Advanced Paralleling of LTC Transformers by the Circulating Current Method

1.0 ABSTRACT

Beckwith Electric Co. Application Note #11, Introduction to Paralleling of LTC Transformers by the Circulating Current Method, builds a system and describes the operation for the basic case of two identical transformers operating in parallel. While perhaps most systems are covered by that definition, there are also many installations which involve

1. more than two transformers, or
2. transformers which are very different in their electrical characteristics.

This Application Note builds on Note #11 to consider these more complicated applications.

2.0 ISSUES

Reiterating from the Introductory Application Note #11, the basic premise for LTC transformers operating in parallel is simple:

1. The transformers must continue their basic function of controlling the load bus voltage as prescribed by the setting on the control.
2. The transformers must act to minimize the current which circulates between them.

Additionally, as discussed in this Note,

3. Installations with more than two transformers in parallel must continue to divide the load between all remaining transformers when one (or more) is removed from service.
4. The transformers must act to minimize the current which circulates between them, as may additionally be due to mismatch in the design of those transformers.

The progression of the system definition to three or more transformers is a straightforward extrapolation of the earlier discussion. The question of mismatched transformers can be more involved—a few situations commonly encountered being the basis of this note.

3.0 CONSIDERATION #1—THREE OR MORE IDENTICAL TRANSFORMERS IN PARALLEL

3.1 Three identical transformers in service, evenly distributed load

To continue the progression from Application Note #11 Figure 8, consider a level of definition for three parallel transformers which describes a circuit including the LTC control (the “90” relay), the paralleling balancer module and the circuit breaker auxiliary “a” and “b” contacts. The overcurrent relay (“50”) and the auxiliary ct are not included in this discussion.

Careful examination of Figure 1 reveals that the schematic is a straightforward extension of the two transformer case. It may be easier to envision the circuit connection changes if it is considered that transformers 1 and 3 are configured just as were transformers 1 and 2 in the previous study; the new transformer has been effectively inserted between them.

Current magnitudes as drawn on Figure 1 assume that there is a 1500 ampere unity power factor load on the system. There is a reactive current of 35 A in T1 because it is on a tap position higher than T2 and T3. Because the load is taken as 1.0 power factor, it is easy to distinguish the control circuit currents which are due to the load (the real components) and those due to circulating current (the reactive components). As should be expected, the load current portion is accommodated independently within the control circuit of each transformer, whereas the circulating current interacts between the controls. In this illustration there is twice as much current in the paralleling input of the 90 relay at T1 as in those on T2 and T3. The tap position on T1 will tend down with twice the bias tending to raise T2 and T3.

3.2 Two of three transformers in service, evenly distributed load

An illustration showing the “a” and “b” contacts based on circuit breaker 52-3 being open is shown in Figure 2, where the load is unchanged and the reactive (circulating) current in T1 remains 35 A. The paralleling balancer associated with T3 is out of the circuit except for the line drop compensation current. The closing of contact 52-3b allows there to be no current in the upper ct of the T3 balancer. The result is that transformers T1 and T2 operate properly in parallel, but their respective LDC circuits continue to recognize only one-third of the total load current.

3.3 Three transformers in service, load bus tie opened

The complete illustration needs to consider that the “52” breakers are closed, but breaker 24-2 has been opened in the bus. Figure 3 depicts the auxiliary switch contacts for this event where the load on T3 has been raised to 600 A to more clearly show the isolated path.

As defined with a unity power factor load and no opportunity for a circulating current, there can be no reactive component of current in T3; that transformer is seen to operate wholly independently of the other two.

Presuming the same 35 A circulating current to be driven by the unequal tap positions results in the current paths shown for T1 and T2, it should come as no surprise that the portion of Figure 3 comprising T1 and T2 is identical to that of Figure 7A of Application Note #11.

3.4 More than three transformers connected in parallel

As will be seen, any number of identical LTC transformers may, in principle, be operated in parallel using the circulating current method; at least one utility operates many substations with four in parallel. The reader may wish to expand on Figures 1 through 3 to add transformers, considering certain combinations of open circuit breakers and defining the load and circulating current path.

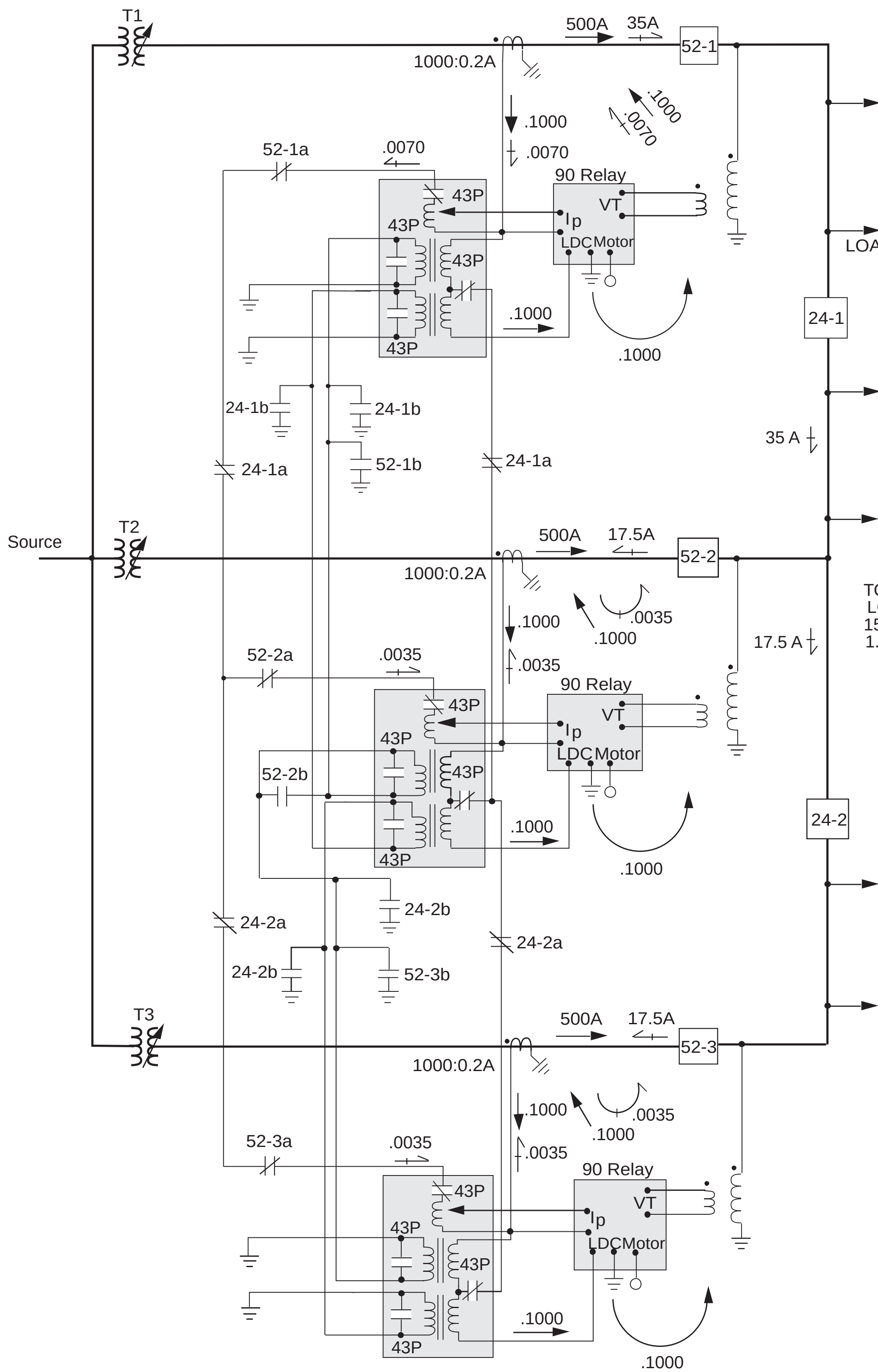


Figure 1 Basic Circuit for Three LTC Transformer Paralleling by the Circulating Current Method Including Circuit Breaker Auxiliary Switch Contacts

