Introduction to Paralleling of LTC Transformers by the Circulating Current Method

1.0 ABSTRACT

This Application Note discusses the elements of paralleling load tapchanging (LTC) transformers and step-voltage regulators by the method most commonly used today: the circulating current method. The ideal, yet also very realistic, system will require that two (or more) nearly identical LTC transformers are required to be operated in parallel. This system, evaluated in this Application Note, will involve transformers of equivalent design, turns ratio and impedance. It is beyond the scope of this note to consider other approaches to the problem or treat cases which involve complications resulting from mismatched transformers.

2.0 ISSUES

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 settings on the control.

2) The transformers must act so as to minimize the current which circulates between them, as would be due to the tapchangers operating on different tap positions.

Paralleling by the circulating current method makes use of the fact that it is desirable that the transformers share the load equally and, therefore, any difference of current in the paralleled transformers is to be minimized. Special circuits have been developed to “break out” the unbalanced current from the total transformer current and manipulate that unbalanced current into a voltage. This voltage is then input to the control in such a manner that the control will be biased to command the tapchanger in such a way as to reduce the unbalanced component of the current.

3.0 CONSIDERATIONS

3.1 Defining the Problem

To illustrate, consider a very common application. There are two LTC transformers (12 / 16 / 20 MVA, 115 kV to 13.8 kV ±10% in 5 / 8% steps) which are to be operated in parallel with each other. The transformers each exhibit an impedance of 9% and include current transformers with ratios of 1000:5 A. The associated voltage transformers (vt) are rated for 120 V at the secondary when the system voltage is exactly 13.8 kV. The system is shown in Figure 1.

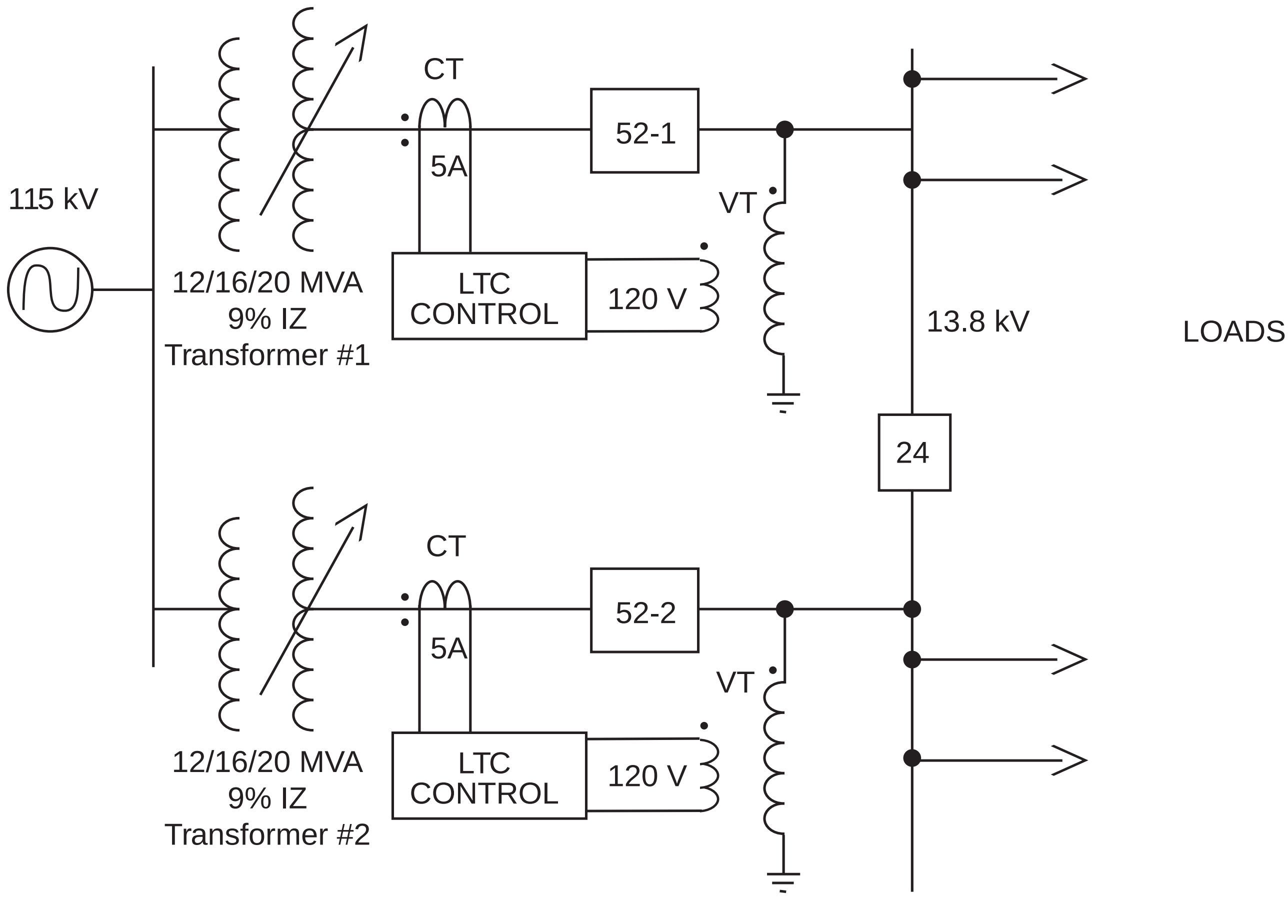

FIGURE 1 System for Study of LTC Transformer Paralleling

If the transformers are identical and operating on the same tap position, then with circuit breakers 52-1 and 52-2 and bus tie breaker 24 closed, the total secondary bus load will divide equally between the transformers.

In this system, no provision has been made for the special requirements of parallel operation, i.e., each LTC will operate independently according to the command of the independent controls. A simple way to illustrate why this is unsuitable for the parallel operation is to consider that, due to load changes, the voltage drops on the 13.8 kV bus. Then a possible scenario is:

1) Both LTC controls sense low voltage and start timing.

2) One control times out before the other - they cannot be identical.

3) The LTC with the control that times out operates.

4) The 13.8 kV bus voltage comes into band after just one unit operates. The second unit no longer needs to operate since its voltage is now also in band. (Note that both vts are monitoring the same voltage.) The transformer taps are now one step apart.

