Innovative Transformer Load Tap Changer Control Using Ethernet-Based Communications

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***Abstract*—This paper describes the design of a load tap changer (LTC) control for up to four parallel transformers using a modified circulating current approach.**

The LTC control discussed in this paper was 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 from each LTC control is passed to all parallel LTC controls using IEC 61850 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 230/115 kV autotransformers on the Santee Cooper system. This paper describes the installation, supervisory control and data acquisition (SCADA) communications and control, and field experience gained with the IEC 61850 LTC control. 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.

I. Introduction

The South Carolina state-owned electric and water utility, Santee Cooper, uses parallel autotransformers to interconnect between differing transmission voltages within their transmission system. They apply load tap changers (LTCs) on the autotransformers to maintain a constant secondary voltage with varying primary voltage and load. Santee Cooper traditionally used a "paralleling balancer" scheme for control of LTCs. However, they found several problems with the paralleling balancer scheme and searched for an alternative solution going forward. This paper describes the development of the new Santee Cooper Ethernet-based IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messaging solution, its installation at the Perry Road Substation, and the operating experience gained in applying it.

II. Previous Experience

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 unbalanced current from the total transformer current and represented that unbalanced current as a voltage. This voltage, representing the unbalanced current, was then input as a bias to the LTC control to cause it to change taps in such a manner as to reduce the circulating current between transformers [1]. 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 at Perry Road and other substations, 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 to run 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.

III. Decision Making

Problems at Perry Road and other substations, such as the problems described in Section II, drove the decision to upgrade the transformer paralleling controls and not use the paralleling balancer scheme going forward.

A master/follower solution was first considered as a replacement because of its simplicity and ease of installation. In this scheme, the master control senses voltage and tells all the other controls (the followers) to change taps. This is also referred to as the "lock-in-step" method because all transformers remain on the same tap [1]. This only works for 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 [2]. 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 devices and transducers.

Because of the 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 consisted of electromechanical switches for remote/local, parallel/independent, automatic/manual, and raise/lower controls and analog meters. These controls were located in a cabinet hung 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.

For these reasons, Santee Cooper decided to rethink how to best accomplish LTC control. They set the following goals in developing a new LTC control solution:

- More integrated topology and less field wiring
- Less susceptibility to lightning and switching transients
- Minimal cable runs and terminations
- More precise parallel control—within one tap
- Reliable tap-position indication
- Less physical RTU 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 pushbuttons 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 (in this case, 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.

IV. Observations Regarding Circulating Currents in Parallel Transformers

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 transformers.

A. Parallel Transformer Model

What was learned can be easily demonstrated using a simplified system model with two transformers in parallel, as shown in Fig. 1.

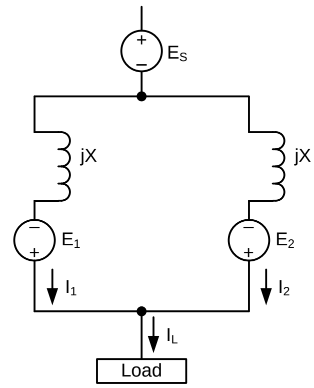

Fig. 1. Simplified two-transformer model

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 E_S 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 would represent a 5/8 percent (or 0.00625 pu) change in E_1 and E_2.

As can be seen from Fig. 2, the currents through each of the transformers are composed of a load current component plus or minus a circulating current component defined as:

$$I_{circ} = \frac{(E_1 - E_2)}{2jX} = \frac{-j(E_1 - E_2)}{2X} \quad (1)$$

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

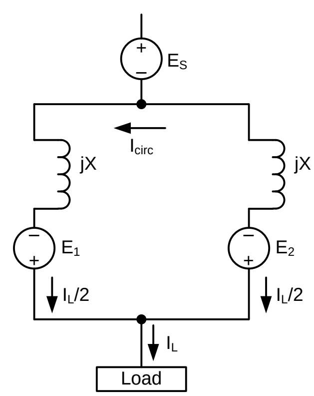

Fig. 2. Two-transformer model showing circulating current

B. Resulting Current Angles

From Fig. 1 and Fig. 2, we can see that:

$$I_1 = \frac{I_L}{2} + I_{circ} \quad (2)$$

$$I_2 = \frac{I_L}{2} - I_{circ} \quad (3)$$

Looking at (1), we can see that I_{circ} has an angle of –90 degrees with respect to the reference voltages. That fact, combined with (2) and (3), results in the vector diagram shown in Fig. 3.

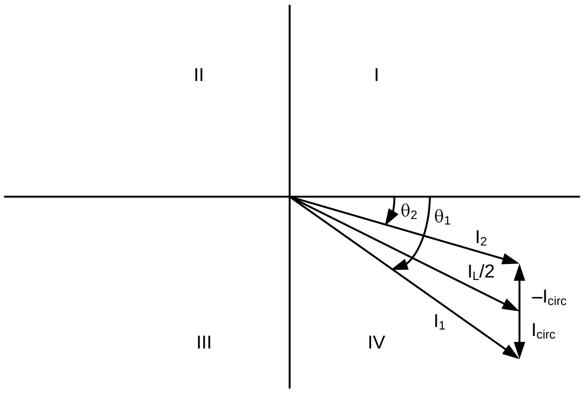

Fig. 3. Vector diagram of parallel transformer currents

We can see 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 transformers 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.