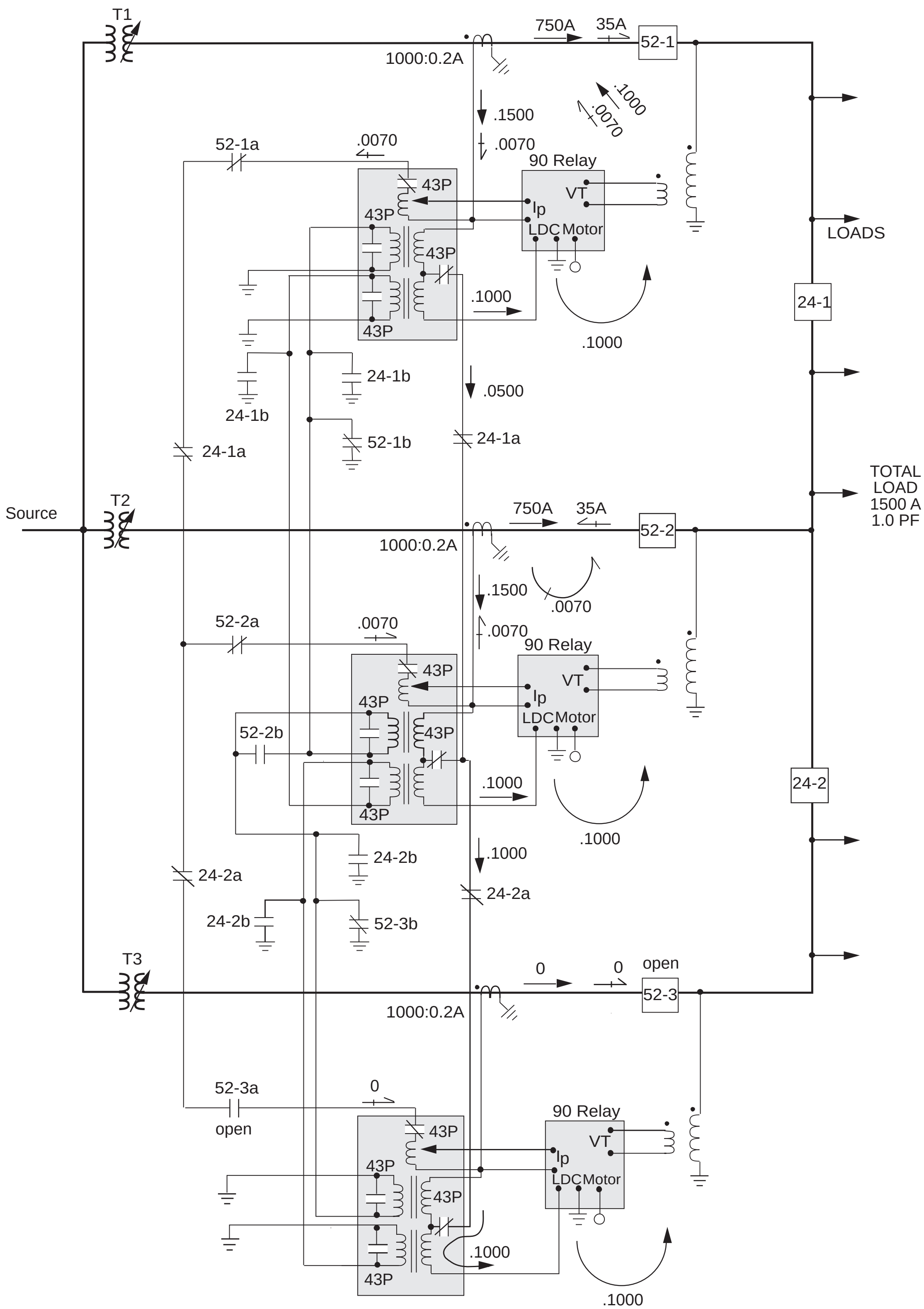


Figure 2 Basic Circuit for Three LTC Transformer Paralleling by the Circulating Current Method
Transformer #3 Out of Service

