Power System Operation and Control Solutions Using IEC 61850

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Abstract—**IEC 61850 need not be applied on a substation-wide basis. There are many power system operation and control challenges that can be solved using parts of the technology outlined in the standard. This paper describes the implementation of a circulating current scheme that uses IEC 61850 GOOSE messages to provide automatic voltage regulation for up to four paralleled power transformers. The paper is a tutorial for junior or graduate engineers to de-mystify the circulating current principle and encourage the use of IEC 61850 and relay logic to solve power system control and protection issues. Hardware selection, scheme design, and network considerations are explored. The paper discusses lessons learned from setting and commissioning in-service solutions.**

I. Introduction

This paper presents a control solution that uses IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messages to create an automatic voltage regulator (AVR) scheme that employs circulating current principles. The paper describes the background of IEC 61850 and some of the solutions GOOSE messaging has enabled. It also explores the requirements for operating transformers in parallel and the need for an adequate control regime.

The paper provides a tutorial on the design of a voltage regulating algorithm that uses relay logic. It develops a voltage-based scheme and adds a circulating current biasing technique to allow the parallel operation of up to four power transformers. The paper explores Ethernet networking topologies and the requirements for their successful integration into the substation environment. Finally, the paper shares commissioning requirements and lessons learned from in-service schemes.

II. Background

A. IEC 61850

The IEC 61850 standard was first released in the latter part of the 1990s. It was adapted from earlier work by the Electric Power Research Institute (EPRI) and the Institute of Electrical and Electronics Engineers (IEEE) that defined the Utility Communications Architecture (UCA). The IEC 61850 standard consists of a set of documents that describe the substation design, configuration, and testing for both client-server and peer-to-peer communications. The standard defines five types of communications services. GOOSE messaging is one of the services defined by the standard and may be the most widely adopted part of the IEC 61850 protocol.

Peer-to-peer communications protocols have been available for many years via serial communications, and they have been used successfully to integrate many protection and control schemes. The flexibility of the logic in modern microprocessor-based (numerical) relays has allowed for the creation of circuit breaker failure, switchgear interlocking, intertripping, and arc-flash schemes without the need for interpanel wiring. Several proprietary protocols also existed for transmitting analog quantities, but these were limited to only a few devices. GOOSE messaging has enabled substation designers to provide communications between devices to solve a range of power system protection and control challenges via Ethernet communications. The use of a standardized protocol has also allowed devices from different manufacturers to transmit analog and digital information from one to one and one to many devices.

B. Parallel Operation of Power Transformers

Connecting transformers in parallel requires consideration of several important factors. First, the total impedance of the paralleled arrangement will be significantly lower than the impedance of either unit. The resulting increase in short-circuit current during faults must not exceed the capabilities of the cabling or switchgear connected to the transformers. In addition, the transformers should have similar voltage ratios and the same phase relationship when connected to the high-voltage (HV) and low-voltage (LV) busbars. Ideally, they will have the same megavolt-ampere (MVA) and impedance ratings [1], although this is not always practicable.

Connecting transformers fitted with on-load tap changers (OLTCs) in parallel requires a regulating regime that can share information. For example, a master-follower scheme requires interpanel connections to allow one AVR to make the tapping decision and control all connected transformers. This has traditionally been achieved through panel selector switches and wiring between inputs and outputs of the regulating relays. The circulating current scheme described in this paper requires the AVRs to share both analog and digital information via an Ethernet connection. There are several advantages to using a circulating current scheme rather than a master-follower scheme. Allowing just one transformer in the scheme to tap reduces the change in busbar voltage. This usually results in fewer taps during the daily load cycle. Circulating current regimes also allow transformers of different ratings to be connected in parallel. This is particularly useful in emergencies or during substation upgrade projects.

III. Calculating Circulating Current

If two or more transformers are connected in parallel, any difference in the voltage produced by the transformers generates a circulating current, as shown in Fig. 1. The current is proportional to the voltage difference between the transformers divided by the sum of the impedances around the circulating path. For a two-transformer substation, the circulating currents in each transformer are equal in magnitude and opposite in direction. Also, they are independent of the load current. Because the impedance of a transformer is largely inductive reactance, the circulating current lags the voltage of the transformer with the highest open circuit voltage by ~90 degrees.

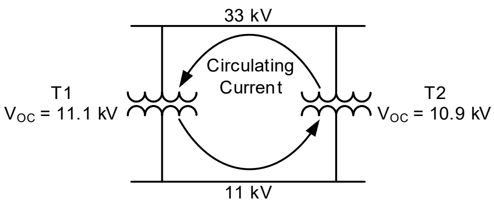


Fig. 1. Circulating Current Between Two Transformers

In this example, we energize a busbar with two identical power transformers that are at their nominal 11 kV tap positions. The busbar voltage is 11 kV and there is no circulating current. If we adjust the tap position of one transformer up and one down, the busbar voltage will remain at 11 kV. However, if each tap step alters the transformer ratio by 100 V primary at 11 kV, Transformers T1 and T2 will try to maintain 11.1 kV and 10.9 kV, respectively. The circulating current is proportional to the open circuit voltage difference between the transformers divided by the sum of the series impedances, as shown in (1).

$$I_{CIRC} = \frac{\left(V_{OCT1} - V_{OCT2}\right)}{\sqrt{3} \bullet \left(Z_{T1} + Z_{T2}\right)} \tag{1}$$

IV. Measuring Circulating Current

We could measure the circulating current directly through the HV or LV busbar between two transformers, but we would need to isolate the load current. Since this is impractical on an in-service system, we instead remove the load mathematically. Fig. 2 shows an example of the reactive power flows in a two-transformer system.

