Module 3 : Sequence Components and Fault Analysis

Lecture 12 : Sequence Modeling of Power Apparatus

Objectives

In this lecture we will discuss

- Per unit calculation and its advantages.
- Modeling aspects of static apparatus like transmission line and transformers.
- Modeling of rotating machine like synchronous machines and induction machines.
- Formation of sequence admittance matrices.
- Evaluation of Thevenin's equivalent.

We begin with a brief review of per unit calculation used in power system analysis.

12.1 Review of Per unit Calculation and Modeling of Apparatus

Per unit value of any quantity is the ratio of that quantity to its base value.

$$Per\ Unit\ Quantity = \frac{Actual\ Quantity}{Base\ Quantity}$$

Quantities like voltage, current, power, impedance etc can be expressed in per unit. In the per unit system, there are four base quantities: base apparent power in volt-amperes, base voltage, base current and base impedance.
The following formulae apply to three phase system, where the base voltage is the line-to-line voltage in volts or kilovolts and the base apparent power is the three phase apparent power in kilovolt-amperes or megavolt-ampere (MVA).

$$Base\ Current(Amp.) = \frac{Base(kVA) \times 1000}{\sqrt{3}\ Base\ Volts}$$

$$Base\ Impedance(Ohm.) = \frac{Base(Volt)}{\sqrt{3}\ Base\ Current}$$

$$Z_{P.U} = \frac{Actual\ Impedance\ (Ohm) \times Base\ (MVA\ in\ 3\ phase)}{(Base(Line\ Voltage\ in\ kV))^2}$$

Briefly, the advantages of doing computation in per unit are as follows.

1. Manufacturers usually provide equipment data with name plate rating as base.
2. Range for acceptable % or p.u. values can be easily fixed.
3. Especially useful in networks with multiple voltage levels interconnected through transformers.
4. P.U impedance of transformer is independent of the kV base.
5. Standard base conversion (scaling with MVA Base) formulae are available.

Note: *Many books in first course on power system analysis cover per unit in detail. Readers who wish to go into more details can look into these references.*
We now begin discussing on the sequence modeling of power apparatus.

12.2 Modeling Aspects of Static Apparatus

We first consider modeling of transmission lines and transformers.

12.2.1 Modeling of Transmission Line

A balanced three phase transmission line model is given by (fig 12.1). The voltage drop across the line in phase coordinates is given by,

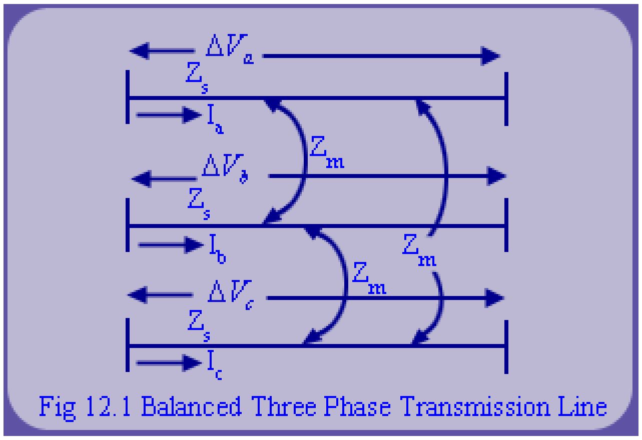

Fig 12.1 Balanced Three Phase Transmission Line

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (1)$$

Applying sequence transformation, we get $\Delta V_1 = Z_1 I_1$, $\Delta V_2 = Z_2 I_2$ and $\Delta V_0 = Z_0 I_0$

Where, $Z_1 = Z_2 = Z_s - Z_m$ and $Z_0 = Z_s + 2Z_m$

Thus, for a transposed transmission line, the positive and negative sequence impedances are equal. A commonly used approximation for Z_0 is to assume it to be three times Z_1.

12.2 Modeling Aspects of Static Apparatus

12.2.2 Modeling of Mutually Coupled Lines

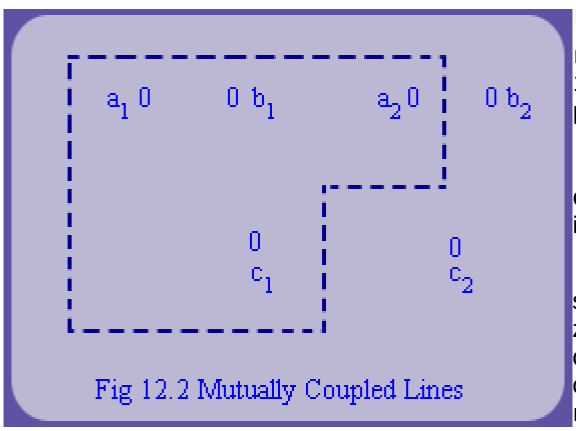

Fig 12.2 Mutually Coupled Lines

If a pair of 3ϕ - transmission lines are far enough, then mutual coupling between them is negligible (or zero). Fig 12.2 shows two three phase transmission lines running parallel and close to each other. As per Ampere's law, $[\oint \vec{Hi}\,\vec{dl} = i_{net}]$ if the lines a_1, b_1 and c_1 carry a positive or negative sequence currents, then flux linking in circuit 2 is zero. The reason for this is $i_{net}(t) = i_a(t) + i_b(t) + i_c(t) = 0$. However, for zero sequence currents in circuit 1, flux linking in circuit 2 is not zero. Thus, we see that for parallel coupled lines, mutual coupling is seen predominantly in the zero sequence circuit. However, it is not modeled for positive and negative sequence circuits. The same result can be mathematically derived as follows.

