Module B4

Per Unit

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Prerequisite Competencies: 1. Three-phase Power Calculations, found in B3
2. Transformer operation, found in T2.
Module Objectives: 1. Transform per phase and three phase circuit quantities from Standard International (SI) units to per unit.
2. Transform per unit circuit quantities to per phase SI and three phase SI units.
3. Per form change of base for per unit quantities.

B4.1 Per Unit Calculations

The transmission system and several portions of the distribution system are operated at voltages in the kilovolt (kV) range. This results in large amounts of power being transmitted in the range of kilowatts to megawatts, and kilovoltamperes to megavoltamperes. As a result, in analysis, it is useful to scale, or normalize quantities with large physical values. This is commonly done in power system analysis and is referred to as the per-unit system. The calculation of system performance conveniently uses a per-unit representation of voltage, current, impedance, power, reactive power, and apparent power (volt-ampere). The numerical per-unit value of any quantity is its ratio to the chosen *base quantity* of the same dimensions. Thus a per-unit quantity is a *normalized* quantity with respect to a chosen base value.

Historically the per-unit conversion was used to simplify hand calculations. With the advent of the digital computer in power system analysis, this advantage has been eliminated. The conversion however, has several other advantages:

- In the per-unit system of representation, device parameters tend to fall in a relatively fixed range, making erroneous values prominent.
- Ideal transformers are eliminated as circuit elements. This results in a large saving in component representation and reduces computational burden.
- The voltage magnitude throughout a given power system is relatively close to unity in the per-unit system for a power system operating normally. This characteristic provides a useful check on the calculations.

In power system calculations the nominal voltage of lines and equipment is almost always known, so the voltage is a convenient base value to choose. The apparent power (volt-ampere) is usually chosen as a second base. In equipment this quantity is usually known and makes a convenient base. The choice of these two base quantities will automatically fix the base of current, impedance, and admittance. In a system study, the volt-ampere base can be selected to be any convenient value such as 100 MVA, 200 MVA, etc.

The same volt-ampere base is used in all parts of the system. One base voltage in a certain part of the system is selected arbitrarily. All other base voltages *must be related* to the arbitrarily selected one by the *turns ratio* of the connecting transformers.

For single-phase systems or three-phase systems where the term current refers to line current, where the term voltage refers to line to neutral voltage, and where the term volt-amperes refers to volt-amperes per phase, the following formulae relate the various quantities:

$$\text{Base current, } A = \frac{base, VA_{l\phi}}{base \quad voltage, V_{LN}} \qquad \text{(B4.1)}$$

$$\text{Base impedance, } \Omega = \frac{base\, voltage, V_{LN}}{base\, current,\ A} \qquad \text{(B4.2)}$$

$$\text{Base impedance, } \Omega = \frac{(base\, voltage, V_{LN})^2}{base, VA_{l\phi}} \qquad \text{(B4.3)}$$

$$\text{Base power, } W_{l\phi} = baseVA_{l\phi} \qquad \text{(B4.4)}$$

$$\text{Base power, } VAR_{l\phi} = baseVA_{l\phi} \qquad \text{(B4.5)}$$

$$\text{Per Unit impedance of an element} = \frac{Actual\ impedance, \Omega}{Base\ impedance, \Omega} \qquad \text{(B4.6)}$$

Normally, in power systems, power bases are specified as kVA or MVA. One must always ensure these values are converted to units of VA before using the above formula (1 kVA=1x10^3 VA, 1 MVA=1x10^6 VA). Likewise, voltage bases are usually specified as kV. One must always ensure these values are converted to units of volts before using the above formula (1 kV=1x10^3 V).

It is common to use subscripted notation to identify base quantities. For example, in contrast to the notation of Eq.(B4.3) , Z_{base} can be used to identify the base impedance, MΩ

In Module B3, Section B3.2.2, we have demonstrated that balanced three-phase circuits can be solved on a per-phase basis. In performing per-phase analysis, the bases for the quantities in the circuit representation are volt-amperes per-phase or kilo-volt-amperes per phase, and volts or kilovolts from line to neutral. System specification is usually given in terms of total three-phase volt-amperes or kilo-volt-amperes or mega-volt-amperes and line-to-line volts or kilovolts. This may result in some confusion regarding the relation between the per-unit value of line-to-line voltage and the per-unit value of phase voltage (line to neutral voltage). In a per-phase circuit, the voltage required for the solution is the line to neutral voltage even though a line-to-line voltage may be specified as a base. The base value of the line to neutral voltage is the base value of the line-to line voltage divided by $\sqrt{3}$. Since this is also the relation between line-to-line and line to neutral voltages of a balanced three-phase system, *the per-unit value of a line to neutral voltage on the line to neutral voltage base is equal to the per-unit value of the line-to-line voltage at the same point on the line-to -line voltage base if the system is balanced.* Similarly, the three-phase volt-amperes is three times the volt-amperes per-phase, and the base value of the three-phase volt-amperes is three times the base value of the per-phase volt-amperes. Therefore, *the per-unit value of the three-phase volt-amperes on the three-phase volt-ampere base is identical to the per-unit value of the volt-amperes per-phase on the volt-ampere per-phase base.*

