TRANSIENTS IN POWER SYSTEM

A Dissertation
submitted in partial fulfilment
of the requirements for the **Degree**
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING (Power System)

By
C.L. WADHWA

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE

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C E R T I F I C A T E

Certified that the dissertation entitled 'TRANSIENTS IN POWER SYSTEM' which is being submitted by Shri C.L.Wadhwa in partial fulfilment for the award of the degree of Master of Engineering in Electrical Power Systems of University of Roorkee, is a record of candidate's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is to certify that he has worked for a period of 7 months from Dec. '65 to June '66 for preparing dissertation for Master of Engineering Degree at the University.

P. Mukhopadhyay
(P.MUKHOPADHYAY)
ASSOCIATE PROFESSOR
DEPTT. OF ELECTRICAL ENGG.
UNIVERSITY OF ROORKEE,
ROORKEE.

Dated: 1.7.66
ROORKEE

SYNOPSIS

In the early years of Electrical Engineering power systems were designed according to the requirements of regular sustained operation. However, experience showed that with switching processes in the circuits and under similar intentional or accidental conditions peculiar phenomena appeared which could greatly disturb the regular operation of the system.

In this work, the unintentional transient phenomena which consists of ground faults, short circuits and break of conductors have been studied. Such accidents nearly always lead to severe disturbances throughout the electric system giving rise to high excess currents or voltages and sometimes currents of different frequency or entirely distorted wave shape.

When considering in substance the various transient phenomena the mathematical methods must be applied. In the present investigation an attempt has been made to use the simplest possible mathematical tools compatible with the individual problem essentially with the elements of differential and integral equations with the sequence networks.

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C.L. WADHWA

DATED

ROORKEE

S Y N O P S I S

In the early years of Electrical Engineering power systems were designed according to the requirements of regular sustained operation. However, experience showed that with switching processes in the circuits and under similar intentional or accidental conditions peculiar phenomena appeared which could greatly disturb the regular operation of the system.

In this work, the unintentional transient phenomena which consists of ground faults, short circuits and break of conductors have been studied. Such accidents nearly always lead to severe disturbances throughout the electric system giving rise to high excess currents or voltages and sometimes currents of different frequency or entirely distorted wave shape.

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LIST OF SYMBOLS

i)	R_{1t}	= Positive sequence resistance of the transformer.
ii)	R_{0t}	= Zero sequence resistance of the transformer.
iii)	R_{1L}	= Positive sequence resistance of transmission line
iv)	L_{1L}	= Positive sequence inductance of the transmission line
v)	R_{0L}	= Zero sequence resistance of the transmission line
vi)	L_{0L}	= Zero sequence inductance of the transmission line
vii)	L_{1t}	= Positive sequence inductance of transformer.
viii)	L_{0t}	= Zero sequence inductance of transformer.
ix)	L_{1g}	= Positive sequence inductance of the generator
x)	L_{0g}	= Zero sequence inductance of the generator
xi)	L_{2g}	= Negative sequence inductance of the generator
xii)	$L_{1t}+L_{1g}$	$= L_1$
xiii)	$L_{1t}+L_{1g}+L_{1L}$	$= L_{1eq}$
xiv)	$R_{1t}+R_{1L}$	$= R_{1eq}$
xv)	C_{1L}	= Positive sequence capacitances of transmission line
xvi)	C_{0L}	= Zero sequence capacitances of transmission line
xviii)	L_{2eq}	$= L_{2g} + L_{1t} + L_{0L}$
xix)	L_{0eq}	$= L_{0g} + L_{0t} + L_{0L}$
xix)	R_{0eq}	$= R_{0t} + R_{0L}$
xx)	Z_f	= Fault shunt impedance

C O N T E N T S

CHAPTER 1

INTRODUCTION

The power system can be considered as made up of linear impedance elements of resistance, inductance and capacitance. The circuit is normally energized and carrying load until a fault suddenly occurs. The fault then corresponds to the closing of a switch (or switches, depending upon the type of fault) in the electrical circuit. The closing of this switch changes the circuit so that a new distribution of currents and voltages is brought about. This redistribution is accompanied in general by a transient period during which the resultant currents and voltages may momentarily be relatively high.

There are two components of voltages in such linear circuits due to the occurrence of a system fault.

i) Fundamental frequency voltages and ii) Natural frequency voltages usually of short duration which are superimposed upon the fundamental frequency voltages. There is a third compoaant also known as harmonic voltages resulting from unbalanced currents flowing in rotating machine in which the reactances in the direct and quadrature axes are unequal.

Natural frequency voltages appear immediately after the sudden occurrence of a fault. They simply add to the fundamental frequency voltages. Since resultant voltages are of greater interest from a practical point of view it will be preferable to speak of the fundamental frequency and natural frequency components simply as a transient voltages. The transient voltage are affected by the number of connections and arrangements of the circuits.

There can be two types of transients. i) Simple transient

ii) Compound transients. While doing analysis it is assumed in t former case that the fault current preceding interruption contain ed only a fundamental frequency term. In other words the circuit was not in a transient state before the switch was opened. There are times when this is not the case e.g. when an expulsion protec tube operates.

As higher speed switching has been developed, the transient fault current has been of increasing importance to the design ers and users of circuit breakers. Consequently, in general the transient accompanying the occurrence of the fault is of importan since it may not have disappeared when the second transient due t the circuit interruption of the fault current, begins. Therefore, it is of interest to inquire with regard to the effects of such compound transients.

For systems that have no water wheel generator in them or more specifically, that have no water wheel generators without adequate amortisseur windings the analysis is simple. However if water wheel generators without amortisseur windings are connected in the system under study, then the overvoltages during unbalanced faults may be increased considerably because of the saliency effects which results in additional generated voltages components of higher harmonic order than the fundamental The overvoltage increase may be abnormally high if the load on the system is predominantly capacitive.

Briefly speaking, there are two reasons for this additional increase in overvoltage during unbalanced faults on a salient pole machine.

1 The difference in permeance of the magnetic circuit in

2. The capacitance of the line at the terminal of the machir

The first of these is the basic cause that produces, unde unbalances fault conditions, distorted (i.e. fundamental frequenc plus higher harmonic) voltages on the unfaulted phases which may have high peak values even with no terminal impedance present, capacitive or otherwise. The second may lead to resonance or parti resonance between the reactance of the machine and the terminal capacitance which will produce still greater distortion of the voltages on the unfaulted phases. The condition for resonance will depend not only on the circuit constant, but also on the type of fault.

The larger and more complex the system, the more serious is the consequence of a fault. If a complex power system is not correctly designed, or is not correctly operated, the after effect of a fault may be catastrophic.

The frequency of the faults is sometimes very large which results in a large percentage of loss of power to the consumers. Such figures bring out very clearly the value of the theoretical and practical work, which has now made it possible to eliminate thi kind of breakdown almost completely. It is clear that with furthe development of power systems, it becomes even more important to - study the transient phenomenon and the means of their control.

The study of transient phenomena in electrical power sys is now of special importance because of the increasing use of elec nic rectifying devices for automatic and remote control.

The operation of a power system under automatic control consists of a continuous sequence of transient effects caused by the action of the automatic devices, and by the reaction of the system on them. Thus an understanding of the nature of the transi is essential for the correct assessment of the operation of the automatic regulators and of their design, adjustment and application under normal working conditions. The distinction between transient and steady states tends to disappear under these conditions. The automatic devices are evidently important elements in determining the transient behaviour of the system.

Transient phenomena can be classified into three types:-

1. Wave propagation phenomena:- The effects of transient voltages due to switching, lightning strokes, or other causes, depends on the"wave" parameters of the system. A change in the mechanical conditions, such as a variation of the speed of a generator or a turbine has no effect on this type of transient process.

2. Electromagnetic Phenomena:- The electromagnetic action is assumed to be unaffected by the mechanical state of the system in which it occurs. For this type of condition the generators are assumed to run at constant speed.

3. Electromechanical phenomena:- The variation of speed of the generators, the turbines, and the motor loads, have a decisive influence on the behavior. The electromagnetic electromechanical effects must be considered together.

Transient disturbances may occur as:-

1. Initiation transients, where a circuit, originally dead is energized.

2. Subsidence transients, in which the final state is a dead one of zero energy.

3. Transition transients, linking two energetic steady stat

4. Complex transients, in which a circuit, while still in a transient state due to one disturbance, is subjected to further disturbances, or in which the disturbing drive is variable.

5. Relaxation transients, in which transitions occurs cycl cally towards states which, when reached, become themse ves unstable. This condition implies non-linearity.

Transients in which only one form of energy storage, magnetic or electric, is concerned are called single energy trans ents. Where both magnetic and electric energies are contained in or acceptable by the circuit, double energy transients are involv Strictly, all circuits are of the latter type, but often one stor ge form is small enough to be neglected without sensible error.

Any transient phenomena may be studied either by assuming linearity for all the circuit parameters or, alternatively by allowing for non-linearity, which is always present to some exten since any process which modifies the physical state of the medium in which it occurs must affect theparameters. In many cases, however the effect may be either wholly or partially neglected. The solution of any transient problem can therefore be carried ou either by a linear method or by a non-linear method. There is an essential difference between the two methods.

A system is defined to be linear in a physical sense, if the nature of any change taking place in it is independent of its magnitude. In a linear system a change due to two or more independent disturbances can be determined as the sume of the changes, caused by each of the disturbances acting seperately.

The whole work is divided mainly into two portions

1. One machine system

2. Two machine system.

The former case has been dealt by two methods

1. Current cancellation method.

2. Classical method.

In cancellation method it is assumed that the fault clearing is instantaneous.

The two machine system has been analysed by the classical method. This method has been suggested by Dr. P.Mukhopadhyay and is better than the zero cancellation method.

Before starting the mathematical analysis it is necessary to make certain assumptions. The assumptions are

1. The fault is a solid fault i.e. there is no arcing.
2. Negative sequence impedance are assumed equal to positive sequence impedances for static equipments.
3. The magnitude of the positive sequence impedance is assumed to be constant for the period in which the overvoltage is to be determined.
4. The effect of saturation and corona are not included. Both would tend to reduce the magnitude of overvoltage. In the region of resonance, saturation may be an important factor in limiting the excessive fundamental frequency overvoltage.
5. Overvoltages caused by unusual system conditions are neglected.
6. The charging current of the transmission line before the fault and load currents are neglected.
7. In the classical method, the circuit is interrupted after a time t_1 of the occurrence of the fault when the current is passing through zero value.

8. The generator is represented by a constant voltage behind a constant reactance, usually, the transient reactance.

9. While doing analysis with ~~which~~ cancellation method it is assumed for the sake of simplicity that $C_{1L} = C_{OL}$

CHAPTER II

ONE MACHINE SYSTEM (Shunt faults)

ONE MACHINE SYSTEM

CANCELLATION METHOD

It is already stated that the occurrence of a fault corre ponds to the closing of a switch in the electrical circuit i.e. it is a switching operation. Any switching operation is either an opening of a closing of a circuit. In opening (breaking) a circuit the current through the contacts is interrupted or cancelled. In closing (making) a circuit, the voltage across the contacts is nullified or cancelled. Therefore the switching operation may be regarded as a cancellation process.

Cancellation voltages(or currents) are fictitious voltages (or currents) impressed across (or through) a switch to simulate its closing (or opening) by cancellation of the voltage (or current) across (or through) the switch.

A cancellation current (-i) superimposed on the current i which would exist if the switch were not opened results in zero current through the switch contacts, and thereby simulates the opening of the switch.

The effects of a cancellation current (or voltage) on any part of a system may be superimposed on the currents and volta already existing there; that is:-

Resultant voltages and currents	=	Those which would exist if switches were not operated	+	Those due to the cancellation voltages or currents

Of course this principle of superposition is valid only for essentially linear systems (no pronounced saturation effects).

The system under study contains a generator connected to long transmission line through a transformer. The generator is represented by its voltage behind the transient reactance and the

THREE PHASE FAULT: (Ref. figure) 1(a) and (b)

In three phase fault the fault shunt to be placed betwe the fault point and the Z.P.B. is zero. So a switch is placed which under closed conditions will simulate the fault condition and when it is opened it will be fault clearing condition.

The fault current will be $i_f(p) = \dfrac{V_1(p)}{R_{1t} + (L_{1g}+L_{1t})p}$

Therefore the recovery voltage i.e. the voltage appearing across the switch with instantaneous clearing, when the switcl is opened will be

$V_r(p) = i_f(p)Z(p)$ where $Z(p)$ will be the impedance as viewed from the switch.

$$Z(p) = \frac{\{R_{1t}+(L_{1g}+L_{1t})p\}\frac{1}{C_{1L}p}}{R_{1t}+(L_{1g}+L_{1t})p+\frac{1}{C_{1L}p}} = \frac{R_{1t}+(L_{1g}+L_{1t})p}{R_{1t}C_{1L}p+L_1C_{1L}p^2+1}$$

$$\therefore V_r(p) = \frac{R_{1t}+L_1p}{R_{1t}C_{1L}p+L_1C_{1L}p^2+1} \cdot \frac{V(p)}{R_{1t}+L_1p}$$

$$= \frac{V(p)}{R_{1t}C_{1L}p+L_1C_{1L}p^2+1}$$

Let the voltage be represented as $v = V_m \cos wt$

$$\therefore V_r(p) = \frac{V_m p}{p^2+w^2} \cdot \frac{1}{R_{1t}C_{1L}p+L_1C_{1L}p^2+1}$$

When $R_{1t} = 0$

$$V_r(p) = \frac{3V_m p}{p^2+w^2} \cdot \frac{1}{L_1C_{1L}p^2+1}$$

LINE TO LINE FAULT: (Ref. fig. 3)

For this the fault shunt to be placed between the zero potential bus and the fault point of the positive sequence network is $Z_2(p)$ i.e. the negative sequence impedance seen between these two points.

To findout the fault current, the switch is first close and the current flowing through the switch is found.

$$Z_2(p) = \frac{(R_{1t} + L_2p)\frac{1}{C_{1L}p}}{L_2p + R_{1t} + \frac{1}{C_{1L}p}}$$

Therefore the total impedance seen by the generator

$$Z(p) = (R_{1t} + L_1p) + \frac{\dfrac{(R_{1t} + L_2p)\frac{1}{C_{1L}p} \cdot \frac{1}{C_{1L}p}}{L_2p + R_{1t} + \frac{1}{C_{1L}p}}}{\dfrac{(R_{1t} + L_2p)\frac{1}{C_{1L}p}}{L_2p + R_{1t} + \frac{1}{C_{1L}p}} + \dfrac{1}{C_{1L}p}}$$

$$= (R_{1t} + L_1p) + \frac{(R_{1t} + L_1p)\frac{1}{C_{1L}p}}{2(R_{1t} + L_1p) + \frac{1}{C_{1L}p}}$$

$$= \frac{2(R_{1t} + L_1p)\left(R_{1t} + L_1p + \frac{1}{C_{1L}p}\right)}{2(R_{1t} + L_1p) + \frac{1}{C_{1L}p}}$$

$$\therefore\ i_f(p) = \frac{V_m p}{p^2 + w^2} \cdot \frac{\{2(R_{1t} + L_1p)\,C_{1L}p + 1\}}{2(R_{1t} + L_1p)\,(R_{1t}\,C_{1L}p + L_1C_{1L}p^2 + 1)}$$

Now to find the impedance as seen through the switch the equivalent circuit will be as shown in fig. 3(a)

$$Z_s(p) = Z_2(p) + \frac{(R_{1t} + L_1 p)\frac{1}{C_{1L}p}}{R_{1t} + L_1 p + \frac{1}{C_{1L}p}}$$

$$= \frac{2(R_{1t} + L_1 p)}{R_{1t}C_{1L}p + L_1 C_{1L}p^2 + 1}$$

Current flowing through the switch branch of positive sequence network.

$$i_f(p) \frac{\frac{1}{C_{1L}p}}{\frac{R_{1t} + L_1 p}{C_{1L}L_1 p^2 + R_{1t}C_{1L}p + 1} + \frac{1}{C_{1L}p}}$$

$$= i_f(p) \cdot \frac{(R_{1t}C_{1L}p + C_{1L}L_1 p^2 + 1)\frac{1}{C_{1L}p}}{(R_{1t} + L_1 p)C_{1L}p + C_{1L}L_1 p^2 + R_{1t}C_{1L}p + 1}$$

$$i_f(p) \frac{(R_{1t}C_{1L}p + C_{1L}L_1 p^2 + 1)}{2(R_{1t} + L_1 p)C_{1L}p + 1}$$

$$= \frac{V_m p}{p^2 + w^2} \cdot \frac{1}{2(R_{1t} + L_1 p)}$$

$\therefore$ Positive sequence voltage component will be

$$\frac{V_m p}{p^2+w^2} \cdot \frac{1}{2(R_{1t} + L_1 p)} \cdot \frac{2(R_{1t} + L_1 p)}{R_{1t}C_{1L}p + L_1 C_{1L}p^2 + 1}$$

$$= \frac{V_m p}{(p^2 + w^2)(R_{1t}C_{1L}p + L_1 C_{1L}p^2 + 1)}$$

The negative sequence component of voltage is given as

$V_{r2}(p) = - i_{f2}(p) \; Z_2(p)$ and for Line to Line fault

$i_{f1} = - i_{f2}$ $\therefore V_{r2}(p) = i_{f1}(p)\, Z_2(p)$

$$\frac{V(p)}{2(R_{1t} + L_1 p} \cdot \frac{(R_{1t} + L_1 p) \cdot \frac{1}{C_{1L}p}}{R_{1t} + L_1 p + \frac{1}{C_{1L}p}} = \frac{V_m p}{2(R_{1t}C_{1L}p + L_1 C_{1L}p^2 + 1)(p}$$

$\therefore$ Total voltage $V_r(p) = V_{r1} + V_{r2}$

$$= \frac{3}{2} \cdot \frac{V_m p}{p^2 + w^2} \cdot \frac{1}{(R_{1t}C_{1L}p + L_1 C_{1L}p^2 + 1)}$$

L-G FAULT:- (Ref. fig. 4)

Here the fault shunt is given as $Z_2(p) + Z_0(p)$

i.e. $$\frac{(R_{1t} + L_1 p) \frac{1}{C_{1L}p}}{R_{1t} + L_1 p + \frac{1}{C_{1L}p}} + \frac{(R_{0t} + L_0 p) \frac{1}{C_{1L}p}}{R_{0t} + L_0 p + \frac{1}{C_{1L}p}}$$

$$= \frac{1}{C_{1L}p} \cdot \frac{\frac{L_1+L_0}{C_{1L}} + 2R_{0t}R_{1t} + 2 R_{1t}L_0 p + \frac{R_{1t}}{C_{1L}p} + 2R_{0t}L_1 p + \frac{R_{0t}}{C_{1L}p} + 2L_0 L_1 p^2}{(R_{1t} + L_1 p + \frac{1}{C_{1L}p})(R_{0t} + L_0 p + \frac{1}{C_{1L}p})}$$

Total impedance seen by the generator

$$\frac{\frac{1}{C_{1L}^2 p^2}\left\{2\left(R_{0t}R_{1t} + (R_{1t}L_0 + R_{0t}L_1)p\right) + \frac{1}{C_{1L}p}(R_{1t}+R_{0t}) + \frac{(L_1+L_0)}{C_{1L}} + 2L_0 L_1 p^2\right.}{(R_{1t} + L_1 p + \frac{1}{C_{1L}p})(R_{0t}+L_0 p + \frac{1}{C_{1L}p})}$$

$$Z(p) = (R_{1t}+L_1 p) + \frac{}{\frac{1}{C_{1L}p} + \frac{\frac{1}{C_{1L}p}\left\{2\left(R_{0t}R_{1t} + (R_{1t}L_0 + R_{0t}L_1)p\right) + \frac{1}{C_{1L}p}(R_{1t}+R_{0t}) + \frac{L_1+L_0}{C_{1L}} + 2L_0 L_1\right.}{}}$$

$$=(R_{1t}+L_1p)+\frac{\frac{1}{C_{1L}p}\left(2\left[R_{0t}R_{1t}+(R_{1t}L_0+R_{0t}L_1)p+L_0L_1p^2\right]+\frac{1}{C_{1L}p}(R_{1t}+R_{0t})+\frac{L_1+L_0}{C_{1L}}\right)}{3R_{1t}R_{0t}+3R_{1t}L_0p+\frac{2R_{1t}}{C_{1L}p}+3R_{0t}L_{1}p+3L_1L_0p^2+\frac{2L_1}{C_{1L}}+\frac{2R_{0t}}{C_{1L}p}+2\frac{L_0}{C_{1L}}+C_{1L}^2}$$

$$=\frac{\begin{array}{l}(3R_{1t}^2R_{0t}+\frac{4L_1R_{1t}}{C_{1L}}+\frac{4L_0R_{1t}}{C_{1L}}+\frac{3R_{0t}L_1}{C_{1L}})+(3R_{1t}^2L_0+6R_{0t}R_{1t}L_1+\frac{2L_1^2}{C_{1L}}+\frac{3L_1L_0}{C_{1L}})p+\\(6L_1L_0R_{0t}+3R_{0t}L_1^2)p^2+3L_1^2L_0p^3+(\frac{2R_{1t}^2}{C_{1L}p}+\frac{4R_{0t}R_{1t}}{C_{1L}p}+\frac{2L_1}{C_{1L}^2p}+\frac{L_0}{C_{1L}p^2})+\frac{1}{C_{1L}^2p^2}(2R_{1t}\ R_{0t}\end{array}}{(3R_{1t}R_{0t}+\frac{2L_1}{C_{1L}}+\frac{2R_{0t}}{C_{1L}}+\frac{2L_0}{C_{1L}})+3(R_{1t}L_0+R_{0t}L_1)p+3L_1L_0p^2+\frac{2R_{1t}}{C_{1L}p}+\frac{1}{C_{1L}^2p^2}}$$

Therefore the current flowing $i_f(p)$ will be

$$i_f(p)=\frac{V_m p}{p^2+w^2}\cdot\frac{1}{Z(p)}$$

Therefore the current flowing through the closed switch

$$i_f(p)\ \frac{1/C_{1L}p}{\frac{1}{C_{1L}p}+Z_2(p)+Z_0(p)}=i_f(p)\ \frac{1/C_{1L}p}{\frac{1}{C_{1L}p}+\frac{(R_{1t}+L_1p)\frac{1}{C_{1L}p}}{R_{1t}+L_1p+\frac{1}{C_{1L}p}}+Z_0(p)}$$

$$\frac{i_f(p)\ (R_{1t}+L_1p+\frac{1}{C_{1L}p})\ (R_{0t}+L_0p+\frac{1}{C_{1L}p})}{(R_{1t}+L_1p+\frac{1}{C_{1L}p})(R_{0t}+L_0p+\frac{1}{C_{1L}p})+2\left[R_{0t}R_{1t}+(R_{1t}L_0+R_{0t}L_1)p\right]+\frac{1}{C_{1L}p}(R_{1t}+R_{0t})+\frac{L_1+L_0}{C_{1L}}+2L_0L_1p^2}$$

The impedance seen through the switch

$$Z_s(p)=Z_0+Z_2+\frac{(R_{1t}+L_1p)\frac{1}{C_{1L}p}}{R_{1t}+L_1+\frac{1}{C_{1L}p}}$$

$$= \frac{1}{C_{1L}p} \cdot \frac{\left(2\left[R_{0t}R_{1t} + (R_{1t}L_0 + R_{0t}L_1)p\right] + \frac{1}{C_{1L}p}(R_{1t} + R_{0t}) + \frac{1}{C_{1L}}(L_1 + L_0) + 2L_0L_1p^2 \right)}{\left(R_{1t} + L_1p + \frac{1}{C_{1L}p}\right)\left(R_{0t} + L_0p + \frac{1}{C_{1L}p}\right)}$$

$$+ \frac{(R_{1t} + L_1p)\frac{1}{C_{1L}p}}{R_{1t} + L_1p + \frac{1}{C_{1L}p}}$$

$$\frac{\frac{1}{C_{1L}}\left[3R_{1t}R_{0t} + 3(R_{1t}L_0 + R_{0t}L_1)p + \frac{2R_{1t}}{C_{1L}p} + \frac{R_{0t}}{C_{1L}p} + \frac{2L_1 + L_0}{C_{1L}} + 3L_1L_0p^2\right]}{\left(R_{1t} + L_1p + \frac{1}{C_{1L}p}\right)\left(R_{0t} + L_0p + \frac{1}{C_{1L}p}\right)}$$

Therefore the recovery voltage positive sequence component

$$V_r(p) = \frac{V_m p}{p^2 + w^2} \cdot \frac{\frac{1}{C_{1L}p}\left(2\left[R_{0t}R_{1t} + (R_{1t}L_0 + R_{0t}L_1)p\right] + \frac{L_1 + L_0}{C_{1L}} + 2L_0L_1p^2 + (R_{1t} + L_1p)(R_{0t} + L_0p + \right.}{3R_{1t}^2R_{0t} + \frac{4L_1R_{1t}}{C_{1L}} + \frac{4L_0R_{1t}}{C_{1L}} + \frac{3R_{0t}L_1}{C_{1L}} + \left(3R_{1t}^2L_0 + 6R_{0t}R_{1t}L_1 + \frac{2L_1^2}{C_{1L}} + \frac{3L_1L_0}{C_{1L}}\right)p + (6L_1L_0R_{1t} + 3R_{0t}L_1^2)p^2 + 3L_1^2L_0p^3 + \left(\frac{2R_{1t}^2}{C_{1L}p} + \frac{4R_{0t}R_{1t}}{C_{1L}p} + \frac{2L_1}{C_{1L}^2p} + \frac{L_0}{C_{1L}^2p}\right) + \frac{1}{C_{1L}^2p^2}(2R_{1t} + R_{0t})}$$

When $R_{1t} = 0$ $R_{0t} = 0$

$$V_{r1}(p) = \frac{V_m p}{p^2 + w^2} \cdot \frac{(3L_0L_1C_{1L}p^2 + 2L_1 + L_0)}{3C_{1L}^2L_1^2L_0p^4 + (3C_{1L}L_1L_0 + 2C_{1L}L_1^2)p^2 + 2L_1 + L_0}$$

In case of Line to ground fault $i_{a1} = i_{a2} = i_{a0}$

∴ The negative sequence component of voltage and zero sequence component of voltage are given respectively

$i_{fs}Z_2(p)$ and $i_{fs}Z_0(p)$

The total voltage is the sum of these three components

DOUBLE LINE TO GROUND FAULT (Ref. fig. 5)

Fault on phases b and c to ground

The fault shunt will be $\dfrac{Z_0 Z_2}{Z_0 + Z_2}$

$$\frac{\frac{1}{C_{1L}p}(R_{1t}+L_1p)(R_{0t}+L_0p)}{(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p})}$$

When the switch is closed the impedance seen will be

$$(R_{1t}+L_1p) + \frac{\frac{1}{C_{1L}p}(R_{1t}+L_1p)(R_{0t}+L_0p)}{(R_{1t}+L_1p)(R_{0t}+L_0p)+(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p})+(R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1}}}$$

Therefore the current flowing will be

$$i_f(p) = \frac{V_m p}{(p^2+w^2)} \cdot \frac{\{(R_{1t}+L_1p)(R_{0t}+L_0p)+(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p})+(R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p}}{(R_{1t}+L_1p)\{(R_{1t}+L_1p)(R_{0t}+L_0p)+(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p})+(R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p})+\frac{1}{C_{1L}p}(R_{0t}+L_0p)\}}$$

Current through the switch will be

$$i_f(p) \cdot \frac{1/C_{1L}p}{\frac{1}{C_{1L}p} + \frac{\frac{1}{C_{1L}p}(R_{1t}+L_1p)(R_{0t}+L_0p)}{(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p})}}$$

Impedance seen through the switch

$$Z_s(p) = \frac{(R_{1t}+L_1p)\frac{1}{C_{1L}p}\{(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p})+(R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p})\}}{(R_{1t}+L_1p+\frac{1}{C_{1L}p})\{(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p})+(R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p})\}}$$

$$\therefore V_{r_1}(p) = i_{fs}(p) Z_s(p)$$

$$= \frac{V_m p}{(p^2+w^2)} \cdot \frac{\frac{1}{C_{1L}p} \left[(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p}) + (R_{1t}+L_1p+\frac{1}{C_{1L}p})(R_{0t}+L_0 \right.}{(R_{1t}+L_1p+\frac{1}{C_{1L}p}) \left[(R_{1t}+L_1p)(R_{0t}+L_0p) + (R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p+ \right. \\ \left. + \frac{1}{C_{1L}p}(R_{0t}+L_0p) \right]}$$

The voltage drop across either of the negative or zero sequence net work

$$i_{fa1}(p) \cdot \frac{Z_0 Z_2}{Z_0+Z_2}$$

Now $$\frac{Z_0 Z_2}{Z_0+Z_2} = \frac{(R_{1t}+L_1p)(R_{0t}+L_0p) \cdot 1/C_{1L}p}{(R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p})}$$

$$\therefore V_{r2}(p) = \frac{V(p) \left[(R_{1t}+L_1p)(R_{0t}+L_0p) \right] 1/C_{1L}p}{(R_{1t}+L_1p) \left[(R_{0t}+L_0p) + (R_{1t}+L_1p) + (R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p) \right. \\ \left. (R_{1t}+L_1p+\frac{1}{C_{1L}p}) + \frac{1}{C_{1L}p}(R_{0t}+L_0p) \right]}$$

$\therefore$ Total voltage will be $V_{r1} + V_{r2} + V_{r0}$

$$\frac{V(p) \cdot \frac{1}{C_{1L}p} \left[2(R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p}) + (R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p \right. \\ \left. + (R_{0t}+L_0p)(R_{1t}+L_1p+\frac{1}{C_{1L}p}) \right]}{(R_{1t}+L_1p+\frac{1}{C_{1L}p}) \left[(R_{1t}+L_1p)(R_{0t}+L_0p) + (R_{1t}+L_1p)(R_{0t}+L_0p+\frac{1}{C_{1L}p}) + (R_{0t}+L_0p)(R_{1t}+L_1p+ \right. \\ \left. + \frac{1}{C_{1L}p}(R_{0t}+L_0p) \right]}$$

When $R_{0t} = 0$ $R_{1t} = 0$

$$V_r(p) = \frac{\dfrac{V(p)}{C_{1L}p}\left[\left(L_1p + \dfrac{1}{C_{1L}p}\right)L_0p + L_1p\left(L_0p + \dfrac{1}{C_{1L}p}\right)\right]}{\left(L\,p + \dfrac{1}{C_{1L}p}\right)\left[L_1L_0p^2 + L_1p\left(L_0p + \dfrac{1}{C_{1L}p}\right) + L_0p\left(L_1p + \dfrac{1}{C_{1L}p}\right) + \dfrac{L_0}{C_{1L}}\right]}$$

$$= \frac{\dfrac{V(p)}{C_{1L}p}\left[5L_1L_0p^2 + \dfrac{4L_0}{C_{1L}} + \dfrac{L_1}{C_{1L}}\right]}{\left(L_1p + \dfrac{1}{C_{1L}p}\right)\left[3\,L_1L_0p^2 + \dfrac{L_1 + 2L_0}{C_{1L}}\right]}$$

CLASSICAL METHOD

THREE PHASE FAULT (Ref. Fig. 1)(a) and (b)

The fault condition is simulated by closing the switch and writing the equation for the loop

$$R_{1t} i + (L_{1g} + L_{1t}) \frac{d_i}{d_t} = V_m \text{Cos } wt$$

Taking laplace Transform on both the sides we have

$$R_{1t} I(p) + (L_{1g} + L_{1t})\, p\, I(p) - L_1\, i(0) = \frac{V_m\, p}{p^2 + w^2}$$

Initially let $i(0) = 0$ we have

$$(R_{1t} + L_1 p)\, I\,(p) = \frac{V_m\, p}{p^2 + w^2}$$

$$\therefore I(p) = \frac{V\, p}{R_{1t}\,(p^2 + w^2)(1 + T p)} \quad \text{where } T = \frac{L_1}{R_{1t}}$$

$$\therefore i(t) = \frac{V}{R_{1t}} \left\{ - \frac{1}{1 + T^2 w^2}\, e^{-\frac{t}{T}} + \frac{1}{\sqrt{1 + T^2 w^2}} \text{Cos}(wt - \phi) \right\} \quad \text{Where}$$

$$\phi = \tan^{-1} wT$$

When the switch is opened let the voltage be represented as $v = V_m$ Cos (wt and suppose the switch is opened after $t = t_1$ the fault has occurred. Here $\lambda = wt_1$.