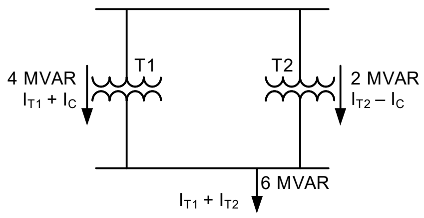
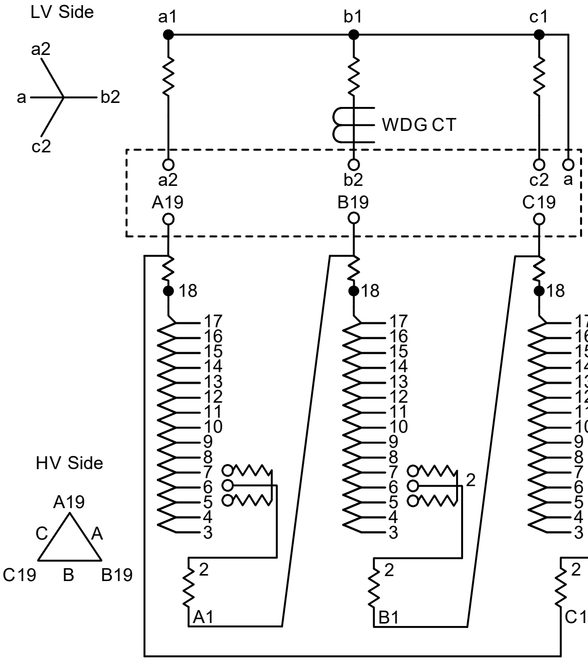


Fig. 2. Circulating Current With Load

The total reactive power in the load is the sum of the reactive power flowing through each transformer. The matched transformers in Fig. 2 provide a reactive component of 6 MVAR to the load. Each transformer contributes its share of load current plus or minus the circulating current (I_C). With matched transformers, we expect each to contribute the same amount to the load. The difference between the expected contribution and the actual contribution is the circulating current. In Fig. 2, there is 1 MVAR of reactive power flowing between the transformers.

V. Transformer Parameters

Fig. 3 shows a typical power transformer nameplate. For existing installations, the nameplate is usually the only information available about the transformer.



HV Volts: 33,000
LV Volts: 11,000
HV Amperes: 11.5 MVA = 201.20 A; 23 MVA = 402.40 A
LV Amperes: 11.5 MVA = 603.6 A; 23 MVA = 1,207.2 A
Impedance: 11.5 MVA = 9.64%; 23 MVA = 19.23%

Oil Quantity: 7,760 Litres
Oil Weight: 6,751 kg
WT. Code & Winding: 17,059 kg
Total Weight
(Inc. OLTC.) 29,050 kg
Fan: ASTEC 600
Pump: NCP-10-160
Diagram No: LC-040
Serial No:
Year of Manufacture: 1987

1,500/23,000 kVA 50 Hz 3 Phase ONAN/OFAF Transformers
Vector Group Symbol Dyn 11 To: BS 171:1978

Tap Position	HV Side Amperes			Switch Connect
	Voltage	11.5 MVA	23 MVA	
1	34,485	192.53	385.07	2-3
2	33,990	195.34	390.68	2-4
3	33,495	198.22	396.45	2-5
4	33,000	201.20	402.40	2-6
5	32,505	204.26	408.52	2-7
6	32,010	207.42	414.84	2-8
7	31,515	210.68	421.36	2-9
8	31,020	214.04	428.06	2-10
9	30,525	217.51	435.02	2-11
10	30,030	221.10	442.19	2-12
11	29,535	224.80	449.60	2-13
12	29,040	228.63	457.27	2-14
13	28,545	232.60	465.20	2-15
14	28,050	236.70	473.41	2-16
15	27,555	240.96	481.91	2-17

Fig. 3. Typical Power Transformer Nameplate Details

The nameplate provides the connection arrangement, tap position and voltage ratios, power and impedance ratings, and some mechanical information. A summary of the Fig. 3 nameplate details of interest is shown as T2 in Table I. Based on the voltage ratios in Fig. 3, we can use the voltage at the nominal Tap Position 4 and Tap Position 3 to determine the transformer tap change step, as shown in (2).

$$\frac{33,495-33,000}{33,000} \bullet 100 = 1.5\% \text{ per step} \tag{2}$$

Table I describes the parameters for a three-transformer substation used in this paper to demonstrate the principles of an AVR scheme design.

TABLE I
EXAMPLE THREE-TRANSFORMER SUBSTATION

Nameplate Parameter	T1	T2	T3
Rating (MVA)	15	11.5	11.5
HV (V primary)	33,000	33,000	33,000
LV (V primary)	11,000	11,000	11,000
Impedance (% of rating)	10.74	9.64	9.75
Number of taps	17	15	10
Tap step (%)	1.25	1.5	2

VI. VOLTAGE-ONLY REGULATION

Modern numerical relays not only provide dedicated protection and control functions but many have extensive logic programming capabilities as well. These include the use of timers, Boolean and math variables, latches, and counters. Using a voltage measurement to decide whether to raise or lower the voltage is a reasonably simple programming exercise.

