

IEEE Guide for Paralleling Regulating Transformers

IEEE Power and Energy Society

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Transformers Committee

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IEEE Guide for Paralleling Regulating Transformers

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Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: Control methods of paralleling regulating transformers are described and compared in this guide. The control methods include: master/follower, circulating current, power factor, circulating reactive current and negative reactance methods. Operating philosophy descriptions, sample wiring diagrams, typical operational variations, the provision of adequate backup protection, and typical misapplication consequences are presented. This guide does not apply to phase-shifting regulating transformers.

Keywords: backup protection, circulating current method, circulating reactive current method, IEEE C57.153™, line current compensation, line drop compensation, master/follower method, negative reactance method, power factor method, tap changer control, transformer loading, transformer paralleling, voltage control

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Introduction

This introduction is not part of IEEE Std C57.153-2015, IEEE Guide for Paralleling Regulating Transformers.

This guide was prepared by the C57.153 Working Group of the Power Transformers Subcommittee of the Transformers Committee of the IEEE Power and Energy Society.

The intent of this new guide is to present information for the selection and application of transformer paralleling methods used to maintain power system operations. This guide describes paralleling methods in common practice at the time this guide was written and provides information concerning the operational requirements and limitations of each method. Additional information is provided for cases of paralleling transformers with unequal ratings and other operational conditions requiring special considerations.

Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	1
2. Normative references.....	1
3. Definitions, acronyms, and abbreviations	2
3.1 Definitions	2
3.2 Acronyms and abbreviations	3
4. Basic paralleling information	3
4.1 General application.....	3
4.2 Reasons for paralleled transformer operation.....	6
4.3 Basic voltage-control operation.....	6
4.4 Effects of off-tap operation.....	10
4.5 Consequences of less-than-optimal paralleling operation.....	14
4.6 Regulating transformer/system requirements for parallel operation.....	15
5. Requirements of the paralleling control system	16
5.1 Need for paralleling operation control.....	16
5.2 Basic paralleling control requirements	18
6. Equipment involved in paralleling.....	21
6.1 Regulating transformers.....	21
6.2 Step-voltage regulators	22
7. Parallel control method choice considerations	24
7.1 Paralleled transformer impedance	24
7.2 Unequal voltage-regulating tap-sizes and ranges.....	26
7.3 Transformers with multiple windings.....	26
7.4 Multiple (greater than two) paralleled transformers	28
7.5 Source bus configurations.....	28
8. Master/follower (MF) paralleling method.....	29
8.1 Operating principle	29
8.2 Control arrangements.....	29
8.3 Settings and sensitivity	31
8.4 Backup methods	32
8.5 Effects of non-similar transformers/configuration.....	33
8.6 Frequent application errors.....	37
9. Power factor (PF) paralleling method.....	37
9.1 Operating principle	37
9.2 Control arrangements.....	41
9.3 Settings and sensitivity	41
9.4 Backup methods	43
9.5 Effects of non-similar transformer/configuration	43
10. Negative (reverse) reactance paralleling method.....	48
10.1 Operating principle—control voltage biasing.....	48
10.2 Control arrangements.....	53

10.3 Settings and sensitivity	53
10.4 Backup methods	55
10.5 Effects of non-similar transformer/configuration	56
10.6 Frequent application errors	60
11. Circulating current (CC) paralleling method	60
11.1 Operating principle—control voltage (set point) biasing	60
11.2 Control arrangements.....	62
11.3 Settings/sensitivity	64
11.4 Backup methods	66
11.5 Effects of non-similar transformers/configurations	67
11.6 Frequent application errors and solutions	72
12. Circulating reactive current (CRC) paralleling method.....	72
12.1 Operating principle—control voltage (set point) biasing	72
12.2 Control arrangements.....	75
12.3 Settings/sensitivity.....	77
12.4 Backup methods	79
12.5 Effects of non-similar transformers/configurations	80
Annex A (informative) Bibliography	85
Annex B (informative) Paralleling transformers—impedance issues.....	86
B.1 Transformers of equal ratings	86
B.2 Transformers of different ratings	87
Annex C (informative) Concept of apparent circulating current	90
C.1 Paralleling issues.....	90
C.2 Apparent circulating current examples	91

IEEE Guide for Paralleling Regulating Transformers

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1. Overview

1.1 Scope

This paralleling guide describes and compares control methods of paralleling regulating transformers. The control methods include: master/follower, circulating current, power factor, circulating reactive current, and negative reactance methods. This guide presents operating philosophy descriptions, sample wiring diagrams, typical operational variations, the provision of adequate backup protection, and typical misapplication consequences. This guide does not apply to phase-shifting regulating transformers.

1.2 Purpose

The purpose of this guide is to provide power transformer paralleling users with an easily accessible source for comparing control methods of transformer paralleling. This comparison allows the proper choice of control method and proper operation to best maintain proper system operations. The guide also provides an operational understanding to assist in the analysis of changing system configurations on paralleling operations.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is

explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C57.12.70™, IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers.^{1,2}

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.131™, IEEE Standard Requirements for Tap Changers.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online*³ and IEEE Std C57.12.80™ should be consulted for terms not defined in this clause.

apparent circulating current: An expression of the difference in currents between paralleled regulating transformers due to a transformer turns ratio discrepancy, transformer impedance, or other external factors. *See also* **circulating current**; **system-induced circulating current**; **tap position–induced circulating current**.

circulating current: An expression of the difference in currents between paralleled regulating transformers. *See also* **apparent circulating current**; **system-induced circulating current**; **tap position–induced circulating current**.

general paralleling application (GPA): Two or more paralleled regulating transformers connected to a common source bus, with matching impedances, load tap changers with equal tap step sizes, and ranges.

hunting condition: A system condition in which no combination of paralleled regulating transformers with either load tap changer or step-voltage regulator tap positions can satisfy the control requirements resulting in erratic voltage regulation.

matched impedances: A system condition where the impedances of paralleled regulating transformers at each transformer's highest MVA rating are equal.

off-tap operation: An operating condition in which a paralleled regulating transformer's tap position is not in the position to yield the lowest difference in load currents between the paralleled regulating transformers relative to their MVA ratings.

operational transformer impedance variation: An operating condition of paralleled regulating transformers such that simultaneous increasing or decreasing tap positions creates non-similar impedance changes.

regulating transformer: For the purposes of this guide, a transformer equipped with a voltage-regulating device, which may be either a load tap changer or an external step-voltage regulator.

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³ *IEEE Standards Dictionary Online* subscription is available at:
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runback: An algorithm that overrides the primary voltage-control algorithm to restore the terminal voltage within a defined range. A runback level is a voltage level that triggers the runback algorithm.

separate source buses: A system condition in which paralleled regulating transformers do not have a common source bus.

system-induced circulating current: An expression of the difference in currents between paralleled regulating transformers caused by system or equipment variations. *See also* **apparent circulating current**.

tap position-induced circulating current: An expression of the difference in currents between paralleled regulating transformers caused by the disparity of turns ratio of the transformers, most commonly due to different tap positions of the transformer load tap changers or step-voltage regulators. *See also* **apparent circulating current**.

