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RESEARCH ARTICLE

TRANSFORMER MONITORING AND ON-LOAD TAP CHANGER CONTROL USING PROGRAMMABLE LOGIC

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ABSTRACT

This paper presents a study of transformer monitoring and load tap-changer control. Earlier control schemes were the "paralleling balancer", the "master/follower" and the "circulating current" schemes. These schemes had their drawbacks. The scheme as presented in this paper is implemented using programmable logic, math functions and IEC 61850 communications over fiber-optic Ethernet. The presented scheme achieves ease and speed of installation, a more integrated system with less field using, minimal control cable runs and terminations and minimal overall installation time. With SCADA control accomplished over a DNP3 loop, need for electromechanical switches is eliminated. The LTC control was field tested on three parallel 230/115KV autotransformers on the Santee Cooper system.

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INTRODUCTION

Transformer monitoring and load tap changer control (LTC) as presented in this paper is implemented using programmable logic, math functions and IEC 61850 communications over fiber-optic Ethernet. One LTC control is associated with each transformer. The current angle form each LTC control is passed to all parallel LTC controls using IEC61850 Generic Object-Oriented Substation Event (GOOSE) messaging. A decision is made in each control as to whether it should be the next control to tap up, tap down, or remain unchanged should the voltage magnitude go outside the upper and lower band settings for a predetermined time. This selection is then communicated to all LTC controls. The LTC control also keeps track of the tap position by monitoring raise and lower motor current in the LTC. The LTC control was field tested on three parallel 230/115KV autotransformers on the Santee Cooper system. This Ethernet-based system requires no wiring between transformers to derive circulating current because each LTC control is essentially standalone and all required information for controlling the LTCs is communicated over a network. This simplified installation and troubleshooting.

Background of study

In the past, Santee Cooper used the "paralleling balancer" scheme for control of LTCs. The paralleling balancer scheme required that current transformer (CT) secondary current be run some distance between transformers through a fairly complex system of auxiliary CTs. These circuits separated the imbalanced current from the total transformer current and represented that imbalanced current as a voltage. This voltage, representing the imbalanced current, was then input as a bias to the LTC control to curse it to change taps in such a manner as to reduce the circulating current between transformers (Alstom, 2002). Otherwise, circulating currents could become quite high and cause a transformer to exceed its rating. While this approach proved reliable, it demonstrated some drawbacks in its application, because of the difference in size and impedance of the third transformer. Santee Cooper found it difficult to balance out the circulating current circuits for paralleling. Therefore, they were forced to accept a tolerance of up to a two-tap difference between the transformers, which led to a significant amount of circulating current. Santee Cooper system operators constantly had to monitor these units and often were required to adjust the taps manually. In addition, the system was somewhat difficult to troubleshoot when there was a problem. It could take even the most experienced technician many hours to track down a problem in the current loop. The amount of cable and number of terminations required running a continuous current loop through all three transformers, all of the associated high and low-side circuit breakers and the bus-tie breakers were also costly. A master/follower solution was first considered as a replacement because of its simplicity and ease of installation. This is the set up: the master control senses voltage and tells all the other controls (the followers) to change taps. This is also

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referred to as the "lock-in-steps" method because all transformers remain on the same tap (Anderson, 1995). This only works parallel transformers with the same number of taps. The master/follower solution was rejected because of the difficulty Santee Cooper had experienced in obtaining reliable tap-position information. With the typical master/follower method, the tap changer locks out when there is a tap disparity for longer than a set time (Blackburn, 1998). The tap-position indication apparatus that were being used on the system, including selsyns and potentiometers and their associated transducers, were complex, expensive maintenance prone, and not very adaptable to different types of tap changer mechanisms. They also proved very susceptible to damage from lightning and switching surges. This made it desirable to revisit how tap position was tracked and, if possible do away with these electromechanical device and transducers. Due to these difficulties previously experienced in obtaining reliable and accurate tap-position information, Santee Cooper decided to continue using some method, such as the circulating current method, that would not absolutely require accurate tap-position information. Remote control of the system was an issue in considering an upgrade as well. The old Santee Cooper scheme required that they design and build their own apparatus for remote control. This consists of electromechanical switches for remote/local, parallel/Independent, automatic/manual, and raise/lower controls and analog meters. These controls were located in a cabinet lying adjacent to the existing control cabinet and connected to dry contacts in the remote terminal unit (RTU) by long runs of cable. With this system, there was a large amount of time involved in design, wiring, field installation and cable termination. The following was considered when undergoing the design;