In this exercise, we will use the T1 parameters from Table I to set up a voltage-only control scheme. The first thing to decide is the voltage at which we want to regulate the substation busbar. The set-point voltage is usually above the substation nominal voltage to allow for a voltage drop along the line during load. For simplicity, we will avoid the addition of line-drop compensation, even though this would be a relatively simple addition to the numerical relaying logic. We will choose a set-point voltage of 11,100 V and enter it in the relay as follows:

setpointvoltage = 11,100 # V pri

The next decision is how far from the set-point voltage the busbar voltage can deviate before the AVR issues a tap change. This is known as the bandwidth of operation. A value of less than 50 percent of one tap step will cause unstable operation of the controller known as hunting. A good compromise between voltage control and stability is 75 percent, as follows:

tapstep = 1.25 # % of tap step

setpoint = 75 # % of tap step

nominalvoltage = 11,000

We can calculate and set the desired bandwidth to a voltage value, or we can use the transformer nameplate parameters to calculate the voltage, as shown in (2). Using the nameplate values has the advantage that the nameplate values of future schemes can be used by the AVR to calculate the operational bandwidth. The bandwidth is calculated as shown in (3).

$$bandwidth = \frac{tapstep \bullet setpoint \bullet nominalvoltage}{10{,}000} \tag{3}$$

For our example T1 values, the bandwidth is 103 V primary at 11 kV.

If the difference between the busbar voltage and the set-point voltage exceeds the bandwidth setting, then the AVR should issue a tap change. If we reference the difference between the set point and the measured voltages to the bandwidth, we can calculate a voltage deviation in per unit (pu), as shown in (4).

$$voltagedeviation = \frac{measuredvoltage - setpointvoltage}{bandwidth} \tag{4}$$

A negative number indicates a busbar voltage below the set point. If the voltage deviation drops below –1 pu, the AVR should raise the voltage (i.e., increase the tap number).

Next, a delay in operation is required. This gives the tap change mechanism time to reset between successive operations and prevents operation for transient conditions, such as switching of load or operation of the protection system. If a tap change is issued during a fault, the high current can damage diverter switches. Some units use a fixed delay; others use two or more delays depending on how far the busbar voltage is from the set-point voltage.

Because we are using a per-unit deviation, we can simply create an inverse-time delay. Choose a maximum time to tap for when the voltage is just out of band (i.e., ±1 pu). In this example, we will use a maximum time of 60 seconds. The time to tap is calculated as shown in (5).

maximumtime = 60 # seconds

$$timetotap := \frac{maximumtime}{voltagedeviation^2} \tag{5}$$

For a voltage deviation of 1 pu, the AVR issues a tap change after 60 seconds; for a deviation of 2 pu, the AVR issues a tap change after 15 seconds; and so on.

In a numerical relay, we can create a 1-second pulse to increment a counter when the voltage deviation exceeds 1 pu as follows:

timer1pickup = 1.0 seconds

timer1initiate = $voltagedeviation^2$ *>= 1 AND NOT timer1timedout*

countup = timer1timedout

When the counter exceeds the time to tap, the AVR issues a tap change using the following logic:

raisetap = presentcountervalue > timetotap AND voltagedeviation <= –1

lowertap = presentcountervalue > timetotap AND voltagedeviation >= 1

A Boolean variable, *tapchangeinprogress*, can be the OR combination of *raisetap, lowertap,* and a logical input from the tap change mechanism.

To create a minimum time between taps, we can use (5) to calculate the deviation. For a minimum time of 5 seconds, for example, the deviation needs to exceed 3.46 pu. To prevent switching during a fault condition or a sudden increase in load, the operation should be blocked long enough to allow the transient system condition to clear. Create a Boolean variable called *blocktapchange* and prevent the counter from incrementing as follows:

blocktapchange = voltagedeviation < –3.46

resetcounter = tapchangeinprogress OR $voltagedeviation^2$ *< 1 OR blocktapchange*

Other conditions can be added to the *blocktapchange* variable if necessary. Refer to the Practical Application Considerations section of this paper for details.

When the *resetcounter* Boolean variable equates to a logical 1, the counter will be set at 0 and no tap change will be allowed. A summary of the variables used so far is provided in Table II for T1 and T2. These are suitable for the correct operation of T1 and T2 in isolation from each other.

TABLE II
VOLTAGE-ONLY REGULATION SETTINGS

Variable	Type	T1	T2
tapstep (%)	Math	1.25	1.5
setpoint (% tap step)	Math	75	75
nominalvoltage (V)	Math	11,000	11,000
setpointvoltage (V)	Math	11,100	11,100
bandwidth	Math	103 V per Equation (3)	123 V per Equation (3)
voltagedeviation	Math	Measured – Equation (4)	Measured – Equation (4)
maximumtime (seconds)	Math	60	60
timetotap	Math	Equation (5)	Equation (5)
timer1pickup (seconds)	Analog	1.0	1.0
timer1initiate	Boolean	Logic	Logic
countup	Boolean / counter	Logic	Logic
raisetap	Output / Boolean	Logic	Logic
lowertap	Output / Boolean	Logic	Logic
tapchangeinprogress	Input / Boolean	Logic	Logic
blocktapchange	Boolean	Logic	Logic
resetcounter	Boolean / counter	Logic	Logic

VII. PARALLEL OPERATION USING CIRCULATING CURRENT BIAS

If T1 and T2 were placed in parallel, how would the AVR controllers using a voltage-only algorithm behave? Since the voltage bandwidth of T1 is lower than that of T2, it is likely that T2 will never issue a tap change and only T1 will regulate the voltage.

A circulating current algorithm can be placed into service with the voltage regulating algorithm to bias the correct transformer to change tap. The voltage-only settings calculated previously are relevant and necessary for the overall operation of the scheme. The raise and lower tap conditions, however, must be modified and several more variables are required.