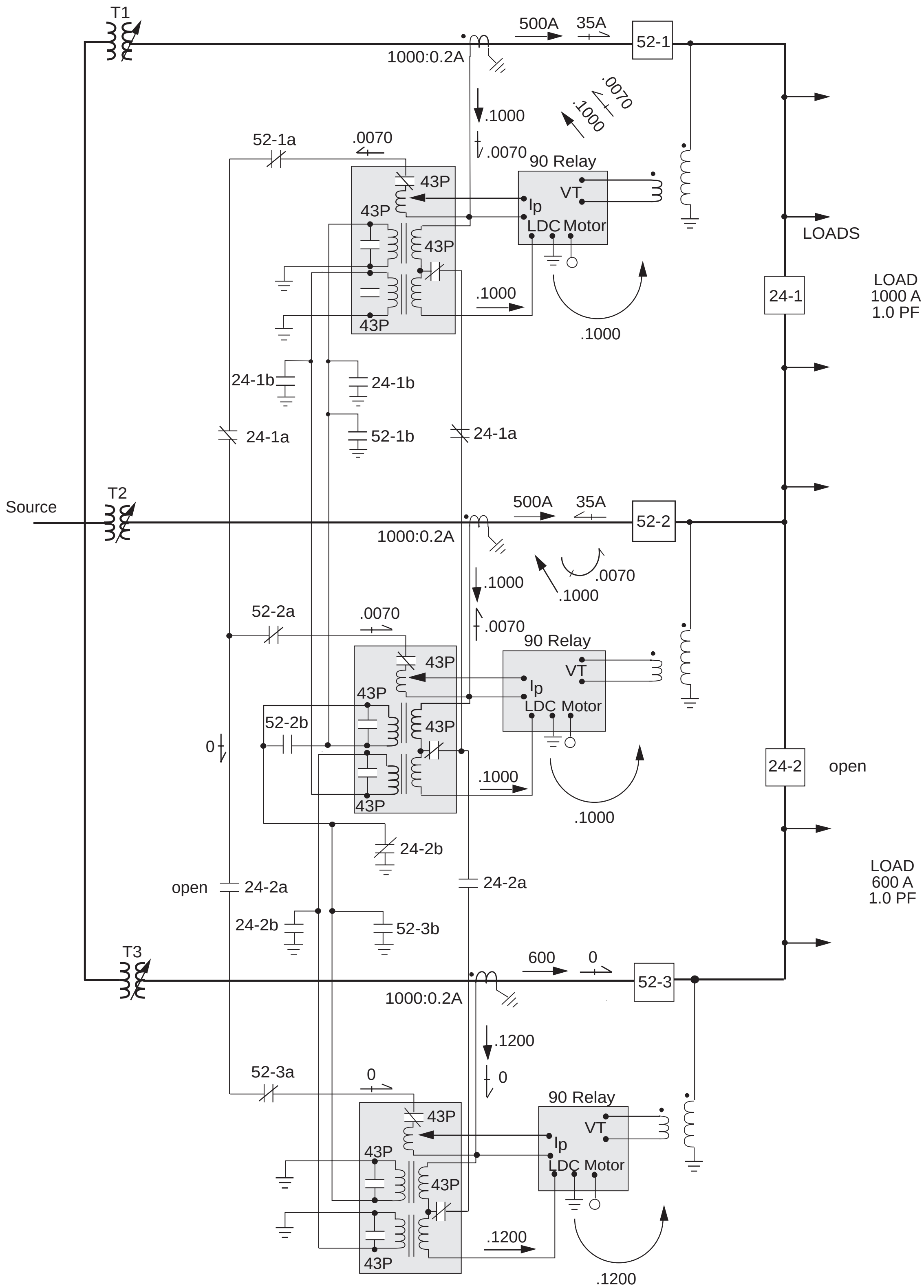


Figure 3 Basic Circuit for Three LTC Transformer Paralleling by the Circulating Current Method
Bus Tie Breaker 24-2 is Open

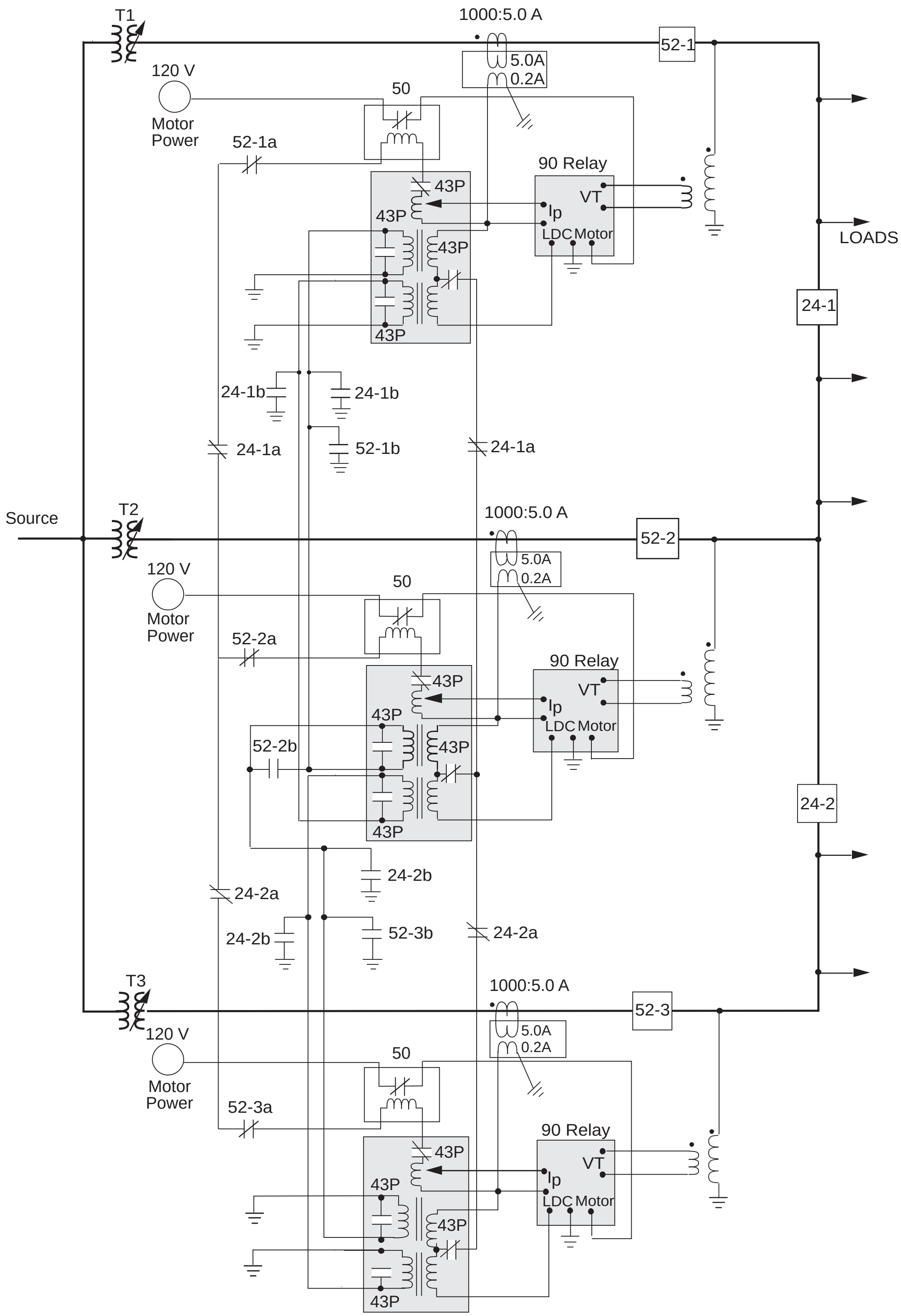


Figure 4 Basic Circuit for Three LTC Transformer Paralleling by the Circulating Current Method Including Circuit Breaker Auxiliary Switch Contacts

3.5 Complete circuit with auxiliary ct and ac current relay

In Figure 4, three auxiliary 5.0 A to 0.2 A cts and three ac current relays are added to form the complete circuit. The question is sometimes raised as to why, in the two transformer case, two such relays are required, since being in series they are redundant. In fact one such relay per transformer is only required when there are three or more involved. Referring back to the case of Figure 1, it is noted that the coil current of the "50" device is 0.0070 A for T1 but only 0.0035 A for each of T2 and T3. Since T1 is the one unit digressing from the others, it is appropriate that its LTC be disabled first, as will be the case if all of the current relays are set the same. Recall that the bias of T2 and T3 in Figure 1 is such as to raise their tap position, which will tend to bring them into conformity with T1 as the bus voltage and settings of the "90" relays may dictate.

4.0 CONSIDERATION #2—DISSIMILAR TRANSFORMERS IN PARALLEL

4.1 Basic Requirements

Before attempting to operate two LTC transformers in parallel, it must first be established that the transformers, viewed as black boxes, exhibit essentially the same voltage ratio and identical line phasing; otherwise, paralleling is not possible.

1. Two transformers might have slightly different voltage ratios; for example, one is rated 13.8 kV and the other 13.2 kV on the secondary. These can be used in parallel after adjusting no-load taps, if available, to obtain identical turns ratio, or by recognizing that the transformers will find optimum operating load taps which will not be the same on the two units.

2. It is required that line phasing be nominally identical. This is to say that the two transformers must exhibit the same phase shift, primary to secondary. Wye-wye or delta-delta banks will be configured for zero phase shift, but note that wye-delta and delta-wye banks will be bussed to exhibit a shift of 30°. Thus, it is not possible to operate a wye-wye or a delta-delta bank in parallel with a wye-delta bank. The resulting 30° phase shift difference of the banks would result in a heavy real (not reactive) circulation of power between the transformers.

