Enhanced Voltage Control

EAVC Settings Calculation Guide

Fundamentals Reference F9183

15/08/2018

Confidential

Electricity North West Ltd
Enhanced Voltage Control
ENWL011

About this report

Version Information

Rev	Date	Purpose of Issue / Changes	Authored	Checked	Approved
1.0	15/08/2018	Issued for customer review	H. Shishtawi	H. Shishtawi	H. Shishtawi

Table of Contents

Abbreviations

EAVC	Enhanced Voltage Control
AC	Alternating Current
FACTS	Flexible AC Transmission Systems
OLTC	On Load Tapchanger
AVC	Automatic Voltage Control
LDC	Load Drop Compensation
kV	Kilo Volt
MVA	Mega Volt Ampere
A	Ampere
HV	High Voltage
DG	Distributed Generation
PCC	Point of Common Coupling
LV	Low Voltage
TAPP	Transformer Automatic Paralleling Package
TCC	True Circulating Current
VT	Voltage Transformer
CT	Current Transformer
SCADA	Supervisory Control and Data Acquisition
TPI	Tap Position Indication
DC	Direct Current
mA	milli Ampere
DSS	Directional Sequence Switch
LR	Load Ratio

1 Introduction

This report provides the reader with the needed knowledge to design and calculate EAVC settings to accommodate for basic and advanced voltage control applications.

The report is structured into two sections; the first section covers the basic voltage control applications while the second section covers the advanced applications. A background of the voltage control techniques, paralleling methodologies and additional network services is also covered.

2 A Brief Introduction to Voltage Control

The operation and management of power systems are very important aspects to keep the customers satisfied. Voltage control can be considered as one of the most vital elements that keeps the system in a healthy steady state condition. A wrongly set up or a faulty voltage control system can affect the grid very badly; causing power cuts in some cases.

Voltage control can be deployed in any of the different network levels of the grid; i.e. transmission network, distribution network and others. There are many technologies, old and new, that can deliver some element of voltage control or voltage support; such as the use of Flexible AC Transmission Systems (FACTS) in the transmission network. One of the most widely used voltage control techniques, in both the transmission and the distribution systems, is changing power transformers' transformation ratios using On Load Tapchangers (OLTC); which is the focus of this report.

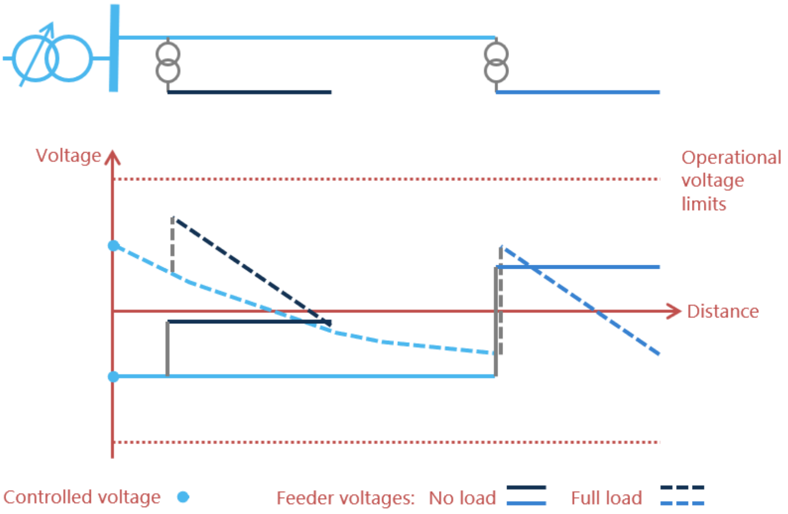
There are two main objectives for any voltage control system that utilises the OLTC technique:

1. Maintain the customer voltages, at the end of every feeder, within the statutory limits as defined by the system regulator.
2. Maintain healthy paralleling between any transformers operating in parallel.

2.1 Maintaining Customer Voltages

Primary substations (usually with busbar voltages of 11kV or 6.6kV) can be, electrically, far from end users that typically utilise single phase voltages in the 230V level. The relationships between the customer voltage, the total load level and the voltage drop across feeders is directly proportional.

Figure 1 The relationship between voltage, load level and feeder length



2.1.1 Line Drop Compensation

Historically, customer voltages were maintained using the line drop compensation method. This method requires simulating the impedance of feeders into the AVC relay by inputting the resistance and reactance values of feeder as settings. Some of the problems associated with using this method are:

1. Feeder impedance parameters are not always easy to obtain; especially that these parameters are usually provided as a function of the length of the electric cable.
2. The line drop compensation function utilises a single resistance value and a single reactance value. Each primary substation has a number of outgoing feeders; hence it is not easy to determine which feeder we would like to base the compensation on.

The above mentioned reasons make the line drop compensation method hard to use and hence undesirable.

2.1.2 Load Drop Compensation

Unlike the line drop compensation, the load drop compensation method (LDC) does not require line impedance information. Instead, the largest voltage drop across the longest feeder at the highest permissible load condition is what is needed for this application. It is also preferred to know the lowest voltage drop across the shortest feeder at the highest permissible load condition.

By using these two parameters, an adequate LDC level can be calculated and applied to maintain the end user's voltage within the healthy desirable range. The desired calculated LDC is then inputted to the AVC system as a setting.

When the AVC system is configured correctly, it will boost the busbar voltage up by a factor equivalent to the LDC setting.

The operational effective LDC level applied to the voltage control system should only compensate for voltage drops caused by load currents; any voltage drop caused by any other factors, such as network circulating currents, will not be addressed by the LDC application. Assuming that the load power factor matches the power factor setting within the EAVC relay, the effective used LDC level is calculated as shown below:

Equation 1

$$\boldsymbol{Applied\ LDC}\ (\%) = \frac{\boldsymbol{true\ group\ load}}{\boldsymbol{LDC\ rating}} * \boldsymbol{LDCsetting}\ (\%)$$

The LDC rating in the above equation is sometimes referred to as the firm capacity of the substation. Usually this parameter describes the 'n-1' load level of the substation; which takes into account security of supply aspects.

2.1.2.1 Load Drop Compensation Example

Assuming a two transformer substation with the following parameters:

- Transformer nominal transformation ratio: 33kV to 11kV.
- The MVA rating of each transformer is 20MVA; which is equivalent to 1050A single phase.
- The maximum substation load is 1050A.
- The maximum voltage drop at 1050A is 6% @ 20MVA base.
- The minimum voltage drop at 1050A is 2% @ 20MVA base.

The EAVC settings should be:

Table 1 Load drop compensation setting example

Setting	Value
LDC rating	20MVA/1050A
Network power factor	0.97 lag
LDC level	4%; this is the average between the maximum and minimum voltage drops. This is not a rule, however the LDC level value should not cause the voltage at the closest electrical point to go above the operational limit.

In the above example, the applied LDC can be calculated at different loading conditions using Equation 1 (and assuming the load power factor is 0.97 lag in this case):

Table 2 Calculated LDC for different loading conditions

Load level	Applied LDC
262.5A (quarter load)	1%
525A (half load)	2%
900A	3.42%
1050A	4%
1500A	4%

As shown in Table 2 the applied LDC is linearly directly proportional to the load level. The LDC application should be capped to a maximum; if it is not capped then at overload situations unnecessary high voltage conditions can occur.

The minimum voltage drop at the full substation load usually occurs on short feeders; i.e. customers relatively close to the primary substation. Hence, the minimum voltage drop at full load conditions is used to make sure that if the full specified LDC is applied the voltage on these nodes is still within limits and are not very high.

The correct operation of the LDC function relies mainly on inputting the correct settings into the EAVC relay and understanding the application.

2.1.3 Reverse Load Drop Compensation

Sometimes it is desired to drop down the busbar voltage in proportion to the current exported back to the HV grid. This effect is usually seen at substations with a significant level of distributed generation (DG) utilised within the network they serve.

In the reverse power flow case the LDC function should not operate. However, if it is desired to drop down the busbar voltage in proportion to the reverse power flow, the reverse LDC function should be utilised.

The reverse LDC should be enabled within the EAVC settings. When enabled, the same LDC curve used for forward power flows will be utilised. Some advanced EAVC relays gives the user the option to choose a different curve for the reverse LDC.

The reverse LDC can address issues like busbar voltage rises due to reverse voltage drops across transformer impedances, maximising the penetration of DG in the network and reducing the effect of the voltage rise at the point of common coupling (PCC). The reverse LDC level can be calculated to address these voltage rise issues.

2.2 Transformers Paralleling

As important as maintaining the customer voltage is, ensuring that transformers are paralleled correctly is equally important. The reason we operate transformers in parallel is to increase the system security of supply.

Healthy paralleling means that the circulating current flowing between transformers operating in parallel is kept to its possible minimum level. Ideally, if two identical transformers coupled at the HV side and operating in parallel (coupled at the LV side as well), the net circulating current flowing between them should be equal to zero. However, in practice there will always be some circulating current flowing between the two transformers.

A number of methods can be used to parallel transformers:

1. The Master-Follower method.
2. The Negative Reactance Compounding method.
3. The Transformer Automatic Paralleling Package (TAPP) method.
4. The True Circulating Current method.
5. The Enhanced TAPP method.

2.2.1 The Master Follower Paralleling Method

The key prerequisites for this method are:

- The parallel transformers should have the same capacity.
- The parallel transformers should have the same tap step size.
- The parallel transformers should have the same impedance value.
- The parallel transformers should have the same number of tap positions.
- The parallel transformers nominal transformation ratios should be the same.
- The parallel transformers should be fed from the same source, or at least coupled at the HV side.

If any of the above-mentioned prerequisites are not met, then the Master-Follower method will fail to minimise the circulating current between the parallel transformers.

The Master-Follower method assumes that there is a master transformer with equipment that continuously monitors the busbar voltage. When the busbar voltage deviates outside the bandwidth setting, the master relay taps the transformer it is controlling to compensate for the voltage deviation. Each follower transformer then taps to follow the operation of the master relay.

This method can be complicated to implement (especially if it is to be installed as a hardwired solution). Some other problems with this method are:

- If a transformer needs replacement, only a bespoke transformer identical to the parallel transformers can be used.
- The busbar voltage changes in full steps; fraction steps for more accurate voltage control applications are not achievable.
- This method promotes for radial networks and cannot deal with meshed networks approach. For instance, you cannot feed a primary substation from two different grid substations.

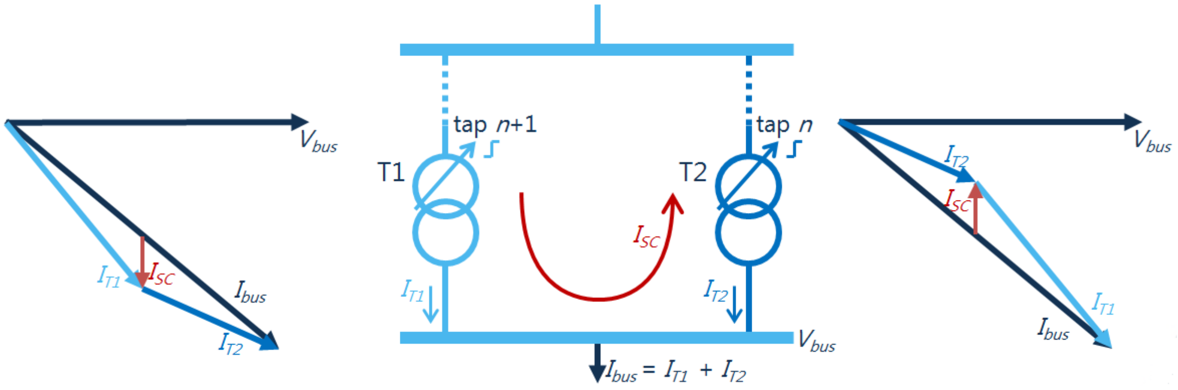
Hence it is not advised to use the Master-Follower paralleling method unless there are justifiable reasons to why any other paralleling method should not be used.