3.2 Acronyms and abbreviations

CC	circulating current
CRC	circulating reactive current
CT	current transformer
GPA	general paralleling application
LCC	line current compensation
LDC	line drop compensation
LTC	load tap changer (<i>Syn</i> : on-load tap changer [OLTC] in International Electrotechnical Commission documents)
MF	master/follower
NR	negative reactance
PF	power factor
PTP	peer-to-peer
VT	voltage transformer

4. Basic paralleling information

4.1 General application

Two or more transformers connected in such a manner that they share in the supply of a common load bus (actively regulated voltage bus) are considered to be paralleled. The common load bus will usually be passive in nature, but may contain any types of load such as switched capacitors, shunt reactors, or generation. A general paralleling application (GPA) is when two or more paralleled regulating transformers are connected to a common source bus, with matching impedances and load tap changers (LTCs) with equal tap step sizes and ranges.

This guide describes and compares control methods and operations of paralleled transformers equipped with either LTCs or step-voltage regulators. In every case of voltage regulation, the paralleled regulating transformer control voltage must be that of the regulated common load bus.

Paralleled transformers are typically equipped with either an internal LTC or a separate, external step-voltage regulator. These voltage-regulating mechanisms may be connected to either the high-voltage (HV) or the low-voltage (LV) winding of the transformer. Special considerations are necessary if the voltage-regulating mechanisms are not similarly located on each paralleled transformer. See 4.4.3.

4.1.1 Radial distribution substation transformers

Distribution substation transformers are in parallel operation when either of the following conditions is met (see Figure 1):

- Both tie breakers shown are closed *and* at least one of the incoming source lines is connected to the primary bus (common source bus).
- The load bus tie breaker is closed *and* both of the incoming source lines are connected to the primary bus(s) (regardless of the status of the primary bus tie breaker).

Distribution substation transformers are not in parallel operation when either of the following conditions is met (see Figure 1):

- The load bus tie breaker is open (required closed for paralleling definition of common load bus).
- There is a *coincidental* loss of a supply line connection (locally or remotely) *and* an open primary bus tie breaker.

NOTE—This effectively creates a series connection of the transformers (with intermediate secondary voltage load) that requires removal of paralleling control).⁴

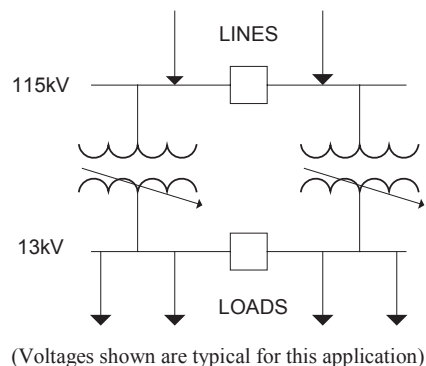


Figure 1—Distribution substation

4.1.2 Network intertie transformers

In this paralleling guide, *network intertie transformers* will refer to paralleled regulating transformers between systems with generation capabilities on both the primary and secondary systems. In contrast to radially operated distribution substation paralleled regulating transformers (no secondary generation), Figure 2 illustrates the possibility for line power flows in either direction in the network intertie application.

At any given time, network intertie transformers must have a designated *regulated bus*. For LTC control purposes, the HV bus may be designated either the *regulated bus* or the *non-regulated bus*, but not both simultaneously. The same is true for the low-voltage bus. In every application of LTC voltage regulation, the control voltage must be that of the designated *regulated bus*.

⁴ Notes to text, tables, and figures are for information only and do not contain requirements needed to implement the standard.

Once the regulated bus has been established, the control system acts similar to the distribution substation of 4.1.1 regardless of power flow direction. The regulated bus designation may be automatically determined and assigned by real and/or reactive power flow analysis or other system considerations.

Additional care must be taken when automatic voltage control is applied to network intertie transformers. The aggregate effects of other remote intertie transformers in “virtual” parallel may affect the paralleling operation. The changes in system reactive power (VAR) flow and number of tap operations from normal operation may become excessive.

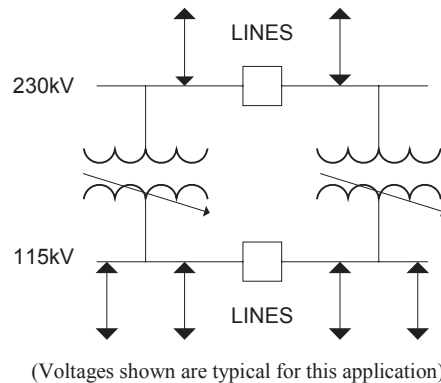


Figure 2—Network intertie substation

4.1.3 Distribution substations with generation

Figure 3 shows a typical distribution substation with generation. In this application, there may be only one or several regulating transformers in parallel with one or more generation systems. The generation acts as an alternate source of power to the load and/or to the system. As such, it can have a large effect on the voltage of the distribution bus. If there is no active voltage control on the bus from the generator, as is most common in an induction generator application, the generator appears as a varying load to the system. In this case, the LTC is not considered to be in a paralleling application. However, if a generator voltage bus control is present, the LTC must be considered in parallel for most advantageous operation of both the generation and the system power flows.

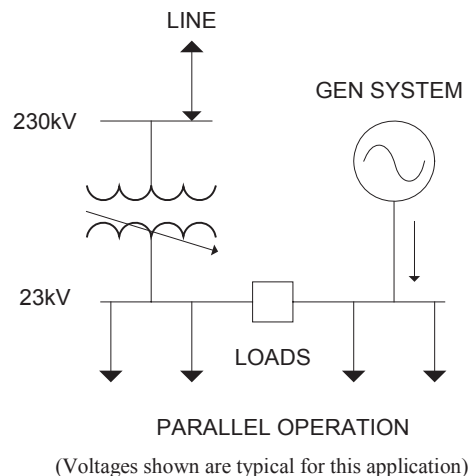


Figure 3—Distribution substation with generation

The problem with a transformer voltage-regulating control and a generator bus voltage control is the relative speeds of operation. A generating system automatic voltage regulator (AVR) is much faster than the slowly operating LTC. With no paralleling control, the AVR will cause the generator to supply VARs to/from the system to regulate the bus voltage. This generator AVR action results in limiting LTC action until the generation has exhausted its var capability and the bus voltage varies beyond the LTC control bandwidth.

This application is described in this guide only to alert users to the possible interaction of paralleled regulating transformers and distributed generation and to the possible effects on their transformer paralleling strategies.

