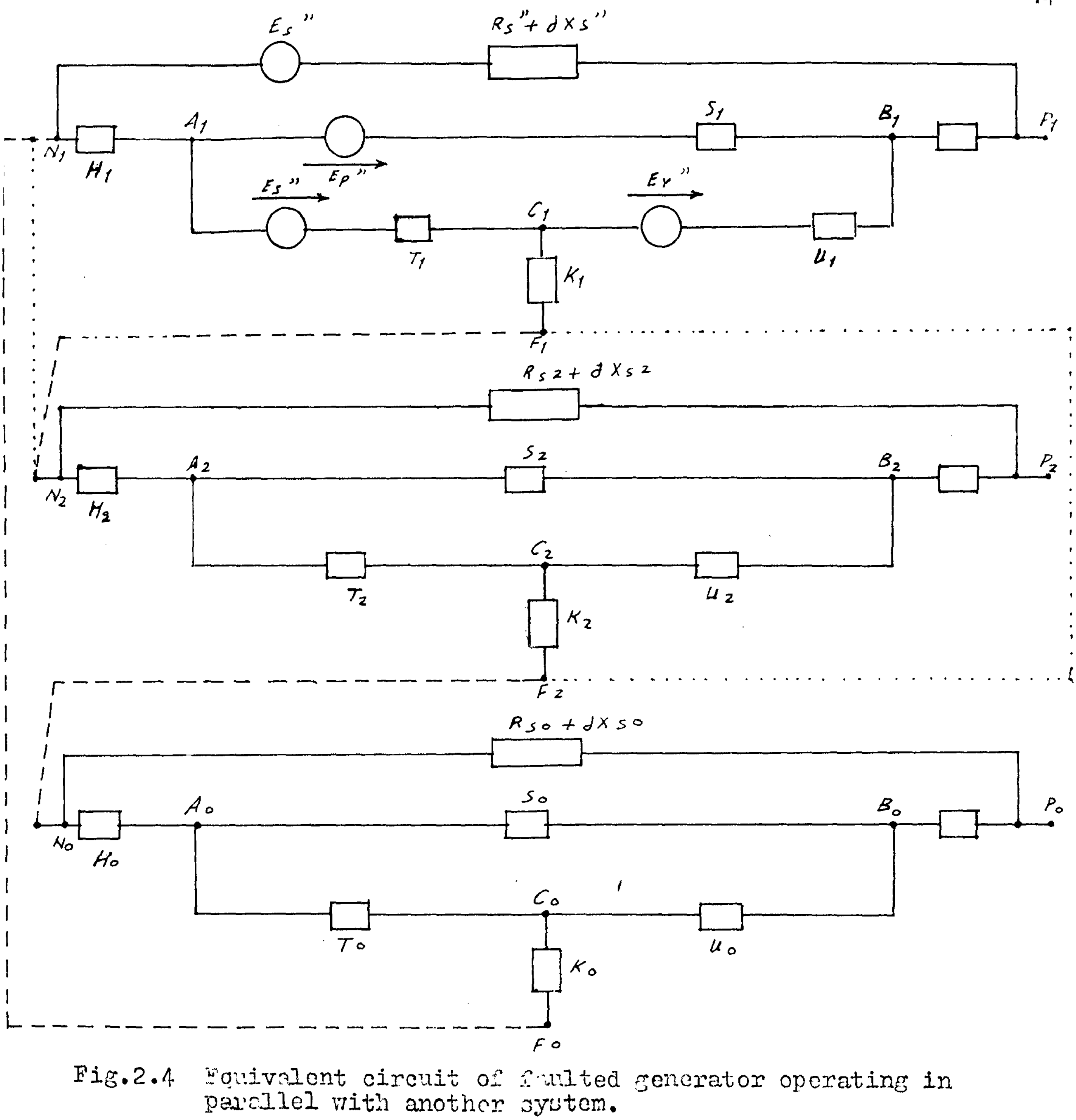


Fig.2.4 Equivalent circuit of faulted generator operating in parallel with another system.

H_1, H_2, H_0; T_1, T_2, T_0; S_1, S_2, S_0; U_1, U_2, U_0; K_1, K_2, K_0 have the same meaning as those in Fig.2.3. $(R_s" + jX_s")$, $(R_{s2}+jX_{s2})$; $(R_{so}+jX_{so})$ are the subtransient positive, negative and zero sequence impedances of the system, respectively.

to-line fault involving unequal numbers of turns in the two phases we shall have two networks with the same configuration as in Fig. 2.4 connected in parallel. The corresponding inductances and mutual inductances will have different values, depending upon the location of the fault. In such a case the application of sequence components is more cumbersome than the application of circuit theorems.

2.7 HARMONICS IN FAULT CURRENTS:

When a synchronous machine operates under fault condition (unbalance), third-harmonic voltages are induced in the various branches due to the flow of negative-sequence currents in the corresponding branches. The third-harmonic voltage (E_{3f}) induced in the 'f' winding can be determined from (2.1)[1].

$$E_{3f} = \frac{3}{2} I_{f2} W \left\{ (L_{fq}'' - M_{pfq}'' - M_{frq}'') - (L_{fd}'' - M_{pfd}'' - M_{frd}'') \right\}$$

With a phase shift (δ_{3f}) given by (2.1)

$$\delta_{3f} = \frac{\pi}{2} + \phi_{f2} + \theta_f'' \quad (2.2)$$

where I_{f2} is the negative-sequence current of fundamental frequency in the 'f' winding; W is the angular frequency; L_{fd}'' and L_{fq}'' are the subtransient inductances of the 'f' winding in the direct and quadrature axes, respectively;

M_{pfd}'' and M_{pfq}'' are the mutual inductances between the 'p' and 'f' windings in the direct and quadrature axes, respectively; M_{frd}'' and M_{frq}'' are the mutual inductances between the 'f' and 'r' windings in the direct and quadrature, axes, respectively; ϕ_{f2} is the phase angle of the negative-sequence current in the 'f' winding; θ_f'' is the phase angle of subtransient impedance difference between the direct and quadrature axes of the 'f' winding.

The third-harmonic voltages can be determined by (2.1) and (2.2) with the corresponding values for each branch of the faulted machine and for any machine in the network. The equivalent network for the third harmonic is similar to that of the fundamental frequency, but with inductive reactances three times greater than the corresponding reactances of the fundamental frequency. The third-harmonic voltages are inserted into the third-harmonic positive-sequence network and the third-harmonic currents can be determined.

