Automatic Voltage Regulator Function Block COLTC RET 54_

Application and Setting Guide

ABB

Contents:

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1. Scope

This document refers to the transformer terminal RET 54_ when the terminal is used as an automatic voltage regulator for power transformers with on-load tap-changer.

The operation mode of automatic and manual voltage control of the transformer function block (COLTC) is described. The settings required for the different operation principles are explained in application examples.

Single and parallel use of power transformers are described. The COLTC function block supports three different parallel operation principles, i.e. the Master/Follower principle (M/F), the Minimizing Circulating Current principle (MCC) and the Negative Reactance principle (NRP).

KEYWORDS: *RET 54_*, *COLTC*, *AVR*, *Voltage regulator*, *Tap changer*

2. Introduction

Automatic voltage regulators (AVR) are used to maintain a stable voltage on the load side of the power transformer under varying network load conditions.

The on-load tap-changer of a power transformer can be controlled with an AVR, which measures the voltage on the side of the power transformer where the voltage is to be controlled, normally the LV side.

Provided with the function block COLTC, the transformer terminal RET 54_ is able to control the tap changer of the power transformer. The function block COLTC can be used to control the tap changer of a single transformer or it can operate in parallel with AVRs of other transformers feeding the same busbar.

3. Operation principle

3.1. General

The COLTC function block is used to control the voltage on the load side of the power transformer. Based on the voltage (and current) measured, the function block determines whether the voltage needs to be increased or decreased. The voltage is regulated by Raise or Lower commands sent to the tap changer.

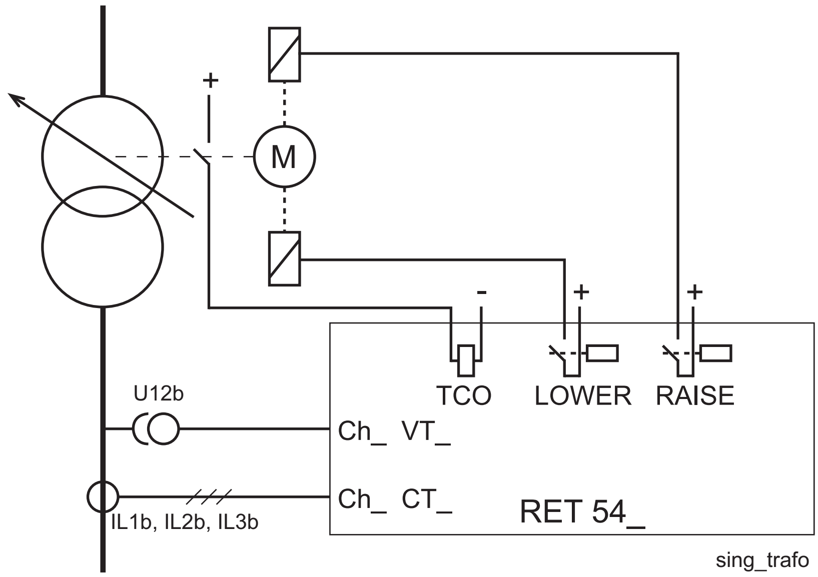

Fig. 3.1.-1 Basic connection diagram for the voltage regulator.

The basic principle for voltage regulation is that no regulation will take place as long as the voltage stays within the bandwidth setting. The measured voltage is always compared with the *Control voltage* (Up), which is calculated using equation (1). Once the measured voltage deviates from the bandwidth, the delay time T1 starts. When the set delay time elapses, a raise or lower control pulse is sent to the tap changer. Should, after one tap change, the measured voltage still be outside the bandwidth, the delay time T2 starts. T2 is normally shorter than T1 (see Fig. 3.1.-2).

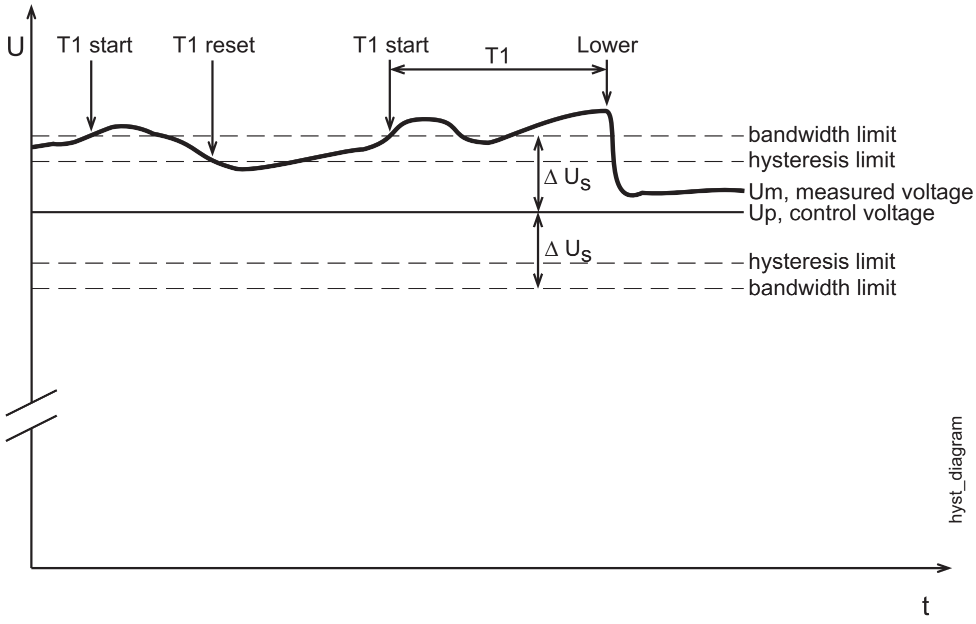

Fig. 3.1.-2 Principle of the voltage regulating function.