Again writing the equation when the fault is cleared

$$V_m \text{ Cos } (wt + \lambda) = R_{1t}\, i + (L_{1g} + L_{1t}) \frac{di}{dt} + \frac{1}{C_{1L}} \int i\, dt$$

Taking Laplace on both the sides

$$\frac{V_m \text{ Cos}\lambda\ p}{p^2 + w^2} - \frac{V_m \text{ Sin}\lambda\ w}{p^2 + w^2} = R_{1t}\, I\,(p) + L_1 p I(p) - L_1 i(0) + \frac{I(p)}{C_{1L} p} + \frac{q_0}{p}$$

Here $q_0 = 0$ since initially the capacitor is shorted through the switch a

$$i\,(0) = \frac{V}{R_{1t}} \left[- \frac{1}{1 + T^2 w^2} e^{-\frac{t_1}{T}} + \frac{1}{\sqrt{1 + T^2 w^2}} \operatorname{Cos}\,(wt_1 - \phi) \right]$$

$$\frac{V_m \operatorname{Cos}\lambda \; p}{p^2 + w^2} - \frac{V_m \operatorname{Sin}\lambda \; w}{p^2 + w^2} + L\,i\,(0) = \left(R_{1t} + L_1 p + \frac{1}{C_{1L} p}\right) I\,(p)$$

$$= \left(R_{1t}\, C_{1L} p + L_1\, C_{1L} p^2 + 1\right) \frac{I\,(p)}{C_{1L} p}$$

Now recovery voltage $= \dfrac{I\,(p)}{C_{1L} p}$

$$\frac{3}{C_{1L}\, L_1 p^2 + R_{1t}\, C_{1L} p + 1} \left\{ \frac{V_m \operatorname{Cos}\lambda\, p}{p^2 + w^2} - \frac{V_m \operatorname{Sin}\lambda \; w}{p^2 + w^2} + \frac{L\,V}{R_{1t}} \left[- \frac{1}{1 + T^2 w^2} e^{-\frac{t_1}{T}} + \frac{1}{\sqrt{1 + T^2 w^2}} \operatorname{Cos}\,(wt_1 - \phi) \right] \right\}$$

LINE TO LINE FAULT (Ref. fig.2 & 3)

The fault shunt $Z_2(p) = \dfrac{\frac{1}{C_{1L}p}\left\{ R_{1t} + (L_{1t} + L_{2g})p \right\}}{R_{1t} + L_2p + \frac{1}{C_{1L}p}}$

Parallel combination of $Z_2(p)$ and C_{1L}

$$\frac{\frac{1}{C_{1L}p}(R_{1t} + L_2 p)}{2R_{1t} + 2L_2p + \frac{1}{C_{1L}p}}$$

Total impedance seen by the generator

$$\frac{\frac{1}{C_{1L}p}(R_{1t} + L_2 p)}{2R_{1t} + 2L_2 p + \frac{1}{C_{1L}p}} + R_{1t} + L_2p$$

$$\frac{2C_{1L}L_1p^3L_2 + 2(C_{1L}L_1R_{1t} + R_{1t}C_{1L}L_2)p^2 + (L_2 + L_1 + 2R^2_{1t}C_{1L})p + 2R_{1t}}{2C_{1L}L_2p^2 + 2C_{1L}R_{1t}p + 1}$$

Therefore fault current will be

$$\frac{Vp}{(p^2+w^2)} \frac{2C_{1L}L_2p^2 + 2C_{1L}R_{1t}p + 1}{\left\{2C_{1L}L_1L_2p^3 + 2(C_{1L}L_1R_{1t} + R_{1t}C_{1L}L_2)p^2 + (L_2 + L_1 + 2R^2_{1t}C_{1L})p + 2R_{1t}\right\}} \quad ----(\beta)$$

Current flowing through switch branch will be

$$i_{fs} = \frac{Vp}{(p^2+w^2)} \frac{(C_{1L}L_2p^2 + R_{1t}C_{1L}p + 1)}{\left\{2C_{1L}L_1L_2p^3 + (2C_{1L}L_1R_{1t} + 2R_{1t}C_{1L}L_2)p^2 + (L_2 + L_1 + 2R^2_{1t}C_{1L})p + 2R_{1t}\right\}}$$

The current flowing through capacitor branch

$$= i_{fs} \cdot \frac{(C_{1L}p(R_{1t} + L_2p)}{2R_{1t}C_{1L}p + 2L_2C_{1L}p^2 + 1}$$

$$= \frac{Vp^2 C_{1L} \quad (R_{1t} + L_2 p)}{(p^2+w^2)\,[2C_{1L}L_1L_2p^3 + (2C_{1L}L_1R_{1t} + 2R_{1t}C_{1L}L_2)p^2 + (L_2+L_1+2R_{1t}^2 \; C_{1L})p + 2R_{1t}\,]} \quad \text{- - - - (}$$

We shall now write the equation when the switch is opened.

Let the voltage be represented as $v = V_m \text{ Cos } (wt + \lambda)$

$$V_m \text{ Cos } (wt + \lambda) = R_{1t}\, i_1 + L_1 \frac{di1}{dt} + \frac{1}{C_{1L}}\int i_1 \, dt$$

Taking Laplace Transform we have

$$\frac{V_m \text{ Cos}\lambda\, p}{p^2 + w^2} - \frac{V_m \text{ Sin}\lambda\, w}{p^2 + w^2} = R_{1t}\, I_1(p) + L_1 p\, I_1(p) - L_1 i_1(0) + \frac{I_1(p)}{C_{1L}p} + \frac{q_0}{p}$$

$$\frac{V_m \text{Cos}\lambda\, p}{p^2 + w^2} - \frac{V_m \text{ Sin } \lambda \; w}{p^2 + w^2} + L_1\, i_1(0) - \frac{q_0}{p} = \frac{I_1(p)}{C_{1L}p}\,(R_{1t}C_{1L}p + C_{1L}\, L_1 p^2 + 1\,)$$

The positive sequence recovery voltage will be $\dfrac{I_1(p)}{C_{1L}p}$

$$\frac{1}{C_{1L}L_1p^2 + R_{1t}C_{1L}p + 1}\,\left[\,\frac{V_m \text{ Cos}\lambda\, p}{p^2 + w^2} - \frac{V_m \text{ Sin}\lambda\; w}{p^2 + w^2} + L_1 i_1(0) - \frac{q_0}{p}\right]$$

Where $i_1(0)$ is obtained when $t = t_1$ is put in the above expression (time domain) (β)

$q_0 = \int_0^{t_1} i\,dt$ where i is the current in time domain

when found from expression (α) as written above.

Now to calculate the negative sequence voltage. The equation for this circu

when the switch is opened will be

$$(L_{2g} + L_{1t})\frac{di_2}{dt} + R_{1t}\; i_2 + \frac{1}{C_{1L}}\int i_2 \; dt \quad = 0$$

Taking Laplace on both sides

$$L_2 p\; I_2(p) - L_2 i_2(0) + R_{1t} I_2(p) + \frac{I_2(p)}{C_{1L}p} + \frac{q'_0}{p} = 0$$

$$\frac{I_2(p)}{C_{1L}p}\left(C_{1L}L_2p^2+R_{1t}\; C_{1L}\; p + 1\right) = L_2\; i_2(0) - \frac{q_0'}{p} = 0$$

The negative sequence voltage will be $\frac{I_2(p)}{C_{1L}p}$

$$V_{r2}\;(p) = \frac{1}{C_{1L}L_2p^2+R_{1t}C_{1L}p + 1}\left[L_2i_2(0) - \frac{q_0'}{p}\right]$$

$\therefore$ Total voltage $V_r(p) = V_{r1}(p) + V_{r2}\;(p)$

$$\frac{1}{C_{1L}L_1p^2+C_{1L}R_{1t}p+1}\left[\frac{V_m\cos\lambda\; p}{p^2+w^2} - \frac{V_m\sin\lambda\; w}{p^2+w^2} + L_1i_1(0) - \frac{q_0}{p}\right] + \frac{1}{C_{1L}L_2p^2+R_{1t}C_{1L}p +}$$

$$\left[L_2\; i_2(0) - \frac{q_0'}{p}\right]$$

LINE TO ~~LINE~~ Ground FAULT :- (Ref. fig. 4)

The negative and zero sequence impedances as seen through the switches respectively are

$$Z_2(p) = \frac{\frac{1}{C_{1L}\,p}(R_{1t}+L_2p)}{R_{1t}+L_2p + \frac{1}{C_{1L}p}} \quad \text{and}$$

$$Z_0(p) = \frac{\frac{1}{C_{0L}p}(R_{0t}+L_0p)}{R_{0t}+L_0p + \frac{1}{C_{0L}p}}$$

The fault shunt for Line to Ground fault will be

$$Z_2(p) + Z_0\,(p)$$

$$= \frac{(R_{1t}+L_2p)(R_{0t}C_{0L}p + C_{0L}L_0p^2+1) + (R_{0t}+L_0p)(R_{1t}C_{1L}p + L_2C_{1L}p^2+1)}{(R_{1t}C_{1L}p + L_2C_{1L}p^2+1)\;(R_{0t}C_{0L}p + L_0C_{0L}p^2+1)}$$

Let $Z_f = Z_2(p) + Z_0\,(p)$

The total impedance seen by the generator when fault condition is simulated i.e. the switch is closed.

$$(R_{1t}+L_1p) + \frac{Z_f \cdot \frac{1}{C_{1L}p}}{Z_f + \frac{1}{C_{1L}p}}$$

$$= \frac{(R_{1t}+L_1p)\;(Z_fC_{1L}p+1) + Z_f}{(Z_fC_{1L}p+1)}$$

Let voltage be represented as $v = V_m \cos wt$ and after writing the equation for the positive sequence network and considering all initial conditions to be zero iy id gounf yhey zero it is found that the current

$$I(p) = \frac{V(p)}{Z(p)} = \frac{V_m p}{(p^2+w^2)} \cdot \frac{(Z_f C_{1L} p + 1)}{\{(R_{1t}+L_1 p)(Z_f C_{1L} p+1)+Z_f\}}$$

The current flowing through the capacitor branch of positive sequence network

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{Z_f C_{1L} p}{\{(R_{1t}+L_1 p)(Z_f C_{1L} p+1)+Z_f\}}$$

The current through fault shunt branch will be

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{\{(R_{1t}+L_1 p)(Z_f C_{1L} p + 1) + Z_f\}}$$

The current through the capacitive branch of the negative sequence network

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{\{(R_{1t}+L_1 p)(Z_f C_{1L} p + 1^*) + Z_f\}} \cdot \frac{(R_{1t}+L_2 p)}{\{R_{1t}+L_2 p+\frac{1}{C_{1L} p}\}}$$

The current through inductive branch of negative sequence network

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{\{(R_{1t}+L_1 p)(Z_f C_{1L} p + 1) + Z_f\}} \cdot \frac{1}{(C_{1L} L_2 p^2 + R_{1t} C_{1L} p + 1)}$$

Similarly current distribution in the zero sequence network can be found out

Let the fault be interrupted after a time t_1 and let the voltage then be V_m Cos(

The desired equation for positive sequence network will be

$$V_m \cos(wt+\lambda) = R_{1t}\, i_1 + L_1 \frac{di_1}{dt} + \frac{1}{C_{1L}} \int i_1\, dt$$

After taking laplace transform and as it is known that positive sequence voltage component is $\frac{I_1(p)}{C_{1L} p}$

$$V_{r1}(p) = \frac{1}{C_{1L} L_1 p^2 + R_{1t} C_{1L} p + 1} \left\{ \frac{V_m \cos\lambda\, p}{p^2 + w^2} - \frac{V_m \sin\lambda\, w}{= p^2 + w^2} + L_1 i_1(0) - \frac{q_0}{p} \right\}$$

Now to calculate negative sequence and zero sequence voltages when the switch is opened. The equation will be

$$R_{1t} i_2 + L_2 \frac{di_2}{dt} + \frac{1}{C_{1L}} \int i_2 \, dt = 0 \quad \text{and}$$

$$R_{0t} i_0 + L_0 \frac{di_0}{dt} + \frac{1}{C_{0L}} \int i_0 \, dt = 0$$

∴ Negative sequence voltage will be

$$L_2 i_2(0) - \frac{q_2(0)}{p} \times \frac{1}{C_{1L} L_2 p^2 + R_{1t} C_{1L} p + 1}$$ and zero sequence voltage will

$$\times \; L_0 i_0(0) - \frac{q_0(0)}{p} \times \frac{1}{C_{0L} L_0 p^2 + R_{0t} C_{0L} p + 1}$$

Therefore the total voltage $V_{r}(p) = V_{r1}(p) + V_{r2}(p) + V_{r0}(p)$

Now the actual value of denominator of different current expressions is found after substituting the value of Z_f.

$$I(p) = \frac{V_m p}{(p^2+w^2)} \; \frac{N'}{\times \big[(L_2 C_{0L} L_0 C_{1L} L_1 + L_0 C_{1L} L_2 L_1 + C_{1L} L_2 C_{0L} L_0 L_1) p + (R_{1t} C_{0L} L_0 C_{1L} L_1 +}$$

$$R_{1t} C_{1L} C_{0L} L_0 L_1 + R_{0t} C_{0L} L_2 C_{1L} L_1 + R_{0t} C_{1L}^2 L_2 L_1 + L_0 R_{1t} C_{1L}^2 L_1 + C_{1L} L_2 R_{0t} C_{0L} L_1 +$$

$$L_2 C_{0L} L_0 C_{1L} R_{1t} + L_0 C_{1L}^2 L_2 R_{1t} + C_{1L} L_2 C_{0L} L_0 R_{1t}) p^4 + (R_{1t} R_{0t} C_{0L} C_{1L} + L_2 C_{1L} L_1 +$$

$$R_{0t} R_{1t} C_{1L}^2 L_1 + L_0 C_{1L} L_1 + R_{1t} R_{0t} C_{1L} C_{0L} L_1 + C_{1L} L_2 L_1 + C_{0L} L_0 L_1 + R_{0t} C_{0L} L_2 C_{1L} R_{1t} +$$

$$R_{0t} C_{1L}^2 L_2 R_{1t} + L_0 R_{1t}^2 C_{1L}^2 + C_{1L} L_2 R_{0t} C_{0L} R_{1t} + R_{1t}^2 C_{0L} L_0 C_{1L} + L_2 C_{0L} L_0 + L_0 C_{1L} L_2) p^3 +$$

$$(R_{1t} C_{1L} L_1 + R_{0t} C_{0L} L_1 + R_{1t} C_{1L} L_1 + R_{0t} C_{1L} L_1 + R_{1t}^2 R_{0t} C_{0L} C_{1L} + L_2 C_{1L} R_{1t} + R_{0t} R_{1t}^2 C_{1L}^2 +$$

$$L_0 C_{1L} R_{1t} + R_{1t}^2 R_{0t} C_{1L} C_{0L} + C_{1L} L_2 R_{1t} + C_{0L} L_0 R_{1t} + R_{1t} C_{0L} L_0 + R_{1t} C_{0L} L_2 +$$

$$R_{0t} C_{1L} L_2 + L_0 R_{1t} C_{1L}) p^2 + (L_1 + R_{1t}^2 C_{1L} + R_{0t} C_{0L} R_{1t} + R_{1t}^2 C_{1L} + R_{0t} C_{1L} R_{1t} +$$

$$R_{1t} R_{0t} C_{0L} + L_2 + R_{0t} R_{1t} C_{1L} + L_0) p + R_{1t} + R_{1t} + R_{0t}$$

Where $N' = N C_{1L} p + Z_{2d} Z_{0d}$

Where $N = (L_2 C_{0L} L_0 C_{1L} + L_0 C_{1L} L_2) p^3 + (R_{1t} C_{0L} L_0 + R_{0t} C_{0L} L_2 + R_{0t} C_{1L} L_2 + L_0 R_{1t} C_{1L}) p^2 +$

$(R_{1t} R_{0t} C_{0L} + L_2 + R_{0t} R_{1t} C_{1L} + L_0) p + R_{1t} + R_{0t}$

Z_{2d} = denominator of negative sequence impedance and

Z_{0d} = denominator of zero sequence impedance

L-L-G FAULT (Ref. Fig. 5)

Here the fault shunt is $\frac{Z_0 Z_2}{Z_0+Z_2}$ where

$$Z_0 = \frac{R_{0t}+L_0 p}{R_{0t} C_{0L} p + L_0 C_{0L} p^2 + 1} \quad \text{and}$$

$$Z_2 = \frac{R_{1t} + L_2 p}{R_{1t} C_{1L} p + L_2 C_{1L} p^2 + 1}$$

Let ~~zero~~ Z_{0n} = Numerator of Z_0 , Z_{2n} = Numerator of Z_2

Z_{0d} = Denominator of Z_0 Z_{2d} = Denominator of Z_2

$$\text{Then } Z_f = \frac{Z_0 Z_2}{Z_0+Z_2} = \frac{Z_{0n} Z_{2n}}{Z_{2n} Z_{0d} + Z_{0n} Z_{2d}} = \frac{Z_{0n} Z_{2n}}{Z_D}$$

The expression for the positive sequence recoveryvoltage will be the same as for Line to Ground fault except for the fact that here

$$Z_f = \frac{Z_0 Z_2}{Z_0+Z_2} \quad \text{instead of } Z_0 + Z_2$$

The current flowing through fault shunt branch

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{(R_{1t}+L_1 p)(Z_f C_{1L} p + 1) + Z_f}$$

The current through negative sequence circuit will be

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{(R_{1t}+L_1 p)(Z_f C_{1L} p + 1) + Z_f} \quad \frac{Z_0}{Z_0 + Z_2}$$

$\therefore$ The current throughnegative sequence circuit capacitor will be

$$\frac{V_m p}{(p^2+w^2)} \quad \frac{1}{(R_{1t}+L_1 p)(Z_f C_{1L} p+1)+Z_f} \quad \frac{Z_0}{Z_0+Z_2} \quad \frac{R_{1t}+L_2 p}{R_{1t}+L_2 p+\frac{1}{C_{1L}p}}$$

$$= \frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{(R_{1t}+L_2 p)}{(R_{1t}+L_1 p)\left(\frac{C_{1L} Z_{0n} Z_{2n} p}{Z_D}+1\right)+\frac{Z_{0n} Z_{2n}}{Z_D}} \cdot \frac{Z_{0n}/Z_{0d}}{Z_D/Z_{0d} Z_{2d}} \cdot \frac{1}{Z_{2d}}$$

$$\frac{V_m p^2 C_{1L}}{(p^2+w^2)} \quad \frac{(R_{1t}+L_2 p)\, Z_{0n}}{(R_{1t}+L_1 p)(C_{1L} Z_{0n} Z_{2n} p+Z_D)+Z_{0n} Z_{2n}}$$

Here $Z_{0n} Z_{2n} = R_{1t} R_{0t} + L_2 L_0 p^2 + (R_{1t} L_0 + R_{0t} L_2)\, p$

$$Z_{2n} Z_{0d} = L_0 C_{0L} L_2 p^3 + (L_2 R_{0t} C_{0L} + R_{1t} L_0 C_{1L}) p^2 + (R_{1t} R_{0t} C_{0L} + L_2) p + R_{1t}$$

$$Z_{0n} Z_{2d} = L_2 C_{1L} L_0 p^3 + (L_0 R_{1t} C_{1L} + L_2 C_{1L} R_{0t}) p^2 + (R_{0t} R_{1t} C_{0L} + L_2)\, p + R_{0t}$$

$$C_{1L} Z_{0n} Z_{2n} p + Z_D = (L_2 L_0 C_{1L} + L_2 C_{1L} L_0 + L_0 C_{0L} L_2)\, p^3 + (R_{1t} L_0 C_{1L} + R_{0t} L_2 C_{1L} + L_0 R_{1t} C_{1L} + L_2 C_{1L} R_{0t} + L_2 R_{0t} C_{0L} + R_{1t} L_0 C_{0L})\, p^2 + (R_{1t} R_{0t} C_{1L} + R_{0t} R_{1t} C_{1L} + L_0 + R_{1t} R_{0t} C_{0L} + L_2)\, p + R_{0t} + R_{1t}$$

Now $(R_{1t}+L_1 p)(C_{1L} Z_{0n} Z_{2n} p + Z_D) + Z_{0n} Z_{2n} = (L_2 L_0 C_{1L} L_1 + L_2 C_{1L} L_0 L_1 + L_0 C_{0L} L_2 L_1)\, p^4 +$

$$(R_{1t} L_0 C_{1L} L_1 + R_{0t} L_2 C_{1L} L_1 + L_0 R_{1t} C_{1L} L_1 + L_2 C_{1L} R_{0t} L_1 + L_2 R_{0t} C_{0L} L_1 + R_{1t} L_0 C_{0L} L_1 + L_2 L_0 C_{1L} R_{1t} + L_2 C_{1L} L_0 R_{1t} + L_0 C_{0L} L_2 R_{1t})\, p^3 + (R_{1t} R_{0t} C_{1L} L_1 + R_{0t} R_{1t} C_{1L} L_1 + L_0 L_1 + R_{1t} R_{0t} C_{0L} L_1 + L_2 L_1 + R_{1t}^2 L_0 C_{1L} + R_{0t} L_2 C_{1L} R_{1t} + L_0 R_{1t}^2 C_{1L} + L_2 C_{1L} R_{0t} R_{1t} + L_2 R_{0t} C_{0L} R_{1t} + R_{1t}^2 L_0 C_{0L} + L_2 L_0)\, p^2 + (R_{0t} L_1 + R_{1t} L_1 + R_{1t} L_0 + R_{0t} L_2 + R_{1t}^2 R_{0t} C_{1L} + R_{0t} R_{1t}^2 C_{1L} + L_0 R_{1t} + R_{1t}^2 R_{0t} C_{0L} + L_2 R_{1t})\, p + 2 R_{1t} R_{0t} + R_{1t}^2$$

The current I (p) i.e. the current flowing through the positive sequence network under fault condition

$$= \frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{(R_{1t} + L_1 p) + \dfrac{Z_f}{Z_f C_{1L} p + 1}}$$

$$= \frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{(R_{1t} + L_1 p) + \dfrac{Z_{0n} Z_{2n} / Z_D}{\dfrac{Z_{0n} Z_{2n} C_{1L} p + Z_D}{Z_D}}}$$

$$= \frac{V_m p}{(p^2+w^2)} \cdot \frac{Z_{0n} Z_{2n} C_{1L} p + Z_D}{(R_{1t} + L_1 p)(Z_{0n} Z_{2n} C_{1L} p + Z_D) + Z_{0n} Z_{2n}}$$

The current through condenser branch of positive sequence network

$$\frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{1}{(R_{1t} + L_1 p)\left(C_{1L} p + \dfrac{1}{Z_f}\right) + 1}$$

$$= \frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{1}{(R_{1t} + L_1 p)\left(C_{1L} p + \dfrac{Z_D}{Z_{0n} Z_{2n}}\right) + 1}$$

$$= \frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{Z_{0n} Z_{2n}}{(R_{1t} + L_1 p)(C_{1L} Z_{0n} Z_{2n} p + Z_D) + Z_{0n} Z_{2n}}$$

The current through inductive branch of negative seugnece network

$$\frac{V_m p}{(p^2 + w^2)} \quad \frac{Z_{0n}}{\ldots}$$

The current through condenser of Zero sequence network

$$\frac{V_m p^2 C_{dL}}{(p^2+w^2)} \quad \frac{Z_{2n}(R_{0t}+L_0 p)}{(R_{1t}+L_1 p)(C_{1L}Z_{0n}Z_{2n}p+Z_D)+Z_{0n}Z_{2n}}$$

Similarly current flowing through inductive branch will be

$$\frac{V_m p}{(p^2+w^2)} \quad \frac{Z_{2n}}{(R_{1t}+L_1 p)(C_{1L}Z_{0n}Z_{2n}p+Z_D)+Z_{0n}Z_{2n}}$$

The expression for the recovery voltage will be of the same nature as for Line to Ground fault but the values of $i_1(0)$, $i_2(0)$, $i_0(0)$ and q_0, $q_2(0)$ and $q_1(0)$ will be different.

FAULT AT THE FAR END OF THE LINE

Here the transmission line is represented by a T circuit.

<u>3 PHASE FAULT</u> (Ref. Fig. 6(a) and (b)

Let $(R_{1t}+R_{1L}) + (L_{1g}+L_{1t}+L_{1L})p = R_{1eq}+L_{1eq}p$

The fault condition is simulated by closing the switch. The impedance seen by the generator will be

$$(R_{1eq}+L_{1eq}p) + \frac{\frac{1}{C_{1L}p}(R_{1L}+L_{1L}p)}{R_{1L}+L_{1L}p+\frac{1}{C_{1L}p}}$$

$$=(R_{1eq}+L_{1eq}p) + \frac{(R_{1L}+L_{1L})}{R_{1L}C_{1L}p+L_{1L}C_{1L}p^2+1}$$

$$= \frac{(R_{1eq}+L_{1eq}p)\ (R_{1L}C_{1L}p+L_{1L}C_{1L}p^2+1) + (R_{1L}+L_{1L})}{(R_{1L}C_{1L}p + L_{1L}C_{1L}p^2 + 1)}$$

Let the voltage be represented as $v = V_m \cos wt$ and assuming that all the initial conditions are zero, the current delivered by the generator under fault conditions will be

$$I\ (p) = \frac{V_m\, p}{(p^2+w^2)} \; \frac{C_{1L}R_{1L}p + C_{1L}L_{1L}p^2 + 1}{(R_{1eq}+L_{1eq}p)(C_{1L}R_{1L}p+C_{1L}L_{1L}p^2+1)+R_{1L}+L_{1L}p}$$

The current through capacitor branch

$$\frac{V_m\, p}{(p^2+w^2)} \cdot \frac{C_{1L}\ R_{1L}p + C_{1L}L_{1L}p^2+ 1}{(R_{1eq}+L_{1eq}p)(C_{1L}R_{1L}p+C_{1L}L_{1L}p^2+1) + R_{1L}+L_{1L}p} \cdot \frac{(R_{1L}+L_{1L}p)}{R_{1L}+L_{1L}p + \frac{1}{C_{1L}p}}$$

$$\frac{V_m p^2}{(p^2+w^2)} \quad \frac{C_{1L}\,(R_{1L} + L_{1L}p)}{(R_{1eq}+L_{1eq}p)(C_{1L}R_{1L}p + C_{1L}L_{1L}p^2 + 1) + R_{1L}+L_{1L}p}$$

When the switch is opened i.e. the fault is interrupted after a time t_1 and let the voltage then be represented by

$v = V_m \mathrm{Cos}\,(wt + \lambda)$, the equation can be written as

$$V_m \cos\,(wt + \lambda) = R_{1eq}\,i + L_{1eq}\frac{di}{dt} + \frac{1}{C_{1L}}\int i\,dt$$

Taking Laplace transform we have

$$\frac{V_m \cos\lambda\; p}{p^2+w^2} - \frac{V_m \sin\lambda\; w}{p^2 + w^2} = R_{1eq}I(p) + R_{1eq}p\;I(p) - L_{1eq}i(0) + \frac{I(p)}{C_{1L}p} + \frac{q_0}{p}$$

The positive sequence voltage across the switch $\dfrac{3\,I\,(p)}{C_{1L}p}$

$$= \frac{1}{R_{1eq}C_{1L}p + C_{1L}L_{1eq}p^2 + 1}\left\{\frac{V_m \cos\lambda\, p}{p^2 + w^2} - \frac{V_m \sin\lambda\;\; w}{p^2 + w^2} + L_{1eq}i\,(0) \quad - \quad \frac{q_0}{p}\right\}$$

The denominator of the current expression is simplified as

$$(R_{1eq}+L_{1eq}p)\;(C_{1L}R_{1L}p + C_{1L}L_{1L}p^2+1) + R_{1L}+L_{1L}p \;= L_{1eq}C_{1L}L_{1L}p^3 +$$

$$(R_{1L}C_{1L}L_{1eq}+C_{1L}L_{1L}R_{1eq})\;p^2 + (R_{1eq}C_{1L}R_{1L}+L_{1eq}+L_{1L}\;)p + R_{1eq}+R_{1L}$$

LINE TO LINE FAULT : (Ref. Fig. 7) and 8

Let $R_{1L}+L_{1L}p + Z_f = Z'_f$

When the switch is closed i.e. the fault condition is simulated the impedance seen by the generator.

$$(R_{1eq}+L_{1eq}p) + \frac{\frac{1}{C_{1L}p} \cdot Z'_f}{Z'_f + \frac{1}{C_{1L}p}} = R_{1eq}+L_{1eq}p + \frac{Z'_f}{C_{1L}\, Z'_f\, p + 1}$$

$$= \frac{(R_{1eq}+L_{1eq}p)\,(C_{1L}Z'_f p + 1) + Z'_f}{(C_{1L}Z'_f p + 1)}$$

The fault current supplied by the generator assuming

$v = V_m \cos wt$

$$I(p) = \frac{V_m\, p}{(p^2+w^2)} \cdot \frac{C_{1L}Z'_f p + 1}{(R_{1eq}+L_{1eq}p)(C_{1L}Z'_f p+1) + Z'_f}$$

The current through the fault shunt branch

$$\frac{I(p)\ 1/C_{1L}p}{Z'_f + 1/C_{1L}p} = \frac{I(p)}{Z'_f\, C_{1L}p + 1}$$

$$= \frac{V_m\, p}{(p^2+w^2)} \cdot \frac{1}{(R_{1eq}+L_{1eq}p)\,(C_{1L}Z'_f\, p + 1) + Z'_f}$$