Consider two three phase transmission lines on the same tower. Assume that both lines are transposed. Then, all the mutual impedances between the two circuits are equal. Let mutual impedance of phase a_2 with phases a_1, b_1 and c_1 be equal to α. Then the model of such transmission line in phase coordinates is given by,

$$\begin{bmatrix} \Delta v^{a1} \\ \Delta v^{b1} \\ \Delta v^{c1} \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I^{a1} \\ I^{b1} \\ I^{c1} \end{bmatrix} + j\alpha \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I^{a2} \\ I^{b2} \\ I^{c2} \end{bmatrix}$$

Applying sequence transformation we will get,

$$\begin{bmatrix} \Delta v^{0^1} \\ \Delta v^{1^1} \\ \Delta v^{2^1} \end{bmatrix} = \begin{bmatrix} Z_s + 2Z_m & & \\ & Z_s - Z_m & \\ & & Z_s - Z_m \end{bmatrix} \begin{bmatrix} I^{0^1} \\ I^{1^1} \\ I^{2^1} \end{bmatrix} + j \begin{bmatrix} 3\alpha & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I^{0^2} \\ I^{1^2} \\ I^{2^2} \end{bmatrix}$$

It can be seen that mutual coupling between positive and negative sequence network of parallel transmission lines is zero. But, mutual coupling in zero sequence network is not zero. Hence, three phase faults and line to line faults will not be affected by mutual coupling. However, for all faults involving ground, fault current will be affected by mutual coupling. This can affect the performance of relays.

12.2.3 Modeling of Ground

With positive or negative sequence currents, the ground potential at the two distinct ends of say a transmission line can be taken as zero. If there is a neutral conductor, no-current flows through it because phasor summation of such balanced currents is zero. However, the story with zero sequence currents is a bit different. The summation of zero sequence currents in the three phases does not add to zero unless, the current itself is zero. Thus, there will be a drop in voltage across the two ground terminals which depends upon resistance of ground or ground wire. For simplicity, of analysis, this ground impedance (with a scaling factor of 3) is incorporated in the transmission line impedance of zero sequence network.

12.2 Modeling Aspects of Static Apparatus

12.2.4 Modeling of Transformer

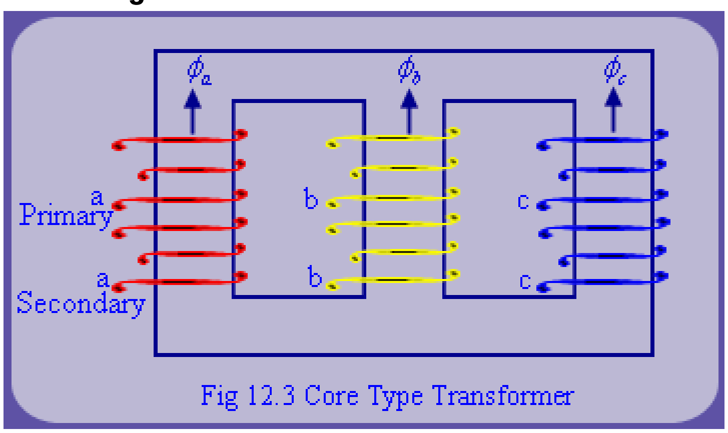

Fig 12.3 Core Type Transformer

The equivalent sequence diagram for a 2 winding three phase transformer depends upon (1) magnetic circuit design and (2) transformer connection. By magnetic circuit design, we imply different designs like three phase three limb core, three phase 5 limb shell, a bank of three single phase transformers or three phase auto transformers. For modeling of transformers, the magnetization branch is usually neglected because magnetizing current is very small when the transformer core is not saturated. Hence, only leakage impedance is taken into consideration.

The leakage impedance is not affected appreciably by a change in phase sequence (a-b-c or b-a-c) as the transformer is a static device. Therefore, for transformers, positive sequence impedance and negative sequence impedance are identical.

However, excitation for zero sequence flux of the transformer depends on the type of core used. For a core type (fig 12.3) transformer, $\vec{\phi}_a + \vec{\phi}_b + \vec{\phi}_c = 0$. This follows from the analogy of KCL. Now, if the windings of the transformer are provided with zero sequence excitation, then $\vec{\phi}_a = \vec{\phi}_b = \vec{\phi}_c = \vec{\phi}_0$. Substitutiting it in above equation we get $\vec{\phi}_0 = 0$. Practically, the flux, ϕ_a , ϕ_b and ϕ_c will not be zero. Rather a leakage flux would exist in the high reluctance path through air and transformer tank. Since, transformer tank is not stacked, it leads to heating of the tank. Hence, 3ϕ - core transformers should not be preferred for use in systems where load is unbalanced e.g. a 3ϕ distribution system. In contrast, for a shell type transformer (fig 12.4) there exists a low reluctance path through side limbs for zero sequence flux. Hence, there is no over heating of transformer tank.

