Using IEC 61850 Analogue GOOSE Messages for OLTC Control of Parallel Transformers

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KEYWORDS

Automatic On-load Tap-Changer Control, Power Transformer Control, Analogue GOOSE Messages.

1. INTRODUCTION

The paper will present a utility experience from a project where protection and control for the whole substation is done by using IEC 61850 Standard. The special attention will be given to the control of parallel transformers with on-load tap-changer (OLTC), which has been achieved by using IEC 61850 analogue GOOSE messages between the regulators.

In this substation, there are two 20MVA, 110/20kV, YNd5 transformers with OLTC. Each power transformer has a dedicated IED which provides integrated protection and control for the transformer. Thus, all power transformer protection functions like 87T, 87N, 50/51, 50N/51N, 49 as well as OLTC control function 90 are integrated into a single device. Transformer backup protections are allocated in the additional protection device (50N/51N) and in busbar protection bay unit (21T, 50/51) for the transformer bay. Because the two transformers can operate in parallel, the OLTC control is based on the minimizing circulating current principle.

Integration of several protection functions in single protection IED is common praxis for many electric utilities across the world. Application of automatic control function using protection IED provokes sometimes a discussion about justification for such decision. Nevertheless, utilities experience shows technical and economical benefits for such applications.

2. VOLTAGE REGULATION FOR SINGLE TRANSFORMER

When the load in a power network is increased the voltage will decrease and vice versa. To maintain the network voltage at a constant level, power transformers are usually equipped with an on-load tap changer (OLTC). This alters the power transformer ratio in a number of predefined steps and in this way changes the voltage. Each step usually represents a change in voltage of approximately 0.5–1.7%.

The voltage can be controlled at the point of voltage measurement, or at a load point located out in the network. In the latter case, the load point voltage is calculated based on the measured load current and the known impedance from the voltage measuring point to the load point.

Automatic voltage control can be either for a single transformer, or for parallel transformers. Parallel control of power transformers can be made in different ways:

- With the reverse reactance method
- With the master-follower method
- With the circulating current method

Of these alternatives, the second and third require communication between the voltage control functions for the transformers in the parallel group.

2.1. VOLTAGE REGULATION FUNCTIONALITY

The voltage control function is designed to automatically maintain the voltage at the LV-side of a power transformer to within given limits around a set target voltage. To accomplish this, the voltage control function measures the magnitude of the LV-side busbar voltage UB and, if no other additional features are enabled (e.g. line voltage drop compensation), this voltage is then used for the voltage regulation.

The voltage control function compares the measured voltage to the set target voltage. To avoid unnecessary switching around the setpoint, a deadband (i.e. a degree of insensitivity) is introduced. In this illustration the deadband is symmetrical around the setpoint, and in fact comprises an outer as well as an inner deadband – see Figure 1.

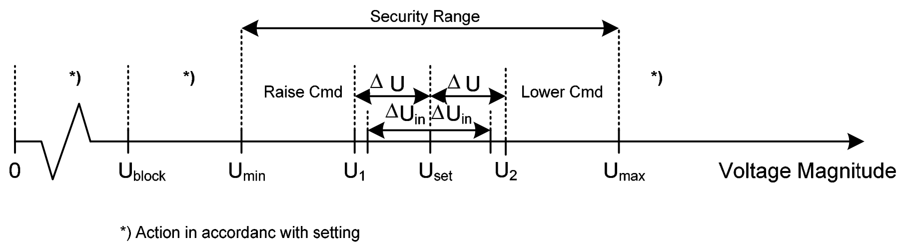

Fig. 1: Voltage scale for control actions

One half of the outer deadband, shown as ΔU in Figure 1 should have a value near to the power transformer's tap changer voltage step (typically 75%—125% of the tap changer step).

During normal operating conditions, if the busbar voltage UB stays within the outer deadband (i.e. within the interval between U1 and U2 in Figure 1), no actions will be taken by the voltage control function. However, if the UB voltage is measured to be outside the outer deadband (i.e. if UB becomes smaller than U1, or greater than U2), the sequence will start. The first step in the sequence is to start a time delay. The timer will run as long as the voltage stays outside the outer deadband. The appropriate raise or lower command will be issued if the UB voltage is still measured to be outside the outer deadband when the time delay has elapsed.