2.2.2 The NRC Method

This method relies on the power factor of the current flowing through each transformer to achieve correct paralleling and to minimise the circulating current. Unlike the Master-Follower method, there are not any constraints on the parallel transformers specification for this method to work.

The easiest way to describe how this method works is by an example.

Figure 2 NRC paralleling method



As shown in Figure 2, two transformers are operating in parallel with T1 operating on a higher tap position than T2. In this case T1 exports negative reactive current, denoted I_{SC}, which is imported by T2. This reactive circulating current makes the power factor of the current flowing through T1 more lagging and the current flowing through T2 more leading.

The NRC method utilises the deviation in the power factor and converts the **approximated** circulating current vector (magnitude and direction) into a voltage bias to keep the transformers coupled. When the parallel transformers are operating with minimum circulating current flowing between them, then the voltage bias will be negligible and the transformers will not tap unless the voltage deviates beyond the dead band. Figure 3 and Figure 4 show how the circulating current is converted into voltage biases. The calculated voltage bias is then added to the busbar voltage to form the measured voltage vector. The measured voltage vector is then compared against the required voltage target for the tapping operation decision making process. The power factors in Figure 3 and Figure 4 are exaggerated for illustration purposes.

Figure 3 NRC voltage bias calculation – tap down

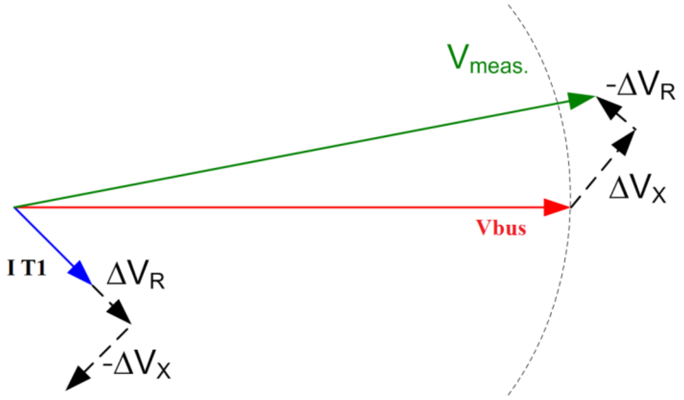
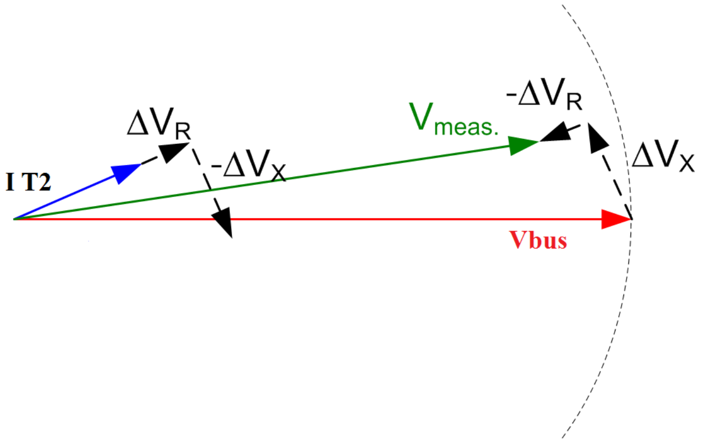


Figure 4 NRC voltage bias calculation – tap up



The problem with the NRC paralleling method is that NRC assumes that the normal load power factor is unity; which is not true. Since the power factor of loads is usually lagging, the NRC paralleling method can introduce low voltage errors to the system.

Another problem with power factor-based voltage controllers is that if the load is not domestic, e.g. industrial loads or networks with DG penetration, with a poor power factor then the voltage control operation will be compromised.

Some of the advantages of the original NRC paralleling method are:

- Simple to implement.
- Does not require communication links between the AVC relays.

Older AVC relays with NRC paralleling method cannot provide the LDC function since the R and X settings, which are usually used for LDC purposes, are used for coupling parallel transformers together.

2.2.3 The TAPP Method

The original TAPP method realises and addresses the power factor related shortcomings of the NRC paralleling method. Hence, the original TAPP method assumes that the power factor of the load is about 0.965 lagging. This way, the TAPP method responds to power factor deviations away from the ≈-16° access rather than from the 0° axis.

Unfortunately, the original TAPP method suffers from the same problems power factor-based voltage controllers suffer from. However, this was then resolved using numeric relays; where the target power factor is settable by the user to reflect the true network condition.

2.2.4 The TCC Method

The TCC method requires a communication link between AVC relays. In this case, the AVC relays will share the transformer loading information between them and will be able to calculate the reactive current circulating between them. In the same manner as with the NRC, the calculated circulating current is then converted to voltage biases; however, another important factor for this calculation is the transformer impedance.

AVC relays using the TCC method need to know the busbar configuration arrangement to deduce which transformers are operating in parallel. The busbar configuration can be determined by feeding the status of the bus section CBs to the AVC relays.

2.2.5 The Enhanced TAPP Method

This method uses the TCC approach and the TAPP approach together. The TCC method mainly serves for paralleling transformers that exist in the same substation with a communication link established for the circulating current calculations.

Additionally, the TAPP method is used for paralleling substations across the network. For instance, if the transformers in the same substation are paralleled correctly but the true load power factor does not match the system power factor setting, then the power factor deviation suggests that this substation is operating in parallel with another substation that has different voltage level at its busbars; of course, the power factor deviation level might suggest differently. In this case the TAPP mode will convert the power factor deviation to a voltage bias applied on all the AVC relays in the substation to adjust the busbar voltage rather than individual transformer voltage outputs.

3 Basic EAVC Settings

This section looks into the EAVC settings essential for the basic voltage control requirements. The settings that will be addressed in this section are:

- Voltage target settings.
- Network settings.
- Transformer settings.
- VTs and CTs settings.
- Voltage target adjustments.
- Tapchanger settings.
- Alarm settings.
- Busbar grouping using settings groups.

3.1 Voltage Target Settings

3.1.1 Basic Voltage Target

This is the voltage that the EAVC relay will aim for when there is no other contribution from other biases; i.e. when site circulating current is equal to zero, network circulating current is equal to zero, LDC bias is equal to zero and so on.

This setting is usually in percent based on the system nominal voltage and **not** the transformer nominal voltage.

For ordinary sites, an adequate basic voltage target can be calculated by simulating the network, using a load flow simulation tool, and finding the minimum and maximum voltage levels at the LV busbars. The basic voltage target can be in the middle of these two readings; the rest of the voltage drop can be compensated for using other means such as LDC.

If a site has special circumstances, then these should be considered when calculating the basic voltage target.

Another factor that can have a big impact on the voltage target calculation is the difference between the minimum and the maximum load and the rate of change of load.

3.1.2 Effective Voltage Target

It was mentioned in section 3.1.1 that the basic voltage target is what the EAVC relay will aim for in the absence of any other voltage bias contributions from any other applications; in this case the effective voltage target is equal to the basic voltage target.

Generally, the effective voltage target, what the EAVC relay will aim to achieve, is described in the below expression:

Equation 2

$$\boldsymbol{V_{Ef}} = V_{Basic} + \boldsymbol{V_{Circ}} + \boldsymbol{V_{Net}} + \boldsymbol{V_{LDC}} + \boldsymbol{V_{Gen}} + V_{Adj} + \cdots$$

Where:

- V_{Ef} is the calculated effective voltage target.
- V_{Basic} is the basic voltage target setting (see section 3.1.1).
- V_{Circ} is the calculated site circulating current reduction bias (see section 2.2).

- V_{Net} is the calculated network circulating current reduction bias (see section 2.2).
- V_{LDC} is the calculated LDC bias (see section 2.1.2).
- V_{Gen} is the calculated generation bias (see section 0).
- V_{Adj} is the applied voltage adjustment contribution (see sections 3.5 and 4.3).

3.1.3 Bandwidth

The bandwidth, sometimes referred to as the dead-band, is a range of voltages deviating from the effective voltage target and is acceptable by the EAVC relay; i.e. the EAVC relay will tolerate these voltages and will not try to correct the voltage neither by tapping up nor by tapping down.

The bandwidth is usually described as a percentage of the system nominal voltage in the form:

$$Bandwidth = \pm Bw\ \%$$

Ideally the bandwidth value in the above equation, which describes half of the dead-band as shown in Figure 5, is set to be equal to a single tap step size:

$$Bandwidth = \pm TapStepSize\ \%$$

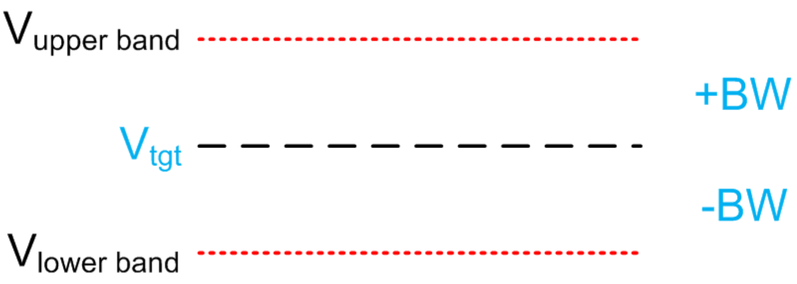
This way if the measured voltage is just on the edge of the dead-band a single tap operation should be sufficient to bring the voltage to middle of the band.

If the OLTC is required to carry out fewer tapping operations, then the bandwidth setting can be increased; of course, this will be on account of the tolerated voltage level. On the other hand, if a more accurate voltage control is required then the bandwidth setting can be minimised. The minimum value the bandwidth setting can take is higher than half a step size; if the bandwidth is set to a half step size or lower then hunting can occur. Hunting is defined to be the state where the voltage control relay cannot bring the voltage back to the dead band; i.e. every time the OLTC tries to correct for voltage deviations it will cause the voltage to jump outside the other end of the dead-band.

As an example, the ideal bandwidth for a transformer with 33kV/11kV nominal voltage, OLTC fitted at the HV side and the voltage step size is 420V:

$$Bandwidth\ (\%) = TapStepSize\ (\%) = \frac{420V}{33000V} \times 100 = 1.27\% \ \cong 1.3\ \%$$

Figure 5 Bandwidth explained



3.1.4 Initial Tap Time Delay

This is a time grading setting and is used to serve two main purposes:

- Differentiate between transient voltage deviations/fluctuations and genuine voltage changes.
- Allow OLTCs installed at higher voltage levels to tap first. This is because you would usually have fewer number of OLTCs installed upstream compared with downstream and hence fewer tapchangers will tap to correct for the voltage deviations.

When the measured voltage deviates beyond the bandwidth the 'initial tap time delay timer' starts timing down from the setting value to zero. When the timer reaches zero a tap change command is issued.

EAVC relays usually utilise an integral type timer for this application; if the voltage gets back to the dead-band range after the timer started, the timer will start incrementing itself instead of immediately resetting to its original value.