5) Again, the load changes. The same pattern of steps 1 through 4 is followed and the same transformer again corrects the voltage. The transformers are now operating on tap positions two steps apart.

Thus, without some form of feedback or interaction between the LTC controls, the independently operating tapchangers will run to different tap positions.

3.2 Conditions When Transformer Tap Positions Are Not Identical

We have seen that the tap position of two LTC transformers operating in parallel may digress, but why is that bad so long as the desired secondary bus voltage is maintained? Of course, the answer is that when the transformers are operating on unequal step positions, there is a current that circulates between them which merely serves to increase losses and transformer heating while serving no useful purpose at the load.

Note in Figure 2 that the previously defined transformers are illustrated as operating on differing taps, one step removed from each other.

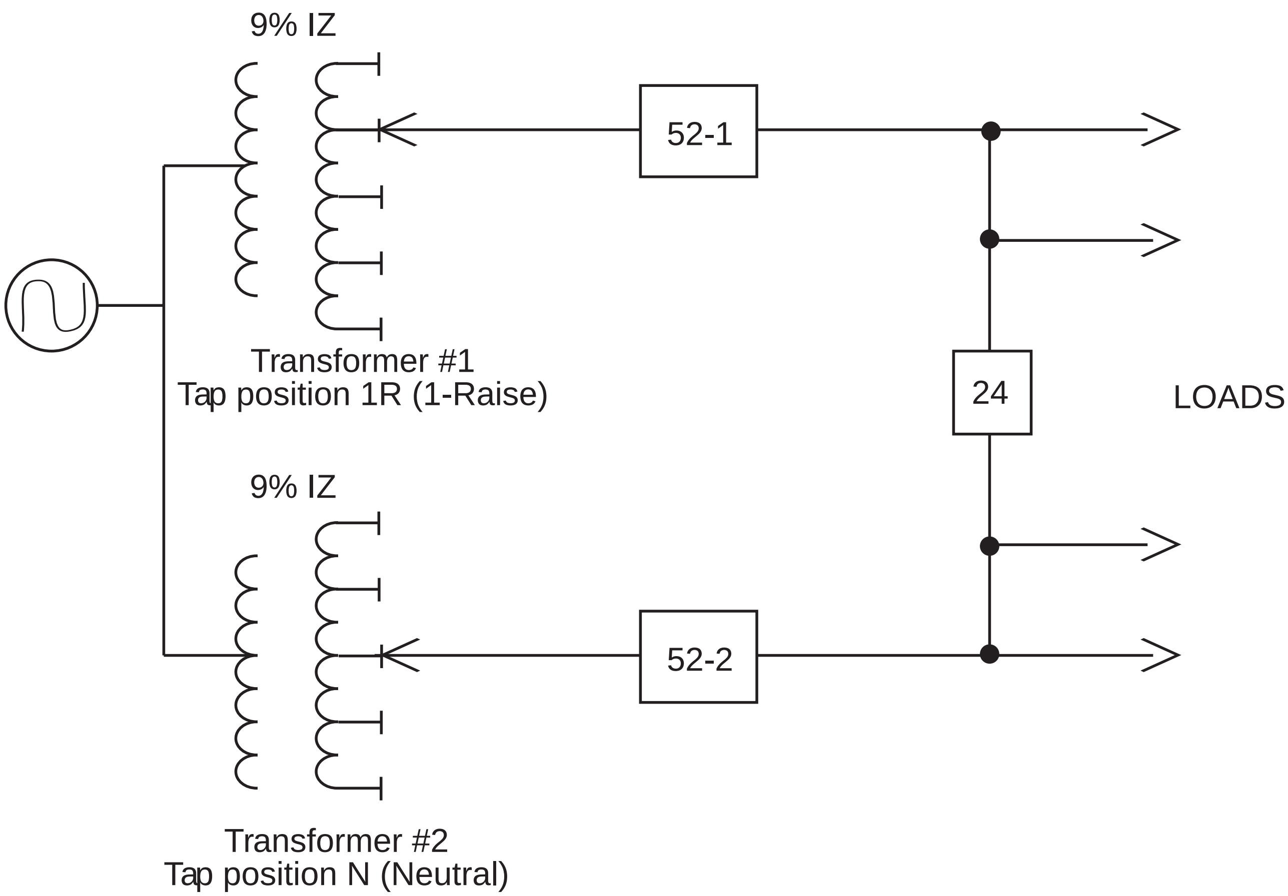

FIGURE 2 Transformers Operating on Different Tap Positions

Here the voltage difference between the two transformer secondaries will drive a circulating current which is limited only by the impedance of the two transformers. Since the transformer voltage change per tap is 5/8% (.00625 pu) the driving voltage for the current is:

$$V = .00625 \times \frac{13,800}{\sqrt{3}} = 49.8\text{ V}$$

and the loop impedance is:

$$
\begin{aligned}
Z_{loop} &= 2 \times Z_{transformer} \\
&= 2\left[9\% \times Z_{base}\right] \\
Z_{base} &= \frac{kV^2}{MVA} = \frac{13.8^2}{12} = 15.87\Omega \\
Z_{loop} &= 2 \times .09 \times 15.87 \\
&= 2.86\Omega \text{ (reactive)} \\
&= j2.86\Omega
\end{aligned}
$$

So the circulating current resulting from a one-step tap discrepancy is:

$$I_{CIRC} = \frac{49.8\text{ V}}{j2.86\Omega} = -j17.43\text{ A}$$

This current exists regardless of the load. It is added to the load current to determine the total loading of the transformers.

3.2.1. Effect of Transformer Loading Due to Tap Discrepancy

To scale the problem, consider that the transformers are loaded at 10 MVA at 0.8 PF each and that their tap positions have digressed by four steps.

A phasor diagram will reveal the situation.

1) Each transformer handles 10 MVA load at 0.8 PF:

$$I_{LOAD} = \frac{10{,}000\text{ kVA}}{13.8\text{ kV}\sqrt{3}} = 418\text{ A @ 0.8 PF}$$

$$I_{LOAD} = 334 - j251\text{A}$$

2) The current that circulates in the loop between the transformers:

$$I_{CIRC} = 4\text{ steps} \times (-j17.43\text{A/step}) \cong -j70\text{ A}$$

Since the circulating current has effectively no "real" component, but is purely reactive, it is convenient to simply consider the current as seen by the CT in one transformer as -j70A and the other as +j70A, due to the effective change of direction of current, or 180° phase shift, in the two CTs.