- More integrated topology and less filed wiring
- Less susceptibility to lighting and switching
- Transients
- Minimal cable runs and terminations
- More precise parallel control – within one tap
- Reliable tap-position indication
- Less physical fill space
- Minimal installation time
- Easier troubleshooting
- More cost-effective

It was decided that these goals could best be met using a microprocessor-based device with direct current and voltage inputs, front panel push buttons and metering, an open communications protocol (IEC 61850) for communication between controls, and the DNP3 communications protocol for monitoring and control via supervisory control and data acquisition (SCADA). A device was selected (a transformer monitor) that met these goals and had the necessary programmable logic elements (timers, latches, counters and Math variables) needed to implement the logic.

Parallel transformer circulating current characteristics

In order to determine how to best use the measured analog values of voltage and current to implement the scheme, it was necessary to revisit the characteristics of circulating current in parallel transformer.

A.Parallel Transformer Model

Consider a simplified system model with two transformers in parallel as shown in Fig. 1.

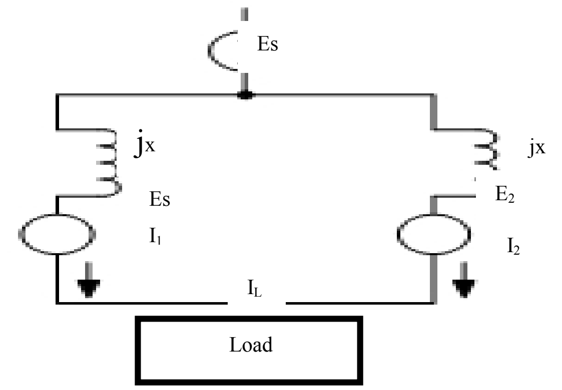

Fig. 1. Simplified two-transformer model

In Fig. 1, for simplification, both transformers are identical and have the same impedance, JX. They each supply a portion of the load current, I_L. While Es is the system voltage, voltages E_1 and E_2 represent the voltage change presented by the LTCs. At nominal tap $E_1 = E_2 = 0$. On a standard ± 16 – position tap changer each change up or down world represent a 5/8 percent (or $0.00625\rho\mu$) change in E_1 and E_2 .As can be seen in Fig. 2, the currents through each of the transformers are composed of a load current component plus or minus a circulating current component that is

I_{circ} = (E1E2) / 2jX = -j(E1E2) / 2X --------------------------(1)

Therefore, the transformer that provides a high voltage will also provide circulating current.

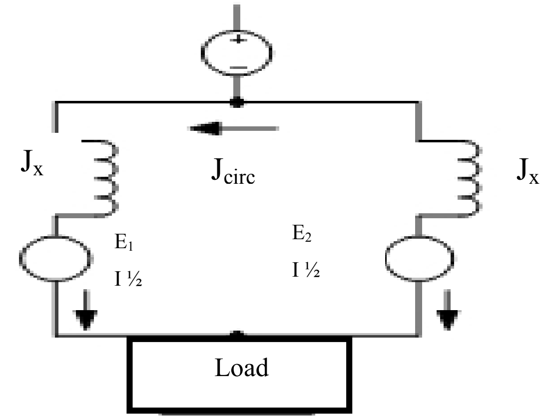

Fig. 2. Two-transformer model: circulating current.

B.Resulting Current Angles

From Fig. 3 and Fig. 4, observe that;

I_1 = (IL / 2)I_{circ} --------------------------------------- (2)

I2 = (IL /2)Icirc -- (3)

Observing equation (1) above, notice that I_{circ} has an angle of – 90 degree with respect to the reference voltage. That fact, combined with 2 and 3, results in the vector diagram as shown in Fig. 3.

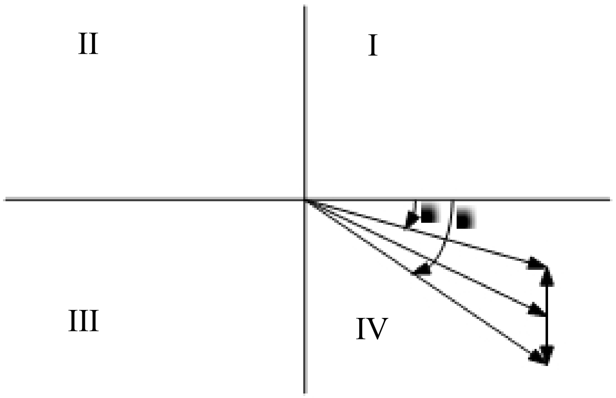

Fig. 3. Vector diagram of parallel transformer current

Observe from Fig. 3, that the current angle of I_1, or θ_1 lags the current angle of I_2 or θ_2. That is, the current angle of the transformer supplying circulating current lags the current angle of the transformer receiving circulating current. This is true for any number of transformers and for dissimilar transformer as well.