EAVC relays installed at primary substations usually utilise a 120s initial tap time, while similar relays installed at grid substations would usually use a 60s initial tap time. This is, of course, dependant upon the utility company voltage control policy.

3.1.5 LDC Level and LDC Rating

This is described in section 2.1.

3.2 Network Settings

3.2.1 Nominal Voltage

The nominal voltage setting is required to aid the EAVC relay in the internal calculations required for the voltage control operation. This setting should reflect the exact system nominal voltage.

3.2.2 Phase Rotation

This setting is also required for the internal EAVC calculations, and it should reflect the phase rotation of the system/transformer. Normal phase rotation is denoted 'A-B-C' while reversed phase rotation is denoted 'A-C-B'.

3.2.3 Network Power Factor

The network power factor setting should reflect the power factor of the load supplied by the substation. The power factor for ordinary sites (non-industrial, no DG, etc.) is about 0.97 lag.

3.3 Transformer Settings

3.3.1 Transformer ID

EAVC relays can accommodate several transformers operating in parallel; generally in the region of 8 transformers. EAVC relays utilise communication links between them, i.e. peer-to-peer communication. For this purpose, every transformer should be uniquely identified.

3.3.2 Transformer Rating

Some EAVC functions need to know the rating of the transformer it is controlling to ensure correct operation. It should be noted that this setting does not necessarily need to be the same as the LDC rating. While the LDC rating setting describes the maximum load supplied by the substation, the transformer rating describes the maximum MVA the transformer is rated for. The maximum transformer rating, including any fans and pumps, is usually used here.

3.3.3 Transformer Impedance

The transformer impedance is an essential quantity for the voltage control operation. The transformer impedance used here should be:

- Taken at the nominal tap position.

- Taken at the full rating of the transformer including fans and pumps, referred to as continuous emergency rating (CER). Unless another transformer rating setting is used, see section 3.3.2, then the impedance should be taken at the CER rating.

The transformer impedance setting value is usually in (%) using the transformer ratings as a base.

3.3.4 Overcurrent Limit

This setting, percentage of the transformer rating, is used to inhibit the operation of the EAVC if the loading of the transformer exceeds the value it is set to. This helps to protect the OLTC against switching currents outside of its operational range.

3.4 VTs and CTs Settings

3.4.1 VT Settings

Given the importance of the VT measured voltage to the AVC application, it is essential to configure the VT settings correctly. The following VT settings should be configured:

- What is the VT connected to?
- What is the VT transformation ratio?
- What VT phases are connected to the EAVC relay?

The VT can be connected to:

- The winding of the transformer controlled by the EAVC relay; or the first winding of a double secondary winding transformer.
- The second winding of the double secondary winding transformer controlled by the EAVC relay.
- Another transformer, not controlled by the EAVC relay, to provide phase reference. This can be connected to different busbars and/or bus sections.

Or others.

The phase of the VT connection can be:

- A-B,
- B-C,
- C-A,
- A-Earth,
- B-Earth,
- and C-Earth.

Finally, the VT ratio setting should reflect the correct physical VT ratio.

If a three phase VT connection is to be connected to the EAVC relay the following should be done:

- Wire the A-B connection to the first VT input and the B-C connection to the second VT input.
- In the settings, both inputs should be connected to the same VT.
- In the settings, set the first VT connection to A-B and the second one to B-C.
- In the settings, both VTs should have the same transformation ratio which should reflect the ratio of the physical VT.

3.4.2 CT Settings

The CT settings are as important as the VT settings. The LDC CT current is an essential quantity for EAVC relays to calculate the circulating current. The following CT settings should be configured:

- CT function.
- Number of interposer turns.
- CT ratio.
- CT connection phase.
- Bus section connection[1].

The advanced CT functions are discussed in section 4.10. However, the basic CT function is the 'transformer winding' function. This means that the CT connection comes from the LDC CT of the power transformer.

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

For EAVC relays that utilise an interposing CT (clip-on or solid core) the number of turns through the interposer CT should be specified to the EAVC relay in the settings. For SuperTAPP SG relays, the number of interposer turns should reflect a resultant of **5Ampere×turns**.

For instance, if the secondary of the CT is rated at 5A, then only one turn around the interposing CT will be required. In the same manner, if the secondary of the CT is rated at 1A then 5 turns will be required.

3.5 Voltage Target Adjustments

Voltage target adjustments modify the effective voltage target to serve, for instance, operational purposes; such as demand reduction. These adjustments can be activated through SCADA; hardwired or through a communication link.

When a voltage adjustment function is triggered the corresponding voltage adjustment value (configured through settings) is applied to the effective voltage target equation.

Voltage target adjustments can be used to increase the busbar voltage (a positive setting value is used for demand increase applications) and can be used to decrease the busbar voltage (a negative setting value is used for demand reduction applications).

3.6 Tapchanger Settings

3.6.1 Inter-tap Time Delay

Unlike the initial tap time delay, described in section 3.1.4, the inter-tap time delay is a tapchanger parameter rather than a network one.

The inter-tap time delay is a timer used by EAVC relays to trigger additional tap change commands after the initial one if required. The main objectives of the inter-tap time delay are:

- Delay issuing any further raise/lower commands until the tapchanger has finished the previous tap operation.
- Give time for the voltage change resulting from the previous tap change operation to settle into steady state.

To set up the inter-tap time delay setting to its minimum, the following procedure is recommended:

1. Measure the longest time the tapchanger needs to perform a single tap change operation. The longest tap time can occur when tapping in the other direction reference to the previous operation (e.g. a raise operation after a lower operation or vice versa).

---

[1] See section 4.10

2. Add 10%-20% on top of the time value measured in the previous step; this can be considered as a safety factor. This can account for different oil viscosities in different seasons for example.

Of course the procedure above describes the minimum adequate inter-tap time delay that can be used if the network requires that. For faster inter-tap time delays, a faster OLTC should be used. The value of this setting can also be used to time-grade the tapchanger operation.

3.6.2 Tap Pulse Time

The tap pulse time is also a parameter of the tapchanger. This is the minimum time required to hold an electric pulse so that the tapchanger mechanism engages in a tap change operation. Normally when a tapchanger mechanism engages in a tap change operation no external supply is required; as the mechanism is usually electrically self-sustaining.

3.6.3 Tap Operation Time

This is another tapchanger parameter which describes the longest time required to finish a single tap change operation. EAVC relays that provide tapchanger monitoring and runaway prevention functions require this setting.

Tapchanger runaway is a faulty tapchanger situation that can be defined as: the continuous running of the tapchanger motor, and hence the continuous changing of the tap position, caused by a faulty component within the tapchanger control system. An example of such faulty components is a faulty contact on a raise/lower contactor relay which provides permanent power to the tapchanger motor. These situations should be avoided.

Some considerations should be taken into account when configuring this setting:

- If the tapchanger mechanism is under oil, the oil viscosity can affect the tap operation time: especially in different seasons of the year.
- The longest tap change time usually occurs when changing the tap position in the different direction relevant to the last tap change operation; i.e. if you raise the tap position of the transformer twice and then lower it once then the second raise operation will take less time than the first lower operation. This is true if there are not any transfer tap positions. If transfer tap positions exist, then the longest operation time will be as described in this point however when passing through the maximum number of transfer taps. Transfer tap positions are explained in section 3.6.4.

3.6.4 Number of Consecutive Transfer Taps

Some tapchangers, especially ones with coarse winding selection, can require more than one tap change (the motor will run for multiple times) for a single raise/lower operation to be completed. In this case the additional tap changes are required to pass through transfer tap positions.

Transfer taps directly impact EAVC relays that provide tapchanger monitoring functions; such as runaway prevention and tap change incomplete detection. This type of EAVC relay monitors a number of signals, to ensure healthy tap operations and to protect against faulty ones, such as:

- Tap position.
- Tap raise sense.
- Tap lower sense.
- Tap change in progress indication and duration.

When transfer taps exist, multiple ‘tap change in progress signals’ are raised for a single tap change operation. These additional in progress signals come without any tap raise sense or tap lower sense signals; which is a runaway condition from an EAVC relay point of view with tapchanger monitoring functions.

Two main things should be considered when setting up an EAVC relay controlling a tapchanger with transfer taps:

- The maximum number of transfer taps.
- The transfer tap-positions and their interaction with the TPI sender unit.

The number of transfer taps is important as it provides the EAVC relay with an indication of how many tap change in progress signals will be raised during a tap change operation passing through the transfer taps. Referring to Figure 6 where tap position 8B is a physical position while tap positions 8A and 8C are transfer positions. In this case when tapping up from tap 7 the tapchanger will pass through tap 8A. On the other hand, when tapping down from tap 9 the tapchanger will pass through tap 8C. Hence, the maximum number of transfer taps is 1.

Figure 6 Transfer tap positions example

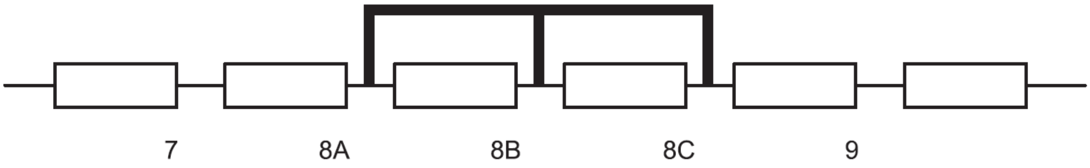


Figure 6 also shows that, for a resistor chain TPI sender unit, each transfer tap has got its own position with an independent indication resistor. It should be ensured that the TPI sender unit does not change the tap position sent to the EAVC relay when passing through a transfer tap position. In the case of the resistor chain shown in Figure 6 this can be overcome by shorting out the transfer tap position as shown in Figure 6. If the sender unit is not a resistor chain, then the sender unit should be configured correctly to send the same tap position signal for all the transfer tap positions. The above example is intended for clarification purposes only and may not reflect standard tapchanger arrangements.

3.6.5 Extra Top and Bottom Resistors for Resistor Chain Sender Units

Legacy hardwired SCADA systems supported the transfer of tap position to the control room via analogue DC mA signals. These signals are produced by applying a fixed level of DC voltage across the resistor chain and measure the voltage drop between 'the bottom of the chain and the wiper' and between 'the top of the chain and the wiper'. The measured voltages (mainly the bottom to wiper) are then converted, using an adequate transducer, into DC mA current scaled to reflect the tap selected position.

To differentiate between the bottom tap position and a faulty mA transducer an additional bottom resistor is added to the bottom of the resistor chain; in this case when the bottom tap position is selected then the mA output from the transducer is not '0'. In the same manner a top resistor is added to differentiate between the selection of the top tap position and a faulty transducer producing the maximum scale output.

If top and/or bottom resistors are used, then this should be programmed into the EAVC settings. The EAVC should:

- Know there are top and/or bottom resistors present in scheme.
- Be told what the values of these additional resistors are.

Some AVC and EAVC relays assume that the value of additional resistor matches that of the resistor chain individual resistor values. However, advanced relays allow the user to set the value of these resistors in the settings; mostly as a value relative to the resistor chain induvial resistor value.

For instance, if the resistor chain individual resistor value is 400Ω and the top/bottom resistor value is 200Ω, the top/bottom resistor value should be set to 0.5 tap. Another example, using the same resistor chain from the previous example, and 800Ω top/bottom resistor then the corresponding setting value should be set to 2 taps.