4.2 Two transformers of equal kVA, unequal impedance—the basic problem

Two transformers operated in parallel on equal voltage tap positions will be loaded inversely as their impedances; or inversely as their per unit impedances when expressed on the same base.

To exaggerate to make a point, consider two 12 MVA transformers, T1 of 6% IZ and T2 of 12% IZ, connected in parallel as shown in Figure 5.

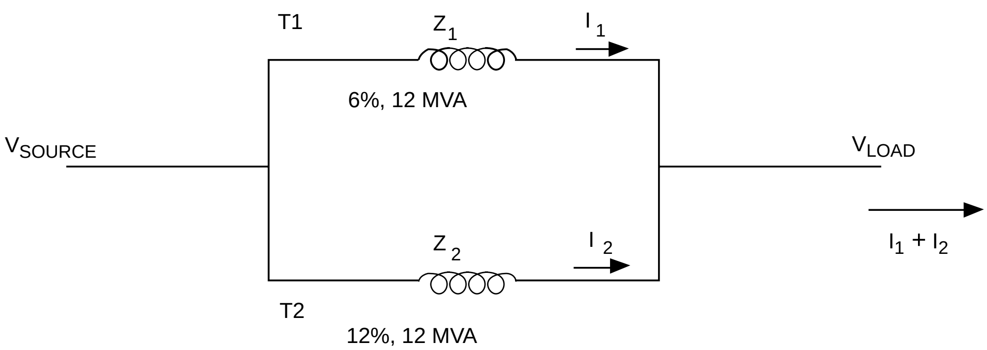


Figure 5 Two transformers of unequal impedance in parallel

A phasor diagram, Figure 6, reveals the voltage and current relationships where, for illustration, a 0.966 lagging power factor load is presumed ($I_1 + I_2$ lags V_{load} by 15°). Since $V_{source} – Z_1I_1 = V_{load}$ and $V_{source} – Z_2I_2 = V_{load}$, it is evident that $Z_1I_1 = Z_2I_2$.

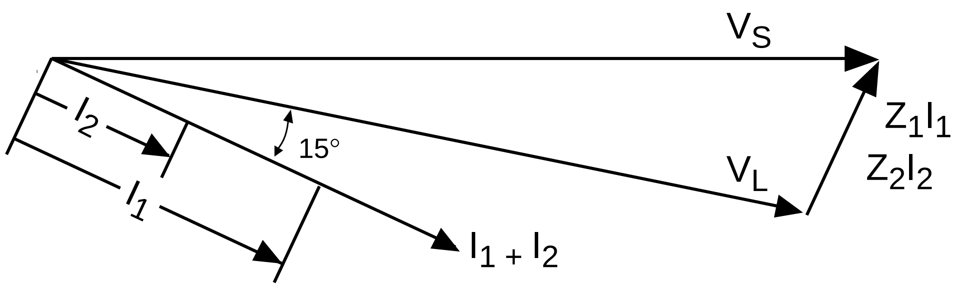


Figure 6 Phasor diagram for two transformers of unequal impedance in parallel

Since Z_1 and Z_2 are both taken to be pure reactances, I_1 and I_2 will be in phase with each other. In order to satisfy the system,

$$I_2 = (1/2)I_1$$

The problem is that both transformers are rated for 12 MVA, but the circuit impedances define a system where T2 will be loaded to only one-half that of T1. Thus, when T1 is fully loaded, T2 is loaded at only 50%; conversely T2 cannot be loaded to its capacity without severely overloading T1.

It is sometimes suggested that this shortcoming could be circumvented by simply operating T2 on a higher voltage tap position, i.e., a tap position which would boost the output of T2 such that the currents I_1 and I_2 are made equal, thereby making possible loading to the rating of both transformers. A circuit designed to attempt this solution is that of Figure 7, being identical to Figure 5 but including a voltage boost, V_2, on transformer T2. The phasor diagram is now more complex, and must be solved recognizing certain relationships:

- The load power factor has not changed, therefore $\vec{I}_1 + \vec{I}_2$ continues to lag V_{load} by 15°

- $V_{source} - Z_1 I_1 = V_{load}$
- $V_{source} + V_2 - Z_2 I_2 = V_{load}$

Further, the objective is to make $|I_1| = |I_2|$ which demands that since $Z_2 = 2Z_1$ that $|Z_2 I_2| = 2|Z_1 I_1|$

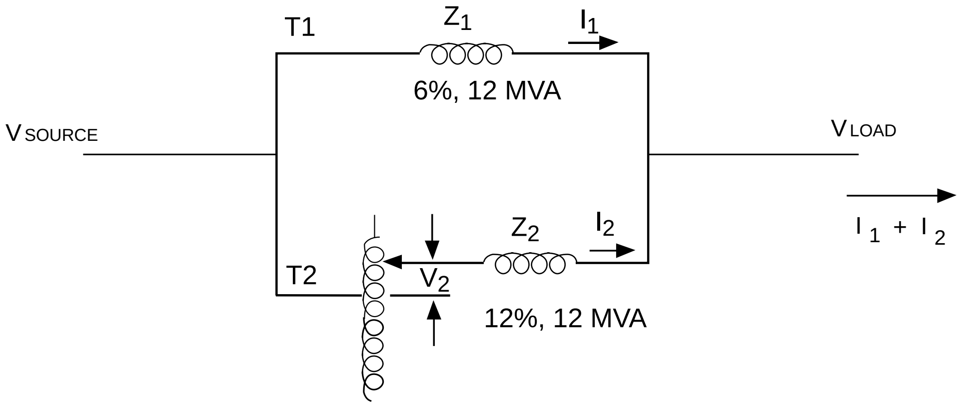


Figure 7 Two transformers of unequal impedance and tap position in parallel

Figure 8, drawn to the same scale as Figure 6, reveals the solution where all phasors satisfy the problem definition. Thus, while I_2 has been made equal in magnitude to I_1, they are grossly out of phase with each other. That I_1 is now a leading current is indicative of a very large circulating current between the transformers. Since the current balance method of paralleling is based on the differences in I_1 and I_2 (magnitude and phase) and the phasing of I_1 and I_2 are very different in Figure 8, this is inoperable as it does not represent a valid solution for the paralleling balancer method. Thus, in principle, two transformers with unequal impedance should not be operated in parallel. Some discrepancy in impedance, however, can be tolerated. As a general rule, parallel operation is possible when the impedances of the two transformers expressed on the same base, are within 7.5% of each other.