If necessary, the procedure will be repeated until the magnitude of the busbar voltage is measured to be inside the inner deadband.

One half of the inner deadband, shown as ΔUin in Figure 1 should have a value smaller than ΔU – a recommended value is 25–70% of the ΔU value.

2.1.1. Time characteristic

The time characteristic defines the time that must elapse between the moment when measured voltage exceeds the deadband interval until the appropriate raise or lower command is initiated. This time delay (inverse time or definite time) is required to avoid unnecessary operation for short duration voltage excursions outside the outer deadband (for which tapping is not required, and furthermore any tap action may just have to be reversed), and in order to coordinate with other automatic voltage controllers in the system, the objective being to limit the number of unnecessary OLTC operations. This can be done by setting a longer time delay closer to the consumer and shorter time delays higher up in the system.

2.1.2. Line drop compensation

The purpose with the line voltage drop compensation is to control the voltage, not at the power transformer low voltage side, but at a point closer to the load point, i.e. to regulate UL to the setpoint rather than UB. UL can be obtained by a simple vector calculation – see Figure 2. UB is the measured busbar voltage and IL the load current on the line – this quantity must also be measured. RL and XL are the line resistance and reactance from the station busbar to the load point, and must be entered as settings. If more than one line is connected to the LV busbar, an equivalent impedance should be calculated and this entered as the setting.

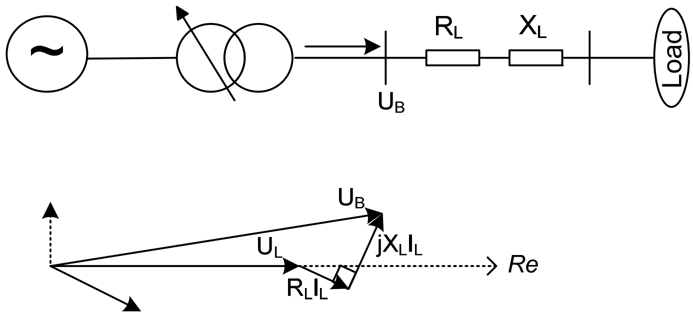

Fig. 2: Vector diagram for line drop compensation

3. AUTOMATIC CONTROL OF PARALLEL TRANSFORMERS

Parallel control of power transformers means control of two or more power transformers connected to the same busbar on the LV side and in most cases also on the HV side. As indicated previously, three alternative methods can be used, i.e. the master-follower method, the circulating current method, and the reverse reactance method. As only the first two require communication between the voltage control functions on the transformers in the parallel group, only these two will be considered further in this paper.

3.1. Parallel control with the master-follower method

In the master-follower method, one of the transformers is selected to be master, and will regulate the voltage in accordance with the principles described above. Selection of the master and followers is typically made with a three position switch in the substation – see Figure 3.