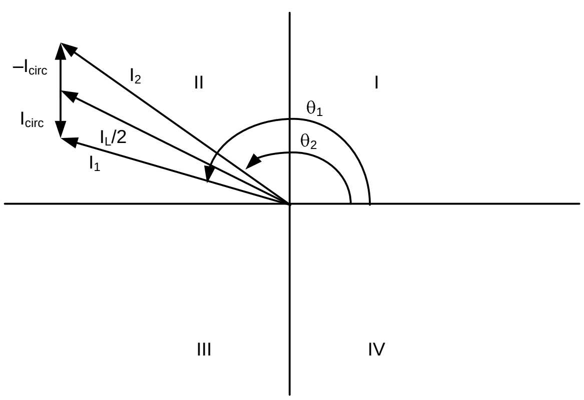

Fig. 4. Parallel transformer currents when operating in Power Quadrant II

We can see from Fig. 4 that, when operating in Power Quadrant II, the current angle of I_1, or θ_1, leads the current angle of I_2, or θ_2. That is, for operation in Power Quadrant II, 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 transformers.

C. Rules for Parallel LTC Control

The results shown in Fig. 3 and Fig. 4 led to the conclusion that a comparison of current angles could be used as a basis for developing rules for LTC control. The rules are as follows:

1. 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.
2. 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.
3. 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.
4. When operating in Power Quadrant II or III, if it is necessary to lower the voltage, tap down the transformer that has 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 [3]. This provided some level of comfort regarding the method. However, to the authors' knowledge, it had not previously been applied in the field.

V. 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) Pushbuttons

Four pushbuttons 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 Diodes (LEDs)

Front-panel target LEDs include the following:

- *Enabled* – indicates that the control is in service.
- *Alarm* – indicates an 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 is 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
- Line 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 a local bit; however, a separate hard-wired switch was used for operator ease.

B. Hard-Wired I/O

Table I 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 tie 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 and I_LOWER 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 II.

TABLE I
HARD-WIRED I/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
VPOS1	Potentiometer total volts	Analog (0–10 V)
VPOS2	Potentiometer wiper volts	Analog (0–10 V)
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 amperes	Current
I_LOWER	Lower motor amperes	Current

TABLE II
SETTINGS

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 tap	e.g., –16
IMAX	Maximum current (exceeding this value causes auto inhibit)	A
NO_PARA	Number of parallel transformers	1–4
POS_SELECT	Tap-position indication selector	0 = INTERNAL 1 = VOLTAGE 2 = CURRENT
E52A_OTHER	Enables other 52a contact input for parallel operation (used for tie breakers)	1 = ENABLED
COUNTER_PRE	Preset for operations counter	
27POT	Pickup for minimum secondary voltage loss of potential	Percent
LDC	Line-drop constant (for line-drop compensation)	V/A
VHI_LIM	Maximum voltage (will not raise tap beyond this point)	kV
VLO_LIM	Minimum voltage (will not lower tap beyond this point)	kV

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. Each LTC control refers to the other controls as LTC1 or LTC2 or, where used, LTC3. This perspective varies for each control. LTC0 subscribes to the GOOSE message data published by LTC1 to LTC3.

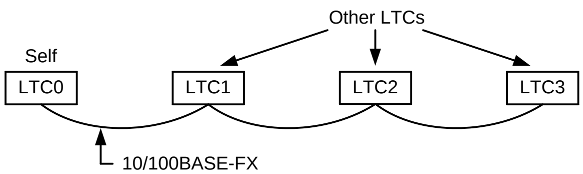

Fig. 5. IEC 61850 system architecture

Table III shows the GOOSE messages that are published and subscribed to by each of the LTC controls.

TABLE III
IEC 61850 GOOSE MESSAGES*

Name	Description	Type
IA_MAG_*n*	Measured current magnitude	Analog
IA_ANG_*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 claims the next lower	Digital
ALARM_*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
LTC*n*_BQ	Bad-quality GOOSE message	Digital

* Note: n = 1, 2, or 3

Each of the LTC controls decides whether it should be the next control to tap up or down by 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. This process has been likened to an outfielder on the baseball diamond communicating to the other players, "I've got it."

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 off
- Parallel operation on
- Line-drop compensation off
- Line-drop compensation on

VI. LTC CONTROL LOGIC DESIGN

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

A. Parallel Logic

Parallel logic, as shown in Fig. 6, is used to determine if a transformer is in service 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).