The following numerical example clarifies the relationships.

$$\text{Base Three Phase Kilovolt-ampere} = Base\ kVA_{3\phi} = 45{,}000kVA$$

and

$$\text{Base Line-to-line Voltage} = Base\ kV_{LL} = 180kV$$

We then have

$$\text{Base Per-phase Kilovolt-ampere} = Base\ kVA_{1\phi} = \frac{45{,}000kVA}{3} = 15{,}000kVA$$

and

$$\text{Base Line-to-neutral voltage} = Base\ kV_{LN} = \frac{180}{\sqrt{3}} = 103.92kV$$

We will now calculate the per-unit quantities for a line-to-line voltage of a 162 kV and a total three-phase power of 24,000 kW.

Line-to-Line Base

$$\text{Per - unit Voltage} = \left(\frac{162\times10^3}{180\times10^3}\right) = (0.90)$$

$$\text{Per - unit Power} = \frac{24{,}000\times10^3}{45{,}000\times10^3} = 0.533$$

Line-to-Neutral Base

For an actual line-to-line voltage of 162 kV, in a balanced three-phase system, the line to neutral voltage is $\frac{162}{\sqrt{3}} = 93.5307kV$, and

$$\text{Per-unit voltage} = \frac{93.5307\times10^3}{103.92\times10^3} = 0.90$$

For a total three-phase power of 24,000 kW the power per-phase is $\frac{24{,}000k}{3} = 8000kW$, and

$$\text{Per-unit power} = \frac{8000\times10^3}{15000\times10^3} = 0.533$$

Throughout the above discussion mega-volt-ampere and megawatt may be substituted for kilo-volt-ampere and kilo-watt respectively. *Conventionally*, a given value of base voltage in a three-phase system is a line-to-line voltage, and a given value of base kilo-volt-amperes or base mega-volt-amperes is the total three-phase base.

The values of base impedance and base current can be computed from base values of voltage and volt-amperes as shown earlier in the section. If the base values of volt-amperes and voltage are specified as the volt-amperes for the total three phases and voltage from line-to-line in a balanced three-phase system respectively, we have

$$\text{Base current, } A = \frac{baseVA_{3\phi}}{\sqrt{3} \times base\ \ voltage, V_{LL}} \tag{B4.7}$$

$$\text{Base impedance, } \Omega = \frac{(base\ \ voltage, V_{LL})^2}{baseVA_{3\phi}} \tag{B4.8}$$

$$\text{Base impedance, } \Omega = \frac{(base\ \ voltage, V_{LN})^2}{baseVA_{1\phi}} \tag{B4.9}$$

When using these equations, as previously mentioned, it is important to express all voltages and powers in units of volts and volt-amperes rather then kV and kVA or MVA.

Example B 4.1

In the circuit shown in Figure B4.1, a load having an impedance of $39 + j26\Omega$ is fed from a voltage source through a line having an impedance of $1 + j8\Omega$. The effective, or RMS, value of the source voltage is 220 V.

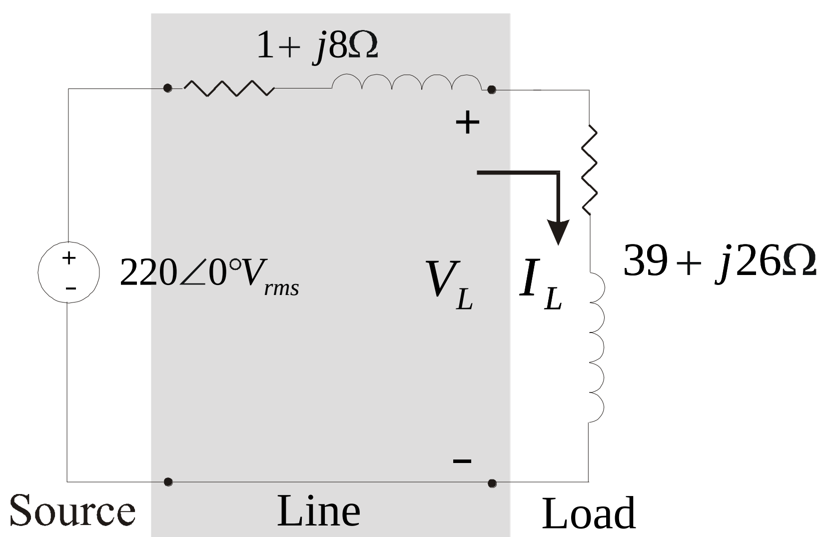


Figure B4.1

a) Calculate the load current I_L and voltage V_L .
b) Calculate the average and reactive power delivered to the load.
c) Repeat the above calculation in per-unit choosing a base of 220 V for the voltage, and a base of 1500 VA for the volt-amperes.
d) Verify the values obtained in c) with those obtained in a), and b).

