14 Parallel operation of one phase and two phase transformers

By parallel operation we mean two or more transformers are connected to the same supply bus bars on the primary side and to a common bus bar/load on the secondary side. Such requirement is frequently encountered in practice. The reasons that necessitate parallel operation are as follows.

1. Non-availability of a single large transformer to meet the total load requirement.
2. The power demand might have increased over a time necessitating augmentation of the capacity. More transformers connected in parallel will then be pressed into service.
3. To ensure improved reliability. Even if one of the transformers gets into a fault or is taken out for maintenance/repair the load can continued to be serviced.
4. To reduce the spare capacity. If many smaller size transformers are used one machine can be used as spare. If only one large machine is feeding the load, a spare of similar rating has to be available. The problem of spares becomes more acute with fewer machines in service at a location.
5. When transportation problems limit installation of large transformers at site, it may be easier to transport smaller ones to site and work them in parallel.

Fig. 37 shows the physical arrangement of two single phase transformers working in parallel on the primary side. Transformer A and Transformer B are connected to input voltage bus bars. After ascertaining the polarities they are connected to output/load bus

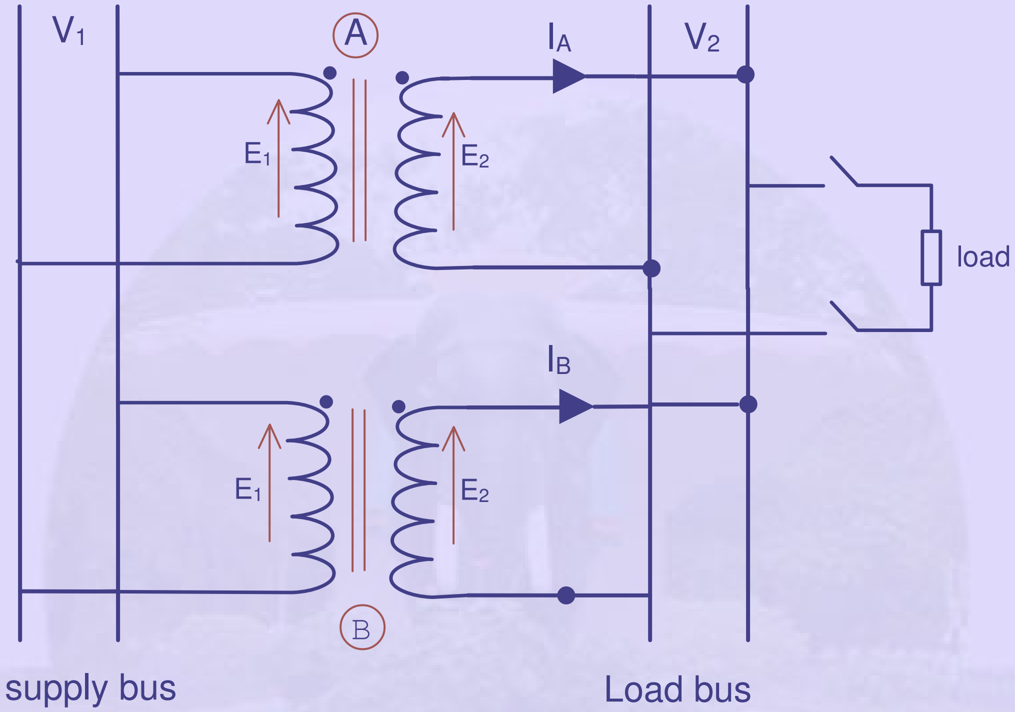


Figure 37: Parallel Operation of Two Single Phase Transformers - Physical

bars. Certain conditions have to be met before two or more transformers are connected in parallel and share a common load satisfactorily. They are,

1. The voltage ratio must be the same.
2. The per unit impedance of each machine on its own base must be the same.
3. The polarity must be the same, so that there is no circulating current between the transformers.
4. The phase sequence must be the same and no phase difference must exist between the voltages of the two transformers.

These conditions are examined first with reference to single phase transformers and then the three phase cases are discussed.

Same voltage ratio Generally the turns ratio and voltage ratio are taken to be the same. If the ratio is large there can be considerable error in the voltages even if the turns ratios are the same. When the primaries are connected to same bus bars, if the secondaries do not show the same voltage, paralleling them would result in a circulating current between the secondaries. Reflected circulating current will be there on the primary side also. Thus even without connecting a load considerable current can be drawn by the transformers and they produce copper losses. In two identical transformers with percentage impedance of 5 percent, a no-load voltage difference of one percent will result in a circulating current of 10 percent of full load current. This circulating current gets added to the load current when the load is connected resulting in unequal sharing of the load. In such cases the combined full load of the two transformers can never be met without one transformer getting overloaded.