3.6.6 Lockout for Tap Change Tapchanger Runaway and Incomplete

A tapchanger lockout can be defined as the situation where the supply to the tapchanger motor has been tripped. In this case, it is not possible to change the tap position of the transformer unless:

- The supply is restored to the motor.
- The tapchanger is manually operated using a crank handle.

A lockout situation can take place for various reasons such as:

- Motor supply trip due to a thermal overload condition.
- A detection of a runaway condition by an EAVC or a tapchanger monitoring equipment.
- A detection of a tap change incomplete condition by an EAVC or a tapchanger monitoring equipment.

3.6.6.1 Tapchanger runaway

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The essential signals and parameters for a tapchanger runaway detection system are:

- Tap change sense signals; raise/lower sense signals. Which are signals used by the EAVC equipment to realise the initiation of a tap change operation. This signal originates from the tap change initiation source; such as the EAVC relay itself or any raise/lower push button available within the scheme.
- Tap change in progress signal. This is a signal derived from the tapchanger mechanism (DSS switch, micro switches, repeat relays, etc.) and indicates that the motor of the tapchanger is running.
- Tap change operation time.
- Maximum number of transfer taps.

A tapchanger runaway condition exists if the tapchanger initiates a tap change operation on its own; i.e. no raise/lower signals detected by the EAVC/monitoring relay.

An example of the above would be if an EAVC relay initiates a single tap change operation by issuing (and sensing) a raise/lower signal, and when the tap change operation has been completed another operation is initiated on its own (no raise/lower commands sensed). In this case, the EAVC relay should issue a lockout signal to trip the tapchanger supply after the second tap change operation (the first runaway tap change) has finished.

If it is not desired to trip the motor supply if any of the above cases is detected, then the lockout functionality for tapchanger runaway should be disabled in the settings.

3.6.6.2 Tap Change incomplete

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The tap change incomplete is a term used to describe any of the following situations:

- A persistent sense of a raise or lower signal.

- No signs of a tap change operation after sensing a raise or a lower signal.
- A persistent tap change in progress signal after the tap change operation time has elapsed.

If any of the above is detected by the relay, then relay will lockout for tap change incomplete. If it is not desired to trip the motor supply if any of the above cases is detected, then the lockout functionality for tap change incomplete should be disabled in the settings.

3.7 Alarms

3.7.1 Voltage High Limit

The voltage high limit can be thought of as the maximum operational voltage allowed in the system, or the statutory limits imposed by the system regulator. EAVC relays should block tap change operations that can take the system voltage above the level specified by this setting. This setting is in percent of the system voltage; for instance a 110% limit on an 11kV system equals to a 12.1kV high limit.

The SuperTAPP SG EAVC relay starts blocking for raise operations when:

$$Measured\ Voltage\ \geq Voltage\ High\ Limit - Bandwidth\ Setting$$

3.7.2 Voltage Low Limit

As with the voltage high limit, the voltage low limit should be configured to the lowest allowed operational voltage level. Similarly this setting is in percent of the system voltage, hence a 90% limit on an 11kV system equals to 9.9kV low limit.

The SuperTAPP SG EAVC relay starts blocking for lower operation when:

$$Measure\ Voltage\ \leq Voltage\ Low\ Limit + Bandwidth\ Setting$$

3.7.3 Alarm Time

This setting reflects the time delay before the EAVC sets an alarm off. Examples of these alarms are voltage out of band alarm, voltage high alarm, voltage low alarm and loss of phase reference.

The value this delay timer is set to should consider the EAVC and the tapchanger response times.

For instance, the timer should be long enough so that the EAVC can take actions to correct for the problem causing the alarm condition to exist. For example, if the alarm is indicating a voltage out of band situation, then the delay should be long enough for the tapchanger to be able to issue the adequate number of tap change operation commands to rectify the problem before the EAVC alarms.

It should be noted that some alarm conditions; such as VT fuse failure and CAN communication errors are instantaneous alarms and are not delayed by this setting.

3.7.4 Low Voltage Inhibit Level

This setting is used to inhibit the operation of the voltage control system during system fault conditions.

This setting is in percentage of the basic voltage target. When the measured voltage level is equal to or below the voltage level specified by this setting, then the EAVC relay inhibits the voltage control operation.

For example if the basic voltage target is set to 95% and the low voltage inhibit level is set to 80%, then the EAVC relay block for voltages below 76% or 8.36kV on an 11kV system.

3.8 Binary Inputs and Outputs

3.8.1 Binary Inputs

The settings range covered by the binary inputs menu should enable the user to provide external interactions with the AVC system. Examples of these functions are:

- Switch to auto control mode;
- Switch to manual control mode;
- Manual raise/lower;
- Block tapping;
- And setting group changes.

3.8.1.1 Edge triggered and level triggered inputs

Depending on the selected function, some of the inputs require an 'Edge' signal while others require a 'Level' signal. If the function requires a permanent signal to stay active then the corresponding input (mapped in the settings) should have a permanent high signal into it. When the signal clears the function deactivates. If the function is required to activate when the high signal goes low and deactivates when there is a permanent high signal applied then the corresponding input should be inverted in the settings.

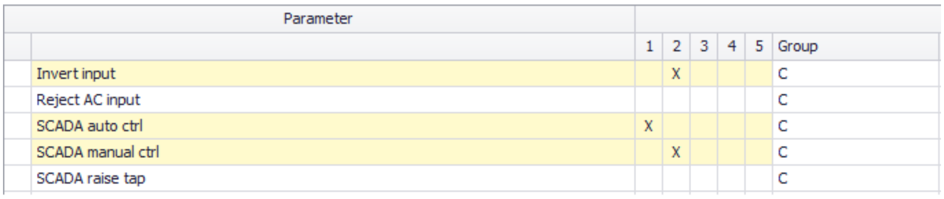
Edge triggered inputs change their state when a positive edge is detected; i.e. a change of state of the input signal from low (normally zero) to high. If a negative edge is required to operate the function then the corresponding individual input can be inverted in the setting. Although this type of inputs only requires a pulse signal having a permanent signal present does not change the expected behaviour.

3.8.1.2 Edge triggered input example

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

An example of an edge triggered function/input is changing the mode of operation of the relay from 'SCADA auto' to 'SCADA manual' and vice versa. Assuming we have assigned input 1 to change the mode of operation to 'Auto' using a positive edge and input 2 to change the mode of operation to 'Manual' using a negative edge, the settings are configured as shown in Figure 7.

Figure 7 Edge triggered inputs



Parameter					
	1	2	3	4	5	Group
Invert input		X				C
Reject AC input						C
SCADA auto ctrl	X					C
SCADA manual ctrl		X				C
SCADA raise tap						C

Some functions are naturally edge triggered such as the 'SCADA raise tap' and the 'SCADA lower tap' functions. For instance, if a permanent high signal is applied to the raise input, only one tap raise operation will be initiated.

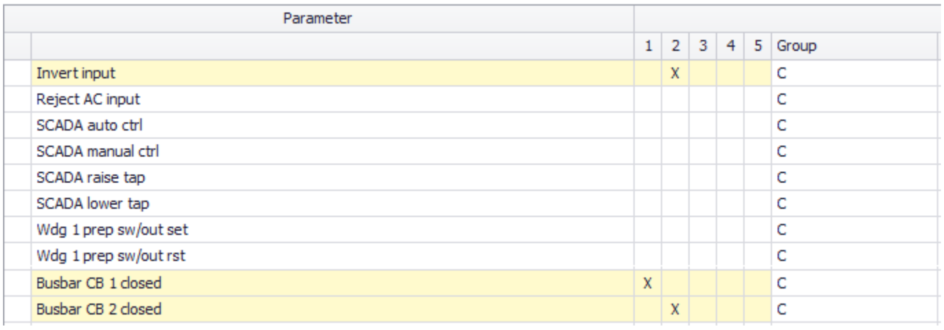
3.8.1.3 Level triggered input example

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

An example of level triggered function/input is the CB statuses function. The associated CB status input function is called 'Busbar CB x closed'; where x represents the CB number. This function requires a permanent signal applied to the back of the relay to indicate the CB is closed. If the signal indicates the CB is open then the corresponding individual input should be inverted.

Assuming we are measuring the status of 2 CB signals, where CB 1 provides a high signal when it is closed and is connected to input 1, and CB 2 provides a high signal when it is open and is connected to input 2, the settings are configured as shown in Figure 8.

Figure 8 Level triggered inputs



Parameter						
	1	2	3	4	5	Group
Invert input		X				C
Reject AC input						C
SCADA auto ctrl						C
SCADA manual ctrl						C
SCADA raise tap						C
SCADA lower tap						C
Wdg 1 prep sw/out set						C
Wdg 1 prep sw/out rst						C
Busbar CB 1 closed	X					C
Busbar CB 2 closed		X				C

3.8.2 Binary Outputs

The settings range covered by the binary outputs menu provides a link from site to the SCADA system which enables information sharing between the substation and the control centre. Examples of binary output indications usually covered by EAVC relays are:

- Relay healthy/faulty;
- Relay in auto;
- Relay in manual;
- And voltage high/ low/out of band.

Binary outputs are usually freely assignable volt-free contacts (sometimes referred to as dry contacts) that can be:

- Normally open;
- Normally closed;
- Or changeovers.

The intention with binary outputs is that they change their normal state when the function they are assigned to evaluates to true.

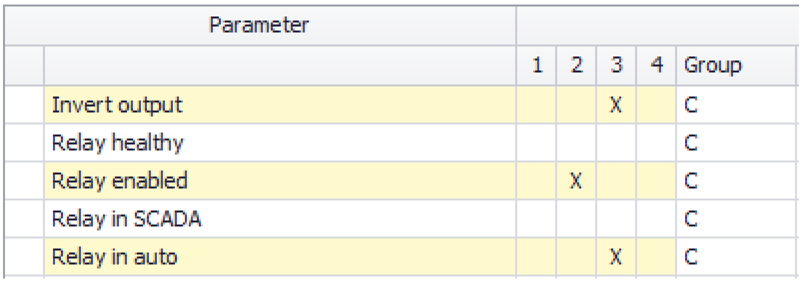
3.8.2.1 Software selection for a normally open/close output

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

As mentioned in the previous section, binary outputs can be normally open or normally closed and they change their states when the function assigned to them evaluates to true. The SuperTAPP SG EAVC relay offers this through a standard changeover and normally open contacts. If it is desired to change the state of the output contact when the function evaluates to false (which is the same as using a normally closed contact) then the corresponding individual output should be inverted in the settings.

For example, let’s assume that it is required to raise a signal when the SuperTAPP SG relay is enabled (assigned to output 2) and raise another signal when the SuperTAPP SG relay is in non-auto mode (i.e. manual mode, assigned to output 3) then the settings should be configured as shown in Figure 9.

Figure 9 Binary output settings



Parameter	1	2	3	4	Group
Invert output			X		C
Relay healthy					C
Relay enabled		X			C
Relay in SCADA					C
Relay in auto			X		C

3.9 Settings Groups

A setting group is a collection of settings operating together to achieve the required outcome under a set of specific circumstances. Most EAVC relays come with multiple number of settings groups to provide more flexibility to the operator.

Settings groups can address network operational requirements such as:

- Seasonal changes; summer settings, winter settings, etc.;
- High DG penetration periods against lower DG penetration periods;
- And transformer parallel groups.