However, the LTC control is applied on an autotransformer that can have power flow in either direction. Therefore, the parallel autotransformers may not be operating in power Quadrant IV as shown in Fig. 3, but rather in power quadrant II as shown in Fig. 4.

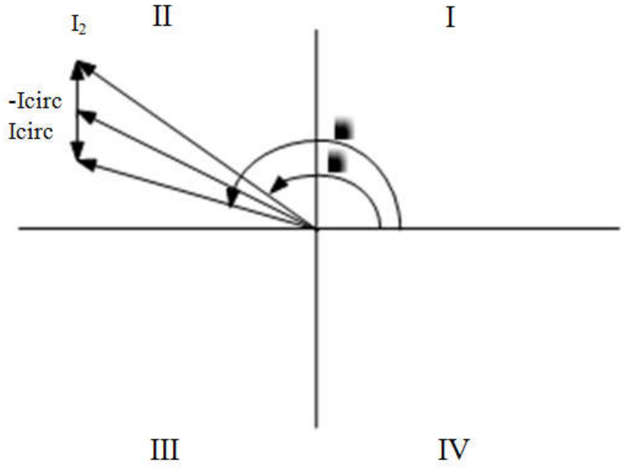

Fig. 4. Parallel transformer current when operating in power quadrant II

Observe from Fig. 4 that, when operating in power Quadrant II, the current angle of I_1, or θ_1, that is for operation in power quadrant the current angle of the transformer supplying circulating current leads the current angle of the transformer receiving circulating current. Again, this is true for any number of transformers and for dissimilar transformer.

Rules for parallel ltc control

Using the above result in Fig. 3 and Fig. 4, which leads to the conclusion, that a comparison of current angles could be used as a basis for developing rules for LTC control, these includes. When operating in power quadrant I or IV, if it is necessary to raise the voltage, tap up the transformer that has the most leading current angle.

1. When operating in power quadrant I or IV, if it is necessary to lower the voltage, tap down the transformer that has the most lagging current angle.
2. When operating in power quadrant II or III, if it is necessary to raise the voltage, tap up the transformer that has the most lagging current angle.
3. When operating in power quadrant II or III, if it is necessary to lower the voltage, tap down the transformer that gas the most leading current angle.

These rules seemed novel at first; however, it was discovered that rules 1 and 2 had been previously suggested and successfully tested using synchrophasors and real-time digital simulation (Bosma and Thomas, 2003). This provide some level of contort regarding the method. However, to the author's knowledge, it had not previously been applied in the field.

Table 1. Hard-wired 1/O

Name	Description	Type
Remote	Remote enable	Digital
52AH	High-side breaker 52a	Digital
52AX	Low-side breaker 52a	Digital
52A – OTHER	Other breaker(s) 52a	Digital
CONT-VOLT	Control voltage	Digital
VPOSI	Potentiometer total volts	Analog (0-10V)
VPOS2	Potentiometer wipes volts	Analog (0-10V)
IPOS	Tap-position current	Analog (mA or V)
IA	IA	Current
IB	IB	Current
IC	IC	Current
VA	VA	Voltage
VB	VB	Voltage
VC	VC	Voltage
I-RAISE	Raise motor ampere	Current
I-LOWER	Lower motor amperes	Current
Name	Description	Range/Units
VMAX	Maximum limit of voltage band	KV
VMIN	Minimum limit of voltage band	KV
TAPMAX	Maximum tap	e.g, 16
TAPMIN	Minimum current (exceeding this value causes auto inhibit)	
No-PARA	Number of Parallel transformers	1-4
POS-SELECT	TAP-position indication selector	0 = INTERNAL 1 = VOLTAGE 2 = CURRENT
ES2A_OTHER	Enables other 52a contact imput for parallel operation (Used for time breakers)	I = ENABLED
COUNTER_PRE	Preset for operations counter	Percent
27 POT	Pickup for minimum secondary voltage loss of potential	
LDC	Line-drop constant (for line-drop compensation).	V/A
VHI_LIM	Maximum voltage (will not lower tap beyond this point	KV

LTC control features

A program was designed for the LTC control to implement the LTC rules and meet the goals described in section III. The resulting features are described in the following subsections.