Under certain circumstances, the automatic voltage regulator needs to be enhanced with additional functions such as Line Drop Compensation (LDC) and Reduce Set Voltage (RSV). Also, various parallel operation modes are available to fit applications where two or more power transformers are connected to the same busbar at the same time. The parallel operation modes i.e. the Master/Follower (M/F), Minimizing Circulating Current (MCC) and Negative Reactance Principle (NRP) will be explained later in this document.

All these features mentioned affect the control voltage, i.e. the requested voltage calculated, towards which the COLTC function block regulates the measured voltage.

$$U_p = U_s + U_z + U_{ci} - U_{rsv} \tag{1}$$

where:

U_p	=	control voltage
U_s	=	reference voltage setting
U_z	=	line drop compensation term
U_{ci}	=	circulating current term
U_{rsv}	=	voltage reduction by the RSV function

3.2. Tap-changer position indication

The tap-changer position can be measured by the RET 54_ terminal. Besides tap position indication, an out-of-step function and alarms can be obtained by measuring the position of the tap changer.

Tap-changer position information can be brought to the RET 54_ terminal in three different ways: as a mA signal, a resistance value or a binary coded decimal value (BCD).

When tap-changer position information is connected to the RET 54_ terminal in the form of a mA signal or a resistance value, the signal is connected to the input of an optional RTD card for the RET 54_ terminal.

Fig. 3.2.-1 and Fig. 3.2.-2 show an example of how the mA signal and resistance value is connected to the RTD input, and how it is configured.

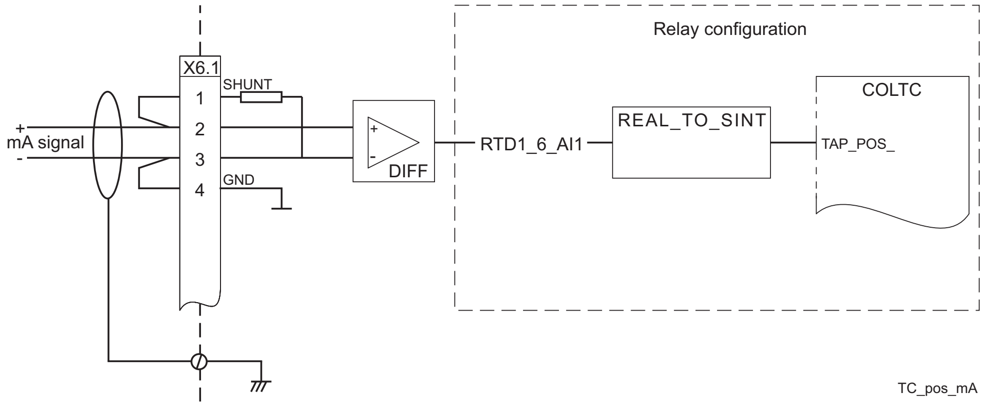

Fig. 3.2.-1 Tap-changer position information wired as a mA signal to RTD input 1.

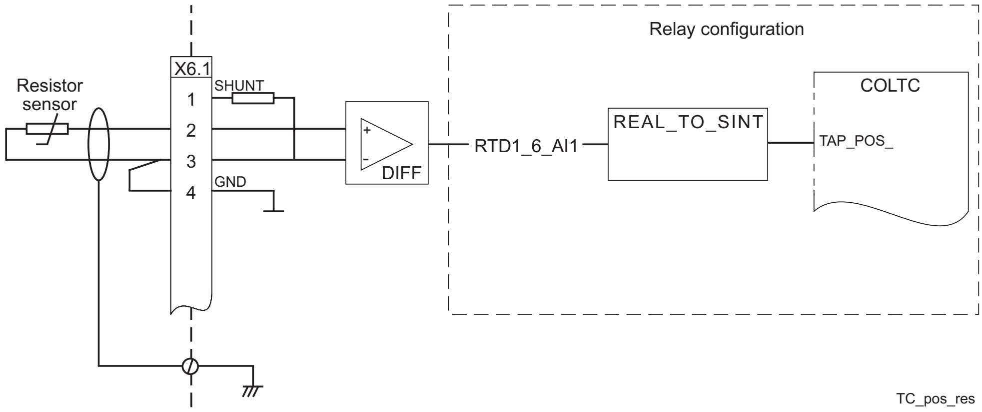

Fig. 3.2.-2 Tap-changer position information supplied as a resistance signal using a two-wire connection from the tap changer to the RTD input 1.

The mA or resistance signal also has to be calibrated to match the different tap-changer positions. The mA signal or resistance value can be easily calibrated with the Transducer Linearization Tool (TLT) of CAP 505. This tool allows the input signal to be accurately calibrated, also in the event of a non-linear signal.

The mA signal should be calibrated before the power transformer is put into service. For the calibration the Transducer Linearization Tool needs at least two positions, but with additional positions available, the calibration result will be more accurate, if the mA signal is not absolutely linear.

Before starting the TLT tool, set the following parameters in the CAP 505 Relay Setting Tool under `Configuration/RTD1/Input _` according to the tap position signal used.

- Input mode (current or resistance)
- Current range (if a mA signal is used)
- Resistance range (if a resistance signal is used)
- Linear curve = Disabled

When calibrating the tap-changer position *Input values* from the tap changer, the signal can be read from the relay setting tool under `Status/RTD1/Input`. The input values are first read for different tap positions, one at a time, and then entered into the TLT accordingly. The tool has a capacity of maximum 10 values. The linearization curve is uploaded to the relay with the Relay download tool. To activate the linearization curve, set the parameter *Linear curve* = Enabled.

