Advanced Transformer Paralleling

E. Tom Jauch
IEEE Member
Manager of Application Engineering, Beckwith Electric Co., Inc.

I. INTRODUCTION

This paper introduces an innovative method for providing control of paralleled LTC transformers, and compares and evaluates other paralleling methods presently in use. The new paralleling method provides optimal operation for substation configurations that are becoming more prevalent in present-day power systems; these configurations have never been addressed by other paralleling methods. The comparison includes the following methods: negative reactance, master/follower, power factor, and circulating current.

There are three premises for transformers operating in parallel [1]:

A. The transformers must continue their basic function of controlling the load bus voltage as prescribed by the setting on the control.
B. The transformer must act so as to minimize the current that circulates between them, as would be due to the tapchangers operating on inappropriate (not necessarily equal) tap positions.
C. Actions A. and B., above, must operate correctly in multiple transformer applications regardless of system configuration changes or station breaker operations and resultant station configuration changes.

Of special interest are paralleling operations with the following system conditions:

- the primary windings of the paralleled transformers might be fed from different source transmission lines or
- there is a large variation in relative impedances of the paralleled transformers as tap changes occur.

These special interest conditions can result in undesirable operations for paralleled transformers controlled using negative reactance, master/follower, power factor or circulating current type controls. The response of each method to these conditions will be discussed and compared to the operation of the newly introduced VAr balancing scheme (ΔVAR[TM]).

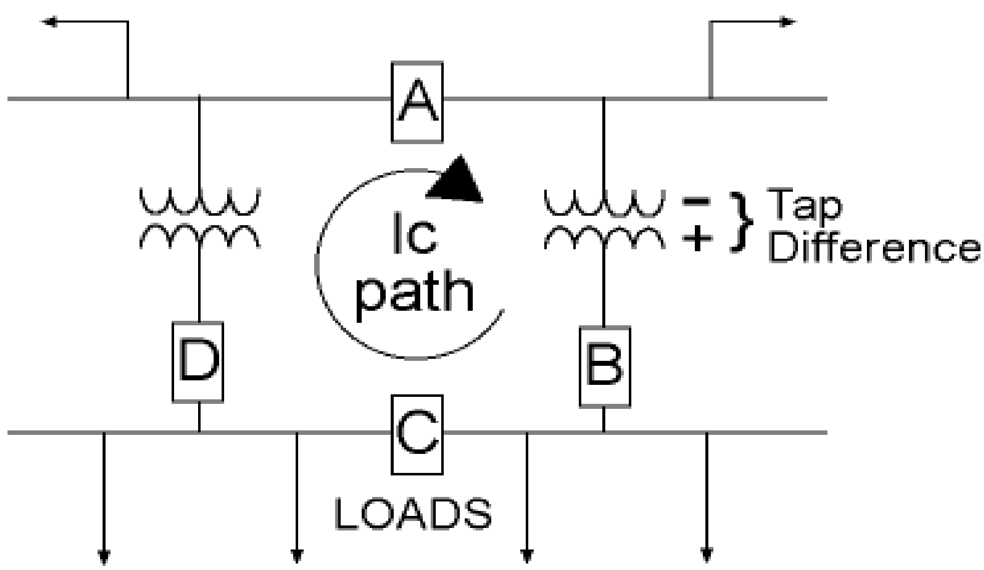

Fig. 1 A Substation Configuration that can result in Paralleled Transformers

II. UNDERSTANDING THE SYSTEM

Referring to Fig. 1:

- A tap difference causes a circulating current (I_C)
- I_C is calculable from the tap step voltage and transformer impedances
- If C is open = Independent operation – LDC currents assumed equal – no correction needed
- If B or D is open = Independent operation – LDC current doubles – current correction needed
- If A is open = Parallel operation – separate sources (VAr balance required)
- I_C is mostly VArs since transformer impedances are mostly reactance.

One of the most important facts to consider is that kW flows are *not* effectively controlled by tap position but by relative impedances or phase shifting transformers.

A power transformer has a very high (25 to 50) X/R ratio. That is, power systems in general are reactive and the resistive portion of transformer impedances is negligible.

An in-phase voltage change (as in a tapchanger operation) applied to a reactive circuit (as in paralleled transformer configuration) significantly changes the transformer VAr flows but *not* the Watt flows.