The third-harmonic currents of negative sequence in each branch of unsymmetrical synchronous machines induce fifth-harmonic voltages in the corresponding branches , which can be calculated from equations similar to (2.1) and (2.2). The fifth-harmonic currents can be determined by inserting the induced fifth-harmonic voltages into the fifth-harmonic network. Usually the fifth-harmonic currents are relatively small and can be neglected in the internal fault calculation. Thus, the total a.c. component of fault current in the 'f' winding is

$$i_f = I_{f1} \sin(Wt + \phi_{f1}) + I_{f3} \sin(Wt + \phi_{f3}) \quad (2.3)$$

Where I_{f1} and I_{f3} are the amplitudes of the current of the fundamental and third harmonic, respectively, ϕ_{f1} and ϕ_{f3} are the phase angles of the fundamental and third harmonic currents, respectively, in respect to the chosen reference. The d.c. component is equal to the a.c. component at the switching time t = 0.

We can also conclude from (2.1) that in cylindrical-rotor machines, third and higher harmonic-currents are exteremely small as L_{fq}'', M_{pfq}'' and M_{frq}'' are almost equal to L_{fd}'', M_{pfd}'' and M_{frd}'', respectively.

2.8 DETERMINATION OF INDUCTANCES:

To calculate initial values of fault currents, the subtransient values of inductances should be used in the sequence-networks equivalent circuit. The subtransient inductance (L'') per phase of a polyphase armature winding is given by

$$L'' = \frac{L_d'' + L_q''}{2} + \frac{L_d'' - L_q''}{2} \cos 2\theta \quad \text{[Bib.2]} \quad (2.4)$$

where L_d'' and L_q'' are the subtransient self-inductances per phase in the direct and quadrature axes, respectively. For the positive-sequence θ is equal to the rotor displacement angle δ, for the negative and zero sequence, however, θ varies from 0 to 2π. For a cylindrical rotor machine the variable part of the inductance given by (2.4) is equal to zero.

The inductance of one parallel branch, in a system of 'a' parallel branches, is 'a' times greater than that of the entire phase. Therefore the subtransient inductance (L_p'') of the 'p' winding in the positive sequence is given by

$$L_p'' = \frac{a}{a-1} \left(\frac{L_d'' + L_q''}{2} + \frac{L_d'' - L_q''}{2} \cos 2\theta \right)$$

in the negative sequence (L_{p2}) is given by

$$L_{p2} = \frac{a}{a-1} \left(\frac{L_d'' + L_q''}{2} \right)$$

and in the zero sequence (L_{po}) is given by

$$L_{po} = \frac{a}{a-1} (L_o) \qquad (2.5)$$

Where L_o is the zero-sequence inductance of the whole phase.

The inductances of the 'f' and 'r' windings are proportional to the square of 'N_f' and 'N_r', respectively.

Thus the inductance of the 'f' winding in the three sequences can be written as shown below:

$$L_{f}'' = a\left(\frac{N_f}{N}\right)^2\left(\frac{L_d''+L_q''}{2} + \frac{L_d''-L_q''}{2}\cos 2\delta_f\right)$$

$$L_{f2} = a\left(\frac{N_f}{N}\right)^2\left(\frac{L_d''+L_d''}{2}\right)$$

$$L_{fo} = a\left(\frac{N_f}{N}\right)^2 (L_o) \qquad (2.6)$$

Where δ_f is the rotor displacement angle corresponding to the 'f' winding when this winding is regarded as a polyphase one.

The inductance of the 'r' winding can be calculated using (2.6) but inserting the corresponding number of turns and rotor displacement angle.

2.9 DETERMINATION OF MUTUAL INDUCTANCES:

The mutual inductance between the separated branch and the equivalent parallel branch in the positive sequence can be found from the total flux linkages in the separated branch caused by a positive-sequence current (I_1) flowing in the entire armature winding, except in the separated branch with the rotor windings short-circuited. With phase A as a reference, the positive-sequence currents are

$$\bar{I}_{a1} = I_1$$

$$\bar{I}_{b1} = \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right) I_1$$

$$\bar{I}_{c1} = \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) I_1$$

Where $\bar{I}_{a1}$, $\bar{I}_{b1}$ and $\bar{I}_{c1}$ are the positive-sequence currents in the A,B and C phases, respectively. Considering that the separated branch belongs to phase A, the positive-sequence current (I_{ap1}) flowing in the 'p' winding is given by

$$I_{ap1} = \left(\frac{a-1}{a}\right) I_1 \tag{2.8}$$

The total flux linkages ($\bar{\psi}_{ap1}$) in the separated branch caused by the positive-sequence currents are given by

$$\overline{\psi_{ap1}} = \overline{M_{ap''}}\ \overline{I_{ap1}} + \overline{M_{ab}''}\ \overline{I_{b1}} + \overline{M_{ac}''}\ \overline{I_{c1}}$$

$$= \left[\left(\frac{a-1}{a}\right) \overline{M_{ap}''} + \overline{M_{ab}''} \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right) + M_{ac}''\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) \right. \tag{2.9}$$

The expression in the square brakets of (2.9) is the positive sequence mutual inductance between the separated branch and the equivalent parallel branch.

The positive-sequence mutual inductance between the 'f' and 'p' windings can be found from (2.9) by considering $\overline{M_{ap}}''$, $\overline{M_{ab}}''$ and $\overline{M_{ac}}''$ as mutual inductances between the 'f' winding and the 'p' winding and phases B and C, respectively. These mutual inductance are [4].

$$\overline{M_{ap}}'' = A_a'' + B_a'' \cos 2\theta - j(C_a'' + D_a'' \cos 2\theta)$$

$$\overline{M_{ab}}'' = A_b'' + B_b'' \cos(2\theta - 120) + j\left[C_b'' + D_b'' \cos(2\theta - 120)\right]$$

$$\overline{M_{ac}}'' = A_b'' + B_b'' \cos(2\theta + 120) + j\left[C_b'' + D_b'' \cos(2\theta + 120)\right]$$

(2.10)

where, the coefficients of the mutual inductance between the 'f' and 'p' windings are [4].

$$A_a'' = M_{st} + k_t k_r \left[\frac{W M_{ad}^2}{2(C_f^2 + D_f^2)} (C_f X_e - D_f R_e) - F_e W L_Q\right]$$

$$B_a'' = L_{mt} + k_t k_r \left[\frac{W M_{ad}^2}{2(C_f^2 + D_f^2)} (C_f X_e - D_f R_e) + F_e W L_Q\right]$$

$$C_a'' = k_t k_r \left[\frac{W M_{ad}^2}{2(C_f^2 + D_f^2)} (C_f R_e + D_f X_e) + F_e R_Q\right]$$

resistance and the self-inductance, respectively, of the damper winding in the direct axis, and M_{aq} is the mutual inductance between the single-phase armature winding and the rotor winding in the quadrature axis.