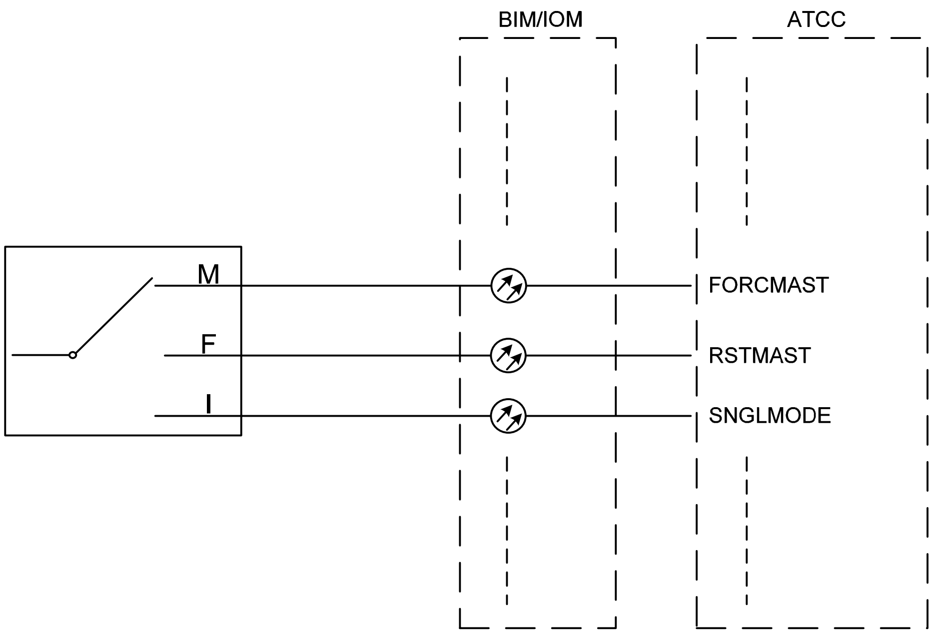

Fig. 3: Three-position switch selection

The selected master needs to inform the other voltage control functions operating in the same parallel group of its status as the selected master. The followers can generally act in two alternative ways:

1. Follow the master's raise and lower commands irrespective of their individual tap positions. For operation in this way, the master, on deciding to issue a raise or lower command, must send this information to all followers in the same parallel group. Effectively this means that if the tap positions of the followers were harmonized with the master from the beginning, they would stay like that as long as all transformers in the parallel group continue to participate in the parallel control. On the other hand if, e.g., one transformer is disconnected from the group and misses a one tap step operation (homing not enabled), and thereafter is reconnected to the group again, it will thereafter participate in the regulation but with a one tap position offset.

2. Follow the master's tap position. The followers will read the tap position of the master and adopt the same tap position, or a tap position with a predetermined offset relative to the master. For operation in this way, the master must send out its tap position to all followers in the same parallel group.

In order for the master to perform line drop compensation that uses the total load current IL, it is necessary for the master to calculate this. Each voltage control function measures I, the current flowing through its transformer. The total load current IL can be calculated by summing together all these measured currents, i.e.

$$I_L = \sum_{i=1}^{k} I_i,$$

where the subscript i signifies the transformer bay number (i.e. the measured current Ii represents the current lowing through transformer i), and "k" the number of parallel transformers in the group. In order for the master to make this calculation, the voltage control function on each follower transformer must send its measured current value to the voltage control function on the master.

If automatic voltage control of the master is, for some reason, blocked, the followers will not tap by themselves, so the blocked status of the master need not be sent to the followers. However, if the voltage control of a follower is blocked, there is a need to send this to the master, as the master must then block its automatic voltage control. Any blocked follower must therefore send the information of its blocked status to the master.

Information of the busbar topology, i.e. position of circuit breakers and isolators, indicating which transformers are connected to which busbar, and which busbars are connected to each other, is vital information that must be supplied to the voltage control function, as this tells it which transformers it has to consider in the parallel control, i.e. which transformers are in its parallel group. When a transformer in the parallel group becomes disconnected, such that it is no longer an active participant in the group (LV-side circuit breaker opened), its voltage control function must send notification of this to all other voltage control functions operating in the same parallel group. In the master-follower mode, it is normal for a blocking signal to be generated if the tap difference between a follower and the master is greater than some value, so if a follower has become disconnected, this information is required to prevent this blocking signal from being generated. If the LV circuit breaker of the master is opened, automatic control must be blocked.

If the control mode for the master is set to manual, the followers should continue to follow the master in the same way as when the master is set to automatic mode. Conversely, if the control mode for one follower in the parallel group is set to manual, the rest of the group should continue in automatic master-follower control with the follower in manual mode now disregarding any tapping of the master.

The following list summarizes the required signal to be communicated for the master-follower method:

1. Voltage control function is forced to master: Activated by the voltage control function that has 'forced to master' selected – used to give a blocking signal if more than one master is selected.

2. Voltage control function is master: Activated by the voltage control function that is the selected master.

3. Voltage control function is ready for master-follower: Activated when the voltage control function is ready for master-follower parallel control.

4. Control is automatic: Activated when the voltage control function is selected to automatic.

5. Blocked status: Activated when the automatic control is blocked – used for blocking of the master if a follower becomes blocked.