Since tap changes do not create changes in circulating KW flow, KW flow must not be a factor in controlling the paralleled tapchangers. If system or equipment characteristics (other than tap mismatch) can substantially affect the KW flow through the transformers, VAr flow must be the only determining control quantity.

Transformers with directly-connected secondaries that supply the load are in parallel regardless of the high side connection configuration.

III. DEFINING THE PROBLEM

In all transformer paralleling applications, except master/follower which is addressed later, the individual tapchanger controls are energized by separate VT's and separate CT's. Although these VT's and CT's may have the same ratios and specifications, they cannot have identical outputs. Also, while each transformer has equivalent controls, they cannot be identical in voltage sensing and timer operation. Another possibility is that one tapchanger may operate faster than another. This leads to the distinct possibility of the operation of one transformer tapchanger adjusting a bus voltage while the second does not. Generally, if there was some variation that makes one tapchanger operate first, that same variation would cause the same transformer to operate first the next time a voltage adjustment is needed. For these reasons, additional paralleling equipment is required to maintain the taps in the most beneficial position.

Following is a description of the operation premises for different paralleling methods:

A. **The negative reactance paralleling method** is generally used as a short-term emergency solution to paralleling transformers. It consists of using the LDC (line drop compensation) setting at a negative reactance value.

   LDC R (resistance) and X (reactance) settings are feeder impedance-related values that voltage controls use to increase the voltage setpoint to compensate for line voltage drop. This compensation effectively controls the voltage at the end of the line rather than at the bus.

   Using a negative X setting essentially results in the biasing of the voltage control setpoint of the paralleled transformers according to their VAr flow. A transformer with a tap higher than a paralleled transformer will have a higher VAr flow than the paralleled one. The negative X effect is to lower the setpoint of the advanced tap transformer more than the paralleled unit. This operational bias causes the next tap operation to be in the direction to bring them back together.

   The major problem of extended use of this method is that KVAr bus loading results in lower bus voltage—the opposite of normal LDC operation.

B. **The master/follower paralleling method** assumes that, under all system operating configurations, the desired operation objectives are met by maintaining the same physical tap position on all paralleled transformers. The operation consists of one active control commanding additional transformers' tapchangers to follow. A tap operation feedback scheme (usually with external auxiliary relays) is required to confirm to the controlling unit that the following unit has operated. If that feedback is not received, the controls usually are set to lockout further operations.

C. **The power factor paralleling method** assumes that the most desirable combination of tap positions on paralleled transformers is one that maintains equal power factors in the transformers.

   Relative power factors can be determined by comparing the relative angle of the transformer currents only, since the voltages are equal when the units are paralleled. This method usually does not bias the controls to operate, but rather blocks the control from operating in the wrong

direction based on the power factor. Further, it is difficult to apply power factor methods in substations with more than two parallelled transformers without a daisy chain arrangement. In applications where there is a difference in impedance, the power factor method will result in the transformer with the highest KW loading (lowest impedance) also having the highest VAr loading.

D. **The circulating current paralleling method** assumes that a continuous circulating current path is maintained for all system operating configurations, and that any changes in the circulating current magnitude are a result of an undesirable change in the relative tap positions of the paralleled transformers. The circulating current method biases all paralleled controls to operate next in the direction that minimizes the circulating current. This is similar to the bias of the LDC unit described in the negative reactance method.

   Additional equipment is necessary to separate the total transformer currents into a load current portion and a circulating current portion. This is shown in Fig. 2. These individual currents are input to the voltage control which determines the direction and amount of the individual biases. Rather than varying the voltage bias between units based on VAr flow, as in the negative reactance method, the higher-tapped tranformer control setpoint is biased down while the lower-tapped transformer control is biased up by an equal amount. The actual center of the setpoints of the combination is still equal to the original setpoint. This assures proper voltage levels are maintained on the bus.

   An overcurrent relay in the circulating current path is generally used with the circulating current method to block further operations if the variation in the transformers' tap positions becomes too great. [2]

E. **The VAr balancing (ΔVAR) paralleling method's** theoretical basis is that paralleled transformers are meant to share the VAr load (as well as the KW load) of the load bus. Since the KW sharing of the paralleled transformers is determined by the relative transformer and system impedances and *not* the tap position, KW flow should not be able to affect tap position choice. Further, that the best choice of loading parallel transformers is to maintain the VAr sharing regardless of KW loading.