In studies typically involving transformer protection, e.g. estimation of inrush current computation and overfluxing, saturation of transformer core cannot be neglected. However, such elaborate studies are not carried out with short circuit analysis programs. Rather, time domain simulation Electro Magnetic Transient Program (EMTP) is used.

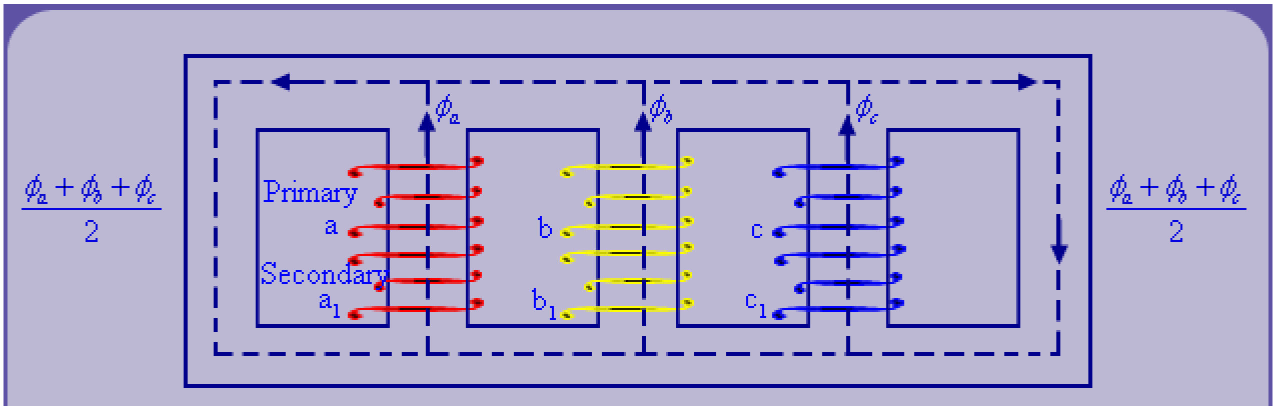

Fig 12.4 Shell Type Transformer

12.2 Modeling Aspects of Static Apparatus

12.2.4 Modeling of Transformer (contd..)

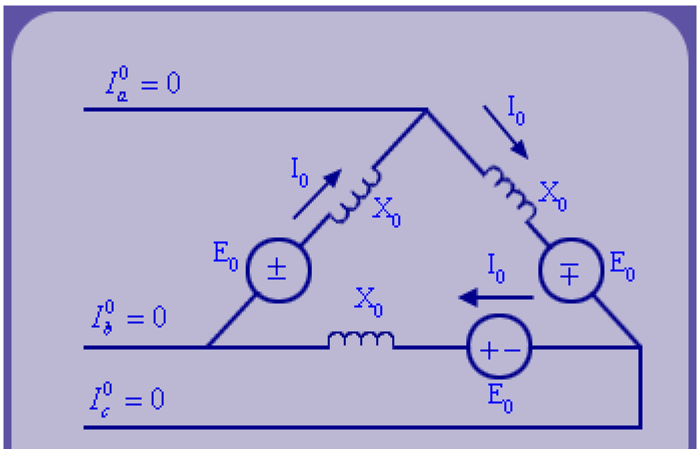

Fig 12.5 Delta Connected Transformer

In case of a bank of three single phase transformers, it can be easily argued that for such a configuration, independent low reluctance zero sequence flux path exists and hence appreciable zero sequence flux can stay in the core. Therefore, zero sequence impedance of three phase transformer bank can be as high as the positive sequence impedance. It should be mentioned that actual impedance will also include resistance of the windings. However, X/R ratio of transformers can be quite high.

To summarize, the positive and negative sequence reactances of all transformers are identical. Zero sequence reactance is the transformer leakage impedance. In 3-phase core-type transformers the construction does not provide an iron path for zero sequence. For these, the zero-sequence flux must pass from the core to the tank and return. Hence, for these types X_0 usually is 0.85 to 0.9 X_1, and when known the specific value shall be used. For shell type transformers which are preferred in distribution systems, zero sequence impedance is same as positive and negative sequence impedance.

Role of Circuit Connection

So far we have discussed design issues that characterize the zero sequence impedance of a three phase transformer. However, this impedance may not always appear between the H (HV) to L (LV) bus. In case of positive or negative sequence currents, there is always a path for line currents from H to L through the sequence leakage impedance. This is irrespective of the transformer connection (D/Y or Y/Y etc) because, there is always a path for positive and negative sequence line currents to flow.

However, zero sequence line currents for a transformer depend not only on zero sequence impedance but also on the type of transformer connection. For example, a star ungrounded winding does not provide any path for flow of zero sequence current. The neutral current is given by $I_n = I_a + I_b + I_c = 3I_0$. Since, neutral is ungrounded $I_n = 0$ and hence I_0 is also zero. Delta winding permit circulating zero sequence currents which cannot appear in the line. (fig 12.5).