6. Disconnected status: Activated if a transformer becomes disconnected by opening of its LV side circuit breaker – used by the master so it doesn't act on a blocking signal generated by a disconnected follower if the tap difference between it and the master becomes greater than some value.

7. Raise voltage command: Order from the master to the followers to tap up.

8. Lower voltage command: Order from the master to the followers to tap down.

9. Tap position: Actual tap position from the master to the followers – used by the followers when the way of operation is to follow the master's tap position; and to determine if the tap difference between any follower and the master is greater than some value.

10. Measured transformer current (real and imaginary parts): Enables the master to calculate the total load current flowing through the parallel group, which is then used for line drop compensation based on the total load current.

3.2. Parallel control with the circulating current method

In a parallel group, a transformer with a higher tap position will typically have a higher (LV side) no-load voltage than one with a lower tap position. These unequal no-load voltages (unequal tap positions) will cause a circulating current to flow through the parallel connected transformers. A transformer with higher no-load voltage (typically higher tap position) will produce circulating current, while a transformer with lower no-load voltage (typically lower tap position) will receive circulating current. When load is put on the transformers, the circulating current will remain the same, but now it will be superimposed on the load current in each transformer, i.e. for a transformer producing circulating current, this will be added to its load current, and for a transformer receiving circulating current, this will be subtracted from its load current. Voltage control of parallel transformers with the circulating current method aims to minimize the circulating current at the given voltage target value, thereby ensuring that:

- The busbar, or load, voltage is regulated to the preset target value.
- The total reactive load is shared between parallel transformers in proportion to their rating.

This method requires extensive exchange of data between the voltage control functions.

The busbar voltage UB is measured individually for each transformer in the parallel group by its associated voltage control function. To ensure that the same value of busbar voltage is used by all voltage control functions, thereby avoiding that one erroneous measurement from one VT could upset the voltage regulation, each voltage control function should calculate UBmean, the mean value of all measured UB values, and then use this instead of its measured UB for the voltage regulation. To accomplish this, the measured UB value by any voltage control function must be sent to all other voltage control functions whose transformers are operating in the same parallel group.

$$U_{Bmean} = \frac{1}{k} \cdot \sum_{i=1}^{k} U_{Bi},$$

where UBi represents the measured busbar voltage for transformer I and k number of transformers in the parallel group.

As stated before, each voltage control function measures I, the current flowing through its transformer. However, in order to carry out the voltage regulation using the circulating current method, each voltage control function must determine what is the circulating current Icc that flows through its transformer. The way each does this is by subtracting from its measured current its contribution to the total load current IL that flows through the parallel group. In order for each to calculate its contribution to the total load current, each must first calculate the total load current IL. This is done as already described, i.e.

$$I_L = \sum_{i=1}^{k} I_i.$$

and requires that each voltage control function send to all other voltage control functions operating in the same parallel group its value of measured current Ii.

Next, each voltage control function must calculate the contribution through its transformer to the total load current.

$$I_{Li} = K_i I_L,$$

where Ki is a constant for transformer i which depends on the number of transformers in the parallel group and their short-circuit reactance, and ILi the contribution through transformer i to the total load current. For each voltage control function to calculate its Ki, each must send its setting for its transformers short-circuit reactance to all other voltage control functions operating in the same parallel group. Each voltage control function can now calculate the circulating current flowing in its own transformer as:

$$I_{CCi} = -I_m(I_i - I_{Li}).$$

The minus sign is added in the above equation in order to get a positive value of the circulating current for the transformer that generates it. Im signifies the imaginary part of the expression in brackets.

Having calculated the circulating flowing in its own transformer, each voltage control function in the parallel group, in order to calculate its transformers no-load voltage, must now convert this to a voltage deviation Ud.

$$U_{di} = C_i I_{CCi} X_i.$$

Where Udi is the calculated voltage deviation for transformer i, and Xi is the short-circuit reactance of transformer i (Ci is a setting parameter that serves the purpose of alternatively increasing or decreasing the impact of the circulating current in the calculations).

Ud will have positive values for transformers that produce circulating currents, and negative values for transformers that receive circulating currents.

Finally, each voltage control function can now calculate the magnitude of its transformers no-load voltage, which can be approximated as:

$$U_i = U_{Bmean} + U_{di},$$

where Ui is the no-load voltage for transformer i.