Now $Z_f = (R_{1L}+L_{1L}p) + \dfrac{1/C_{1L}p\ (R_{1eq}+L_{2eq}p)}{R_{1eq}+L_{2eq}p + 1/C_{1L}p}$

$$= \frac{(R_{1L}+L_{1L}p)(R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1) + R_{1eq} + L_{2eq}p}{R_{1eq}C_{1L}p + L_{2eq}C_{1L}\,p^2 + 1}$$

$$\therefore Z'_f = \frac{(R_{1L}+L_{1L}p)(R_{1eq}C_{1L}p+L_{2eq}C_{1L}p^2+1) + R_{1eq}+L_{2eq}p}{R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2+1} + R_{1L} + L_{1L}p$$

$$= \frac{2(R_{1L}+L_{1L}p)(R_{1eq}C_{1L}p+L_{2eq}C_{1L}p^2+1)+(R_{1eq}+L_{2eq}p\ \ )}{R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1}$$

The current through condenser of the positive sequence network

$$\frac{V_m\,p^2}{(p^2+w^2\ )} \cdot \frac{C_{1L}}{\{R_{1eq}+L_{1eq}p\ \}\ \{C_{1L}p + \frac{1}{Z'_f}\ \} + 1}$$

$$\frac{V_m\,p^2\ C_{1l}}{(p^2+w^2\ )}\ \frac{1}{(R_{1eq}+L_{1eq}p)\ C_{1L}p + \dfrac{R_{1eq}\ C_{1L}p + L_{2eq}C_{1L}p^2 + 1}{2(R_{1L}+L_{1L}p)(R_{1eq}C_{1L}p+L_{2eq}C_{1L}p+1)(R_{1eq}+L} + 1}$$

$$\frac{V_m\,p^2C_{1L}}{p^2+w^2}\ \frac{(R_{1eq}+2\ R_{1L})+(L_{2eq}+2R_{1L}R_{1eq}C_{1L}+2\ L_{1L})p+2(R_{1L}L_{2eq}C_{1L}+R_{1eq}C_{1L}L_{1L})\ p^2 + 2L_{1L}L_{2eq}C_{1L}p^3}{D}$$

where

$$D = 2(R_{1eq}+R_{1L}) + 2\Big(R_{1L}C_{1L}R_{1eq} + R_{1eq}^2C_{1L} + \frac{L_{1eq}+L_{2eq}}{2} + R_{1L}R_{1eq}C_{1L} + L_{1L}\Big)p + 2\big(R_{1L}R_{1eq}^2C_{1L}^2 + L_{1L}C_{1L}R_{1eq} + L_{2eq}C_{1L}R_{1eq} + R_{1L}C_{1L}L_{1eq} + R_{1eq}C_{1L}L_{1eq}\cdot R_{1L}L_{2eq}C_{1L} + R_{1eq}C_{1L}L_{1L}\big)p^2 + 2\big(R_{1L}L_{2eq}C_{1L}^2R_{1eq} + R_{1eq}^2C_{1L}^2L_{1L} + R_{1L}R_{1eq}C_{1L}^2 + L_{1L}C_{1L}L_{1eq} + L_{2eq}L_{1eq}C_{1L} + L_{1L}L_{2eq}C_{1L}\big)p^3 + 2\big(L_{1L}L_{2eq}C_{1L}^2R_{1eq} + R_{1L}L_{2eq}C_{1L}^2L_{1eq} +$$

$R_{1eq}C^2$ [illegible]

The current through condenser branch of the negative sequence network

$$\frac{V_m p}{(p^2+w^2)} \quad \frac{1}{(R_{1eq}L_{1eq}p)(C_{1L}Z'_f p + 1) + Z'_f} \quad \frac{(R_{1eq}+L_{2eq}p)}{R_{1eq}+L_{2eq}p + \frac{1}{C_{1L}p}}$$

$$= \frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{(R_{1eq}+L_{2eq}p)}{\left\{(R_{1eq}+L_{1eq}p)(C_{1L}Z'_f p+1) + Z'_f\right\}(R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1)}$$

The current through inductive branch will be

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{\left\{(R_{1eq}+L_{1eq}p)(C_{1L}Z'_f p+1)+Z'_f\right\}(R_{1eq}C_{1L}p+L_{2eq}C_{1L}p^2+1)}$$

$$I_{c2} = \frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{(R_{1eq}+L_{2eq}p)}{\left\{(R_{1eq}+L_{1eq}p)(C_{1L}p+\frac{1}{Z'_f})+1\right\}\left\{2(R_{1L}+L_{1L}p)(R_{1eq}C_{1L}p+L_{2eq}C_{1L}p^2+1)+(R_{1eq} L_{2eq}p)\right.}$$

$$\frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{(R_{1eq}+L_{2eq}p)}{(R_{1eq}+R_{1L}+(R_{1L}C_{1L}R_{1eq}+R_{1eq}^2 C_{1L}+\frac{L_{1eq}+L_{2eq}}{2}+R_{1L}R_{1eq}C_{1L}+L_{1L})\,p + }$$

The denominator is equal to D.

Now let the circuit be interrupted after a time t_1 and let the voltage be represented as $v = V_m \cos(wt+\lambda)$

$$V_m \cos(wt + \lambda) = R_{1eq} i_1 + L_{1eq} \frac{di_1}{dt} + \frac{1}{C_{1L}} \int i_1 \, dt$$

Again after taking Laplace transform on both the sides and noting that positive sequence voltage will be $\frac{I_1(p)}{C_{1L} p}$

$$= \frac{1}{R_{1eq} C_{1L} p + C_{1L} L_{1eq} p^2 + 1} \left\{ \frac{V_m \cos\lambda \, p}{p^2 + w^2} - \frac{V_m \sin\lambda \, w}{p^2 + w^2} + L_{1eq} i(0) - \frac{q(0)}{p} \right.$$

Similarly the negative sequence voltage will be

$$V_{r_2}(p) = \frac{1}{R_{1eq} C_{1L} p + C_{1L} L_{2eq} p^2 + 1} \quad L_{2eq} \, i_2(0) - \frac{q_2(0)}{p}$$

The total voltage will be $V_r(p) = V_{r_1}(p) + V_{r_2}(p)$

LINE TO GROUND FAULT: - (Ref. Fig. 9)

Here the fault shunt $Z_f = Z_0 + Z_2$, where Z_0 and Z_2 are the zero and negative sequence impedances seen at the fault point.

$$Z_f = Z_0 + Z_2 = \frac{Z_{0d} Z_{2n} + Z_{0n} Z_{2d}}{Z_{0d} Z_{2d}}$$

$$Z'_f = Z_0 + Z_2 + R_{1L} + L_{1L} p = \frac{Z_{0d} Z_{2n} + Z_{0n} Z_{2d} + Z_{0d} Z_{2d} (R_{1L} + L_{1L} p)}{Z_{0d} Z_{2d}}$$

$$Z_{0d} Z_{2d} = (R_{1eq} C_{1L} p + L_{2eq} C_{1L} p^2 + 1)\ (R_{0eq} C_{0L} p + L_{0eq} C_{0L} p^2 + 1) =$$

$$R_{1eq} C_{1L} R_{0eq} C_{0L} p^2 + R_{1eq} C_{1L} L_{0eq} C_{0L} p^3 + R_{1eq} C_{1L} p + L_{2eq} C_{1L} R_{0eq} C_{0L} p^3 + L_{2eq} C_{1L} L_{0eq} C_{0L}$$

$$L_{2eq} C_{1L} p^2 + R_{0eq} C_{0L} p + L_{0eq} C_{0L} p^2 + 1$$

Num. of $Z_f' = (L_{2eq} C_{1L} L_{0L} L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L} L_{0eq} C_{0L} + L_{2eq} C_{1L} L_{0eq} C_{0L} L_{1L}) p^5 +$

$(L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} + R_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L} + L_{0L} L_{0eq} C_{0L} R_{1eq} C_{1L} + R_{1eq} L_{1L} C_{1L} L_{0eq} C_{0L} +$

$R_{1L} L_{2eq} C_{1L} L_{0eq} C_{0L} + R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L} + R_{1eq} C_{1L} L_{0eq} C_{0L} L_{1L} + L_{2eq} C_{1L} R_{0eq} C_{0L} L_{1L} +$

$R_{1L} L_{2eq} C_{1L} L_{0eq} C_{0L}) p^4 + (L_{0L} L_{0eq} C_{0L} + L_{2eq} L_{0eq} C_{1L} + L_{2eq} C_{1L} L_{0L} + R_{0L} R_{0eq} C_{0L}$

$L_{2eq} C_{1L} + R_{1eq} C_{1L} L_{0L} R_{0eq} C_{0L} + R_{1eq} C_{1L} R_{0L} L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L} + L_{0eq} C_{0L} L_{2eq} +$

$L_{1L} L_{0eq} C_{0L} + L_{0eq} C_{0L} R_{1L} R_{1eq} C_{1L} + R_{0eq} C_{0L} R_{1eq} L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L} R_{0eq} C_{0L} +$

$L_{0eq} C_{0L} L_{1L} + L_{2eq} C_{1L} L_{1L} + R_{1eq} C_{1L} R_{0eq} C_{0L} L_{1L} + R_{1L} L_{2eq} C_{1L} R_{0eq} C_{0L} +$

$R_{1L} R_{1eq} C_{1L} L_{0eq} C_{0L}) p^3 + (L_{0L} R_{0eq} C_{0L} + R_{0L} L_{0eq} C_{0L} + L_{2eq} C_{1L} R_{0eq} + R_{0L} L_{2eq} C_{1L} +$

$R_{1eq} C_{1L} L_{0eq} + L_{0L} R_{1eq} C_{1L} + R_{0L} R_{0eq} C_{0L} R_{1eq} C_{1L} + R_{1eq} L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L} +$

$R_{1eq} L_{0eq} C_{0L} + R_{1L} L_{0eq} C_{0L} + R_{0eq} C_{0L} L_{2eq} +$ [illegible]

$R_{0eq} C_{0L} L_{1L} + R_{1eq} C_{1L} L_{1L} + R_{1L} L_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L} + R_{1L} R_{1eq} C_{1L} R_{0eq} C_{0L}) p^2 +$

$(L_{0eq} + L_{0L} + R_{0L} R_{0eq} C_{0L} + R_{1eq} R_{0eq} C_{1L} + R_{0L} R_{1eq} C_{1L} + L_{2eq} + L_{1L} + R_{1L} R_{1eq} C_{1L} +$

$R_{0eq} C_{0L} R_{1eq} + R_{0eq} C_{0L} R_{1L} + R_{1L} R_{1eq} C_{1L} + R_{1L} R_{0eq} C_{0L} + L_{1L}) p + R_{0eq} + R_{0L} +$

$R_{1eq} + R_{1L}$

The deno. of Z'_f will be

$L_{2eq} C_{1L} L_{0eq} C_{0L} p^4 + (L_{2eq} C_{1L} R_{0eq} C_{0L} + R_{1eq} C_{1L} L_{0eq} C_{0L}) p^3 + (L_{0eq} C_{0L} + L_{2eq} C_{1L} +$

$R_{1eq} C_{1L} R_{0eq} C_{0L}) p^2 + (R_{0eq} C_{0L} + R_{1eq} C_{1L}) p + 1$

The fault current supplied by the generator, considering all initial conditions to be zero

$$I(p) = \frac{V_m p}{(p^2+w^2)} \quad \frac{C_{1L} Z'_f p + 1}{(R_{1eq} + L_{1eq} p)(C_{1L} Z'_f p+1) + Z'_f}$$

$$= \frac{V_m p}{(p^2+w^2)} \quad \frac{1}{(R_{1eq} + L_{1eq} p) + \dfrac{Z'_f}{C_{1L} Z'_f p+1}}$$

Now Let $Z'_f = \dfrac{N}{Z_{0d} \; Z_{2d}}$ then

$$I(p) = \frac{V_m p}{(p^2+w^2)} \quad \frac{1}{(R_{1eq} + L_{1eq} p) + \dfrac{N/Z_{2d} Z_{0d}}{\dfrac{C_{1L} N p}{Z_{2d} Z_{0d}} + 1}}$$

$$= \frac{V_m p}{(p^2 + w^2)} \cdot \frac{1}{(R_{1eq} + L_{1eq} p) + \frac{N}{C_{1L} Np + Z_{0d} Z_{2d}}}$$

$$\frac{V_m p}{(p^2 + w^2)} \cdot \frac{C_{1L} Np + Z_{0d} Z_{2d}}{(R_{1eq} + L_{1eq} p)(C_{1L} Np + Z_{0d} Z_{2d}) + N}$$

The current through condenser of the positive sequence network

$$\frac{V_m p^2 C_{1L}}{(p + w)} \cdot \frac{1}{(R_{1eq} + L_{1eq} p)(C_{1L} p + \frac{1}{Z''_f}) + 1}$$

$$= \frac{V_m p^2}{(p^2 + w^2)} \cdot \frac{C_{1L}}{(R_{1eq} + L_{1eq} p)\frac{(C_{1L} Np + Z_{0d} Z_{2d})}{N} + 1}$$

$$= \frac{V_m p^2}{(p^2 + w^2)} \quad \frac{C_{1L} \qquad N}{(R_{1eq} + L_{1eq} p)(C_{1L} Np + Z_{0d} Z_{2d}) + N}$$

The current flowing through fault shunt branch

$$\frac{V_m p}{(p^2 + w^2)} \quad \frac{1}{(R_{1eq} + L_{1eq} p)(\frac{C_{1L} Np}{Z_{0d} Z_{2d}} + 1) + \frac{N}{Z_{0d} Z_{2d}}}$$

$$I'(p) = \frac{V_m p}{(p^2 + w^2)} \quad \frac{Z_{0d} Z_{2d}}{(R_{1eq} + L_{1eq} p)(C_{1L} Np + Z_{0d} Z_{2d}) + N}$$

The current through the condenser of the negative sequence network

$$I'(p) \cdot \frac{R_{1eq}+L_{2eq}p}{R_{1eq}+L_{2eq}p + \frac{1}{C_{1L}p}}$$

$$= \frac{V_m p^2}{(p^2 + w^2)} \cdot \frac{(R_{1eq}+L_{2eq}p)\ Z_{0d} C_{1L}}{(R_{1eq}+L_{1eq}p)(C_{1L}Np+Z_{0d}\ Z_{2d}) + N}$$

The current through the inductor of the negative sequence network.

$$I'(p) \cdot \frac{1/C_{1L}p}{R_{1eq}+L_{2eq}p + \frac{1}{C_{1L}p}} = I'(p) \cdot \frac{1}{R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1}$$

$$= \frac{V_m p}{(p^2+w^2)} \cdot \frac{Z_{0d}}{(R_{1eq}+L_{1eq}p)(C_{1L}Np + Z_{0d}Z_{2d}) + N}$$

Similarly the current through the condenser of zero sequence network

$$\frac{V_m p^2}{(p^2+w^2)} \cdot \frac{(R_{1eq}+L_{0eq}p)\ C_{0L}\ Z_{2d}}{(R_{1eq}+L_{1eq}p)(C_{1L}Np + Z_{0d}Z_{2d}) + N}$$

and the current flowing through the inductor of zero sequence network

$$\frac{V_m p}{(p^2+w^2)} \cdot \frac{Z_{2d}}{(R_{1eq}+L_{1eq}p)\ (C_{1L}Np + Z_{0d}Z_{2d}) + N}$$

Now we shall calculate certain terms that will help in seeing the nature of the expressions for the currents.

$$
\begin{aligned}
& C_{1L} N p + Z_{od} Z_{2d} = (L_{2eq} C_{1L}^2 L_{0L} L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L}^2 L_{0eq} C_{0L} + L_{2eq} C_{1L}^2 \\
& L_{0eq} C_{0L} L_{1L}) p^6 + (L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L}^2 + R_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L}^2 + L_{0L} L_{0eq} C_{0L} R_{1eq} C_{1L}^2 + \\
& R_{1eq} L_{1L} C_{1L}^2 L_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L}^2 L_{0eq} C_{0L} + R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L}^2 + R_{1eq} C_{1L}^2 L_{0eq} C_{0L} L_{1L} \\
& + L_{2eq} C_{1L}^2 R_{0eq} C_{0L} L_{1L} + R_{1L} L_{2eq} C_{1L}^2 L_{0eq} C_{0L}) p^5 + (L_{0L} L_{0eq} C_{0L} C_{1L} + \\
& L_{2eq} L_{0eq} C_{1L}^2 + L_{2eq} C_{1L}^2 L_{0L} + R_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L}^2 + R_{1eq} C_{1L}^2 L_{0L} R_{0eq} C_{0L} + R_{1eq} C_{1L}^2 R_{0L} \\
& L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L}^2 + L_{0eq} C_{0L} L_{2eq} C_{1L} + L_{1L} L_{0eq} C_{0L} C_{1L} + L_{0eq} C_{0L} R_{1L} R_{1eq} C_{1L}^2 + \\
& R_{0eq} C_{0L} R_{1eq} L_{1L} C_{1L}^2 + R_{1L} L_{2eq} C_{1L}^2 R_{0eq} C_{0L} + L_{0eq} C_{0L} L_{1L} C_{1L} + L_{2eq} C_{1L}^2 L_{1L} + \\
& R_{1eq} C_{1L}^2 R_{0eq} C_{0L} L_{1L} + R_{1L} L_{2eq} C_{1L}^2 R_{0eq} C_{0L} + R_{1L} R_{1eq} C_{1L}^2 L_{0eq} C_{0L} + L_{2eq} C_{1L} L_{0eq} C_{0L}) \\
& p^4 + (L_{0L} R_{0eq} C_{0L} C_{1L} + R_{0L} L_{0eq} C_{0L} C_{1L} + L_{2eq} C_{1L}^2 R_{0eq} + R_{0L} L_{2eq} C_{1L}^2 + \\
& R_{1eq} C_{1L}^2 L_{0eq} + L_{0L} R_{1eq} C_{1L}^2 + R_{0L} R_{0eq} C_{0L} R_{1eq} C_{1L}^2 + R_{1eq} L_{1L} C_{1L}^2 + R_{1L} L_{2eq} C_{1L}^2 + \\
& R_{1eq} L_{0eq} C_{0L} C_{1L} + R_{1L} L_{0eq} C_{0L} C_{1L} + R_{0eq} C_{0L} L_{2eq} C_{1L} + R_{0eq} C_{0L} L_{1L} C_{1L} + R_{1L} R_{1eq} \\
& C_{1L}^2 R_{0eq} C_{0L} + R_{0eq} C_{0L} L_{1L} C_{1L} + R_{1eq} L_{1L} C_{1L}^2 + R_{1L} L_{0eq} C_{0L} C_{1L} + R_{1L} L_{2eq} C_{1L}^2 + \\
& R_{1L} R_{1eq} C_{1L}^2 R_{0eq} C_{0L} + L_{2eq} C_{1L} R_{0eq} C_{0L} + R_{1eq} C_{1L} L_{0eq} C_{0L}) p^3 + (L_{0eq} C_{1L} + L_{0L} C_{1L} + \\
& R_{0L} R_{0eq} C_{0L} C_{1L} + R_{1eq} R_{0eq} C_{1L}^2 + R_{0L} R_{1eq} C_{1L}^2 + L_{2eq} C_{1L} + L_{1L} C_{1L} + R_{1L} R_{1eq} C_{1L}^2 + \\
& R_{0eq} C_{0L} R_{1eq} C_{1L} + R_{0eq} C_{0L} R_{1L} C_{1L} + R_{1L} R_{1eq} C_{1L}^2 + R_{1L} R_{0eq} C_{0L} C_{1L} + L_{1L} C_{1L} + L_{0eq} C_{0L} + \\
& L_{2eq} C_{1L} + R_{1eq} C_{1L} R_{0eq} C_{0L}) p^2 + (R_{0eq} C_{1L} + R_{0L} C_{1L} + R_{1eq} C_{1L} + R_{1L} C_{1L} + R_{0eq} C_{0L} + \\
& R_{1eq} C_{1L}) p + 1
\end{aligned}
$$

Also

$$Z_{0d}(R_{1eq}+L_{2eq}p) = L_{2eq}L_{0eq}C_{0L}p^3 + (R_{1eq}L_{0eq}C_{0L}+L_{2eq}R_{0eq}C_{0L})p^2 +$$

$$(R_{1eq}R_{0eq}C_{0L}+L_{2eq})p + R_{1eq}$$

$$Z_{2d}(R_{0eq}+L_{0eq}p) = L_{2eq}C_{1L}L_{0eq}p^3 + (R_{1eq}C_{1L}L_{0eq}+R_{0eq}L_{2eq}C_{1L})p^2 +$$

$$(R_{0eq}R_{1eq}C_{1L}+L_{0eq})p + R_{0eq}$$

The expression $(R_{1eq}+L_{1eq}p)(C_{1L}Mp + Z_{0d}Z_{2d})+N$ after simplification

can be written as

$$(L_{2eq}C_{1L}^2L_{0L}L_{0eq}C_{0L}L_{1eq} + L_{1L}L_{2eq}C_{1L}^2L_{0eq}C_{0L}L_{1eq} + L_{2eq}C_{1L}^2L_{0eq}C_{0L}L_{1L}L_{1eq})p^7 +$$

$$(L_{0L}R_{0eq}C_{0L}L_{2eq}C_{1L}^2L_{1eq} + R_{0L}L_{0eq}C_{0L}L_{2eq}C_{1L}^2L_{1eq} + L_{0L}L_{0eq}C_{0L}R_{1eq}C_{1L}^2L_{1eq} + R_{1eq}L_{1L}C_{1L}^2$$

$$L_{0eq}C_{0L}L_{1eq} + R_{1L}L_{2eq}C_{1L}^2L_{0eq}C_{0L}L_{1eq} + R_{0eq}C_{0L}L_{1L}L_{2eq}C_{1L}^2L_{1eq} + R_{1eq}C_{1L}^2L_{0eq}C_{0L}L_{1L}L_{1eq} +$$

$$L_{2eq}C_{1L}^2R_{0eq}C_{0L}L_{1L}L_{1eq} + R_{1L}L_{2eq}C_{1L}^2L_{0eq}C_{0L}L_{1eq} + L_{2eq}C_{1L}^2L_{0L}L_{0eq}C_{0L}R_{1eq} + L_{1L}L_{2eq}C_{1L}^2$$

$$L_{0eq}C_{0L}R_{1eq} + L_{2eq}C_{1L}^2L_{0eq}C_{0L}L_{1L}R_{1eq})p^6 + (L_{0L}L_{0eq}C_{0L}C_{1L}L_{1eq} + L_{2eq}L_{0eq}C_{1L}^2L_{1eq} +$$

$$L_{2eq}C_{1L}^2L_{0L}L_{1eq} + R_{0L}R_{0eq}C_{0L}L_{2eq}C_{1L}^2L_{1eq} + R_{1eq}C_{1L}^2L_{0L}R_{0eq}C_{0L}L_{1eq} + R_{1eq}C_{1L}^2R_{0L}L_{0eq}$$

$$C_{0L}L_{1eq} + L_{1L}L_{2eq}C_{1L}^2L_{1eq} + L_{0eq}C_{0L}L_{2eq}C_{1L}L_{1eq} + L_{1L}L_{0eq}C_{0L}C_{1L}L_{1eq} + L_{1eq}C_{0L}R_{1L}R_{1eq}$$

$$C_{1L}^2L_{1eq} + R_{0L}C_{0L}R_{1eq}L_{1L}C_{1L}^2L_{1eq} + R_{1L}L_{2eq}C_{1L}^2R_{0eq}C_{0L}L_{1eq} + L_{0eq}C_{0L}L_{1L}C_{1L}L_{1eq} +$$

$$L_{2eq}C_{1L}^2L_{1L}L_{1eq} + R_{1eq}C_{1L}^2R_{0eq}C_{0L}L_{1L}L_{1eq} + R_{1L}L_{2eq}C_{1L}^2R_{0eq}C_{0L}L_{1eq} + R_{1L}L_{1eq}C_{1L}^2L_{0eq}C_{0L}L_{1eq} +$$

$$L_{2eq}C_{1L}L_{0eq}C_{0L}L_{1eq} + L_{0L}R_{0eq}C_{0L}L_{2eq}C_{1L}^2R_{1eq} + R_{0L}L_{0eq}C_{0L}L_{2eq}C_{1L}^2R_{1eq} + L_{0L}L_{0eq}C_{0L}$$

$$R_{1eq}^2C_{1L}^2 + R_{1eq}^2L_{1L}C_{1L}^2L_{0eq}C_{0L} + R_{1L}L_{2eq}C_{1L}^2L_{0eq}C_{0L}R_{1eq} + R_{0eq}C_{0L}L_{1L}L_{2eq}C_{1L}^2R_{1eq} +$$

$$R_{1eq}^2C_{1L}^2L_{0eq}C_{0L}L_{1t} + L_{2eq}C_{1L}^2R_{0eq}C_{0L}L_{1L}R_{1eq} + R_{1L}L_{2eq}C_{1L}^2L_{0eq}C_{0L}R_{1eq} + L_{2eq}C_{1L}$$

$$L_{0L}L_{0eq}C_{0L} + L_{1L}L_{2eq}C_{1L}L_{0eq}C_{0L} + L_{2eq}C_{1L}L_{0eq}C_{0L}L_{1L})p^5 + (L_{0}R_{0eq}C_{0L}C_{1L}L_{1eq} +$$

$$R_{0L}L_{0eq}C_{0L}C_{1L}L_{1eq} + L_{2eq}C_{1L}^2R_{0eq}L_{1eq} + R_{0L}L_{2eq}C_{1L}^2L_{1eq} + R_{1eq}C_{1L}^2L_{0eq}L_{1eq} +$$

$$L_{0L} R_{1eq} C_{1L}^2 L_{1eq} + R_{0L} R_{0eq} C_{0L} R_{1eq} C_{1L}^2 L_{1eq} + R_{1eq} L_{1L} C_{1L}^2 L_{1eq} + R_{1L} L_{2eq} C_{1L}^2 L_{1eq} +$$

$$R_{1eq} L_{0eq} C_{0L} C_{1L} L_{1eq} + R_{1L} L_{0eq} C_{0L} C_{1L} L_{1eq} + R_{0eq} C_{0L} L_{2eq} C_{1L} L_{1eq} + R_{0eq} C_{0L} L_{1L} C_{1L} L_{1eq} +$$

$$R_{1L} R_{1eq} C_{1L}^2 R_{0eq} C_{0L} L_{1eq} + R_{0eq} C_{0L} L_{1L} C_{1L} L_{1eq} + R_{1eq} L_{1L} C_{1L}^2 L_{1eq} + R_{1L} L_{0eq} C_{0L} C_{1L} L_{1eq} +$$

$$R_{1L} L_{2eq} C_{1L}^2 L_{1eq} + R_{1L} R_{1eq} C_{1L} R_{0eq} C_{0L} L_{1eq} + L_{2eq} C_{1L} R_{0eq} C_{0L} L_{1eq} + R_{1eq} C_{1L} L_{0eq} C_{0L} L_{1eq} +$$

$$L_{0L} L_{0eq} C_{0L} C_{1L} R_{1eq} + L_{2eq} L_{0eq} C_{1L}^2 R_{1eq} + L_{2eq} C_{1L}^2 L_{0L} R_{1eq} + R_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L}^2 R_{1eq} +$$

$$R_{1eq}^2 C_{1L}^2 L_{0L} R_{0eq} C_{0L} + R_{1eq}^2 C_{1L}^2 R_{0L} L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L}^2 R_{1eq} + L_{0eq} C_{0L} L_{2eq} C_{1L} R_{1eq} +$$

$$L_{1L} L_{0eq} C_{0L} C_{1L} R_{1eq} + L_{0eq} C_{0L} R_{1L} R_{1eq}^2 C_{1L}^2 + R_{0eq} C_{0L} R_{1eq}^2 L_{1L} C_{1L}^2 + R_{1L} L_{2eq} C_{1L}^2 R_{0eq} C_{0L} R_{1eq} +$$

$$R_{1L} R_{1eq}^2 C_{1L}^2 L_{0eq} C_{0L} + L_{2eq} C_{1L} L_{0eq} C_{0L} + R_{1eq} + L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} + L_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L}$$

$$+ L_{0L} L_{0eq} C_{0L} R_{1eq} C_{1L} + R_{1eq} L_{1L} C_{1L} L_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L} L_{0eq} C_{0L} + R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L} +$$

$$R_{1eq} C_{1L} L_{0eq} C_{0L} L_{1L} + L_{2eq} C_{1L} R_{0eq} C_{0L} L_{1L} + R_{1L} L_{2eq} C_{1L} L_{0eq} C_{0L}) p^4 + (L_{0eq} C_{1L} L_{1eq} +$$

$$L_{0L} C_{1L} L_{1eq} + R_{0L} R_{0eq} C_{0L} C_{1L} L_{1eq} + R_{1eq} R_{0eq} C_{1L}^2 L_{1eq} + R_{0L} R_{1eq} C_{1L}^2 L_{1eq} + L_{2eq} C_{1L} L_{1eq} +$$

$$L_{1L} C_{1L} L_{1eq} + R_{1L} R_{1eq} C_{1L}^2 L_{1eq} + R_{0eq} C_{0L} R_{1eq} C_{1L} L_{1eq} + R_{0eq} C_{0L} R_{1L} C_{1L} L_{1eq} + R_{1L} R_{1eq} C_{1L}^2 L_{1eq}$$

$$+ R_{1L} R_{0eq} C_{0L} C_{1L} L_{1eq} + L_{1L} C_{1L} L_{1eq} + L_{0eq} C_{0L} L_{1eq} + L_{2eq} C_{1L} L_{1eq} + R_{1eq} C_{1L} R_{0eq} C_{0L} L_{1eq} +$$

$$L_{0L} R_{0eq} C_{0L} C_{1L} R_{1eq} + R_{0L} L_{0eq} C_{0L} C_{1L} R_{1eq} + L_{2eq} C_{1L}^2 R_{0eq} R_{1eq} + R_{0L} L_{2eq} C_{1L}^2 R_{1eq} +$$

$$R_{1eq}^2 C_{1L}^2 L_{0eq} + L_{0L} R_{1eq}^2 C_{1L}^2 + R_{0L} R_{0eq} C_{0L} R_{1eq}^2 C_{1L}^2 + R_{1eq}^2 L_{1L} C_{1L}^2 + R_{1L} L_{2eq} C_{1L}^2 R_{1eq} +$$

$$R_{1eq}^2 L_{0eq} C_{0L} C_{1L} + R_{1L} L_{0eq} C_{0L} C_{1L} R_{1eq} + R_{0eq} C_{0L} L_{2eq} C_{1L} R_{1eq} + R_{0eq} C_{0L} L_{1L} C_{1L} R_{1eq} +$$

$$R_{1L} R_{1eq}^2 C_{1L}^2 R_{0eq} C_{0L} + R_{0eq} C_{0L} L_{1L} C_{1L} R_{1eq} + R_{1eq}^2 L_{1L} C_{1L}^2 + R_{1L} L_{0eq} C_{0L} C_{1L} R_{1eq} + R_{1L} L_{0eq}$$

$$C_{1L}^2 R_{1eq} + R_{1L} R_{1eq}^2 C_{1L}^2 R_{0eq} C_{0L} + L_{2eq} C_{1L} R_{0eq} C_{0L} R_{1eq} + R_{1eq}^2 C_{1L} L_{0eq} C_{0L} + L_{0L} L_{0eq} C_{0L} +$$

$$L_{2eq} L_{0eq} C_{1L} + L_{2eq} C_{1L} L_{0L} + R_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} + R_{1eq} C_{1L} L_{0L} R_{0eq} C_{0L} + R_{1eq} C_{1L} R_{0L} L_{0eq} C_{0L}$$

$$+ L_{1L} L_{2eq} C_{1L} + L_{0eq} C_{0L} L_{2eq} + L_{1L} L_{0eq} C_{0L} + L_{2eq} C_{0L} R_{1L} R_{1eq} C_{1L} + R_{0eq} C_{0L} R_{1eq}$$

$$L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L} R_{0eq} C_{0L} + L_{0eq} C_{0L} L_{1L} + L_{2eq} C_{1L} L_{1L} + R_{1eq} C_{1L} R_{0eq} C_{0L} L_{1L} +$$

$$R_{1L} L_{2eq} C_{1L} R_{0eq} C_{0L} + R_{1L} R_{1eq} C_{1L} L_{0eq} C_{0L}) p^3 + (R_{0eq} C_{1L} L_{1eq} + R_{0L} C_{1L} L_{1eq} + R_{1L} C_{1L} L_{1eq} +$$

$$R_{0eq} C_{0L} L_{1eq} + R_{1eq} C_{1L} L_{1eq} + L_{0eq} C_{1L} R_{1eq} + L_{0L} C_{1L} R_{1eq} + R_{0L} R_{0eq} C_{0L} C_{1L} R_{1eq} +$$

$$R_{1eq}^2 R_{oeq} C_{1L}^2 + R_{oL} R_{1eq}^2 C_{1L}^2 + L_{2eq} C_{1L} R_{1eq} + L_{1L} C_{1L} R_{1eq} + R_{1L} R_{1eq}^2 C_{1L}^2 +$$

$$R_{oeq} C_{oL} R_{1eq}^2 C_{1L} + R_{oeq} C_{oL} R_{1L} C_{1L} R_{1eq} + R_{1L} R_{1eq}^2 C_{1L}^2 + R_{1L} R_{oeq} C_{oL} C_{1L} R_{1eq}$$

$$+ L_{1L} C_{1L} R_{1eq} + L_{oeq} C_{oL} R_{1eq} + L_{2eq} C_{1L} R_{1eq} + R_{1eq}^2 C_{1L} R_{oeq} C_{oL} + L_{oL} R_{oeq} C_{oL} +$$

$$R_{oL} L_{oeq} C_{oL} + L_{2eq} C_{1L} R_{oeq} + R_{oL} L_{2eq} C_{1L} + R_{1eq} C_{1L} L_{oeq} + L_{oL} R_{1eq} C_{1L} + R_{oL} R_{oeq}$$

$$C_{oL} R_{1eq} C_{1L} + R_{1eq} L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L} + R_{1eq} L_{oeq} C_{oL} + R_{1L} L_{oeq} C_{oL} + R_{oeq} C_{oL} L_{2eq}$$

$$+ R_{oeq} C_{oL} L_{1L} + R_{1L} R_{1eq} C_{1L} R_{oeq} C_{oL} + R_{oeq} C_{oL} L_{1L} + R_{1eq} C_{1L} L_{1L} + R_{1L} L_{oeq} C_{oL} +$$

$$R_{1L} L_{2eq} C_{1L} + R_{1L} R_{1eq} C_{1L} R_{oeq} C_{oL}) p^2 + (L_{1eq} + R_{oeq} C_{1L} R_{1eq} + R_{oL} C_{1L} R_{1eq} +$$

$$R_{1eq}^2 C_{1L} + R_{1L} C_{1L} R_{1eq} + R_{oeq} C_{oL} R_{1eq} + R_{1eq}^2 C_{1L} + L_{oeq} + L_{oL} + R_{oL} R_{oeq} C_{oL} +$$

$$R_{1eq} R_{oeq} C_{1L} + R_{oL} R_{1eq} C_{1L} + L_{2eq} + L_{1L} + R_{1L} R_{1eq} C_{1L} + R_{oeq} C_{oL} R_{1eq} +$$

$$R_{oeq} C_{oL} R_{1L} + R_{1L} R_{1eq} C_{1L} + R_{1L} R_{oeq} C_{oL} + L_{1L}) p + 3 R_{1eq} + R_{oL} + R_{1L}$$