4.2 Reasons for paralleled transformer operation

The reasons transformer paralleling is undertaken include:

- To improve system reliability and security and to provide local backup capability. When two or more transformers are connected together at load side, when one transformer fails (and is isolated from the source and load buses) the other transformer(s) will continue to serve either full load or partial load without interruption. Actual operation will depend on the ratings of the other transformers still connected in parallel. Paralleling transformers may avoid the possibility of critical load being interrupted by the tripping of one transformer.
- To increase substation capacity. When load increases beyond the existing transformer's capacity, another transformer can be connected in parallel to increase capacity. Fault-interrupting capability of bus equipment must be considered when making the decision to parallel transformers.
- To provide flexibility for scheduled outages and improve access for maintenance and repair purposes.

4.3 Basic voltage-control operation

4.3.1 Basic voltage control

Figure 4 illustrates the major inputs/outputs to/from either LTC or step-voltage regulator controls. The values shown indicate typical ranges. These typically include:

- The voltage transformer (VT) input magnitude of one phase of the regulated bus voltage.
- The current transformer (CT) input magnitude of one (same) phase of the transformer regulated bus current.
- A current input for parallel operation (not shown).
- An output connection to the voltage-regulating mechanism to raise or to lower the taps to maintain the specified regulated bus voltage.
- Also indicated is the capability to select a desired bus voltage (V) level setting, a voltage tolerance or bandwidth (BW), a time delay (TD) setting, and line drop compensation (LDC) settings (line drop compensation settings will be discussed in 4.3.2).

Figure 5 illustrates the functions of LTC/step-voltage regulator controls. These typically include:

- The desired bus voltage level setting (V).
- The BW or tolerance setting describing the voltage variation allowed before correcting action is taken ($V + 0.5 \text{ BW}$ to $V - 0.5 \text{ BW}$).
- The time delay (TD) setting establishing the time interval the voltage is allowed to remain outside the bandwidth before correcting action is taken. As shown in Figure 5, when the TD setting is exceeded, the control signals a voltage-regulating mechanism to raise or lower to correct the voltage back into the bandwidth.
- A block raise (BR) level at which the control raise action is blocked.
- A block lower (BL) level at which the control lower action is blocked.
- A runback (RB) level at which a lower or raise command is issued.

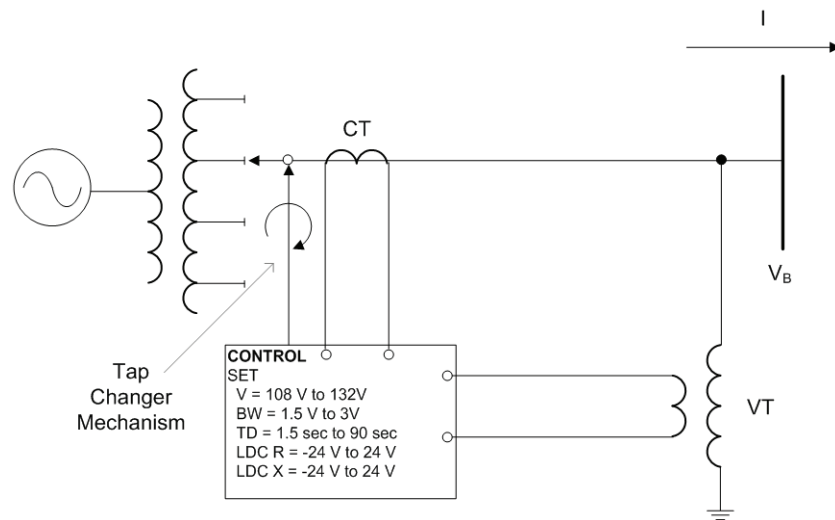


Figure 4—Basic control inputs

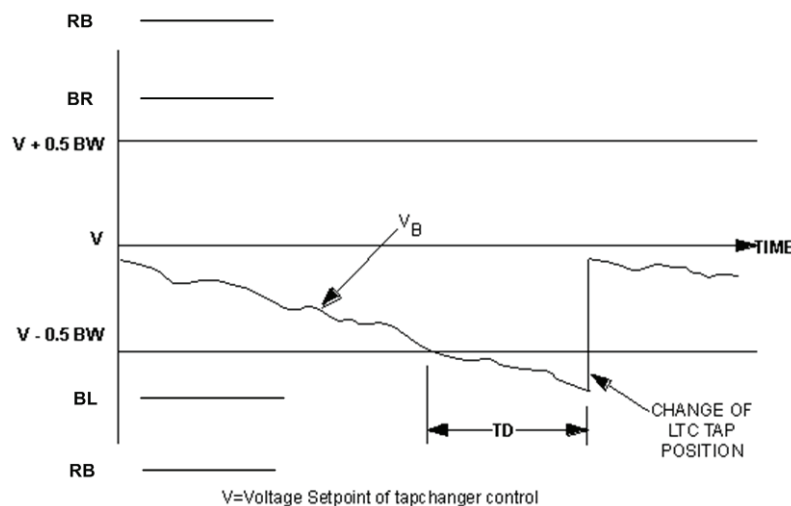


Figure 5—Operation example—control function

4.3.2 Line drop compensation (LDC)

The application of LDC to paralleled voltage-regulating controls may dramatically change control operation under contingency conditions. Consideration should be given to potential overvoltages or undervoltages that may occur if one transformer goes out of parallel when choosing LDC settings. This is described in the LDC section of each paralleling method.

4.3.2.1 R&X method

The most commonly used form of distribution LDC is known as the R&X method, illustrated in Figure 6. The purpose of the R&X method of LDC is to regulate the voltage at a point on the distribution system remote from the regulating transformer. This point is shown as the load center in Figure 6. This function is especially effective when applied on long lines to distant load centers with minimal distributed loads (or switched capacitors) between the regulating transformer location and the load center.

The effectiveness of many R&X applications suffer from inaccurate line impedance calculations, unequal impedances between phases, and from distributed loads on the circuit. When applied to a bus with several circuits or a circuit with several branches between the regulating transformer and the load center, accurate settings for total system operation are not practical. Since these additional circuit or additional branches are effectively distributed loads along the line to the load center, their effect must be included in the setting calculations.

As an alternative to performing impedance calculations, some utilities will adjust the R and X settings based on actual voltage readings at the user-selected load center. R and X values are increased or decreased until the desired voltage at the load center is achieved. When using this method, it is helpful to know the approximate X/R ratio of the system impedance to the load center. This ratio is maintained when selecting the R and X set points.