The coefficients of the mutual inductances between the 'f' winding and phase B or C are:

$$A_b'' = - k_t \left[M_s + \frac{WMad^2}{4(C_f^2 + D_f^2)} (C_f X_e - D_f R_e) - \frac{F_e WL_Q}{2} \right]$$

$$B_b'' = k_t \left[L_m + \frac{WM_{ad}^2}{2(C_f^2 + D_f^2)} (C_f X_e - D_f R_e) + F_e WLQ \right]$$

$$C_b'' = k_t \left[\frac{WM_{ad}^2}{4(C_f^2 + D_f^2)} (C_f R_e + D_f X_e) + \frac{F_e R_Q}{2} \right]$$

$$D_b'' = k_t \left[- \frac{W M_{ad}^2}{2(C_f^2 + D_f^2)} (C_f R_e + D_f X_e) + F_e R_Q \right] \qquad (2.13)$$

Where M_s is the constant part of the mutual inductance between the entire phases and L_m is the amplitude of the variable part of mutual inductance between the entire phases.

$$D_a'' = k_t k_r \left[\frac{W\,M_{ad}^2}{2(C_f^2+D_f^2)}(C_f R_e + D_f X_e) - F_e R_Q \right] \qquad (2.11)$$

Where M_{st} is the constant part of the mutual inductance between the 'f' winding and the remaining part of the phase to which the 'f' winding belongs; L_{mt} is the amplitude of the variable part of the mutual inductance between the 'f' winding and the remaining part of the phase to which the 'f' belongs; M_{ad} is the mutual inductance between the single phase armature winding and the rotor winding in the direct axis; L_Q and R_Q are the self-inductance and the resistance of the damper winding in the quadrature axis, respectively; k_t is the effective turns ratio between the 'f' winding and the entire phase; and k_r is the effective turns ratio between the 'p' branch and the entire phase. The other factors in (2.11) are:

$$C_f = R_f\,R_D - W^2\,(L_f\,L_D - M_{ad}^2)$$

$$D_f = W\,(L_f\,R_D + L_D\,R_f)$$

$$R_e = R_f + R_D$$

$$X_e = W\,(L_D + L_f - 2M_{ad})$$

$$F_e = \frac{W\,M_{aq}^2}{2(R_Q^2 + W^2\,L_Q^2)} \qquad (2.12)$$

Where, R_f and L_f are the resistance and self-inductance, respectively, of the field winding. R_D and L_D are the

Inserting (2.10) in (2.9) the positive-sequence mutual inductance between the 'f' and the 'p' windings becomes, by considering that the rotor angle θ is equal to the rotor displacement angle δ_f.

$$\overline{M_{fp}}'' = \left(\frac{a-1}{a}\right) A_a'' - A_b'' + \left[\left(\frac{a-1}{a}\right)B_a'' + \frac{1}{2} B_b''\right] \cos 2\delta_f + \frac{3}{2} D_b'' \operatorname{Sin} 2\delta_f - j \left[\left(\frac{a-1}{a}\right)C_a'' + C_b'' + \left[\left(\frac{a-1}{a}\right)D_a'' - \frac{1}{2} D_b''\right] \cos \delta_f + \frac{3}{2} B_b'' \sin 2\delta_f\right]$$

(2.14)

The total flux linkage ($\bar{\psi}_{ap2}$) in the separated branch caused by the negative-sequence current (I_2) can be determined as in the case of the positive-sequence current.

$$\bar{\psi}_{ap2} = \left[\left(\frac{a-1}{a}\right) \bar{M}_{ap}'' + \bar{M}_{ab}''\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) + \bar{M}_{ac}''\left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\right] I_2$$

(2.15)

The rotor angle θ changes periodically from 0 to 2π in the negative sequence. Therefore by inserting (2.10)in (2.15), the average value of the negative-sequence mutual inductance ($\bar{M}_{fp2}$) between the 'f' and 'p' windings should be considered and this becomes

$$\bar{M}_{fp2} = \left(\frac{a-1}{a}\right)A_a'' - Ab'' - j\left[\left(\frac{a-1}{a}\right)C_a''+C_b''\right]. \quad (2.16)$$

Any zero-sequence current I_o, will produce a third-harmonic field in the air gap. Consequently, in order to obtain the corresponding mutual inductances in the zero sequence, the mutual inductances given by (2.10) should be multiplied by the factor $\left(\frac{2}{3m}\right)\left(\frac{k_3}{k_1}\right)^2$, where m is the number of phases and k_1 and k_3 are the winding factors for the fundamental and third-harmonic components, respectively [Bib.3]. Similarly the total flux linkages ($\bar{\Psi}_{apo}$) in the separated branch caused by the zero-sequence current become

$$\bar{\Psi}_{apo} = \left[\left(\frac{a-1}{a}\right)\bar{M}_{apo} + \bar{M}_{abo} + \bar{M}_{aco}\right] I_o \quad (2.17)$$

The zero-sequence mutual inductance ($\bar{M}_{pfo}$) between the 'f' and the 'p' windings is obtained by inserting (2.10) into (2.17) with the proper multiplication factor and considering the rotor angle θ to change periodically from 0 to 2π.

$$\bar{M}_{pfo} = \frac{2}{3m}\left(\frac{k_3}{k_1}\right)^2\left[\left(\frac{a-1}{a}\right)A_a''+2A_b''-j\left[\left(\frac{a-1}{a}\right)C_a''-2C_b''\right]\right]$$

(2.18)

The mutual inductances between the 'r' and 'p' windings $\bar{M}_{pr}''$, $\bar{M}_{pr2}$ and $\bar{M}_{pro}$ can be determined from (2.14),(2.16) and (2.18) by inserting the corresponding values.

The negative-sequence mutual inductance ($\overline{M}_{fr2}$) between the 'f' and 'r' windings can be determined from (2.20) by considering θ to vary periodically from 0 to 2π. Thus,

$$\overline{M}_{fr2} = \frac{1}{a} (A_a'' - jCa'') \qquad (2.22)$$

The zero-sequence mutual inductance ($\overline{M}_{fro}$) between the $\bar{f}$' and 'r' windings can also be determined from (2.20) by considering the third-harmonic flux in the air gap and the periodical change in the rotor angle. Thus,

$$\overline{M}_{fro} = \frac{2}{3\ am} \left(\frac{k_3}{k_1} \right)^2 (A_a'' - j\ C_a'') \qquad (2.23)$$

The imaginary part in the expressions for mutual-inductances is caused by the resistance of the rotor winding.