Now let the circuit be interrupted after a time t_1 and between the voltage be represented as $v = V_m \cos(wt + \lambda)$

$$V_m \cos(wt + \lambda) = R_{1eq}\, i_1 + L_{1eq}\frac{di_1}{dt} \quad \frac{1}{C_{1L}}\int i_1 \, dt$$

Again after taking Laplace transform on both sides and noting that positive sequence voltage will be $\dfrac{I_1(p)}{C_{1L}p}$

$$\frac{I_1(p)}{C_{1L}p} = \frac{1}{R_{1eq}C_{1L}p + C_{1L}L_{1eq}p^2 + 1}\left\{\frac{V_m \cos\lambda\, p}{p^2 + w^2} - \frac{V_m \sin\lambda\, w}{p^2 + w^2} + L_{1eq}i_1(0) - \frac{q_0}{p}\right\}$$

The negative sequence voltage will be

$$V_{r2}(p) = \frac{1}{R_{1eq}C_{1L}p + C_{1L}L_{2eq}p^2 + 1}\left\{L_{2eq}i_2(0) - \frac{q_2(0)}{p}\right\}$$

Similarly the zero sequence voltage will be

$$V_{r0}(p) = \frac{1}{R_{0eq}\,C_{1L}p + C_{1L}L_{0eq}p^2 + 1}\left\{L_{0eq}i_0(0) - \frac{q_0(0)}{p}\right\}$$

Therefore the total voltage $V_r(p) = V_{r1}(p) + V_{r2}(p) + V_{r0}(p)$

L-L-G Fault;- (Ref. Fig. 10)

Here the fault shunt $Z_f = \dfrac{Z_0 \, Z_2}{Z_0 + Z_2}$ where

Z_0 and Z_2 are the zero and negative sequence impedances seen at the fault point.

$$Z_0 = \frac{(R_{0L}+L_{0L}p)\,(R_{0eq}C_{0L}p + L_{0eq}C_{0L}p^2+1) + (R_{0eq}+L_{0eq}p)}{R_{0eq}\,C_{0L}p + L_{0eq}C_{0L}p^2 + 1}$$

$$Z_2 = \frac{(R_{1eq}+L_{1L}p)(R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2+1)+(R_{1eq}+L_{2eq}p)}{R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1}$$

Num of Z_2 x Num. of Z_0 = $(R_{1L}R_{1eq}C_{1L}p+R_{1L}L_{2eq}C_{1L}p^2+ R_{1L}+R_{1eq}L_{1L}C_{1L}p^2+$

$L_{1L}L_{2eq}C_{1L}p^3+L_{1L}p+R_{1eq}+L_{2eq}p)(R_{0L}R_{0eq}C_{0L}p+R_{0L}L_{0eq}C_{0L}p^2+R_{0L}+L_{0eq}R_{0eq}C_{0L}p^2+$

$L_{0L}L_{0eq}C_{0L}p^3+L_{0L}p+R_{0eq}+L_{0eq}p\,)$

$Z_{2n} Z_{0d} = (R_{1L}\, R_{1eq}\, C_{1L}\, R_{0eq}\, C_{0L} + R_{0eq}\, C_{0L} L_{1L} + R_{0eq} C_{0L}\, L_{2eq} + R_{1L}\, L_{0eq}\, C_{0L} +$

$R_{1eq}\, L_{0eq}\, C_{0L} + R_{1L}\, L_{2eq} C_{1L} + R_{1eq}\, C_{1L}\, L_{1L})\, p^2 + (R_{1L}\, L_{2eq}\, C_{1L}\, R_{0eq} C_{0L} + R_{0eq} C_{0L}$

$R_{1eq}\, L_{1L}\, C_{1L} + L_{0eq}\, C_{0L}\, R_{1L}\, R_{1eq}\, C_{1L} + L_{1L} L_{0eq}\, C_{0L} + L_{0eq} C_{0L}\, L_{2eq} + L_{1L} L_{2eq} C_{1L})\, p^3$

$+ (R_{0eq}\, C_{0L}\, L_{1L} L_{2eq}\, C_{1L} + R_{1L}\, L_{2eq}\, C_{1L} L_{0eq}\, C_{0L} + R_{1eq} L_{1L} C_{1L} L_{0eq} C_{0L})\, p^4 +$

$L_{1L}\, L_{2eq}\, C_{1L}\, L_{0eq}\, C_{0L}\, p^5 + (R_{0eq}\, C_{0L}\, R_{1L} + R_{0eq} C_{0L}\, R_{1eq} + R_{1L}\, R_{1eq}\, C_{1L} + L_1 + L_{2eq})\, p$

$+ R_{1L} + R_{1eq}$

$$\text{Again } Z_f = \frac{Z_{2n} Z_{0n}}{Z_{2n} Z_{0d} + Z_{0n} Z_{2d}}$$

$$Z'_f = Z_f + R_{1L} + L_{1L}p = \frac{Z_{2n} Z_{0n} + (R_{1L} + L_{1L}p)(Z_{2n} Z_{0d} + Z_{0n} Z_{2d})}{Z_{2n} Z_{0d} + Z_{0n} Z_{2d}}$$

Let the numerator of this expression be represented by N. The value of N after simplification comes as

$$(L_{1L} L_{2eq} C_{1L} L_{0L} L_{0eq} C_{0L} + L_{1L}^2 L_{2eq} C_{1L} L_{0eq} C_{0L} + L_{2eq} C_{1L} L_{0L} L_{0eq} C_{0L} L_{1L}) p^6 +$$

$$(R_{1L} L_{2eq} C_{1L} L_{0L} L_{0eq} C_{0L} + R_{1eq} L_{1L} C_{1L} L_{0L} L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L} R_{0L} L_{0eq} C_{0L} +$$
$$L_{0L} R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L} + R_{1L} L_{1L} L_{2eq} C_{1L} L_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L} L_{0L} L_{0eq} C_{0L} + R_{0eq} C_{0L}$$
$$L_{1L}^2 L_{2eq} C_{1L} + R_{1L}^2 L_{2eq} C_{1L} L_{0eq} C_{0L} + R_{1eq} L_{1L}^2 C_{1L} L_{0eq} C_{0L} + L_{0L} L_{0eq} C_{0L} R_{1eq} C_{1L} L_{1L}$$
$$+ R_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L} L_{1L} + L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} L_{1L}) p^5 + (R_{1L} R_{1eq} C_{1L} L_{0L} L_{0eq} C_{0L} +$$
$$R_{0L} R_{1L} L_{0eq} C_{1L} C_{0L} L_{2eq} + R_{1L} L_{2eq} C_{1L} L_{0L} R_{0eq} C_{0L} + R_{1eq} L_{1L} C_{1L} R_{0L} L_{0eq} C_{0L} + L_{0L} R_{1eq}$$
$$R_{0eq} C_{1L} C_{0L} L_{1L} + R_{0L} R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L} + L_{1L} L_{2eq} C_{1L} L_{0L} + L_{1L} L_{2eq} C_{1L} L_{0eq} +$$
$$L_{1L} L_{0L} L_{0eq} C_{0L} + L_{2eq} L_{0L} L_{0eq} C_{0L} + R_{1L} R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L} + R_{1L}^2 L_{0eq} C_{0L} L_{2eq} C_{1L} +$$
$$R_{1L} R_{1eq} L_{1L} C_{1L} L_{0eq} C_{0L} + R_{1L} L_{0L} L_{0eq} C_{0L} R_{1eq} C_{1L} + R_{1L} R_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L} +$$
$$R_{1L} L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} + R_{1L} L_{2eq} C_{1L} R_{0eq} C_{0L} L_{1L} + R_{0eq} C_{0L} R_{1eq} L_{1L}^2 C_{1L} + L_{0eq} C_{0L}$$
$$R_{1L} R_{1eq} C_{1L} L_{1L} + L_{1L}^2 L_{0eq} C_{0L} + L_{0eq} C_{0L} L_{2eq} L_{1L} + L_{1L}^2 L_{2eq} C_{1L} + R_{1eq} C_{1L} R_{0L}$$
$$L_{0eq} C_{0L} L_{1L} + R_{1eq} C_{1L} L_{0L} R_{0eq} C_{0L} L_{1L} + R_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} L_{1L} + L_{2eq} C_{1L} L_{0L}$$
$$L_{1L} + L_{2eq} L_{0eq} C_{1L} L_{1L} + L_{0L} L_{0eq} C_{0L} L_{1L}) p^4 + (R_{1L} R_{1eq} C_{1L} R_{0L} L_{0eq} C_{0L} + R_{1L} R_{1eq} C_{1L}$$
$$L_{0L} R_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L} R_{0L} R_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L} L_{0L} + R_{1L} L_{2eq} C_{1L} L_{0eq} + R_{1L} L_{0L}$$
$$L_{0eq} C_{0L} + R_{1eq} L_{1L} C_{1L} R_{0L} R_{0eq} C_{0L} + R_{1eq} L_{1L} C_{1L} L_{0L} + R_{1eq} L_{1L} C_{1L} L_{0eq} + R_{0L} L_{1L} L_{2eq} C_{1L}$$
$$+ L_{1L} L_{2eq} C_{1L} R_{0eq} + R_{0eq} L_{1L} L_{2eq} C_{1L} + L_{1L} R_{0L} L_{0eq} C_{0L} + L_{1L} L_{0L} R_{0eq} C_{0L} + L_{0L} L_{0eq}$$
$$C_{0L} R_{1eq} + L_{2eq} R_{0L} L_{0eq} C_{0L} + L_{0L} R_{0eq} C_{0L} L_{2eq} + R_{1L}^2 L_{2eq} C_{1L} R_{0eq} C_{0L} + R_{0eq} C_{0L}$$

[illegible]

$$R_{1L} L_{0eq} C_{0L} L_{2eq} + L_{1L} L_{2eq} C_{1L} R_{1L} + R_{1L} R_{1eq} C_{1L} R_{0L} L_{0eq} C_{0L} + R_{1L} R_{1eq} C_{1L} L_{0L} R_{0eq} C_{0L} +$$

$$R_{1L} R_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L} + R_{1L} L_{2eq} C_{1L} L_{0L} + R_{1L} L_{2eq} L_{0eq} C_{1L} + R_{1L} L_{0L} L_{0eq} C_{0L} +$$

$$R_{1L} R_{1eq} C_{1L} R_{0eq} C_{0L} L_{1L} + R_{0eq} C_{0L} L_{1L}^{2} + R_{0eq} C_{0L} L_{2eq} L_{1L} + R_{1L} L_{0eq} C_{0L} L_{1L} + R_{1eq} L_{0eq}$$

$$C_{0L} L_{1L} + R_{1L} L_{2eq} C_{1L} L_{1L} + R_{1eq} L_{1L}^{2} C_{1L} + R_{0L} R_{0eq} C_{0L} R_{1eq} C_{1L} L_{1L} + L_{0L} R_{1eq} C_{1L} L_{1L} +$$

$$R_{1eq} C_{1L} L_{0eq} L_{1L} + R_{0L} L_{2eq} C_{1L} L_{1L} + L_{2eq} C_{1L} R_{0eq} L_{1L} + R_{0L} L_{0eq} C_{0L} L_{1L} + L_{0L} R_{0eq} C_{0L}$$

$$L_{1L}) p^{3} + (R_{1L} R_{1eq} R_{0L} R_{0eq} C_{1L} C_{0L} + R_{1L} R_{1eq} L_{0L} C_{1L} + R_{1L} R_{1eq} C_{1L} L_{0eq} + R_{1L} L_{2eq} C_{1L} R_{0L}$$

$$+ R_{1L} L_{2eq} C_{1L} R_{0eq} + R_{1L} R_{0L} L_{0eq} C_{0L} + R_{1L} L_{0L} R_{0eq} C_{0L} + R_{1eq} R_{0L} L_{1L} C_{1L} + R_{1eq} R_{0eq} L_{1L} C_{1L}$$

$$+ L_{1L} R_{0L} R_{0eq} C_{0L} + L_{0L} L_{1L} + L_{1L} L_{0eq} + R_{1eq} R_{0L} L_{0eq} C_{0L} + L_{0L} R_{0eq} C_{0L} R_{1eq} + L_{2eq} R_{0L}$$

$$R_{0eq} C_{0L} + L_{2eq} L_{0L} + L_{2eq} L_{0eq} + R_{1L}^{2} R_{1eq} R_{0eq} C_{1L} C_{0L} + R_{1L} R_{0eq} C_{0L} L_{1L} + R_{0eq} C_{0L}$$

$$L_{2eq} R_{1L} + R_{1L}^{2} L_{0eq} C_{0L} + R_{1L} R_{1eq} L_{0eq} C_{0L} + R_{1L}^{2} L_{2eq} C_{1L} + R_{1L} R_{1eq} L_{1L} C_{1L} + R_{1L} R_{0L}$$

$$R_{0eq} C_{0L} R_{1eq} C_{1L} + R_{1L} L_{0L} R_{1eq} C_{1L} + R_{1L} R_{1eq} C_{1L} L_{0eq} + R_{0L} R_{1L} L_{2eq} C_{1L} + R_{1L} L_{2eq}$$

$$C_{1L} R_{0eq} + R_{1L} R_{0L} L_{0eq} C_{0L} + R_{1L} L_{0L} R_{0eq} C_{0L} + R_{0eq} C_{0L} R_{1L} L_{1L} + R_{0eq} C_{0L} R_{1eq} L_{1L} +$$

$$R_{1L} R_{1eq} C_{1L} L_{1L} + L_{1L}^{2} + L_{2eq} L_{1L} + R_{0L} R_{1eq} C_{1L} L_{1L} + R_{1eq} R_{0eq} C_{1L} L_{1L} + R_{0L} R_{0eq} C_{0L}$$

$$L_{1L} + L_{0L} L_{1L} + L_{0eq} L_{1L}) p^{2} + (R_{1L} R_{1eq} C_{1L} R_{0L} + R_{1L} R_{1eq} R_{0eq} C_{1L} + R_{1L} R_{0L} R_{0eq} C_{0L} +$$

$$R_{1L} L_{0L} + R_{1L} L_{0eq} + L_{1L} R_{0L} + L_{1L} R_{0eq} + R_{0L} R_{0eq} R_{1eq} C_{0L} + R_{1eq} L_{0L} + R_{1eq} L_{0eq} +$$

$$R_{0L} L_{2eq} + L_{2eq} R_{0eq} + R_{0eq} C_{0L} R_{1L}^{2} + R_{1L} R_{0eq} C_{0L} R_{1eq} + R_{1L}^{2} R_{1eq} C_{1L} + R_{1L} L_{1L} +$$

$$R_{1L} L_{2eq} + R_{1L} R_{0L} R_{1eq} C_{1L} + R_{1L} R_{1eq} R_{0eq} C_{1L} + R_{1L} R_{0L} R_{0eq} C_{0L} + R_{1L} L_{0L} +$$

$$R_{1L} L_{0eq} + R_{1L} L_{1L} + R_{1eq} L_{1L} + R_{0L} L_{1L} + R_{0eq} L_{1L}) p + 2 R_{1L} R_{0L} + 2 R_{1L} R_{0eq} +$$

$$R_{1eq} R_{0L} + R_{1eq} R_{0eq} + R_{1L}^{2}$$

$$\text{Again} \quad Z'_f C_{1L} p + 1 = \frac{N C_{1L} p}{Z_{0n} Z_{2d} + Z_{2n} Z_{0d}} + 1 = \frac{N C_{1L} p + Z_{2n} Z_{0d} + Z_{0n} Z_{2d}}{Z_{2n} Z_{0d} + Z_{0n} Z_{2d}}$$

The fault current supplied by the generator, considering all initial conditions to be zero

$$I(p) = \frac{V_m p}{(p^2 + w^2)} \cdot \frac{C_{1L} Z'_f p + 1}{(R_{1eq} + L_{1eq} p)(C_{1L} Z'_f p + 1) + Z'_f}$$

$$\frac{V_m p}{(p^2 + w^2)} \cdot \frac{N C_{1L} p + Z_{0n} Z_{2d} + Z_{2n} Z_{0d}}{(R_{1eq} + L_{1eq} p)(N C_{1L} p + Z_{2n} Z_{0d} + Z_{0n} Z_{2d}) + N}$$

Here the expression $(N C_{1L} p + Z_{2n} Z_{0d} + Z_{0n} Z_{2d})$ after simplification comes out to be as follows:-

$$(L_{1L}^2 L_{2eq} C_{1L}^2 L_{0eq} C_{0L} + L_{2eq} C_{1L}^2 L_{0L} L_{0eq} C_{0L} L_{1L}) p^7 + (R_{1L} L_{1L} L_{2eq} C_{1L}^2 L_{0eq} C_{0L} +$$

$$R_{1L} L_{2eq} C_{1L}^2 L_{0L} C_{0L} + L_{0L} R_{1L} L_{2eq} C_{1L}^2 L_{0eq} C_{0L} + R_{1eq} L_{1L}^2 C_{1L}^2 L_{0eq} C_{0L} + L_{0L} L_{0eq} C_{0L}$$

$$R_{1eq} C_{1L}^2 L_{1L} + R_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L}^2 L_{1L} + L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L}^2 L_{1L} + R_{1L} L_{2eq} C_{1L}^2 L_{0L}$$

$$L_{0eq} C_{0L} + R_{1eq} L_{1L} C_{1L}^2 L_{0L} L_{0eq} C_{0L} + L_{1L} L_{2eq} C_{1L}^2 R_{0L} L_{0eq} C_{0L} + L_{0L} R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L}^2) p^6$$

$$+ (R_{1L} R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L}^2 + R_{1L}^2 L_{2eq} C_{1L}^2 L_{0eq} C_{0L} + R_{1L} R_{1eq} L_{1L} C_{1L}^2 L_{0eq} C_{0L} +$$

$$R_{1L} L_{0L} L_{0eq} C_{0L} R_{1eq} C_{1L}^2 + R_{1L} R_{0L} L_{0eq} C_{0L} L_{2eq} C_{1L}^2 + R_{1L} L_{0L} R_{0eq} C_{0L} L_{2eq} C_{1L}^2 + R_{1L}$$

$$L_{2eq} C_{1L}^2 R_{0eq} C_{0L} L_{1L} + L_{0eq} C_{0L} R_{1L} R_{1eq} C_{1L}^2 L_{1L} + L_{1L}^2 L_{0eq} C_{0L} C_{1L} + L_{0eq} C_{0L} L_{2eq}$$

$$L_{1L} C_{1L} + L_{1L}^2 L_{2eq} C_{1L}^2 + R_{1eq} C_{1L}^2 R_{0L} L_{0eq} C_{0L} L_{1L} + R_{1eq} C_{1L}^2 L_{0L} R_{0eq} C_{0L} L_{1L} + R_{0L} R_{0eq}$$

$$C_{0L} L_{2eq} C_{1L}^2 L_{1L} + L_{2eq} C_{1L}^2 L_{0L} L_{1L} + L_{2eq} L_{0eq} C_{1L}^2 L_{1L} + L_{0L} L_{0eq} C_{0L} L_{1L} C_{1L} + L_{1L} L_{2eq}$$

$$C_{1L} L_{0eq} C_{0L} + L_{2eq} C_{1L} L_{0L} L_{0eq} C_{0L} + R_{1L} R_{1eq} C_{1L}^2 L_{0L} L_{0eq} C_{0L} + R_{1L} L_{2eq} C_{1L}^2 L_{0L}$$

$$R_{0eq} C_{0L} + R_{1eq} L_{1L} C_{1L}^2 R_{0L} L_{0eq} C_{0L} + L_{0L} R_{1eq} R_{0eq} C_{1L}^2 C_{0L} L_{1L} + R_{0L} R_{0eq} C_{0L} L_{1L} L_{2eq} C_{1L}^2$$

$$+ L_{1L} L_{2eq} C_{1L}^2 L_{0L} + L_{1L} L_{2eq} C_{1L}^2 L_{0eq} + L_{1L} L_{0L} L_{0eq} C_{0L} C_{1L} + L_{2eq} L_{0L} L_{0eq} C_{0L} C_{1L}) p^5 +$$

$$\left(R_{1L}^2 L_{2eq} C_{1L}^2 R_{oeq} C_{oL} + R_{oeq} C_{oL} R_{1eq} L_{1L} C_{1L}^2 R_{1L} + R_{1L}^2 L_{oeq} C_{oL} R_{1eq} C_{1L}^2 + \right.$$

$$R_{1L} L_{1L} L_{oeq} C_{oL} C_{1L} + R_{1L} L_{oeq} C_{oL} L_{2eq} C_{1L} + L_{1L} L_{2eq} C_{1L}^2 R_{1L} + R_{1L} R_{1eq} C_{1L} R_{oL}$$

$$L_{oeq} C_{oL} C_{1L} + R_{1L} R_{1eq} C_{1L}^2 L_{oL} R_{oeq} C_{oL} + R_{1L} R_{oL} R_{oeq} C_{oL} L_{2eq} C_{1L}^2 + R_{1L} L_{2eq}$$

$$C_{1L}^2 L_{oL} + R_{1L} L_{2eq} L_{oeq} C_{1L}^2 + R_{1L} L_{oL} L_{oeq} C_{oL} C_{1L} + R_{1L} R_{1eq} C_{1L}^2 R_{oeq} C_{oL} L_{1L} +$$

$$R_{1L} L_{oeq} C_{oL} L_{1L} C_{1L} + R_{1eq} L_{oeq} C_{oL} L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L}^2 L_{1L} + R_{1eq} L_{1L}^2 C_{1L}^2 +$$

$$R_{oeq} R_{oL} C_{oL} R_{1eq} C_{1L}^2 L_{1L} + L_{oL} R_{1eq} C_{1L}^2 L_{1L} + R_{1eq} C_{1L}^2 L_{oeq} L_{1L} + R_{oL} L_{2eq} C_{1L}^2 L_{1L} +$$

$$L_{2eq} C_{1L}^2 R_{oeq} L_{1L} + R_{oL} L_{oeq} C_{oL} L_{1L} C_{1L} + L_{oL} R_{oeq} C_{oL} L_{1L} C_{1L} + R_{oeq} C_{oL} L_{1L} L_{2eq} C_{1L}$$

$$+ R_{1L} L_{2eq} C_{1L} L_{oeq} C_{oL} + R_{1eq} L_{1L} C_{1L} L_{oeq} C_{oL} + L_{oL} L_{oeq} C_{oL} R_{1eq} C_{1L} + R_{oL} L_{oeq} C_{oL} L_{2eq} C_{1L}$$

$$+ L_{oL} R_{oeq} C_{oL} L_{2eq} C_{1L} + R_{1L} R_{1eq} C_{1L}^2 R_{oL} L_{oeq} C_{oL} + R_{1L} R_{1eq} C_{1L}^2 L_{oL} R_{oeq} C_{oL} + R_{1L}$$

$$L_{2eq} C_{1L}^2 R_{oL} R_{2eq} C_{oL} + R_{1L} L_{2eq} C_{1L}^2 L_{oL} + R_{1L} L_{2eq} C_{1L}^2 L_{oeq} + R_{1L} L_{oL} L_{oeq} C_{oL} C_{1L} +$$

$$R_{1eq} L_{1L} C_{1L}^2 R_{oL} R_{oeq} C_{oL} + R_{1eq} L_{1L} C_{1L}^2 L_{oL} + R_{1eq} L_{1L} C_{1L}^2 L_{oeq} + R_{oL} L_{1L} L_{2eq} C_{1L}^2 +$$

$$L_{1L} L_{2eq} C_{1L}^2 R_{oeq} + R_{oeq} L_{1L} L_{2eq} C_{1L}^2 + L_{1L} R_{oL} L_{oeq} C_{oL} C_{1L} + L_{1L} L_{oL} R_{oeq} C_{oL} C_{1L} +$$

$$\left. L_{oL} L_{oeq} C_{oL} R_{1eq} C_{1L} + L_{2eq} R_{oL} L_{oeq} C_{oL} C_{1L} + L_{1L} R_{oeq} C_{oL} L_{2eq} C_{1L} \right) p^4 + \left(R_{1L}^2 R_{1eq} \right.$$

$$C_{1L}^2 R_{oeq} C_{oL} + R_{1L} R_{oeq} C_{oL} L_{1L} C_{1L} + R_{oeq} C_{oL} L_{2eq} R_{1L} C_{1L} + R_{1L}^2 L_{oeq} C_{oL} C_{1L} + R_{1L} R_{1eq}$$

$$L_{oeq} C_{oL} C_{1L} + R_{1L}^2 L_{2eq} C_{1L}^2 + R_{1L} R_{1eq} L_{1L} C_{1L}^2 + R_{1L} R_{oL} R_{oeq} C_{oL} R_{1eq} C_{1L}^2 + R_{1L} L_{oL}$$

$$R_{1eq} C_{1L}^2 + R_{1L} R_{1eq} C_{1L}^2 L_{oeq} + R_{oL} R_{1L} L_{2eq} C_{1L}^2 + R_{1L} L_{2eq} C_{1L}^2 R_{oeq} + R_{1L} R_{oL} L_{2eq} C_{oL}$$

$$C_{1L} + R_{1L} L_{oL} R_{oeq} C_{oL} C_{1L} + R_{oeq} C_{oL} R_{1L} L_{1L} C_{1L} + R_{1L} R_{1eq} C_{1L} L_{1L} C_{1L} + L_{1L}^2 C_{1L}$$

$$+ L_{2eq} L_{1L} C_{1L} + R_{oeq} R_{1eq} C_{1L}^2 L_{1L} + R_{1eq} R_{oeq} C_{1L}^2 L_{1L} + R_{oL} R_{oeq} C_{oL} C_{1L} L_{1L} +$$

$$L_{oL} L_{1L} C_{1L} + L_{oeq} L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L} R_{oeq} C_{oL} + R_{oeq} C_{oL} R_{1eq} L_{1L} C_{1L} + L_{oeq} C_{oL}$$

$$R_{1L} R_{1eq} C_{1L} + L_{1L} L_{oeq} C_{oL} + L_{oeq} C_{oL} L_{2eq} + L_{1L} L_{2eq} C_{1L} + R_{1eq} C_{1L} R_{oL} L_{2eq} C_{oL} +$$

$$R_{1eq} C_{1L} L_{oL} R_{oeq} C_{oL} + R_{oL} R_{oeq} C_{oL} L_{2eq} C_{1L} + L_{2eq} C_{1L} L_{oL} + L_{2eq} L_{oeq} C_{1L} + L_{oL} L_{oeq} C_{oL} +$$

$R_{1L} R_{1eq} R_{oL} R_{oeq} C_{1L}^2 C_{oL} + R_{1L} R_{1eq} L_{oL} C_{1L}^2 + R_{1L} R_{1eq} C_{1L}^2 L_{oeq} + R_{1L} L_{2eq} C_{1L}^2 R_{oL} +$

$R_{1L} L_{2eq} C_{1L}^2 R_{oL} + R_{1L} R_{oL} L_{2eq} C_{oL} C_{1L} + R_{1L} L_{oL} R_{oeq} C_{oL} C_{1L} + R_{1eq} R_{oL} L_{1L} C_{1L}^2 +$

$R_{1eq} R_{oeq} L_{1L} C_{1L}^2 + L_{1L} R_{oL} R_{oeq} C_{oL} C_{1L} + L_{oL} L_{1L} C_{1L} + L_{1L} L_{oeq} C_{1L} + R_{1eq} R_{oL} L_{oeq}$

$C_{oL} C_{1L} + L_{oL} R_{oeq} C_{oL} R_{1eq} C_{1L} + L_{2eq} R_{oL} R_{oeq} C_{oL} C_{1L} + L_{2eq} L_{oL} C_{1L} + L_{2eq} L_{oeq} C_{1L}) p^3$

$+ (R_{oeq} C_{oL} R_{1L}^2 C_{1L} + R_{1L}^2 R_{1eq} C_{1L}^2 + R_{1L} L_{1L} C_{1L} + R_{1L} L_{2eq} C_{1L} + R_{1L} R_{oL} R_{1eq} C_{1L}^2 +$

$R_{1L} R_{1eq} R_{oeq} C_{1L}^2 + R_{1L} R_{oL} R_{oeq} C_{oL} C_{1L} + R_{1L} L_{oL} C_{1L} + R_{1L} L_{oeq} C_{1L} + R_{1L} L_{1L} C_{1L} +$

$R_{1eq} L_{1L} C_{1L} + R_{oL} L_{1L} C_{1L} + R_{oeq} L_{1L} C_{1L} + R_{1L} R_{1eq} C_{1L} + R_{oeq} C_{oL} + R_{oeq} C_{oL} L_{1L} +$

$R_{oeq} C_{oL} L_{2eq} + R_{1L} L_{oeq} C_{oL} + R_{1eq} L_{oeq} C_{oL} + R_{1L} L_{2eq} C_{1L} + R_{1eq} L_{1L} C_{1L} + R_{oL} R_{oeq}$

$C_{oL} R_{1eq} C_{1L} + L_{oL} R_{1eq} C_{1L} + R_{1eq} C_{1L} L_{oeq} + R_{oL} L_{2eq} C_{1L} + L_{2eq} C_{1L} R_{oeq} + R_{oL}$ ~~L_{oeq}~~

$C_{oL} + L_{oL} R_{oeq} C_{oL} + R_{1L} R_{1eq} C_{1L}^2 R_{oL} + R_{1L} R_{1eq} R_{oeq} C_{1L}^2 + R_{1L} R_{oL} R_{oeq} C_{oL} C_{1L} +$

$R_{1L} L_{oeq} C_{1L} + R_{1L} L_{oeq} C_{1L} + L_{1L} R_{oL} C_{1L} + L_{1L} R_{oeq} C_{1L} + R_{oL} R_{oeq} R_{1eq} C_{oL} C_{1L} +$

$R_{1eq} L_{oL} C_{1L} + R_{1eq} L_{oeq} C_{1L} + R_{oL} L_{2eq} C_{1L} + L_{2eq} R_{oeq} C_{1L}) p^2 + (R_{1L} R_{oeq} C_{oL} +$

$R_{1L}^2 C_{1L} + R_{1eq} R_{1L} C_{1L} + R_{1L} R_{oL} C_{1L} +$ ~~$L_{1L} L_{2eq} C_{1L} L_{oeq} C_{oL}$~~ $R_{1L} R_{oeq} C_{1L} + R_{oeq} C_{oL}$

$R_{1L} + R_{oeq} C_{oL} R_{1eq} + R_{1L} R_{1eq} C_{1L} + L_{1L} + L_{2eq} + R_{oL} R_{1eq} C_{1L} + R_{1eq} R_{oeq} C_{1L} +$

$R_{oL} R_{oeq} C_{oL} + L_{oL} + L_{oeq} + R_{1L} R_{oL} C_{1L} + R_{1L} R_{oeq} C_{1L} + R_{1eq} R_{oL} C_{1L} + R_{1eq} R_{oeq} C_{1L}) p$

$+ R_{1L} + R_{1eq} + R_{oL} + R_{oeq}$

Hence the total value of denominator can be foundout .