12.2 Modeling Aspects of Static Apparatus

12.2.4 Modeling of Transformer (contd..)

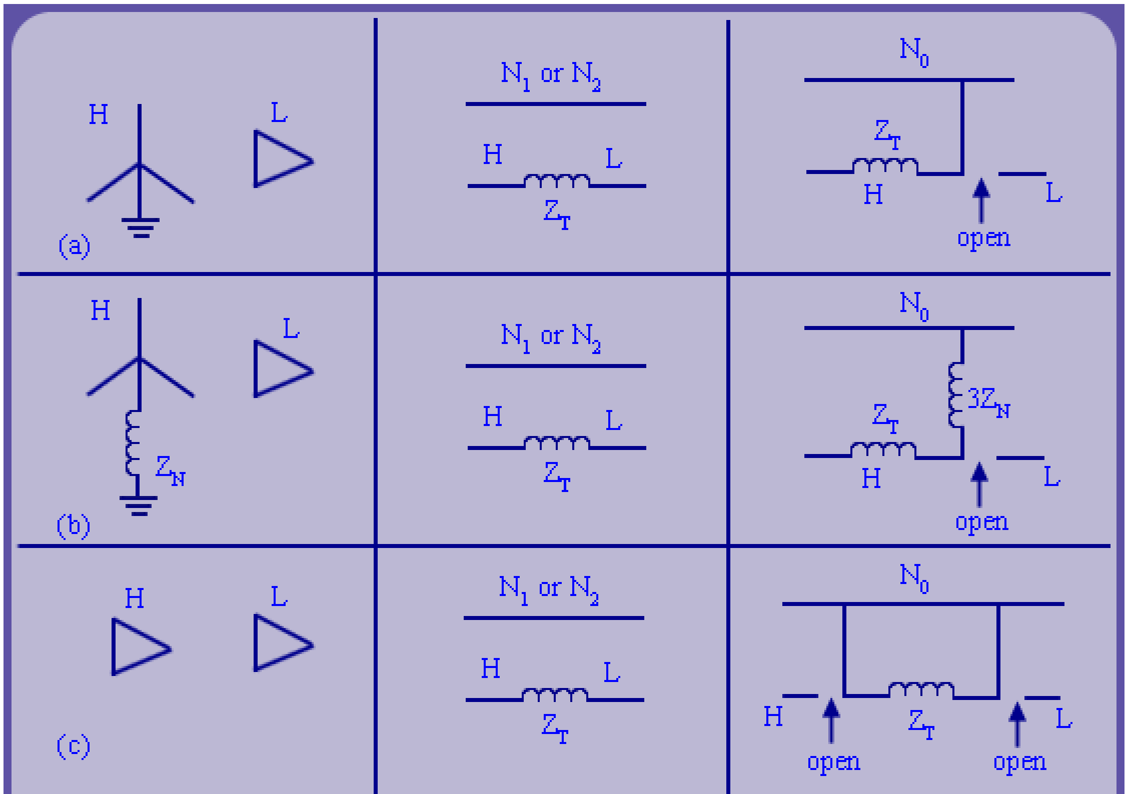

Fig 12.6 (a) Zero Sequence Modeling for Different Transformer Connections

Fig 12.6 summarizes the effect of winding connections on positive, negative and zero sequence circuit for 3ϕ transformer. N_1 indicates neutral bus for positive sequence, N_2 indicates neutral bus for negative sequence and N_0 for zero sequence networks.