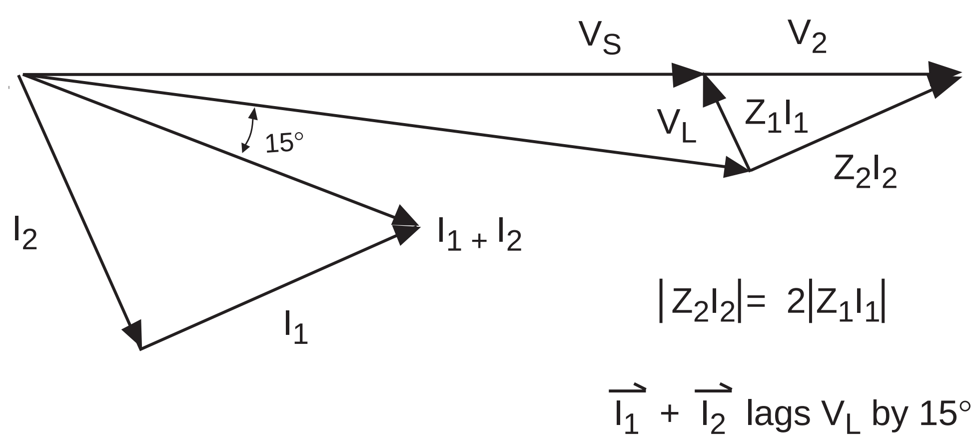


Figure 8 Phasor diagram, two transformers with unequal impedance but equal current magnitudes

4.3 Paralleling transformers of unequal kVA rating or impedance

The conclusion of section 4.2 not withstanding, it is common that there will be two transformers, perhaps of different manufacture or age, which display significantly different nameplate ratings as to kVA or impedance. The objective is to load them in parallel in order to avoid the capital expenditure of a new transformer.

Where the transformers are of different ratings or impedance, the objective will not be to load each transformer to its rating, but to divide the load between the two in parallel according to the kVA of each, adjusted so that the impedances are numerically equal when expressed on the individual unit base.

As illustration, consider the realistically sized transformers of Figure 9.

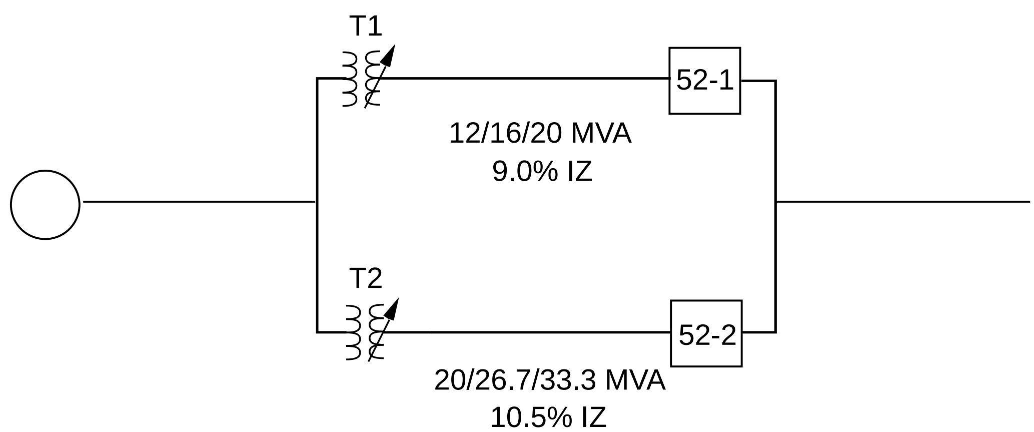


Figure 9 Two realistic transformers of unequal rating

Recognize that the percent impedance voltage of power transformers is based on the self-cooled (OA) rating, so for

T1: IZ = 0.090 per unit on 12.0 MVA base

T2: IZ = 0.105 per unit on 20.0 MVA base.

Since the transformers do not exhibit the same impedance on their design OA bases, it is first necessary to determine to what rating each transformer can be effectively applied if the % IZ's are made equal. Since the percent impedance varies as the MVA base (presuming equal voltage ratios):

1. Relating to the 9.0% IZ on 12 MVA base of T1

   T1: 0.090 pu IZ on 12.0 MVA base

   T2: (0.090 / 0.105) x 20 MVA = 17.14 MVA

   T2: 0.090 pu IZ on 17.14 MVA base

   If T1 is fully loaded, T2 is loaded to less than its rating.

2. Relating to the 10.5% IZ on 20 MVA base of T2

T1: (0.105 / 0.090) x 12 MVA = 14.0 MVA

T1: 0.105 pu IZ on 14 MVA base

T2: 0.105 pu IZ on 20 MVA base

If T2 is fully loaded, T1 is loaded in excess of its rating

It is seen that when the transformer impedances are stated as the same per unit value, transformer T2 is effectively rated only 43% higher than T1, instead of the 67% which would be indicated by their nameplates. It is in this ratio, 1.43:1, that T2 should be loaded relative to T1 when they are operated in parallel.

It has been determined that the rating of T1 will establish the rating of the bank (kVA T1 + 1.43 kVA T1 = 2.43 kVA T1) because to base the bank on the rating of T2 would overload T1. Therefore the objective becomes one of effectively making the rating of transformer 2 be 1.43 x 12 MVA = 17.14 MVA, rather than 20 MVA.

To accomplish this step involves knowledge of the current transformer (cts) monitoring the load current. Consideration of this matter is given in the Appendix.

Presuming now that vts and cts are used in each transformer which are compatible, it is necessary to scale the ct input of the LTC control on T2 so that its base is 1.43 times that of T1. Stated otherwise, when loaded to 12 x 1.43 = 17.14 MVA, the ct on T2 should produce the same current magnitude signal as T1 when T1 is loaded to 12 MVA. When this is satisfied, the paralleling equipment will recognize a balanced situation when those transformers are loaded in the ratio T2 to T1 = 1.43.

Since T1 will remain the basis, it is reasonable to use the ct in it and modify only that in T2. Figure 10 shows the system including ct ratios which might be found based only on the transformer rating. Note that T1 will be overloaded if the total load exceeds 2.43 times the rating of T1. Other equipment could be applied to detect this condition.

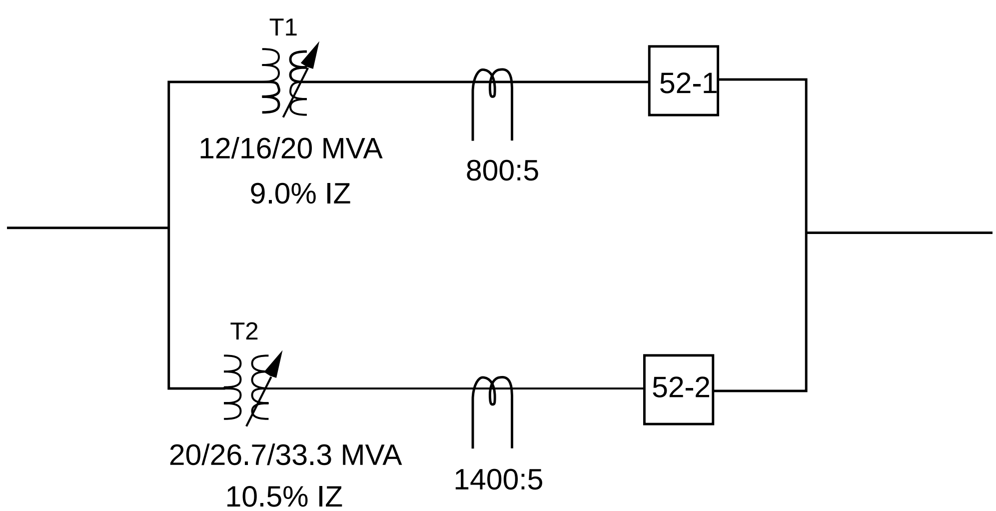


Figure 10 Two transformers of unequal rating showing installed cts

If the cts are used as is, the loading ratio is 1.75:1 which loading ratio, it has been shown, is not to be used. Instead, the T2 transformer ct should present an effective primary rating of the ct on T1, times 1.43 or

ct primary T2 = 800 x 1.43 = 1144 A

or a ratio of 1144:5.0A instead of 1400:5. It is certainly much more feasible to work at the secondary by including an auxiliary ct rated 5.0:6.12 so that the overall ratio is 1400:6.12, equal to 1144:5.0.