For this example, we will start with the T1 and T2 values in Table I. The impedance of a transformer is given as a percentage of the MVA rating. We can use the MVA rating and impedance percentage to calculate an ohmic value. For T1, this is calculated as shown in (6).

$$\frac{\text{MVA rating}}{\text{\% impedance}} = \frac{15}{10.74\%} = 139\ \text{MVA(SC)} \tag{6}$$

where MVA(SC) is the short circuit capability of the transformer.

For T2, this is calculated as shown in (7).

$$\frac{\text{MVA rating}}{\text{\% impedance}} = \frac{11.5}{9.34\%} = 123\ \text{MVA(SC)} \tag{7}$$

The short circuit impedance is a measure of the ohmic resistance of the transformers. The impedance offered by a transformer to current flow can be expressed as shown in (8).

$$Z = \frac{\text{kV}^2}{\text{MVA(SC)}} \Omega \tag{8}$$

Changing the tap position of a transformer adds winding to or subtracts winding from the unit. This alters the impedance of the transformer and therefore affects the short circuit capability. However, in practice the variation over the entire tapping range is not significant for determining the circulating current parameters. It is simpler to avoid the added complexity.

Based on (8), the impedances of T1 and T2 can be calculated as shown in (9).

$$\begin{aligned} Z_{T1} &= \frac{11^2}{\frac{15}{10.74}\%} = j0.866\ \Omega \\ Z_{T2} &= \frac{11^2}{\frac{11.5}{9.34}\%} = j0.982\ \Omega \end{aligned} \tag{9}$$

Recall that the difference between the open circuit voltages of the transformers, shown in (10), is the electromotive force (EMF) that drives the circulating current.

$$\begin{aligned} V_{T1OC} &= 1.25\% \bullet 11,000 = 137\ \text{V} \\ V_{T2OC} &= 1.50\% \bullet 11,000 = 165\ \text{V} \end{aligned} \tag{10}$$

Based on (1), the circulating current with T1 raised one tap is as shown in (11).

$$I_{CIRC} = \frac{\frac{V_{T1OC}}{\sqrt{3}}}{Z_{T1} + Z_{T2}} = \frac{\frac{137}{\sqrt{3}}}{0.866 + 0.982} = 42.7\ \text{A pri @ 11 kV} \tag{11}$$

The circulating current with T2 raised one tap is as shown in (12).

$$I_{CIRC} = \frac{\frac{V_{T2OC}}{\sqrt{3}}}{Z_{T1} + Z_{T2}} = \frac{\frac{165}{\sqrt{3}}}{0.866 + 0.982} = 51.5\ \text{A pri @ 11 kV} \tag{12}$$

Choose a circulating current set point of 150 percent for each transformer as follows to allow operation at one tap step apart but not two:

circulatingcurrentsetpoint (T1) = 63 A

circulatingcurrentsetpoint (T2) = 77 A

As discussed previously, the reactive power flowing between two transformers is the difference between the measured reactive current and the proportion of the current that should be flowing based on the impedance of the transformer (see Fig. 2). We can measure the reactive power (Q) for T1 and T2. The split of reactive power between the transformers is based on the ratio of the impedance offered and the total reactive power. The difference between the measured and calculated reactive power gives us the circulating reactive power (Q_{CIRC}), as shown in (13).

$$Q_{CIRCT1} = Q_{T1} - \left\{ \left(Q_{T1} + Q_{T2} \right) \bullet \left(1 - \frac{MVASC_{T1}}{MVASC_{T1} + MVASC_{T2}} \right) \right\} \tag{13}$$

The circulating current can then be derived using (14).

$$I_{CIRC} = \frac{Q_{CIRC}}{\sqrt{3} \bullet V_{BUSBAR}} \text{A} \tag{14}$$

Once we have calculated the circulating current, we can calculate the current deviation using (15).

$$currentdeviation = \frac{I_{CIRC}}{circulatingcurrentsetpoint} \text{pu} \tag{15}$$

As with the voltage deviation, a negative number indicates that the tap needs to be raised. Adding the circulating current condition requires that two conditions exist before a tap change can be added. If we add the previously calculated *voltagedeviation* value to the *currentdeviation* value calculated in (15), we can create the variable *totaldeviation* as shown in (16).

$$totaldeviation = voltagedeviation + currentdeviation \text{ pu} \tag{16}$$

For a two-transformer substation, the circulating currents are equal in magnitude and opposite in direction. The voltage deviation will be the same; however, the current deviations will add to one and subtract from the other. To add the circulating current bias to the voltage control algorithm, simply include the total deviation, as follows:

raisetap = presentcountervalue > timetotap AND voltagedeviation <= –1 AND totaldeviation^2 *>= 1*

lowertap = presentcountervalue > timetotap AND voltagedeviation >= 1 AND totaldeviation^2 *>= 1*

The additional variables required to supplement the voltage algorithm with a circulating current bias are shown in Table III.

TABLE III
CIRCULATING CURRENT VARIABLES

Variable	Type	T1	T2
Circulatingcurrentsetpoint (A pri)	Math	63	77
MVA	Math	15	11.5
I_{CIRC} (A pri)	Math	Equation (14)	Equation (14)
Currentdeviation (pu)	Math	Equation (15)	Equation (15)
Totaldeviation (pu)	Math	Equation (16)	Equation (16)

For our example substation, assume that the load has required T1 to tap up one step, T2 is at nominal, and the load has increased to the point that the busbar voltage is again 103 V below the set point. The T1 deviations are calculated as follows:

voltagedeviation = –103/103 = –1 pu

currentdeviation = 42.4/63 = 0.67 pu

totaldeviation = –1 + 0.67 = 0.33 pu

The T2 deviations are calculated as follows:

voltagedeviation = –103/123 = –0.83 pu

currentdeviation = –42.4/77 = –0.55 pu

totaldeviation = –0.83 + –0.55 = –1.38 pu

The previous deviations and the raise/lower Boolean expressions show that T1 will not issue a tap change because the total deviation is less than 1 pu. The total deviation for T2 exceeds 1 pu, but the voltage deviation does not, so neither transformer will change tap. As the load increases further, T2 will issue the next tap change (raise) when the voltage deviation drops below –1 pu.