The system for study is now reduced to that of Figure 3.

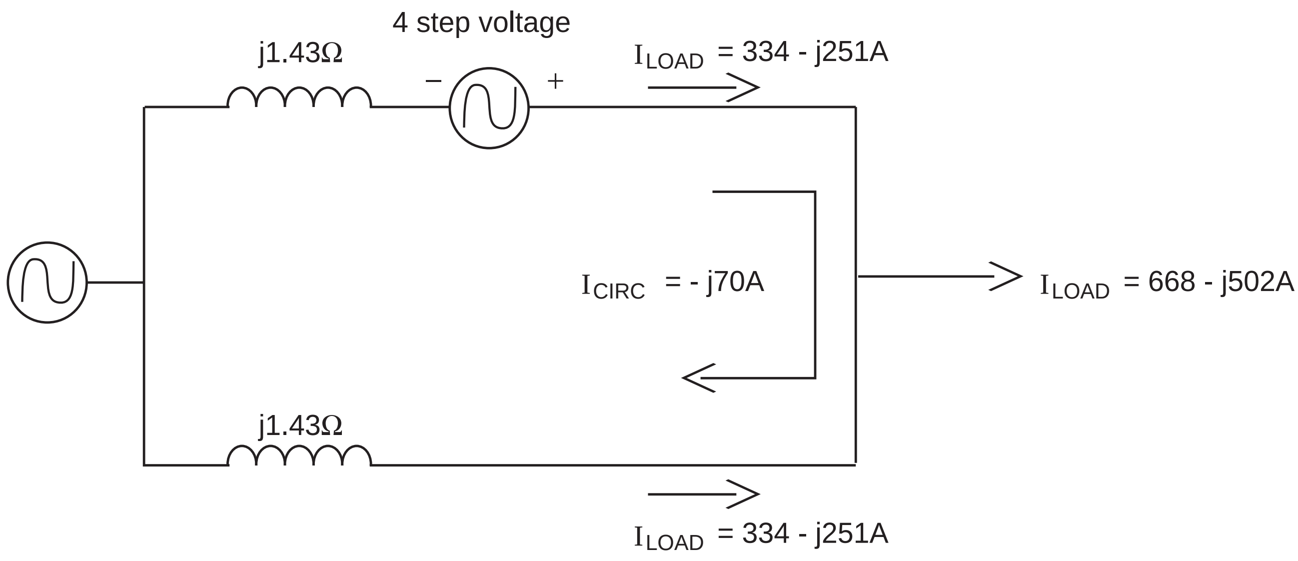

FIGURE 3 Distribution of Currents Due to Load and Four-Step Tap Discrepancy

3) The summation of the load and circulating currents are:

Transformer #1

$$I_{\#1} = \text{Load Current} + \text{Circulating Current}$$
$$= 334 - j251 - j70 = 334 - j321 = 463\angle -44^\circ$$

Transformer #2

$$I_{\#2} = \text{Load Current} - \text{Circulating Current}$$
$$= 334 - j251 - (-j70) = 334 - j181 = 380\angle -28^\circ$$

These phasors are plotted in Figure 4. Note that the through-put of the individual transformers is now:

$$KVA_{\#1} = 13.8 \times \sqrt{3} \times 463 = 11{,}067\ \text{kVA}$$
$$KVA_{\#2} = 13.8 \times \sqrt{3} \times 380 = 9{,}083\ \text{kVA}$$

For a total of 11,067 + 9,083 = 20,150 kVA, where the load represents only 20,000 kVA.

A similar calculation, considering that the transformer load loss is a function of I^2, shows that the total loss of the two transformers increases by about 2.8% because of the 70 A circulating current.

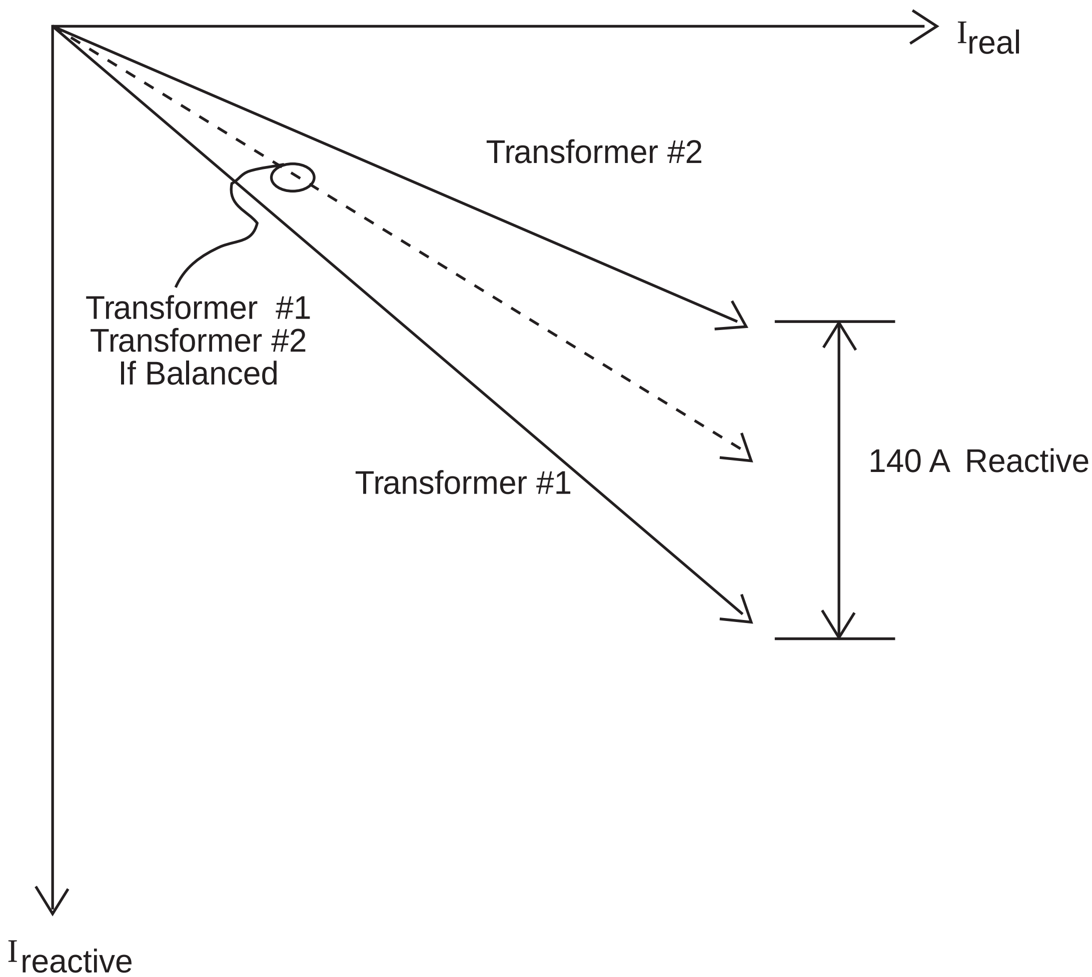

FIGURE 4 Phasor Diagram Showing Currents in Transformers with Four-Step Tap Discrepancy