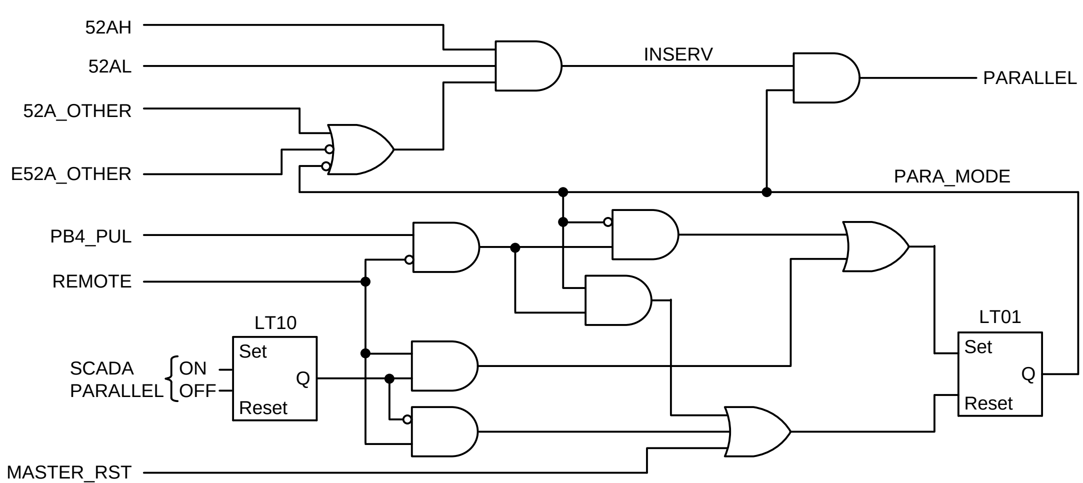

Fig. 6. Parallel logic

B. Automatic Mode Logic

As seen in Fig. 7, the LTC control operates in automatic mode when the mode has been selected by the pushbutton or SCADA (AUTO_MODE), the LTC is operating in PARALLEL, and the autopermissive 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 not been selected.

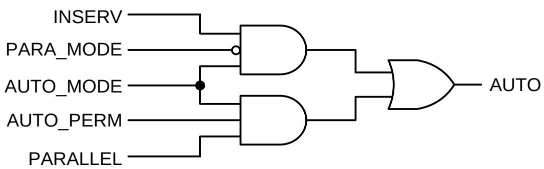

Fig. 7. Automatic mode logic

The autopermissive 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 paralleled transformers also have automatic mode (AUTO_MODE_*n*) enabled.

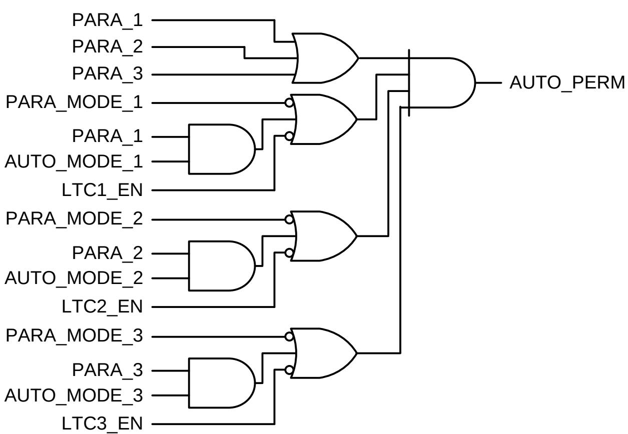

Fig. 8. Autopermissive logic

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_ANG*n*) and determines if it is the highest or the lowest. Note that the current angle is referenced to the bus voltage on all controls, providing a common reference. If other LTC controls are not enabled (LTC*n*_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).