Solution

a) Since the line and load are in series across the voltage source, the load current equals the voltage divided by the total impedance. Thus

$$I_L = \frac{220\angle 0°}{40 + j34} = 3.193 - j2.714 = 4.1906\angle -40.364° A$$

The load voltage is the product of the load current and load impedance:

$$V_L = (39 + j26) I_L = 195.09 - j22.83 = 196.424\angle -6.674° A$$

b) The average and reactive power delivered to the load is given by

$$S = V_L I_L^* = (195.09 - j22.83)\cdot(3.193 + j2.714) = 684.889 + j456.592 VA$$

c) Voltage Base = 220 V, Voltampere Base = 1500 VA

From Eq. (B4.1) $Current\ Base = \dfrac{1500}{220} = 6.8181 A$

From Eq. (B4.2) $Impedance = \dfrac{220}{6.8181} = 32.267\Omega$

The circuit diagram in Figure B4.1 can now be represented in per-unit. The per-unit values of the various quantities are given by

$$V_g = \frac{220\angle 0°}{220\angle 0°} = 1.0$$

$$Z_{line} = \frac{1 + j8}{32.267} = 0.03099 + j0.2479$$

$$Z_{load} = \frac{39 + j26}{32.267} = 1.20867 + j0.805$$

The per-unitized circuit is shown in Figure B4.2.

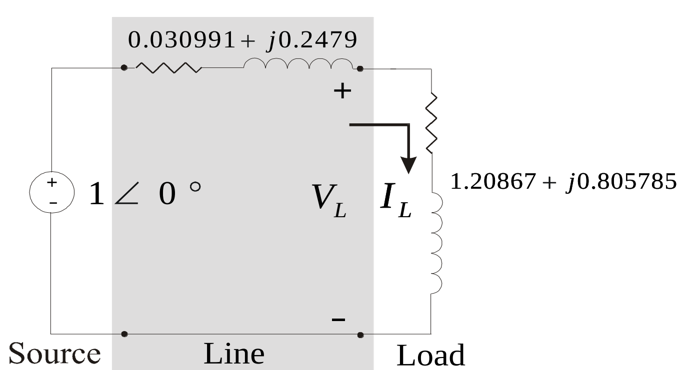


Figure B4.2 Per-Unit Representation

$$I_L = \frac{1\angle 0°}{1.23966 + j1.053685} = 0.614642\angle -40.364°$$

$$V_L = (1.20867 + j0.805785)I_L = 0.886805 - j0.103761$$
$$= 0.8928557\angle -6.674°$$

$$S = V_L I_L^* = 0.5487866\angle 33.69° = 0.456618 + j0.3044115$$

d) In order to verify the per-unit values obtained above, we multiply the per-unit values by their respective base values to obtain the actual values.

$$I_L = (0.614642\angle -40.364°)\times 6.8181 = 4.1906\angle -40.364° A$$

$$V_L = (0.8928557\angle -6.674°)\times 220 = 196.42\angle -6.674° V$$

$$S = (0.456618 + j0.3044115)\times 1500 = 684.899 + j456.592 VA$$

These values check with the values obtained in a) and b).

B4.1.1 Change of Base in Per Unit Quantities

In most instances, the per-unit impedance of a component is specified on the rated component base which is different from the base selected for the part of the system in which the component is located. When performing calculations, all impedances in any one part of the system must be expressed on the same impedance base. As a result, it is necessary to have a means of converting per-unit impedances from one base to another. Substituting the expression for base impedance given be Eq. (B4.3) or (B4.9) for base impedance in Eq. (B4.6) gives

$$Per-Unit\ \ Impedance = \frac{(actual\ \ impedance, \Omega) x (baseVA)}{(base\ \ voltage, V)^2} \tag{B4.10}$$

Given a component impedance in per-unit on a specified base, the process of changing this per-unit value of impedance to per-unit on a new base can be done as follows. We shall refer to the base on which the component per-unit value is originally specified as the old base, and the base on which we want to represent it as the new base. From Eq. (B4.10), we can calculate the actual impedance of the component in Ω, given by

$$Actual\ \ Impedance = \frac{(per-unit\ \ impedance_{old}) x (base\ voltage, V_{old})^2}{(baseVA_{old})} \tag{B4.11}$$

The per-unit value of the above impedance can now be calculated on the new base by substituting the value of the actual impedance Eq. (B4.11) in Eq. (B4.10) with the choice of the new base for voltage and voltamperes. This gives

$$Per-Unit\ Z_{new} = Per-Unit\ Z_{old}\left(\frac{baseV_{old}}{baseV_{new}}\right)^2 \left(\frac{baseVA_{new}}{baseVA_{old}}\right) \tag{B4.12}$$

B4.2 Power System Representation

In the above sections, we have presented an overview of the various components, which constitute a power system. In this section, we demonstrate the assembly of these components to represent a complete system. We have also shown in Section B3.2.4 that a balanced three-phase system is analyzed using a per-phase representation of the system or the equivalent circuit composed of one of the three phases and the neutral return. In drawing a representation of the circuit, the diagram is further simplified by omitting the completed circuit through the neutral and by indicating the component parts by specified symbols rather than their equivalent circuits. This simplified diagram is called a single-line or one-line diagram.