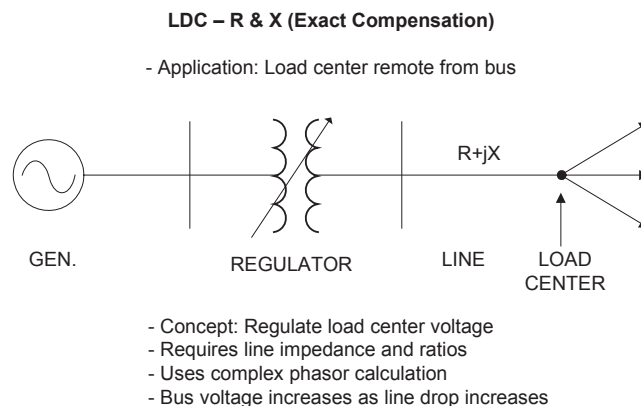


Figure 6 —Single regulating transformer example—R&X method

As shown in Figure 4, the control is supplied with the local bus voltage and the line current. Settings include voltage drops derived from the resistance (R) and reactance (X) of the line section between the regulating transformer and the desired load center voltage-control point (see Figure 6). With those quantities, the control can calculate the voltage drop in the line at any loading condition. Effectively (whether by changing the set point or biasing the input voltage) it raises or lowers the operational set point to compensate for the line drop. The voltage at the load center now has become the regulated voltage point and the local control bus voltage varies to maintain the load center voltage.

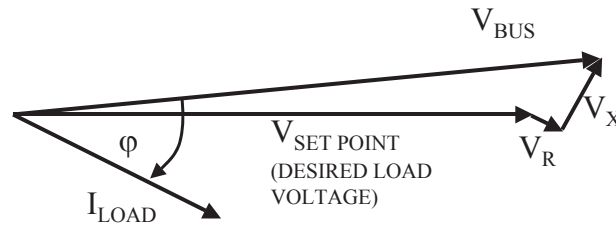


Figure 7 —Compensation voltage diagram—R&X

As illustrated in Figure 7, the calculation of V_{BUS} by the control is best illustrated with a phasor analysis for the real and reactive voltage drops due to line resistance and reactance respectively. Some controls add the compensation to the set point and others subtract the compensation from the measured voltage for equivalent results.

To prevent the control from raising the system voltage too high for loads close to the substation during unusually high load conditions, some form of overvoltage blocking and runback protection is typically used. Overvoltage blocking may be internal to the voltage-regulating control or performed using external devices. If this overvoltage protection is provided externally from the primary control, it will also provide protection in the event of primary control failure.

4.3.2.2 Line current compensation (LCC) method

A second method of line drop compensation, the line current compensation (LCC) method, is used primarily for bus regulating applications. It may be difficult to calculate impedances for multiple dissimilar circuits connected to the bus, such as distributed line loads and distributed capacitor banks as required by the R&X method. The LCC method does not require line impedances settings and operates on the basis of regulating the distribution system voltage strictly as a function of the load current magnitude at the regulating transformer.

Figure 8 illustrates the application for the LCC method. In this example, the current seen by the control is NOT the current in any one line as described for R&X method.

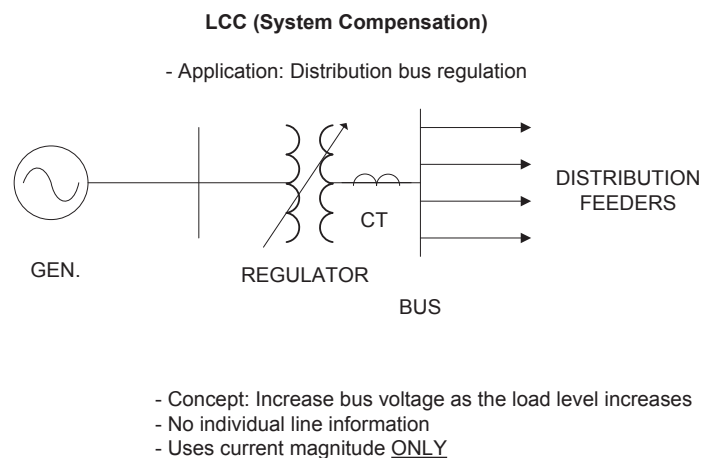


Figure 8 —Single transformer example—LCC

Using the LCC method, the compensation setting (V_{set}) is determined simply as the magnitude of desired bus voltage boost at the rated control current, as shown in Figure 9. The set point (V_{set}) can be the maximum voltage drop in any single feeder on the circuit at maximum load (reflected to the standard LDC CT rated secondary current of 200 mA). This results in a compensation voltage of zero at no load condition and the set point voltage at full load.

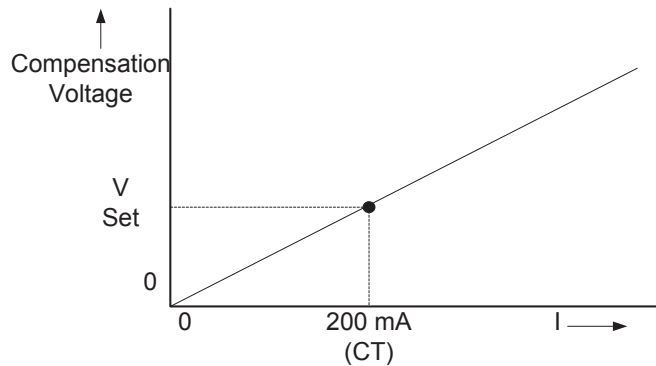


Figure 9 —Compensation voltage diagram—LCC

4.4 Effects of off-tap operation

An off-tap operation is an operating condition where a paralleled regulating transformer's tap position is not in the position to yield the lowest difference in load currents between the paralleled regulating transformers relative to their MVA ratings. This is equivalent to the position for minimum apparent circulating current.

The goal of transformer paralleling systems is to optimize the shared loads of paralleled regulating transformers while maintaining the regulated bus voltage. Optimum transformer loading may be determined differently for different applications and paralleling control strategies. These differences in determining the conditions of optimum transformer loading will be described in the paralleling methods Clause 8 through Clause 12.

As an expression of transformer loading differences, the concept of circulating current has been central to the matter of paralleling regulating transformers. Figure 10 illustrates the concept of circulating current between two transformers. For multiple paralleled transformer applications, the circulating current in any one transformer is the deviation between that transformer's current and the average current of all the other paralleled transformers.

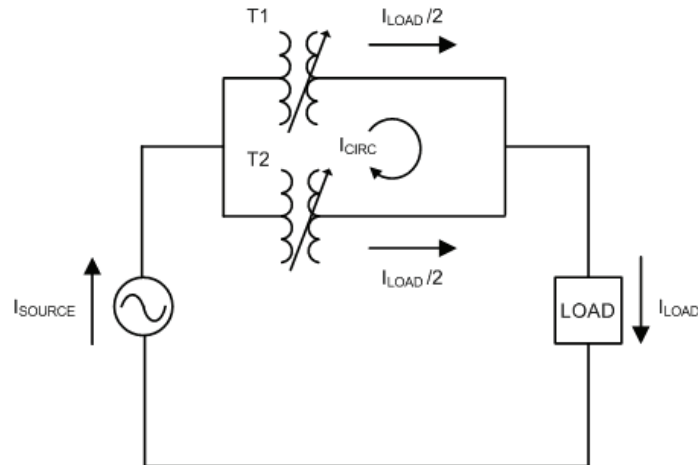


Figure 10—Load and circulating currents

If transformers 1 and 2 have equal impedances, the load current is shared equally by both transformers. Circulating current is zero (the transformer loading difference is lowest) as long as the transformers are on the same tap position.