Note! The settings will not take effect until they are stored and the relay is reset.

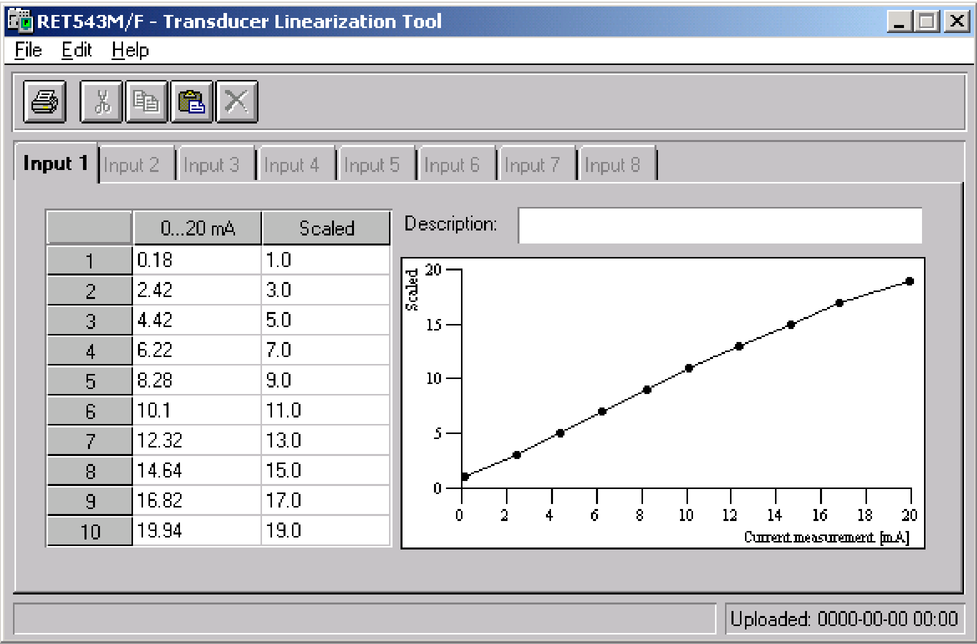

Fig. 3.2.-3 Calibration of mA signal from tap changer with steps from 1 to 19 using Transducer Linearization Tool.

If the tap changer uses a binary coded decimal signal (BCD) for tap-changer position indication, the BCD signals are connected to the dedicated binary inputs of the RET 54_ terminal. For this purpose a special function block, BCD2INT (BCD to integer) which converts the BCD signal into tap-position information is available.

Fig. 3.2.-4 shows a configuration example for tap positions from 1 to 19. If negative tap-changer positions are needed, a separate input is connected to the SIGN_BIT input of the configuration.

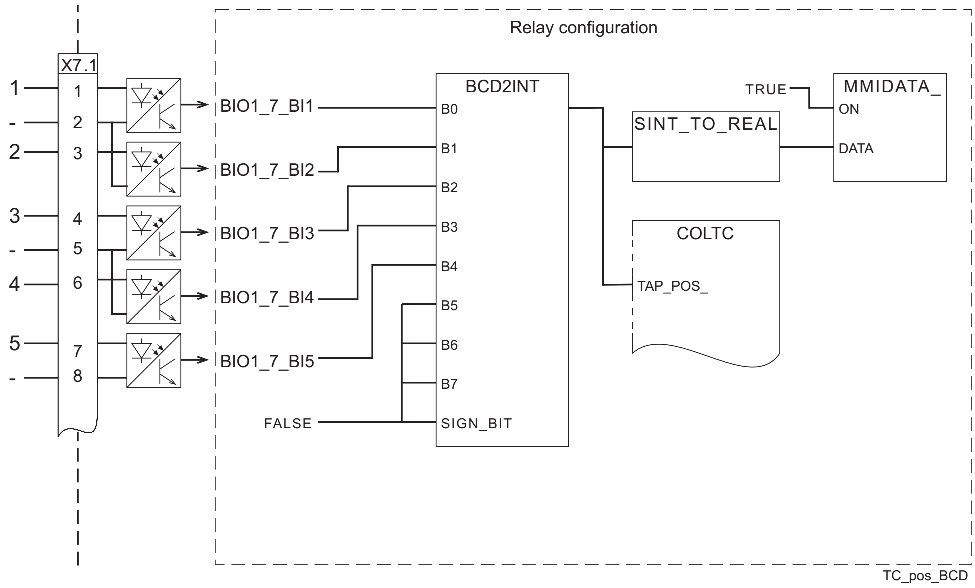

Fig. 3.2.-4 Connection and configuration when five BCD signals from the tap changer are connected to the binary inputs X7.1.

Table 3.2.-1 shows the tap positions corresponding with different combinations of BCD signals.