3.9.1 Customisable settings

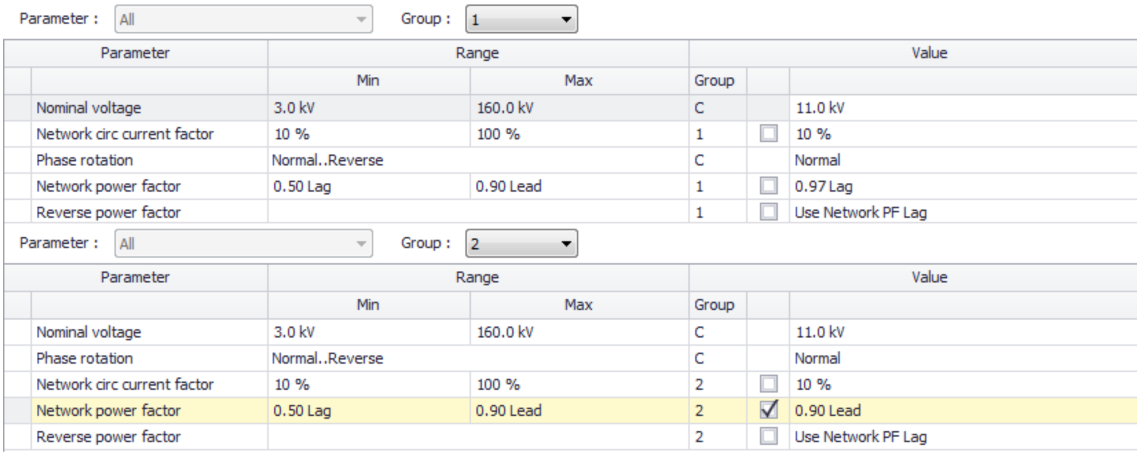
This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The SuperTAPP SG EAVC relay has 8 settings groups each of which can be configured independently. However settings can be classified as:

- Customisable settings; these settings can have different values in different groups.
- Common settings; which are settings that must have the same value across all settings groups.

For instance transformer impedance, system nominal voltage and winding rating are fixed settings across all setting groups. On the other hand, voltage target, source impedance and bandwidth are settings that can vary in each group. As shown in Figure 10 common settings have a 'C' next to them in the group column and no tick boxes available. Customisable settings, however, have the group number in the group column and a tick box next to it. If the tick box is checked, this means that the displayed value for this setting is a customised value for the indicated setting group.

Figure 10 Customisable and common settings



Parameter : All Group : 1

Parameter	Range		Value		
	Min	Max	Group		
Nominal voltage	3.0 kV	160.0 kV	C		11.0 kV
Network circ current factor	10 %	100 %	1	☐	10 %
Phase rotation	Normal..Reverse		C		Normal
Network power factor	0.50 Lag	0.90 Lead	1	☐	0.97 Lag
Reverse power factor			1	☐	Use Network PF Lag

Parameter : All Group : 2

Parameter	Range		Value		
	Min	Max	Group		
Nominal voltage	3.0 kV	160.0 kV	C		11.0 kV
Phase rotation	Normal..Reverse		C		Normal
Network circ current factor	10 %	100 %	2	☐	10 %
Network power factor	0.50 Lag	0.90 Lead	2	☑	0.90 Lead
Reverse power factor			2	☐	Use Network PF Lag

3.10 Busbar Grouping Using Settings Groups

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

Knowing the bus section CB statuses is essential for some of the transformer paralleling approaches as mentioned in section 2.2. The status of bus section CBs is essential for some of the transformer paralleling approaches offered by the SuperTAPP SG EAVC relay.

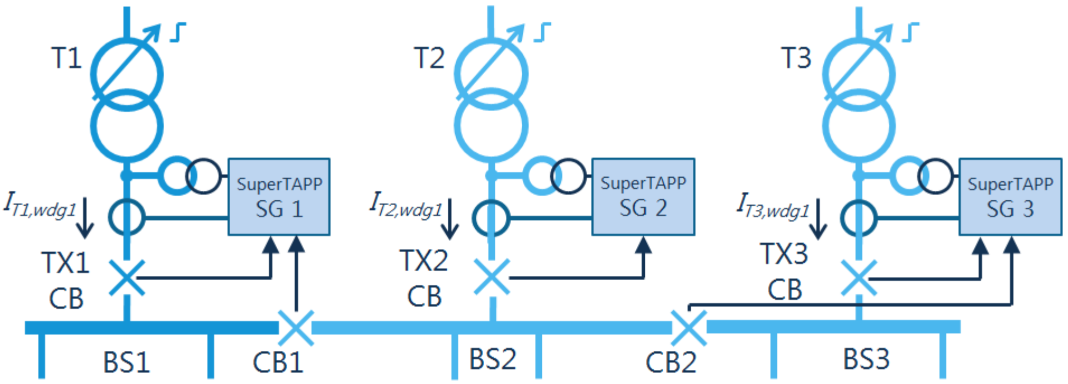
Settings groups offer one way of configuring the paralleling operation with the SuperTAPP SG relays. The procedure is best explained by an example.

Figure 11 shows a busbar with 3 transformers, 3 bus sections and 2 bus section CBs. 4 running arrangements can exist based on the CB statuses as shown in Table 3.

Table 3 Possible busbar running arrangements for the system in Figure 11

	T1 in parallel with	**T2 in parallel with**	**T3 in parallel with**
All CBs closed	T2 and T3	T1 and T3	T1 and T2
CB1 open	Non	T3	T2
CB2 open	T2	T1	Non
All CBs open	Non	Non	Non

Figure 11 Busbar configuration detection



The EAVC settings that address 'setting groups' paralleling are:

- The 'Winding bus section' setting in the 'Transformer' menu.
- The 'Busbar grouping controlled by' setting in the 'Busbar grouping' menu.
- The 'Bus section x is in busbar group' setting in the 'Busbar grouping' menu.

The winding bus section should reflect the correct section the transformer is connected to. Table 4 shows how this should be configured for each SuperTAPP SG relay.

Table 4 Winding bus section setting for the busbar grouping using settings groups example

	T1	T2	T3
Winding 1 bus section	1	2	3

In this example, the bus sections have been numbered in an ascending order from left to right. There is no restriction on the bus section number allocation as long as the method used is consistent. The 'Winding bus section' setting is not customisable per setting group and is applied for all setting groups by default.

Transformer parallel groups, in this section, utilise the settings groups for reflecting the busbar configuration arrangement. As shown in Figure 11 the status of CB1 is measured by the SuperTAPP SG relay that controls T1 while the status of CB2 is measured by the SuperTAPP SG relay that controls T3. A signal from each CB should change the setting group for T1 and/or T3 when the busbar configuration changes. Table 5 shows how each of the three SuperTAPP SG relays should be set up to address the busbar configuration changes.

Table 5 Busbar group settings example

	SuperTAPP SG1		SuperTAPP SG 2	SuperTAPP SG 3	
	Setting group 1	Setting group 2	Setting group 1	Setting group 1	Setting group 2
Bus section 1 in busbar group	A	B			
Bus section 2 in busbar group			A		
Bus section 3 in busbar group				A	C

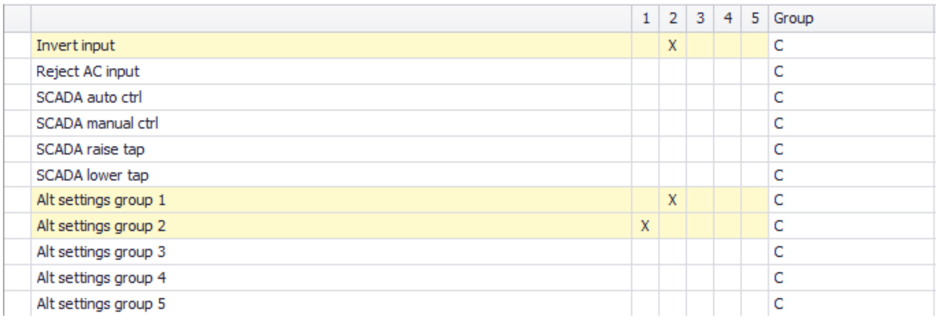
The last step to complete the busbar grouping configuration is to set up the correct inputs on each relay for switching it to the correct settings group. The signals in this case should be taken from the corresponding CB; i.e. a signal from CB1 to SuperTAPP SG1 and a signal from CB2 to SuperTAPP SG3.

The setting group change is required when a bus section CB opens; hence a signal needs to come through the auxiliary switch of the CB when it opens. A normally closed contact, which sometimes referred to as a 'B' switch contact, should be used to rout this signal to the back of the SuperTAPP SG relay.

It should be noted that a group setting change requires an 'Edge' input rather than a level input. For this reason, another edge is required to switch the relay back into the normal settings group (group 1 in this case). This can be done in two ways:

- Wiring a signal through a normally open contact, referred to as an 'A' switch, from the CB to the back of the relay;
- Or duplicating the signal coming from the normally closed contact on the back of the relay and invert the input that switches the relay back to the normal settings group through the settings. This scenario is shown in Figure 12.

Figure 12 Setting group switching setting in the inputs matrix



	1	2	3	4	5	Group
Invert input		X				C
Reject AC input						C
SCADA auto ctrl						C
SCADA manual ctrl						C
SCADA raise tap						C
SCADA lower tap						C
Alt settings group 1		X				C
Alt settings group 2	X					C
Alt settings group 3						C
Alt settings group 4						C
Alt settings group 5						C

The above example, including the use of the different types of CB auxiliary contacts, demonstrates one of the ways to achieve the paralleling objective. Different correct ways can also be used.

4 Advanced AVC Settings

This section looks into the EAVC settings required for advanced voltage control applications; such as DG connections, system interconnectors, excluded loads and others. The settings that will be addressed in this section are:

- Fast tap settings.
- Generator Bias Settings.
- Reverse LDC settings.
- Reverse power factor.
- Network circulating factor and substation paralleling.
- Source impedance.
- Bus section connection settings.
- Reverse current limit settings.
- Load Ratio Settings.
- CT function settings.
- Tapchanger scheme settings.
- Busbar grouping using CB statuses.

4.1 Fast Tap

When the fast tap functionality is used, the initial tap time, described in section 3.1.4, is bypassed and the fast tap time is used instead.

When enabled, the function will activate if the measured voltage is higher/lower than the 'bandwidth limits' by the value set in the 'fast tap threshold' setting. In this case, the initial tap timer will be overridden by the fast tap time delay.

The fast tap function is used for fast recovery of large voltage deviations that can be caused by many reasons such as:

- Very high voltages caused by load switching or load disconnection.
- Very low voltages caused by generation loss, DG disconnection or a sudden drop in a DG output due to environmental factors.

4.1.1 Fast Tap Setting

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The SuperTAPP SG relay offers 3 options for this setting:

- Off;
- Down;
- And 'up and down'.

The differences between these setting options:

- When set to off the fast tap function is disabled.
- When set to down the function will only activates for high voltage situations.
- When set to up/down the function will activate for both high and low voltage situations.