2.10 MUTUAL INDUCTANCE BETWEEN PORTIONS OF THE ARMATURE WINDINGS CONSIDERED IN ISOLATION:

In (2.11) and (2.13) the mutual inductance between the $\bar{f}$' winding and the remaining part of the phase to which the 'f' winding belongs and the mutual inductance between the phases respectively, are required. The main inductance of the 'f' winding is proportional to the square of its number of turns. The mutual inductances between the 'f' and all other windings are proportional to the product of the effective numbers of turns of both corresponding windings. It has been shown [4] that the mutual inductance

The positive-sequence mutual inductance between the 'f' and 'r' windings can be determined from the magnetic linkages of the 'f' winding caused by the positive-sequence current $\frac{I_1}{a}$ flowing in the 'r' winding or vice versa. The magnetic coupling between the 'f' winding of phase A and phases B and C has been considered in the mutual inductances between this winding and the 'p' winding. Consequently, the mutual flux linkages ($\bar{\Psi}_{fr}$) between the 'f' and 'r' windings becomes.

$$\bar{\Psi}_{fr} = \frac{1}{a} I_1 \bar{M}_{ap}'' \qquad (2.19)$$

From (2.19) and (2.10)

$$\bar{M}_{fr}'' = \frac{1}{a} \left[A_a'' + B_a'' \cos 2\theta - j(C_a''+D_a'' \cos 2\theta) \right] \qquad (2.20)$$

The rotor angle θ, in this case, is equal to the displacement angle δ minus one half the angle γ_{fr} between the 'f' and 'r' windings. Thus, the positive-sequence mutual inductance between the 'f' and 'r' windings becomes.

$$\bar{M}_{fr}'' = \frac{1}{a} \left[A_a''+ B_a''\cos 2\left(\delta - \frac{\gamma_{fr}}{2}\right)- j \left\{ C_a''+D_a'' \cos 2\left(\delta - \frac{\gamma_{fr}}{2}\right) \right\} \right] \qquad (2.21)$$

The negative-sequence mutual inductance ($\overline{M}_{fr2}$) between the 'f' and 'r' windings can be determined from (2.20) by considering θ to vary periodically from 0 to 2π. Thus,

$$\overline{M}_{fr2} = \frac{1}{a} (A_a'' - jCa'') \qquad (2.22)$$

The zero-sequence mutual inductance ($\overline{M}_{fro}$) between the 'f' and 'r' windings can also be determined from (2.20) by considering the third-harmonic flux in the air gap and the periodical change in the rotor angle. Thus,

$$\overline{M}_{fro} = \frac{2}{3\ am} \left(\frac{k_3}{k_1} \right)^2 (A_a'' - j\ C_a'') \qquad (2.23)$$

The imaginary part in the expressions for mutual-inductances is caused by the resistance of the rotor winding.

2.10 MUTUAL INDUCTANCE BETWEEN PORTIONS OF THE ARMATURE WINDINGS CONSIDERED IN ISOLATION:

In (2.11) and (2.13) the mutual inductance between the 'f' winding and the remaining part of the phase to which the 'f' winding belongs and the mutual inductance between the phases respectively, are required. The main inductance of the 'f' winding is proportional to the square of its number of turns. The mutual inductances between the 'f' and all other windings are proportional to the product of the effective numbers of turns of both corresponding windings. It has been shown [4] that the mutual inductance

$\overline{M}_{afr}$ between the 'f' and the 'r' windings is given by

$$\overline{M}_{afr} = \frac{N_r k_{pr}}{N_f k_{pf}} L_{mf} \qquad (2.24)$$

Where k_{pr} and k_{pf} are the winding factors of the 'r' and 'f' windings, respectively; L_{mf} is the main inductance of the 'f' winding. The mutual inductance ($\overline{M}_{apf}$) between the 'f' and each parallel path of the same phase is given by

$$\overline{M}_{apf} = \frac{Nk_{pd}}{N_f k_{pf}} L_{mf} \qquad (2.25)$$

Where k_{pd} is the winding factor of the whole armature winding for the main wave. The mutual inductance between the 'f' and the two other phases B and C considering a shift in space to be $\pm$ 120^o, are

$$\overline{M}_{bf} = \frac{Nk_{pd}}{N_f k_{pf}} L_{mf} \cos(120-\alpha_f) \qquad (2.26)$$

$$\overline{M}_{cf} = \frac{Nk_{pd}}{N_f k_{pf}} L_{mf} \cos(240-\alpha_f) \qquad (2.27)$$

Where α_f is the shift angle between the 'f' winding and phase A. Thus the mutual inductance between two phases is always negative as a result of the displacement of the phase windings by 120 electrical degrees in space from each other.

The mutual inductance between the 'r' winding and all other windings are obtained by substituting the corresponding values in (2.24) to (2.27).

CHAPTER-III

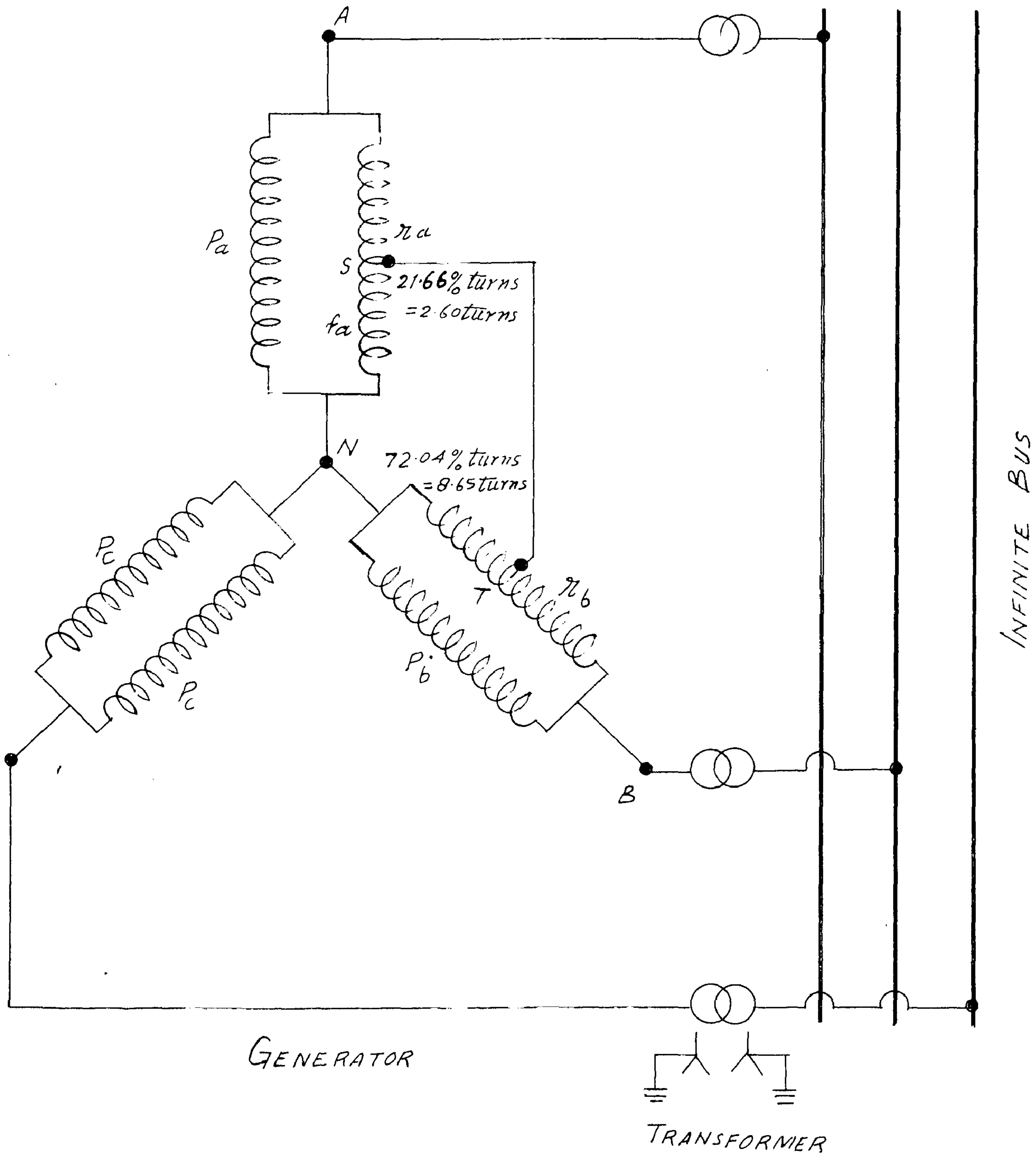
CALCULATION OF FAULT CURRENTS IN A TURBO-GENERATOR WHICH HAS DEVELOPED A LINE-TO-LINE FAULT