Table 3.2.-1 BCD2INT function block inputs and tap positions

Sign.	B7	B6	B5	B4	B3	B2	B1	B0	Pos.
Factor	80	40	20	10	8	4	2	1	
				...					
1	0	0	0	0	1	0	0	1	-9
1	0	0	0	0	1	0	0	0	-8
1	0	0	0	0	0	1	1	1	-7
1	0	0	0	0	0	1	1	0	-6
1	0	0	0	0	0	1	0	1	-5
1	0	0	0	0	0	1	0	0	-4
1	0	0	0	0	0	0	1	1	-3
1	0	0	0	0	0	0	1	0	-2
1	0	0	0	0	0	0	0	1	-1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	1
0	0	0	0	0	0	0	1	0	2
0	0	0	0	0	0	0	1	1	3
0	0	0	0	0	0	1	0	0	4
0	0	0	0	0	0	1	0	1	5
0	0	0	0	0	0	1	1	0	6
0	0	0	0	0	0	1	1	1	7
0	0	0	0	0	1	0	0	0	8
0	0	0	0	0	1	0	0	1	9
0	0	0	0	1	0	0	0	0	10
0	0	0	0	1	0	0	0	1	11
0	0	0	0	1	0	0	1	0	12

Table 3.2.-1 BCD2INT function block inputs and tap positions (Continued)

Sign.	B7	B6	B5	B4	B3	B2	B1	B0	Pos.
Factor	80	40	20	10	8	4	2	1	
0	0	0	0	1	0	0	1	1	13
0	0	0	0	1	0	1	0	0	14
0	0	0	0	1	0	1	0	1	15
0	0	0	0	1	0	1	1	0	16
0	0	0	0	1	0	1	1	1	17
0	0	0	0	1	1	0	0	0	18
0	0	0	0	1	1	0	0	1	19
0	0	0	1	0	0	0	0	0	20
0	0	0	1	0	0	0	0	1	21
0	0	0	1	0	0	0	1	0	22
0	0	0	1	0	0	0	1	1	23
0	0	0	1	0	0	1	0	0	24
0	0	0	1	0	0	1	0	1	25
0	0	0	1	0	0	1	1	0	26
0	0	0	1	0	0	1	1	1	27
0	0	0	1	0	1	0	0	0	28
0	0	0	1	0	1	0	0	1	29
0	0	0	1	1	0	0	0	0	30
0	0	0	1	1	0	0	0	1	31
0	0	0	1	1	0	0	1	0	32
0	0	0	1	1	0	0	1	1	33
0	0	0	1	1	0	1	0	0	34
0	0	0	1	1	0	1	0	1	35
0	0	0	1	1	0	1	1	0	36
				...					...

Tap-changer operating (TCO) signal

If an operating signal is available when the tap changing process is active, it should be connected to the TCO input of the COLTC function block. Since the TCO signal is used only for alarm purposes, it will not affect the operation if left unconnected. If the TCO signal has been active for more than 15 seconds after a control pulse from RET 54_ has been deactivated, an alarm will be generated. An active TCO signal will not prevent new operation commands to the tap changer. If new operation commands must be prevented during the tap-changing process, the TCO signal is connected to the BLOCK input as well.

3.3. Line Drop Compensation (LDC)

When a long line is loaded, it is obvious that the voltage at the load end of the line is lower than the voltage at the transformer end. Because the impedance of a line consists of both a resistive and a reactive component, compensation must be considered for both components. The LDC function allows voltage drops caused by both the resistive and the reactive component to be effectively compensated.

In a network with lines of varying lengths the voltage of a shorter line with less voltage drop is not allowed to rise too high. In such a network, a compromise must be made when the line drop compensation parameters are calculated.

Because the voltage drop of a line increases with the load current, it is important to set a limit to the voltage compensation to prevent overvoltage for consumers located closer to the transformer. Fig. 3.3.-1 shows a voltage compensation curve at different load currents. In this example the maximum voltage compensation is 900 V, which is set using the *LDC limit* parameter. The total voltage compensation consists of both resistive and reactive voltage compensation. Reactive voltage compensation is relevant only when there is a reactive load.

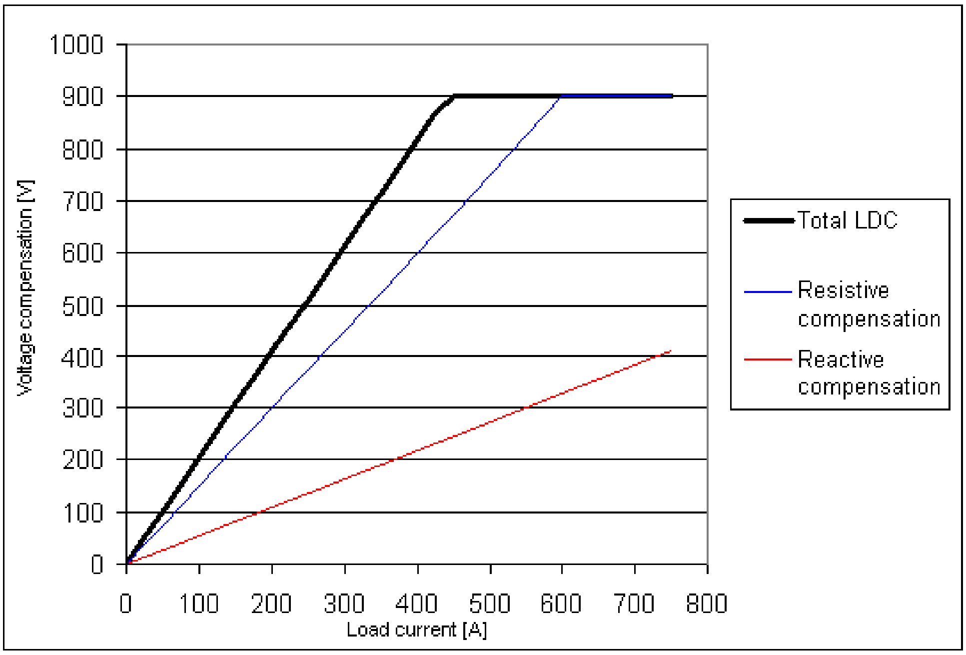

Fig. 3.3.-1 Voltage compensation at different load currents using the LDC function.

The calculation of the line drop compensation parameters U_r and U_x will be explained more in detail in section 4.4 and in the COLTC manual.