The no-load voltage U will be greater than UBmean for transformers producing circulating current, and less than UBmean for transformers receiving circulating current.

Each voltage control function then treats the calculated value of its transformers no-load voltage as the measured busbar voltage, and further control actions are taken in accordance with the automatic voltage control for a single transformer, i.e.:

- The calculated no-load voltage is compared with the set point voltage.
- A steady deviation outside the outer deadband will result in the appropriate raise or lower commands being given.
- In this way the overall control action is always correct as the tap changer position is directly proportional to the transformer no-load voltage.

Different set point values for individual transformers can cause the voltage regulation to be unstable. For this reason a mean value for the set point is recommended for parallel operation with the circulating current method. To accomplish this, each voltage control function must send its set set point value to all other voltage control functions operating in the same parallel group.

If automatic control of any one voltage control function is, for some reason, blocked, all other voltage control functions working in parallel must also have their operation blocked. The affected voltage control function must therefore send notification of its blocked status to all other voltage control functions in the same parallel group. When the mutual block is received, automatic control is blocked in the receiving voltage control functions (all units of the parallel group).

As for the master-follower mode, information of the busbar topology is vital information for the voltage control functions operating in the circulating current mode, as this tells them which transformers are in their parallel group. When a transformer in the parallel group becomes disconnected, such that it is no longer an active participant in the group (LV side circuit breaker opened), its voltage control function must send notification of this to all other voltage control functions operating in the same parallel group. Automatic control will be blocked if the transformer is disconnected from the LV busbar (unless hot-standby, or homing, is selected, in which case it will go into this state).

If the control mode for one voltage control function is set to manual with the others left in automatic, those left in automatic must adapt to the manual tapping of the transformer that has been put in manual mode. Each voltage control function therefore needs to send its control mode status to all other voltage control functions operating in the same parallel group.

If prevention of simultaneous tapping is selected, when it is the turn of any transformer to tap, its voltage control function must send notification to all others in the same parallel group that its timer has started timing. In this way, all the voltage control functions of the other transformers in the same parallel group are prevented from starting a tapping sequence until the voltage control function of the transformer whose turn it is has completed its raise or lower sequence.

Summary of required signals to be communicated for the circulating current method

1. Measured busbar voltage: Enables each voltage control function to calculate the value UBmean.

2. Measured transformer current (real and imaginary parts): Enables each voltage control function to calculate the total load current flowing through the parallel group – used in the circulating current calculation by each voltage control function for its transformer, and by each for line drop compensation based on the total load current.

3. Set transformer reactance (referred to the LV side): Enables each voltage control function to calculate its transformers contribution to the total load current, and subsequently its transformers circulating current.

4. Voltage set point: Enables each voltage control function to calculate the mean set point value.

5. Control is automatic: Activated when the voltage control function is selected to automatic – deactivated signal is used to inform the remaining in automatic to adapt to the voltage control function selected to manual.

6. Blocked status: Activated when the automatic control is blocked – used for blocking all other voltage control functions in the parallel group if one becomes blocked.

7. Disconnected status: Activated if a transformer becomes disconnected by opening of its LV side circuit breaker – used to inform the others in the same parallel group of its disconnected status, so the others will, e.g., not include the measured voltage of the disconnected transformer (even if homing is enabled) in the voltage regulation.

8. Timer on: Activated by the voltage control function whose turn it is to tap and whose delay timer has started – used to prevent others in the parallel group from starting a tapping sequence until its sequence in progress has been completed.

3.2.1. Prevention of simultaneous tapping

This is applicable primarily to the circulating current method of parallel control. One transformer will be selected to tap first. If the measured voltage is outside the outer deadband, the voltage control function of that transformer will then start the timing of the appropriate time delay, and after the time delay has elapsed will issue the raise or lower command. If further tapping is still required to bring the busbar voltage inside the inner deadband, the voltage control function of the selected transformer to tap next will now start the timing of the appropriate time delay, and as before will issue a raise or lower command after the time delay has elapsed, and so on until all measured voltages are such that the sequence resets.