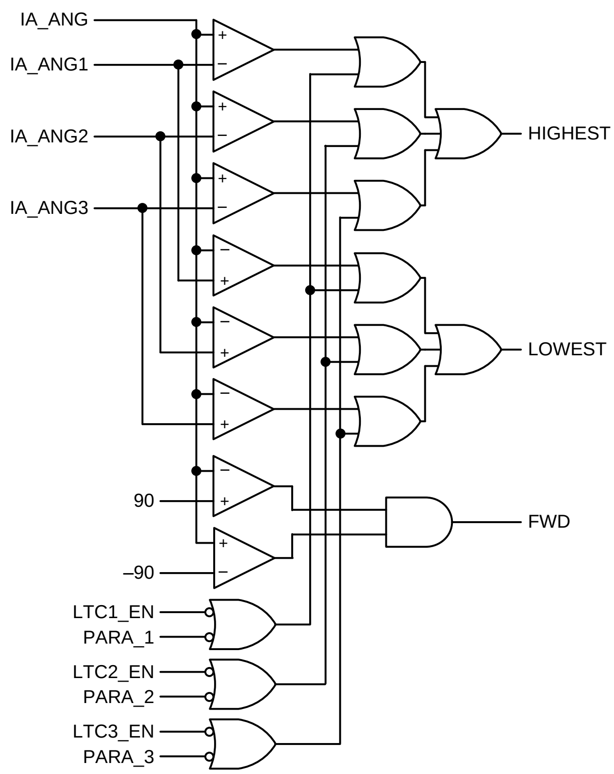

Fig. 9. Angle comparison logic

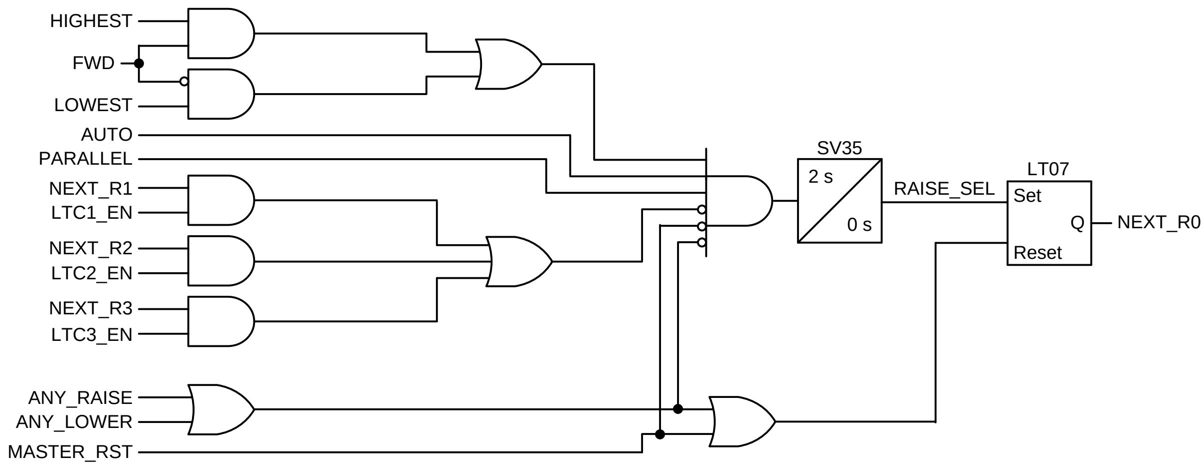

Fig. 10. Select next raise logic

D. Raise Tap Command Logic

Each LTC control determines whether it should be the control to issue the next tap raise command based on Rules 1 and 3 in Section IV, 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 (FWD) 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 transformer is paralleled according to the parallel logic (PARALLEL) shown in Fig. 6, and no other controls have claimed the next raise command (NEXT_R*n* and LTC*n*_EN). A timer (SV35) has a set time delay that varies by 0.25 seconds between LTC controls to coordinate selection of the next control to perform a raise command (NEXT_R0). That is to say, for LTC Controls 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_R0). If these conditions are true for a settable time delay (in this case, 30 seconds), the logic initiates a first raise command (1ST_RAISE). Alternately, if the transformer is in service (INSERV) but not in parallel mode (PARA_MODE), the logic can issue a first raise command independent of current angle.

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_R0). If these conditions are true for a settable time delay (in this case, 5 seconds), the logic initiates a subsequent raise command (2ND+_RAISE). Alternately, if the transformer is not in parallel mode and there has been a raise command issued by this LTC control (RAISE) in the last 15 seconds (SV39), the logic can issue a subsequent raise command independent of current angle.

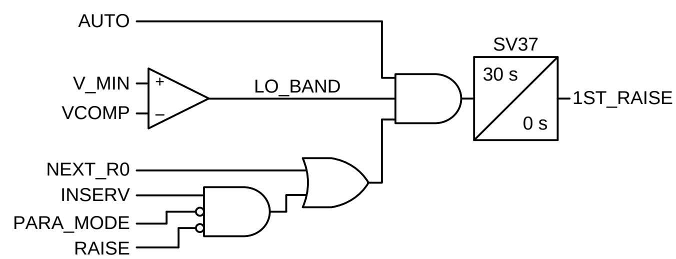

Fig. 11. First raise logic

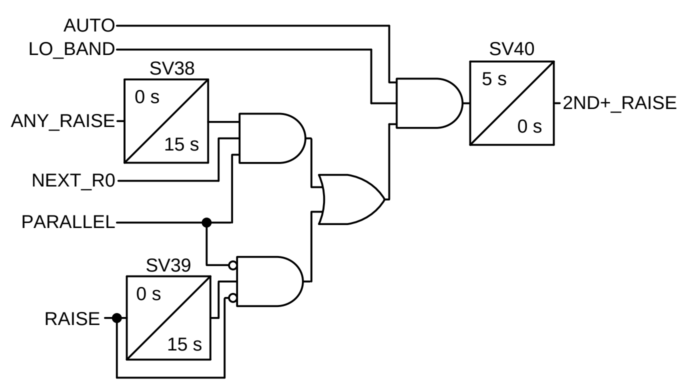

Fig. 12. Subsequent raise logic

The final raise logic that issues the raise tap command is shown in Fig. 13. A raise occurs for a manual raise (MAN_RAISE), an initial raise (1ST_RAISE), or subsequent raise (2ND+_RAISE) provided there is no alarm (ALARM) in this or any other paralleled 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). If these requirements are true, the LTC control sends a 1.5-second raise pulse to the LTC.