Note! It should be noted that if embedded generation is employed on the load side of the transformer, line drop compensation cannot be used.

3.4. Reduce Set Voltage (RSV)

The Reduce Set Voltage function is used to temporarily decrease the load in the network. By setting an integer to the RSV input of the COLTC function block, the control voltage can be lowered. The reduced voltage depends on the integer and the *RSV step* setting. If the *RSV step* is set to 2.00% Un and the RSV input to 1, the reference voltage will be decreased by 1 x 2.00%. When the RSV input is set to 2, the reference voltage will be decreased by 2 x 2.00%, etc.

It should be noted that the reduced power depends on the characteristic of the load when the voltage is decreased. A purely resistive load is decreased by about the square of the voltage, whereas inductive load is decreased less.

Fig. 3.4.-1 shows the decrease of the target voltage when the RSV function is used.

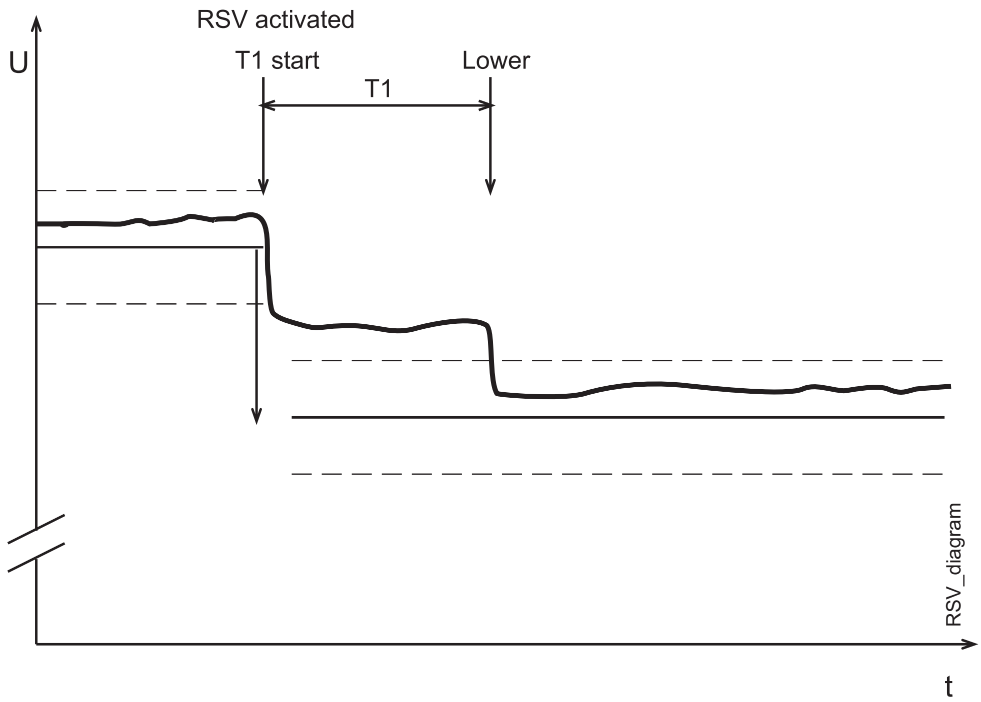

Fig. 3.4.-1 Voltage reduction using the RSV function.

Configuration example with the RSV function available in the COLTC function block manual.

4. Regulation of a single transformer

4.1. Purpose and connections

Basically, the voltage regulation of a single transformer requires only one phase-to-phase voltage from the transformer's LV side to be connected to the COLTC function block. The phase-to-phase voltage may be U_{12b}, U_{23b} or U_{31b}. Also, virtual voltage measurement U_{12bs} can be used if phase voltages are connected to the RET 54_ terminal. If line drop compensation is needed, at least one phase current is required from the LV side of the power transformer. By default the overcurrent blocking function measurement is made on the HV side. If the load current is measured only on the LV side, it will be used for overcurrent blocking instead.

4.2. Settings

Table 4.2.-1 and Table 4.2.-2 show the settings for the voltage regulation of a single transformer. A rule of thumb is that settings not used are set to 0, e.g. *Ur*, *Ux* and *RSV step*.

Table 4.2.-1 Settings found under Control/COLTC/Setting group1/

Parameter	**Setting range**	**Comment**
Reference volt. Us	0.000...2.000 x Un	Target voltage
Delay time 1 T1	1.0 ... 300.0 s	Delay time for first Raise/ Lower pulse
Delay time 2 T2	1.0 ... 300.0 s	Delay time for second Raise/ Lower pulse
Ur [%]	0.0 ... 25.0 % Un	Resistive line drop compensation
Ux [%]	0.0 ... 25.0 % Un	Reactive line drop compensation

Table 4.2.-2 Settings found under Control/COLTC/Control setting/

Parameter	**Setting range**	**Comment**
Operation mode	Autom. Single or Op. mode inputs	When Op. mode input is used the operation mode is selected via the AUTO_MAN input of the COLTC function block
Delay mode	Definite or inverse	Delay time characteristic
Output pulse	0.5 ... 10.0 s	Pulse length of Raise and Lower commands
Bandwidth DUs	0.60 ... 9.00 % Un	The recommended setting is the same as the tap-changer step voltage.
Overcurr. Limit	0.10 ... 5.00 x In	Setting for overcurrent blocking
Undervolt. Limit	0.1 ... 1.20 x Un	Setting for undervoltage blocking
Overvolt. Limit	0.80 ... 1.60 x Un	Setting for fast lower control
Min. volt. Tap	-36 ... 36	Tap position at lowest voltage
Max. volt. Tap	-36 ... 36	Tap position at highest voltage

Table 4.2.-2 Settings found under Control/COLTC/Control setting/

LDC limit	0.00 ... 2.00 x Un	Maximum permitted line drop compensation
LDC selection	ON/OFF	Enable or disable LDC function
RSV step	0.00 ... 9.00 % Un	Step size for Reduced Set Voltage

Further, it is important that the *voltage* and *current transformer* settings and the *Protected unit* scaling are set according to the VT and CT used. These settings can be found under `Configuration` in CAP 505.