3.1 INTRODUCTION:

A 141 MVA, 120 MW, 13.8 kV turbogenerator having two parallel paths per phase has developed a short-circuit between one parallel path of phase A and another of phase B. As the numbers of turns between the fault points and the neutral of the machine in the faulted phases are not equal, the application of symmetrical components for the calculation of fault currents would be very cumbersone. This type of problem can, however, be solved more elegantly by circuit theory method such as the Maxwells' Loop Equations.

3.2 FAULT CONDITION AND MACHINE DATA:

The turbogenerator, 141 MVA, 13.8 kV, 0.85 pf, 50Hz, 2 poles, 2 parallel paths per phase, has developed a short circuit between 21.66 percent turns of one parallel path of phase A and 72.04 percent turns of another parallel path of phase B, as shown in Fig.3.1. The generator is connected to an infinite bus through a star-star, grounded neutral transformer. The latter has a reactance of 0.15 p.u. and negligible resistance.


A
P_a
r_a
S
21·66% turns
=2·60 turns
f_a
N
72·04% turns
=8·65 turns
P_c
P_c
T
r_b
P_b
B
GENERATOR
TRANSFORMER
INFINITE BUS

[illegible].1 [illegible] Con[illegible]

Transient armature reactance in the D-axis	= 0.265 p.u.
Subtransient armature reactance in the D-axis	= 0.206 p.u.
Subtransient resistance at 20 °C in the D-axis	= 0.001664 ohms.
Number of Stator slots	=72
Number of turns per parallel path	=12 .
Coil pitch	=1 to 31
Mutual inductance between single phase armature winding and rotor winding in the D-axis	=1.265 p.u.
Mutual inductance between single phase armature winding and rotor winding in the Q-axis.	=1.222 p.u.
Self-inductance of the damper winding in the D-axis	= 0.0766 p.u.
Main reactance in the D-axis	= 1.480 p.u.
Leakage reactance	= 0.154 p.u.

There is no damper winding in the Q-axis, further, the resistance of the damper winding in the D-axis is unknown and has been assumed to be negligibly small. The per-unit system is used throughout and the capacity (141 MVA) and the terminal voltage (13.8 kV) has been taken as one p.u. each. In the absence of a damper winding in the Q-axis, terms containing L_Q and R_Q in (2.11) and (2.13) will become zero.

3.3 DETERMINATION OF SELF-INDUCTANCES:

The subtransient inductance per phase is 0.206 p.u. hence the subtransient inductance per parallel path is 0.412 p.u. The inductances of the 'f' and 'r' windings are proportional to the square of N_f and N_r, respectively.

Considering Phase-A

$$N_f = \frac{21.66}{100} \times 12 = 2.6 \text{ turns}$$

$$N_r = 12-2.6 = 9.4 \text{ turns}$$

$$X_f = \left(\frac{2.6}{12}\right)^2 \times 0.412 = 0.019 \text{ p.u.}$$

$$X_r = \left(\frac{9.4}{12}\right)^2 \times 0.412 = 0.253 \text{ p.u.}$$

Considering Phase-B

$$N_f = \frac{72.06}{100} \times 12 = 8.65 \text{ turns.}$$

$$N_r = 12-8.65 = 3.35 \text{ turns}$$

$$X_f = \left(\frac{8.65}{12}\right)^2 \times 0.412 = 0.214 \text{ p.u.}$$

$$X_r = \left(\frac{3.35}{12}\right)^2 \times 0.412 = 0.032 \text{ p.u.}$$

3.4 DETERMINATION OF ROTOR DISPLACEMENT ANGLE WHEN DELIVERING RATED LOAD:

The per-unit subtransient resistance of the armature winding (r_a) is given by

$$r_a \text{ p.u.} = \frac{S_b}{(V_b)^2} \times \text{Actual resistance} \quad (3.1)$$

$$r_a \text{ p.u.} = \frac{141}{(13.8)^2} \times 0.001664 = .0012$$

Hence r_a is negligible in comparison to the per unit reactance.

From $$Z_{base} = \frac{(k\ V_{base})^2}{MVA_{base}} \qquad (3.2)$$

$$Z_{base} = \frac{(13.8)^2}{141} = 1.351 \text{ ohms}$$

Actual impedance = 1.351 x 1.48 = 2 ohms

From $P = \sqrt{3}\ I_L\ V_L \cos\phi$ (3.3)

Where P = Power, I_L and V_L are line current and Line voltage, respectively, and ϕ is the phase angle.

$$I_L = I_{phase} = \frac{120}{\sqrt{3} \times 13.8 \times .85} = 5.907 \text{ kA}$$

$$V_{phase} = \frac{13.8}{\sqrt{3}} = 7.968 \text{ kV}$$

$$I_d\ X_d = 5.907 \sin\phi \times 2 = 6.224 \text{ kV}$$

$$I_q\ X_q = 5.907 \cos\phi \times 2 = 10.048 \text{ kV}$$

$$\tan\delta = \frac{10.048}{7.968+6.224} = 0.707$$

Where, δ is the rotor displacement angle.

$$\delta = 35.27^\circ$$

Determination of rotor displacement angle (δ_f) when the 'f' winding is considered as a polyphase one .