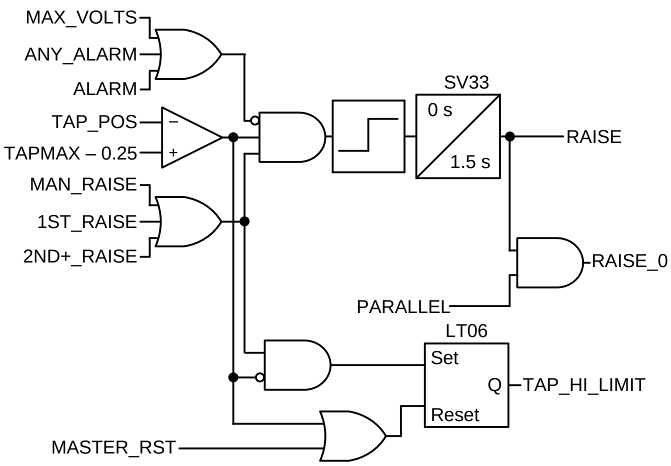

Fig. 13. Raise logic

E. Lower Tap Command Logic

The lower tap command logic works very much like the raise tap command logic. The select next lower logic is based on Rules 2 and 4 in Section IV, 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. Line-Drop Compensation

A simple formula for line-drop compensation (4) was provided in the logic. This had to be an approximation because trigonometric functions were not available. This is considered acceptable because all LTC currents are close to being in phase and power factors are close to unity. The compensated voltage (VCOMP) is the line voltage in kV (VA_MAG) minus the scalar sum of the line current magnitudes (IA_MAG*n*) for the enabled LTCs (LTC*n*_EN) multiplied by a settable line-drop constant (LDC) in volts per ampere provided that line-drop compensation is enabled (LDC_EN).

$$\begin{aligned}&VCOMP = VA\_MAG - \\ &(IA\_MAG + LTC1\_EN \bullet IA\_MAG1 + LTC2\_EN \bullet \\ &IA\_MAG2 + LTC3\_EN \bullet IA\_MAG3) \bullet \\ &LDC\_EN \bullet LDC / 1{,}000\end{aligned} \quad (4)$$

G. 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 lightning and switching surges. An internal tap counter was employed that was based on detecting raise and lower motor currents to indicate a tap change. Fig. 14 shows that a raise condition (RAISE_A) is detected when the 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 0.1 ampere for more than 0.25 seconds.

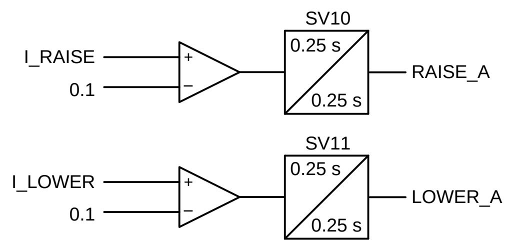

Fig. 14. Raise and lower motor current sensing

This information then feeds into the internal tap-position counter and operations counter, as shown in Fig. 15. The falling edge of a raise condition (RAISE_A) increases the tap counter (SC01). Similarly, the falling edge of a lower condition (LOWER_A) decreases the tap counter. Either increases the operations counter (SC02).

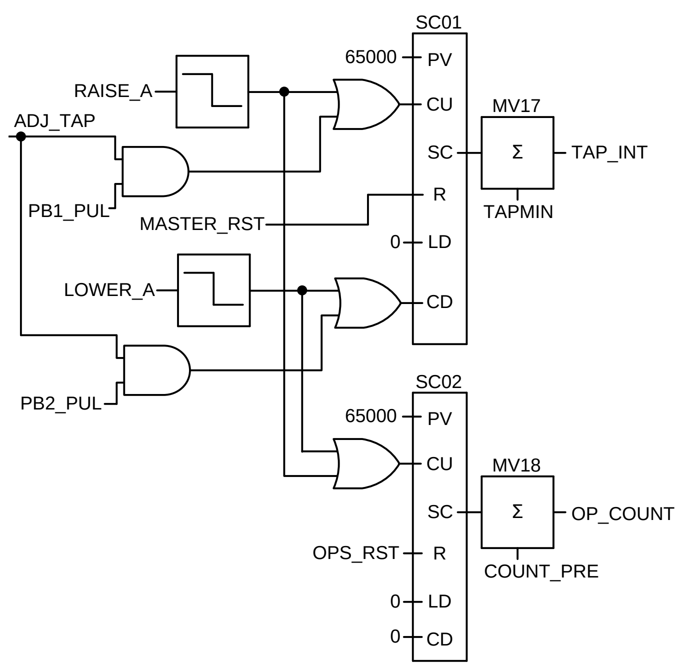

Fig. 15. Internal tap-position counter and operations counter

The value of the internal tap-position counter (TAP_IN) is equal to SC01 plus the minimum tap position (TAPMIN), which is typically –16. The value of the operations counter (OP_CC) is equal to SC02 plus a preset value (COUNT_PRE).

The value of the internal tap-position counter can be adjusted to match the mechanical tap position using the {RAISE} and {LOWER} pushbuttons when the control has been put into an adjust tap mode (ADJ_TAP) by pressing and holding the {AUTO} pushbutton for 3 seconds while in manual mode.