4.3. Example 1: Basic parameters

Fig. 4.3.-1 illustrates a single transformer feeding a busbar. In addition to a stabile busbar voltage the following requirements have to be fulfilled:

- target busbar voltage 20.5 kV
- maximum through-current for tap changer 150 A (HV side)
- overvoltage detection activated at 22.5 kV
- undervoltage blocking
- tap-changer position indication from 1 to 19.

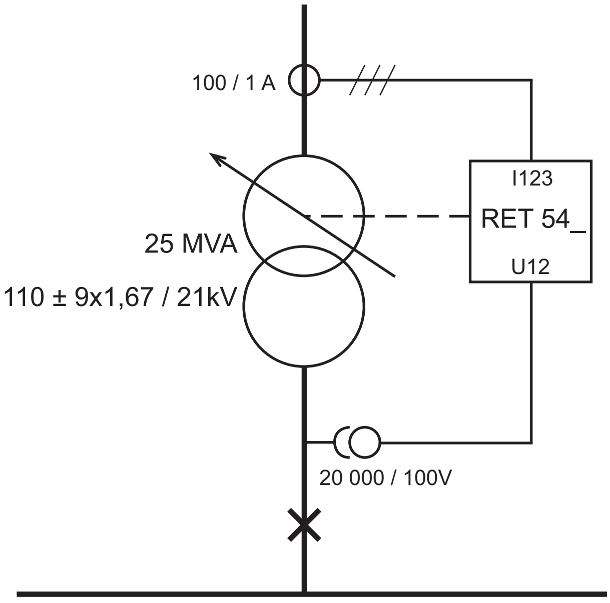

Fig. 4.3.-1 AVR connected to a single transformer

$$I_{nT} = \frac{S_n}{\sqrt{3} \times U_n} \tag{2}$$

where:

I_{nT}	=	rated current of power transformer
S_n	=	rated power of power transformer
U_n	=	rated phase-to-phase voltage

The rated primary current is calculated on the side where the CT is located, in this example the HV side.

$$I_{nT} = \frac{25MVA}{\sqrt{3} \times 110kV} = 131A$$

The rated values of the CT and VT do not match the ratings of the power transformer. Therefore the scaling factors for the protected unit are calculated for the channels to which the CTs and the VTs are connected. The channel scaling settings are found in CAP 50_ under `Configuration/Protected unit/`

Current measurement

$$scalingfactor = \frac{I_{nmd}}{I_{nT}} \tag{3}$$

where:

I_{nmd}	=	rated primary current of CT
I_{nT}	=	rated current of power transformer

$$scalingfactor = \frac{100A}{131A} = 0.763$$

Voltage measurement

The scaling factor of the protected unit is calculated as follows for the voltage measurement:

$$scalingfactor = \frac{U_{nmd}}{U_{nT}} \tag{4}$$

where:

U_{nmd}	=	rated primary current of VT
U_{nT}	=	rated current of power transformer LV side

$$scalingfactor = \frac{20\,000\,V}{21\,000\,V} = 0.952$$

It should be noted that the settings of the protected unit are part of the relay setting and thus affecting all protection function blocks.

Voltage regulator settings

The *Reference voltage* U_s is calculated from the target voltage level of the busbar.

$$U_s = \frac{U_{target}}{U_n} = \frac{20\,500\,V}{20\,000\,V} = 1.025 \times U_n$$

The *Bandwidth* ΔU_s can be set according to the tap-changer step voltage. Too small a value may result in unstable or too sensitive regulation. The bandwidth setting should not be less than half the tap-changer step voltage. The recommended setting is equal to the tap step voltage.

$$\Delta U_s = 1.67\% U_n$$

To avoid damage to the tap changer at overload, the *Overcurrent limit* blocks the operation of the voltage regulator.

$$\text{Overcurr.limit} = \frac{I_{max}}{I_{nT}} = \frac{150A}{131A} = 1.15 \times I_n$$

When the *Overvoltage limit* setting is reached, the voltage regulator starts giving fast lower commands, continuing until the voltage is within the bandwidth.

$$\text{Overvolt.limit} = \frac{U_{max}}{U_{nT}} = \frac{22\,500\,V}{20\,000\,V} = 1.13 \times U_n$$

Once the measured voltage drops below the set *Undervoltage limit*, the undervoltage limit function blocks the operation of the voltage regulator. Therefore, the undervoltage limit should be given a value that will not be reached when the transformer is in normal service. The default value of 0.70 x Un can be used in most situations.

The tap-changer position will be displayed in the range from 1 to 19, where position 1 represents the lowest voltage and 19 the highest voltage. Consequently, *Min.volt.tap* is set to 1 and *Max.volt.tap* to 19. Please refer to Section 3.2. Tap-changer position indication for more details.

4.4. Example 2: Line drop compensation

In this example a transformer is feeding three lines of different length and voltage drop. Suitable line drop compensation parameters, which do not lead to overvoltage on the shortest line or undervoltage on the longest line, are to be found. The voltage in the load end of the lines (A, B and C) should be kept close to 20 kV.