The current through condenser of the positivesequence network.

$$\frac{V_m p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{Z'_f}{(R_{1eq}+L_{1eq}p)\ (C_{1L}Z'_f p+1\ )+Z'_f}$$

$$= \frac{V_m p^2 C_{1L}}{(p^2+w^2\ )} \cdot \frac{1}{(R_{1eq}+L_{1eq}p)\ (C_{1L}p + \dfrac{Z_{2n}\ Z_{0d} + Z_{2d}\ Z_{0n}}{N}\ ) + 1}$$

$$\frac{V_m p^2 C_{1L}}{(p^2+w^2\ )} \cdot \frac{N}{(R_{1eq}+L_{1eq}p)(NC_{1L}p+Z_{2n}Z_{0d}+Z_{2d}Z_{0n}) + N}$$

Current flowing through shunt branch

$$I'(p) = \frac{V_m p}{(p^2+w^2)} \cdot \frac{1}{(R_{1eq}+L_{1eq}p)\ (\dfrac{C_{1L}Np+Z_{2n}Z_{0d}+Z_{0n}Z_{2d}}{Z_{2n}Z_{0d}+Z_{0n}Z_{2d}}) + \dfrac{N}{Z_{2n}Z_{0d}+Z_{0n}Z_{2d}}}$$

$$= \frac{V_m p}{(p^2+w^2)} \cdot \frac{Z_{2n}Z_{0d}+Z_{0n}Z_{2d}}{(R_{1eq}+L_{1eq}p)(NC_{1L}p+Z_{2n}Z_{0d}+Z_{0n}Z_{2d}) + N}$$

Current flowing through negative sequence network

$$I'(p)\ \cdot \frac{Z_0}{Z_0+Z_2}\ = I'(p)\ \cdot\ \frac{Z_{2d}Z_{0n}}{Z_{2n}Z_{0d}+Z_{0n}Z_{2d}}$$

Current flowing through condenser branch of the negative sequence network

$$I'(p)\ \frac{Z_0}{Z_0+Z_2}\cdot\frac{R_{1eq}+L_{1eq}p}{R_{1eq}+L_{2eq}p+1/C_{1L}p}$$

$$=\frac{V_m\,p^2}{(p^2+w^2)}\cdot\frac{C_{1L}\ Z_{0n}\ (R_{1eq}+L_{2eq}p)}{(R_{1eq}+L_{1eq}p)(C_{1L}Np+Z_{2n}Z_{0d}+Z_{0n}Z_{2d})+N}$$

Where $Z_{0n}(R_{1eq}+L_{1eq}p) = L_{0L}L_{0eq}C_{0L}L_{2eq}p^4+(R_{0L}L_{0eq}C_{0L}L_{2eq}+L_{2eq}L_{0L}R_{0eq}C_{0L}+R_{1eq}L_{0L}L_{0eq}C_{0L})p^3+(R_{1eq}R_{0L}L_{0eq}C_{0L}+R_{1eq}L_{0L}R_{0eq}C_{0L}+L_{2eq}R_{0L}R_{0eq}C_{0L}+L_{2eq}L_{0L}+L_{2eq}L_{0eq})p^2+(R_{0L}R_{0eq}C_{0L}R_{1eq}+R_{1eq}L_{0L}+R_{1eq}L_{0eq}+R_{0L}L_{2eq}+L_{2eq}R_{0eq})p+R_{1eq}R_{0L}+R_{1eq}R_{0eq}$

The current flowing through the inductive branch of negative sequence network

$$I'(p)\ \frac{Z_0}{Z_0+Z_2}\cdot\frac{1/C_{1L}p}{(R_{1eq}+L_{2eq}p+1/C_{1L}p)} = I'(p)\ \cdot\ \frac{Z_{0n}}{Z_{0n}Z_{2d}+Z_{2n}Z_{0d}}$$

$$=\frac{V_m\,p}{(p^2+w^2)}\cdot\frac{Z_{0n}}{(R_{1eq}+L_{1eq}p)(NC_{1L}p+Z_{2n}Z_{0d}+Z_{0n}Z_{2d})+N}$$

The current flowing through the zero sequence network

$$I'(p)\ \frac{Z_2}{Z_0+Z_2}$$

The current flowing through the condenser of zero sequence network

$$I'(p)\cdot\frac{Z_{2n}C_{0L}p\ (R_{0eq}+L_{0eq}p)}{Z_{0n}Z_{2d}+Z_{2n}Z_{0d}}$$

$$= \frac{V_m p^2 C_{0L}}{(p^2+w^2)} \quad \frac{Z_{2n}(R_{0eq} + L_{0eq}p)}{(R_{1eq}+L_{1eq}p)(NC_{1L}p+Z_{2n}Z_{0d}+Z_{0n}Z_{2d}) + N}$$

Similarly current flowing through inductive branch will be

$$\frac{V_m p}{(p^2+w^2)} \quad \frac{Z_{2n}}{(R_{1eq}+L_{1eq}p)(NC_{1L}p+Z_{2n}Z_{0d}+Z_{0n}Z_{2d}) + N}$$

Now let the circuit be interrupted after a time t_1 and let the voltage be represented as $v = V_m \text{Cos}(wt + \lambda)$

$$V_m \text{Cos}(wt + \lambda) \pm R_{1eq}i_1 + L_{1eq}\frac{di_1}{dt} + \frac{1}{C_{1L}}\int i_1 dt$$

Again after taking Laplace transform on both the sides and noting that positive sequence voltage will be

$$\frac{I_1(p)}{C_{1L}p} \quad \frac{1}{R_{1eq}C_{1L}p+C_{1L}L_{1eq}p^2+1}\left\{\frac{V_m \text{Cos}\lambda\, p}{p^2+w^2} - \frac{V_m \sin\lambda\, w}{p^2+w^2} + L_{1eq}i_1(0) - \frac{q_0}{p}\right\}$$

The negative sequence voltage will be

$$V_{r2}(p) = \frac{1}{R_{1eq}C_{1L}p+C_{1L}L_{2eq}p^2+1}\left\{L_{1eq}i_2(0) - \frac{q_2(0)}{p}\right\}$$

Similarly the zero sequence voltage will be

$$V_{r0}(p) = \frac{1}{R_{0eq}C_{0L}p+C_{0L}L_{0eq}p^2+1}\left\{L_{0eq}i_0(0) - \frac{q_0(0)}{p}\right\}$$

The total voltage will be the sum of all these three components i.e. $V_r(p) = V_{r1}(p) + V_{r2}(p) + V_{r0}(p)$

CHAPTER III

TWO MACHINE SYSTEM (Shunt faults)

CLASSICAL METHOD

TWO MACHINE SYSTEM

THREE PHASE FAULT :- (Ref. Fig. 11) (a) and (b)

Here we shall assume for the sake of simplicity that both the machine are floating, their voltage are exactly the same i.e. $v = V_m \cos wt$ before the fault occurs.

It is assumed again that the two machine and Xformer are identical. When the switch is closed the fault condition is simulated. We shall find out the distribution of currents with the help of superposition theore

Let Gen. 2 be shorted then the current through switch

$$I_1(p) = \frac{Vp}{(p^2+w^2)} \cdot \frac{1}{R_{1t}+L_1 p}$$ considering all initial conditions to be zero.

Let Gen. 1 be shorted then the current through gen. branch can be found as follows

The total impedance seen

$$(R_{1eq}+L_{1eq}p) + \frac{(R_{1L}+L_{1L}p)\, 1/C_{1L}p}{R_{1L}+L_{1L}p + 1/C_{1L}p}$$

$$= \frac{(R_{1L}+L_{1L}p)+(R_{1eq}+L_{1eq}p)\,(R_{1L}C_{1L}p+L_{1L}C_{1L}p^2+1)}{R_{1L}C_{1L}p + L_{1L}C_{1L}p^2+1}$$

$$\therefore I_2(p) = \frac{Vp}{(p^2+w^2)} \cdot \frac{R_{1L}C_{1L}p + L_{1L}C_{1L}p^2 + 1}{(R_{1L}+L_{1L}p)+(R_{1eq}+L_{1eq}p)(R_{1L}C_{1L}p+L_{1L}C_{1L}p^2+1)}$$

The current due to this through capacity branch will be

$$\frac{V_{\omega}p^2 C_{1L}}{(p^2+w^2)} \cdot \frac{(R_{1L}+L_{1L}p)}{(R_{1L}+L_{1L}p)+(R_{1eq}L_{1eq}p)(R_{1L}C_{1L}p+L_{1L}C_{1L}p^2+1)}$$

The current through switch branch will be i.e. $(R_{1L}+L_{1L}p)$ branch

$$\frac{Vp}{(p^2+w^2)} \quad \frac{1}{(R_{1L}+L_{1L}p)+(R_{1eq}+L_{1eq}p)(R_{1L}C_{1L}p+L_{1L}C_{1L}p^2+1)}$$

The denominator term after simplification reduces to

$$L_{1eq}C_{1L}L_{1L}p^3+(L_{1eq}R_{1L}C_{1L}+R_{1eq}C_{1L}L_{1L})p^2+(R_{1eq}R_{1L}C_{1L}+L_{1eq}+L_{1L})p+R_{1eq}+R_{1L}$$

When the switch is opened i.e. the fault is cleared, let the voltages of the two generators be represented as $v = V_m \ \cos (wt + \lambda)$

Writing equation for loop 1.

$$V_m \cos(wt+\lambda) = R_{1eq}i_1+L_{1eq}\frac{di_1}{dt}+\frac{1}{C_{1L}}\int(i_1+i'_1)\,dt$$

Taking Laplace on both sides.

$$\frac{V_m \cos\lambda\, p}{p^2+w^2}-\frac{V_m \sin\lambda\, w}{p^2+w^2} = R_{1eq}I_1(p)+L_{1eq}pI_1(p) - L_{1eq}i_1(0) + \frac{I_1(p)}{C_{1L}p} +$$

$$\frac{I'_1(p)}{C_{1L}p} + \frac{q_1(0)}{p} + \frac{q'_1(0)}{p}$$

It should be noted here that the meaning of $I_1(p)$ here is is different from that used under fault condition. After simplification the above equation can be written as

$$\frac{R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+1}{C_{1L}p}\ I_1(p) + \frac{I'_1(p)}{C_{1L}p} - \left[\frac{V_m \cos\lambda\, p}{p^2+w^2} - \frac{V_m \sin\lambda\, w}{p^2+w^2} + L_{1eq}i_1(0) - \frac{q_1(0)+q'_1(0)}{p}\right] = 0$$

Similarly writting equation for 2nd loop

$$\frac{R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+1}{C_{1L}p}\ I'_1(p) + \frac{I_1(p)}{C_{1L}p} - \left[\frac{V_m\, p \cos\lambda}{p^2+w^2} - \frac{V_m \sin\lambda\, w}{p^2+w^2} + L_{1eq}i'_1(0) - \frac{q_1(0)+q'_1(0)}{p}\right] = 0$$

The above two equations can be written as

$$a\, I_1(p) + b\, I'_1(p) - K' = 0$$

$$b\, I_1(p) + a\, I'_1(p) - K = 0$$

where $a = \dfrac{R_{1eq}C_{1L}p + L_{1eq}C_{1L}p^2 + 1}{C_{1L}p}$

$$b = \frac{1}{C_{1L}p}$$

$$K' = \frac{V_m \cos\lambda\, p}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} + L_{1eq}i_1(0) - \frac{q_1(0)+q'_1(0)}{p} \quad \text{and}$$

$$K = \frac{V_m \cos\lambda\, p}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} + L_{1eq}i_1(0) - \frac{q_1(0)+q'_1(0)}{p}$$

$I_1(p) = \dfrac{-bK + aK'}{a^2 - b^2}$ and $I'_1(p)$ $\dfrac{aK = bK'}{a^2 \quad b^2}$

$$bK = \frac{1}{C_{1L}p}\left[\frac{V_m p \cos\lambda}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} + L_{1eq} i'_1(0) = \frac{q_1(0)+q'_1(0)}{p}\right]$$

$$aK' = \frac{R_{1eq}C_{1L}p + L_{1eq}C_{1L}p^2+1}{C_{1L}p}\left[\frac{V_m p \cos\lambda}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} + L_{1eq} i_1(0) - \frac{q_1(0)+q'_1(0)}{p}\right.$$

Also $a^2-b^2 = (a+b)(a-b) = \dfrac{(R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+2)}{C_{1L}p}(R_{1eq}+L_{2eq}p)$

$$\therefore I_1(p) = \frac{C_{1L}p}{(R_{1eq}+L_{1eq}p)(R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+2}\left[-\frac{L_{1eq}}{C_{1L}p} i'_1(0) + \right.$$

$$\frac{R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^3+1}{C_{1L}p} L_{1eq} i_1(0) + (R_{1eq}+L_{1eq}p)\left\{\frac{V_m p \cos\lambda}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} - \right.$$

$$\left.\left.\frac{q_1(0)+q'_1(0)}{p}\right\}\right]$$

The drop upto the fault point $I_1(p)\ \{R_{1t}+L_1 p\}$

$\therefore$ Recovery voltage =

$$\frac{V_m p \cos\lambda}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} - I_1(p)\ \{R_{1t}+L_1 p\}$$

$$= \frac{V_m p \cos\lambda}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} - \frac{C_{1L}p \quad R_{1t}+L_1 p}{(R_{1eq}+L_{1eq}p)(R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+2)}\left[\frac{L_{1eq} i'_1(0)}{C_{1L}p} - \right.$$

$$\frac{R_{1eq}C_{1L}p + L_{1eq}C_{1L}p^2+1}{C_{1L}p} +$$

$$\left. L_{1eq} i_1(0) - (R_{1eq}+L_{1eq}p)\left\{\frac{V_m p \cos\lambda}{p^2+w^2} - \frac{V_m w \sin\lambda}{p^2+w^2} - \frac{q_1(0)+q'_1(0)}{}\right\}\right]$$

Also

$$I_1'(p) = \frac{C_{1L}p}{(R_{1eq}+L_{1eq}p)(R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+2} \left[\frac{R_{1eq}C_{1L}p+L_{1eq}C_{1L}p^2+1}{C_{1L}p} \; L_{1eq}i'_1(0) - \frac{L_{1eq}i'_1(}{C_{1L}p} \right.$$

$$\left. (R_{1eq}+L_{1eq}p) \left\{ \frac{V_m\, p \cos\lambda}{p^2+w^2} - \frac{V_m\, w \sin\lambda}{p^2+w^2} - \frac{q_1(0)+q'_1(0)}{p} \right\} \right]$$

LINE TO LINE FAULT :- (Ref. fig. 12) and 13

When the switch is closed, fault condition is simulated. We shall find current distribution with the help of superposition theorem.

shorting Gen. 2, the impedance seen by Generator 1.

$$(R_{1t} + L_1 p) + \frac{N/D \cdot Z_f}{N/D + Z_f}$$ where N/D is defined as follows

$$\frac{N}{D} = \frac{\begin{array}{r} L_{1L} L_{1eq} C_{1L} p^3 + (L_{1L} R_{1eq} C_{1L} + R_{1L} L_{1eq} C_{1L})p^2 + (R_{1L} R_{1eq} C_{1L} + L_{1L} + L_{2eq} \\ R_{1L} + R_1 \end{array}}{L_{1eq} C_{1L} p^2 + R_{1eq} C_{1L} p + 1}$$

$$\therefore \quad I_1(p) = \frac{Vp}{(p^2 + w^2)} \frac{(N + D Z_f)}{(R_{1t} + L_1 p)(N + DZ_f) + NZ_f}$$

In this case $Z_f = Z_2(p)$

$$Z_2(p) = \frac{\begin{array}{l} L_{1L} L_{2eq} C_{1L} L_2 p^4 + (L_{1L} R_{1eq} C_{1L} L_2 + R_{1L} L_{2eq} C_{1L} L_2 + L_{1L} L_{2eq} C_{1L} R_{1t})p^3 + (R_{1L} R_{1eq} C_{1L} L_2 \\ L_{1L} L_2 + L_{2eq} L_2 + R_{1t} L_{1L} R_{1eq} C_{1L} + R_{1L} L_{2eq} C_{1L} R_{1t})p^2 + (R_{1L} L_2 + R_{1eq} L_2 + R_{1L} R_{1eq} C_{1L} R_{1t} + \\ L_{1L} R_{1t} + L_{2eq} R_{1t})p + R_{1L} R_{1t} + R_{1eq} R_{1t} \end{array}}{\begin{array}{l} (L_{2eq} C_{1L} L_2 + L_{1L} L_{2eq} C_{1L})p^3 + (R_{1eq} C_{1L} L_2 + L_{2eq} C_{1L} R_{1t} + L_{1L} R_{1eq} C_{1L} + R_{1L} L_{2eq} C_{1L})p^2 + \\ (L_2 + R_{1eq} C_{1L} R_{1t} + R_{1L} R_{1eq} C_{1L} + L_{1L} + L_{2eq})p + R_{1t} + R_{1L} + R_{1eq} \end{array}}$$

Current through Z_f branch

$$I_1(p) \cdot \frac{N/D}{\frac{N}{D} + Z_f} = I_1(p) \frac{N}{N + D Z_f}$$

$$= \frac{Vp}{(p^2+w^2)} \cdot \frac{N}{(R_{1t}+L_1p)(N+DZ_f)+N\ Z_f}$$

Current in bo branch

$$I_1(p) \cdot \frac{Z}{\frac{N}{D}+Z_f} = I_1(p) \cdot \frac{Z_f\ D}{N+DZ_f}$$

$$\frac{Vp}{(p^2+w^2)} \quad \frac{D\ Z_f}{(R_{1t}+L_1p)\ (N+DZ_f)+N\ Z_f}$$

Current in cn branch

$$\frac{Vp}{(p^2+w^2)} \cdot \frac{DZ_f}{(R_{1t}+L_1p)(N+DZ_f)+NZ_f} \cdot \frac{(R_{1eq}+L_{1eq}\ p\ )}{R_{1eq}+L_{1eq}\ p+\frac{1}{C_{1L}p}}$$

$$= \frac{Vp^2\ C_{1L}}{(p^2+w^2)} \cdot \frac{Z_f\ (R_{1eq}+L_{1eq}p\ )}{(R_{1t}+L_1p\ )(N+DZ_f\ )+N\ Z_f}$$

Current in od branch

$$\frac{Vp}{(p^2+w^2)} \quad \frac{Z_f}{(R_{1t}+L_1p\ )(N+DZ_f\ )+NZ_f}$$

Now Generator 1 is shorted

$$(R_{1L}+L_{1L}p\ ) + \frac{(R_{1t}+L_1p)Z_f}{(R_{1t}+L_1p+Z_f)} = \frac{(R_{1t}+L_1p)Z_f+(R_{1t}+L_{1L}p)\ (R_{1t}+L_1p+Z_f\ )}{R_{1t}+L_1p+Z_f}$$

$$= \frac{N'}{D'} \quad \text{(Say)}$$

$$\frac{\frac{N'}{D'} \cdot 1/C_{1L}p}{\frac{N'}{D'}+1/C_{1L}p} = \frac{N'}{N'C_{1L}p+D'}$$

∴ Total impedance seen by Generator 2 when generator 1 is shorted.

$$\frac{N'}{N'C_{1L}p + D'} + R_{1eq} + L_{1eq}p = \frac{N' + (R_{1eq} + L_{1eq}p)(N'C_{1L}p + D')}{N'C_{1L}p + D'}$$

$$\text{Current } I_1(p) = \frac{Vp}{(p^2 + w^2)} \cdot \frac{N'C_{1L}p + D'}{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'}$$

Current through cn branch due to this current

$$\frac{V p^2 C_{1L}}{(p^2 + w^2)} \cdot \frac{N'}{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'} \cdot \frac{N'/D'}{\frac{N'}{D'} + \frac{1}{C_{1L}p}}$$

Current through cb branch

$$\frac{Vp}{(p^2 + w^2)} \cdot \frac{N'}{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'}$$

Current through Z_f branch

$$\frac{Vp}{(p^2 + w^2)} \cdot \frac{(R_{1t} + L_1 p)}{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'}$$

Current through ba branch will be

$$\frac{Vp}{(p^2 + w^2)} \cdot \frac{Z_f}{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'}$$

The total current flowing through Z_f branch

$$I_{fs} = \frac{Vp}{(p^2 + w^2)} \cdot \frac{N\left\{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'\right\} + (R_{1t} + L_1 p)\left\{(R_{1t} + L_1 p)(N + DZ_f) + NZ_f\right\}}{\left\{(R_{1eq} + L_{1eq}p)(N'C_{1L}p + D') + N'\right\}\left\{(R_{1t} + L_1 p)(N + DZ_f) + N Z_f\right\}}$$

Current through cn branch

$$\frac{Vp^2C_{1L}}{p^2+w^2}\cdot\frac{N'\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}+Z_f(R_{1eq}+L_{1eq}p)\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}}{\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}\left\{(R_{1eq}+L_{1eq}p)N'C_{1L}p+D'+N'\right\}}$$

Current through C_b branch

$$\frac{Vp}{p^2+w^2}\cdot\frac{DZ_f\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}-D'\left\{(R_{1t}+L_1p)N+DZ_f)+NZ_f\right\}}{\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}}$$

Current through ab branch

$$\frac{Vp}{p^2+w^2}\cdot\frac{(N+DZ_f)\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}-Z_f\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}}{\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}}$$

Total current through C_d branch

$$\frac{Vp}{p^2+w^2}\cdot\frac{Z_f\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}-(N'C_{1L}p+D')\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}}{\left\{(R_{1t}+L_1p)(N+DZ_f)+NZ_f\right\}\left\{(R_{1eq}+L_{1eq}p)(N'C_{1L}p+D')+N'\right\}}$$

Now let the fault current through the fault shunt branch be represented as I_{fs}

Current flowing through $(R_{1t}+L_2p)$ branch

$$\frac{I_{fs}\cdot N''/D''}{(R_{1t}+L_2p)+N''/D''}=\frac{I_{fs}\quad N''}{(R_{1t}+L_2p)D''+N''}\text{ where}$$

$$\frac{N''}{D''}=\frac{L_{1L}L_{2eq}C_{1L}p^3+(L_{1L}R_{1eq}C_{1L}+R_{1L}L_{2eq}C_{1L})p^2+(R_{1L}R_{1eq}C_{1L}+L_{1L}+R_{2eq}L_{1eq})p+R_{1L}+R}{L_{2eq}C_{1L}p^2+R_{1eq}C_{1L}p+1}$$

Current flowing through $(R_{1t}+L_{1L}p)$ branch will be

$$\frac{I_{fs}(R_{1t}+L_1p)\ D''}{(R_{1t}+L_2p)D''+N''}$$

Current flowing through capacitor branch of negative seq. network.

$$\frac{I_{fs}(R_{1t}+L_2p)D''}{(R_{1t}+L_2p)\ D''+N''} \cdot \frac{(R_{1eq}+L_{2eq}\ p)}{R_{1eq}+L_{2eq}p+\frac{1}{C_{1L}p}}$$

$$\frac{I_{fs}\ C_{1L}p\ (R_{1t}+L_2p)(R_{1eq}+L_{2eq}\ p)}{(R_{1t}+L_2p)\ D''+N''}$$

Current through $(R_{1eq}+L_{2eq}p)$ branch

$$\frac{I_{fs}\ (R_{1t}+L_2p)}{(R_{1t}+L_2p)\ D''+N''}$$

Now to find the total recovery voltage we need in this type of fault the positive sequence and negative sequence voltage components. The form of the positive sequence voltage component will exactly be that found in the 3 phase fault except for the initial values of the current that will be different and which have already been calculated. To find the negative sequence component.

$$R_{1eq}\ i_2+L_{2eq}\ \frac{d\,i_2}{dt}+\frac{1}{C_{1L}}\int(i_2'+i_2'')\ dt=0 \quad \text{and}$$

$$R_{1eq}\ i'_2+L_{2eq}\ \frac{di_2'}{dt}+\frac{1}{C_{1L}}\int(i_2+i_2')\ dt=0$$

Taking Laplace transform of both the equations and after simplification.

$$(R_{1eq}C_{1L}p+L_{2eq}C_{1L}\ p^2+1)I_2(p)+I_2'(p)+C_{1L}p\ \left\{\frac{q_2(0)}{p}+\frac{q_2'\ (0)}{p}-L_{2eq}i_2(0)\right\}=0$$

$$I_2(p) + (R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1)I'_2(p) + C_{1L}p \left\{ \frac{q'_2(0)}{p} + \frac{q_2(0)}{p} - L_{2eq}\, i'_2(0) \right\} = 0$$

It is to be noted here that the initial value of current for L_{2eq} will be different for its components i.e. $(L_{2g}+L_{1t})$ and L_{1L}. The sign of the initial current should also be considered.

The above two equations are solved for $I_2(p)$

$$I_2(p) = \frac{L_{2eq} i'_2(0) + (R_{1eq}C_{1L}p + L_{2eq}C_{1L}p^2 + 1)\, L_{2eq} i_2(0) - (R_{1eq}C_{1L}p + L_{2eq}C_{1L}p) \left\{ \frac{q'_2(0) + q_2(0)}{p} \right\}}{(R_{1eq} + L_{2eq}\, p)(R_{1eq}\, C_{1L}p + L_{2eq}C_{1L}p^2 + 2)}$$

$\therefore$ The negative sequence voltage will be

$$I_2(p) \left\{ R_{1t} + L_1 p \right\}$$

and the total voltage will be the sum of positive sequence and negative sequence components of voltage.