Consider Phase-A

$$\text{Terminal voltage} = \frac{21.66}{100} \times 7.968 = 1.726 \text{ kV}$$

Phase current $= \frac{21.66}{100} \times 5.907$ $= 1.279$ kA

Phase impedance $= 2 \times \left(\frac{2.6}{12}\right)^2$ $= 0.094$ ohm.

Power factor $= 0.85$

$$I_q X_q = I_{ph} \cos \phi \; Z_{ph} = 1.279 \times 0.85 \times 0.094 = 0.102 \text{ kV}$$

$$I_d X_d = I_{ph} \sin \phi \; Z_{ph} = 1.279 \times 0.527 \times 0.094 = 0.063 \text{ kV}$$

$$\delta_f = \tan^{-1} \frac{0.102}{1.726 + 0.063} = 3.3^o$$

<u>Determination of rotor displacement angle (δ_r) when the 'r' Winding is considered as a polyphase one:</u>

Terminal voltage $= \frac{78.34}{100} \times 7.968$ $= 6.242$ kV

Phase current $= \frac{78.34}{100} \times 5.907$ $= 4.628$ kA

Phase impedance $= \left(\frac{9.4}{12}\right)^2 \times 2$ $= 1.227$ ohms

$$I_q X_q = 4.628 \times 0.85 \times 1.227 = 4.827 \text{ kV}$$

$$I_d X_d = 4.628 \times 0.527 \times 1.227 = 2.993 \text{ kV}$$

$$\delta_r = \tan^{-1} \frac{4.827}{6.242 + 2.993} = 27.6^o$$

<u>Consider Phase-B:</u>

The rotor displacement angle when the 'f' and 'r' windings were considered as forming the polyphase machines, respectively, were determined in a similar method and were found to be

$$\delta_f = 25^\circ$$
$$\delta_r = 5.3^\circ$$

3.5 DETERMINATION OF MUTUAL-INDUCTANCES:

Substituting the values of the constants of the machine in (2.11) and (2.13) we have

$$A_a'' = M_{st} + k_t\, k_r \quad (-1.171)$$
$$B_a'' = k_t\, k_r \quad (-1.171)$$
$$C_a'' = k_t\, k_r \quad (0.060)$$
$$D_a'' = k_t\, k_r \quad (0.060)$$
$$A_b'' = -kt\ (-1.249)$$
$$B_b'' = k_t\ (-1.171)$$
$$C_b'' = k_t\ (0.030)$$
$$D_b'' = k_t\ (-0.060)$$

Consider Phase-A

Determination of mutual inductance between 'f' and 'p' windings (M_{pf})

Main inductance per parallel path = (1.48 - 0.154)2

= 2.652 p.u.

$$L_{mf} = \left(\frac{2.6}{12}\right)^2 \times 2.652 \quad = 0.124 \text{ p.u.}$$

From (2.25)

$$M_{st} = \frac{12}{2.6} \times 0.124 \quad = 0.572 \text{ p.u.}$$

$$k_t = \frac{2.6}{24} = 0.108$$

$$k_r = \frac{12}{24} = 0.5$$

$A_a'' = 0.509$, $B_a'' = -0.063$, $Ca'' = 0.003$, $D_a'' = 0.003$

$A_b'' = 0.135$, $B_b'' = -0.126$, $C_b'' = 0.003$, $D_b'' = -0.006$

From (2.14) $\underline{M_{pf} = 0.025 + j\ 0.012 \text{ p.u.}}$

Determination of Mutual-inductance between the 'r' and 'p' windings (M_{pr}).

$$L_{mr} = \left(\frac{9.4}{12}\right)^2 \times 2.652 = 1.627 \text{ p.u.}$$

$$M_{st} = \frac{12}{9.4} \times 1.627 = 2.076 \text{ p.u.}$$

$$k_t = \frac{9.4}{24} = 0.392, \quad k_r = \frac{12}{24} = 0.5$$

$A_a'' = 1.847$, $B_a'' = -0.230$, $C_a'' = 0.012$, $D_a'' = 0.012$

$A_b'' = 0.490$, $B_b'' = -0.460$, $C_b'' = 0.012$, $D_b'' = -0.024$

Substituting in (2.14) we have

$$\underline{M_{pr} = 0.207 + j.538 \text{ p.u.}}$$

Determination of mutual inductance between the 'r' and 'f' windings (M_{fr}).

$$M_{st} = \frac{9.4}{2.6} \times 0.124 = 0.448 \text{ p.u.}$$

$$k_t = \frac{2.6}{24} = 0.108, \quad k_r = \frac{9.4}{24} = 0.392, \quad \gamma_{fr} = 30^\circ$$

$A_a'' = 0.399$, $B_a'' = -0.099$, $C_a'' = 0.003$, $D_a'' = 0.003$.

Substituting in (2.20) we have

$$\underline{M_{fr} = 0.181 - j\,0.003 \text{ p.u.}}$$

Consider Phase-B:

Determination of mutual inductance between the 'f' and 'p' windings.

$$L_{mf} = \left(\frac{8.65}{12}\right)^2 2.652 = 1.378 \text{ p.u.}$$

$$M_{st} = 1.378\ \frac{12}{8.64} = 1.912 \text{ p.u.}$$

$$k_t = \frac{8.65}{24} = 0.360,\quad k_r = \frac{12}{24} = 0.5$$

$A_a'' = 1.701$, $B_a'' = -0.211$, $C_a'' = 0.011$, $D_a'' = 0.011$

$A_b'' = 0.450$, $B_b'' = -0.422$, $C_b'' = 0.011$, $D_b'' = -0.022$

Substituting in (2.14) we have

$$\underline{M_{pf} = 0.172 + j.457 \text{ p.u.}}$$

Determination of mutual inductance between the 'r' and '$\bar{p}$' windings (M_{pr}).

$$L_{mr} = \left(\frac{3.35}{12}\right)^2 \times 2.652 = 0.207 \text{ p.u.}$$

$$M_{st} = 0.207 \times \frac{12}{3.35} = 0.742 \text{ p.u.}$$

$k_t = \frac{3.35}{24} = 0.140$, $k_r = \frac{12}{24} = 0.5$

$A_a'' = 0.660$, $B_a'' = -0.082$, $C_a'' = 0.004$, $D_a'' = 0.004$

$A_b'' = 0.175$, $B_b'' = -0.164$, $C_b'' = 0.004$, $D_b'' = -0.008$

Substituting in (2.14) we have.

$M_{pr} = 0.032 + j\,0.033$ p.u.

Determination of mutual inductance between the 'f' and 'r' windings.