A.Front-Panel Human-Machine Interface (HMI)

1) Push Buttons

Four push buttons are available on the applied transformer monitor. They are used for the following functions:

{RAISE} –	Performs a manual raise or adjusts the tap – position counter up.
{LOWER} –	Performs a manual lower or adjusts the tap-position counter down.
{AUTO} –	Places the tap changer control in automatic mode.
{PARALLEL} –	Indicates that the transformer is operating in parallel with other tap changers and should be controlled using the rules for parallel LTC control. Paralleling is verified based on breaker inputs.

2) Front – Panel Target light – Emitting Diode (LEDs)

Front –	Panel target LEDs include the following
Enabled –	Indicates that the control is in service.
Alarm –	Indicates on alarm condition.
In service –	Indicates that the transformer is in service based on breaker position.
Auto-Inhibit –	Illuminates when automatic tap changes are inhibited.
High Band –	Indicates that the regulated voltage above the high-band threshold.
In Band –	Indicates that the regulated voltage is between the high-band threshold and low band threshold.
Low Band –	Indicates that the regulated voltage is below the low-band threshold.

3) Display Points

Analog quantities are displayed on the front-panel liquid Crystal display (LCD) for the following.

- Current Magnitude
- Current angle
- Live volts
- Tap position
- Operations counter

Text messages are displayed on the front-panel LCD for the following conditions:

- Tap high limit
- Tap low limit
- Fault
- Raise failure
- Lower failure
- Control voltage failure
- Loss of potential
- Maximum voltage limit
- Minimum voltage limit
- Communications failure
- Line-drop compensation on

4)Local Control Bits

Locally settable control bits, or local bits, are used for the following functions:

- Master Reset – resets the internal tap counter and all latches
- Operations Reset – Resets the operations counter
- Switching of remote/local control modes could have been performed using local bits; however, a separate hard-wired switch was used for operator ease.

B.Hard – Wired I/O

Table 1 shows the hard-wired I/O used for the LTC control. Note the following

- Breaker positions are used to determine when a transformer is in service and in parallel. 52A – OTHER is typically used for the breakers.
- The analog inputs are designed to accept input from existing tap-position indication apparatus but have not been tested in the field.
- The LTC control accepts all three line currents and voltages. However, only one is needed for LTC control, and only one is wired at present.
- The I-RAISE inputs are wired directly in series with the raise and lower motors. A clamp-on CT may alternately be used as an input.

C.Settings

Settings were programmed into the logic as math variables. The available settings are shown in Table 1.

D.IEC 61850 GOOSE Messaging

IEC 61850 GOOSE messaging is used to transmit current angle and other necessary analog and digital information between LTC controls. Communication takes place over a fiber-optic Ethernet network. In this case, the selected hardware has two ports and an internal switch, so no external switch was required. The system architecture is shown in Fig. 5.

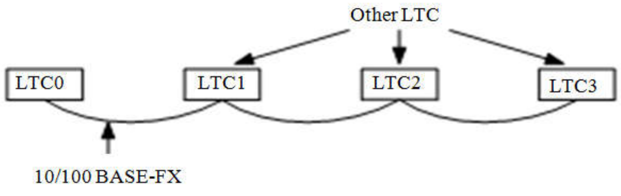

Fig. 5. IEC 61850 System Architecture

Each LTC control refers to the other controls as LTC1 or LCT2 or, where used, LTC3. This perspective varies for each control. LTC0 subscribes to the GOOSE message data published by LTCl to LTC 3. Table 2 shows the GOOSE messages that are published and subscribed to by each of the LTC controls.

Each of the LTC controls decide whether it should be the next control to tap up or down by company (comparing) its current angle against that published by the other controls based on the rules for parallel LTC control. It then publishes the results of that decision and claims the next raise or next lower operation.

Table 2. Iec 61850 goose messages

Name	Description	Types
IA_MAG_n	Measured current magnitude	Analog
IA_MAG_n	Measured current angle	Analog
RAISE_n	Raise command sent from control to its associated LTC	Digital
LOWER_n	Lower command sent from control to its associated LTC	Digital
PARA_n	LTC is parallel and in service	Digital
NEXTR_n	LTC claims the next raise	Digital
NEXTL_n	LTC is in alarm	Digital
LDC_EN_n	LTC has line-drop compensation enabled	Digital
Auto_MODE_n	LTC has automatic mode selected	Digital
PARA_MODE_n	LTC has parallel mode selected	Digital
LTCn_BQ	Bad-quality GOOSE message	Digital

Note: n = 1, 2, or 3.