Per unit impedance Transformers of different ratings may be required to operate in parallel. If they have to share the total load in proportion to their ratings the larger machine has to draw more current. The voltage drop across each machine has to be the same by virtue of their connection at the input and the output ends. Thus the larger machines have smaller impedance and smaller machines must have larger ohmic impedance. Thus the impedances must be in the inverse ratios of the ratings. As the voltage drops must be the same the per unit impedance of each transformer on its own base, must be equal. In addition if active and reactive power are required to be shared in proportion to the ratings the impedance angles also must be the same. Thus we have the requirement that per unit resistance and per unit reactance of both the transformers must be the same for proper load sharing.

Polarity of connection The polarity of connection in the case of single phase transformers can be either same or opposite. Inside the loop formed by the two secondaries the resulting voltage must be zero. If wrong polarity is chosen the two voltages get added and short circuit results. In the case of polyphase banks it is possible to have permanent phase error between the phases with substantial circulating current. Such transformer banks must not be connected in parallel. The turns ratios in such groups can be adjusted to give very close voltage ratios but phase errors cannot be compensated. Phase error of 0.6 degree gives rise to one percent difference in voltage. Hence poly phase transformers belonging to the same vector group alone must be taken for paralleling.

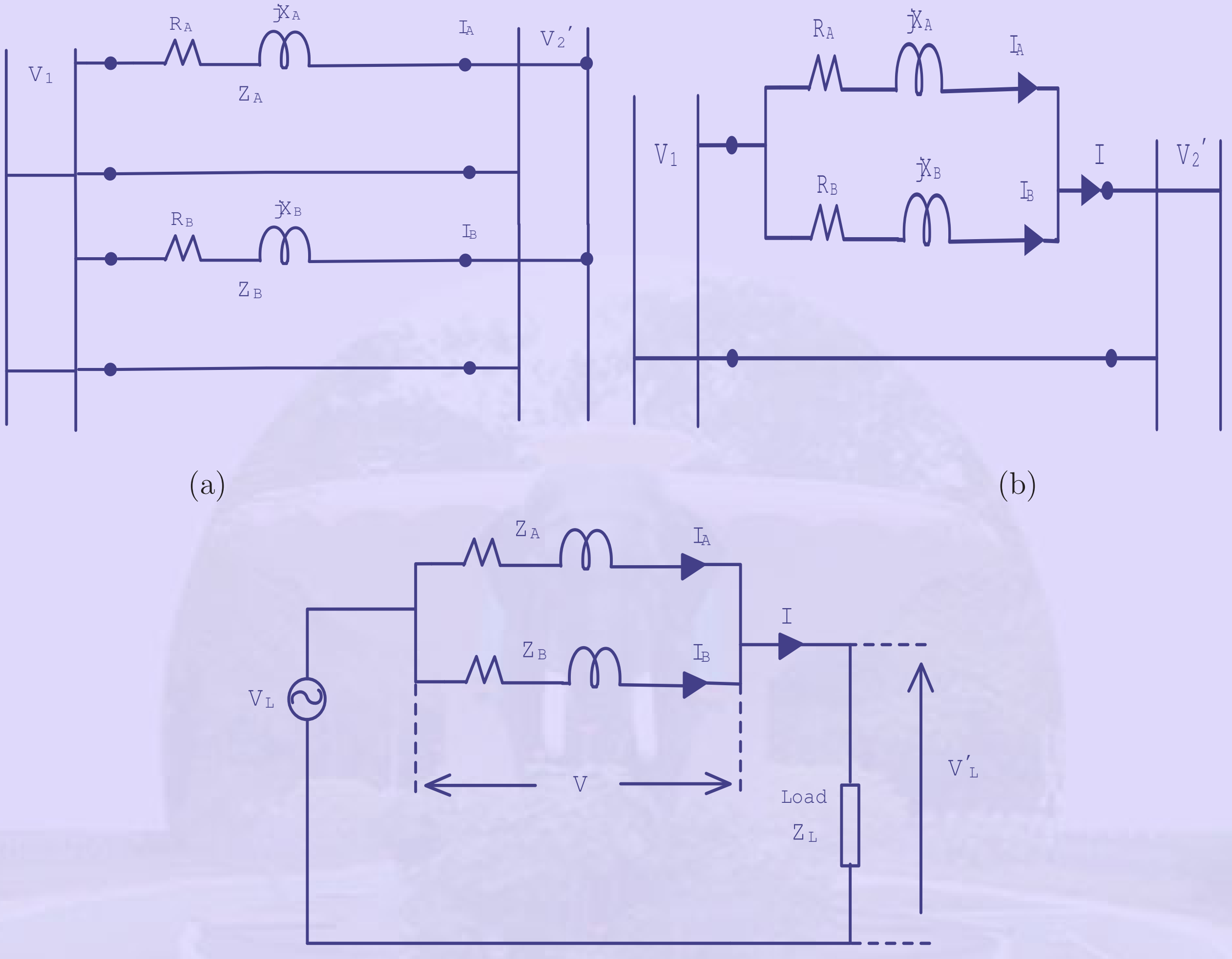
Transformers having $-30°$ angle can be paralleled to that having $+30°$ angle by reversing the phase sequence of both primary and secondary terminals of one of the transformers. This way one can overcome the problem of the phase angle error.