3.2.2. Homing

By homing is meant active automatic control to a correct tap position of a hot-standby transformer in a group that has its LV side circuit breaker open.

4. COMMUNICATION BETWEEN THE VOLTAGE CONTROL FUNCTIONS (INTER-IED COMMUNICATION)

All the required signals, both analog and binary, required for either the master-follower of circulating current modes of operation are communicated between the participating IEDs using GOOSE interbay communication on the IEC 61850-8-1 protocol. Complete exchange of voltage control function data, analog as well as binary, is made using GOOSE messages [1].

For the purposes of this paper (in order to make the explanation of the application simple) it is assumed that each IED contains only one voltage control function. Each voltage control function has data that needs to be transmitted to other voltage control functions. The dataset containing the information that needs to be sent to other voltage control functions must be constructed. Typically this dataset contains the following items– see Figure 4:

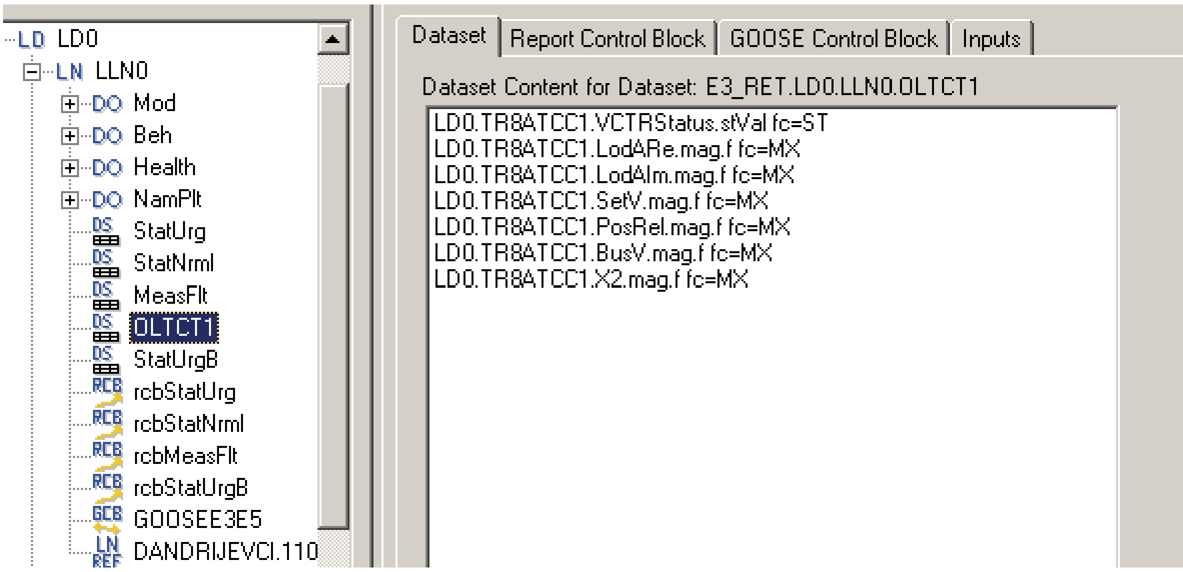

Fig. 4: Dataset with mandatory items for voltage control

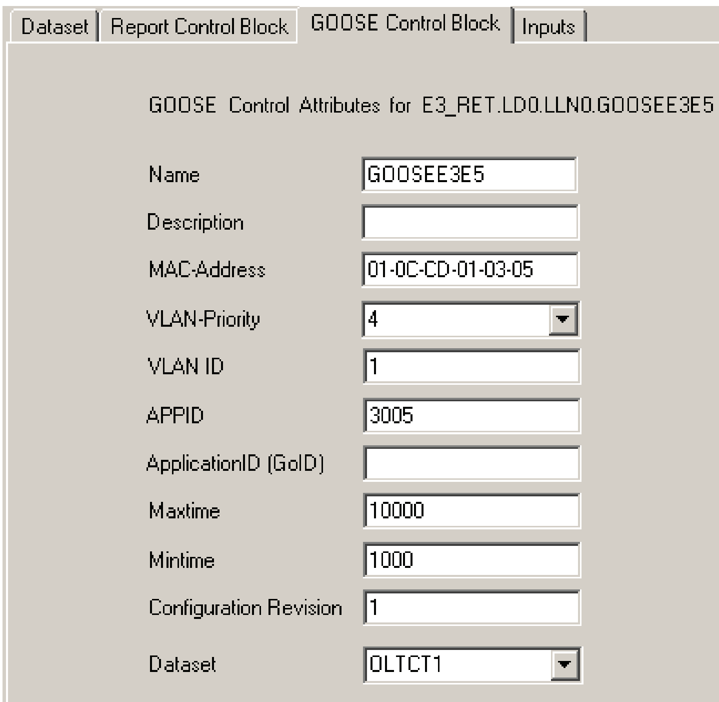

Fig. 5: GOOSE control block for OLTC1 Dataset

This dataset must be added to a GOOSE control block in the appropriate IED. The address definition of the GOOSE control block must be entered along with its required parameters, e.g. min time, max time, MAC address, etc– see Figure 5.

Note that each voltage control block will send the same dataset, but each voltage control block (or more specifically each IED containing a voltage control block) will have unique address definitions for the GOOSE control block. This will ensure that data is unique within the interbay bus. To receive this dataset from the other transformers, the voltage control function must subscribe to the GOOSE messages sent by other IEDs in the system. Subscribing to these GOOSE messages will enable the voltage control function to operate in parallel utilizing the data from the other transformers.

The parallel function should consider only GOOSE messages from the voltage control functions working in parallel (i.e. according to the current station configuration or setting parameter). The status of isolators and circuit breakers in the station (station configuration or topology) are of vital importance since the connected state (i.e. parallel, disconnected etc.) of the transformer depends on these devices. The station configuration information can also be received via GOOSE, and subscribed to, enabling the voltage control functions to determine its connected state and control accordingly. In order for the voltage control functions to subscribe to the station topology information, the isolator and circuit breaker statuses need to be transmitted via GOOSE from