E.SCADA Control Points

If the LTC control is in the remote mode, SCADA can control the following functions by pulsing a binary input using DNP3:

- Raise tap
- Lower tap
- Automatic mode off
- Automatic mode on
- Parallel operation on
- Line-drop compensation off
- Line-drop compensation on

LTC control logic design

Logic was designed for the LTC control to implement the LTC rules and meet the goals described in section V. Because the complete logic cannot be presented here, only the most salient points are covered in details.

A.Parallel Logic

Parallel logic, as shown in Fig. 6 is used and operating in parallel with other transformers. High-side, low side, and other desired breaker auxiliary contact inputs (52AH, 52AL, and 52A – other) are used to determine if the transformer is in service (INSERV). If parallel mode (PARA_MODE) has been selected by the pushbutton (PB4_PUL) or SCADA (LT10) and the transformer is in service, it is known that the transformer is operating in parallel (PARALLEL).

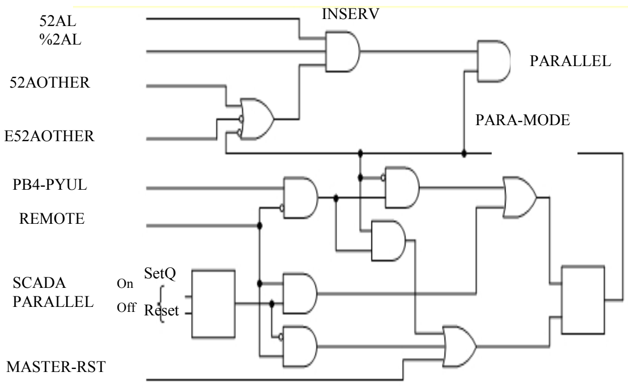

Fig. 6. Parallel Logic

B.Automatic Mode Logic

As shown in Fig. 7, the LTC control operates in automatic mode when they have been selected by the push button or SCADA (Auto_MODE), the LTC is operating in PARALLEL, and the auto-permissive logic (AUTO_PERM) is satisfied. Alternately, the LTC control also operates in automatic mode when the transformer is in service (INSERV) and parallel mode (PARA_MODE) has been selected. The auto permissive logic must be satisfied for the LTC control to act automatically when the transformer is operating in parallel. As shown in Fig. 8, the autopermissive logic requires that at least one other LTC control is operating in parallel (PARA_n) and that any other parallel transformers also have automatic mode (Auto_mode_n) enabled.

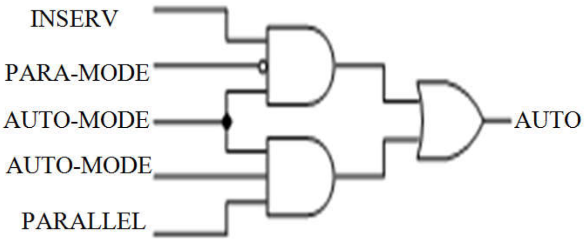

Fig. 7. Automatic Mode Logic

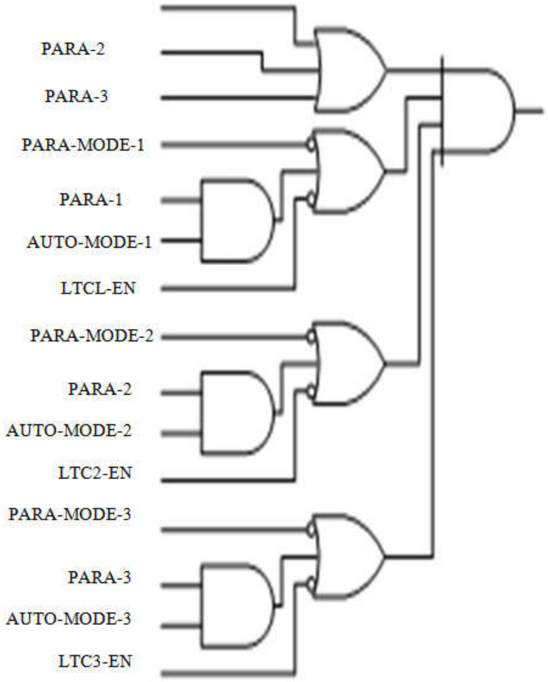

Fig. 8. Auto Permissive Logic

Automatic mode is inhibited whenever any LTC control is in alarm, the bus voltage is at its minimum or maximum settings or the tap position is at its minimum or maximum.