Now it is desired to find the actual value of different terms used.

$$(R_{1t} + L_1 p + Z_f)\, Z_{2d} = (L_{2eq} C_{1L} L_2 L_1 + L_{1L} L_{2eq} C_{1L} L_1 + L_{1L} L_{2eq} C_{1L} L_2)\, p^4 +$$
$$(R_{1eq} C_{1L} L_2 L_1 + L_{2eq} C_{1L} R_{1t} L_1 + L_{1L} R_{1eq} C_{1L} L_1 + R_{1L} L_{2eq} C_{1L} L_1 + L_{2eq} C_{1L} L_2 R_{1t} +$$
$$L_{1L} L_{2eq} C_{1L} R_{1t} + L_{1L} R_{1eq} C_{1L} L_2 + R_{1L} L_{2eq} C_{1L} L_2 + L_{1L} L_{2eq} C_{1L} R_{1t})\, p^3 + (L_2 L_1 +$$
$$R_{1eq} C_{1L} R_{1t} L_1 + R_{1L} R_{1eq} C_{1L} L_1 + L_{1L} L_1 + L_{2eq} L_1 + R_{1eq} C_{1L} L_2 R_{1t} + L_{2eq} C_{1L} R_{1t}^2 +$$
$$L_{1L} R_{1eq} C_{1L} R_{1t} + R_{1L} L_{2eq} C_{1L} R_{1t} + R_{1L} R_{1eq} C_{1L} L_2 + L_{1L} L_2 + L_{2eq} L_2 + R_{1t} L_{1L} R_{1eq} C_{1L} +$$
$$R_{1L} L_{2eq} C_{1L} R_{1t})\, p^2 + (R_{1t} L_1 + R_{1L} L_1 + R_{1eq} L_1 + L_2 R_{1t} + R_{1eq} C_{1L} R_{1t}^2 + R_{1L} R_{1eq} C_{1L} R_{1t} +$$
$$L_{1L} R_{1t} + L_{2eq} R_{1t} + R_{1L} L_2 + R_{1eq} L_2 + R_{1L} R_{1eq} C_{1L} R_{1t} + L_{1L} R_{1t} + L_{2eq} R_{1t})\, p +$$
$$R_{1t}^2 + 2 R_{1t} R_{1L} + 2 R_{1t} R_{1\ldots}$$

$(N + D Z_f)(R_{1t} + L_1 p) \times$ Den. of Z_f =

$(L_{1L} L_{1eq} C_{1L}^2 L_{2eq} L_2 L_1 + L_{1L}^2 L_{1eq} L_{2eq} C_{1L}^2 L_1 + L_{1eq} L_{1L} L_{2eq} C_{1L}^2 L_2 L_1) p^7 + (L_{1L} L_{1eq} C_{1L}^2$
$R_{1eq} L_2 L_1 + L_{1L} L_{1eq} C_{1L}^2 L_{2eq} R_{1t} L_1 + L_{1L}^2 L_{1eq} C_{1L}^2 R_{1eq} L_1 + L_{1L} L_{1eq} C_{1L}^2 R_{1L} L_{2eq} L_1 +$
$L_{1L} R_{1eq} C_{1L}^2 L_2 L_1 L_{2eq} + L_{1L}^2 R_{1eq} L_{2eq} C_{1L}^2 L_1 + R_{1L} L_{1eq} C_{1L}^2 L_{2eq} L_2 L_1 + R_{1L} L_{1L} L_{1eq} L_{2eq}$
$C_{1L}^2 L_1 + L_{1L} R_{1eq} C_{1L}^2 L_{1eq} L_2 L_1 + L_{1eq} C_{1L}^2 R_{1L} L_{2eq} L_2 L_1 + L_{1L} L_{2eq} C_{1L}^2 R_{1t} L_{1eq} L_1 +$
$L_{1L} L_{2eq} C_{1L}^2 L_2 R_{1eq} L_1 + L_{1L} L_{1eq} C_{1L}^2 L_{2eq} L_2 R_{1t} + L_{1L}^2 L_{1eq} L_{2eq} C_{1L}^2 R_{1t} + L_{1eq} L_{1L}$
$L_{2eq} C_{1L}^2 L_2 R_{1t}) p^6 + (L_{1L} L_{1eq} C_{1L} L_2 L_1 + L_{1L} L_{1eq} R_{1eq} C_{1L}^2 R_{1t} L_1 + L_{1L} L_{1eq} R_{1L} R_{1eq}$
$C_{1L}^2 L_1 + L_{1L}^2 L_{1eq} C_{1L} L_1 + L_{1L} L_{1eq} C_{1L} L_{2eq} L_1 + L_{1L} R_{1eq}^2 C_{1L}^2 L_2 L_1 + L_{1L} R_{1eq} C_{1L}^2 L_{2eq} R_{1t} L_1$
$+ L_{1L}^2 R_{1eq}^2 C_{1L}^2 L_1 + L_{1L} R_{1L} L_{2eq} R_{1eq} C_{1L}^2 L_1 + R_{1L} R_{1eq} L_{1eq} C_{1L}^2 L_2 L_1 + R_{1L} L_{1eq} C_{1L}^2 L_{2eq}$
$R_{1t} L_1 + R_{1L} L_{1eq} C_{1L}^2 L_{1L} R_{1eq} + R_{1L}^2 L_{1L} L_{2eq} C_{1L}^2 L_1 + R_{1L} R_{1eq} C_{1L}^2 L_{2eq} L_2 L_1 + R_{1L} R_{1eq} C_{1L}^2$
$L_{1L} L_{2eq} L_1 + L_{1L} L_{2eq} C_{1L} L_2 L_1 + L_{1L}^2 L_{2eq} C_{1L} L_1 + L_{1eq} L_{2eq} C_{1L} L_2 L_1 + L_{1eq} L_{1L} L_{2eq} C_{1L} L_1$
$+ R_{1L} R_{1eq} C_{1L}^2 L_2 L_{1eq} L_1 + L_{1L} L_2 L_{1eq} C_{1L} L_1 + L_{2eq} L_2 L_{1eq} C_{1L} L_1 + R_{1t} L_{1L} R_{1eq} C_{1L}^2 L_{1eq} L_1$
$+ R_{1L} L_{2eq} C_{1L}^2 R_{1t} L_{1eq} L_1 + L_1^2 R_{1eq}^2 C_{1L}^2 L_2 + R_{1L} L_{2eq} C_{1L}^2 L_2 R_{1eq} L_1 + L_{1L} L_{2eq} C_{1L}^2 R_{1t} R_{1eq}$
~~C_{1L}~~ $L_1 + L_{1L} L_{2eq} C_{1L} L_2 L_1 + L_{1L} L_{1eq} C_{1L}^2 R_{1eq} L_2 R_{1t} + L_{1L} L_{1eq} C_{1L}^2 L_{2eq} R_{1t}^2 +$
$L_{1L}^2 L_{1eq} C_{1L}^2 R_{1eq} R_{1t} + L_{1L} L_{1eq} C_{1L}^2 R_{1L} L_{2eq} R_{1t} + L_{1L} R_{1eq} C_{1L}^2 L_2 L_{2eq} R_{1t} + L_{1L}^2 R_{1eq} L_{2eq}$
$C_{1L}^2 R_{1t} + R_{1L} L_{1eq} C_{1L}^2 L_{2eq} L_2 R_{1t} + R_{1L} L_{1L} L_{1eq} L_{2eq} C_{1L}^2 R_{1t} + L_{1L} R_{1eq} C_{1L}^2 L_{1eq} L_2 R_{1t}$
$+ L_{1eq} C_{1L}^2 R_{1L} L_{2eq} L_2 R_{1t} + L_{1L} L_{2eq} C_{1L}^2 R_{1t}^2 L_{1eq} + L_{1L} L_{2eq} C_{1L}^2 L_2 R_{1eq} R_{1t}) p^5 +$
$(L_{1L} L_{1eq} C_{1L} R_{1t} L_1 + L_{1L} L_{1eq} C_{1L} R_{1L} L_1 + L_{1L} L_{1eq} C_{1L} R_{1eq} L_1 + L_{1L} R_{1eq} C_{1L} L_2 L_1 + L_{1L} R_{1eq}^2$
$C_{1L}^2 L_1 R_{1t} + L_{1L} R_{1eq}^2 C_{1L}^2 R_{1L} L_1 + L_{1L}^2 R_{1eq} C_{1L} L_1 + L_{1L} R_{1eq} L_{2eq} C_{1L} L_1 + R_{1L} L_{1eq} C_{1L} L_2 L_1$
$+ R_{1L} L_{1eq} R_{1eq} C_{1L}^2 R_{1t} L_1 + R_{1L}^2 R_{1eq} L_{1eq} C_{1L}^2 L_1 + R_{1L} L_{1eq} C_{1L} L_{1L} L_1 + R_{1L} L_{1eq} L_{2eq} C_{1L} L_1 +$
$R_{1L} R_{1eq}^2 C_{1L}^2 L_2 L_1 + R_{1L} R_{1eq} C_{1L}^2 L_{2eq} R_{1t} L_1 + R_{1L} R_{1eq}^2 L_{1L} C_{1L}^2 L_1 + R_{1L}^2 R_{1eq} L_{2eq} C_{1L}^2 L_1 +$
$R_{1eq} C_{1L} L_2 L_{1L} L_1 + L_{1L} L_{2eq} C_{1L} R_{1t} L_1 + L_{1L}^2 R_{1eq} C_{1L} L_1 + L_{1L} R_{1L} L_{2eq} C_{1L} L_1 + R_{1eq} C_{1L} L_2$
$L_{1eq} L_1 + L_{1eq} L_{2eq} C_{1L} R_{1t} L_1 + L_{1L} L_{1eq} R_{1eq} C_{1L} L_1 + L_{1eq} R_{1L} L_{2eq} C_{1L} L_1 + R_{1L} L_{2eq} C_{1L}$
$L_2 L_1 + R_{1L} L_{1L} L_{2eq} C_{1L} L_1 + R_{1eq} L_{2eq} C_{1L} L_2 L_1 + R_{1eq} L_{1L} L_{2eq} C_{1L} L_1 + R_{1L} L_2 L_{1eq} C_{1L} L_1 +$

$$R_{1eq} L_2 L_{1eq} C_{1L} L_1 + R_{1L} R_{1eq} C_{1L}^2 R_{1t} L_{1eq} L_1 + L_{1L} R_{1t} L_{1eq} C_{1L} L_1 + L_{2eq} R_{1t} L_{1eq} C_{1L} L_1 +$$

$$R_{1L} R_{1eq}^2 C_{1L}^2 L_2 L_1 + L_{1L} L_2 R_{1eq} C_{1L} L_1 + L_{2eq} L_2 R_{1eq} C_{1L} L_1 + R_{1t} L_{1L} R_{1eq}^2 C_{1L}^2 L_1 +$$

$$R_{1L} L_{2eq} C_{1L}^2 R_{1t} R_{1eq} L_1 + L_{1L} R_{1eq} C_{1L} L_2 L_1 + R_{1L} L_{2eq} C_{1L} L_2 L_1 + L_{1L} L_{2eq} C_{1L} R_{1t} L_1 + L_{1L} L_{1eq}$$

$$C_{1L} L_2 R_{1t} + L_{1L} L_{1eq} R_{1eq} C_{1L}^2 R_{1t}^2 + L_{1L} L_{1eq} R_{1L} R_{1eq} C_{1L}^2 R_{1t} + L_{1L}^2 L_{1eq} C_{1L} R_{1t} + L_{1L} L_{1eq}$$

$$C_{1L} L_{2eq} R_{1t} + L_{1L} R_{1eq}^2 C_{1L}^2 L_2 R_{1t} + L_{1L} R_{1eq} C_{1L}^2 L_{2eq} R_{1t}^2 + L_{1L}^2 R_{1eq}^2 C_{1L}^2 R_{1t} + L_{1L} R_{1L} L_{2eq}$$

$$R_{1eq} C_{1L}^2 R_{1t} + R_{1L} R_{1eq} L_{1eq} C_{1L}^2 L_2 R_{1t} + R_{1L} L_{1eq} C_{1L}^2 L_{2eq} R_{1t}^2 + R_{1L} L_{1eq} C_{1L}^2 L_{1L} R_{1eq} R_{1t} +$$

$$R_{1L}^2 L_{1eq} L_{2eq} C_{1L}^2 R_{1t} + R_{1L} R_{1eq} C_{1L}^2 L_{2eq} L_2 R_{1t} + R_{1L} R_{1eq} C_{1L}^2 L_{1L} L_{2eq} R_{1t} + L_{1L} L_{2eq} C_{1L} L_2 R_{1t}$$

$$+ L_{1L}^2 L_{2eq} C_{1L} R_{1t} + L_{1eq} L_{2eq} C_{1L} L_2 R_{1t} + L_{1eq} L_{1L} L_{2eq} C_{1L} R_{1t} + R_{1L} R_{1eq} C_{1L}^2 L_2 L_{1eq} R_{1t} +$$

$$L_{1L} L_2 L_{1eq} C_{1L} R_{1t} + L_{2eq} L_2 L_{1eq} C_{1L} R_{1t} + R_{1t}^2 L_{1L} R_{1eq} C_{1L}^2 L_{1eq} + R_{1L} L_{2eq} C_{1L}^2 R_{1t}^2 L_{1eq} +$$

$$L_{1L} R_{1eq}^2 C_{1L}^2 L_2 R_{1t} + R_{1L} L_{2eq} C_{1L}^2 L_2 R_{1eq} R_{1t} + L_{1L} L_{2eq} C_{1L}^2 R_{1t} R_{1eq} + L_{1L} L_{2eq} C_{1L} L_2 R_{1t}) p^4$$

$$+ (L_{1L} R_{1eq} C_{1L} R_{1t} L_1 + L_{1L} R_{1eq} C_{1L} R_{1L} L_1 + L_{1L} R_{1eq}^2 C_{1L} L_1 + R_{1L} L_{1eq} C_{1L} R_{1t} L_1 + R_{1L}^2 L_{1eq} C_{1L} L_1 +$$

$$R_{1L} L_{1eq} R_{1eq} C_{1L} L_1 + R_{1L} R_{1eq} C_{1L} L_2 L_1 + R_{1L} R_{1eq}^2 C_{1L}^2 R_{1t} L_1 + R_{1L}^2 R_{1eq}^2 C_{1L}^2 L_1 + R_{1L} R_{1eq} C_{1L}$$

$$L_{1L} L_1 + R_{1L} R_{1eq} C_{1L} L_{2eq} L_1 + L_{1L} L_2 L_1 + L_{1L} R_{1eq} C_{1L} R_{1t} L_1 + L_{1L} R_{1L} R_{1eq} C_{1L} L_1 + L_{1L}^2 L_1 +$$

$$L_{1L} L_{2eq} L_1 + L_{1eq} L_2 L_1 + L_{1eq} R_{1eq} C_{1L} R_{1t} L_1 + L_{1eq} R_{1t} R_{1eq} C_{1L} L_1 + L_{1eq} L_{1L} L_1 + L_{1eq} L_{2eq} L_1$$

$$+ R_{1L} R_{1eq} C_{1L} L_2 L_1 + R_{1L} L_{2eq} C_{1L} R_{1t} L_1 + R_{1L} L_{1L} R_{1eq} C_{1L} L_1 + R_{1L}^2 L_{2eq} C_{1L} L_1 + R_{1eq}^2 C_{1L} L_2 L_1$$

$$+ R_{1eq} L_{2eq} C_{1L} R_{1t} L_1 + L_{1L} R_{1eq}^2 C_{1L} L_1 + R_{1L} L_{2eq} C_{1L} R_{1eq} L_1 + R_{1L} R_{1t} L_{1eq} C_{1L} L_1 + R_{1eq} R_{1t}$$

$$L_{1eq} C_{1L} L_1 + R_{1L} L_2 R_{1eq} C_{1L} L_1 + R_{1eq}^2 L_2 C_{1L} L_1 + R_{1L} R_{1eq}^2 C_{1L}^2 R_{1t} L_1 + L_{1L} R_{1t} R_{1eq} C_{1L} L_1 +$$

$$L_{2eq} R_{1t} C_{1L} R_{1eq} L_1 + R_{1L} R_{1eq} C_{1L} L_2 L_1 + L_{1L} L_2 L_1 + L_{2eq} L_2 L_1 + R_{1t} L_{1L} R_{1eq} C_{1L} L_1 + R_{1L}$$

$$L_{2eq} C_{1L} R_{1t} L_1 + L_{1L} L_{1eq} C_{1L} R_{1t}^2 + L_{1L} L_{1eq} C_{1L} R_{1L} R_{1t} + L_{1L} L_{1eq} C_{1L} R_{1eq} R_{1t} + L_{1L} R_{1eq} C_{1L}$$

$$L_2 R_{1t} + L_{1L} R_{1eq}^2 C_{1L}^2 R_{1t}^2 + L_{1L} R_{1eq}^2 C_{1L}^2 R_{1L} R_{1t} + L_{1L}^2 R_{1eq} C_{1L} R_{1t} + L_{1L} R_{1eq} L_{2eq} C_{1L} R_{1t} +$$

$$R_{1L} L_{1eq} C_{1L} L_2 R_{1t} + R_{1L} L_{1eq} R_{1eq} C_{1L}^2 R_{1t}^2 + R_{1L}^2 R_{1eq} L_{1eq} C_{1L}^2 R_{1t} + R_{1L} L_{1eq} C_{1L} L_{1L} R_{1t} +$$

$$R_{1L} L_{1eq} L_{2eq} C_{1L} R_{1t} + R_{1L} R_{1eq}^2 C_{1L}^2 L_2 R_{1t} + R_{1L} R_{1eq} C_{1L}^2 L_{2eq} R_{1t}^2 + R_{1L} R_{1eq}^2 L_{1L} C_{1L}^2 R_{1t} +$$

$$R_{1L}^2 R_{1eq} L_{2eq} C_{1L}^2 R_{1t} + R_{1eq} C_{1L} L_2 L_{1L} R_{1t} + L_{1L} L_{2eq} C_{1L} R_{1t}^2 + L_{1L}^2 R_{1eq} C_{1L} R_{1t} +$$

$$L_{1L} R_{1L} L_{2eq} C_{1L} R_{1t} + R_{1eq} C_{1L} L_2 L_{1eq} R_{1t} + L_{1eq} L_{2eq} C_{1L} R_{1t}^2 + L_{1L} L_{1eq} R_{1eq} C_{1L} R_{1t}$$

$$+ L_{1eq} R_{1L} L_{2eq} C_{1L} R_{1t} + R_{1L} L_{2eq} C_{1L} L_2 R_{1t} + R_{1L} L_{1L} L_{2eq} C_{1L} R_{1t} + R_{1eq} L_{2eq} C_{1L} L_2$$

$$R_{1t} + R_{1eq} L_{1L} L_{2eq} C_{1L} R_{1t} + R_{1L} L_2 L_{1eq} C_{1L} R_{1t} + R_{1eq} L_2 L_{1eq} C_{1L} R_{1t} + R_{1L} R_{1eq} C_{1L}^2$$

$$R_{1t}^2 L_{1eq} + L_{1L} R_{1t}^2 L_{1eq} C_{1L} + L_{2eq} R_{1t}^2 L_{1eq} C_{1L} + R_{1L} R_{1eq}^2 C_{1L}^2 L_2 R_{1t} + L_{1L} L_2 R_{1eq} C_{1L} R_{1t}$$

$$+ L_{2eq} L_2 R_{1eq} C_{1L} R_{1t} + R_{1t}^2 L_{1L} R_{1eq}^2 C_{1L}^2 + R_{1L} L_{2eq} C_{1L}^2 R_{1t}^2 R_{1eq} + L_{1L} R_{1eq} C_{1L} L_2 R_{1t} +$$

$$R_{1L} L_{2eq} C_{1L} L_2 R_{1t} + L_{1L} L_{2eq} C_{1L} R_{1t}^2) p^3 + (L_{1L} R_{1eq} C_{1L} R_{1t}^2 + L_{1L} R_{1eq} C_{1L} R_{1L} R_{1t} +$$

$$L_{1L} R_{1eq}^2 C_{1L} R_{1t} + R_{1L} L_{2eq} C_{1L} R_{1t}^2 + R_{1L}^2 L_{2eq} C_{1L} R_{1t} + R_{1L} L_{2eq} C_{1L} R_{1eq} R_{1t} + R_{1L} R_{1eq}$$

$$C_{1L} L_2 R_{1t} + R_{1L} R_{1eq}^2 C_{1L}^2 R_{1t}^2 + R_{1L}^2 R_{1eq}^2 C_{1L}^2 R_{1t} + R_{1L} R_{1eq} C_{1L} L_{1L} R_{1t} + R_{1L} R_{1eq}$$

$$C_{1L} L_{2eq} R_{1t} + L_{1L} L_2 R_{1t} + R_{1eq} C_{1L} R_{1t}^2 L_{1L} + R_{1L} R_{1eq} C_{1L} L_{1L} R_{1t} + L_{1L}^2 R_{1t} + L_{1L} L_{2eq} R_{1t}$$

$$+ L_{2eq} L_2 R_{1t} + R_{1eq} C_{1L} R_{1t}^2 L_{2eq} + L_{1L} L_{2eq} R_{1t} + L_{2eq}^2 R_{1t} + R_{1L} R_{1eq} C_{1L} L_2 R_{1t} + R_{1L}$$

$$L_{2eq} C_{1L} R_{1t}^2 + R_{1L} L_{1L} R_{1eq} C_{1L} R_{1t} + R_{1L}^2 L_{2eq} C_{1L} R_{1t} + R_{1eq}^2 C_{1L} L_2 R_{1t} + R_{1eq} L_{2eq} C_{1L} R_{1t}^2$$

$$+ L_{1L} R_{1eq}^2 C_{1L} R_{1t} + R_{1eq} R_{1L} L_{2eq} C_{1L} R_{1t} + R_{1eq} R_{1t}^2 L_{2eq} C_{1L} + R_{1L} L_2 R_{1eq} C_{1L} R_{1t} +$$

$$R_{1eq}^2 L_2 C_{1L} R_{1t} + R_{1L} R_{1eq}^2 C_{1L}^2 R_{1t}^2 + L_{1L} R_{1t}^2 R_{1eq} C_{1L} + L_{2eq} R_{1t}^2 C_{1L} R_{1eq} + R_{1L} R_{1eq} C_{1L} L_2 R_{1t}$$

$$+ L_{1L} L_2 R_{1t} + L_{2eq} L_2 R_{1t} + R_{1t}^2 L_{1L} R_{1eq} C_{1L} + R_{1L} L_{2eq} C_{1L} R_{1t}^2) p^2 + (R_{1L} R_{1t} L_1 + R_{1L}^2 L_1 +$$

$$R_{1L} R_{1eq} L_1 + R_{1eq} R_{1t} L_1 + R_{1eq} R_{1L} L_1 + R_{1eq}^2 L_1 + R_{1L} R_{1t} L_1 + R_{1eq} R_{1t} L_1 + R_{1L} R_{1eq} C_{1L} R_{1t}^2$$

$$+ R_{1L}^2 R_{1eq} C_{1L} R_{1t} + R_{1L} R_{1eq}^2 C_{1L} R_{1t} + L_{1L} R_{1t}^2 + L_{1L} R_{1L} R_{1t} + L_{1L} R_{1eq} R_{1t} + L_{2eq} R_{1t}^2 +$$

$$L_{2eq} R_{1L} R_{1t} + L_{2eq} R_{1t} R_{1eq} + R_{1L} L_2 R_{1t} + R_{1L} R_{1eq} C_{1L} R_{1t}^2 + R_{1L}^2 R_{1eq} C_{1L} R_{1t} + R_{1L} L_{1L} R_{1t}$$

$$+ R_{1L} L_{2eq} R_{1t} + R_{1eq} L_2 R_{1t} + R_{1eq}^2 C_{1L} R_{1t}^2 + R_{1eq}^2 R_{1L} C_{1L} R_{1t} + R_{1eq} L_{1L} R_{1t} + R_{1eq}$$

$$L_{2eq} R_{1t} + R_{1L} R_{1t}^2 R_{1eq} C_{1L} + R_{1eq}^2 R_{1t}^2 C_{1L} + R_{1L} L_2 R_{1t} + R_{1eq} L_2 R_{1t} + R_{1L} R_{1eq} C_{1L} R_{1t}^2$$

$$+ L_{1L} R_{1t}^2 + L_{2eq} R_{1t}^2) p + (R_{1L} R_{1eq} C_{1L} + L_{1L} + L_{1eq}) (R_{1t} + R_{1L} + R_{1eq}) L_1 p^2 + (R_{1L} + R_{1eq})$$

$$(L_{2eq} + L_2 + L_{1L} + R_{1eq} C_{1L} R_{1t} + R_{1L} R_{1eq} C_{1L}) L_1 p^2 + (R_{1L} R_{1t} R_{1eq} C_{1L} + R_{1eq}^2 R_{1t} C_{1L}) L_1 p^2 +$$

$$(R_{1L} L_2 + R_{1eq} L_2 + R_{1L} R_{1eq} C_{1L} R_{1t} + L_{1L} R_{1t} + L_{2eq} R_{1t}) L_1 p^2 + R_{1L} R_{1t}^2 + R_{1L}^2 R_{1t} + R_{1L} R_{1eq} R_{1t}$$

$$+ R_{1eq} R_{1t}^2 + R_{1eq} R_{1L} R_{1t} + R^2 \ldots$$

$$
\begin{aligned}
& N Z_f \times \text{Den. of } Z_f = L_{1L}^2 L_{1eq} L_{2eq} C_{1L}^2 L_2 p^7 + \left(L_{1L}^2 R_{1eq} L_{1eq} C_{1L}^2 L_2 + L_{1L} L_{1eq} L_{2eq} \right. \\
& R_{1L} C_{1L}^2 L_2 + L_{1L}^2 L_{1eq} L_{2eq} C_{1L}^2 R_{1t} + L_{1L}^2 L_{2eq} R_{1eq} C_{1L}^2 L_2 + L_{1L} L_{2eq} L_{1eq} R_{1L} C_{1L}^2 \\
& \left. L_2 \right) p^6 + \left(L_{1L} L_{1eq} R_{1L} R_{1eq} C_{1L}^2 L_2 + L_{1L}^2 L_{1eq} C_{1L} L_2 + L_{1L} L_{1eq} L_{2eq} L_2 C_{1L} + \right. \\
& L_{1L}^2 L_{1eq} R_{1t} R_{1eq} C_{1L}^2 + L_{1L} L_{1eq} R_{1L} L_{2eq} C_{1L}^2 R_{1t} + L_{1L}^2 R_{1eq}^2 C_{1L}^2 L_2 + L_{1L} R_{1eq} \\
& R_{1L} L_{2eq} C_{1L}^2 L_2 + L_{1L}^2 L_{2eq} R_{1eq} C_{1L}^2 R_{1t} + L_{1L} R_{1eq} R_{1L} L_{1eq} C_{1L}^2 L_2 + R_{1L}^2 L_{1eq} \\
& L_{2eq} C_{1L}^2 L_2 + R_{1L} L_{1eq} L_{1L} L_{2eq} C_{1L}^2 R_{1t} + R_{1L} R_{1eq} L_{1L} L_{2eq} C_{1L}^2 L_2 + L_{1L}^2 L_{2eq} \\
& \left. C_{1L} L_2 + L_{1L} L_{2eq} C_{1L} L_{1eq} L_2 \right) p^5 + \left(L_{1L} L_{1eq} R_{1L} C_{1L} L_2 + L_{1L} L_{1eq} C_{1L} R_{1eq} L_2 \right. \\
& + L_{1L} L_{1eq} R_{1L} R_{1eq} C_{1L}^2 R_{1t} + L_{1L}^2 L_{1eq} C_{1L} R_{1t} + L_{1L} L_{1eq} L_{2eq} C_{1L} R_{1t} + L_{1L} R_{1eq}^2 \\
& R_{1L} C_{1L}^2 L_2 + L_{1L}^2 R_{1eq} C_{1L} L_2 + L_{1L} R_{1eq} L_{2eq} L_2 C_{1L} + L_{1L}^2 R_{1t} R_{1eq}^2 C_{1L}^2 + L_{1L} R_{1eq} \\
& R_{1L} L_{2eq} C_{1L}^2 R_{1t} + R_{1L}^2 R_{1eq} L_{1eq} C_{1L}^2 L_2 + R_{1L} L_{1eq} L_{1L} C_{1L} L_2 + R_{1L} L_{1eq} C_{1L} L_{2eq} L_2 \\
& + R_{1L} L_{1eq} R_{1t} L_{1L} R_{1eq} C_{1L}^2 + R_{1L}^2 L_{1eq} L_{2eq} C_{1L}^2 R_{1t} + R_{1L} R_{1eq}^2 L_{1L} C_{1L}^2 L_2 + R_{1L}^2 L_{2eq} \\
& R_{1eq} C_{1L}^2 L_2 + R_{1L} R_{1eq} L_{1L} L_{2eq} C_{1L}^2 R_{1t} + L_{1L}^2 R_{1eq} C_{1L} L_2 + R_{1L} L_{2eq} C_{1L} L_2 L_{1L} \\
& L_{1L}^2 L_{2eq} C_{1L} R_{1t} + L_{1L} R_{1eq} C_{1L} L_2 L_{1eq} + R_{1L} L_{2eq} C_{1L} L_2 L_{1eq} + L_{1L} L_{2eq} C_{1L} \\
& \left. R_{1t} L_{1eq} + R_{1L} L_{1L} L_{2eq} C_{1L} L_2 + R_{1eq} L_{1L} L_{2eq} C_{1L} L_2 \right) p^4 + \left(L_{1L} L_{1eq} C_{1L} R_{1L} \right. \\
& R_{1t} + L_{1L} L_{1eq} C_{1L} R_{1eq} R_{1t} + L_{1L} R_{1eq} R_{1L} L_2 C_{1L} + L_{1L} R_{1eq}^2 L_2 C_{1L} + L_{1L} R_{1L} \\
& R_{1eq}^2 C_{1L}^2 R_{1t} + L_{1L}^2 R_{1eq} C_{1L} R_{1t} + L_{1L} R_{1eq} L_{2eq} R_{1t} C_{1L} + R_{1L}^2 L_{1eq} C_{1L} L_2 \\
& + R_{1L} R_{1eq} L_{1eq} C_{1L} L_2 + R_{1L}^2 R_{1eq} C_{1L}^2 R_{1t} + R_{1L} L_{1eq} C_{1L} L_{1L} R_{1t} + R_{1L} L_{1eq} \\
& L_{2eq} C_{1L} R_{1t} + R_{1L}^2 R_{1eq}^2 C_{1L}^2 L_2 + R_{1L} R_{1eq} C_{1L} L_{1L} L_2 + R_{1L} R_{1eq} C_{1L} L_{2eq} L_2 \\
& + R_{1L} R_{1t} L_{1L} R_{1eq}^2 C_{1L}^2 + R_{1L}^2 L_{2eq} R_{1eq} C_{1L}^2 R_{1t} + R_{1L} R_{1eq} C_{1L} L_2 L_{1L} + L_{1L}^2 L_2 + \\
& L_{1L} L_{2eq} L_2 + L_{1L}^2 R_{1t} R_{1eq} C_{1L} + L_{1L} R_{1L} L_{2eq} C_{1L} R_{1t} + R_{1L} R_{1eq} C_{1L} L_2 \\
& L_{1eq} + L_{1L} L_2 L_{1eq} + L_{1eq} L_{2eq} L_2 + L_{1eq} R_{1t} L_{1L} R_{1eq} C_{1L} + L_{1eq} R_{1L} L_{2eq} \\
& C_{1L} R_{1t} + L_{1L} R_{1eq} C_{1L} L_2 R_{1L} + R_{1L}^2 L_{2eq} C_{1L} L_2 + L_{1L} L_{2eq} C_{1L} R_{1t} R_{1L} + \\
& \left. L_{1L} R_{1eq}^2 C_{1L} L_2 + R_{1L} L_{2eq} C_{1L} L_2 R_{1eq} + L_{1L} L_{2eq} C_{1L} R_{1t} R_{1eq} \right) p^3 +
\end{aligned}
$$

$$\left(L_{1L} R_{1eq} C_{1L} R_{1L} R_{1t} + L_{1L} R_{1eq}^2 C_{1L} R_{1t} + R_{1L}^2 R_{1t} L_{1eq} C_{1L} + R_{1L} L_{1eq} R_{1eq} C_{1L} \right.$$

$$R_{1t} + R_{1L}^2 R_{1eq} C_{1L} L_2 + R_{1L} R_{1eq}^2 L_2 C_{1L} + R_{1L}^2 R_{1eq}^2 C_{1L}^2 R_{1t} + R_{1L} R_{1eq} L_{1L}$$

$$R_{1t} C_{1L} + R_{1L} R_{1eq} L_{2eq} C_{1L} R_{1t} + R_{1L} L_2 L_{1L} + R_{1eq} L_2 L_{1L} + R_{1L} R_{1eq} C_{1L} L_{1L}$$

$$R_{1t} + L_{1L}^2 R_{1t} + L_{1L} L_{2eq} R_{1t} + R_{1L} L_2 L_{1eq} + L_{1eq} R_{1eq} L_2 + L_{1eq} R_{1L} R_{1eq}$$

$$C_{1L} R_{1t} + L_{1eq} L_{1L} R_{1t} + L_{1eq} L_{2eq} R_{1t} + R_{1L}^2 R_{1eq} C_{1L} L_2 + R_{1L} L_{1L} L_2 +$$

$$R_{1L} L_{2eq} L_2 + R_{1L} R_{1t} L_{1L} R_{1eq} C_{1L} + R_{1L}^2 L_{2eq} C_{1L} R_{1t} + R_{1L} R_{1eq}^2 C_{1L} L_2 +$$

$$\left. R_{1eq} L_{1L} L_2 + R_{1eq} L_{2eq} L_2 + R_{1eq}^2 R_{1t} L_{1L} C_{1L} + R_{1L} R_{1eq} L_{2eq} C_{1L} R_{1t} \right) p^2 +$$

$$\left(R_{1L}^2 R_{1eq} R_{1t} C_{1L} + R_{1L} R_{1eq}^2 R_{1t} C_{1L} + L_{1L} R_{1L} R_{1t} + L_{1L} R_{1eq} R_{1t} + L_{1eq} R_{1L} \right.$$

$$R_{1t} + L_{1eq} R_{1eq} R_{1t} + R_{1L}^2 L_2 + R_{1eq} R_{1L} L_2 + R_{1L}^2 R_{1eq} C_{1L} R_{1t} + L_{1L} R_{1t} R_{1L}$$

$$+ L_{2eq} R_{1t} R_{1L} + R_{1L} R_{1eq} L_2 + R_{1eq}^2 L_2 + R_{1L} R_{1eq}^2 C_{1L} R_{1t} + L_{1L} R_{1t} R_{1eq}$$

$$\left. + L_{2eq} R_{1eq} R_{1t} \right) p + R_{1L}^2 R_{1t} + R_{1L} R_{1eq} R_{1t} + R_{1eq} R_{1L} R_{1t} + R_{1eq}^2 R_{1t}$$