A transformer's impedance will change slightly with a one tap step change, so the sharing of load current will remain essentially 50-50 if transformer 1 moves to one tap step apart from transformer 2. The significant change with the tap step difference is that a circulating current I_{CIRC} occurs between the transformers.

However, for many paralleling applications there actually are two relevant components of circulating current. The first is a tap position-induced circulating current that is affected by, and adjustable by, tap changes. The second is a system-induced circulating current that is affected by system configuration or transformer characteristics changes.

System-induced circulating current is usually only minimally affected by the tap changes of individual paralleled regulating transformers. Examples of conditions capable of causing system-induced circulating current include unmatched transformer impedances, separate source bus applications, separate source side voltages, multiple load winding transformers, and varying impedance changing designs (operational transformer impedance variation).

In these applications, the total transformer current is the phasor sum of the transformer load current, the tap position-induced circulating current, and the system-induced circulating current. The sum of the tap position-induced and the system-induced circulating currents is described as apparent circulating current. See Annex C for a discussion of apparent circulating current.

4.4.1 Common source bus application

Figure 11a illustrates a two-transformer paralleling application with a common source bus. Assume transformer 2 is in a one tap raised or boost position that results in a lower primary-to-secondary turns ratio for transformer 2 relative to transformer 1.

This tap difference inserts a voltage (tap step-voltage) into the loop comprising both transformers. The impedance of this loop has the extremely high X/R (reactance to resistance) ratio of the transformers. With an in-line voltage source applied to the impedance of the loop, a predominantly reactive current flow (or

VAR load) occurs. This current flow adds to the load of transformer 2 and subtracts from the load of transformer 1. This current is an example of a tap position–induced circulating current.

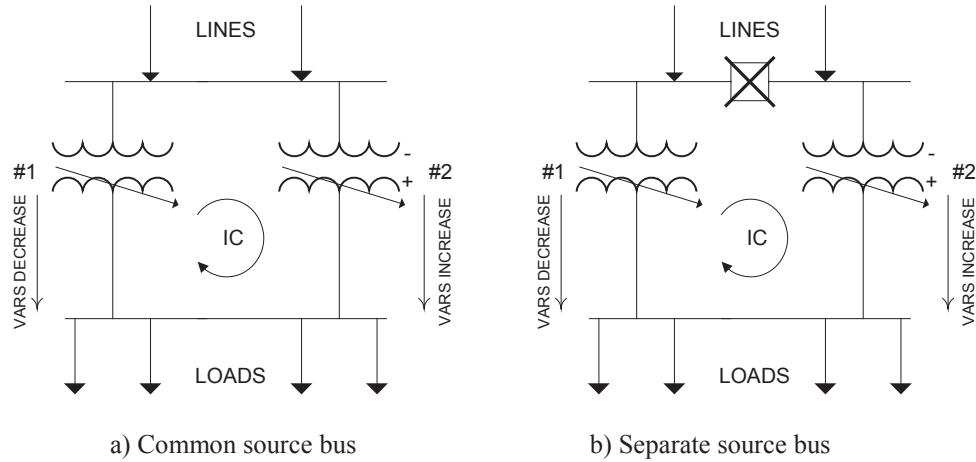


Figure 11 —Paralleled transformer off-tap operation

The circulating current, shown in Figure 11 as IC, is generally determined by measuring or calculating the difference in the transformer currents and dividing by 2.

The circulating current per off step can be approximated for a two-transformer case by the following equation:

$$IC = \frac{\text{Tap voltage}}{(Z_1 + Z_2)} \quad (1)$$

where:

- Z_1 is the impedance of transformer 1
- Z_2 is the impedance of transformer 2

This equation illustrates the fact that any load or supply system changes will not affect the amount of the circulating reactive current flow in a common source bus transformer paralleling application.

In applications with different CT ratios, transformer ratings, or transformer impedances, a difference in load and control current (system-induced circulating current) may occur even in on-tap operations. For example, if unmatched impedance transformers are paralleled, both the load currents will be different in the unmatched transformers (in relation to the impedances). This application creates a difference in load currents (system-induced circulating current) that is not induced by tap-position action. This on-tap circulating current can enhance or interfere with paralleling operation and with LDC operation.

Example: Transformers with significant impedance differences will pass significantly unequal portions of the load current and the $I_{CIRC} = (\text{difference current})/2$ may be incorrectly interpreted as tap position–induced circulating current.

Example: In Figure 11a, if the impedance of T1 = 8% and T2 = 10% it can be determined that

$$I_{\text{Load } 1} = 0.56 \times I_{\text{Load}}$$

$$I_{\text{Load } 2} = 0.44 \times I_{\text{Load}}$$

$$I_{\text{apparent circulating}} = \frac{(0.56 \times I_{\text{Load}} - 0.44 \times I_{\text{Load}})}{2} \pm I_{\text{apparent circulating due to tap position}}$$

As defined, the circulating current IC is almost wholly reactive (near zero power factor), whereas I_{Load} is usually at a high power factor. A phasor calculation must be made to calculate the apparent circulating current.

Because modern systems may need to plan for appreciable apparent circulating current, which differs from the tap position–induced circulating current, it is preferred to use the term *apparent circulating current* for the general case.

The effect of this non-tap position–induced circulating current will be discussed for the various paralleling control methods in Clause 8 through Clause 12.

4.4.2 Separate source bus application

Figure 11b illustrates a two-transformer paralleling application with the source side tie breaker open, resulting in separate, locally independent source buses. This application must anticipate different primary voltages for each of the transformers.

Since the two primary voltage levels and phase angles are not expected to be exactly equal in this application, it is probable some system-induced circulating current will exist even when the transformers are on the same relative taps. As discussed in 4.4.1, this application creates a difference (circulating or apparent) current that is not induced by tap-position action. The effect of this system-induced circulating current will be discussed for the various paralleling control methods in Clause 8 through Clause 12.

Depending on the X/R ratio of the circulating current path impedance, a difference in the relative magnitudes of the source voltages will affect the paralleled transformers' reactive current or VAR flows. A difference in the relative phase angles of the source voltages will affect the paralleled transformers' real current or power flows.

The impedance of the circulating current circuit, for this application, includes the system impedances back to the common primary source. System configuration changes due to system switching will affect the circulating current circuit impedance. The variation of the individual source bus voltages (and therefore system-induced circulating current) will also be a function of the system loading.

These varying system-induced circulating currents are not easily known or calculable for this application and may include substantial real (kW) power. Paralleling techniques are available to parallel transformers with differing primary or source bus voltages and will be discussed later in Clause 8 through Clause 12.