Phase sequence The phase sequence of operation becomes relevant only in the case of poly phase systems. The poly phase banks belonging to same vector group can be connected in parallel. A transformer with +30° phase angle however can be paralleled with the one with −30° phase angle, the phase sequence is reversed for one of them both at primary and secondary terminals. If the phase sequences are not the same then the two transformers cannot be connected in parallel even if they belong to same vector group. The phase sequence can be found out by the use of a phase sequence indicator.

Performance of two or more single phase transformers working in parallel can be computed using their equivalent circuit. In the case of poly phase banks also the approach is identical and the single phase equivalent circuit of the same can be used. Basically two cases arise in these problems. Case A: when the voltage ratio of the two transformers is the same and Case B: when the voltage ratios are not the same. These are discussed now in sequence.

14.1 Case A: Equal voltage ratios

Always two transformers of equal voltage ratios are selected for working in parallel. This way one can avoid a circulating current between the transformers. Load can be switched on subsequently to these bus bars. Neglecting the parallel branch of the equivalent circuit the above connection can be shown as in Fig. 38(a),(b). The equivalent circuit is drawn in terms of the secondary parameters. This may be further simplified as shown under Fig. 38(c). The voltage drop across the two transformers must be the same by virtue of common connection at input as well as output ends. By inspection the voltage equation for the drop can be



(a)

(b)

(c)

Figure 38: Equivalent Circuit for Transformers working in Parallel -Simplified circuit and Further simplification for identical voltage ratio

written as

$$I_A Z_A = I_B Z_B = IZ = v \quad (say) \tag{87}$$

$$\text{Here} I = I_A + I_B \tag{88}$$

And Z is the equivalent impedance of the two transformers given by,

$$Z = \frac{Z_A Z_B}{Z_A + Z_B} \tag{89}$$

$$\text{Thus} \quad I_A = \frac{v}{Z_A} = \frac{IZ}{Z_A} = I.\frac{Z_B}{Z_A + Z_B} \tag{90}$$

$$\text{and } I_B = \frac{v}{Z_B} = \frac{IZ}{Z_B} = I.\frac{Z_A}{Z_A + Z_B}$$

If the terminal voltage is $V = IZ_L$ then the active and reactive power supplied by each of the two transformers is given by

$$P_A = Real(VI_A^*) \text{ and } Q_A = Imag(VI_A^*) \text{ and} \tag{91}$$

$$P_B = Real(VI_B^*) \text{ and } Q_B = Imag(VI_B^*) \tag{92}$$

From the above it is seen that the transformer with higher impedance supplies lesser load current and vice versa. If transformers of dissimilar ratings are paralleled the transformer with larger rating shall have smaller impedance as it has to produce the same drop as the other transformer, at a larger current. Thus the ohmic values of the impedances must be in the inverse ratio of the ratings of the transformers. $I_A Z_A = I_B Z_B$, therefore $\frac{I_A}{I_B} = \frac{Z_B}{Z_A}$. Expressing the voltage drops in p.u basis, we aim at the same per unit drops at any load for the transformers. The per unit impedances must therefore be the same on their respective bases.