B4.2.1 Single Line Diagram

In the single-line diagram, the circuit parameters are not shown, and a transmission line is represented by a single line between its two ends. In addition, associated components are represented by standard symbols [1, 3, 5]. The single line diagram provides important information regarding the system. The level of detail in the single-line diagram varies with the intended use of the diagram, e.g., the representation of circuit breakers is not essential in a steady state analysis of the system. Figure B4.3 illustrates a few symbols for components commonly represented in the power system.

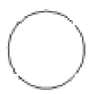
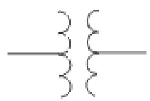
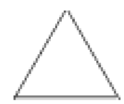
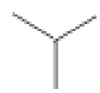
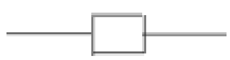
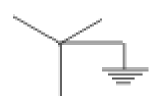
Machine or rotating armature (Basic)		Air circuit breaker	
Two-winding power transformer		Three-phase delta connection	
Three-winding power transformer		Three-phase wye neutral ungrounded	
Power circuit breaker oil or other liquid		Three-phase wye neutral grounded	

Figure B4.3 Component Symbols

Figure B4.4 shows the single line diagram of a simple power system. A generator grounded through a reactor is connected to a bus and through a step-up transformer to a transmission line. Two motors grounded through reactors are connected to a bus through a transformer at the other end of the line. A load is also connected to the bus with the motors. The information regarding the ratings of the generators, transformers, motors, and loads is usually provided on the one-line diagram.

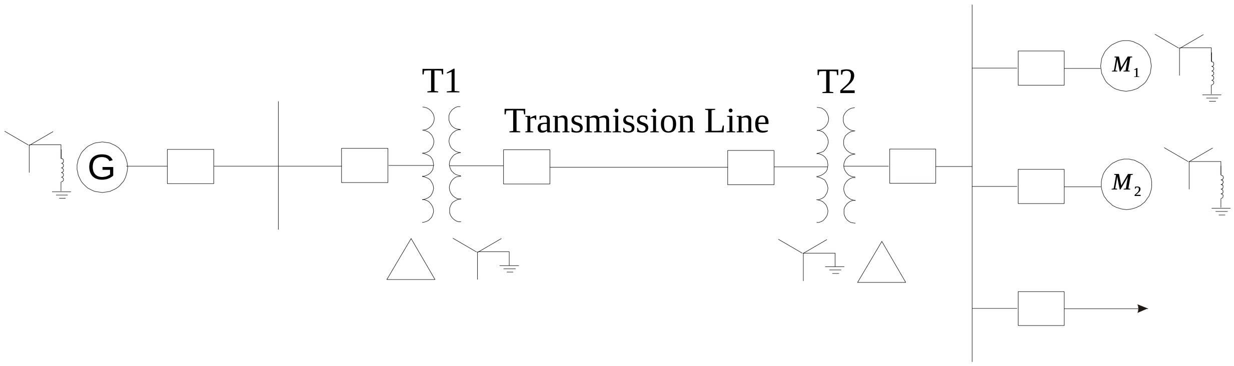


Figure B4.4 Single-Line Diagram of a Sample Power System

B4.3 Impedance and Reactance Diagrams

To analyze the steady-state behavior of the system, or to analyze its response under faulted conditions, the per-phase equivalent circuit has to be obtained. The one line diagram described above is used to generate the per-phase equivalent circuit. In order to obtain the impedance diagram, the appropriate equivalent circuit of each component need to be obtained. This aspect of the analysis will be covered in the subsequent chapters. In general the following representation is adopted for the various components. Rotating machines are represented by constant voltage sources in series with appropriate impedances. Transformers are represented by an equivalent circuit, which has three branches. A series branch representing the primary winding impedance, a shunt branch representing the magnetizing current, and the effect of the no-load losses, and another series branch representing the effect of the secondary winding series impedance. In analysis commonly done, the effect of the magnetizing current is neglected. As a result the shunt branch is eliminated, and the transformer is represented by its series impedance reflected to any one side. Transmission lines are represented by appropriate models based on the length of the line. A commonly used model consists of a series impedance which includes the resistance and reactance, and a shunt capacitance at each end of the line equal to half the total capacitance of the line. Loads are modeled in a variety of ways. A common model used is the representation of the load by an equivalent shunt impedance [4].