4.4.3 Operational transformer impedance variation

Operational transformer impedance variation between paralleled transformers will refer to the unusual but possible application of paralleling transformers with substantially different impedance changes with tap operation. The most likely applications are for transformers with LTCs installed on different windings (primary or secondary) or for LTC windings located differently on the transformer cores. As taps change equally on these transformers, the impedance change on each can be quite different. In some cases, raising

a tap on one will increase the impedance while it will decrease the impedance on the other. IEEE Std C57.131™ illustrates the different positions possible for LTCs in wye and delta configured windings.

The transformer nameplate will indicate the impedance of the transformer. Depending on the design, the impedance of transformers may increase or decrease as the tap position digresses from neutral. The impedance variations of transformers of dissimilar design can result in very significant impedance differences as the tap positions digress from neutral.

For example, two transformers with equal impedances of 10% at rated voltage would be considered as matched impedance transformers. However, when the tap position on each transformer changes in the same direction, one transformer's impedance could change to 9.5% and the other could change to 10.5%. These transformers would not only be unmatched at any non-neutral tap position, but their impedances would be changing under normal operating conditions. The effects of this type of operation for each of the paralleling methods will be described in Clause 8 through Clause 12.

4.5 Consequences of less-than-optimal paralleling operation

4.5.1 Unequal load sharing

For most paralleling applications the importance and the effect of apparent circulating current depends on the load of the paralleled transformers. If the transformers are lightly loaded, the addition of a circulating current affects mostly losses. However, if the transformers are loaded close to their capacity, the addition of unnecessary circulating current can affect the maximum station loading capability. Transformer loss of life and LTC contact wear may also become a concern.

4.5.2 Excessive circulating currents

As illustrated in 5.1.1.2, a control voltage error between units can create excessive tap position–induced circulating currents or a difference in loadings. Without proper paralleling control constraints, during normal operation one LTC could go to full boost while the other goes to full buck. Based on the information provided in 4.4.1, the circulating current for this condition (that does not consider additional load current) can be approximated by:

$$I_{C \max} = \frac{\text{Tap range voltage}}{Z} \quad (2)$$

where:

$I_{C \max}$ is the maximum circulating current in per unit

Z is the impedance of the circulating current path

For example, for two paralleled regulating transformers where the tap voltage range is $\pm 10\%$ and $Z = 8\%$ for each transformer,

$$I_{C \max} = \frac{0.2 \text{ pu volts}}{(2 \times 0.08 \text{ pu impedance})} = 1.25 \text{ per unit}$$

(or 1.25 times rated transformer current)

4.5.3 Excessive LTC operations

As described in detail in 5.1.1.1, a timing difference between paralleled regulating transformers could cause one unit to operate for all required tap changes. This action would essentially double the number of operations of one LTC and reduce the number of operations of the other to zero. This action would also create a tap position–induced circulating current that, depending on the LTC control action, could cause transformer overloading.

Since the maintenance schedule for LTC mechanisms is typically related to the total number of LTC operations, the above operation could require twice the maintenance on the more active LTC.

A LTC position hunting condition can occur due to an inappropriate paralleling control choice, mis-operation, or inappropriate voltage-control settings. Usually this is a problem of sensitivity settings and will be discussed in detail in Clause 8 through Clause 12. Since position hunting usually consists of numerous and frequent series operations, damage to the LTC equipment is a consideration. The system voltage is usually not significantly affected since the voltage usually varies near the control set point.

4.6 Regulating transformer/system requirements for parallel operation

The stated requirements for the parallel operation of regulating transformers for this guide will be less limiting than normally encountered in documents describing paralleling requirements. These relaxed requirements are consistent with:

- a) The purpose of the guide to provide users of paralleled regulating transformers an accessible source for comparing control methods for transformer paralleling applications.
- b) The recognition that many non-compatible or barely compatible regulating transformers, by traditional guidelines, are operated in parallel.
- c) Advancing technology has resulted in the development of control methods previously unavailable. These control functions can better achieve the desirable goal of reducing the difference in currents circulating between paralleled regulating transformers relative to their MVA ratings.

4.6.1 Phasor group

Transformers operating in parallel must have the same phase shift between the HV and LV windings and will be simplified if the windings belong to the same phasor group as described in IEEE Std C57.12.70™.

4.6.2 Impedance requirement

For most efficient transformer capacity usage, the impedances of paralleled transformers should be matched at their highest available rating. This will automatically compensate for transformers having different cooling class ratios from self-cooled to maximum ratings. Matched impedances will allow all transformers to carry their maximum rated load. Impedance matching will be discussed in Clause 8 through Clause 12, and in Annex B.

Although matched impedances provide the most efficient operation, the clauses describing each paralleling control method will include the effects of, and solutions to, nominal or significant impedance differences. It should be noted that higher impedance units in parallel need to be de-rated since full load cannot be achieved without overloading the lower impedance units. Although circulating current is common to both transformers, it will affect the loading of the paralleled transformer with the lower MVA rating the greatest. Step-voltage regulators will experience the same load differentials when used in series with power

transformers with unmatched impedances. Derating of the combination of the higher impedance transformer in series with its step-voltage regulator would be required also.

For example, assume transformer A impedance is 10% and the equally rated paralleled transformer B impedance is 8%. Since the loading is inversely proportional to the impedances (10/8), transformer A load would be (8/10) of the transformer B load. When transformer B reaches full load, transformer A has only reached 80% of its equal rating. Since transformer A cannot be loaded up to rating without overloading transformer B, transformer A must be de-rated by 20%.

4.6.3 Source bus connections

Unlike previously assumed application requirements, the primary windings of paralleled transformers do not have to be permanently connected as normally described. This guide will refer to paralleling applications with different source side voltages as “separate source bus” applications. Paralleling techniques are now available that do not necessarily create improper operation due to the operation of a source bus voltage tie breaker. The effects of source bus connections for different paralleling methods will be described in Clause 8 through Clause 12.

4.6.4 Voltage ratios (rated)

Transformers operating in parallel are not required to have the same voltage ratio as normally described. Paralleling techniques are available to parallel transformers with differing primary or source voltages. For example, in appropriate applications a 230 kV/69 kV transformer can be paralleled with a 115 kV/69 kV transformer. This is an example of a separate source bus case of Figure 11b.

4.6.5 Winding designs

Transformers operating in parallel are not required to be of similar design such as to cause similar individual impedance changes as the taps progress. Depending on paralleled transformer winding locations, equally increasing tap positions may cause the impedances to increase or decrease.

This causes an operational transformer impedance disparity between the paralleled units (see 4.4.3). Paralleling techniques are available that may satisfactorily parallel transformers with operational transformer impedance variation within specific limitations.

5. Requirements of the paralleling control system

5.1 Need for paralleling operation control

Common non-paralleled control functions, described in 4.3, may not adequately provide the appropriate paralleling tap changing action to meet the added requirements of transformer paralleling applications.