If we reduce the load so the busbar voltage rises to the point of needing a tap change, the T1 deviations are calculated as follows:

$voltagedeviation = 103/103 = 1\ pu$

$currentdeviation = 42.4/63 = 0.67\ pu$

$totaldeviation = 1 + 0.67 = 1.67\ pu$

The Transformer T2 deviations are calculated as follows:

$voltagedeviation = 103/123 = 0.83\ pu$

$currentdeviation = -42.4/77 = -0.55\ pu$

$totaldeviation = 0.83 + -0.55 = 0.28\ pu$

The *lowertap* logic conditions for T1 are satisfied, and T1 returns to its nominal position. Neither the raise nor the lower conditions for the operation of the T2 OLTC are satisfied.

VIII. COMMUNICATIONS

We have devised logic to control the tap change operation of paralleled transformers. The next step is to transmit the required information between devices. Although IEC 61850 is interoperable, different setting methodologies have been developed for each manufacturer platform. Some methods include the IEC 61850 settings in the same editor as the relay or AVR settings. Other methods create a separate file and send the configured description to the relay via an Ethernet connection. All methods require that the communicating devices be included in the substation configuration.

For our example two-transformer substation, there will be two Configured IED Description (CID) files containing one GOOSE message each. To minimize bandwidth use, we restrict the messages to only the data required. Each message requires a unique MAC address. Some manufacturers also require a unique APP ID. The VLAN tagging ID and priority are also part of the GOOSE transmit parameters. Fig. 4 shows one manufacturer's tool for editing the transmit parameters of each GOOSE message.

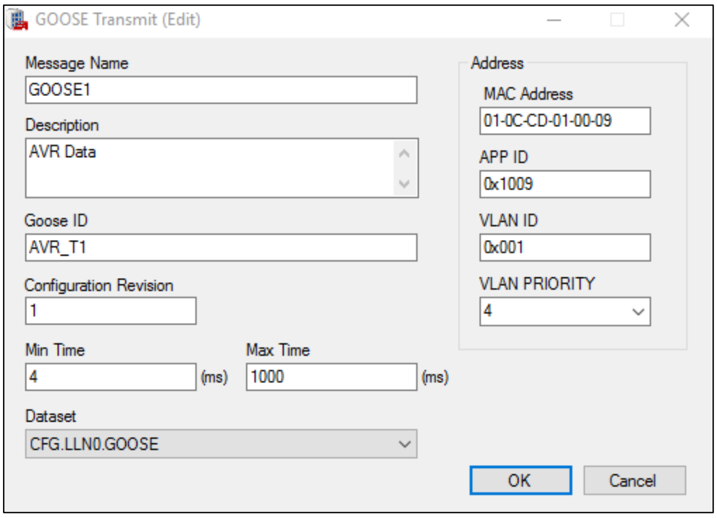


Fig. 4. GOOSE Transmit Parameters

The two CID files need to be linked. Fig. 5 shows that remote analog (RA) RA001 in AVR_T1 contains the metered value VAr for Phase A from AVR_T2. A similar structure can be shown for the digital information received as virtual bits (VBs). The RA and VB assignments need to be used in the AVR logic settings as appropriate.

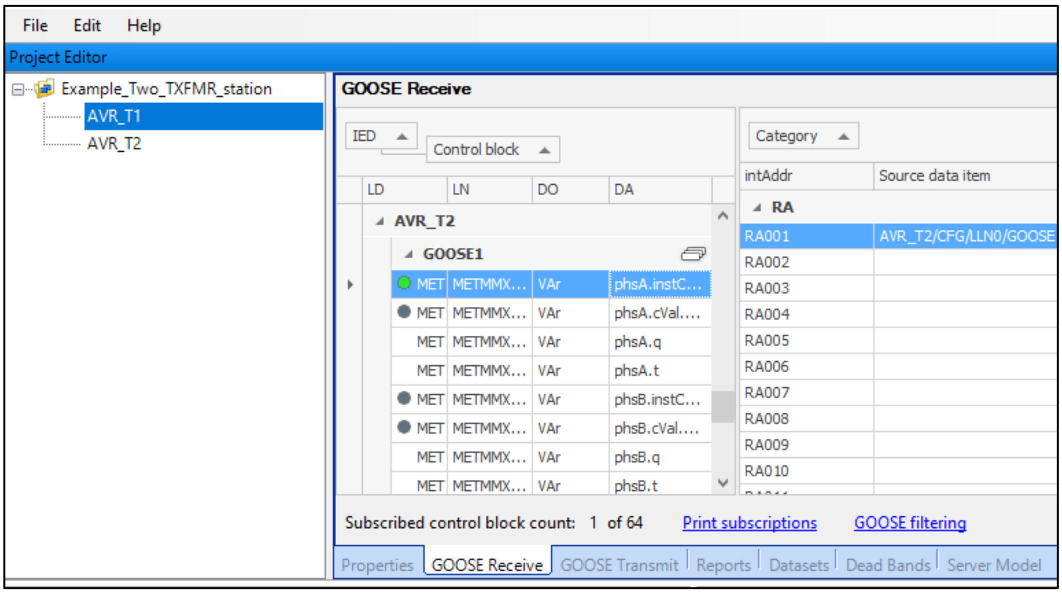


Fig. 5. Linking GOOSE Messages Between Devices

Table IV shows the information to be transmitted to each AVR for the two-transformer example.