12.2 Modeling Aspects of Static Apparatus

12.2.4 Modeling of Transformer (contd..)

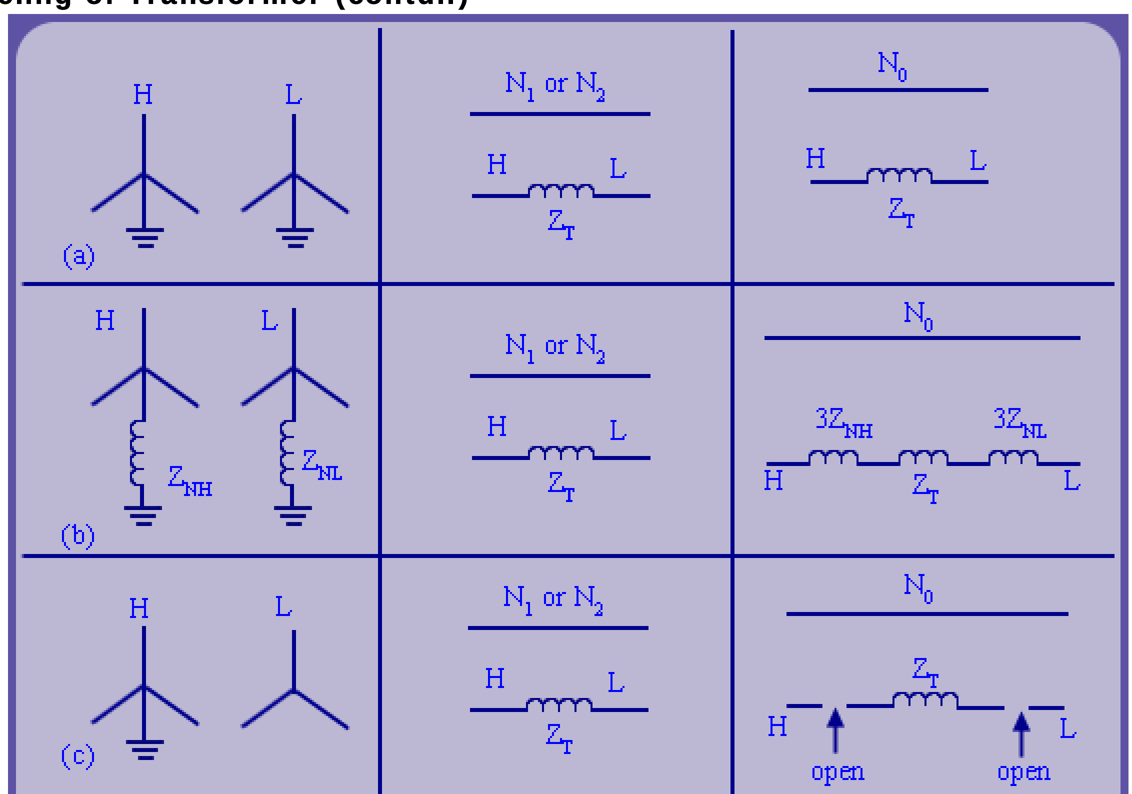

Fig 12.6 (b) Zero Sequence Modeling for Different Transformer Connections

12.2 Modeling Aspects of Static Apparatus

12.2.4 Modeling of Transformer (contd..)

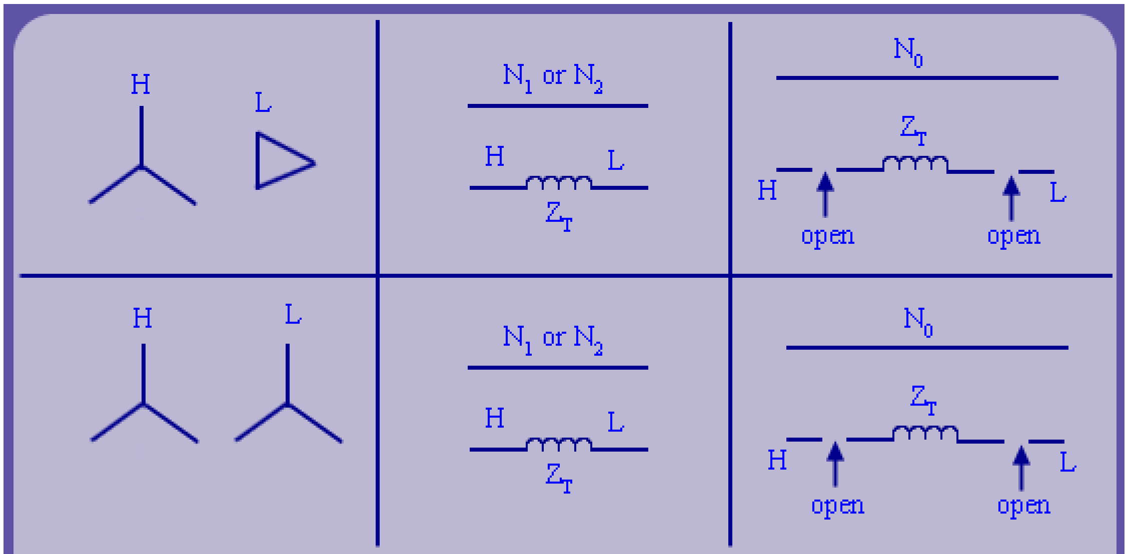

Fig 12.6 (c) Zero Sequence Modeling for Different Transformer Connections

12.3 Modeling of Rotating Machines

12.3.1 Modeling of Synchronous Machines

12.3.1.1 Positive sequence Impedance of Synchronous Generators

The subtransient reactance X''_d determines the current during the first cycle after fault occurs. In about 0.1sec, reactance increases to transient reactance X'_d. In about 0.5sec to 2sec reactance increases to X_d, the synchronous reactance; this is the value that determines the current flow after a steady state condition is reached.
Synchronous generator data available from manufacturers.

12.3.1.2 Positive Sequence Impedance of Synchronous Motors and Condensers

Typically, motors are used in distribution systems. Hence, fault current analysis for distribution systems requires explicit modeling of electrical motors. During a fault, motor acts as a generator to supply fault current. The rotor carrying the field winding is driven by the inertia of the rotor and load. Stator excitation is reduced due to drop in voltage. The fault current diminishes as the rotor decelerates. The generator equivalent circuit is used for synchronous motor. The constant driving voltage and three reactance X''_d, X'_d and X_d are used to establish the current values at three points in time. Synchronous condensers can be treated in same manner as synchronous motors.

12.3 Modeling of Rotating Machines

12.3.1 Modeling of Synchronous Machines

12.3.1.3 Negative Sequence Impedance of Synchronous Machines

For a synchronous machine, positive and negative sequence impedances cannot be equal. In case of a synchronous machine, negative sequence currents create a rotating mmf in opposite direction to the rotor mmf. Hence, double frequency emf and currents are induced in rotor. Negative sequence impedance is 70-95% of subtransient reactance. It can be approximated by subtransient reactance. For a salient pole machine, it is taken as a mean of X''_d and X''_q.

12.3.1.4 Zero Sequence Impedance of Synchronous Machines

Zero Sequence currents cannot create rotating mmf. In fact, with sinusoidally distributed three phase windings, the net flux at any point in the air gap is zero. Hence, zero sequence impedance is only a small % (0.1-0.7) of the positive sequence impedances. It varies so critically with armature winding pitch that an average value can hardly be given. Since synchronous machines only generate positive sequence voltage, the internal voltages used with negative sequence and zero sequence networks are zero. If star point is grounded through impedance , then will have to be added to zero

Z_g $3Z_g$

sequence impedance of generator.