3.3 The Paralleling Balancer

One additional component, a balancing network, is essential to the proper operation of the system. It is the function of the paralleling balancer to “break out” the unequal (or unbalanced) portion of the current in each transformer. The balancer then feeds a signal to each LTC control, based on that unbalanced current, which will, in turn, bias the control to command tap changes to reduce that unbalanced current.

3.3.1 A Fundamental CT Principle

Before delving into the use of the balancer, consider the following basic underlying principle on which its operation is based.

Figure 5 shows two current transformers with their secondary windings connected in series.

The two CTs are identical. I_1 is the current “into polarity” of CT_1, and I_2 is the current “into polarity” of CT_2. $I_1 = I_2$ because the same current flows in the secondary of the identical CTs. Keeping this basic principle in mind will simplify the explanation that follows.

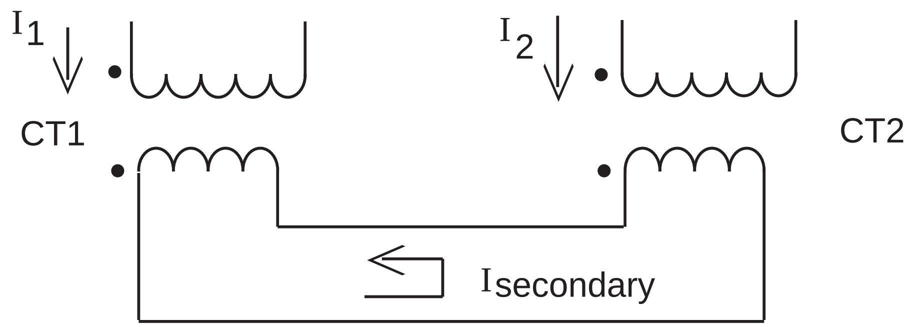

FIGURE 5 Two Current Transformers with Secondary Windings in Series

3.3.2 Basic Balancer Requirements

The simplest use of a paralleling balancer to accommodate two transformers is shown in Figure 6. The circuit includes nothing to accommodate line drop compensation, nor provisions to limit circulating current. The main CTs in the transformer-to-circuit-breaker path are presumed to have 0.2 A secondaries, as required for use by the LTC controls (the "90" relays).

Looking at Figure 6:

1) The two K1 CTs are serving the function described in section 3.3.1, i.e., the secondaries are in series, so the primary currents must be equal.

2) If the currents through transformers T1 and T2 are equal, the currents in the main CTs and in the primaries of K1-1 and K1-2 will also be equal, even if there were no alternate path for current via the balancing reactor and the I_p input of the control. For this case, there is no unbalanced component of current and $I_u = 0$.

3) If the currents through transformers T1 and T2 are not equal, and there exists an unbalanced current I_u, as we will presume to be due to a discrepancy in LTC tap position, the currents at the secondaries of the main CTs must also be unequal, reflecting the unbalance in the transformer loading. However, since the currents in the primaries of K1-1 and K1-2 <u>must</u> <u>still</u> <u>remain</u> <u>equal</u>, any unbalanced component of the load current will be forced to take the path which includes I_p of the control in parallel with the reactor sensitivity adjustment. Note that the adjustable tap on the reactor is only to control sensitivity by forcing more or less of the unbalanced current via the I_p terminals on 90.

By tracing the path of this unbalanced current, it is seen that the direction of the current, the polarity, is opposite in the two controls. Suffice it to say that this polarity difference is the foundation for a positive or negative bias being applied to the control to run the tapchangers.

In Figure 6, I_b represents the desired balanced components of the current. I_u is the unbalanced portion of the current; that portion which is circulating in the local power system between the transformers. These quantities are shown in the power and control circuits without regard to CT scaling.

Note especially that for the currents to satisfy Kirchoff's laws, I_b or the balanced component <u>only</u> flows in K1; the unbalanced portion I_u <u>only</u> flows in the I_p circuit of the controls.