Source side separation, illustrated by Fig. 1 with breaker A open and all others closed, introduces the probable unequal flow of VArs and/or KW's in the two transformers. An equivalent configuration can occur at stations with ring bus or multiple bus breaker arrangements on the source side. This operation violates the assumptions of all methods except the VAr balancing method (ΔVAR) for maintaining the most appropriate tap positions on the paralleled transformers.

IV. OPERATIONAL COMPARISONS

A. Common High- and Low-Side Busses
   Referring to Fig. 1, all breakers (A through D) are closed. After adjusting CT's to compensate for possible different impedances*, circulating current is a function of mismatching tap position operations. Problems can occur if impedance changes in one transformer are substantially different from the impedance changes in the other as tap changes occur. The problem is that the KW (as well as VAr) loading is changing, as reflected in the circulating current, and KW changes could be a factor in tap positioning for all methods—except the VAr balancing method**.**

   *Note: for equally-sized but different impedance transformers, the adjusting CT's mentioned above are no longer required when using the VAr balancing method.

B. Paralleling Interrupted
   Referring to Fig. 1, breakers B through D operate singly or in combination to isolate one transformer from the other. Any paralleling method (except negative reactance) uses "a" or "b" contacts from the breakers (see Fig. 2) to determine this condition and operate appropriately.

C. Source Side Separation
   Referring to Fig. 1, breaker A opens which separates the sources to the paralleled transformers. Although contacts could also indicate this condition, there is no operating procedure for the standard methods of paralleling for these circumstances.

   Before the breaker operation, either KW or VAr's or both could have been flowing from one portion of the transmission system to the other through these lines (or, more load was being supplied by one line than the other). When the breaker opens, the voltages on both lines will reflect the preceding condition by either being at different voltage levels (VAr flow) or different phase angles (KW flow). That is, that flow will attempt to continue through the transformers albeit more limited by the additional transformer impedance inserted into the circuit.

   Since tap changes (in-line voltage changes) will not materially affect KW flow in a reactive circuit and a solution which best equalizes the loading of the paralleled transformers is desired, these responses of the different methods to this condition must be considered. They are:

Master/Follower method of paralleling—no response for correctional action. After the response to a changed load bus voltage, the intersystem flow would be added to one transformer load and subtracted from the other. Since this difference could be substantial, it is unacceptable for most systems.

Power Factor method of paralleling—if the intersystem flow was VArs, the power factor method would block the operation of the appropriate tapchanger to attempt to minimize the difference in power factor. This would result in operation at different tap positions for the transformers which would cause equal VAr flow in the transformers. This is satisfactory operation even though the final positions might take longer to get to because of the blocking action described earlier.

If the intersystem flow was KW, the power factor method would block the operation of the appropriate tapchanger to attempt to minimize the difference in power factor. This would result in operation at different tap positions for the transformers which would cause unequal VAr flow in the transformers. The result is that the transformer with the highest KW load will now be forced to also have the highest VAr loading.

If the intersystem flow was a combination of VArs and KW, the power factor method would operate as in the above paragraph.

Circulating current method of paralleling—if the intersystem flow was VArs, the circulating current method would bias the operation of the tapchangers to attempt to offset the flow. This would result in proper operation at different tap positions for the two transformers and proper sharing of the VAr load from the two sources. That is, the tap difference would equal the voltage level difference thus stopping the flow-through VArs. This is satisfactory operation.

If the intersystem flow was KW, the circulating current method would again bias the operation of the tapchangers to attempt to offset the flow. However, the KW flow cannot be corrected with tapchanger operations. The result is fairly unpredictable but does result in circulating VAr's in one direction and circulating KW in the other. This condition usually results in "hunting" between tapchangers.

If the intersystem flow was a combination of VArs and KW, the circulating current method would bias the operation of the tapchangers to attempt to offset the flow. This condition could result in "hunting" between tapchangers.