12.3.2 Sequence Modeling of Induction Machines

In asynchronous machines, transient state of current is damped quickly i.e. within 1-2 cycle. During a fault, rotor is driven by inertia of load and rotor itself. There is no dc field excitation on rotor. Rotor winding is short circuited. Hence, whatever rotor excitation is present, it is due to the induced fields in the rotor from the rotating stator mmf. As stator excitation is lost and rotor slows down, this field is lost quickly.

The current contribution of an induction motor to a terminal fault reduces and disappears completely after a few cycles. As a consequence, only the sub transient value of reactance X_d'' is assigned for positive and negative sequence. This value is almost equal to the locked rotor reactance. Subsequently, machine behaves as a passive element with impedance of value $Z = \frac{kV^2}{MVA}$ where rated LL voltage and 3 phase MVA rating is used. Zero Sequence modeling can be treated in similar lines as synchronous machines because rotor plays no significant role.

For fault calculations an induction generator can be treated as an induction motor. Wound rotor induction motors normally operating with their rotor rings short circuited will contribute fault current in the same manner as a squirrel cage induction motor. Occasionally, large wound rotor motors operated with some external resistance maintained in their rotor circuits may have sufficiently low short circuit time constants. Hence, their fault contribution is not significant and may be neglected.

12.3 Modeling of Rotating Machines

12.3.3 Modeling of Electrical Utility Systems

The generator equivalent circuit can be used to represent a utility system. Usually, the utility generators are remote from the industrial plant. The current contributed to a fault in the remote plant appears to be merely a small increase in load to the very large central station generators, and this current contribution tends to remain constant. Hence, it is represented at the plant by single valued equivalent impedance referred to the point of connection.

12.3.4 Load Modeling

One approximate way of accounting prefault load flow condition in short circuit analysis associated with transmission system is to model load as positive sequence shunt impedance.

$$\frac{V^1}{I^1} = \frac{|V_i|^2}{(P_i - jQ_i)}$$

The shunt load impedances are added into diagonal of Y_{bus}^{old}.

12.3.5 Modeling of Series Capacitors

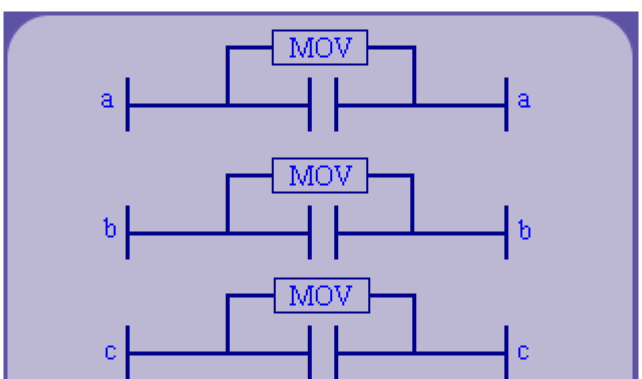

Fig 12.7 Series Capacitors with MOV

In many utilities, series capacitors or Thyristor Controlled Series Compensation (TCSC) as shown in fig 12.7 is used to boost the transmission line power flow capacity. The series capacitors have a negative value of reactance and hence should increase the fault current levels in their vicinity. However, across every capacitor, a metal oxide varistor (MOV) is also connected to limit over voltages during fault.

Typically, during a fault MOV conducts, and reduces the capacitive reactance contribution to the transmission line impedance. Hence, it also reduces fault current values. Since, the behaviour of MOV is non-linear i.e., its V-I characteristics are non-linear, short circuit analysis with series capacitors becomes an iterative process.

Modeling in three phase domain is usually preferred.

12.4 Sequence Network Admittance Matrix Formulation

Now, that, we have necessary information about apparatus modeling, we can start assembling the sequence network. A three phase admittance matrix model for power system in phase coordinates can be expressed as follows:

$$\begin{bmatrix} I_1^{abc} \\ | \\ | \\ | \\ I_n^{abc} \end{bmatrix} = \begin{bmatrix} Y_{11}^{abc} & Y_{12}^{abc} & ---- & Y_{1n}^{abc} \\ Y_{21}^{abc} & Y_{22}^{abc} & ---- & Y_{2n}^{abc} \\ | & | & & | \\ | & | & & | \\ Y_{n1}^{abc} & Y_{n2}^{abc} & ---- & Y_{nn}^{abc} \end{bmatrix} \begin{bmatrix} V_1^{abc} \\ V_2^{abc} \\ | \\ | \\ V_n^{abc} \end{bmatrix}$$

In the above equation, each entry in the Y-matrix is itself a 3×3 matrix with a cyclic structure, $\left[V_i^{abc}\right] = \left[V_i^a, V_i^b, V_i^c\right]^T ; \left[I_i^{abc}\right] = \left[I_i^a, I_i^b, I_i^c\right]^T$. V_i refers to the voltage of a node 'i' and I_i refers to the current injection at a node i. The sequence transformation on nodal voltages can be expressed as follows:

$$\begin{bmatrix} V_1^{abc} \\ V_2^{abc} \\ | \\ | \\ V_n^{abc} \end{bmatrix} = \begin{bmatrix} [T] & & & \\ & [T] & & \\ & & [T] & \\ & & & [T] \end{bmatrix} \begin{bmatrix} V_1^{012} \\ V_2^{012} \\ | \\ | \\ V_n^{012} \end{bmatrix}$$