TABLE IV
GOOSE MESSAGE ASSIGNMENTS

Local Signal	Remote Signal
Incomer status circuit breaker (CB) 52A	VB001
Bus section status CB 52A	VB002
Tap change in progress	VB003
Reactive power (Q)	RA001
Incomer voltage	RA002
Short circuit capability MVA(SC)	RA003

The following information can also be transmitted to create alarms for SCADA systems or operators as necessary:

- Set-point voltage
- Measured voltage
- Tap position

These values are not necessary to successfully control multiple paralleled transformers. The information that needs to be shared between AVRs can be directly measured by instrument transformers and digital inputs or via communications from other devices. If the incomer protection uses IEC 61850, then the reactive current and status information can be transferred to the AVR via the Ethernet network. Sites employing the principles described in this paper use different methods of obtaining the necessary information. Some sites use only IEC 61850 GOOSE, and each AVR subscribes not only to the other AVRs but also to the circuit breaker management relays. Many schemes use a mix of serial communications, Ethernet communications, direct measurements, and hardwired digital I/O.

IX. ETHERNET NETWORK

The Ethernet network can be as simple as a point-to-point connection between the AVR controllers, or it can be embedded as part of the engineering access or SCADA systems.

IEC 61850 GOOSE messages are published as soon as the information in the payload changes. They are then repeated at a decaying rate until the time-to-live (TTL) setting is reached. There is no acknowledgment or handshaking; proof of delivery relies on flooding the network and trusting that a robust network design ensures that one of the messages reaches its intended destination. After the initial flood and decay, each GOOSE message is retransmitted at the TTL rate until a change of payload begins the process again.

Since they flood the network and are always present, GOOSE messages should be segregated from other traffic. They can be used for protection and given higher priority for egress through switches. The GOOSE protocol allows the use of VLAN tagging to limit traffic to only those devices that require it. To embed GOOSE messages in an existing network requires an intelligent switch set to pass or block the appropriate VLAN tag appended to each message.

When adding a new device to an IEC 61850 substation, a new CID file needs to be sent to each device that communicates with each AVR. Any network switches involved must also be configured to pass the VLAN traffic. The effects of changing an existing network need to be considered at the design stage. The decision to embed GOOSE messaging in an existing network or to create a separate standalone connection depends on the existing hardware and capability of the devices. Adding a communications-based scheme not only requires testing of the AVR scheme but also proving that any existing schemes and devices are not adversely affected. If GOOSE messaging is used to source information from existing incomer (main) and bus-section relays, the commissioning and future maintenance will add significant costs to the project. It is no longer adequate to commission the devices separately and worry about the communications later. The communications system has become an integral part of the modern control solution [2].

X. PRACTICAL APPLICATION CONSIDERATIONS

Legacy SCADA systems usually accept DNP3 or Modbus protocols. Adopting an IEC 61850-capable device does not require Manufacturing Message Specification (MMS) or other services offered by IEC 61850. Simple is usually best. Retaining the existing SCADA protocols and adding an Ethernet connection between the controllers for GOOSE messages will have the least impact on an existing substation. Adding GOOSE messaging to an existing network requires CID files to be sent to all devices in the scheme. Embedded schemes require a new testing philosophy and can no longer be treated in isolation.

At most substations, three phase voltage transformers (VTs) are available. Legacy systems sometimes regulate with a single phase-to-phase voltage. Numerical relays are flexible enough to allow the choice to either copy the legacy arrangement or to use one or more of the three phase voltages. The current signal can be derived from a single line-drop compensation current transformer (CT) located on the transformer or from the switchgear CTs associated with each incomer. The reactive power measurement is critical to this scheme. The relationship between the measured voltage and current needs to be known. Differences such as CT polarities and VT connections need to be accounted for.

The tap changer position can be added to the AVR. Although not strictly necessary for voltage regulation, it is useful for creating alarms and assists with manual operation of the OLTC and with placing transformers back in parallel.

If transformers can be added or removed from the busbar, the AVR must adjust the algorithm accordingly. This is usually achieved with auxiliary contacts wired to the inputs of a local relay or to a remote relay and transmitted via a communications link. Latching logic can be used to reflect whether a unit is connected in parallel or is operating independently. If we set the latch to a logical 1 when connected in parallel and a logical 0 when independent, we can adjust the total deviation to null out the *currentdeviation*, as shown in (17).

$$totaldeviation = voltagedeviation + currentdeviation \bullet latch01 \quad (17)$$

The Boolean variable *blocktapchange* can be amended to block automatic tap changer operation for alarms or manual/local control when necessary.

Alarm and indication requirements are many, and they vary between regions. Some common alarms, controls, and other information are listed in Table V.

TABLE V
COMMON ALARMS AND INDICATIONS

Name	Type
Auto / manual	Control / indication
Local / remote	Control / indication
Raise voltage	Control
Lower voltage	Control
Raise/lower set point	Control
Load-drop compensation	Control
Tap change in progress	Indication
Tap change incomplete	Alarm
Tap change operation blocked	Alarm
End of tapping range	Alarm
Maximum tap apart	Alarm
Loss of communications	Alarm
Total number of tap operations	Indication
Number of taps per day	Indication

Many transformer monitoring relays (TMRs) support thermal modeling and winding hot-spot calculations. They can have analog or resistance temperature detector transducers connected. They provide control of cooling systems based on the modeled and measured temperatures. Marshalling of transformer alarms is convenient in a numerical TMR, particularly if it is mounted on the transformer.