With this simple addition, Figure 10 evolves into Figure 11 showing that effectively T2 is 1.43 times T1 in usable capacity.

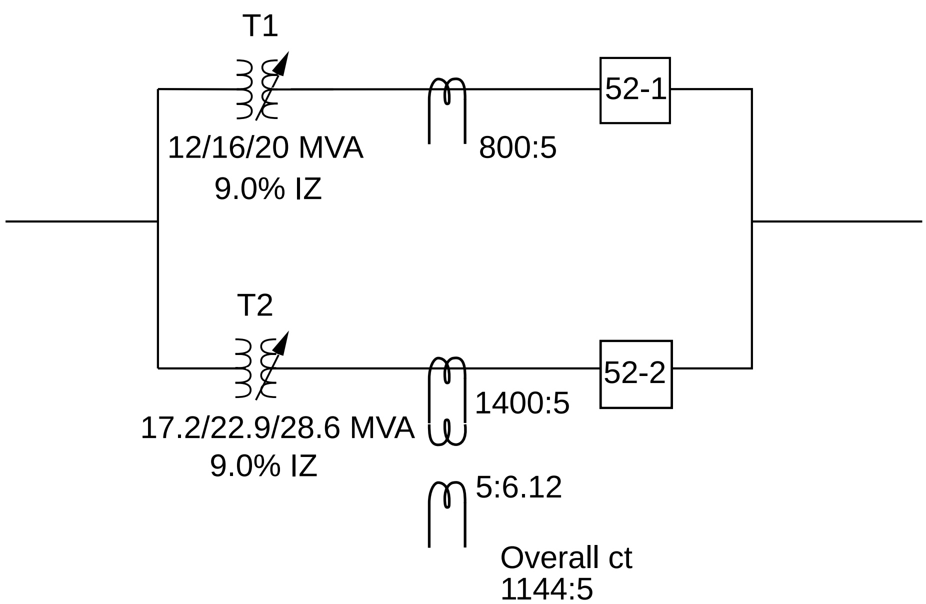


Figure 11 Two transformers sized for equal per unit impedance

Note that while this system will result in the transformers being loaded in the ratio of their usable capacity, it does not properly account for a circulating current due to unequal tap position. For the case of Figure 11, a presumed 40 A circulating current results in different ct secondary current in T1 and T2. Figure 12 portrays the situation with the currents scaled down to 0.2 A. For this illustration, there is no load current, only 40 A of circulating current. Yet, 15% of the circulating current finds its return path through the 90 relay line drop compensation circuit, which would normally recognize only the load portion of the current. This is not a problem for installations where the objective is bus regulation and LDC is set to zero.

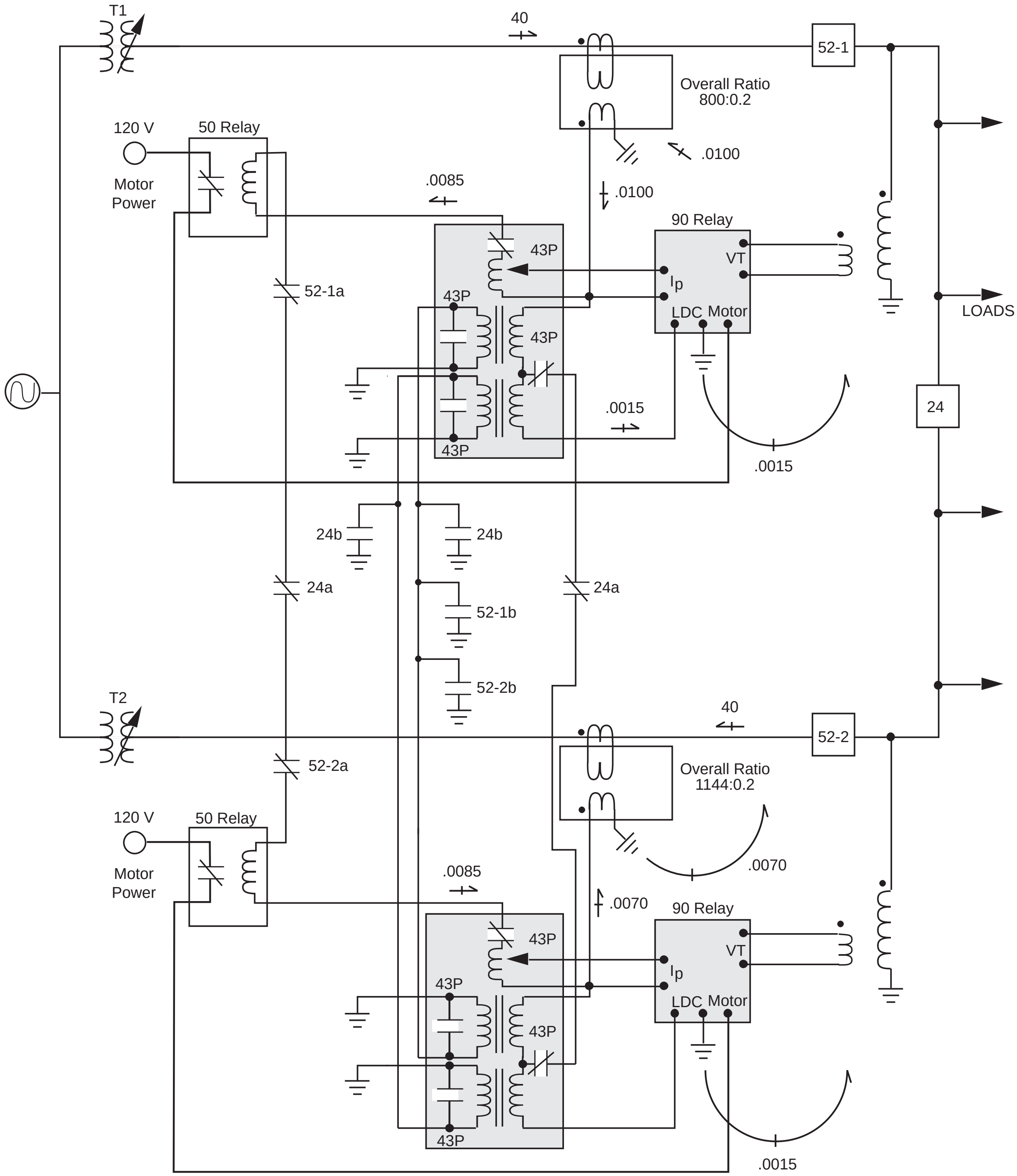


FIGURE 12 Two transformers with cts sized for Unequal Impedance Showing Path of Circulating Current

4.4 Paralleling systems with an intermediate load tap

It occasionally happens that the system to be paralleled is that of Figure 13. In this case, the upper path is transformers T11 and T12 in series which are together in parallel with another transformer, T2. There is load taken from the bus between T11 and T12. The transformers are shown as impedances in Figure 14.