The desirable goal of all paralleling methods is to reduce the difference in currents circulating between paralleled regulating transformers relative to their MVA ratings as much as possible for all credible system or equipment conditions. This goal should be achieved while maintaining the regulated bus voltage specified by control settings.

5.1.1 Possible basic control mis-operation examples

If appropriate preventive measures and/or paralleling control features are not implemented, a timing error or voltage level error may occur.

5.1.1.1 Timing error

A timing error can be caused by control timing circuit tolerances or by tap changer mechanical operating times. The variable for this case is the timing of the control or physical tap operations of the two transformers.

Assume the transformer 1 voltage-regulating mechanism consistently operates faster than the transformer 2 voltage-regulating mechanism. As the bus voltage and the control voltages increase or decrease together, there is no operating difference until the voltages reach the band edges. However, when the control voltages reach both band edges (which signal both controls to begin timing and sends signals to their tap changers to operate) the overall time to tap operation of each transformer will not be equal.

Whenever the bus voltage reaches the upper band edge (which calls for a tap reduction) the faster voltage-regulating mechanism (#1) operates. This lower #1 tap operation reduces the regulated bus voltage and both control voltages return back into band and the controls stop their call for any further action. Whenever the bus voltage reaches the lower band edge (which calls for a tap increase) the faster voltage-regulating mechanism (#1) again operates. Now the #1 raise tap operation raises the regulated bus voltage and both control voltages return back into band and the controls stop their call for any further action.

The result of this timing difference is that the #1 voltage-regulating mechanism is doing all the regulation and operation while the #2 voltage-regulating mechanism does not operate. This not only causes different duties on the mechanisms and mechanism contacts but also has detrimental effects on the loading and heating of both units. These system effects of differences in tap positions of the transformers are described in more detail in 4.4.

5.1.1.2 Voltage level error

Figure 12 illustrates an example of a voltage error. In this example operating times may be equal but the value of the voltages V1 and V2, as seen by the two controls, are unequal. Control voltage V1 is shown to be higher than the control voltage V2 in magnitude. This difference may be a result of the accuracy tolerances of the voltage transformers (VT) supplying the individual voltages to the controls, accuracy tolerances of the control, or individual loading differences of the VTs. The variable for this case is the direction of the physical tap operations of the two transformers.

As the bus voltage and the control voltages increase or decrease together, there is no operating difference as long as neither voltage reaches the band edge. However, during increasing voltage conditions, control voltage V1 will reach the upper band edge first and operate the #1 voltage-regulating mechanism to reduce the voltage back into its bandwidth. In contrast, during decreasing voltage conditions V2 will reach the lower band edge first and operate the #2 voltage-regulating mechanism to increase the voltage back into its own bandwidth.

The result of these unequal applied control voltages is that the #1 voltage-regulating mechanism completes all the tap operations to lower the voltage while the #2 voltage-regulating mechanism completes all the tap operations to raise the voltage. Consequently, the diverging tap positions between the two transformers can only continue to regulate the voltage until one reaches a limiting raise or lower tap position. The final result of such operations can be forcing the transformers to opposite ends of the tap ranges with no remaining voltage control. As described in 4.5.2, this can cause extremely high and damaging tap position-induced circulating or difference current.

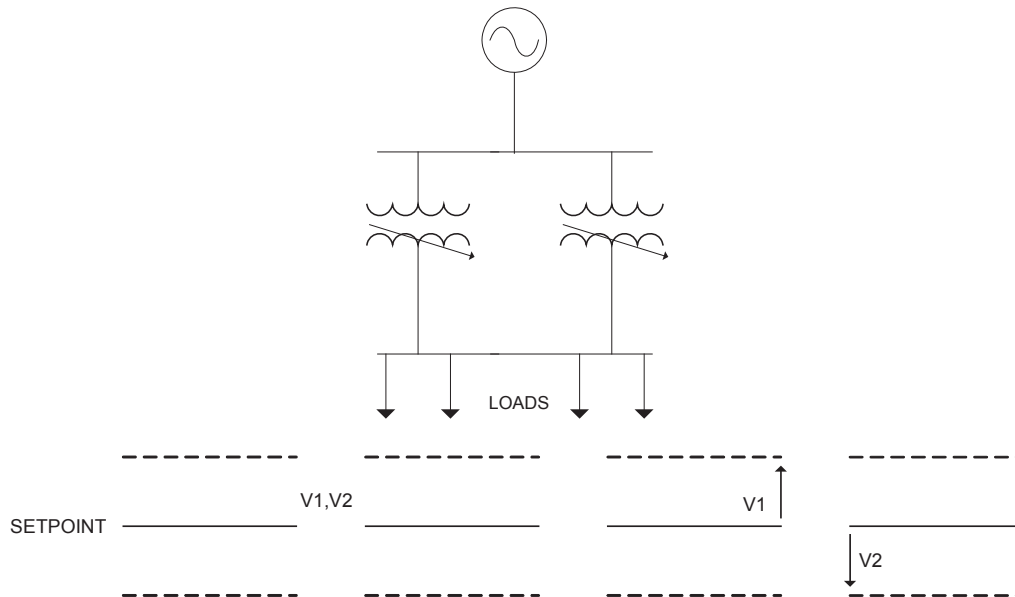


Figure 12—Voltage error example

5.2 Basic paralleling control requirements

5.2.1 Basic responsibility

The desirable goal of all paralleled regulating systems is to reduce the loading difference between paralleled transformers relative to their MVA ratings as much as possible while maintaining the regulated bus voltage. This action will allow the maximum loading capability of the combined or paralleled transformers. It is recognized that an LTC tap change in a reactive system will affect reactive (VAR) flows to a greater extent than it will affect real power (kW) flows, according to the overall circuit X/R (reactive impedance/resistive impedance) ratio.

There are three basic requirements for the appropriate control of multiple paralleled regulating transformers:

- The regulating transformers must continue their basic function of controlling the regulated bus voltage as prescribed by the basic settings on the control (band center, bandwidth, time delay, and line drop compensation).
- The voltage-regulating mechanisms shall be operated to maintain tap positions that meet the particular goals of the application and the chosen paralleling method. These goals may include: 1) maintain the same tap position (transformer turns ratio) of all paralleled regulating transformers, 2) reduce the total current difference between the transformers, 3) reduce the reactive current difference between the transformers, or 4) equalize the paralleled transformer load power factors.

NOTE—Depending on the designs of the transformers or the system application, the appropriate tap positions on the paralleled transformers may not necessarily be the same numerical tap.

- The previous functions should operate correctly in applications with multiple paralleled transformers regardless of credible system configuration changes or breaker operations that alter the parallel connection, loading, or operation of the regulating transformers.

5.2.2 System or bus configuration

In addition to the responsibilities discussed in 5.2.1, the paralleling control system must be designed and capable of performing its duties without causing operations that will be detrimental to equipment/power system services or create safety issues.