XI. EXPANSION TO THREE OR FOUR TERMINALS

The algorithm for a two-transformer substation is the same in each relay. The setting differences in the AVR controllers are the nameplate setting parameters and the circulating current set point. All other parameters are the same. Since a three- or four-transformer substation can have different transformers paralleled, the settings are unique for each AVR. This section assumes that the busbar arrangement allows any transformer to operate independently or to be connected in parallel with any other transformer.

The circulating reactive power calculation from (13) is relatively straightforward and can be easily expanded to include four transformers in parallel, as shown in (18).

$$Q_{CIRCT1} = Q_{T1} - \left\{ \left(Q_{T1} + Q_{T2} + Q_{T3} + Q_{T4} \right) \bullet \left(1 - \frac{MVASC_{T1}}{MVASC_{T1} + MVASC_{T2} + MVASC_{T3} + MVASC_{T4}} \right) \right\} \quad (18)$$

Logic variables (LV1 through LV6) need to be assigned to track the parallel arrangement of the transformers (see Table VI). This allows us to null out the redundant terms of the circulating current as the configuration of the busbar requires.

TABLE VI
LOGIC VARIABLES TO TRACK BUSBAR SWITCHING (// DENOTES "IN PARALLEL WITH")

LV1	T1//T2*
LV2	T1//T3
LV3	T1//T4
LV4	T2//T3
LV5	T2//T4
LV6	T3//T4

LV1 is a logical 1 when all the relevant conditions needed to parallel T1 and T2 are met. LV2 through LV6 cover all other possible combinations. Table VII shows which logic variable is needed to add the paralleled transformer to the circulating current calculation for each AVR. AVR1 is used with T1, AVR2 is used with T2, and so on.

TABLE VII
TRANSFORMER CURRENTS NEEDED TO CALCULATE CIRCULATING CURRENT

Transformer	AVR1	AVR2	AVR3	AVR4
T1	NA	LV1	LV2	LV3
T2	LV1	NA	LV4	LV5
T3	LV2	LV4	NA	LV6
T4	LV3	LV5	LV6	NA

To add the T1 reactive power to the circulating current calculation for AVR2, we use LV1; to add the T1 reactive power to the AVR3 calculation, we use LV2; and so on. Equation (18) can now be modified to calculate the circulating current for all combinations of paralleled transformers. Equations (19) and (20) show the circulating current equations for AVR1 and AVR2, respectively.

$$Q_{CIRCT1} = Q_{T1} - \left\{ \begin{aligned} &\left(Q_{T1} + Q_{T2} \bullet LV1 + Q_{T3} \bullet LV2 + Q_{T4} \bullet LV3\right) \bullet \\ &\left(1 - \frac{MVASC_{T1}}{MVASC_{T1} + MVASC_{T2} \bullet LV1 + MVASC_{T3} \bullet LV2 + MVASC_{T4} \bullet LV3}\right) \end{aligned} \right\} \tag{19}$$

$$Q_{CIRCT2} = Q_{T2} - \left\{ \begin{aligned} &\left(Q_{T1} \bullet LV1 + Q_{T2} + Q_{T3} \bullet LV4 + Q_{T4} \bullet LV5\right) \bullet \\ &\left(1 - \frac{MVASC_{T2}}{MVASC_{T1} \bullet LV1 + MVASC_{T2} + MVASC_{T3} \bullet LV4 + MVASC_{T4} \bullet LV5}\right) \end{aligned} \right\} \tag{20}$$

A similar process can be used to derive the equations for AVR3 and AVR4.

Recall that the amount of circulating current is determined by the open circuit voltage difference between the transformers and the series impedance. Each transformer can be connected in parallel with one, two, or three other transformers. For each of these arrangements, the series impedance changes and, thus, so does the circulating current.

If we add T3 to our example substation, the impedance offered by T3 is calculated by (21).

$$Z_{T3} = \frac{11^2}{\frac{11.5}{9.75}\%} = j1.026\,\Omega \tag{21}$$

The circulating current flowing when T1 is raised one tap and paralleled with one or two transformers is calculated as follows, based on (11).

For T1//T2:

$$I_{CIRC} = 42.7 \text{ A pri @ 11 kV} \tag{22}$$

For T1//T3:

$$I_{CIRC} = \frac{\frac{V_{T1OC}}{\sqrt{3}}}{Z_{T1} + Z_{T3}} = \frac{\frac{137}{\sqrt{3}}}{0.866 + 1.026} = 41.8 \text{ A pri @ 11 kV} \tag{23}$$

For T1//T2//T3:

$$I_{CIRC} = \frac{\frac{V_{T1OC}}{\sqrt{3}}}{Z_{T1} + \frac{Z_{T2} \bullet Z_{T3}}{Z_{T2} + Z_{T3}}} = \frac{\frac{137}{\sqrt{3}}}{0.866 + \frac{0.982 \bullet 1.026}{0.982 + 1.026}} = 57.8 \text{ A pri @ 11 kV} \tag{24}$$

When T1 is connected in parallel with one transformer (T2 or T3), there is ~42 A of circulating current per tap step. When the three transformers are in parallel, the circulating current in T1 is ~58 A.