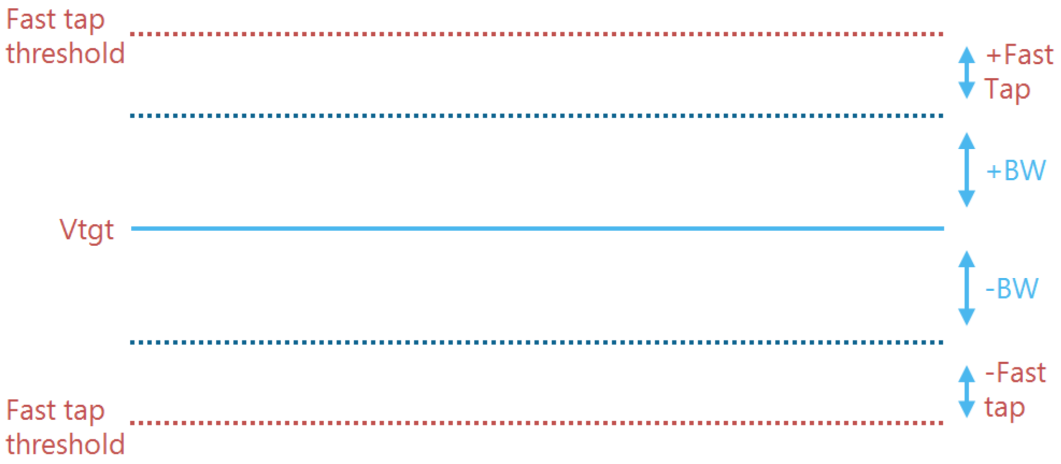
It is recommended that this setting is at least set to down to protect against high voltage situations; which can cause damage to customer equipment. If the system has a high level of DG penetration then it is recommended that this setting is set to 'up and down'.

4.1.2 Fast Tap Threshold

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The fast tap threshold is the level by which the measured voltage should deviate away from the bandwidth limits for the function to activate. This is shown in Figure 13.

Figure 13 Fast tap threshold



4.1.3 Fast Tap Time Delay

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The value of this setting replaces the initial tap time delay when the fast tap function activates. The minimum value for this setting is 3 seconds. The reason behind having a delay at all and not tap instantaneously is to avoid correcting the voltage for changes caused by transient system conditions.

4.2 Source Impedance

Network running arrangements can vary depending on network needs. For security of supply reasons, sometimes parallel transformers are run uncoupled at the HV side; this is to allow each of the transformer to be fed from a different source.

The concept of circulating current is explained in section 2.2. For the transformers in Figure 2 the circulating current is calculated as:

Equation 3

$$I_{SC}(A) \cong \frac{Number\ of\ taps\ apart \times tap\ step\ size(\%)}{X_{T1}(\%) + X_{T2}(\%)} \times I_{Base}$$

The above equation assumes that the parallel transformers are identical.

Figure 14 shows two transformers coupled at the LV side but not coupled at the HV side. Circulating currents can still exist between these two transformers. Assuming the transformers are identical and not operating on the same tap position, then the circulating current is calculated as:

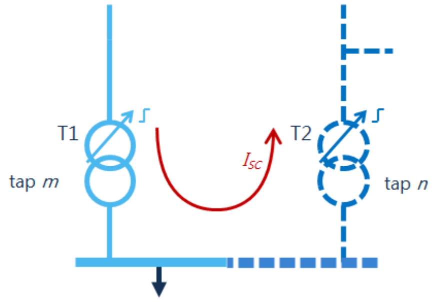
Equation 4

$$I_{SC}(A) \cong \frac{Number\ of\ taps\ apart \times tap\ step\ size(\%)}{X_{T1}(\%) + X_{T2}(\%) + X_{Source}(\%)} \times I_{Base}$$

As mentioned in earlier sections, and as shown in Equation 4, the circulating current loop impedance has got a big influence on the level of circulating current flowing between parallel transformers. The circulating current will have to circulate through the HV network in this case and the network impedance will form part of the loop impedance.

The negative effect of this network running arrangement is that the impedance of the system decreases the resultant circulating current measured by the EAVC relay which in turn reduces the coupling between the parallel transformers. Another issue is the losses caused by the reactive current circulating through the transformers and the network.

Figure 14 Parallel transformers uncoupled at the HV side



To overcome the sensitivity issue, the source impedance should be measured and added to the EAVC settings. Some EAVC relays, such as the SuperTAPP SG, have provisions for the source impedance and hence have independent settings for it.

For two transformers operating in parallel but not coupled at the HV side, the source impedance can be calculated using the following procedure:

1. Start this procedure with the transformer in parallel operating with minimum circulating current flowing between them, on the same tap position for identical transformers, and record these initial positions.
2. Tap the first transformer (T1) up and record the measured change in circulating current.
3. Tap the second transformer (T2) down and record the measured change in circulating current.
4. Tap the first transformer (T1) up, again, taking the transformers to 3 taps apart and record the measured change in circulating current.
5. Tap the second transformer (T2) down, again, taking the transformers to 4 taps apart and record the measured change in circulating current.
6. Return the transformers to the initial positions.
7. Repeat steps 1 through 5; tapping the second transformer (T2) up and the first transformer (T1) down.
8. Calculate the average total impedance using:

Equation 5

$$X_{Total} = \frac{Number\ of\ taps\ apart\ \times tap\ step\ size}{Measured\ chaning\ in\ circualting\ current}$$

9. Subtract the transformer impedances (X_{T1} and X_{T2}) from the calculated average total impedance.

After calculating the source impedance modify the EAVC settings using the calculated value. Make sure that the calculated source impedance is referred to the same impedance base value.

4.3 Advanced Voltage Target Adjustments

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The SuperTAPP SG relay offers two independent types of voltage target adjustments:

- Voltage offsets A;
- And voltage offsets B.

Each type has four independent voltage offset instances.

Table 6 Voltage offsets A and B comparison

	Voltage offsets A	Voltage offsets B
Activation process	▲ A manual SCADA command sent to a relay(s) via a communication link; ▲ Or a level detected hardwired input	▲ A manual SCADA command sent to a relay(s) via a communication link; ▲ Or an edge detected hardwired input
CAN bus sharing	Shared between relays in the same busbar group	Shared between all relays on the same CAN bus
Deactivation process	▲ Manually deactivated with a SCADA command via a communication link; ▲ Or by removing all applied level inputs used for the activation	▲ Manually deactivated with a SACADA command via a communication; ▲ Manually deactivated via an edge detected input ▲ Automatically deactivated when the associated timer deactivates
Priority and interaction between instances	If more than one instant are activated at the same time, then the priority is for the highest numbered instance; i.e. *offset A4 has a higher priority than A3 which has a higher priority than A2 which has a higher priority than A1*	The latest activated instance always has the highest priority; and when activated the reset timer is reinitialised

4.4 Tapchanger Scheme

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

There are two options for this setting:

- Basic;
- And step-by-step

If this setting is set to basic then the behaviour of the tapchanger monitoring function remains unmodified. However, if this setting is set to step-by-step then the behaviour is modified.

When selected to step-by-step the SuperTAPP SG relay blocks tap raise and lower commands, by activating the blocking contacts, as long as the tapchanger motor is running.

4.5 Busbar Grouping Using CB Statuses

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

Section Busbar Grouping Using Settings Groups3.10 described how busbar grouping can be achieved by switching settings groups. This approach is very useful for standard busbar configurations. However, if the busbar is more complex then the settings group approach can become harder to use. In this case, it is recommended to configure the busbar grouping using CB statuses instead.

The 'Busbar grouping controlled by' setting should be set in this case to 'CB statuses' on all SuperTAPP SG relays working together. This setting and the associated CB status settings are common for all settings groups.

Figure 15 Busbar grouping using CB statuses

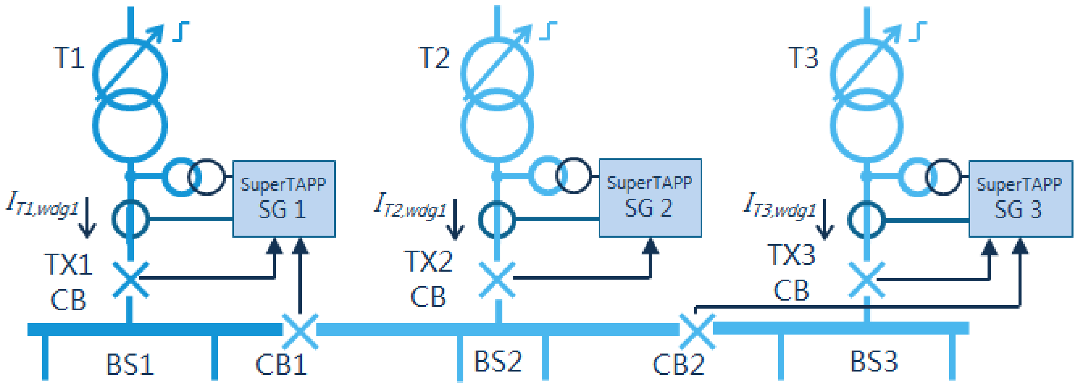


Figure 15 shows a busbar with:

- Two bus section CBs;
- Three bus sections;
- And three transformers.

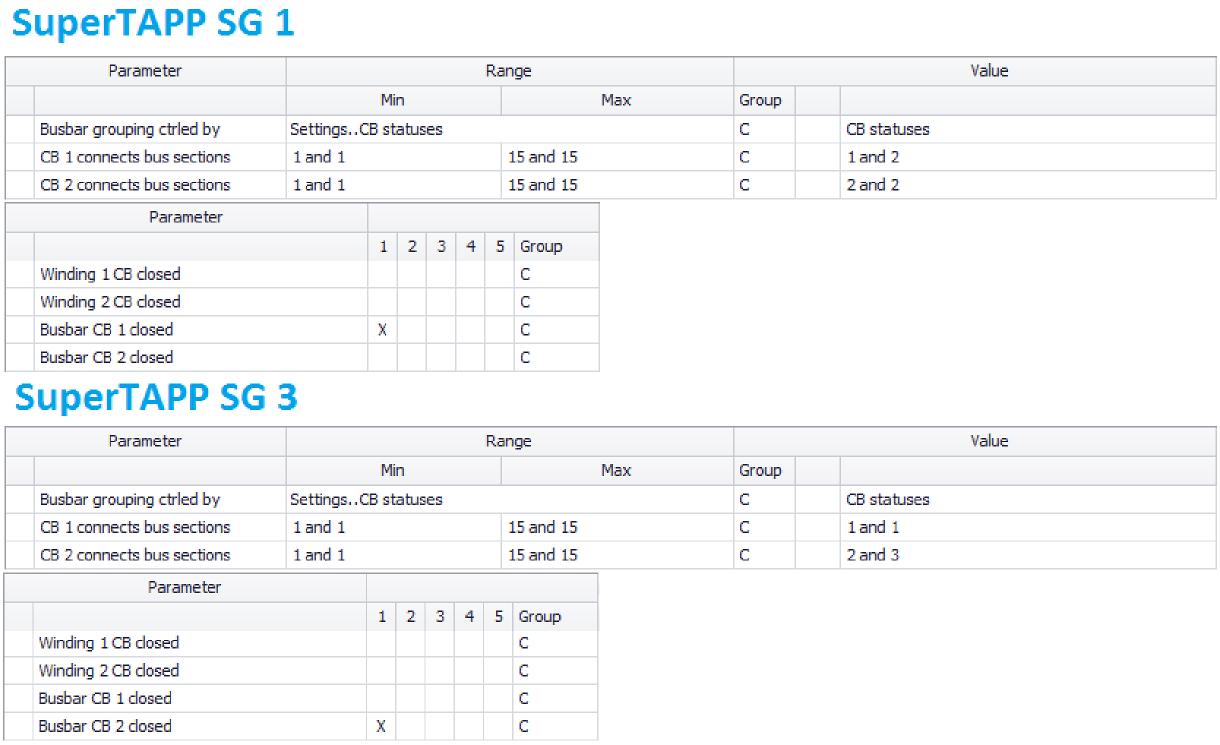
To configure the busbar grouping settings for the example in Figure 15 the following should be done:

- Draw a single line diagram (SLD) of the busbar arrangement.
- Assign numbers to each of the bus section CBs; CB1, CB2.
- Assign numbers to each of the bus sections; bus section 1, bus section 2, bus section 3.
- Configure the rest of the settings as shown in Table 7 and Figure 16.