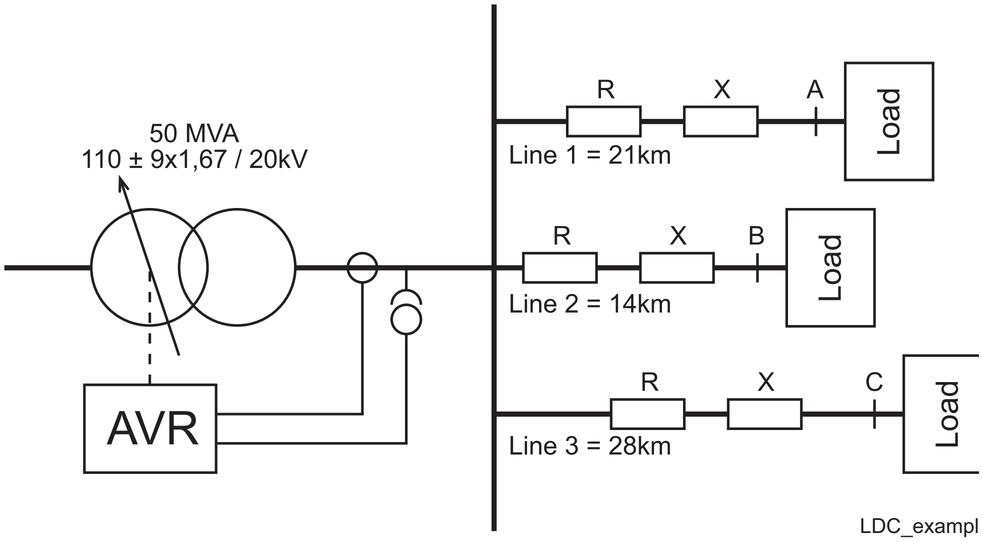

Fig. 4.4.-1 A transformer feeding several lines of different length.

The resistance and reactance for the line type used are R = 0.164 Ω/km and X = 0.120 Ω/km

First, the total resistance and reactance of the lines are calculated.

Line 1: 21 km

$$R_{Line1} = 0.164\ \Omega/km \times 21\ km = 3.444\Omega$$

$$X_{Line1} = 0.120\ \Omega/km \times 21\ km = 2.520\ \Omega$$

Line 2: 14 km

$$R_{Line2} = 0.164\ \Omega/km \times 14\ km = 2.296\ \Omega$$

$$X_{Line2} = 0.120\ \Omega/km \times 14\ km = 1.680\ \Omega$$

Line 3: 28 km

$$R_{Line3} = 0.164\ \Omega/km \times 28\ km = 4.592\ \Omega$$

$$X_{Line3} = 0.120\ \Omega/km \times 28\ km = 3.360\ \Omega$$

Since there are three separate lines with different voltage drops, a compromise must be made. In general, the most convenient way is to calculate the average of the line with the biggest and the smallest voltage drop. In this example, this is Line 2 and Line 3.

$$R_{average} = \frac{2.296\Omega + 4.592\Omega}{2} = 3.444\Omega$$

$$X_{average} = \frac{1.680\Omega + 3.360\Omega}{2} = 2.520\Omega$$

The R and X values used when calculating the line drop compensation parameters must also be divided by the number of lines fed by the power transformer.

$$R = 3.444\Omega / 3 = 1.148\Omega$$

$$X = 2.520\Omega / 3 = 0.840\Omega$$

It is now possible to calculate the setting parameters U_r and U_x using the following formulas:

$$U_r\% = \frac{\sqrt{3} \times I_{nT} \times R}{U_n} \times 100\% \tag{5}$$

$$U_x\% = \frac{\sqrt{3} \times I_{nT} \times X}{U_n} \times 100\% \tag{6}$$

where:

InT	=	rated current of power transformer
R	=	line resistance, Ω/phase
X	=	line reactance, Ω/phase
Un	=	rated voltage of power transformer

Rated current of LV side power transformer

$$I_{nT} = \frac{50MVA}{\sqrt{3} \times 20kV} = 1443A$$

$$U_r\% = \frac{\sqrt{3} \times 1443A \times 1.148\Omega}{20\,000V} \times 100\% = 14.35\% U_n$$

$$U_x\% = \frac{\sqrt{3} \times 1443A \times 0.840\Omega}{20\,000V} \times 100\% = 10.50\% U_n$$

Line drop compensation has to be activated by means of the LDC parameter (`Control/COLTC/Control setting`).

4.5. Commissioning and troubleshooting

Before commissioning a transformer provided with voltage regulation check the following:

First, select manual mode for the voltage regulator.

- Check that the COLTC function block measures the correct voltage and current (`Control/COLTC/Input data/`)
  Voltage U12
  Primary and/or Second. Current
- If LDC is used, check that the phase angle measured by the COLTC function block is correct (`Control/COLTC/Input data/Angle U1-IL1`). It should be equal to the phase angle of the load.
- Check that no blockings are active (`Control/COLTC/Output data/`)
- Raise the tap changer manually, verifying that the voltage and tap position do rise. Then, lower the tap changer manually and verify the changes.
- Select Automatic mode for the voltage regulator, either via the binary inputs or the MIMIC.
- Check that the present operation mode is correct (`Control/COLTC/Output data/Output OPER_MODE` = *Automatic*)
- Check that no alarms are active (`Control/COLTC/Output data/Alarm reason` = *000*)

In the event of abnormal operation or incorrect measurement, check Table 4.5.-1 for a solution.