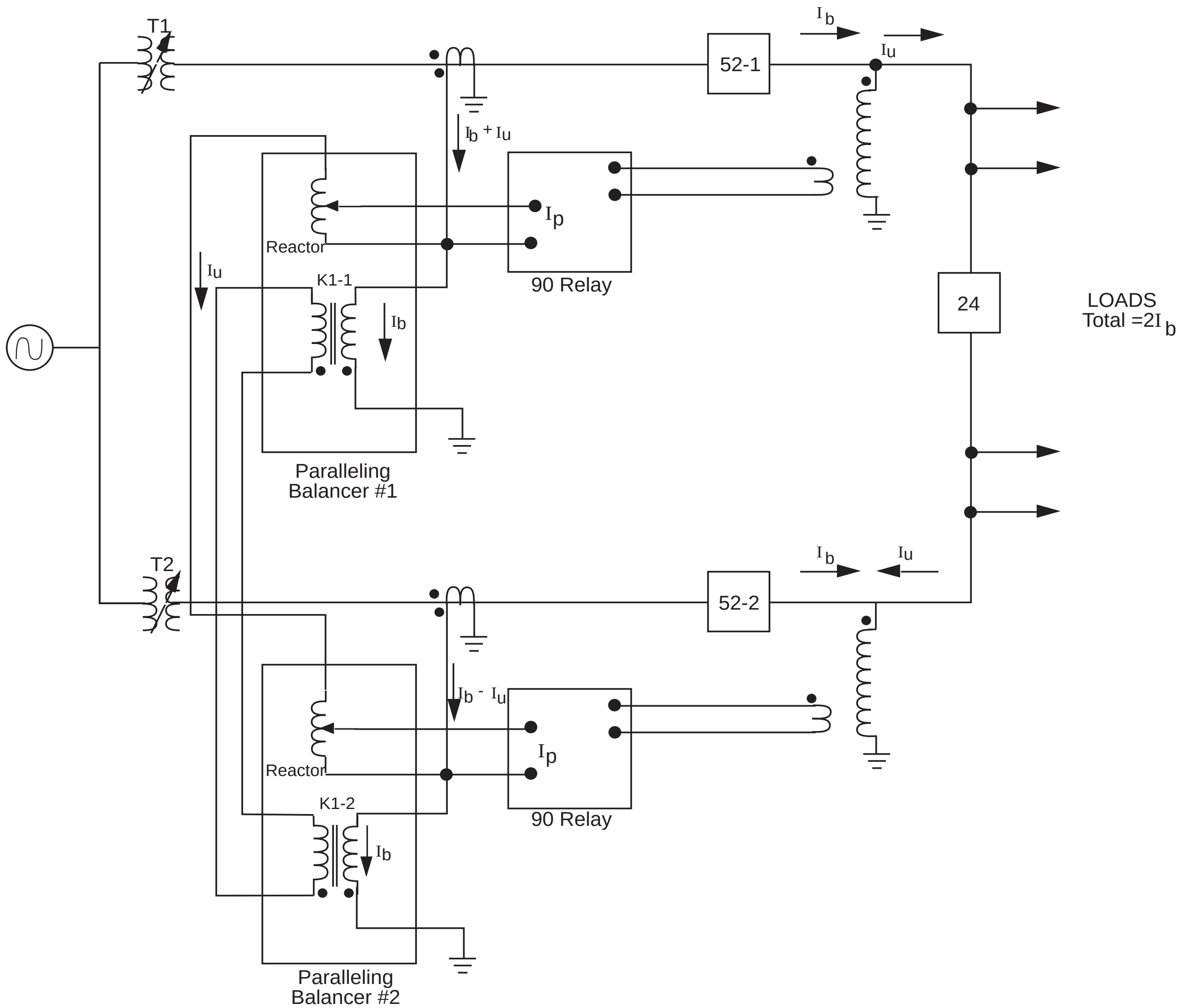

FIGURE 6 Minimal Circuit for Transformer Paralleling by Circulating Current Method

3.3.3 The Use of Line Drop Compensation

The next level of complexity in the circuit is that which is required to accommodate line drop compensation. A special situation exists when the transformers are intended for use in parallel, but one is out of service. If the currents I_b (in K1-1 and K1-2) were simply passed through the LDC circuit of each of the 90 relays, $2I_b$ would pass through the control on T1 when T2 is out of service. The problem is that $2I_b$ in one control LDC circuit results in two times the compensation intended for that unit, with the possible result of an overvoltage condition at the secondary bus.

The addition to the circuit to avoid this situation is accomplished in the balancer with a second CT, K2, which is configured like K1 in that the primary currents again must be equal. Figure 7A illustrates the new portion of the circuit; only minor changes are required to accommodate a circuit which will force the balanced component of current, only, through the LDC path of the 90 relay.

Figures 7A and 7B show the circuit with K2-1 and K2-2 and some realistic values of current. For the case of Figure 7A consider:

1) The main power circuit CT ratios are 1000:0.2 A.

2) The total load current is 1000 A at 1.0 PF.

3) The transformers are operating in parallel on unequal tap positions. Transformer #1 is on a tap two positions higher than Transformer #2.

The resulting currents, in amperes, are shown in the figure. The case is simplified for illustration by stating that the load is at unity power factor, meaning that all of the balanced component of current can be shown as real (—>) and all of the unbalanced or circulating component is shown as reactive (→).

1) The 1000 A of load current divides evenly between T1 and T2 at 500 A each. This is reduced to 0.1000 A (real) in the CT secondaries.

2) The real 0.1000 A, representing the balanced portion in each circuit, passes individually through K1 and K2 of each balancing reactor and the appropriate LDC circuit of the 90 relay. The return path is to the same CT secondary.

3) Per the earlier example, the unbalanced, or circulating component of current will be 2 steps x 17.43 A per step 35 A reactive, or 0.007 A on the base of the CT secondary.

Note that the direction, or sense of this current, is opposite in the two line CTs. This is broken out at the node before K1; a portion of it, depending upon the balancer sensitivity adjustment, is forced through the I_p terminals of the control. The 0.007 A is fed to Balancer #2 where the same current passes through I_p of the second control with the opposite polarity. The path to close the circuit for this current is between the CT secondaries. The unbalanced current passing in different sense through the controls causes those controls to act to lower the tap of T1 and raise the tap of T2.

A second case for illustration is shown in Figure 7B. Here, circuit breaker 52-2 is considered to have opened, forcing the total 1000 A load into T1. Again, the resulting currents, in amperes, are shown. Obviously, with a unity power factor load and no transformer in parallel to possibly operate on a different tap position, the total current is the 1000 A real component. Figure 7B anticipates points from section 3.3.4 to illustrate paths which will be opened or shorted conicidentally with the 52-2 opening. Note especially that a short circuit across the K1 secondaries eliminates the requirement that the K1-1 and K1-2 currents be identical, thereby permitting .2000 A to flow in K1-1 while there is no current in K1-2. The result is that the line drop compensation circuits continue to accept the even division of current. The output voltage of T1 will not be overcompensated and will stay within the limits established based upon T1 and T2 operating in parallel.