With the **VAr balancing method of paralleling**, since the ΔVAR method ignores all KW flows, it has only one purpose under all system conditions with the transformers paralleled. That purpose is to equalize the transformer VAr flows to the substation load by the appropriate ratio of the size of the paralleled transformers. This "appropriate ratio" is determined by the choice of the current transformer ratios used to correctly parallel differently-sized transformers. Although auxiliary CT's are not required for equally-sized transformers with different impedances, the total ratios do need to reflect the different sizes of the transformers. For example, if a 100 MVA transformer is paralleled with a 50 MVA transformer, the desired VAr loading ratio is 2. This is accomplished automatically if the CT ratios are different by a factor of 2, which would be normal. [3]

V. IMPLEMENTATION OF VAR BALANCING METHOD

Since the VAr calculations are completed in the algorithms of the voltage control, the ΔVAR method uses the same auxiliary equipment as the circulating current method. Namely, a parallel balancing module (which separates the load current from the difference or circulating current) and an overcurrent relay (which gives independent backup protection to the paralleling operation). This makes it a direct replacement for other controls already using circulating current methods. Fig. 2 illustrates those connections for three identical LTC transformers in parallel.

The circuit in Fig. 2 includes the LTC control (the "90" control), the parallel balancing module (the "43" device) and the circuit breaker "a" and "b" contact arrangement. The overcurrent relay (the "50" device) normally used is not shown in this figure but would monitor the circulating current and operate to cut the motor power. The "90" control can be programmed to use either the "circulating current" method or the "ΔVAR" method of paralleling. It is a straightforward extension of this schematic to apply to either the two transformer or the multiple transformer paralleling application.

Current magnitudes as drawn in Fig. 2 assume 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 or T3. Because we assumed a unity power factor load, 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 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 to the 90 control at T1 as in those on T2 and T3. The T1 control setpoint bias will be biased down twice as much as T2 and T3 are biased up.

Complete development and analysis of this circuit is available in [2].