Fig. 39 shows the phasor diagram of operation for these conditions. The drops are magnified and shown to improve clarity. It is seen that the total voltage drop inside the

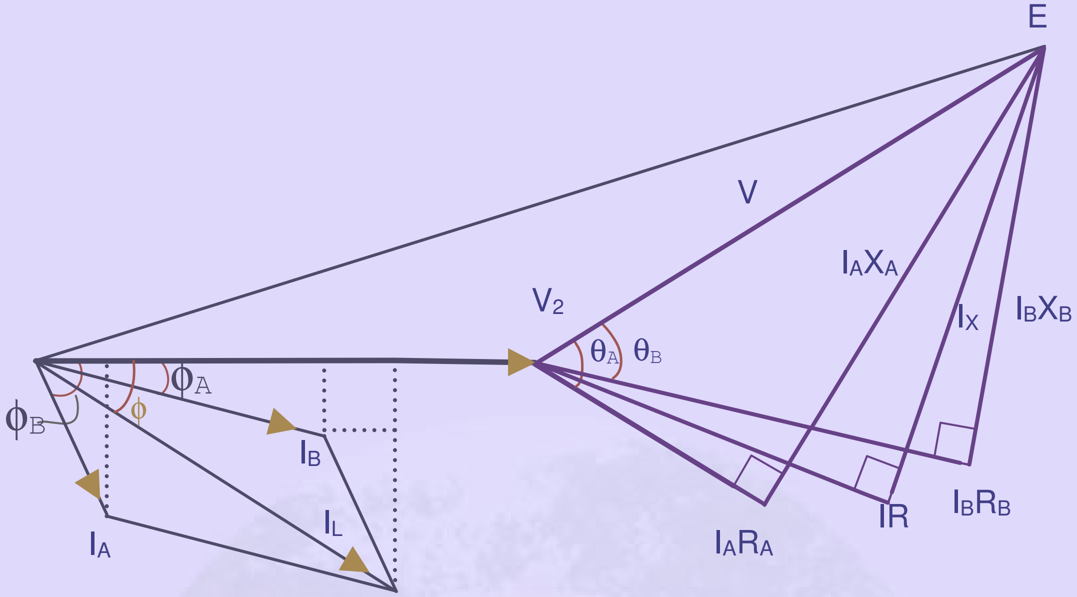


Figure 39: Phasor Diagram of Operation for two Transformers working in Parallel

transformers is v but the currents I_A and I_B are forced to have a different phase angle due to the difference in the internal power factor angles θ_A and θ_B. This forces the active and reactive components of the currents drawn by each transformer to be different (even in the case when current in each transformer is the same). If we want them to share the load current in proportion to their ratings, their percentage (or p.u) impedances must be the same. In order to avoid any divergence and to share active and reactive powers also properly, $\theta_A = \theta_B$. Thus the condition for satisfactory parallel operation is that the p.u resistances and p.u reactance must be the same on their respective bases for the two transformers. To determine the sharing of currents and power either p.u parameters or ohmic values can be used.

14.2 Case B :Unequal voltage ratios

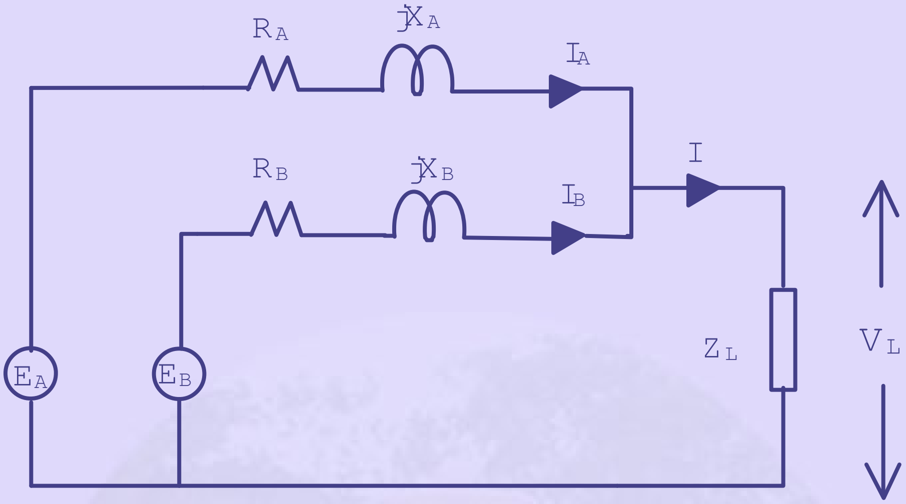


Figure 40: Equivalent Circuit for unequal Voltage Ratio

One may not be able to get two transformers of identical voltage ratio in spite of ones best efforts. Due to manufacturing differences, even in transformers built as per the same design, the voltage ratios may not be the same. In such cases the circuit representation for parallel operation will be different as shown in Fig. 40. In this case the two input voltages cannot be merged to one, as they are different. The load brings about a common connection at the output side. E_A and E_B are the no-load secondary emf. Z_L is the load impedance at the secondary terminals. By inspection the voltage equation can be written as below:

$$\begin{aligned} E_A &= I_A Z_A + (I_A + I_B) Z_L = V + I_A Z_A \cdot \\ E_B &= I_B Z_B + (I_A + I_B) Z_L = V + I_B Z_B \cdot \end{aligned} \tag{93}$$