VII. LTC Control Logic Verification

A simulator was built to test the LTC control logic. It consisted of three LTC controls; a feeder protection and automation system to simulate the transformers; a communications processor to communicate analog information from the feeder protection and automation system; potentiometers to input transformer high-side voltage (E_S), load MVA (MVA_L), and load power factor (PF) to the feeder protection and automation system; and six 60 W light bulbs to mimic the raise and lower motor currents. Although its big knobs and bulbs made it look like a relic from Dr. Frankenstein's lab, the simulator served its purpose well.

The feeder protection and automation system was essentially an advanced overcurrent relay with 1,000 lines of programmable automation logic and advanced math capability. It was used to simulate the behavior of three parallel transformers with LTCs, as shown in Fig. 16.

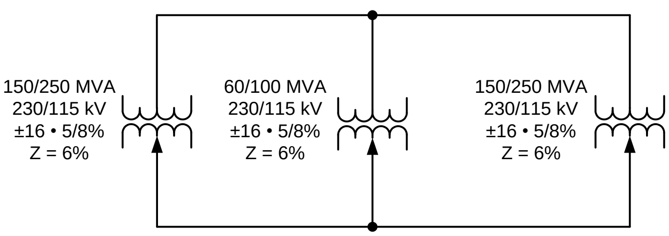

Fig. 16. Transformer arrangement used for simulation

The parallel transformers were modeled with a base MVA of 150 as shown in Fig. 17. The feeder protection and automation system calculated transformer secondary bus voltage and transformer currents using superposition based on the three inputs from the potentiometers—E_S, MVA_L, and PF. It then communicated the bus voltage and individual transformer current magnitudes and angles to the appropriate LTC controls serially via the communications processor. The LTC controls then sent corresponding hard-wired raise and lower signals to the feeder protection and automation system. The feeder protection and automation system responded by changing the tap value; changing E_1, E_2, or E_3 in the model by 5/8 percent (or 0.00625 pu) according to the tap change; pulsing the appropriate light bulb to simulate raise or lower current; and then recalculating the bus voltage and transformer currents. The LTC controls tracked tap position based on the raise and lower currents simulated by the light bulbs.

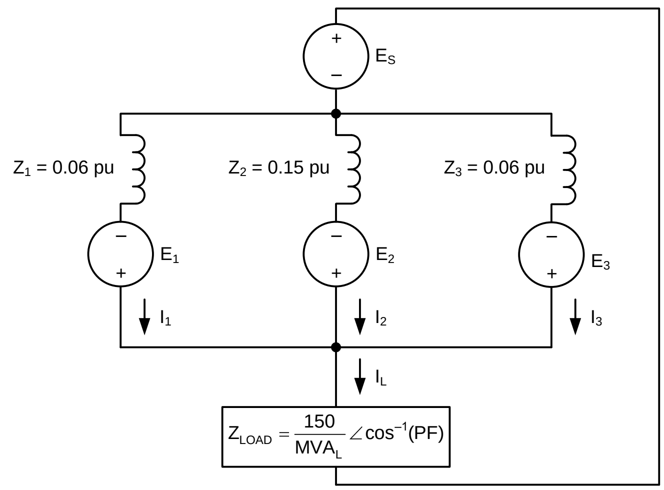

Fig. 17. Parallel transformer model

The LTC control simulator proved that by sharing and comparing current angle over a network, the LTC control logic controlled the transformer bus voltage within the specified voltage band, minimized circulating currents by keeping tap position to only one tap apart, and reliably tracked tap position using its internal tap-position counter.