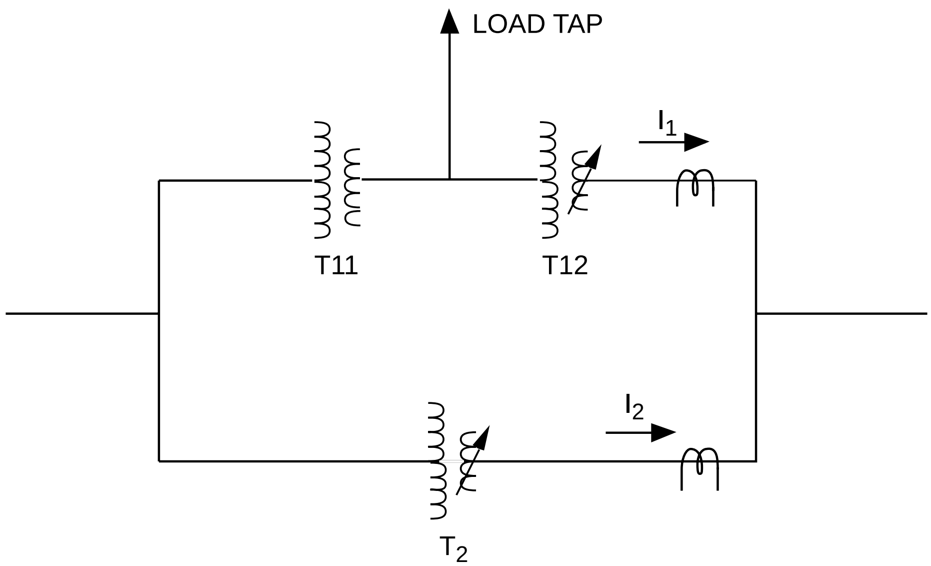


Figure 13 Paralleling system with intermediate load tap

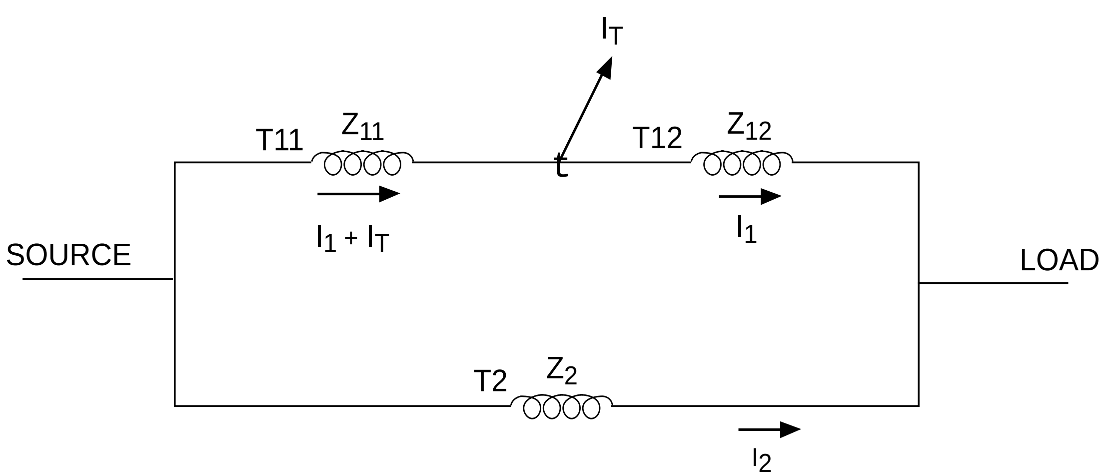


Figure 14 Impedances circuit of paralleling system with intermediate load tap.

Writing the voltage drop equations:

$$V_{source} – Z_2I_2 = V_{load}$$

$$V_{source} – [Z_{11}(I_1 + I_T) + Z_{12}I_1] = V_{load}$$

so

$$Z_2I_2 = Z_{11}(I_1 + I_T) + Z_{12}I_1$$

I_T in T11 results in a voltage drop in the upper path which does not occur in the lower path. Note that because of this, if $I_1 = I_2$ then $Z_2 = Z_{11} + Z_{12}$ or, conversely, the parallel impedance paths must be different in order for the LTC load currents to be the same.

The effect of the I_TZ_{11} drop is equivalent to an additional impedance in the Z_1 path, Z_{13} such that

$$Z_{11}I_T \text{—} Z_{13}I_1$$

Where Z_{13} is a fictitious impedance included to simulate the drop of $Z_{11}I_T$. Now the circuit can be further simplified to that of Figure 15 where the upper path series impedance consists of the impedances of transformers T11 and T12 plus the new Z_{13}. The effective value of this new impedance for calculation is determined as

$$Z_{11}(I_1+I_T) + Z_{12}I_1 = (Z_{11} + Z_{13} + Z_{12})\ I_1$$

$$(Z_{11} + Z_{12})I_1 + Z_{11}I_T = (Z_{11} + Z_{12})I_1 + Z_{13}I_1$$

$$Z_{11}I_T=Z_{13}I_1$$

$$Z_{13} = (I_T / I_1)Z_{11}$$

so Z_{13} varies with I_T and I_1, but is constant if the ratio I_T / I_1 is constant.

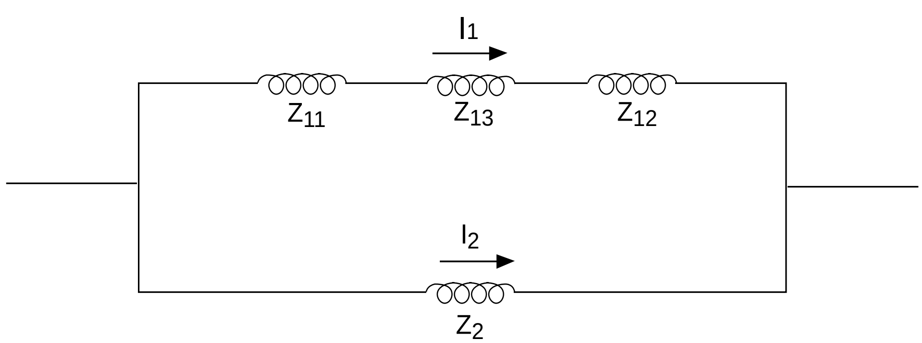


Figure 15 Equivalent impedance circuit of paralleling system with intermediate load tap

For proper paralleling operation, $Z_2 = Z_{11} + Z_{13} + Z_{12}$, i.e., the impedance of T2 should be equal to

$$Z_2 = Z_{11} + (I_T / I_1)Z_{11} + Z_{12}$$

$$Z2 = (1 + I_T / I_1)Z_{11} + Z_{12}$$

for example if $Z_{11} = 0.03$ pu, $Z_{12} = 0.08$ pu and $I_T = 1/2\ I_1$ then, with all impedances to the same base,

$$Z_2 = (1 + 0.5)\ 0.03 + 0.08$$

$$Z_2 = 0.125 \text{ pu.}$$

This procedure is correct only if the load ratio I_T / I_1 is constant. The procedure could be applied to a system where I_T represents the load on an unregulated tertiary winding if the equivalent circuit positive sequence impedances of the transformer primary, secondary, and tertiary windings are known.

5.0 Conclusion

Paralleling of LTC transformers by the circulating current method can involve systems which are much more complex than the basic two-identical-transformer case usually studied.

The basic approach defined for two identical transformers is readily expanded to three (or more) transformers in parallel and, with some special considerations, is applied to transformers of unequal rating or asymmetric configuration.