$k_t = \frac{8.65}{24} = 0.360$, $k_r = \frac{3.35}{24} = 0.140$

$M_{st} = 1.378 \times \frac{3.35}{8.65} = 0.535$ p.u.

$A_a'' = 0.475$, $B_a'' = -0.059$, $C_a'' = 0.003$, $D_a'' = 0.003$

Substituting in (2.20) we have

$M_{fr} = 0.215 - j\,0.003$ p.u.

Consider phase - C

Determination of mutual inductance between the two parallel paths.

$k_t = \frac{12}{24} = 0.5$, $k_r = 0.5$; $M_{st} = 2.652 \times \frac{12}{12} = 2.652$ p.u.

$A_a'' = 2.359$, $B_a'' = -0.293$, $C_a'' = 0.015$, $D_a'' = 0.015$

$A_b'' = 0.624$, $B_b'' = -0.586$, $C_b'' = 0.015$, $D_b'' = -0.030$

Substituting in (2.14) we have

Mutual inductance between 2 parallel paths = $0.367 + j\,0.797$.

3.6 DETERMINATION OF SUBTRANSIENT GENERATED VOLTAGE:

The subtransient generated voltage (E'') is given by $\bar{E}'' = V_t + j\, I_1\, X_d''$. (3.4)

Where V_t is the terminal voltage and I_1 is the current flowing before occurrence of fault.

$$E'' = \sqrt{(V_t + I_d X_d'')^2 + (I_q X_q'')^2}$$

$$= 0.707 \text{ p.u.}$$

Hence voltage generated in 'f' winding of Phase A

$$= \frac{21.66}{100} \times 0.707 = 0.153 \angle 0 \text{ p.u.}$$

Voltage generated in 'f' winding of phase B

$$= \frac{72.04}{100} \times 0.707 \angle 120^0 = 0.509 \angle 120^0 = -0.255 - j0.441 \text{ p.u.}$$

3.7 DETERMINATION OF FAULT CURRENTS

The equivalent circuit of the faulted machine and the system is as shown in Fig. 3.2 where,

$F_A = 0.019 - 0.181 + j.003 - 0.025 - j0.012 \quad = -0.187 - j0.009$

$R_A = 0.253 - 0.207 - j0.538 - 0.181 + j0.003 \quad = -0.135 - j0.535$

$P_A = 0.412 - 0.207 - j0.538 - 0.025 - j0.012 \quad = 0.180 - j0.550$

$F_B = 0.214 - 0.172 - j0.457 - 0.215 + j0.003 \quad = -0.173 - j0.454$

$R_B = 0.032 - 0.032 - j0.033 - 0.215 + j0.003 \quad = -0.215 - j0.030$

$P_B = 0.412 - 0.032 - j0.033 - 0.172 - j0.457 \quad = 0.208 - j0.490$

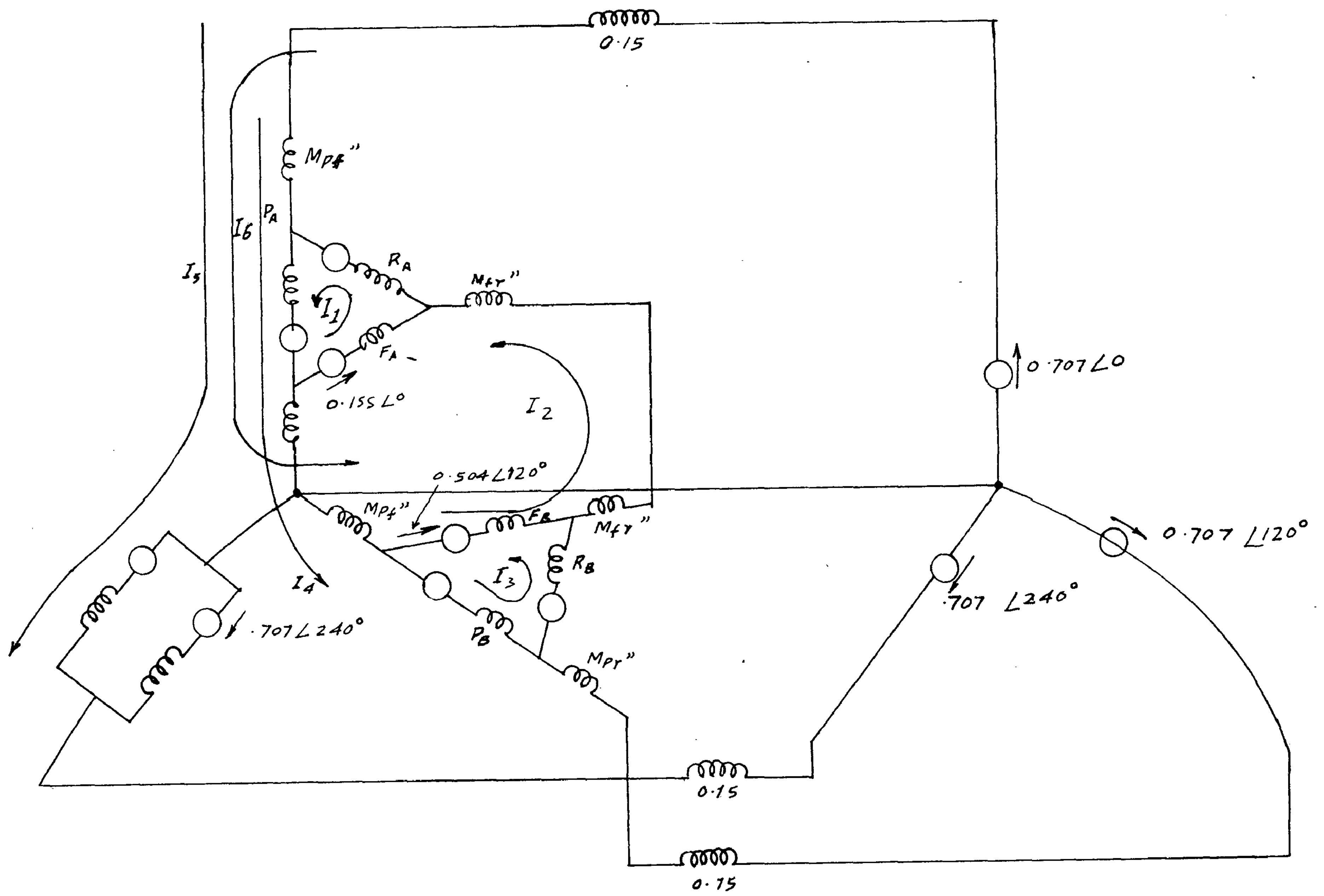


Fig.3.2 Complete equivalent circuit

Applying Maxwells' Loop Equations

$$0 = I_1(-0.142-j1.094)+ I_2(0.187-j0.009)+I_4(0.180-j0.550) + I_5(0.180-j0.550)+I_6(0.180-j0.550)$$

$$408+j0.441) = I_1(0.187+j0.009)+I_2(0.233)+I_3(0.173+j0.454) +I_4(0.197+j0.469)+I_5(0.025+j0.012) + I_6(0.025+j0.012).$$

$$0 = I_2(0.173+j0.454) - I_3(0.180+j0.974) + I_4(0.208-j0.490).$$

$$0 = I_1(0.180-j0.550) + I_2(0.197+j0.469)+I_3(0.208-j0.490) + I_4(1.124)+I_5(0.562) + I_6(0.562)$$

$$0 = I_1(0.180-j0.550)+ I_2(0.025+j0.012) + I_4(0.562) + I_5(1.124) + I_6(0.562)$$

$$0 = I_1(0.180-j0.550)+ I_2(0.025+j0.012)+ I_4(0.562) + I_5(0.562) + I_6(0.562) \quad (3.4)$$