This additional requirement generally creates a need for some means of communication connections between the control system and equipment in or beyond the station. This clause is by no means inclusive of all possible configurations and is meant to exemplify the paralleling control considerations required for any system or bus configuration change.

A major requirement of most paralleling control systems operation, except for the negative reactance method, is the automatic (or manual) determination of the system or bus configuration. Without an accurate determination of when regulating transformers are in parallel and the system configuration, the ability to meet the three basic requirements described in 5.2.1 may not be consistent during system configuration changes.

This status information may be communicated by: a) external wiring between paralleled regulating controls and inputs of breaker position contacts, b) communication between one or more of the regulating controls and the inputs of breaker position contacts, or c) independent devices that can receive the system external information and communicate settings or changes directly to the controls or to the voltage-regulating mechanisms.

5.2.3 Configuration effect examples

Many different bus configurations are possible. Case A is a two-transformer arrangement with source side bus tiebreaker; case B is a three-transformer arrangement with source side bus tie breakers; and case C is a three-transformer load ring bus arrangement with source side bus tie breakers.

The presence of the source voltage breakers may have a large effect on the applicability of different paralleling methods. However, if the applied paralleling control method is appropriate for separate source bus voltages, a single source bus breaker status change does not add to different paralleling strategies. Multiple source bus or certain source bus/load bus combinations will increase possible the number of configurations.

5.2.3.1 Case A—two-transformer arrangement with source bus and load bus tie circuit breakers

Case A is a two-transformer arrangement with source bus and load bus tie circuit breakers as shown in Figure 13.

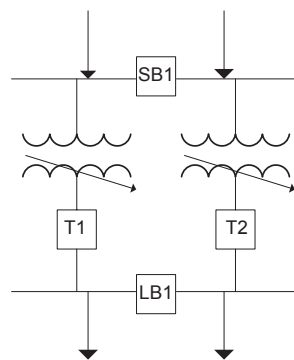


Figure 13—Case A

- The transformers are NOT in parallel if any of the T1, T2, or LB1 breakers are open.
- If either T1 or T2 breakers are open, the LDC response must be appropriate for the configuration and paralleling control de-activated.
- If LB1 is open, LDC settings may need correction depending on the resultant distribution feeder configuration and loading. (The transformers are no longer in parallel operation.)
- With sources on both incoming supply buses, as shown, the operation of breaker SB1 has no effect on the *paralleling status*; however, if this condition of open SB1 can occur several paralleling control methods (as described in Clause 8 through Clause 12) may not be appropriate.

5.2.3.2 Case B—three-transformer arrangement with source bus and load bus tie circuit breakers

Case B is a three-transformer arrangement with source bus and load bus tie circuit breakers as shown in Figure 14.

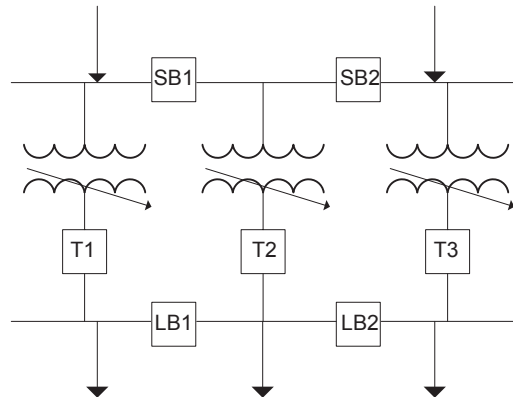


Figure 14—Case B

- If T1 is open and LB2 is closed, T2 and T3 are in parallel (similar analysis for either T2 or T3 individually opened). As such, the T2 and T3 transformer loading has changed requiring LDC setting changes.
- If LB1 *or* LB2 are opened, two transformers are still in parallel and the third is in independent operation. All loading has changed requiring LDC setting changes.
- If both LB1 *and* LB2 are open, all three transformers are in independent operation and the paralleling control de-activated. All loading has changed requiring LDC setting changes.
- Operation of SB1 *or* SB2 does not affect the *paralleled status*. However, if this condition occurs some paralleling control methods are not applicable. Individual LDC is not generally applicable under this condition.
- Operation of both SB1 and SB2 removes transformer 2 from service and from paralleling, similar to opening T2. Note that transformer 2 remains energized unless T2 is also opened. Since the high side buses are also disconnected, several paralleling control methods are not applicable. Individual LDC is not generally applicable under this condition.
- For multiple transformer applications, if SBx and LBx breakers (example SB2 and LB2) are open, the paralleling transformers on either side must be established into individual independent paralleled groups.

5.2.3.3 Case C—three-transformer arrangement with source bus and load ring bus

Case C is a three-transformer arrangement with source bus and load ring bus as shown in Figure 15.

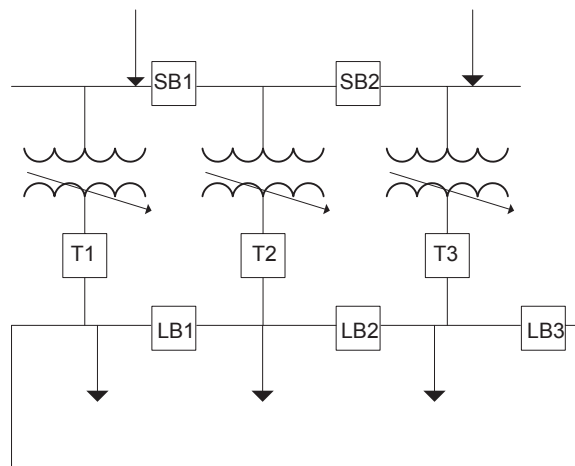


Figure 15—Case C

- The individual operations of T1, T2, T3, SB1, and SB2 have similar effects as in case B.
- The operation of load bus intertie breakers LB1, LB2, and LB3 causes much different conditions than case B. For instance, the individual operation of any load bus tie breaker has no immediate effect on loading or paralleling status of any transformer. However, the *combination* of load bus intertie breakers operation becomes significant and must be accounted for in the paralleling strategy.
- When more complicated bus configurations, such as breaker and half schemes or double bus/double breaker schemes are applied, the accurate determination of system configuration and desired paralleling equipment operation also becomes more complicated.

6. Equipment involved in paralleling

6.1 Regulating transformers

When paralleling regulating transformers, the relative impedance of each transformer will determine the load sharing. Therefore, if transformers of the same rating, ratio, and impedance are paralleled they will share load equally. Transformers are considered suitable for paralleling if their impedances do not exceed the following tolerances:

- | | |
|---|-------------|
| a) Two-winding transformers | $\pm 7.5\%$ |
| b) Duplicate two-winding transformers | $\pm 7.5\%$ |
| c) Three or more windings or zigzag | $\pm 10\%$ |
| d) Duplicate three or more windings or zigzag | $\pm 10\%$ |
| e) Autotransformers | $\pm 10\%$ |
| f) Duplicate autotransformers | $\pm 10\%$ |