Table 7 CB statuses busbar grouping settings

	SuperTAPP SG 1	SuperTAPP SG 2	SuperTAPP SG 3
CB 1 connects bus sections	1 and 2		
CB 1 connects bus sections			2 and 3

Figure 16 CB statuses busbar grouping settings



SuperTAPP SG 1

	Parameter	Range		Value		
		Min	Max	Group		
	Busbar grouping ctrled by	Settings..CB statuses		C		CB statuses
	CB 1 connects bus sections	1 and 1	15 and 15	C		1 and 2
	CB 2 connects bus sections	1 and 1	15 and 15	C		2 and 2

	Parameter					
		1	2	3	4	5	Group
	Winding 1 CB closed						C
	Winding 2 CB closed						C
	Busbar CB 1 closed	X					C
	Busbar CB 2 closed						C

SuperTAPP SG 3

	Parameter	Range		Value		
		Min	Max	Group		
	Busbar grouping ctrled by	Settings..CB statuses		C		CB statuses
	CB 1 connects bus sections	1 and 1	15 and 15	C		1 and 1
	CB 2 connects bus sections	1 and 1	15 and 15	C		2 and 3

	Parameter						
		1	2	3	4	5	Group
	Winding 1 CB closed						C
	Winding 2 CB closed						C
	Busbar CB 1 closed						C
	Busbar CB 2 closed	X					C

4.6 Generator Bias

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The generator bias function is designed to address such situations where the DG contribution introduces a significant rise in the voltage at the PCC. In these cases, it is desired to drop the busbar voltage of the substation where the DG is connected to; via direct or indirect connection.

In the same manner as with the LDC application the generator bias modifies the voltage target with a negative voltage bias to drop down the busbar voltage in proportion to the total generation, measured and estimated.

The generator bias setting is in per-cent of the nominal system voltage and should be set up as follows:

1. Calculate the maximum voltage rise at the PCC using a load flow software with updated figures for generators and loads. The worst-case scenario should be considered; hence different loading conditions against different generation conditions should be examined.
2. Use the value calculated in the previous step to set up the generator bias setting with.

The SuperTAPP SG relay calculates the generation contribution as:

- Directly measured contribution from independent firm generator connections to the substation busbar.
- Estimated calculated contribution of generators indirectly connected to the substation via downstream connections.

The applied generator bias level is then calculated by the SuperTAPP SG relay as shown below:

Equation 6

$$\boldsymbol{Applied\ Genbias}\ (\%) = \frac{\boldsymbol{Total\ generation}}{\boldsymbol{Generator\ rating}} \times \boldsymbol{GenBias\ setting}\ (\%)$$

$$\boldsymbol{where\ Total\ generation = measured\ generation + calculated\ generation}$$

The generator rating setting is discussed in sections 4.10.3 and 4.10.4.

4.7 Reverse LDC

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

As the name suggests, this setting reduces the busbar voltage in proportion to the reverse current flowing through the transformer/substation. This function is used to address busbar voltage rises caused by reverse power flows through transformers.

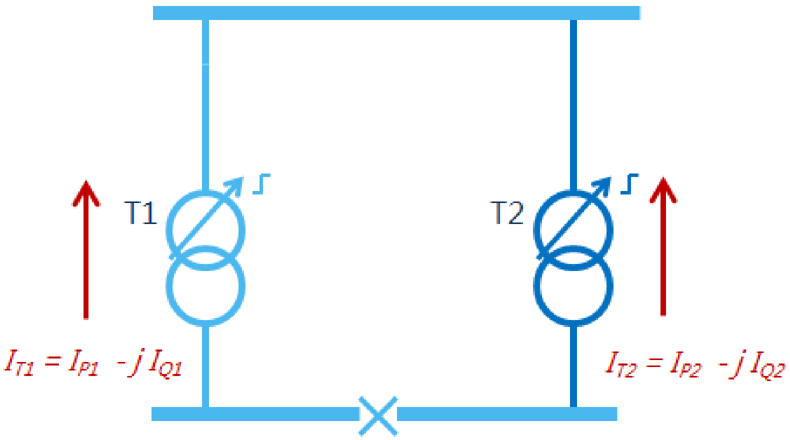
In forward power flow situations, a voltage drop across the transformer impedance results in the LV voltage becoming lower than the HV voltage; assuming the transformers in consideration are operating on the nominal tap position. When the power flow reverses, the voltage drop across the transformers also reverses resulting in the LV voltage becoming higher than the HV voltage; assuming that the transformers are operating on the nominal tap position.

The applied reverse LDC is calculated by the SuperTAPP SG relay as:

Equation 7

$$Applied\ \boldsymbol{Rev}LDC\ (\%) = \frac{\boldsymbol{Max\ reverse\ power\ level}}{\boldsymbol{Rev}LDC\ rating} * \boldsymbol{Rev}LDCsetting\ (\%)$$

Figure 17 Reverse power flow



4.7.1 Reverse LDC Level

This setting is the counterpart of the LDC level and is calculated using:

- The maximum assumed reverse power flow;
- And the transformer impedance(s).

The calculated maximum voltage rise using the above mentioned parameters in percent is then used to set up the reverse LDC level.

This step can be skipped and the forward LDC level can be used here as a rough estimate.

4.7.2 Reverse LDC Rating

This setting should be based on the maximum reverse power level for the system in consideration. However, this step can also be skipped and the forward LDC rating level can be used as a rough estimate.

4.7.3 Reverse Power Factor

As with the forward LDC, the SuperTAPP SG applies the reverse LDC based on the reverse power factor set up within the settings. If the reverse power flow power factor does not match the one set up within the settings then the applied reverse LDC level will be lower.

4.8 Reverse Current Limit

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

This function blocks the operation of the voltage control if the reverse load flowing through the transformer exceeds the level set up. This function can serve to protect tapchangers with reverse power flow limitations.

For example, if a tapchanger is capable of handling 60% reverse power flow, where the 60% is in reference to the transformer rating, then this setting should be set up to 60%. In this case if the reverse current flowing through the transformer exceeds 60% then no raise or lower commands are permitted to protect the tapchanger.

4.9 Load Ratio

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

The load ratio (LR) is a function used to estimate downstream generation and the load masked by this generation. The load ratio is defined to be the ratio of the load flowing through non-measured feeders to the load flowing through measured feeders.

A 'measured feeder' is a feeder with the current flowing through it measured by the SuperTAPP SG relay. The load ratio is calculated as:

Equation 8

$$LR\ (\%) = \frac{Load\ on\ measured\ feeders\ (min/max/average)}{\sum Load\ on\ 'non-measured'\ feeders\ (min/max/average)}$$

It should be noted that loads in the above equation should be the true feeder loads without any generation contribution. The load ratio function is best explained by an example.

Assume that the maximum load of each of the feeders shown in Figure 18 is as shown in Table 8.

Table 8 Feeder loads for the load ratio example

Feeder number	Feeder load
Feeder 1 (most left)	200
Feeder 2	180
Feeder 3	260
Feeder 4	300
Feeder 5	160
Feeder 6 (measured feeder, most right)	100

In the example shown in Figure 18, and using the data from Table 8, the load ratio is:

$$LR = \frac{100(A)}{1100(A)} \approx 9.1\%$$

The apparent summated load served by the substation, i.e. non-measured load, is equal to the transformer load in addition to the measured generation:

$$Apparent\ load = 200A + 200A + 150A = 550A$$

The approximated load masked by the downstream generation is:

$$Approximated\ load = LR * 'non-measured\ load' \rightarrow 9.1\% * 550 = 50A$$

Hence, the true group load is:

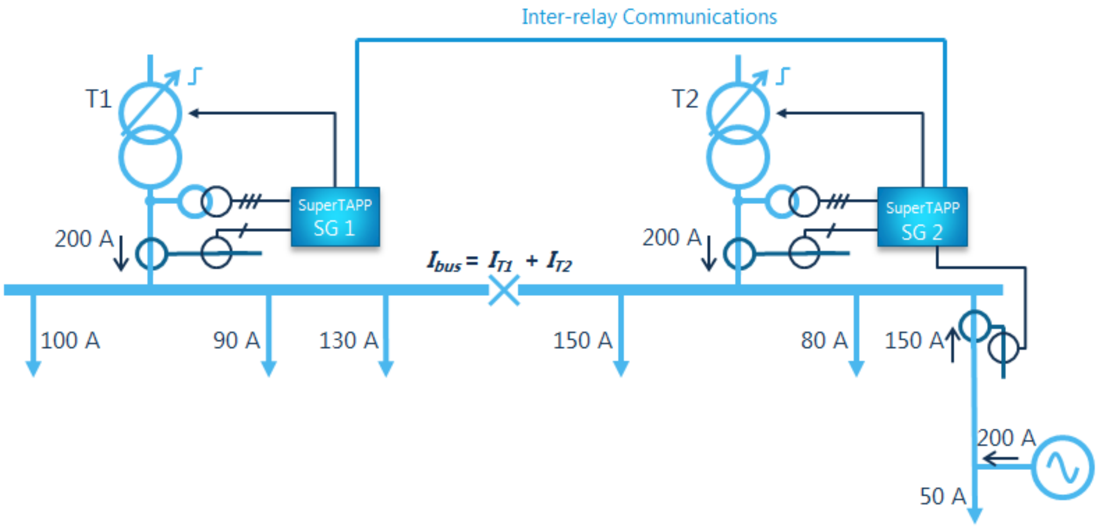
$$True\ group\ load = 'non-measured\ load' + approximated\ load = 600A$$

The approximated generation contribution is then calculated as:

$$Generation\ contribution = approximated\ feeder\ load - measured\ feeder\ current$$

$$\rightarrow Generation\ contribution = 50 - (-150) = 200A$$

Figure 18 Load ratio example



The true group load and the approximated generation contribution are then used for the relevant LDC and GenBias calculations.

4.10 CT Functions

This section is intended for describing the operation of the SuperTAPP SG EAVC relay.

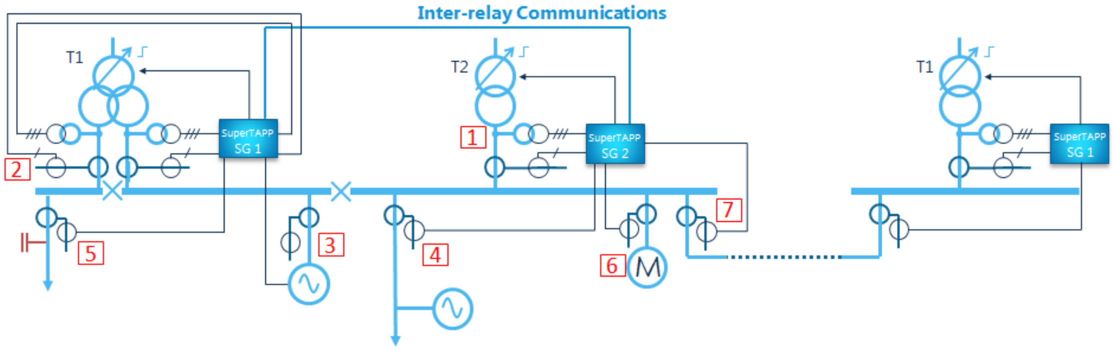
The SuperTAPP SG relay offers a lot of AVC flexibility by utilising feeder current measurements. The relay offers various functions that allow the user to optimise the voltage control operation to best fit the requirements.