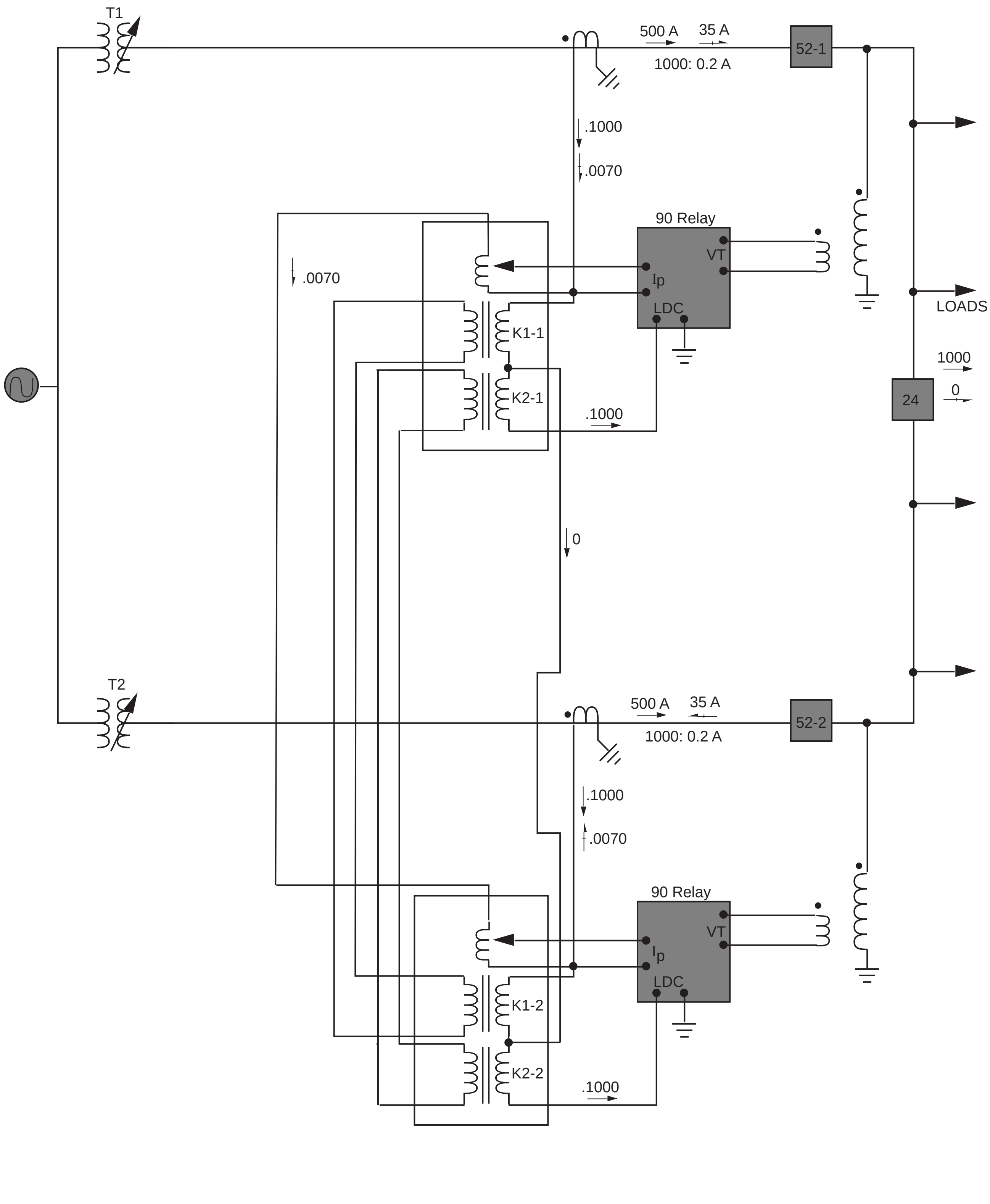

FIGURE 7A Circuit for LTC Transformer Paralleling by Circulating Current Method, Including Provision for Line Drop Compensation