With the appropriate component models briefly described above, the one line diagram shown in Fig. B4.4 has a per-phase impedance representation as shown in Fig. B4.5

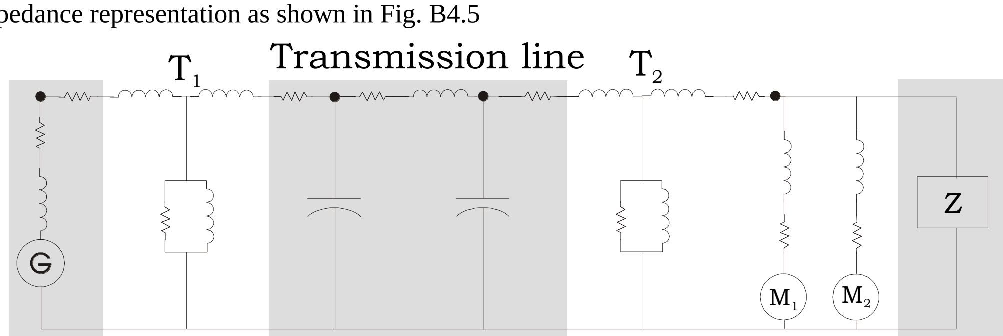


Figure B4.5 The Per-Phase Impedance Representation
for the Single-Line Diagram in Figure B4.4.

In most realistic power systems, the line reactance is much larger than the resistance. In most analyses, the line resistance is neglected. In addition, for transmission lines of short length (50 miles or less), the shunt capacitance can be neglected, as a result, only the series reactance is represented. In several cases, the magnetizing current of transformers is neglected, and the series resistance is small compared to the reactance. Based on these assumptions, Example B4.2, depicts the development of a simplified impedance diagram on a common system base in per-unit consisting largely of reactances for the purpose of analysis.

Example B 4.2

Given the system shown in the single-line diagram in figure B4.4, we select a base voltage of 161 kV for the transmission line, and a base volt-ampere of 20 MVA. Find the per-unit impedances of all components referred to these bases. The components have ratings as follows:

Generator G:	15 MVA, 13.8 kV, x= 0.15 per-unit
Motor M_1:	5 MVA, 13.2 kV, x= 0.15 per-unit
Motor M_2:	5 MVA, 13.2 kV, x= 0.15 per-unit
Transformer T_1:	25 MVA, 13.2 kV-161 kV, x= 0.10 per-unit
Transformer T_2:	15 MVA, 13.8 kV-161 kV, x= 0.10 per-unit
Load:	4 MVA at 0.8 pf lag
Transmission Line:	x = j100 Ω

Solution

Using Eq. (B4.12), we first convert the reactance of the various components to the specified system base of 161 kV in the transmission line, and 20 MVA.

Transformer T_1, has a transformation ratio of 161 kV: 13.2 kV, as a result, it converts the 161 kV base voltage in the transmission line to 13.2 kV on the generator side. This step of determining the appropriate base voltage in different parts of the system based on the transformation ratio of the transformer involved is a key step in converting all the components to a common base. The per-unit impedance of the transformer referred to either side is identical. The power on either side of the transformer is the same, as a result, the base value of the volt-ampere on either side of the transformer is the same. With the new system base values identified, the per-unit reactance of the generator G, and transformer T_1, can now be determined.

Generator G: $$x = (0.15)\left(\frac{20}{15}\right)\left(\frac{13.8}{13.2}\right)^2 = 0.21859 \text{ per-unit}$$

Transformer T_1: $$x = (0.10)\left(\frac{20}{25}\right)\left(\frac{161}{161}\right)^2 = 0.080 \text{ per-unit}$$

Transformer T_2, has a transformation ratio of 161 kV: 13.8 kV, as a result it converts the 161 kV base voltage in the transmission line to 13.8 kV on the load side. The per-unit reactance of the motors and the load are then given by,

Motor M_1 and M_2: $$x = (0.15)\left(\frac{20}{5}\right)\left(\frac{13.2}{13.8}\right)^2 = 0.54896 \text{ per-unit}$$

For the transmission line we must convert from ohmic values to per-unit values. We divide the actual value of the reactance by the base value given by Eq. (B4.10)

Transmission line, $$x = \frac{(j100\Omega)(20x10^6)}{(161x10^3)^2} = j0.07715 \text{ per-unit}$$

For the load we first evaluate a parallel R-X representation using Eqs. (B3.31, B3.32)

For the given load, $S = P + jQ$

$$
\begin{aligned}
&= |S| \cdot (\cos\phi + j\sin\phi) \\
&= 4 \cdot (0.8 + j0.6) \\
&= 3.2 + j2.4 MVA
\end{aligned}
$$

$R_{load} = \frac{|V_{load}|^2}{P}\Omega$, $X_{load} = \frac{|V_{load}|^2}{Q}\Omega$, where V_{load} is the voltage at the load bus which can be determined if the operating conditions for the motors are known.