Similar transformation is defined for current vector. Thus, in the sequence coordinates, the admittance model is given by the following equation,

$$\begin{bmatrix} I_1^{012} \\ I_2^{012} \\ | \\ | \\ I_n^{012} \end{bmatrix} = \begin{bmatrix} T^{-1} Y_{11}^{abc} T & T^{-1} Y_{12}^{abc} T ---- & T^{-1} Y_{1n}^{abc} T \\ T^{-1} Y_{21}^{abc} T & T^{-1} Y_{22}^{abc} T ---- & T^{-1} Y_{2n}^{abc} T \\ | & | & | \\ | & | & | \\ T^{-1} Y_{n1}^{abc} T & T^{-1} Y_{n2}^{abc} T ---- & T^{-1} Y_{nn}^{abc} T \end{bmatrix} \begin{bmatrix} V_1^{012} \\ V_2^{012} \\ | \\ | \\ V_n^{012} \end{bmatrix}$$

12.4 Sequence Network Admittance Matrix Formulation (contd..)

It can be verified that if 3×3 matrix Y_{ij}^{abc} enjoys a cyclic structure, then

$$\left[Y_{ij}^{012}\right] = T^{-1}\left[Y_{ij}^{abc}\right]T = \begin{bmatrix} Y_{ij}^0 & & \\ & Y_{ij}^1 & \\ & & Y_{ij}^2 \end{bmatrix}$$

In other words, there is no coupling between the zero, positive and negative sequence components of a balanced network because 3×3 matrices $\left[Y_{ij}^{012}\right]$ and $\left[Y_{ii}^{012}\right]$ are diagonal matrices. By permuting the rows and columns in such a way that all the zero sequence, positive sequence and negative sequence quantities are grouped together, a three phase admittance matrix can be described by three decoupled sequence matrices as follows,

$$\begin{bmatrix} I_{bus}^0 \\ I_{bus}^1 \\ I_{bus}^2 \end{bmatrix} = \begin{bmatrix} Y_{BUS}^0 & & \\ & Y_{BUS}^1 & \\ & & Y_{BUS}^2 \end{bmatrix} \begin{bmatrix} V_{bus}^0 \\ V_{bus}^1 \\ V_{bus}^2 \end{bmatrix}$$

In the above equation, each of the sequence admittance matrix represents the corresponding sequence network.

Differences between Y_{BUS} Modeling in Short Circuit Analysis and Load Flow Analysis

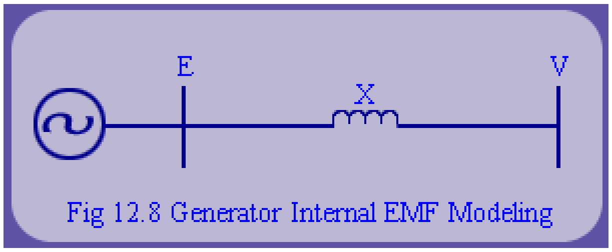

Fig 12.8 Generator Internal EMF Modeling

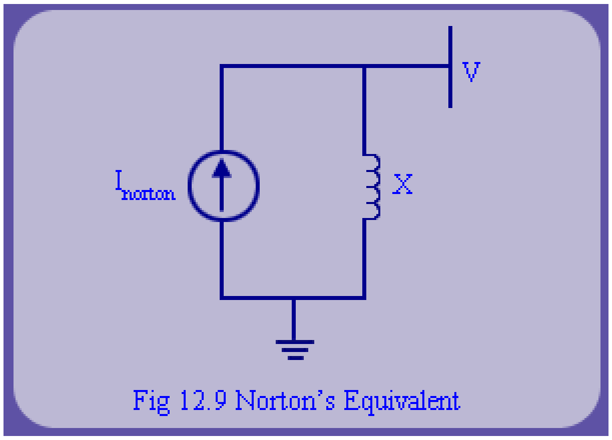

Fig 12.9 Norton's Equivalent

Load flow analysis uses only positive sequence admittance matrix while short circuit analysis requires positive, negative and zero sequence admittance matrix. The admittance matrix formulation used in load flow analysis and short circuit analysis have some subtle differences. In load flow analysis, the voltage at generator terminal is assumed to be fixed. Hence, source impedance and internal generator voltages are not modeled.

In contrast, in short circuit analysis, the generator model is an internal emf source (open circuit source voltage) behind a transient reactance (see fig 12.8) which leads to equivalent Norton circuit as shown in fig 12.9. Hence, machine sequence impedances admittance have to be added to the corresponding diagonal entries of Y_{BUS} in short circuit analysis. Similar remarks hold for load modeling. Hence, positive sequence Y_{BUS} of load flow analysis and short circuit analysis are not identical.