the device where the information is wired to. This could typically be a bay control IED in the substation automation system. This bay control IED would contain a GOOSE control block with associated datasets containing XCBR, XSWI and CSWI information which the voltage control function could subscribe to. Automatic control is automatically blocked if the horizontal GOOSE communication for any one of the voltage control functions in the parallel group fails (all voltage control functions which belong to the same parallel group will be blocked).

5. CONCLUSION

The paper has described a typical voltage control functionality for parallel transformer applications, with emphasis on the signals that need to be communicated between the voltage control functions (one associated with each transformer) for both the master-follower and circulating methods of parallel control. The chosen communication interface is GOOSE interbay communication based on the IEC 61850-8-1 protocol, albeit using a vendor specific dataset. Nevertheless, because it utilizes the IEC 61850, it does not require an additional proprietary communications interface, but can be implemented on an existing IEC 61850-8-1 infrastructure already present in the substation. Furthermore, it is able to take advantage of all the other benefits that can be obtained from an IEC 61850-8-1 installation.

The OLTC control functionality is implemented in accordance with IEC 61850 Standard. Thus, two logical nodes, namely YLTC and ATCC, are available in each of the two IEDs. The YLTC logical nodes represents the OLTC mechanism and integrate functionality like tap position reading, OLTC mechanism supervision and issuing of the manual and automatic raise and lower commands to the OLTC mechanism. The ATCC logical node represents the regulator itself and integrates functionality like voltage measurement and supervision, timing, line drop compensation, circulating current measurement and compensation etc.

Because of the parallel control it is necessary to exchange information about measured current, measured voltage, etc. between the two IEDs. This information exchange is performed by using analog GOOSE messages in accordance with IEC 61850 Standard between the two IEDs. The whole engineering flow follows the IEC 61850 standard and it has been performed by an external system integrator.

Since September 2007 first substation with such control system is in full commercial operation. Second substation with similar on-load voltage control is as well in mean time put in service, while FAT for third substation is completed but commissioning and SAT is expected to commence in the near future.

REFERENCES

[1] ABB Document 1MRK 504 086-UEN, "Technical reference manual, Transformer Protection IED RET 670", Product version: 1.1, ABB Power Technologies AB, Västerås, Sweden, (2007).