C. Angle Comparison Logic

The angle comparison logic, as shown in Fig. 9, compares the current angle of this control (IA_ANG) against the others (IA_ANGn) and determines if it is the highest or the lowest.

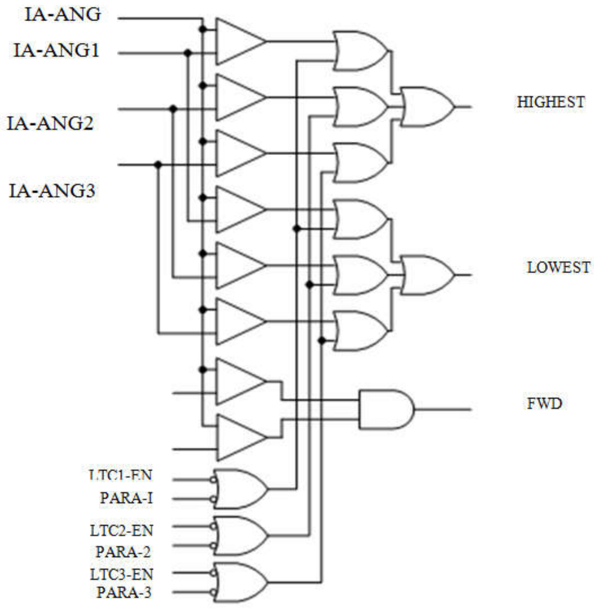

Fig. 9. Angle Comparison

Note the current angle is referenced to the bus voltage on all controls, providing a common reference. If other LTC controls are not enabled (LTCn-EN) or not operating in parallel (PARA-n), their angle comparison is neglected. If the current angle is between –90 and 90 degrees, power flow is in power quadrants I or IV, the forward direction (FWD).