Choose set points for T1 at 150 percent of the expected circulating current for a difference of one tap step. Following the same rationale, we can choose set points for T2 and T3. Circulating current set points are shown in Table VIII.

TABLE VIII
CIRCULATING CURRENT SET POINTS FOR EXAMPLE THREE-TRANSFORMER SUBSTATION

Transformers in Parallel	T1 (A pri)	T2 (A pri)	T3 (A pri)
2	63	72	96
3	85	96	127

For a four-transformer substation, there are three different circulating current set points. We can use logic variables to null out irrelevant set points, depending on the busbar/switching configuration.

Three variables in addition to those of Table VI are required to determine how many transformers are paralleled. They will allow us to use a single Boolean expression to null out the irrelevant current set points. The logic variables for AVR1 and T1 are shown in Table IX. These conditions must be modified for AVRs 2, 3, and 4.

TABLE IX
LOGIC VARIABLES REFLECTING THE NUMBER OF TRANSFORMERS IN PARALLEL

Logic Variable	Transformers in Parallel With T1	Logic Conditions
LV7	1	LV1 AND NOT (LV2 OR LV3) OR LV2 AND NOT (LV1 OR LV3) OR LV3 AND NOT (LV1 OR LV2)
LV8	2	LV1 AND LV2 AND NOT LV3 OR LV1 AND NOT LV2 AND LV3 OR NOT LV1 AND LV2 AND LV3
LV9	3	LV1 AND LV2 AND LV3

Equation (25) adjusts the current set-point value based on the number of transformers in parallel.

$$currentsetpoint = setpoint1tx \bullet \mathrm{LV7} + setpoint2tx \bullet \mathrm{LV8} + setpoint3tx \bullet \mathrm{LV9} \quad (25)$$

To add transformers to the IEC 61850 GOOSE configuration requires unique virtual bit and remote analog assignments for each AVR. A two-transformer scheme only needs to know about one remote device. A four-transformer scheme has three devices to consider. Expanding on Table IV, the assignments for a four-transformer scheme are shown in Table X.

TABLE X
GOOSE MESSAGE ASSIGNMENTS FOR A FOUR-TRANSFORMER SUBSTATION

Local Signal	AVR_T1	AVR_T2	AVR_T3	AVR_T4
Incomer status CB 52A	VB011	VB021	VB031	VB041
Bus section status CB 52A	VB012	VB022	VB032	VB042
Tap change in progress	VB013	VB023	VB033	VB043
Reactive power (Q)	RA011	RA021	RA031	RA041
Incomer voltage	RA012	RA022	RA032	RA042
Short circuit capability MVA(SC)	RA013	RA023	RA033	RA043

XII. COMMISSIONING AND LESSONS LEARNED

Commissioning an AVR scheme is like placing any numerical device in service. The usual checks of current and voltage measurement accuracy should be performed along with checking the correct wiring and the operation of the outputs and inputs. Subsequent tests can then be performed to confirm correct scheme operation.

If the AVR upgrade is a retrofit of old equipment, the upgrade is usually completed one transformer at a time. Operate each transformer via SCADA (remotely) and locally. If tap position transducers use 4 to 20 mA inputs, they will need to be scaled accordingly at the extents of the transformer tap positions.

Automatic operation using voltage-only control should be verified. After all of the AVRs are upgraded, combinations of the transformers can be placed in parallel. With the transformers on the same tap, the voltage deviation should be the same between devices. Manually raise the voltage one tap and verify that the voltage and current deviations are negative. Confirm that the circulating current set points are appropriate. Repeat this process for all possible transformer combinations.

When transformers are connected in parallel, regulate using just one voltage and transfer this value to all the transformers. Using the incomer VT of each transformer can lead to errors and can cause the scheme to misoperate. The voltage deviation of one transformer can be above 1 pu, but the circulating current bias can prevent operation. If measurement errors leave the other transformer at a ~0.95 pu deviation, it will also not be able to change tap. A simple logic statement can be added to select one VT signal when in parallel and another when independent.

Investigate the possibilities of the transformers being connected in parallel due to switching of the power system outside of the substation. One such switching operation at the 400 V level resulted in protection trips of the transformers (33/11 kV) due to the presence of huge circulating currents. The 11 kV bus sections were open, forcing the AVRs to operate independently. They have since been set to alarm if the circulating current exceeds a threshold regardless of whether the transformers are independent or in parallel.

XIII. Conclusion

The use of Ethernet has enabled peer-to-peer communications to evolve from one-to-one to one-to-many topologies via IEC 61850. Many protection and control schemes are now possible without additional hardware, wiring, and physical inputs and outputs. The example in this paper of an AVR solution using numerical relays and a circulating current principle has been widely adopted by many distribution companies. It has proven to be robust, reliable, and flexible. However, the additional capability brings complexity. Ethernet network design, commissioning, maintenance, future expansion, and effects on existing substation automation schemes must be considered during the design phase.

One of the fundamental requirements of good engineering is to keep it simple. Modern numerical relays have many functions and extensive programming capabilities. As design engineers, we not only need to make schemes that perform, we need to consider who is going to install, maintain, and test the equipment. Keep it as simple as possible.

XIV. References

[1] M. J. Heathcote, *The J & P Transformer Book: A Practical Technology of the Power Transformer,* 12th Ed. Newnes, Burlington, MA, 1998.

[2] D. Burkart, W. Edwards, A. Atalay, and S. Snuggs, “If You Cannot Test It, You Cannot Use It – IEC 61850 GOOSE System Designed With Testing in Mind,” proceedings of the 70th Annual Conference for Protective Relay Engineers, College Station, TX, April 2017.