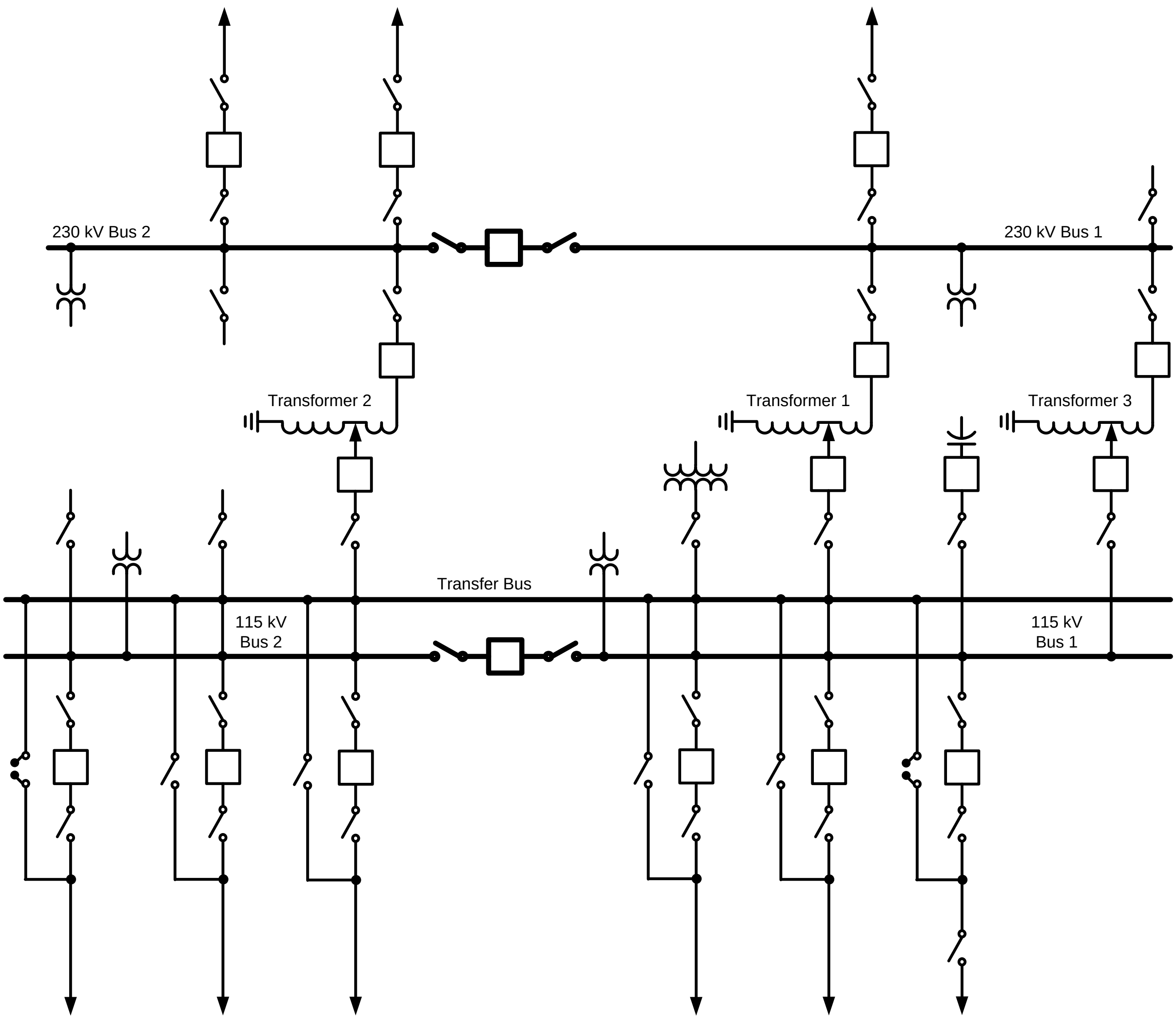

Fig. 18. Perry Road Substation one-line diagram

VIII. Test Substation

The first network-based LTC controls were installed at the Santee Cooper Perry Road Substation. Perry Road is a 230/115 kV substation (depicted in Fig. 18) situated in Santee Cooper's Myrtle Beach service territory. It consists of two 230 kV buses and two 115 kV buses. Transformer 1 and Transformer 2 are identical 150 MVA units, with 6.1 percent impedance, and are located on Bus 1 and Bus 2, respectively. Transformer 3 is located on Bus 1 and is rated at 90 MVA, with an impedance of 4.23 percent.

Each bus is separated by a bus-tie breaker and each transformer has its own high- and low-side breakers.

Myrtle Beach is a highly congested and heavily loaded area on the Santee Cooper transmission system. During peak loading conditions, almost any disturbance at the Perry Road Substation will cause unacceptable contingencies to exist throughout the area. Voltage support and proper VAR flow in this substation are deemed critical to serving the load in this area.

IX. Observations From Installation and Commissioning

Installation of the new LTC controls was quite simple. Only fiber-optic cable needed to be run between the transformers and to the control house, and there were few connections to be made in the transformer control cabinet.

If there was any difficulty in the physical installation and commissioning process, it was caused by the amount of control wiring and cable that needed to be removed in order to convert to the new system. There was a large amount of control wiring that was either no longer needed or was redundant with the new system. Each connection was tagged for removal or retention on a design print prior to starting the project and then rechecked before removal in the field. Control cables between the transformers, breakers, and control house were disconnected, tagged, and left in the cable trench because their removal would have been difficult and time-consuming.

One of the biggest challenges during the project was the tight schedule required for clearances on the equipment. The installation had to be accomplished during a two-week period of very light system loading, and only one transformer could be removed from service at any given time. This was due to the sensitive nature of this substation. The work also needed to be accomplished in parallel with relay upgrades that were scheduled for the substation. Therefore, simplicity and minimal installation and commissioning time were very important.

Testing the installed system for parallel mode had to be accomplished under actual operating conditions and only after the new controls were installed on all three units. During this time, precautions were taken so that the system could be immediately switched into manual mode. This was done to prevent unwanted tap movement in case there was an unforeseen problem with the new control system.

Commissioning turned out to be very successful because it was uneventful. The system operated as designed. The normal test procedure for new parallel LTC control installations was to move each individual unit two or three taps higher or lower than the others and observe that they corrected themselves to the proper tap. In this case, the controls are only designed to respond when they are required to regulate the voltage. If operating correctly, there will never be more than a one-tap difference between the transformers. Therefore, an alternative test needed to be devised.