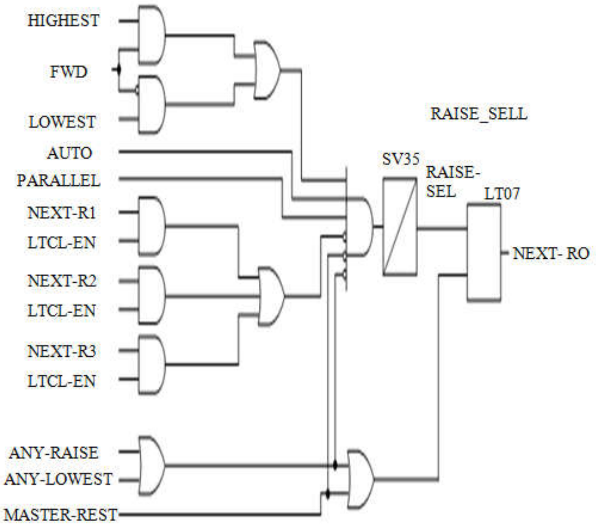

Fig. 10 Select Next Raise Logic

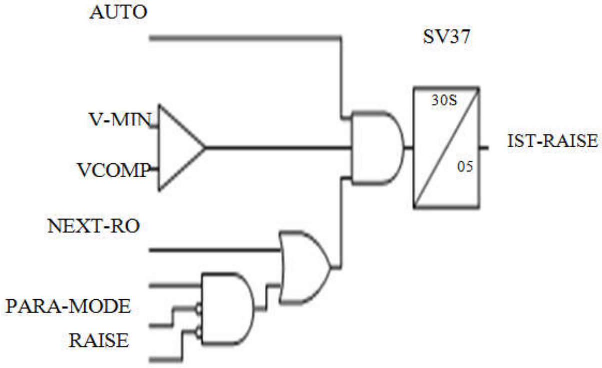

Fig. 11. First Raise Logic

D. Raise Tap Command Logic

Each LTC control determines whether it should be the control to issue the tap raise command base on Rule 1 and 3 in Section V, subsection C as shown in Fig. 10, immediately after a tap change by any LTC control (ANY_RAISE or ANY_ LOWER), the logic selects this LTC control to raise if its measured current angle is the highest (HIGHEST) and is operating in the forward direction (TWO) or if its measured current angle is the lowest (LOWEST) and is operating in the reverse direction. This is provided that the control is operating in automatic mode (AUTO), the (PARALLEL) shown in Fig. 7 and no other controls have claimed the next raise command (NEXT_En and LTCn_EN). A timer (SV35) has a set time delay that varies by 0.25 seconds between LTC controls to co-ordinate selection of the next control to perform a raise command (NEXT_RO). That is to say, for LTC control 1 through 3, the time delay may be set to 1.75, 2.00 and 2.25 seconds respectively. The initial raise command for a tap sequence is governed by the first raise logic shown in Fig. 11. The logic requires that the LTC control is in automatic mode, the compensated line voltage (VCOMP) is less than the minimum voltage band setting (V-MIN) and this LTC control is selected to perform the next raise command (NEXT_RO). If these conditions are true for a settable time delay (in this case, 30 seconds), the logic initiates a first raise command (I^{st}_RAISE). Alternatively, if the transformer is in service (INSERV) but not in parallel mode (PARA_MODE), the logic can issue a first raise command independent of the current angle.

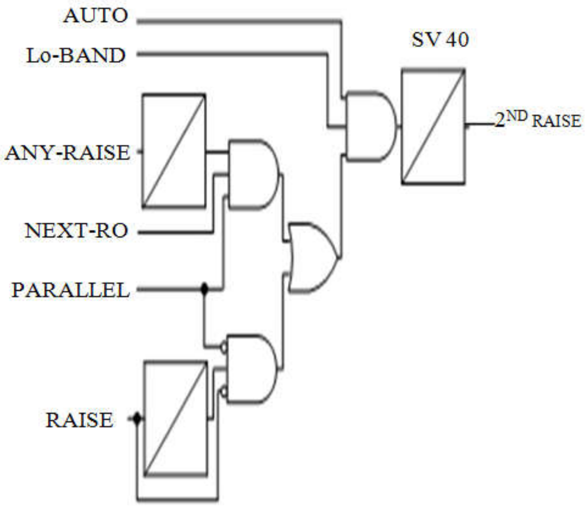

Fig. 12. Subsequent Raise Logic

Subsequent raise commands for a tap sequence are governed by the subsequent raise logic shown in Fig. 12. The logic requires that the LTC control is in automatic mode, the compensated line voltage is less than the minimum voltage band setting (LO_BAND), there has been a raise command issued by an LTC control (ANY_RAISE) in the last 15 seconds (SV38) and this LTC control is selected to perform the next raise (NEXT_RO). If these condition are true for a settable time delay (in this case, 5 seconds), the logic initiates a subsequent raise command (2^{ND} +_RAISE). Alternatively, if the transformer is not in parallel mode and there has been a raise command issued by the LTC control (RAISE) in the last 15 seconds (SV39), the logic can issue a subsequent raise command independent of current angle.

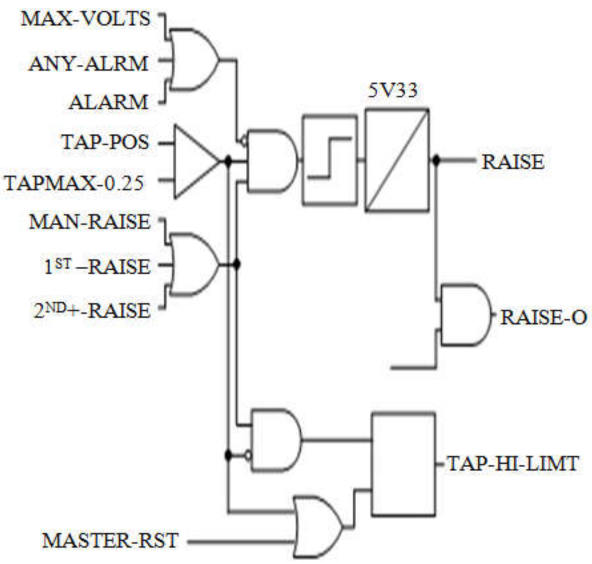

Fig. 13. Raise Logic

The final raise logic that issues the raise tap command is shown is Fig. 13. A raise (1st_RAISE), or subsequent raise (2ND ± RAISE) provided there is no alarm (ALARM) in this or any other parallel LTC control (ANY-ALARM) and the line voltage is below the maximum voltage limit. It is also required that the tap position (TAP_POS) be less than the maximum tap position (TAP_MAX) is there requirements are true, the LTC control sends a 1.5 second raise pulse to the LTC.