Line to Ground Fault: (Ref. fig. 14)

The current through fault shunt branch as found in case of Line to Line fault

$$= \frac{Vp}{(p^2+\omega^2)} \cdot \frac{N\left\{(R_{1cq}+L_{1cq}p)(N'C_{1L}p+D')+M'\right\} + (R_{1t}+L_1p)\left\{(R_{1t}+L_1p)(M+DZ_f)+NZ_f\right\}}{\left\{(R_{2cq}+L_{1cq}p)(N'C_{1L}p+D')+M'\right\}\left\{(R_{1t}+L_1p)(M+DZ_f)+NZ_f\right\}}$$

Here $Z = Z_0 + Z_2$ where Z_0 and Z_2 are defined as follows for this particular location of the fault.

$$Z_2(p) = \frac{\begin{gathered} L_{1L}L_{2cq}C_{1L}L_2p^4 + (L_{1L}R_{1cq}C_{1L}L_2 + R_{1L}L_{2cq}C_{1L}L_2 + L_{1L}L_{2cq}C_{1L}R_{1t})p^3 + (R_{1L}R_{1cq}C_{1L}L_2 + L_{1L}L_2 + \\ L_{2cq}L_2 + R_{1t}L_{1L}R_{1cq}C_{1L} + R_{1L}L_{2cq}C_{1L}R_{1t})p^2 + (R_{1L}L_2 + R_{1cq}L_2 + R_{1L}R_{1cq}C_{1L}R_{1t} + L_{1L}R_{1t} + L_{2cq}R_{1t})p + \\ R_{1L}R_{1t} + R_{1cq}R_{1t} \end{gathered}}{\begin{gathered} (L_{2cq}C_{1L}L_2 + L_{1L}L_{2cq}C_{1L})p^3 + (R_{1cq}C_{1L}L_2 + L_{2cq}C_{1L}R_{1t} + L_{1L}R_{1cq}C_{1L} + R_{1L}L_{2cq}C_{1L})p^2 + \\ (L_2 + R_{1cq}C_{1L}R_{1t} + R_{1L}R_{1cq}C_{1L} + L_{1L} + L_{2cq})p + R_{1t} + R_{1L} + R_{1cq} \end{gathered}}$$

and

$$Z_0(p) = \frac{\begin{gathered} L_{0L}L_{0cq}C_{0L}L_0p^4 + (L_{0L}R_{0cq}C_{0L}L_0 + R_{0L}L_{0cq}C_{0L}L_0 + L_{0L}L_{0cq}C_{0L}R_{0t})p^3 + (R_{0L}R_{0cq}C_{0L}L_0) + \\ L_{0L}L_0 + L_{0cq}L_0 + R_{0t}L_{0L}R_{0cq}C_{0L} + R_{0L}L_{0cq}C_{0L}R_{0t})p^2 + R_{0L}L_0 + R_{0cq}L_0 + R_{0L}R_{0cq}C_{0L}R_{0t} \\ + L_{0L}R_{0t} + L_{0cq}R_{0t})p + R_{0L}R_{0t} + R_{0cq}R_{0t} \end{gathered}}{\begin{gathered} (L_{0cq}C_{0L}L_0 + L_{0L}L_{0cq}C_{0L})p^3 + (R_{0cq}C_{0L}L_0 + L_{0cq}C_{0L}R_{0t} + L_{0L}R_{0cq}C_{0L} + R_{0L}L_{0cq}C_{0L})p^2 + \\ (L_0 + R_{0cq}C_{0L}R_{0t} + R_{0L}R_{0cq}C_{0L} + L_{0L} + L_{0cq})p + R_{0t} + R_{0L} + R_{0cq} \end{gathered}}$$

Let the fault shunt current be represented by I_{fs}.

The current distribution in different branches of the negative sequence network will be exactly the same as in the Line to Line fault except for the value of Z_f.

The current flowing through ($R_{0t} + L_0 p$) branch of Zero sequence network

$$\frac{I_{fs} N_0''}{(R_{0t} + L_0 p)\, D_0'' + N_0''}$$

where

$$\frac{N_0''}{D_0''} = \frac{L_{0L} L_{0eq} C_{0L} p^3 + (L_{0L} R_{0eq} C_{0L} + R_{0L} L_{0eq} C_{0L}) p^2 + (R_{0L} R_{0eq} C_{0L} + L_{0L} + L_{0eq}) p + R_{0L} + R_{0eq}}{L_{0eq} C_{0L} p^2 + R_{0eq} C_{0L} p + 1}$$

current flowing through ($R_{0L} + L_{0L} p$) branch

$$\frac{I_{fs} (R_{0t} + L_0 p)\, D_0''}{(R_{0t} + L_0 p) D''_0 + N''_0}$$

current flowing through capacitor branch of zero sequence network

$$\frac{I_{fs}\, C_{0L} p\, (R_{0t} + L_0 p)(R_{0eq} + L_{0eq} p)}{(R_{0t} + L_0 p)\, D''_0 + N''_0}$$

Current through ($R_{0eq} + L_{0eq}\, p$) branch will be

$$\frac{I_{fs} (R_{0t} + L_0 p)}{(R_{0t} + L_0 p)\, D''_0 + N''_0}$$

Now the aim is to find the positive, negative and zero sequence voltage when the switch is opened i.e. the fault is cleared.

The form of positive sequence voltage will be exactly same as for 3 phase fault, except for the initial conditions of the currents in different branches. It should again be noted that while writing rather the current flowing through (R_{1t} + L_1p) and R_{1L}+ $L_{1L}p$) branches is i_1, where as in the initial condition they are not same so while putting this initial condition we should break up (R_{1eq} + $L_{1eq}p$) into two portions (R_{1t} + L_1p) and (R_{1L}+ $L_{1L}p$) and put the respective initial condition with of course proper sign.

Similarly this will be the case for negative and zero sequence voltages. Similar equations will be written as in the case of Line to Line fault and hence their values can be found out.

Here it is to be noted that actual value of the denominator for the current expression has not been found out. The reason is that it leads to very lengthy calculations.

L-L-G FAULT (Ref. Fig. 15)

Here $Z_f = \dfrac{Z_0 Z_2}{Z_0 + Z_2}$ where Z_0 and Z_2 have been defined in L-G fault case. The current through fault shunt branch as found in Line to Line fault.

$$\frac{V\,p}{(p^2+w^2)} \; \frac{(N \; (R_{1eq}+L_{1eq}p)(N'C_{11}p+D')+N' \quad (R_{1t}+L_1 p) \; (R_{1t}+L_1 p)(N+DZ_f)+NZ_f}{(R_{1eq}+L_{1eq}p)(N'C_{11}p+D')+N' \quad (R_{1t}+L_1 p)(N+DZ_f)+NZ_f}$$

Let this current be represented by I_{fs} i.e. current through fault shunt branch.

The current distribution in the negative sequence network will be

$I_{fs} \cdot \dfrac{Z_0}{Z_0 + Z_2}$ and that in the zero sequence network.

$I_{fs} \cdot \dfrac{Z_2}{Z_0 + Z_2}$. So current distribution in different branches of the negative sequence network can be found by just multi - plying the different current in the Line to Ground fault condition by the factor $\dfrac{Z_0}{Z_0+Z_2}$ and that in the zero sequence network by $\dfrac{Z_2}{Z_0 + Z_2}$

The form of the positive, negative and zero sequence voltage will be the same as in Line to Ground fault except for the initial value of the current.

CHAPTER IV

TWO MACHINE SYSTEM (SERIES FAULTS)

OPEN CONDUCTOR (Ref. fig. 16) (a)

First of all the steady state value of the current in different parts of the circuit before the fault takes place is found

Let $(R_{1t}+R_{1L}) + j(L_{1g}+L_{1t}+L_{1L})\,w = Z_1$ and

$$\frac{1}{wC_{1L}} = Z_2$$

Let Generator 2 be shorted, the impedance seen by Generator 1.

$$Z_1 + \frac{Z_1 Z_2}{Z_1+Z_2} = \frac{Z_1(Z_1+Z_2) + Z_1 Z_2}{Z_1+Z_2}$$

∴ Current in branch Z_1 near Generator 1 will be

$$\frac{V_m \operatorname{Cos} wt.\ (Z_1+Z_2)}{Z_1(Z_1+Z_2) + Z_1 Z_2}$$

∴ Current in Z_2 branch

$$\frac{V_m \operatorname{Cos} wt}{Z_1 + 2Z_2}$$

Similarly current in Z_1 branch near Generator 2 will be

$$\frac{V_m \operatorname{Cos} wt}{Z_1(Z_1+Z_2) + Z_1 Z_2} \cdot Z_2$$

When generator 1 is shorted the impedance seen by Generator 2 will again be the same i.e. $\dfrac{Z_1(Z_1+Z_2) + Z_1 Z_2}{Z_1 + Z_2}$

∴ Current in branch Z_1 near Generator 2 will be

$$\frac{V_m \operatorname{Cos}(wt - \lambda)(Z_1+Z_2)}{Z_1(Z_1+Z_2) + Z_1 Z_2}$$

∴ Total current in this branch will be

$$\frac{1}{Z_1(Z_1+Z_2) + Z_1Z_2} \left\{ Z_2 V_m \cos wt - (Z_1+Z_2) V_m \cos(wt - \lambda) \right\}$$

Current in Z_2 branch due to generator 2 will be

$$\frac{V_m \cos (wt - \lambda)}{Z_1 + 2Z_2}$$

$\therefore$ Total current in Z_2 branch

$$\frac{1}{Z_1 + 2Z_2} \left\{ V_m \cos wt + V_m \cos (wt - \lambda) \right\}$$

Current in Z_1 branch near Generator 1 due to Generator 2 will be

$$\frac{Z_2 \; V_m \cos (wt - \lambda)}{Z_1(Z_1+Z_2) + Z_1 Z_2}$$

$\therefore$ Total current in this branch

$$\frac{1}{Z_1(Z_1+Z_2)+ Z_1Z_2} \left\{ (Z_1+Z_2) V_m \cos wt - Z_2 \; V_m \cos (wt - \lambda) \right\}$$

Here it is assumed that both the generators are ungrounded so that $Z_0(p) = \infty$

This assumption has been made just to simplify the calculations. With this it is possible to illustrate as to how to calculate the voltage rises. With this assumption only one open conductor condition need be considered. Otherwise if the generators are grounded, the equivalent series impedance for one open conductor will be

$$\frac{Z_0 Z_2}{Z_0 + Z_2}$$ and for two open conductors it will be

$$Z_0 + Z_2$$

Let the fault be anywhere on the transmission line, the equivalent series impedance will be the same as it is a symmetric circuit.

$$Z_2(p) = \frac{L^2_{2eq} C_{1L} p^3 + (R_{1eq} L_{2eq} C_{1L} + R_{1eq} C_{1L} L_{2eq})p^2 + (R^2_{1eq} C_{1L} + 2L_{2eq})p + 2R_{1eq}}{L_{2eq} C_{1L} p^2 + R_{1eq} C_{1L} p + 1}$$

The equivalent circuit for one open conductor will be(Ref.fig. 16 b)

After a time t_1 the fault has occurred let the voltages of the two generators be $V_m \operatorname{Cos}(wt + \alpha)$ and $V_m \operatorname{Cos}(wt + \alpha - \lambda) = V_m \operatorname{Cos}(wt + \gamma)$ and writing equations for the two loops.

$$R_{1eq} i_1 + L_{1eq} \frac{di_1}{dt} + \frac{1}{C_{1L}} \int (i_1 + i_2)dt = V_m \operatorname{Cos}(wt + \alpha)$$

$$R'_{1eq} i_2 + L'_{1eq} \frac{di_2}{dt} + \frac{1}{C_{1L}} \int (i_1 + i_2)\, dt = V_m \operatorname{Cos}(wt + \gamma)$$

Taking laplace transform of both the equations and after certain simplifications

$$a\, I_1(p) + I_2(p) + K = 0$$

$$I_1(p) + bI_2(p) + K' = 0$$

$$\therefore \frac{I_1(p)}{K' - bK} = \frac{I_2(p)}{K - aK'} = \frac{1}{ab - 1}$$

$$I_2(p) = \frac{K - aK'}{ab - 1} \text{ and } I_1(p) = \frac{K' - bK}{ab - 1}$$

The positive sequence voltage across generator 1 will be

$$I_1(p) \left[R_{1eq} + L''_{1eq} p \right] + \left[I_1(p) + I_2(p) \right] \frac{1}{C_{1L} p}$$

$$= I_1(p) \left[R_{1eq} + L''_{1eq} p + \frac{1}{C_{1L} p} \right] + \frac{I_2(p)}{C_{1L} p}$$

Ref. fig. The current flowing through generator 1 branch

$$\frac{I_2(p)}{R_{1eq} C_{1L} p + L_{2eq} C_{1L} p^2 + 1}$$

$\therefore$ The negative sequence voltage drop will be

$$= \frac{I_2(p)}{R_{1eq}C_{1L}p + L_{2eq}\,C_{1L}\,p^2 + 1} \cdot L_{2g}p$$

$\therefore$ Total voltage across the terminals of the generator 1.

$$\frac{I_1(p)\,[R_{1eq}\,C_{1L}p + L''_{1eq}\,C_{1L}p^2 + 1\,] + I_2(p)}{C_{1L}p} - \frac{I_2(p)\,L_{2g}p}{R_{1eq}C_{1L}p + L_{2eq}C_{1L}\,p^2\,1}$$

$$\frac{I_1(p)}{C_{1L}p}\,[R_{1eq}C_{1L}p + L''_{1eq}\,C_{1L}p^2 + 1\,] + I_2(p)\,\left[\frac{R_{1eq}\,C_{1L}p + L_{2eq}\,C_{1L}p^2 - L_{2g}\,C_{1L}\,p^2 + 1}{C_{1L}p\,[R_{1eq}C_{1L}p + L_{2eq}C_{1L}\,p^2 + 1\,]}\right]$$

Where $K' = C_{1L}p\left\{\left[\frac{q_1(0)+q_2(0)}{p} - L'_{1eq}i_1(0)\right] - \left[\frac{V_m p\,\cos\gamma}{p^2 + w^2} - \frac{V_m \sin\gamma\,w}{p^2 + w^2}\right]\right\}$

$$K = C_{1L}p\left\{\left[\frac{q_1(0) + q_2()}{p} - L_{1eq}\,i_1(0)\right] - \left[\frac{V_m\,p\,\cos\alpha}{p^2 + w^2} - \frac{V_m\,\sin\alpha\,w}{p^2 + w^2}\right]\right\}$$

$$a = R_{1eq}\,C_{1L}p + L_{1eq}C_{1L}\,p^2 + 1$$

$$b = R'_{1eq}\,C_{1L}p + L'_{1eq}\,C_{1L}p^2 + 1$$

and $L''_{1eq} = (L_{1t} + L_{1L}\,)$

CHAPTER V

THREE PHASE FAULT ON AN IDEAL LONG TRANSMISSION LINE.

THREE FACE FAULT ON AN IDEAL LONG TRANSMISSION LINE : (Ref. fig 17)

The following two electrostatic and electromagnetic flux equation are well known.

$d\psi = ec\, dx$ and

$d\phi = iL\, dx$

Now the voltage drop in the positive direction of x of the element dx due to d and the line resistance is

$$-de = -\frac{\partial e}{\partial x}\, dx = iR\, dx + \frac{\partial}{\partial t}(d\phi) = (R + L\frac{\partial}{\partial t})\, i\, dx$$

Here negative sign has been assigned because it is a drop in the voltage similarly

$$-di = -\frac{\partial i}{\partial x} dx = eG\, dx + \frac{\partial}{\partial t}(d\psi) = (G + C\frac{\partial}{\partial t})\, e\, dx$$

$$\text{or} -\frac{\partial e}{\partial x} = (R + Lp)i = Z\, i \quad \text{and} \quad \text{———}(3)$$

$$-\frac{\partial i}{\partial x} = (G + Cp)\, e = Ye \quad \text{———}(4)$$

Equation (3) and (4) are well known equations of single circuit transmission line. Differentiating (3) with respect to x and substituting (4)

$$\frac{\partial^2 e}{\partial x^2} = -Z\frac{\partial i}{\partial x} = YZe = [RG + (RC + GL)p + LCp^2]\, e \quad \text{——}(5)$$

Now for loss less line R = 0 G = 0

$$\therefore \quad \frac{\partial^2 e}{\partial x^2} = LC \cdot \frac{\partial^2 e}{\partial t^2} \quad \text{———}(6)$$

$$\text{or} \quad \frac{\partial^2 V}{\partial x^2} = LC\frac{\partial^2 V}{\partial t^2} \quad \text{———}(7)$$

$$\therefore V = (A_1 e^{\sqrt{LC}px} + A_2 e^{-LC\ px}) \text{———}(8)$$

or $\bar{V} = V_x \; V(p)$ ———(10)

and $\frac{\partial^2 V}{\partial x^2} = V_t \frac{\partial^2 V_x}{\partial x^2}$ ——(11) and $\frac{\partial^2 V}{\partial t^2} = V_x \frac{\partial^2 V_t}{\partial t^2}$ ——(12)

$V(p) \frac{\partial^2 V_x}{\partial x^2} = LC \, Vx \, p^2 \, V(p)$

or $\frac{\partial^2 V_x}{\partial x^2} = LC \, V_x \, p^2$

or $V_x = (A_1 e^{\sqrt{LC}\,px} + A_2 e^{-\sqrt{LC}\,px})$

$\therefore \bar{V} = (A_1 e^{\sqrt{LC}\,px} + A_2 e^{-\sqrt{LC}\,px}) \, V(p)$

At $x = 0$ $\bar{V} = (A_1 + A_2) \cdot \frac{p}{p^2 + w^2} = \frac{V_m \, p}{p^2 + w^2}$

$\therefore A_1 + A_2 = V_m$

At $x = l$ $A_1 e^{\sqrt{LC}\,pl} + A_2 e^{-\sqrt{LC}\,pl} = 0$

$A_1 e^{\sqrt{LC}\,pl} + (V_m - A_1) e^{-\sqrt{LC}\,pl} = 0$

$\therefore A_1 = \frac{V_m e^{-2\sqrt{LC}\,pl}}{e^{-2\sqrt{LC}\,pl} - 1}$

$A_2 = \frac{V_m}{1 - e^{-2\sqrt{LC}\,pl}}$

Now $L \frac{\partial i}{\partial t} = \frac{\partial V}{\partial x}$ or $L\,pi = \frac{\partial V}{\partial x}$

or $i = \frac{1}{Lp} \cdot \frac{\partial V}{\partial x}$

$I(p) = \frac{1}{Lp} \frac{\partial \bar{V}}{\partial x}$

$$Now\ I(p) = \frac{1}{Lp}\left[\sqrt{LC}\ p \cdot A_1 e^{\sqrt{LC}\ pl} - \sqrt{LC}\ p\ A_2 e^{-\sqrt{LC}\ pl}\right] \cdot \frac{p}{p^2+w^2}$$

$$= V_m \sqrt{\frac{C}{L}} \left(\frac{e^{-2\sqrt{LC}\,pl}\ e^{\sqrt{LC}\,pl}}{e^{-2\sqrt{LC}\,pl}-1} + \frac{e^{-\sqrt{LC}\,pl}}{e^{-2\sqrt{LC}\,pl}-1} \right) \frac{p}{p^2+w^2}$$

$$= V_m \sqrt{\frac{C}{L}} \cdot \frac{1}{\sinh ap} \cdot \frac{p}{p^2+w^2}$$

Multiplying this by p to change it to Heaviside operator so that it is possible to use Heaviside expansion theorem to solve it.

$$Let\ F(p) = \frac{1}{\sinh ap} \cdot \frac{p^2}{p^2+w^2}$$

$$= \frac{1}{\sinh ap + \frac{w^2}{p^2} \sinh ap}$$

Let $p = jm \quad \therefore \quad dp = jdm$

$$Z(p) = \sin am - \frac{w^2}{m^2} \cdot \sin am$$

$$or \quad \frac{Y(p)}{Z(p)} = \frac{-1}{+\sin am + \frac{w^2}{m^2} \sin am}$$

$$m = \frac{s\pi}{a}$$

$$\therefore \quad p_1 = \frac{j\pi}{a} \qquad p_2 = \frac{2j\pi}{a} \qquad p_3 = \frac{3j\pi}{a}$$

$$Also\ \frac{dZ}{dp} = \frac{dZ}{dm} \cdot \frac{dm}{dp} = -j\frac{dZ}{dm}$$

$$\frac{dZ}{dm} = -a\cos am + w^2 \left[\frac{am^2 \cos am - \sin am \cdot 2m}{m^4} \right]$$

$$= a \cos am \left(\frac{w^2}{m^2} - 1 \right) - \frac{2w^2}{m^3} \sin am$$

$$\therefore \frac{dZ}{dp} = \frac{j\,2w^2 \sin am}{m^3} - j\,a \cos am \left(\frac{w^2}{m^2} - 1 \right)$$

$$p \frac{dZ}{dp} = am \cos am \left(\frac{w^2}{m^2} - 1 \right) - \frac{2\,w^2}{m^2} \sin am$$

$$\left(p \frac{dZ}{dp} \right)_{p = ps} = (-1)^s\, a \,.\, \frac{s\pi}{a} \left[\frac{w^2}{\left(\frac{s\pi}{a}\right)^2} - 1 \right]$$

$$y = - \sum_{s=1}^{\infty} \frac{(-1)^s \, e^{j \frac{s\pi}{a} t}}{s\pi \left[\frac{w^2}{\left(\frac{s\pi}{a}\right)^2} - 1 \right]} + \left[\frac{Y(p)}{Z(p)} \right]_{p=0}$$

Now if we substitute directly $p = 0$ in the expression for $\frac{Y(p)}{Z(p)}$ we find it gives an indeterminate quantity

So applying La Hospitals Theorem

We have $$\frac{Y(p)}{Z(p)} = \frac{p^2}{p^2 + \sinh ap + w^2 \sinh ap}$$

Differentiating Numerater & denominator seperately

$$\text{Limit}_{p \to 0} \frac{2p}{\sinh ap \,.\, 2p + p^2 \,.\, a \cosh ap + w^2\, a \cosh ap}$$

$$= \frac{0}{w^2\, a} = 0$$

So the limiting value of $\frac{Y(p)}{Z(p)}$ for $p = 0$ is zero

$\therefore$ The solution to the above current expression in time domain will be

$$Y = - \sum^{\infty} \frac{(-1)^s \, e^{j \frac{s\pi}{a} t}}{}$$

CALCULATIONS

It is desirable now to do calculation part in which the p.u. values of different elements of the power system are substituted in the current (under fault condition) expressions and thus the presence of different frequencies in the current will be studied.

The following set of values will be used:-

Total line impedance $= 10.3 \angle 80^\circ$

$\therefore$ Reactance 10.15 and resistance = 1.8 Ω

Let the usual transmission line reactance be 0.2 p.u.

Then $L_k = L_{21} = 0.2$ p.u. and $R_k = R_{11} = 0.0355$ p.u.

Line Zero sequence resistance and reactance :- Let neutral impedance be $2 \angle 80$ then total impedance

$10.3 + 2 \times 3 = 16.3\ \Omega$

$\therefore$ Total reactance = 16 and resistance 2.82 Ω

$\therefore$ $R_{01} = 0.055$ p.u. and $L_{01} \equiv 0.315$ p.u.

For Transformer $X_1 = X_2 = X_0 = 0.1$ p.u.

$R_{0t} = R_{1t} = R_{2t} = 0.025$ p.u.

For generator $X'd = 0.25$ p.u. $X_2 = 0.15$ p.u. $X_0 = 0.1$ p.u.

Now let the condenser value be 2.5 μF when we consider transmission line represented by a π circuit and 5 μF when T - circuit.

Actual value of reactance $\dfrac{10^6}{314 \times 2.5} = 1325\ \Omega$

Base value $= 50.75\ \Omega$

$\therefore$ p.u. capacitance value will be 26.1 p.u.

$\therefore$ when 5 μF unit will be 13.05 p.u. $\simeq$ 13 p.u.

FAULT AT THE SENDING END (One machine system)

<u>3 PHASE FAULT</u>

The current contains only the power frequency and natural frequency of the system. The recovery voltage expression contains the expression.