Dividing these values by the base impedance we get

$$R_{load} = \frac{|V_{load}|^2 (20 \times 10^6)}{(3.2)(13.8 \times 10^3)^2} = \frac{(V_{load}\, p.u.)^2 (20)}{(3.2)} \text{ per-unit}$$

$$X_{load} = \frac{|V_{load}|^2 (20 \times 10^6)}{(2.4)(13.8 \times 10^3)^2} = \frac{(V_{load}\, p.u.)^2 (20)}{(2.4)} \text{ per-unit}$$

Example B 4.3

A balanced Y-connected voltage source with $V_{ab} = 480 + j0V$ is applied to a balanced Δ - connected load $Z_\Delta = 45\angle 40°\Omega$. The impedance between the source and the load is $Z_L = 1\angle 86°\Omega$. Calculate the per-unit current and actual current in phase "a" of the line using $S_{base-3} = 15kVA$ and $V_{base-LL} = 480V$.

Solution

The first step is to convert the Z_Δ into an equivalent Z_Y

$$Z_Y = \frac{Z_\Delta}{3} = \frac{45\angle 40°}{3} = 15\angle 40^\circ \Omega$$

The base impedance is given by

$$Z_{base} = \frac{(base\, V_{LL})^2}{base\, VA_{3\phi}} = \frac{(480)^2}{(1500)} = 15.36\Omega$$

The per-unit line and load impedances are

$$Z_{Lp.u.} = \frac{Z_L}{Z_{base}} = \frac{1\angle 86^\circ}{15.36} = 0.065104\angle 86^\circ \text{ per-unit}$$

and

$$Z_{Yp.u.} = \frac{Z_Y}{Z_{base}} = \frac{15\angle 40^\circ}{15.36} 0.97656\angle 40^\circ \text{ per-unit}$$

also

$$V_{baseLN} = \frac{V_{baseLL}}{\sqrt{3}} = \frac{480}{\sqrt{3}} = 277V$$

$$V_{anp.u.} = \frac{V_{an}}{V_{baseLN}} = \frac{277\angle -30°}{277} \ (1.0\angle -30°) \text{ per-unit}$$

The equivalent circuit in the per-unit representation is shown below in Figure B4.6 below.

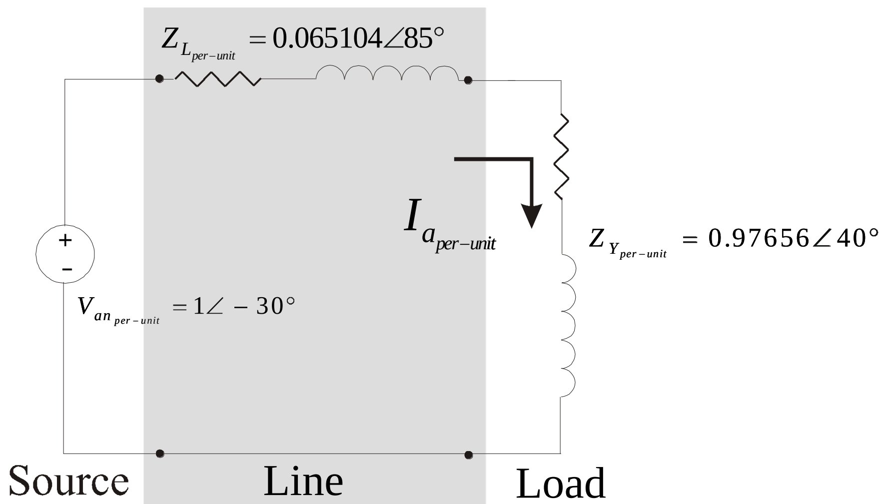


Figure B4.6 Per-Unit Representation for Example B4.3

$$I_{a_{p.u.}} = \frac{V_{an_{p.u.}}}{Z_{Lp.u.} + Z_{Yp.u.}} = \frac{1\angle -30^\circ}{0.065104\angle 86^\circ + 0.97656\angle 40^\circ}$$

$$= \frac{1\angle -30^\circ}{(0.0045414 + j\,0.064945) + (0.748088 + j\,0.62772)}$$

$$= \frac{1\angle -30^\circ}{(0.752629 + j\,0.692666)} = \frac{1\angle -30^\circ}{1.022857\angle 42.62^\circ}$$

$$= 0.97765\angle -72.62^\circ \ per-unit$$

The base current is

$$I_{base} = \frac{kVA_{base3\phi}}{\sqrt{3}\cdot kV_{baseLL}} = \frac{15}{\sqrt{30}\times 0.480} = 18.042\ A$$

and the actual phase "a" line current is

$$I_a = (0.9776\angle -72.62^\circ)(18.042) = 17.6388\angle -72.62^\circ\ A$$

Example B 4.4

Prepare a per-phase schematic of the system shown below in Figure B4.7 and show all impedances in per-unit on a 100 MVA, 154 kV base in the transmission line circuit. Necessary data for this problem are as follows