12.5 Short Circuit Analysis Using Sequence Components

Let the prefault network be described by the following model, $\left[I^s\right]=\left[Y^s_{bus}\right]\left[V^s\right]$ where 's' can be 0, 1 or 2, are the sequence components under consideration. Typically, for a balanced system representing a prefault transmission network, $\left[I^0\right]=\left[I^2\right]=0$. Hence, in the prefault condition, the only equation of interest is $\left[I^1\right]=\left[Y_{bus}\right]\left[V^1\right]$. We use subscript *old* to indicate the prefault value. Hence, prefault equation is given by $\left[I^{old1}\right]=\left[Y^{old1}_{bus}\right]\left[V^{old1}\right]$

12.5.1 Construction of Thevenin's Equivalent

Estimation of the fault current requires construction of Thevenin's equivalent circuit at the faulted busses. Interconnection of thevenin's equivalents in sequence domain will depend upon fault type. Faults in a power system can be classified into shunt faults and series faults. Shunt faults are typically, bus faults viz. L-L-L, L-L, L-G and L-L-G. An example of series fault is opening of a phase conductor in a transmission line. A simultaneous fault involves multiple occurances of fault at the same time instant. For example, a phase conductor breaking and falling to ground is a simultaneous fault which is mix of both shunt and series faults. Most of above faults can be analyzed in sequence components.

For simplicity, we restrict analysis to bus fault which is created at a bus *i* . Faults on intermediate points of transmission line can be modeled by introducing *phantom* buses. The prefault load flow analysis (typically carried out on the positive sequence network) provide the Thevenin's (open circuit) voltage (V_i^{th}), while the fault impedance (Z_f) is treated as the “load impedance” on the i^{th} bus.

To compute the Thevenin's impedance at faulted bus *'i'* , all the current sources are open circuited (made zero) and then 1 p.u. of current is injected at bus *'i'* . In the vector notations, this process is represented by current injection vector e_i where e_i is the i^{th} column of identity matrix. Then, the equation $\left[Y^{old1}_{bus}\right]\left[V^1\right]=\left[e_i\right]$ is solved by sparse LU factorization and forward backward substitution. The i^{th} element of the resulting voltage V_i gives the Thevenin's impedance. The computation of Thevenin's impedance for negative and zero sequence networks proceed on similar lines. The fault currents are computed by well known sequence network interconnections, discussed in the lecture no. 10.

12.5 Short Circuit Analysis Using Sequence Components

12.5.2 Calculation of Short Circuit MVA

When short circuit analysis program is used to determine the rating of circuit breakers, short circuit MVA at the fault bus is specified. Typically, it is computed for a three phase fault. The following equations summarize its calculation.

$$3\phi-short\ circuit\ MVA=I_{3\phi}(in\ pu)\times 3\phi-base\ MVA$$

$$S-L-G-short\ circuit\ MVA=I_{S-L-G}(in\ pu)\times 3\phi-base\ MVA$$

Since, from design considerations, the maximum fault MVA is of interest, the faults considered are bolted faults. Short circuit MVA is also used to specify the strength of the utility interconnection, while carrying out fault analysis for distribution system. For example, if short circuit MVA level is specified as 500MVA at the point of interconnection, then on a 100kVA system base, it implies a source impedance of $j\frac{100}{500} = j0.2pu$. A bus with high value of fault MVA is said to be a strong bus and conversely a bus with low fault MVA, is said to be a weak bus.

12.6 Closing Remarks:

Fault analysis involves quasi-sinusoidal-steady-state modeling of a dynamical system involving fault. It assumes that (a) the system is stable and (b) network natural transient are neglected. Evaluation of the system stability i.e. whether post-fault system will retain synchronism or not requires transient stability analysis. The justification for such approximation in fault analysis is that, it is used to determine rating of circuit breakers, and pickup settings for relays which depend on fault currents. A more involved analysis of transient behaviour immediately after a fault (a few cycles) requires usage of Electro Magnetic Transient Program (EMTP). EMTP models fast transients but usually neglects electromechanical transients which are essentially slower due to inertia of rotors. Thus, fault current levels can as well be extracted by EMTP. However, data requirement of EMTP modeling is quite high. In absence of data for such detailed modeling, short circuit analysis program provide a fast and conservative estimate of fault currents. However, fault analysis programs cannot model onset of dc offset current.

Many standards like IEC, ANSI/IEEE, VDE specify empirical multiplication factors to obtain the maximum asymmetrical fault current levels. For industrial systems, an approximate value that can be used is 1.6 i.e. maximum asymmetrical fault current can be taken to be 1.6 times maximum symmetrical fault current. At transmission system level, this value can increase further. It can be of the order of 2.7-3.0. Finally, when setting for time delayed relays have to be evaluated (example, setting of backup relays), then the values of source impedances also have to be altered. Standards specify the requisite multiplication factors. Considering, all such issues, we conclude that fault analysis is a flavour of both "science and art".

Review Questions

1. What are the advantages of per unit computation?
2. How does mutual coupling between transmission lines affect the fault current?
3. Why is the zero sequence impedance of a shell type transformer different than that of a core type transformer?
4. The zero sequence impedance of a synchronous machine is small compared to its positive sequence impedance.

   Why?
5. A 3ϕ fault MVA of an industrial power system at the point of connection with utility system is 50kVA . On a 100kVA

   base, determine the sequence impedances for utility system.

Recap

In this lecture we have learnt the following:

- The advantages of per unit calculation.
- Modeling of static apparatus.
- Effect of mutual coupling on the zero sequence impedance of transmission line.
- Modeling of synchronous machines and induction machines.

- Sequence network admittance matrix formulation.