Rather than perform the test described above, the controls were placed in manual mode and the voltage bandwidth was narrowed slightly. The taps were moved until the bus voltage was outside of the bandwidth and there was one transformer that was one tap off from the others. The system was then observed as it corrected the bus voltage to see that the unit that was one tap off was the one that moved. This test was repeated in both the raise and lower directions for each transformer.

The SCADA remote control portion of the system was then tested from both the RTU and the system control room.

X. Operating Experience

This system was installed in April 2010. Since that time, there has been only one trouble call initiated for the system. The problem was not with the LTC control; it turned out to be a failed EIA-232-to-EIA-485 converter on the serial DNP3 loop to the RTU.

There have been several instances during maintenance where field crews have removed the 125 Vdc power from the LTC control. This required the tap position to be reset because it is not stored in nonvolatile memory. Until there was sufficient training conducted on this procedure, instructions had to be given to technicians over the telephone to reset the tap position.

Operating data gathered from the Santee Cooper energy management system (EMS) show that there is never more than a one-tap difference between transformers. The 115 kV bus is successfully maintained within the voltage bandwidth of 116.5 to 119.5 kV. The circulating current has been minimized, and the system operators no longer need to monitor it continuously.

Other than when power was removed, the system has maintained the correct tap position. Only the internal tap-position indication, based on raise and lower currents, has been used. This eliminates the need for the external electromechanical devices and transducers that were unreliable.

Line-drop compensation was not required for the Perry Road Substation and has not been tested in the field.

In short, the system is operating exactly as it was designed, with minimal maintenance and monitoring.

XI. Benefits Realized

Three of the stated goals of this project concerned the ease and speed of installation. Santee Cooper wanted a more integrated system with less field wiring, minimal control cable runs and terminations, and minimal overall installation time. All of these goals were achieved. There is only one 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 of the 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. This allowed Santee Cooper to meet the tight schedule and save valuable labor and material costs.

Two of the stated goals concerned reliability. Santee Cooper wanted a system that was less susceptible to lightning and switching transients. Thus far, the LTC controls have operated through two summer lightning seasons, with multiple strikes in the local area. To date, there have been no issues with the equipment.

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.

Another goal for the project was more precise operation. Santee Cooper wanted to be able to keep the transformers within one tap of each other at all times. EMS data and feedback from the system operators prove that the system has achieved this goal. The tap-position information has also been proven to be correct and reliable. The only times that accurate tap-position data were not obtained were when field crews accidentally removed power from the relay and it needed to be reset. In these cases, it was immediately obvious to system operators what had happened, so there was no misinterpretation of the data.

Finally, because the remote control portion of the system operates over DNP3, the control and data acquisition were able to be upgraded while using much less physical RTU space.

Most importantly, all of these goals were accomplished in less time and for less overall cost than other comparable projects.

XII. Conclusion

The new Santee Cooper Ethernet-based LTC control has performed very well, meeting all of the utility's stated goals. It has been accepted as the standard for parallel tap-changing control for the Santee Cooper system.

Several future installations are planned, with the next one occurring in 2012. In future installations, Santee Cooper plans to migrate toward a total Ethernet-based solution, using Ethernet for DNP3-based SCADA, engineering access, and IEC 61850 GOOSE messaging for LTC control. Santee Cooper also plans to enable the transformer monitoring functions available in the hardware used for the LTC control and expand the logic to include fan control.

XIII. References

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XIV. Biographies

Adam Taylor, P.E., received a B.S. in Electrical Engineering in 1998 from The Citadel, The Military College of South Carolina, and he holds an M.B.A. from The Citadel College of Graduate and Professional Studies. From 1998 until 2001, he worked as an Electrical Maintenance Engineer for Copperweld Corporation designing and maintaining various PLC, motor drive, and plant power distribution systems. In 2001, he joined Santee Cooper as a Substation Maintenance Engineer and was tasked with administering the testing and maintenance programs for transmission class circuit breakers and transformers. In 2011, Adam spent several months as a Power Supply Planning Engineer. He has recently been promoted to Supervisor, Area Transmission Engineering at Santee Cooper, an engineering group that supports Transmission Operations and Right-of-Way field crews. Adam is a registered professional engineer in South Carolina.

Larry Wright, P.E., received a B.S. in Electrical Engineering in 1982 from North Carolina State University. From 1982 until 2003, he worked for Duke Energy designing nuclear, hydroelectric, and fossil-powered generating stations for Duke Energy and other utilities and independent power producers. From 2003 to 2005, Larry served as the subject matter expert on protective relaying for Duke Energy's generating stations. He joined Devine Tarbell Associates in 2005 as Manager of Electrical Engineering, providing consulting services to the hydroelectric industry. In 2008, he joined Schweitzer Engineering Laboratories, Inc., where he is presently employed as a field application engineer. Larry is a registered professional engineer in the states of North Carolina and South Carolina.

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