Solving the two equations the expression for I_A and I_B can be obtained as

$$\begin{aligned} I_A &= \frac{E_A Z_B + (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)} \quad \text{and} \\ I_B &= \frac{E_B Z_A + (E_B - E_A) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)} \end{aligned} \tag{94}$$

Z_A and Z_B are phasors and hence there can be angular difference also in addition to the difference in magnitude. When load is not connected there will be a circulating current between the transformers. The currents in that case can be obtained by putting $Z_L = \infty$ (after dividing the numerator and the denominator by Z_L). Then,

$$I_A = -I_B = \frac{(E_A - E_B)}{(Z_A + Z_B)} \tag{95}$$

If the load impedance becomes zero as in the case of a short circuit, we have,

$$I_A = \frac{E_A}{Z_A} \quad \text{and} \quad I_B = \frac{E_B}{Z_B} \tag{96}$$

Instead of the value of Z_L if the value of V is known , the currents can be easily determined (from Eqns. 93) as

$$I_A = \frac{E_A - V}{Z_A} \quad \text{and} \quad I_B = \frac{E_B - V}{Z_B} \tag{97}$$

If more than two transformers are connected across a load then the calculation of load currents following the method suggested above involves considerable amount of computational labor. A simpler and more elegant method for the case depicted in Fig. 41 is given below. It is known by the name parallel generator theorem.

$$\begin{aligned} I_L &= I_A + I_B + I_C + \ldots\ldots \\ \text{But} \quad I_A &= \frac{E_A - V}{Z_A}, \quad I_B = \frac{E_B - V}{Z_B}, \quad I_C = \frac{E_C - V}{Z_C} \\ V &= I_L . Z_L \end{aligned} \tag{98}$$

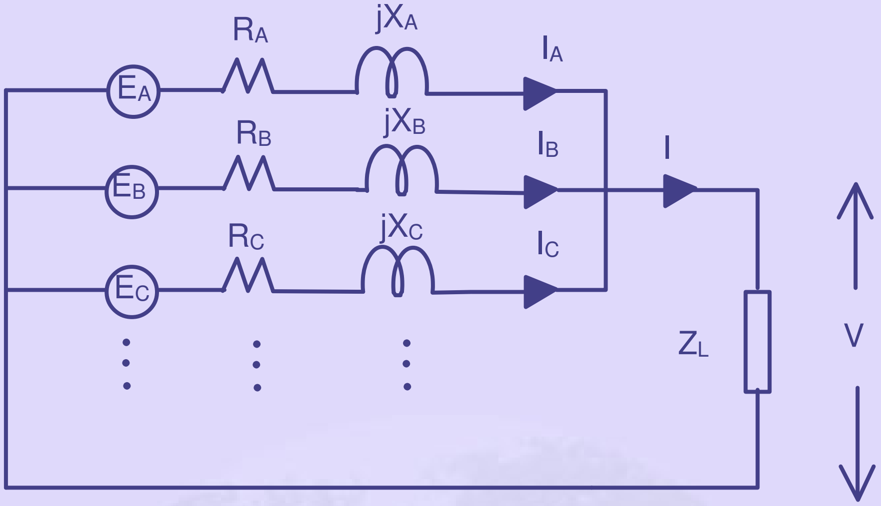


Figure 41: Parallel Generator Theorem

Combining these equations

$$\frac{V}{Z_L} = \frac{E_A - V}{Z_A} + \frac{E_B - V}{Z_B} + \frac{E_C - V}{Z_C} + ... \tag{99}$$

Grouping the terms together

$$V(\frac{1}{Z_L} + \frac{1}{Z_A} + \frac{1}{Z_B} + \frac{1}{Z_C} + ...) = \frac{E_A}{Z_A} + \frac{E_B}{Z_B} + \frac{E_C}{Z_C} + ...$$

$$= I_{SCA} + I_{SCB} + I_{SCC} + ... \tag{100}$$

$$(\frac{1}{Z_L} + \frac{1}{Z_A} + \frac{1}{Z_B} + \frac{1}{Z_C} + ...) = \frac{1}{Z} \tag{101}$$

$$V = Z(I_{SCA} + I_{SCB} + I_{SCC} + ...) \tag{102}$$

From this V can be obtained. Substituting V in Eqn. 98, I_A, I_B etc can be obtained. Knowing the individual current phasor, the load shared by each transformer can be computed.