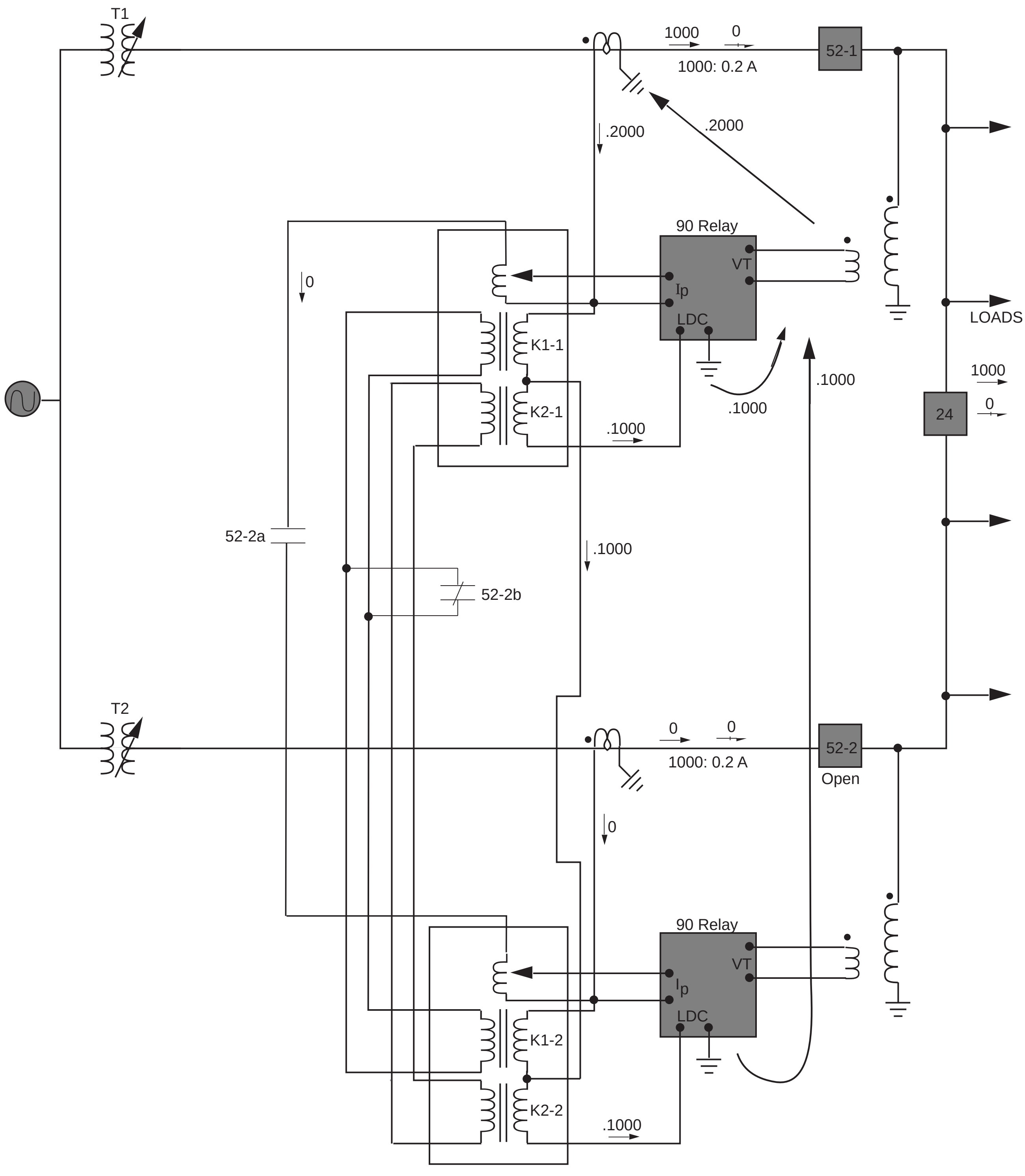

FIGURE 7B Circuit for LTC Transformer Paralleling by Circulating Current Method, Illustrating Purpose of K2 for Line Drop Compensation

3.3.4 Parallel/Independent Operation

The circuit developed thus far has considered only that two transformers are involved, and that they will always be operated in parallel with each other. Recognition must be made that one transformer may occasionally be removed from service and the other must continue to operate independently. Under this condition, it is required to remove the circulating current paths from the control and balancer of the out-of-service transformer.

In Figure 8, the circuit has been drawn again, and now includes a set of switch contacts as follows:

43P	A total of four contacts in each Paralleling Balancer Module. The contacts are switched for **parallel** or **independent** operation. Two contacts are closed and two are open during parallel operation; the positions being reversed during independent operation.
52-1a	An auxiliary contact associated with circuit breaker 52-1, which is open when 52-1 is open and closed when 52-1 is closed.
52-1b	An auxiliary contact associated with circuit breaker 52-1, which is closed when 52-1 is open and open when 52-1 is closed.
52-2a, 52-2b, 24a, 24b	Contacts on the respective circuit breakers that adhere to the logic described for circuit breaker 52-1 above.

Another change is also introduced in Figure 8: the circulating current paths for the secondaries of K1 and K2 are not shown as complete hardwire connections, but show those paths completed using ground connections, as will be commonly done in practice.

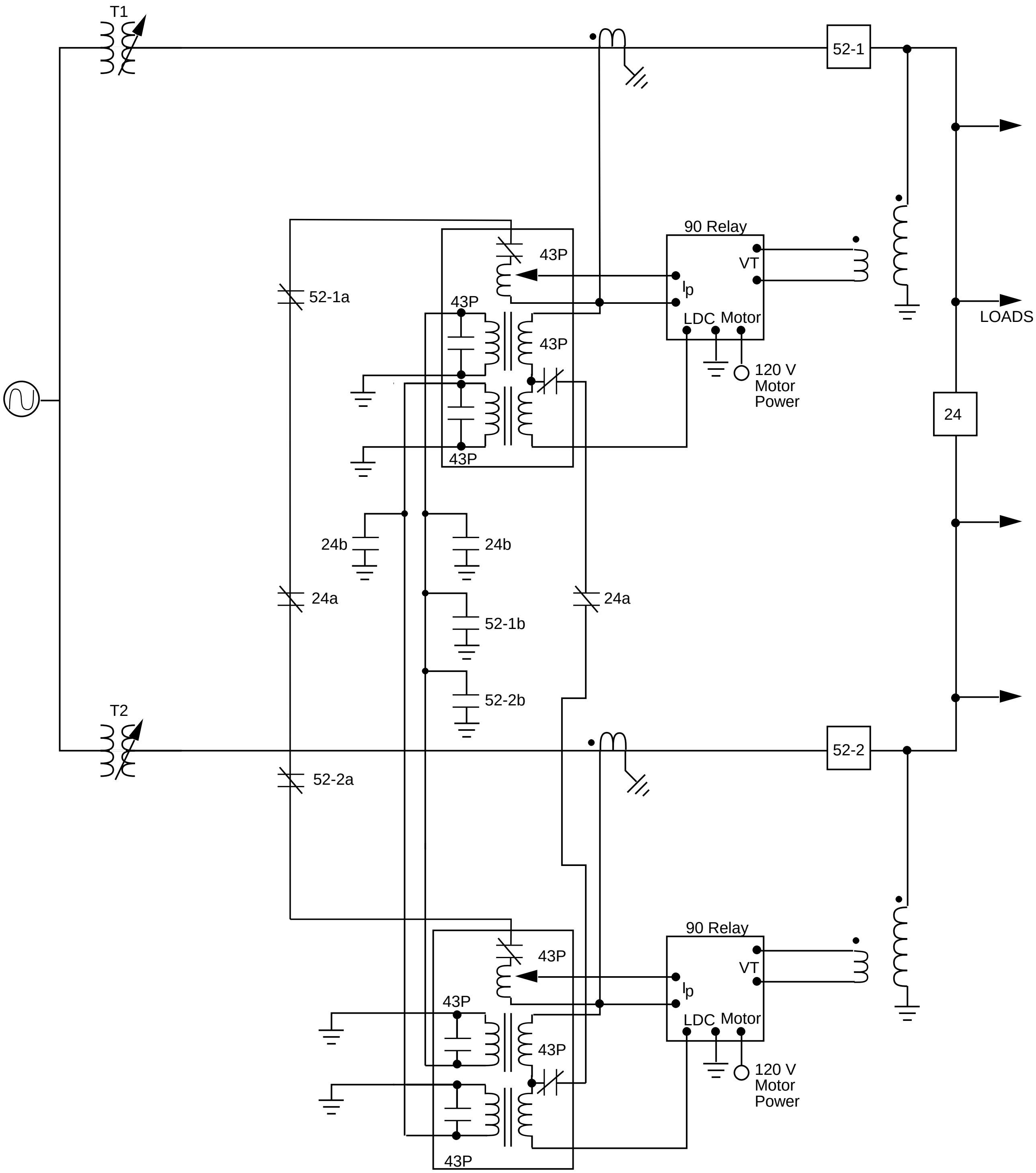

FIGURE 8 Circuit for LTC Transformer Paralleling by Circulating Current Method, Including Circuit Breaker Auxiliary Switch Contacts

Figure 8 illustrates the switch contacts considering that the two transformers are operating in parallel with circuit breakers 52-1, 52-2 and 24 closed. Also, the parallel / independent switch on the balancing module is set for parallel operation. Three other modes of operation are possible.