G1: 50 MVA, 13.8 kV, X = 0.15 per-unit
G2: 20 MVA, 14.4 kV, X = 0.15 per-unit
T1: 60 MVA, 13.2/161 kV, X = 0.10 per-unit
T2: 25 MVA, 13.2/161 kV, X = 0.10 per-unit
Load: 25 MVA, 0.80 pf lag

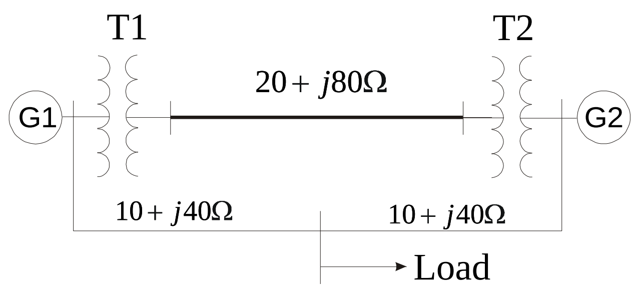


Figure B4.7 One-Line Diagram for System in Example B4.4

Solution

Base kV in the Transmission Line = 154 kV

Base kV in G1 and G2 = $154 \times \frac{13.2}{161} = 12.63\,kV$

Note: Once the Base kV is specified in the transmission line circuit, the Base kV in all other circuits is determined by the transformation ratio of the appropriate transformers. In this example T1 and T2 have the same transformation ratio. Hence the Base kV in G1 and G2 are equal. If the transformation ratios were not the same then the appropriate transformation ratios should be used to determine the base voltage.

$$\mathrm{G1: X} = 0.15 \times \frac{100}{50} \times \left(\frac{13.8}{12.63}\right)^2 = 0.3583\,per-unit$$

$$\mathrm{G2: X} = 0.15 \times \frac{100}{20} \times \left(\frac{14.4}{12.63}\right)^2 = 0.9755\,per-unit$$

$$\mathrm{T1: X} = 0.10 \times \frac{100}{60} \times \left(\frac{161}{154}\right)^2 = 0.10 \times \frac{100}{60} \times \left(\frac{13.2}{12.63}\right)^2 = 0.18216\,per-unit$$

$$\mathrm{T2: X} = 0.10 \times \frac{100}{25} \times \left(\frac{161}{154}\right)^2 = 0.10 \times \frac{100}{25} \times \left(\frac{13.2}{12.63}\right)^2 = 0.4372\,per-unit$$

$$\text{Base Impedance in Transmission Line Circuit} = \frac{(154\text{x}10^3)^2}{100\text{x}10^6} = 237.16\Omega$$

$$Z_{\mathrm{T.Line}} = \frac{20 + j80}{237.16} = 0.084 + j0.3373\,per-unit$$

$$\text{Base Impedance in Load Circuit} = \frac{(12.63x10^3)^2}{100x10^6} = 1.595\Omega$$

$$Z_{D.Line} = \frac{10 + j40}{1.595} = 6.269 + j25.075\, per - unit$$

Load = 25(0.8 + j0.6) = 20 + j15 MVA

$$\text{R}_\text{u} = \frac{|V_{load}|^2 (100x10^6)}{20x10^6 \times (12.63x10^3)^2}, \qquad \text{X}_\text{u} = \frac{|V_{load}|^2 (100x10^6)}{15x10^6 \times (12.63x10^3)^2}$$