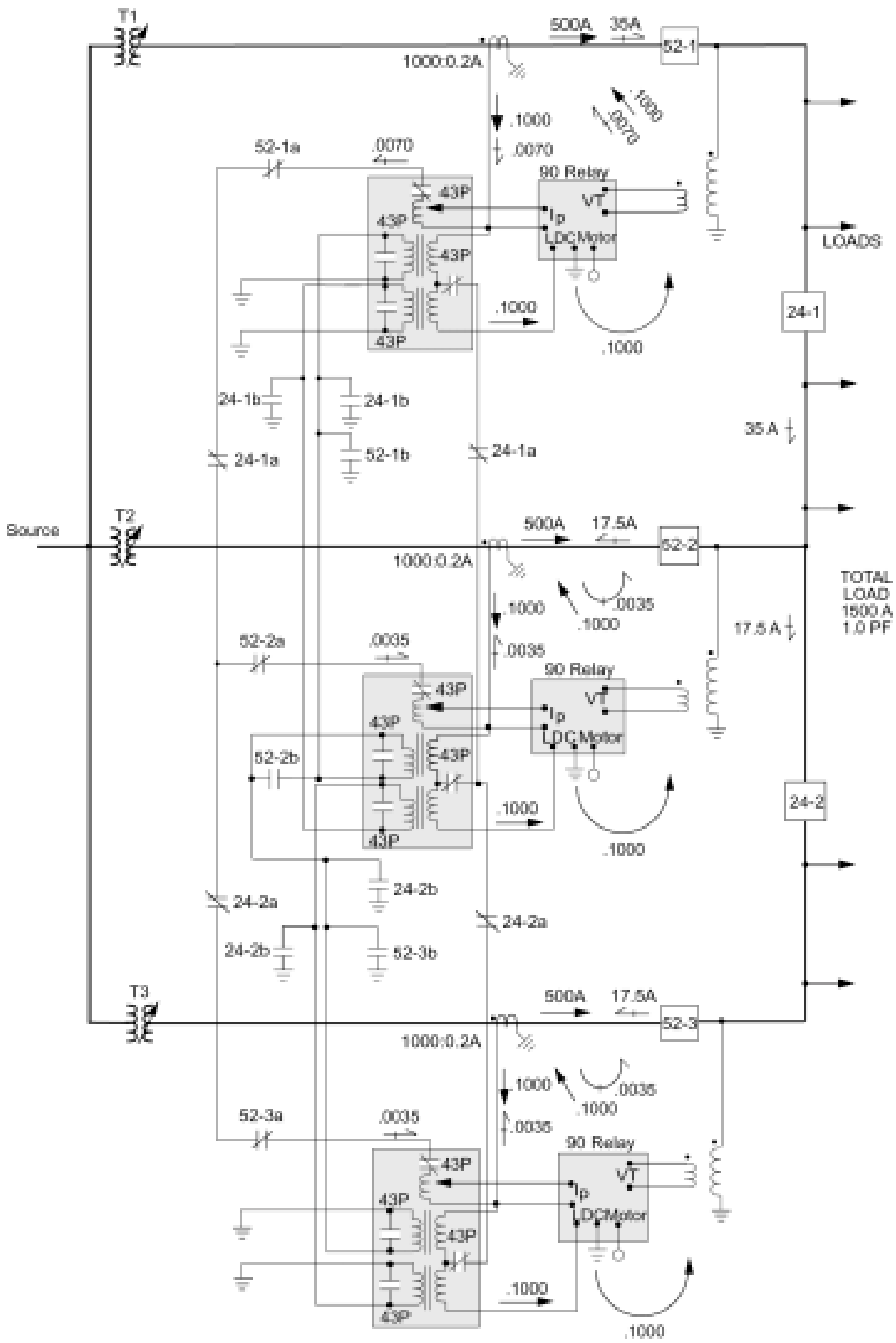

Fig. 2 Complete Circuit for Three-Transformer Paralleling by Circulating Current Method

VI. CONCLUSION

Several methods of controlling paralleled transformers or transformer/regulator combinations have been used over the years. Each of these methods operates appropriately with varying assumptions as to desired results and system conditions. Each has advantages or disadvantages depending on the system conditions under which they are required to operate.

The negative reactance method tends to bias the operation of the tapchanger controls, by using the LDC feature, to equalize the VAr flow in the transformers. It is appropriate only for emergency temporary operations or where the substation loading is very near unity power factor at all times. Otherwise, it results in substantially lower bus voltages because of normal LDC action on load currents. The settings of the negative reactance must consider differences in transformer sizes, impedances and loading so as to not result in "hunting" by the tapchangers.

The master/follower method assumes that the appropriate relative tap positions between transformers remain constant for all system conditions. This fact limits its use. The auxiliary feedback system is usually complicated and subject to misoperation.

The circulating current method (the most widely-used method) assumes that a circulating current path is maintained and that any difference in current between the transformers is a result of an undesireable relative tap positons on the paralleled transformers. Any difference in transformer ratings (as reflected in relative impedances) must be compensated for with auxiliary CT's. If the impedance difference is too extreme, operation may be effected because an actual circulating current will appear differently in the separate controls.

The power factor method assumes the best operating position for the transformer taps is one that maintains equal power factor in all transformers. The validity of this assumption is arguable in many applications thereby rendering the power factor method as less than desirable.

The VAr balancing (ΔVAR) method operates to equalize the VAr flow in all paralleled transformers. In this respect, it is most similar to the negative reactance method but without the detrimental effects of the LDC normal operation. This method also allows automatic operation when various substation breakers operate. LDC can be used with this method whereas that function is not available when using negative reactance method. Since this method acts to balance the VAr loading of the paralleled transformers and differently-sized transformers are commonly paralleled, the CT ratios used must reflect any MVA rating differences. The same equipment used by the circulating current method to determine load versus circulating current is used.

The use of ring bus and multiple bus configurations in substations with paralleled transformers is leading to more applications where these transformers can be fed from separate transmission lines. The philosophy of feeding parallel transformers from separate transmission lines for reliability improvements is also adding to these applications. None of the previously used paralleling schemes will operate to result in the most appropriate tap positions in paralleled transformers under these circumstances. In fact, some of the methods will result in complete loss of voltage regulation or tremendously high numbers of operations in a short period of time.

REFERENCES

[1] "Introduction to Paralleling of LTC Transformers by the Circulating Current Method", Tapchanger Control Application Note #11, Beckwith Electric Co., Inc., February 1998.

[2] "Advanced Paralleling of LTC Transformers by the Circulating Current Method", Tapchanger Control Application Note #13, Beckwith Electric Co., Inc., 1999.

[3] "Advanced Paralleling of LTC Transformers by ΔVAR™ Method", Preliminary Tapchanger Control Application Note, Beckwith Electric Co., Inc., July 2000.