1) Due to the opening of circuit breaker 52-1, or 52-2 the controls must switch so as to continue proper regulation of the load using only the one remaining transformer which is handling the total load, but its line drop compensation circuit recognizes only one-half of the total load.

2) Due to the opening of circuit breaker 24, the controls must switch so as to handle their respective loads independently, i.e. not in parallel.

3) Due to operator local selection of independent operation, the controls must switch so as to operate independently even though circuit-wise the transformers may remain in parallel. (This mode of operation would probably be used only for testing the system.)

The reader is encouraged to make copies of Figure 8 to mark-up three times to depict the auxiliary contact make-up associated with each of the above conditions to satisfy himself that the proper circuit paths exist.

3.5 CT Correction and Circulating Current Limit

Two additional components complete the common two transformer paralleling circuit: an auxiliary CT and provision to limit circulating current.

1) **Auxiliary CT**: The standard for the current transformer secondary inside of the LTC transformer is 5.0 A, however, the standard input for the LTC control is 0.2 A necessitating an auxiliary CT to adjust these bases. Note that step-voltage regulators most often use 0.2 A CT secondaries obviating the need for the auxiliary CT in those applications.

2) **Current Relay**: It is frequently required that a means be provided to inhibit additional tap change operations if the circulating current becomes too great. This is based on the premise that the current is high because the transformers are already too many steps apart due to some malfunction, and it is desired to avoid a further digression of the tap positions. This is easily accomplished by inserting a current magnitude sensitive relay in the path that represents the circulating current. Excessive current opens a normally closed contact on the “50” device, which simply opens the motor power source circuit to the 90 relays.

The last figure, Figure 9, adds these components and completes the circuit.

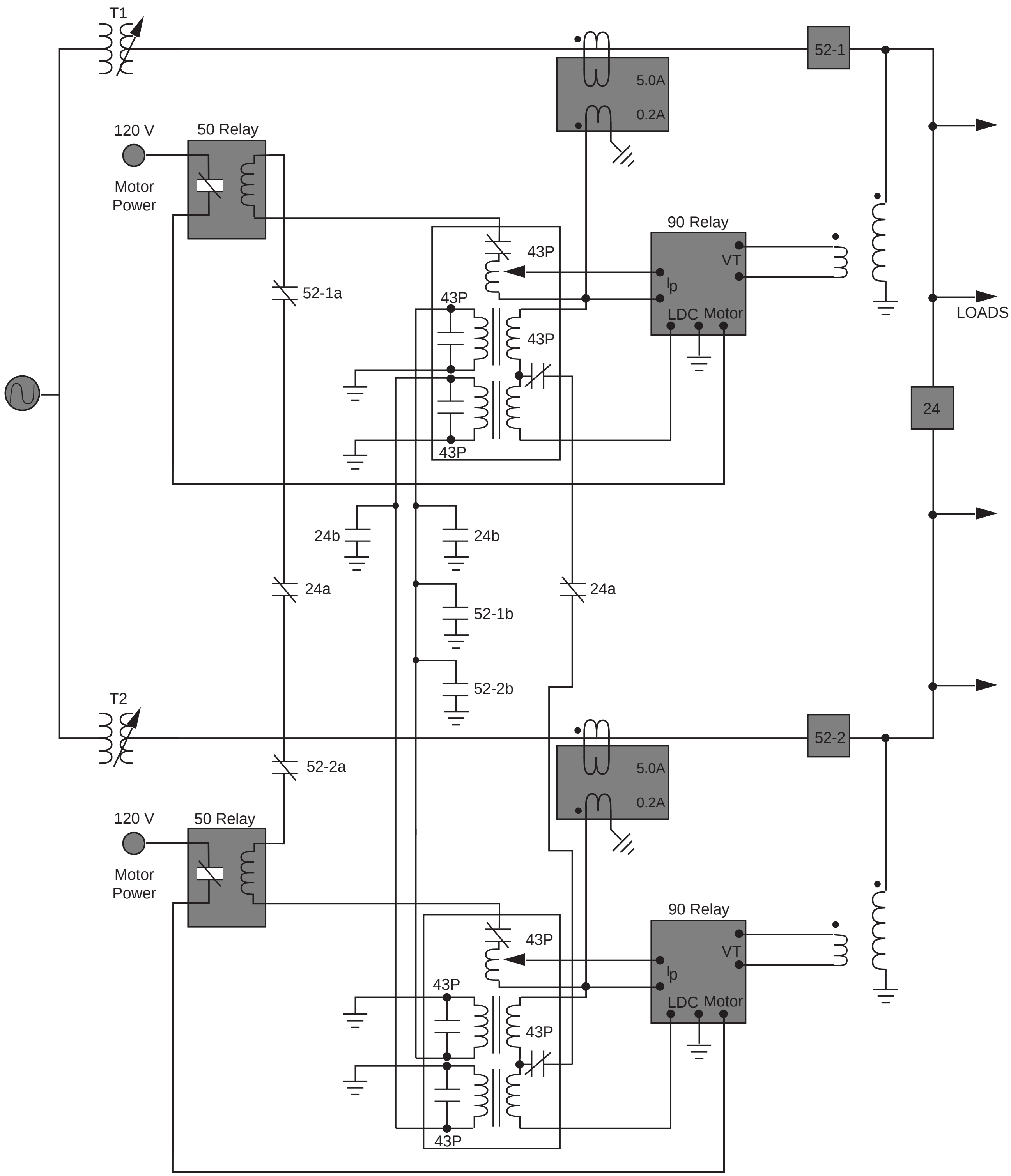

FIGURE 9 Complete Circuit for LTC Transformer Paralleling by the Circulating Current Method

4.0 CONCLUSION

The circuits used for proper operation of two LTC transformers in parallel are not complex but may be intimidating if only the complete circuit is shown without adequate explanation of the principles involved and the purpose of each component. This Application Note has built the system from the basic requirements and shown how each component is an integral part of the whole.

As noted in the title, this Application Note is only an introduction to the topic of LTC transformer paralleling. Other matters for evaluation include the extensions of the idea in this note to the case of three or more transformers in parallel, and the study of applications where the parallel paths are not identical.

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