E.Lower tap command logic

The lower tap command logic works very much like the raise to command logic. The select next lower logic is based on Rule 2 and 4 in section V subsection C. The first lower logic and subsequent lower logic are based on the compensated line voltage being higher than the maximum voltage band setting. The lower logic requires that there are no alarms and that the tap position is greater than the minimum tap position.

F.Internal Tap-position counter

One of the goals of the project was to provide reliable tap-position indication that was not susceptible to damage from lighting and switching surges. An internal tap counter was employed that was based on detective raise and lower motor currents to indicate a tap change. Fig. 14 shows that a raise motor current (I_RAISE) is greater than 0.1 ampere for more than 0.25 seconds. Similarly, a lower condition (LOWER_A) is detected when the lower motor current (I_LOWER) is greater than one ampere for more than 0.25 seconds.

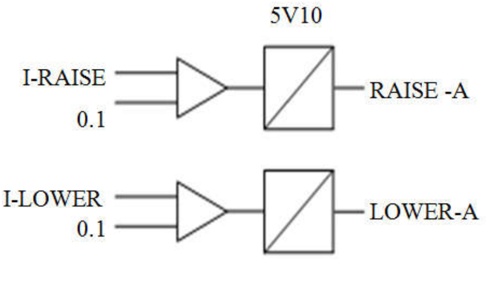

Fig. 14. Raise Lower Motor Current Sensing

This information then feeds into the internal tap-position counter and operations counters as shown in Fig. 15. The falling edge of a raise condition (RAISE-A) increases the tap counter (SCO1) Similarly, the falling edge of a lower condition (LOWER_A_ decreases the tap counter. Either increases the operations counter (SC) 2).

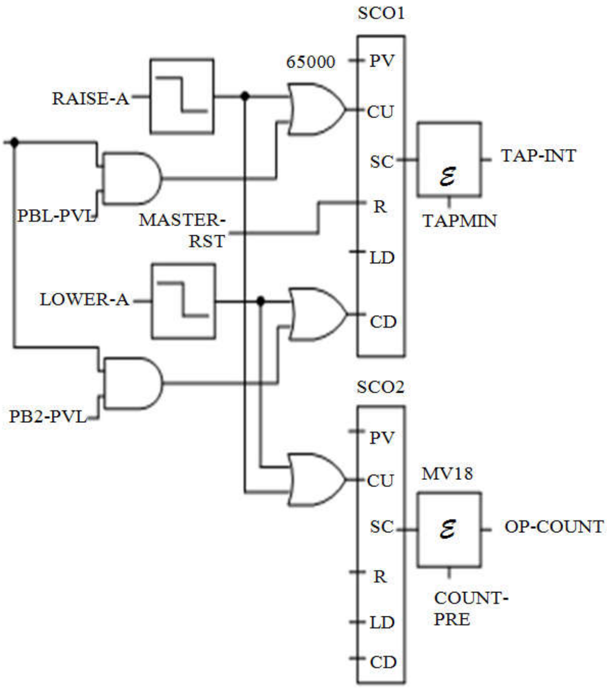

Fig. 15. Internal Tap-Position Counter and Operations Counter

Fig. 15 Internal Tap-Position Counter and Operations Counter. The value of the internal tap-position counter (TAP_IN) is equal to SCOL plus the minimum tap position (TAPMIN), which is typically -16. The value of the operations counter (OP_CC) is equal to SCO$_2$ plus a present value (COUNCT_PRE). The value of the internal tap-position counter can be adjusted to match the mechanical tap position using the (RAISE}{LOWER} push buttons when the control has been put into an adjust tap mode (ADJ-TAP) by pressing and holding the {AUTO} push button for 3 seconds while in manual mode.

Conclusion

Three of the stated goals in this paper concerned the ease and speed of installation, a more integrated system with less field using, minimal control cable runs and terminations and minimal overall installation time, all of these goals can be achieved. There is only one (1) device to install. It contains all of the logic and all of the I/O and instrumentation terminations. The automatic/manual, independent/parallel, and raise/lower functions are all selectable on the front panel. SCADA control is accomplished over a DNP3 loop, which means there is no longer a need for electromechanical switches for any previously mentioned functions. Using DNP3 also eliminates the need for large control cable runs and associated terminations. This approach is more integrated than the old control scheme, making installation much less complex. Another goal was to make the system easier to troubleshoot. The integrated design makes it much less complex so that when there are problems, they are easier to find.

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