The relay is natively capable of:

- Accommodating AVC for double-secondary winding transformers;
- Taking DG contribution into the AVC account;
- Dealing with AVC troublesome loads and network devices (industrial loads, capacitor banks, etc.);
- Operating in parallel with other incompatible AVC relays.

This section describes how the SuperTAPP SG relay utilises the different measured currents to optimise the voltage control operation. Figure 19 shows the different CT functions available with the SuperTAPP SG EAVC relay.

Figure 19 SuperTAPP SG CT functions



4.10.1 Transformer Winding 1 CT Function

This function is used for single secondary winding transformer current measurement applications.

In this case the measured current will be used for the essential voltage control needs; such as:

- Circulating current calculations and transformer paralleling.
- LDC and reverse LDC applications.

Table 9 Transformer winding 1 CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'

4.10.2 Transformer Winding 2 CT Function

For double secondary winding transformers two winding currents exist; winding 1's current and winding 2's current. Both currents should be measured by the SuperTAPP SG relay for the essential voltage control needs.

The relay will autonomously use these two measured currents together for circulating current, LDC and other purposes.

The settings for 'Transformer winding 2 CT function' are identical to the ones shown in Table 9 and should be set up in the same way.

4.10.3 Generator CT Function

This setting is used for current measurements of generators directly connected to the substation busbar through dedicated feeders without any load attached to them. This is highlighted as '3' in Figure 19.

Table 10 Generator CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the generator is connected to
Function rating	This setting reflects the generator rating in amps on the system nominal voltage

4.10.4 Generator Feeder CT Function

Distributed generators are not always directly connected to substation busbars; however, they are sometimes teed into a load feeder. The generator feeder CT function should be used for feeders were both load and generation exist on them. This is highlighted as '4' in Figure 19.

Table 11 Generator feeder CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the generator is connected to
Function rating	This setting reflects the generator rating in amps on the system nominal voltage
Load ratio	As explained in section 4.9, the individual load ratio of each feeder is calculated as: $LR = \frac{Feeder\ load\ (excluding\ generation)}{\sum All\ non - measured\ feeder\ loads}$

4.10.5 Excluded Load CT Function

Power factor deviations can cause problems for voltage control systems as described in section 2.2. This setting is dedicated for loads that can change the power factor without having a major contribution to the real power flow; such as capacitor banks which is highlighted as '5' in Figure 19.

Such loads, capacitor banks for instance, can have effects as shown in Figure 20; where the capacitor bank current can take the power factor of the current seen by the AVC relay to leading power factors which can be troublesome for the voltage control operation.

The SuperTAPP SG offers an easy way to deal with such situations. In this case the capacitor bank current is measured by the SuperTAPP SG and is then excluded from the voltage control equation as shown in Figure 21.

Table 12 Excluded load CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the generation is connected to

Figure 20 Capacitor bank effect on voltage control

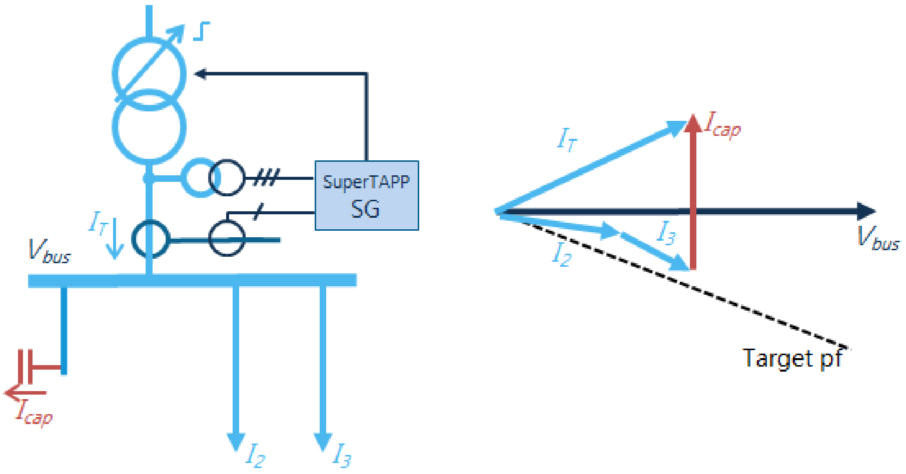
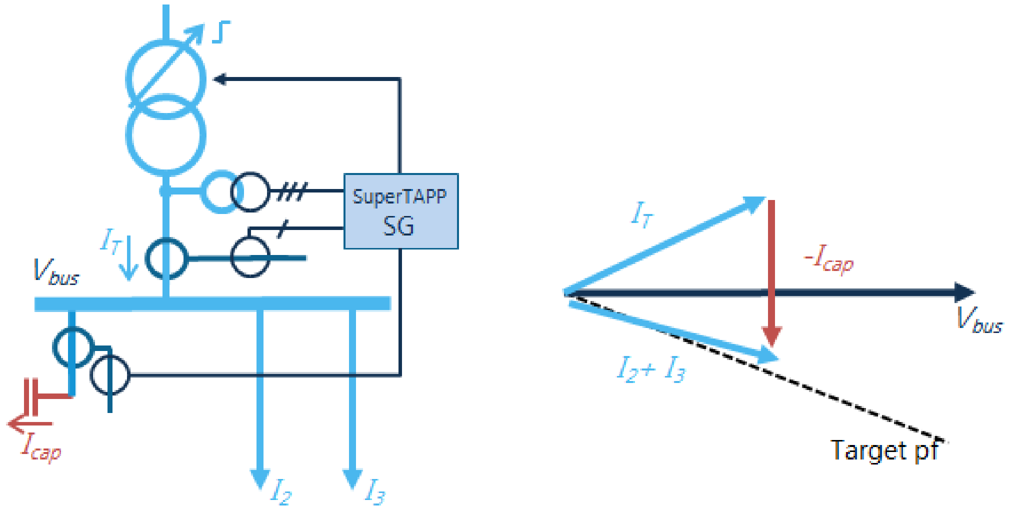


Figure 21 Excluded load CT function



4.10.6 Corrected Load CT Function

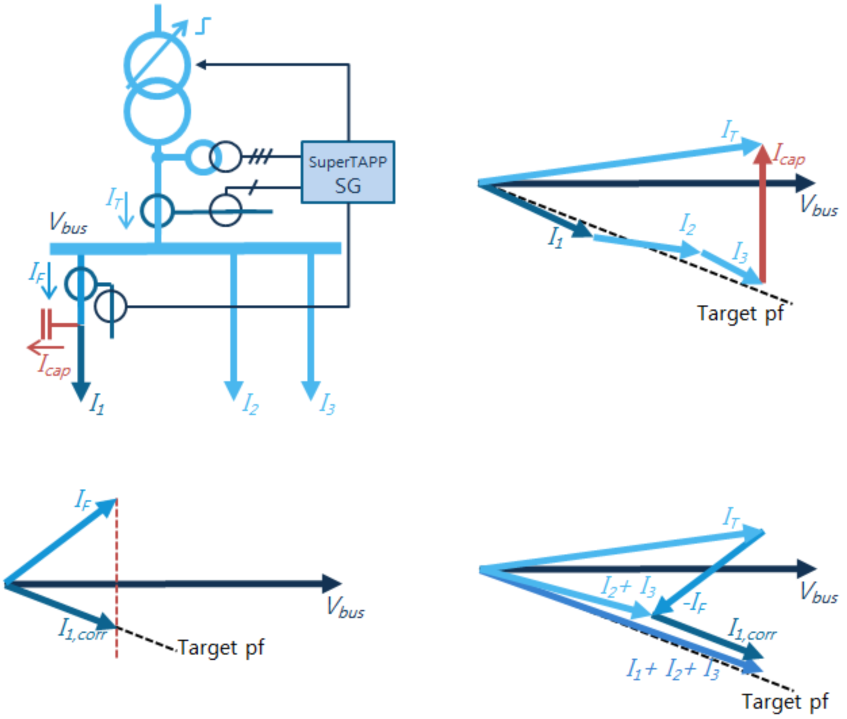
Power factor deviations can be problematic to voltage control systems as described in section 2.2. This CT function is used in situations where a poor power factor feeder current is required for the voltage control operation; e.g. for LDC application purposes. This is highlighted as '6' in Figure 19.

When this function is used, the measured feeder current is projected onto the target power factor line which corresponds to the network power factor setting.

Table 13 Corrected load CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the generation is connected to

Figure 22 Corrected load CT function



4.10.7 Interconnector CT Function

An interconnector is a long busbar/cable that connects two nodes of the system together; highlighted as '7' in Figure 19. If there is a difference in the voltage level between the interconnected nodes, then circulating reactive current can flow through the interconnector. This circulating current can cause losses and is sometimes undesired.

When this CT function is used the SuperTAPP SG relay minimises the site circulating current using the true circulating current method and controls the interconnector current power factor using the modified TAPP method. In this case, the SuperTAPP SG relays at each end of the interconnector will modify the corresponding busbar voltage to influence the reactive power flow through the interconnector to match the power factor value specified in the network power factor setting.

Table 14 Interconnector CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the generation is connected to

4.10.8 Extra Transformer CT Function

The extra transformer CT function is used for situations where an adjacent parallel transformer is not equipped with a compatible AVC relay for inter-relay communication. Paralleling in this case is not an easy thing to achieve.

Assuming two transformers operating in parallel; where T1 utilises a SuperTAPP SG relay and T2 utilises a different relay where the two relays cannot exchange information through a communication link. The LDC CT current of T2 can be routed through the SuperTAPP SG relay, and using the extra transformer CT function, the SuperTAPP SG can adjust its voltage target using the Enhanced TAPP method, described in section 2.2.5.

Table 15 Extra transformer CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to ‘Yes’, otherwise it should be set to ‘No’
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the generation is connected to
Function rating	This setting reflects the extra transformer rating in amps on the system nominal voltage
Function coefficient	This setting reflect the impedance of the extra transformer on the extra transformer rating

4.10.9 Monitor CT Function

The monitor CT function is used when a feeder current is required to be monitored but not required to address any voltage control related issues. An indication of the monitored current can then be sent back to SCADA.

Table 16 Monitor CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the monitored feeder is connected to

4.10.10 Included for Load Ratio CT Function

The load ratio function is explained in detail in section 4.9.

When this function is used, the measured feeder current replaces the denominator in Equation 8. This function is used if a particular feeder has a significantly larger load compared to other feeders or if the trend of the load on a particular feeder represents the best fit curve of the total substation load.

Table 17 Included for load ratio CT function settings

Setting	Explanation
Number of interposer turns	Explained in section 3.4.2
Ratio	The primary and secondary rated currents of the generator CT; e.g. 1050A:1A
Phase	The phase of the physical CT connection to the relay
Reversed connection	If the hardwired connection has been mistakenly crossed then this can be set to 'Yes', otherwise it should be set to 'No'
Connected to bus section	Using the methodology explained in section 4.5, this setting should reflect the assigned number of the bus section the load ratio feeder is connected to