Other very special considerations may occur; each must be evaluated with a sound understanding of the basic principles in order to assess the possibility of paralleling the transformers using the circulating current method.

APPENDIX
INSTRUMENT TRANSFORMER CONFIGURATION

There are many different possible means of connecting the voltage transformers (vts) and current transformers (cts) which are the input sources to the LTC control. Since the case under consideration will involve different power transformer designs, possibly of different manufacture, it is probable that the instrument transformers are not configured the same on the two power transformers.

The instrument transformers of the two units to be operated in parallel are considered to be configured the same if the output (secondaries) of both the vts and cts, as input to the LTC controls, are

1. of equal magnitude when the output voltage is the same and the transformers are loaded to their effective rating for the installation, and

2. of equivalent phasing.

It is usually the case that the phase angle between the voltage and current signals will be zero degrees at forward power flow, unity power factor. If not zero degrees, the angle must at least be the same for both transformers in order to satisfy 2 above.

The crux of the matter is that the vt and ct phasing and magnitude must be known for both transformers. If not equivalent, at least one must be adjusted.

Three possible schemes are those of Figure A1, shown with the accompanying phasor relationship. Each produces a single phase input to the LTC control.

a. One vt, one ct on same phase,

b. One vt connected line-line, two cts on same phases as vt

c. One vt, two cts on phases not used for vt

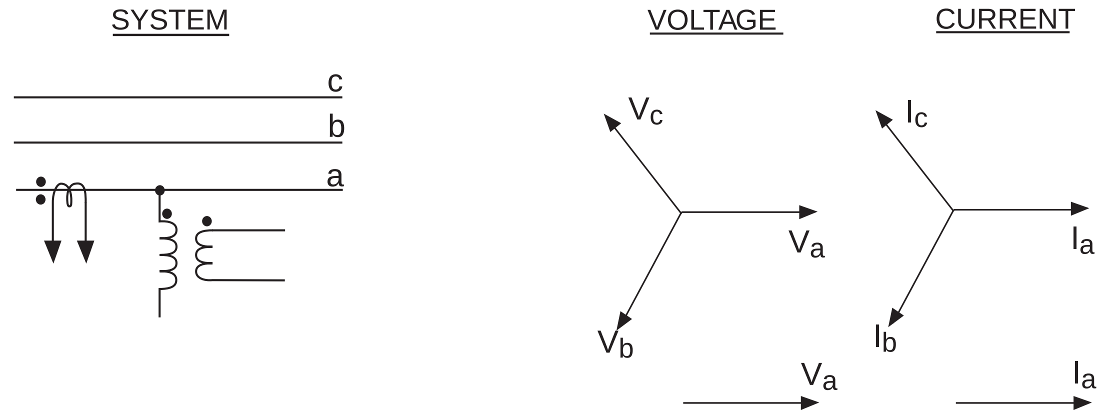
Several observations should be made from the resulting phasor diagrams:

1. In every case, the voltage and current signals are in phase.

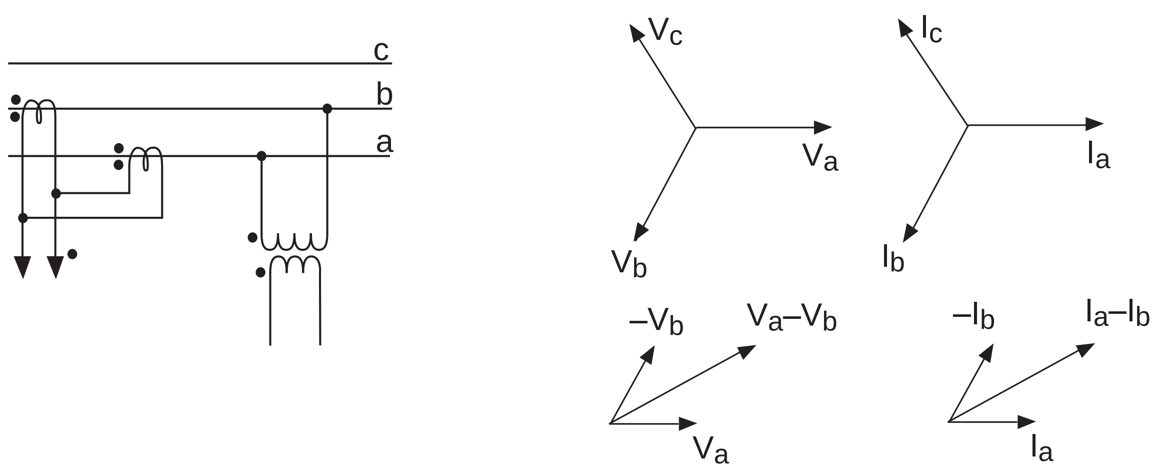
2. In cases a and c the vt secondary should be 120V; in case b, 69V so that the resultant phasor is 120V.

3. In case a the ct secondary of 5.0A will appear to the control. In cases b and c the ct signal to the control will be $\sqrt{3}$ more than the individual ct secondaries. This is 8.66 A if the ct's are rated 5.0 A, a common case. An auxiliary ct is required to adjust the 8.66 A input to 5.0 A.

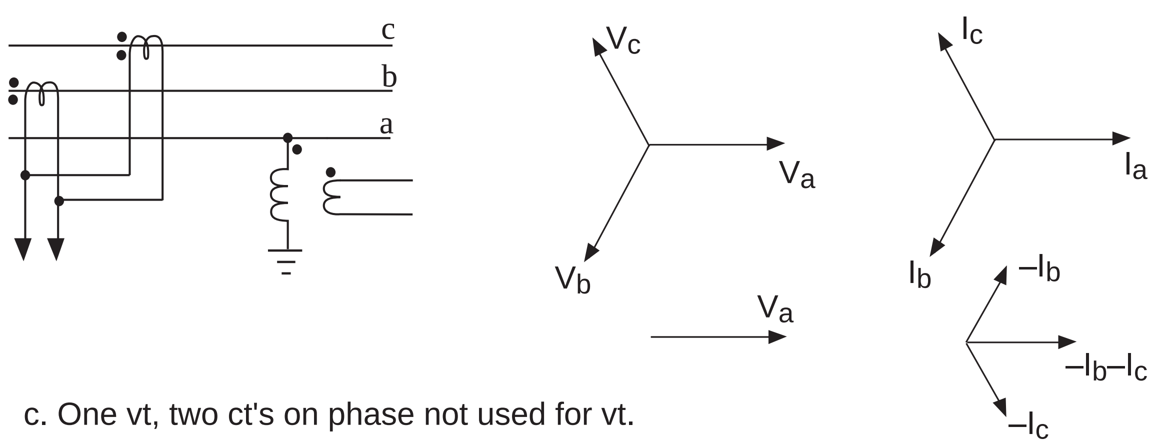
It is further interesting to note that, with only proper scaling being applied, that a transformer using scheme a is compatible with another using scheme c because both result in the equivalent phasing. Scheme b is not to be used with a or c because of the inherent 30° phase shift between the signals of those configurations.



a. One vt, one ct on same phase.



b. One vt connected line-line, two ct's on same phase as vt.



c. One vt, two ct's on phase not used for vt.

Figure A1 Three possible ct, vt combinations in LTC transformer