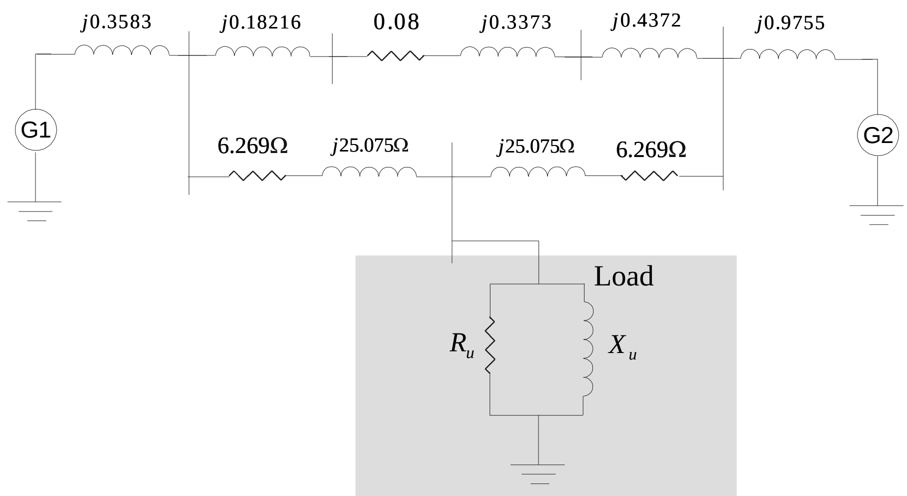


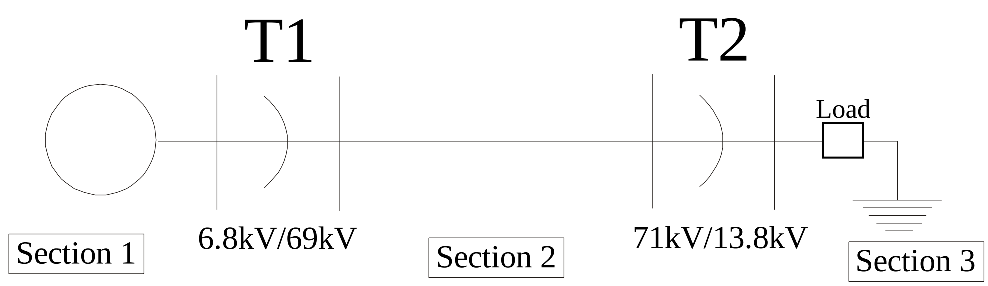
Figure B4.8 Impedance Diagram with Per-Unit Representation

PROBLEMS

Problem 1

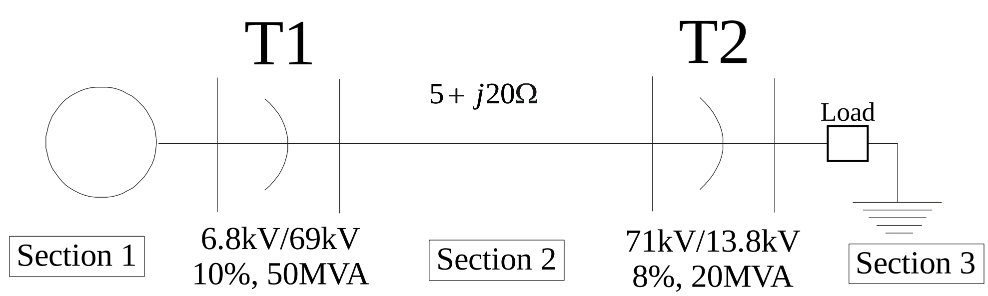
Consider the power system shown below. Choose a system power base 100MVA and a line-to-line voltage base for section 1 as 6.9kV. The load in section 3 consumes 10MVA at 0.8pf leading when the line-to-line voltage at the load is 13.8kV

(a) Determine the ohmic value of a R+jX load (R and X connected in series) in section 3 that consumes this same amount of power at the specified voltage level (i.e., that consumes 10 MVA at 0.8 pf leading at 13.8kV line-to-line).
(b) Compute the impedance base for the section 3 load.



Problem 2

Consider the power system shown below. Choose a system power base of 100MVA and a line-to-line voltage base for section 1 as 6.9kV. Determine the appropriate values of per unit impedance for transformers T1, T2, and the transmission line.



Problem 3

A generator is connected to a transmission line through a transformer having a rated turns ratio (ratio of line to line voltages) of:

20 kV (generator side) to 100 kV (transmission line side).

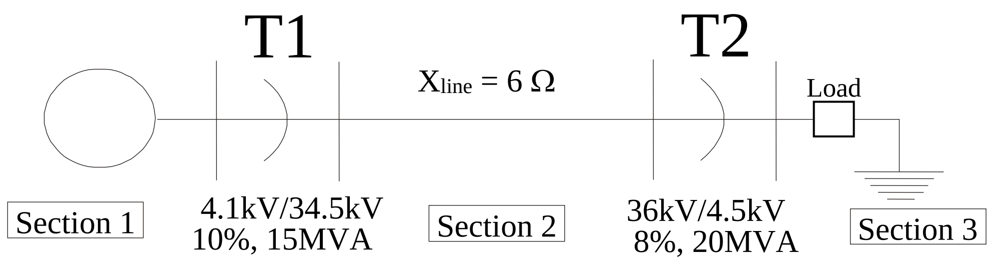
The generator has a per unit reactance of 0.08 pu on a 19 kV, 50 MVA base.

Select the base voltage on the transmission line side to be 110 kV.

a. Compute the base voltage on the generator side.
b. Compute the pu reactance of the generator using a 100 MVA system power base.

Problem 4

Choose a system MVA base of 100 MVA and a voltage base of 4.0 kV for the load portion of the system. Find per-unit values of impedances for both transformers and the transmission line.



Problem 5

You receive the following data from a manufacturer regarding a new three-phase transformer:

Ratio of line-line voltages:	13.8kV/225kV
Power rating:	400 MVA
Per unit reactance on component base:	8%

You are considering replacement of an existing transformer in your three-phase system with this new one, and you want to see how it would affect the currents. Below is a circuit of your system. All data is in per unit on a 100 MVA base. The voltage base for the transmission line is 230 kV and the voltage base for the low side of transformer 1 is 14.1067 kV. The per unit impedances of the transmission line, transformer 2, and the load are:

Z_t=0.0004+j0.005 pu $\quad X_{X2}$=0.02 pu $\quad R_L$=0.8 pu

a. Compute the per unit reactance of the transformer on the system bases.
b. Compute the magnitude of the current I_t in the transmission line, in per unit, and in amperes.