$9.15\ p^2 + 0.625\ p + 1$

which has its roots as

$-0.03562842 + j\ 0.32866432$ and

$-\ 0.03562842 - j\ 0.32866432$

The imaginary part of it shows the p.u. natural frequency present

L-L fault

ii) The current contains the expression

$4.5675\ p^3 + 0.783\ p^2 + 0.600125p + 0.05$ and its roots are

$-\ 0.08824612,\ -\ 0.04159122 - j\ 0.34974262,$

$-\ 0.04159122 + j\ 0.34974262$

iii) LINE TO GROUND FAULT

$35.763525\ p^5 + 10.60133\ p^4 + 10.69143\ p^3 + 2.1199319\ p^2 + 0.647875p + 0.075$

The roots are

$-0.13787595 + j\ 0.00000003,\ -\ 0.03786460 - j\ 0.27941236$

$-0.03786460 + j\ 0.27941236,\ -\ 0.04141172 + j\ 0.43542540$

$-\ 0.04141172 - j\ 0.4354254$

iv) L-L-G FAULT

$0.137025\ p^4 + 0.19020375\ p^3 + 0.16182025\ p^2 + 0.041223437\ p + 0.001875$

The roots are

$-0.05770552_{\text{}} - 0.1282195,\ -0.08875 - j\ 0.61379054$

Fault at the far end

i) 3 Phase fault;

$$1.43p^3+0.411125\ p^2+0.77792075\ p+0.096$$

The roots are

$-0.06070988+j\ 0.38775092\quad -0.06078986-j\ 0.38775092\quad -0.13737775$

ii) Line to Line fault;

$$16.731\ p^5+7.0595525\ p^4+12.6355974\ p^3+3.1691193397\ p^2+1.6068495\ p+0.192$$

$-0.15490199,\ -0.08149348+j\ 0.73186364,\ -0.08149348-j\ 0.73186364$

$-0.07831824+j\ 0.59720536,\ -0.07831823-j\ 0.59720535$

iii) LINE TO GROUND FAULT;

$$200.2251054\ p^7+115.35598622\ p^6+181.4330957\ p^5+68.9067696\ p^4+$$
$$43.3285516\ p^3+9.802095593\ p^2+2.84578265\ p+0.2915$$

The roots are

$-0.06380900-j\ 0.35681155,\quad -0.07681173-j\ 0.68452191$

$-0.06380900+j\ 0.35681155,\quad -0.07681173+j\ 0.68452191$

$-0.08118575+j\ 0.41187470,\quad -0.13251883$

$-0.08118575-j\ 0.41187470,$

iv) L-L-G fault;

$$46.485828675\ p^8+33.34922345\ p^7+61.79253185\ p^6+45.55875759\ p^5+$$
$$25.783635\ p^4+9.995528668\ p^3+4.004068623\ p^2+0.6695049\ p+0.204103$$

The roots are

0.07262845 - j 0.95005359, - 0.4208328 + j 0.29492421

0.07262845 + j 0.95005359, - 0.4208328 - j 0.29492421

0.3535678 + j 0.38144865, - 0.04585556 + j 0.35025670

0.03535678 - j 0.38144865, - 0.04585556 - j 0.35026671

Two machine system

L-L fault:- The current expression contains two terms i.e. multiplication of two terms and they are

$2.4678235\, p^7 + 1.554089\, p^6 + 2.3623864\, p^5 + 1.0204993\, p^4 + 0.53451288\, p^3 + 0.153364057\, p^2 + 0.0168342\, p + 0.005808$

and

$2.4678325\, p^7 + 1.554060475\, p^6 + 2.48750555\, p^5 + 1.0634429\, p^4 + 0.66893982\, p^3 + 0.1796041\, p^2 + 0.05474388\, p + 0.005268$

and their respective roots are

- 0.11876120, - 0.06624833, - 0.20372836,

- 0.03391568 + j 0.52350846, - 0.08391168 - j 0.72558409

- 0.3391568 - j 0.52350846, - 0.08391167 + j 0.72558408

and

-0.12816721, - 0.17673490 + j 0.34445746, 0.00750502 + j 0.45484516

- 0.17673490 - j 0.34445746, 0.00750502 - j 0.45484516

- 0.08155123 - j 0.72822859 , - 0.08155123 + j 0.72822859

L-G fault;- This again contains two terms

$6.8765427\ p^{10} + 618542812\ p^{9} + 11.2009\ p^{8} + 7.56185367\ p^{7} + 6.6824317\ p^{6} +$

$2.6316559\ p^{5} + 0.93168308\ p^{4} + 0.2053214\ p^{3} + 0.04877394\ p^{2} + 0.00390122\ p +$

0.000136533

and their respective roots are

$-0.05197898 - j\ 0.0286876,\ - 0.22807192 - j\ 0.24552475$

$-0.05197898 + j\ 0.0286876,\ - 0.22807192 + j\ 0.24552475$

$- 0.04427291 - j\ 0.28540490\ ,\ - 0.41533085 - j\ 0.73042203$

$0.04427291 = j\ 0.28540490,\ - 0.41533085 + j\ 0.73042203$

$0.15275007 - j\ 0.84172047$

$0.15275007 + j\ 0.84172047$

and

$- 0.07951083,\ 0.11660599,\ - 0.14365233,\ - 0.20793618 - j\ 0.00000003$

$- 0.03118903 - j\ 0.47636259,\ - 0.11443015 + j\ 0.57816419$

$- 0.03118903 + j\ 0.47636259,\ - 0.11443015 - j\ 0.57816419$

$- 0.04290329 - j\ 0.71377517$

$- 0.04290379 + j\ 0.71377574$

L-L-G fault; This again contains two terms;

$1.54566\ p^{11} + 1.5294501\ p^{10} + 2.63548869\ p^{9} + 1.9022957\ p^{8} + 2.59996988\ p^{7} +$

$1.228066\ p^{6} + 0.6304533\ p^{5} + 0.23823835\ p^{4} + 0.0508173\ p^{3} + 0.01671314\ p^{2} +$

$0.00245794\ p + 0.0000776328$

and

$1.54566412\ p^{11} + 1.52944736\ p^{10} + 2.6354852\ p^{9} + 1.911165\ p^{8} + 1.489592\ p^{7} +$

$1.10592486\ p^{6} + 0.36428509\ p^{5} + 0.2013725\ p^{4} + 0.0315514\ p^{3} + 0.0023614897\ p^{2} +$

$0.000213359\ p + 0.0000116451$

and their roots are

$-0.04262111,\ -0.15333863,\ -0.37283631$

$0.09551746 - j\ 0.30139859,\quad -0.5235553 + j\ 0.44033870$

$0.09551746 + j\ 0.30139859,\quad -0.5235553 - j\ 0.44033870$

$0.36391258 - j\ 0.9103144,\quad -0.61743288 + j\ 0.84249563$

$0.36391258 + j\ 0.9103144,\quad -0.61743288 - j\ 0.84249563$

and

$-0.09608214,\ -0.10582475,\ -0.01346703 - j\ 0.52780009$

$0.01058160\ + j0.08559195\quad -0.01346703 + j\ 0.52780009$

$0.01058160\ + j0.08359195\quad -0.38621206 + j\ 0.91911762$

$0.24733754 + j\ 0.69735973\quad -0.28621206 - j\ 0.91911762$

$0.24733754 - j\ 0.68735973\quad -0.70408142$

```
C   C 9ROOTS OF POLYNOMIAL EQUATION OF DEGREE N WITH COMPLEX COEFFI.IEN
      DIMENSION AR(129), AI(129)
 1    READ 700, N,IM
      NUTS= 1111
      M=N+1
      DO 2 J=1,M
      READ 701,AR(J)
      IF (SENSE SWITCH 3) 21,2
 21   PRINT 701, AR(J)
 2    CONTINUE
      DO 30 J=1,M
      IF (IM)24,23,24
 24   READ 701,AI(J)
      GO TO 26
 23   AI(J) =0.0
 26   IF (SENSE SWITCH 3) 25,30
 25   PRINT 701, AI(J)
 30   CONTINUE
 5    KOUNT =0
      TOL= 1.E-10
      ITR8= 50
      P1R =AR(N+1)+AR(N)+AR(N-1)
      P1I =AI(N+1)+AI(N)+AI(N-1)
      P2R =AR(N+1)
      P2I =AI(N+1)
      U =AR( N )**2-AI( N )**2-4.0*(AR(N-1)*AR(N+1)-AI(N-1)*AI(N+1))
      V= 2.0*AR(N)*AI(N)-4.0*(AR(N-1)*AI(N+1)+AI(N-1)*AR(N+1))
      Q=AR(N)
      R=AI(N)
      KRAD=1
  500 TEMP=SQRTF(U*U+V*V)
      IF (TEMP+U) 5001,5001,5002
 5001 RADR= 0.0
      GO TO 5003
 5002 RADR=SQRTF(TEMP+U)
 5003 IF (TEMP -U) 5004,5004,5005
 5004 RADI= 0.0
      GO TO 5006
 5005 RADI=SQRTF(TEMP-U)
 5006 TEMP= Q*RADR+R*RADI
      IF (TEMP) 501,501,502
 501  RADR= Q-RADR/1.4142135
      RADI= R-RADI/1.4142135
      GO TO 503
 502  RADR= Q+RADR/1.4142135
      RADI= R+RADI/1.4142135
 503  GO TO ( 50,526) , KRAD
 50   TEMP=RADR**2+RADI**2
      IF (TEMP) 510,510,511
 510  XR= .5
      XI= 0.0
      GO TO 512
 511  XR =-2.0*(AR(N+1)*RADR+AI(N+1)*RADI)/TEMP
      XI= -2.0*(AI(N+1)*RADR-AR(N+1)*RADI)/TEMP
 512  HR= XR
      HI=XI
      WR=-XR
      WI=-XI
 51   KPOLY=2
 41   M=N+1
      PR= AR(1)
      PI= AI(1)
      DO 42 J=2,M
```

```
      IF(ABSF(PR)+ABSF(PI)-1.E48)42,42,420
42     CONTINUE
420    GO TO (43,504,527) , KPOLY
 504 TEMP = (ABSF(PR)+ABSF(PI))/(ABSF(P2R)+ABSF(P2I))
       IF (TEMP-10.) 505,505,506
506    WR= .5*WR
       WI= .5*WI
       HR=-WR
       HI=-WI
       XR=HR
       XI=HI
       GO TO 51
505    P3R=PR
       P3I=PI
  52 DEN = ABSF(P3R) + ABSF(P3I)
       IF (DEN) 71,71,5211
5211   XRO=XR
       XIO=XI
      IF (ABSF(P1R-P2R)-1.E-25) 521,521,525
 521 IF (ABSF(P1I-P2I)-1.E-25) 522,522,525
 522 IF (ABSF(P1R-P3R)-1.E-25) 523,523,525
 523 IF(ABSF(P1I-P3I)-1.E-25)524,524,525
524    WR=1.0
       WI=0.0
       GO TO 53
525    TEMP=WR+1.0
       DR=TEMP*P3R-WI*P3I
       DI=TEMP*P3I+WI*P3R
       Q= TEMP*P2R-WI*P2I
       R= TEMP*P2I+WI*P2R
       TEMP= WR*P1R-WI*P1I-Q+P3R
       FI= WR*P1I+WI*P1R-R+P3I
       FR= WR*TEMP-WI*FI
       FI= WR*FI+WI*TEMP
       Q=FR-Q+DR
       R=FI-R+DI
       U= Q*Q-R*R-4.0*(DR*FR-DI*FI)
       V= 2.0*Q*R-4.0*(DR*FI+DI*FR)
       KRAD=2
       GO TO 500
526    TEMP= RADR**2+RADI**2
       WR = -2.0*(DR*RADR+DI*RADI)/TEMP
       WI= -2.0*(DI*RADR-DR*RADI)/TEMP
53     HRO=HR
       HIO=HI
       HR= WR*HRO-WI*HIO
       HI= WR*HIO+WI*HRO
       XR= HR+XRO
       XI= HI+ XIO
       KPOLY=3
       GO TO 41
 527 TEMP = (ABSF(PR)+ABSF(PI))/DEN
       IF (TEMP-10.) 6,6,528
528    WR=0.5*WR
       WI=0.5*WI
       HR=HRO
       HI=HIO
       GO TO 53
6      KOUNT =KOUNT+1
      TEST = ABSF(XR-XRO)+ABSF(XI-XIO)
      TEMP = ABSF(XR)+ABSF(XI)
```

```
      IF (TEMP-1.0) 62,62,61                                    1
61    TEST= TEST/TEMP                                           1
62    IF (TEST-TOL) 7,7,64                                      1
64    P1R=P2R                                                   1
      P1I=P2I                                                   1
      P2R=P3R                                                   1
      P2I=P3I                                                   1
      P3R=PR                                                    1
      P3I=PI                                                    1
      IF (KOUNT-ITR8)52,542,542                                 1
542   PRINT 703, ITR8                                           1
      PAUSE                                                     1
      IF (SENSE SWITCH 2) 543,544                               1
543   ITR8= ITR8+10                                             1
      TOL= TOL*10.                                              1
      PRINT 703, ITR8, TOL                                      1
      GO TO 52                                                  1
544   PRINT 703, ITR8                                           1
      PAUSE                                                     1
      IF (SENSE SWITCH 2) 71, 545                               1
545   PRINT 703, ITR8                                           1
     GO TO 1                                                    1
  71 KPOLY=1
      GO TO 41                                                  2
43    PUNCH 702, XR,XI,PR,PI                                    2
     IF(N-1)9,9,3
   3  M= N+1                                                    1
      DO 76 J=2,M                                               1
      AR(J)= AR(J)+XR*AR(J-1)-XI*AI(J-1)                        1
76    AI(J)= AI(J)+XR*AI(J-1)+XI*AR(J-1)                        1
      REMR=AR(M)                                                1
      REMI= AI(M)                                               1
      N=N-1                                                     1
      IF (N-1) 9,81,5                                           1
81    TEMP= AR(1)**2+AI(1)**2                                   1
      XR= -(AR(2)*AR(1)+AI(2)*AI(1))/TEMP                       1
      XI=  (AR(2)*AI(1)-AI(2)*AR(1))/TEMP                       1
      KPOLY =1                                                  2
      GO TO 41                                                  5
9     NUTS= 9999                                                1
      PRINT 703, NUTS                                           1
      GO TO 1                                                   1
 700 FORMAT(I3,I1)
 701 FORMAT(F16.8)
 702 FORMAT(4F16.8)
 703 FORMAT(I5,2E16.8)
 705 FORMAT(2I5,2E16.8)
      END                                                       2
```

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i) Travelling waves on Transmission System
by L.V.Bewely

ii) Transients in Power System
by Harold A. Peterson

iii) Power System Transients
Edited by Openshaw Taylor

iv) Transient Phenomena in Electrical
Power Systems

By Venikov

v) Transient performance of Electric power
Systems ~~s~~
By Rudenberg.

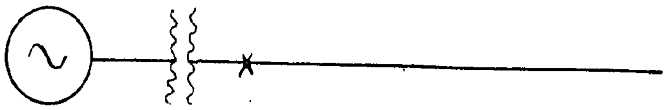

FIG. 1. (a)

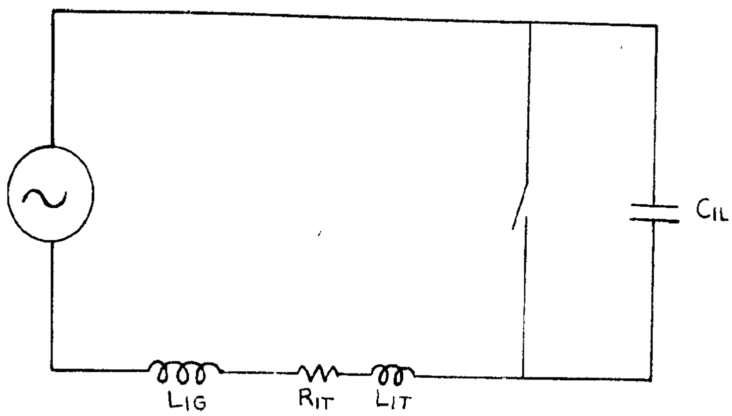

FIG 1. (b)

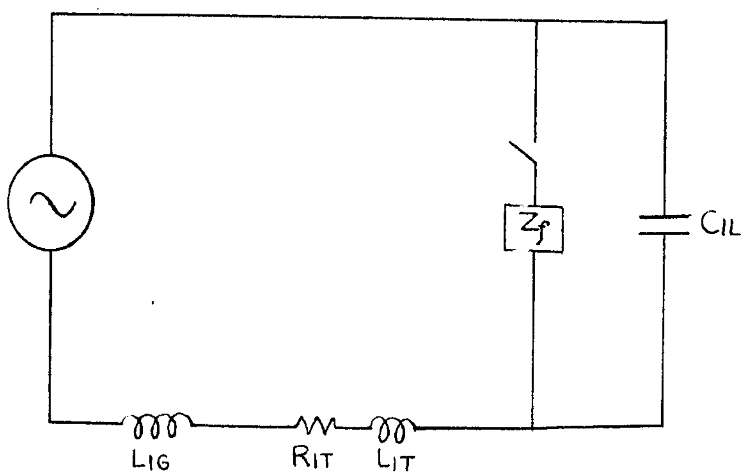

FIG. 2

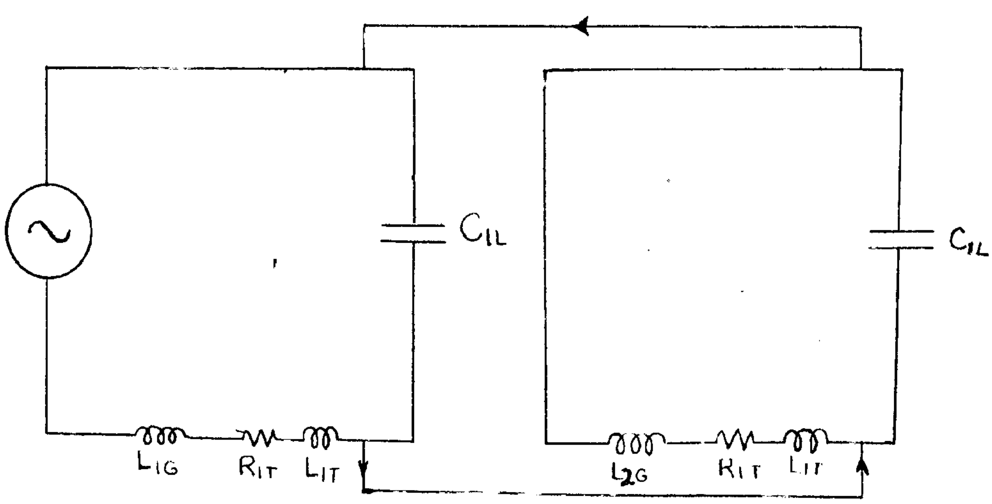

FIG. 3

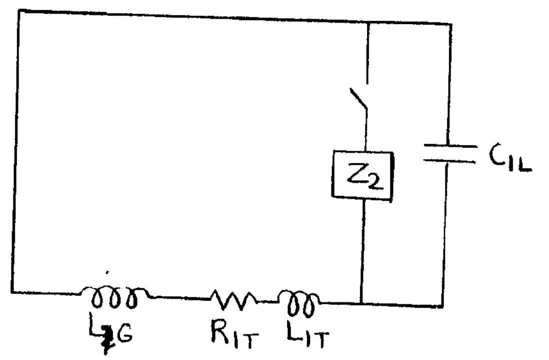

FIG. 3 a

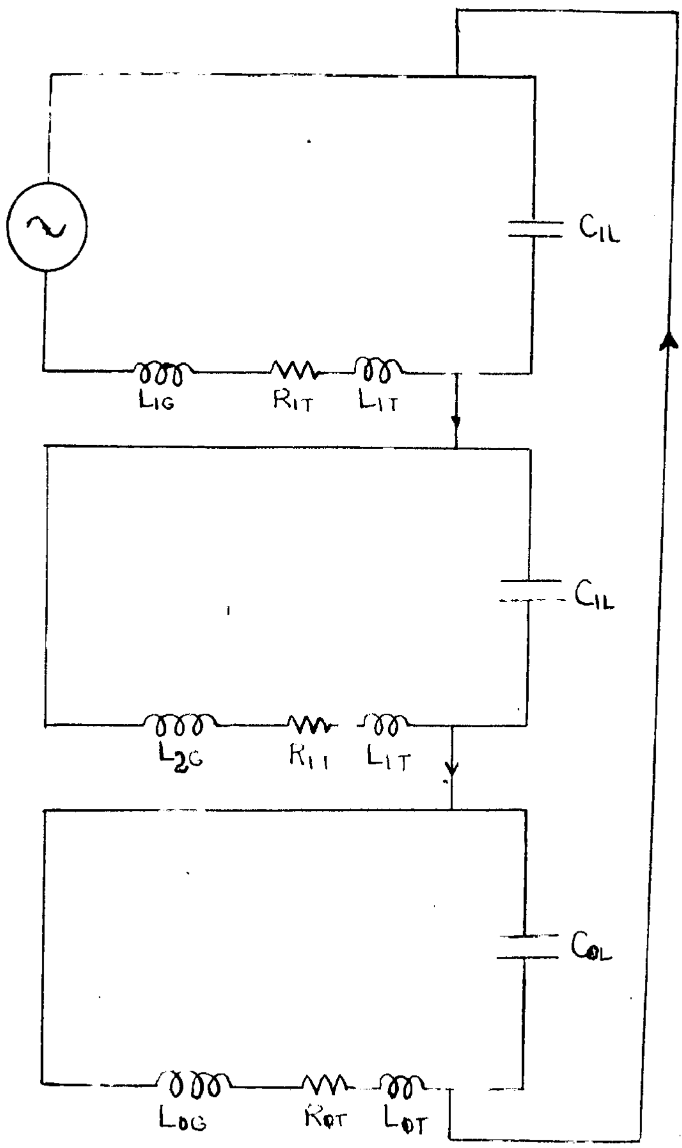

FIG. 4

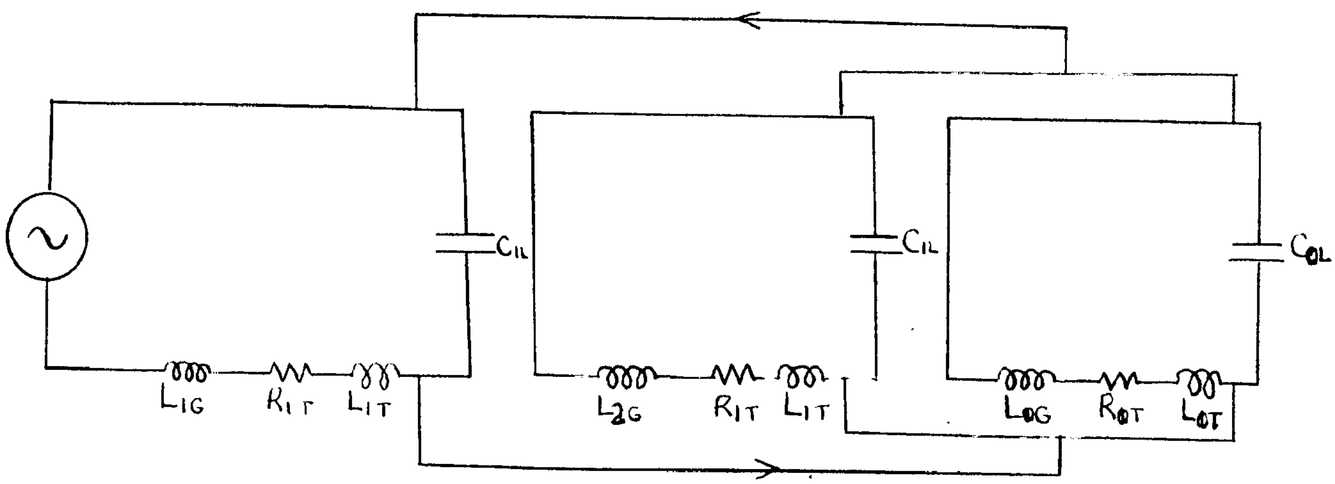

FIG 5

FIG. 6 (a)

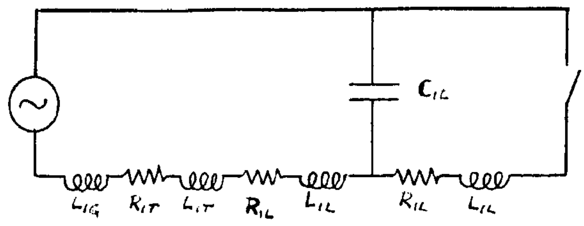

FIG 6(b)

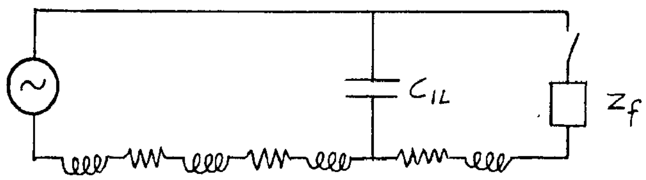

FIG. 7

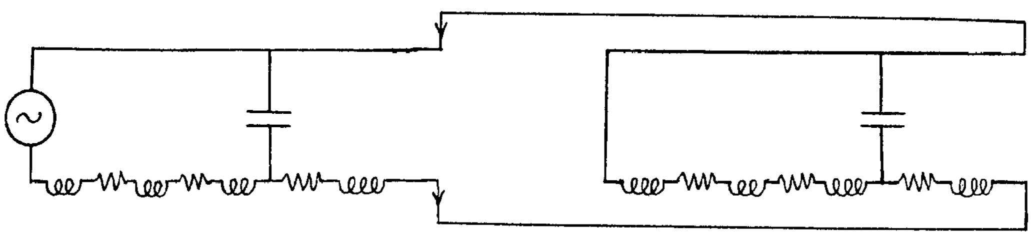

FIG. 8

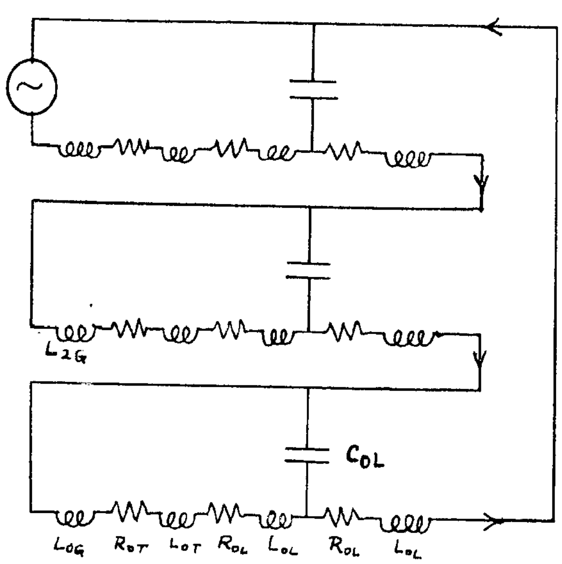

FIG. 9

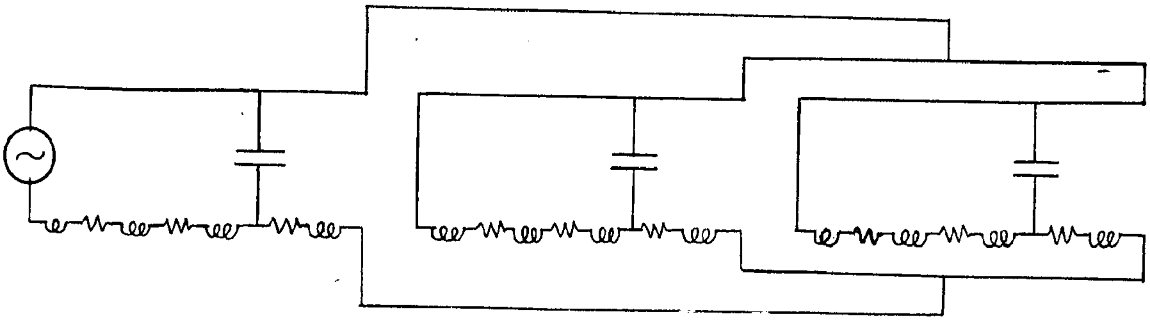

FIG. 10

FIG 11 (a)

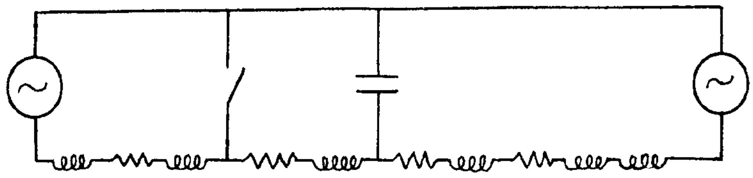

FIG. 11 (b)

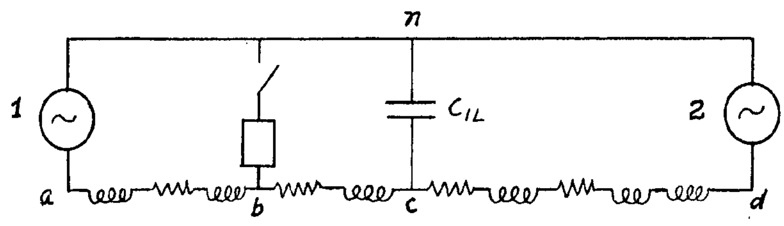

FIG 12

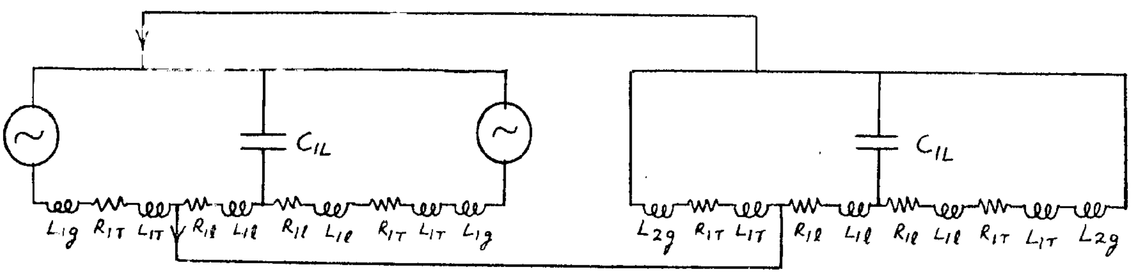

FIG 13

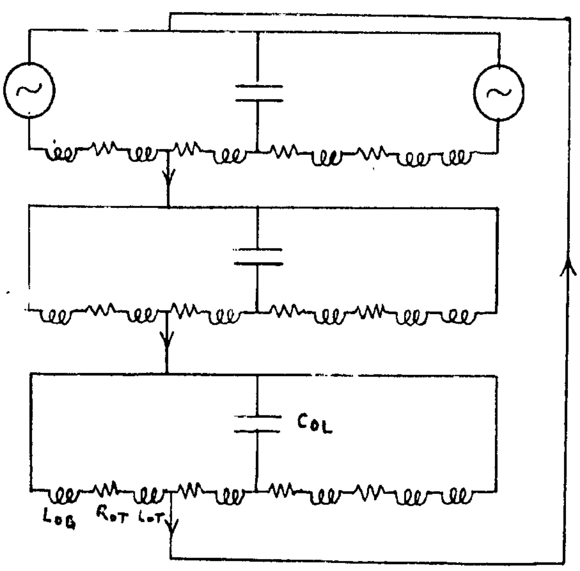

FIG. 14

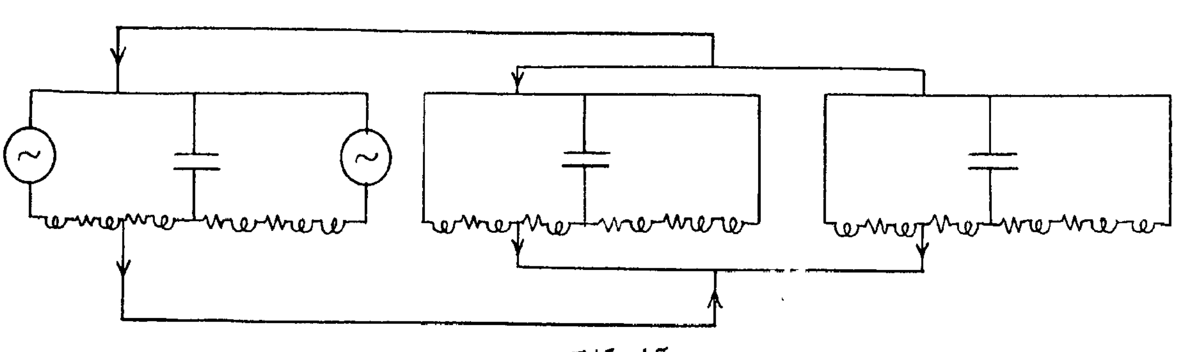

FIG 15

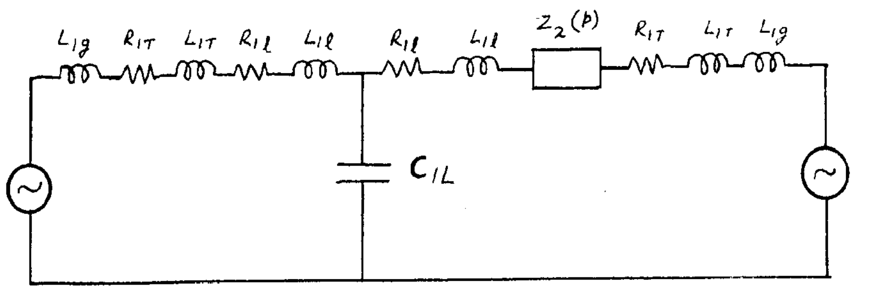

FIG 16 (a)

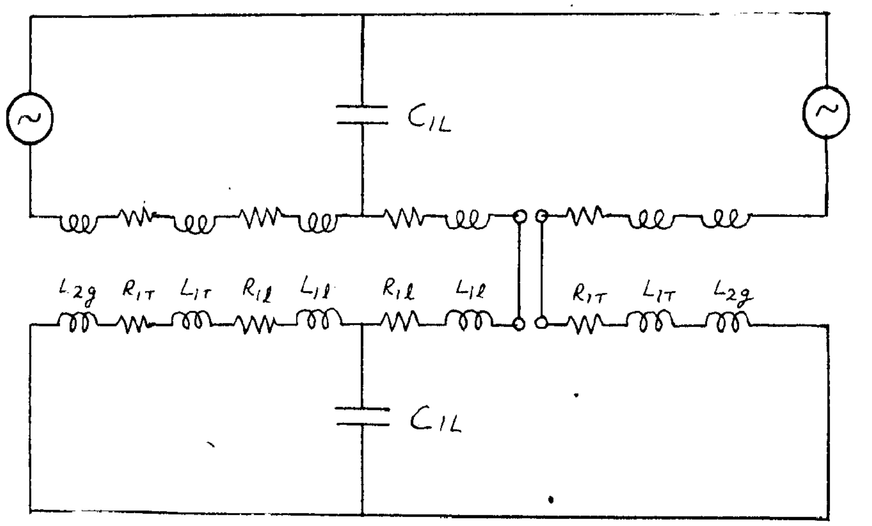

FIG 16(b)

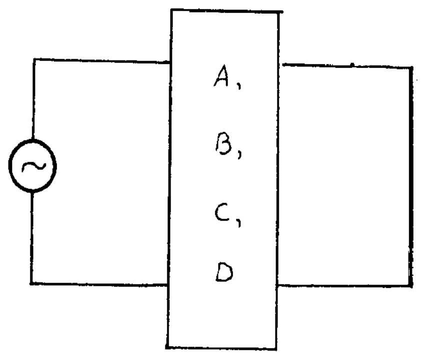

FIG. 17