Solving (3.4) simultaneously we have

$I_1 = 0.83 \angle -96.1^\circ$, $I_2 = 3.93 \angle -173.9^\circ$, $I_3 = 3.45 \angle 22.3^\circ$

$I_4 = -3.66 \angle 14.4^\circ$, $I_5 = 0$, $I_6 = 4.31 \angle 13^\circ$

3.8 CALCULATED VALUES OF FAULT CURRENTS

Considering phase-A

Fault current in 'f'winding$=I_2-I_1 = 4.19 \angle 17.4^\circ$p.u.

Fault current in 'F' winding $= I_1$ $= 0.83 \angle -96.1^{\circ}$ p.u.

Fault current in 'p' winding $= I_1 + I_4 + I_5 + I_6 = 0.95 \angle -53.9^{\circ}$

Considering phase-B

Fault current in 'f' winding $= I_2 - I_3$ $= 1.14 \angle 51^{\circ}$ p.u.

Fault current in 'r' winding $= I_3$ $= 3.45 \angle 22.3^{\circ}$ p.u.

Fault current in 'p' winding $= I_3 + I_4$ $= 0.54 \angle -48^{\circ}$ p.u.

The fault current calculations have, also, been performed for a Line-to-line-to-earth fault. The fault condition is the same as for the line-to-line case and no earth impedance have been considered. Maxwells' Loop Equations have been applied and the following results have been obtained.

Considering Phase-A:

Fault current in the 'f' winding $= 4.11 \angle 64.6^{\circ}$ p.u.

Fault current in the 'r' winding $= 0.88 \angle -49.9^{\circ}$ p.u.

Fault current in the 'p' winding $= 1.15 \angle 14^{\circ}$ p.u.

Considering Phase-B:

Fault current in the 'f' winding $= 0.74 \angle 27^{\circ}$ p.u.

Fault current in the 'r' winding $= 0.20 \angle 5.7^{\circ}$ p.u.

Fault current in the 'p' winding $= 0.07 \angle 74.1^{\circ}$ p.u.

Fault current to earth $= 3.3 \angle 55.5^{\circ}$ p.u.

CHAPTER-IV

SUMMARY AND CONCLUSIONS

4.1 DISCUSSION:

It has been shown that a synchronous machine with an internal fault can be represented by its sequence networks. The sequence networks should be connected according to the type of fault and the fault currents calculated in accordance with the method of symmetrical components. In the case of a line-to-line fault where the numbers of turns between fault point and neutral are not the same the method of symmetrical components becomes more cumbersome than that of circuit theory methods.

The calculated values of fault currents in the various parts of the armature windings should be compared to 0.5 p.u. as this is the normal rated current per parallel path. The values of fault currents calculated seem to be reasonable. As expected the heaviest fault currents have been shown to flow in the 'f' winding of phase A and 'r' winding of phase B, which are eight and seven times the normal currents, respectively. There is also a net flow of current and hence power into the faulted generator from the system.

4.2 LIMITATIONS:

Errors in the calculated values of fault currents are due to the use of simplified equations for the calculation of machine mutual inductances. The fact that saturation and non-linearity of the stator and rotor materials have not been considered, all calculated values of mutual inductances, which have been done by conventional methods, are ~~lower~~ higher than actual values. This results in the calculated values of fault currents being lower than the actual ones. In fact it has been shown in a previous work [1] that for a line-to-ground fault, all calculated values of fault currents are less than the measured ones, when the mutual inductances are calculated using (2.10). However, it is felt that the obtained accuracy is sufficient for the correct choice of the machine protection against internal fault.

4.3 SCOPE FOR FURTHER WORK:

The method of fault currents calculations is all right but calculated values of fault currents are less than the actual ones due to the use of simplified equations for the calculation of mutual inductances. Hence better methods should be devised for more accurate calculations of their values.

When magnetic non-linearity of the stator and rotor materials are considered the machine reactances become dependent on the saturation conditions in the machine, which are a function of the operating conditions. Hence, the values of reactances used in the fault current calculations should have been those obtained under operating conditions.

It has been shown recently [5] that the reactances and the load angle under saturated conditions are actually less than those obtained from their classical unsaturated values. Hence in future work the values of reactances and load angle under saturated conditions should be used. This would most probably reduce the margin of difference between the calculated and measured values of fault currents.

REFERENCES

1. V.A. Kinitsky, " Calculation of internal fault currents in synchronous machines". IEEE Transactions. PAS-84, 1965, P. 381 - 389.

2. V.A. Kinitsky, " Digital computer calculation of internal fault currents in a synchronous machine", IEEE Transactions. PAS - 87, 1968, P. 1675 - 1679.

3. V.A. Kinitsky, " Inductances of a portion of the armature winding of synchronous machines", IEEE Transactions PAS-84, 1965, p. 389 - 396.

4. V.A. Kinitsky, " Mutual inductances of synchronous machines with damper windings". IEEE Tranactions PAS -83, 1964, p. 997-1001.

5. V.K. Garg, N.A. Danerdash, L.L. Grigsby "Dynamic model of saturated synchronous machines " IEE Transactions PAS - 95, 1976.

BIBLIOGRAPHY

1. M.E. Talaat, ' A new approach to the calculation of synchronous machine reactances-I', Transactions AIEE PAS VOL 74, April 1955, p 176-183, II Vol 75, June 1956, p 317 - 327.

2. C. Concordia, ' Synchronous machines' New York Wiley, 1951.

3. W. Schnisky Berechnug. Electrisener Maschinen. Berlin Springer, 1960.

4. E. Clarke 'Circuit analysis of A.C. power systems' New York Wiley Vol. 2

5. V.A. Kinitsky 'Relay scheme protects generators against all internal faults'. Electrical World p 44-45 Oct. 3, 1960.