Table 4.5.-1 Troubleshooting

Problem	**Solution**
Wrong phase angle measured in COLTC	• Check the polarity of the voltage and/or current connection. • Check that the phase currents are connected to the correct terminal.
Tap changer moves in wrong direction	• Check the *Min. volt. Tap* and *Max. volt. Tap* settings. • Check the Raise and Lower wiring. • Check the polarity of the voltage and current connection. • Check that the phase currents are connected to the correct terminals
Wrong tap-changer position indication	• Calibrate the tap-changer position signal with the Transducer Linearization Tool. • Check that *Linear curve* is “Enabled” in CAP under `Configuration/RTD1/Input _` • Make sure that the settings are stored and the relay restarted.

Table 4.5.-1 Troubleshooting (Continued)

Problem	Solution
Delay times T1 and T2 are not according to setting	• Alarm activated. The *Alarm reason* parameter should be 000, otherwise T1 and T2 are doubled. Check which alarm is active from `Control/COLTC/Output data/Alarm reason` • Check that the correct setting group is active.
The voltage regulator does not increase the voltage even if the dU value is greater than the bandwidth setting.	• If the line drop compensation function is used, the *LDC limit* may have been reached and therefore the regulator is prevented from increasing the voltage • External blocking activated • The extreme tap changer position has been reached
“Command error” alarm (Alarm reason = 001)	• The tap-changer position did not respond to a Raise or Lower command within 20 seconds. • The position did not change at all, or changed more than one step. Re-calibrate the tap-changer position signal. • The tap changer moved in the wrong direction. The Raise and Lower wiring might be swapped.
“TCO signal does not fall" alarm (Alarm reason = 010)	• The TCO signal stays active for more than 15 seconds after a Raise or Lower command. • Possible tap-changer control failure
"Regulator pumping" alarm (Alarm reason = 100)	• Too many Raise and Lower commands during one hour. • Unstable regulation. The reason may be too small *Bandwidth* and/or T1, T2 setting values. • Check if Controls per 1h is set according to the permitted limit. (`Control/COLTC/Control setting/`)

To reset an alarm manually, press the **C** button for two seconds.

5. Parallel operation

Parallel operation means that two or several power transformers are feeding the same busbar. Further, the parallel power transformers must all be fed from the same source. Since single-operation mode of the voltage regulator cannot be used with parallel transformers, a suitable parallel mode must be used.

The COLTC function block supports three different parallel operation modes, i.e. the Master/Follower mode (M/F), Minimizing Circulating Current mode (MCC) and Negative Reactance principle (NRP).

To avoid incorrect operation, the settings of all parallel AVRs have to be identical. However, the setting of the stability parameter used in the MCC and NRP mode, is proportional to the rated currents of the power transformers.

The operation mode is selected with the *Operation mode* parameter. The actual operation mode can be set to be fixed or selectable via the inputs of the function block. With the parameter setting *Op. mode inputs*, the operation depends on the states of the PARAL_MODE, AUTO_MAN and PARALLEL inputs of the function block.

Table 5.-1 shows the operation mode at different values of the inputs of the COLTC function block.

Table 5.-1 Operation mode of voltage regulator

Operation mode parameter	PARAL_MODE	AUTO_MAN	PARALLEL	Actual operation mode
Op. mode input	0 or 1 or 2	0	0	Manual
Op. mode input	0	0	1	Automatic follower
Op. mode input	0 or 1 or 2	1	0	Automatic single
Op. mode input	0	1	1	Automatic master
Op. mode input	1	0 or 1	1	MCC
Op. mode input	2	0 or 1	1	NRP
Other setting	NA	NA	NA	According to Op. mode parameter

Fig. 5.-1 shows an example of a configuration used for switching between different operation modes with external switches connected to the binary inputs BI9 and BI10. Binary input BI9 is used for switching to parallel mode, whereas BI10, when active, switches the COLTC function block to automatic mode.

The OPER_MODE output is used to indicate the operation mode of the voltage regulator. In this example, the operation mode is shown on the MIMIC display and also by two state output relays.

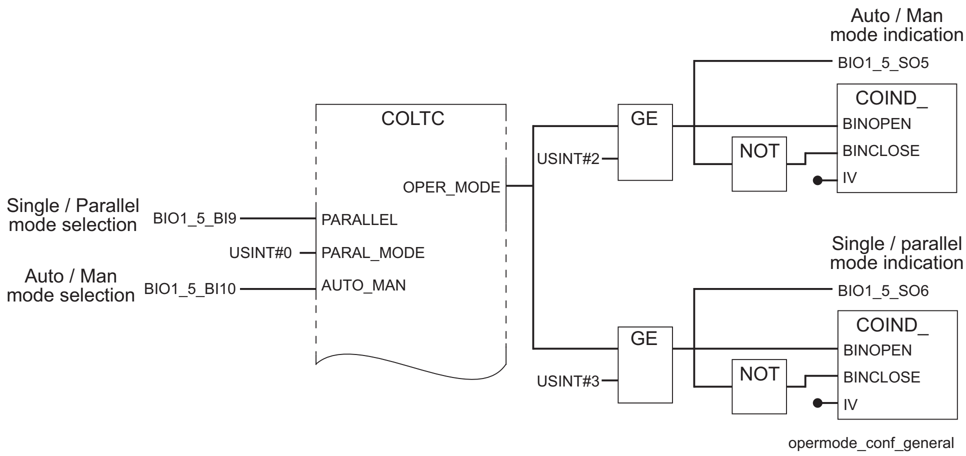

Fig. 5.-1 Configuration for switching between manual, automatic and parallel mode

The OPER_MODE output provides an integer between 0 and 6 representing the actual operation mode of the COLTC function block:

0 = Not in use

1 = Manual

2 = Autom. Single

3 = Autom. Master

4 = Autom. Follower

5 = NRP

6 = MCC

5.1. Master / Follower (M/F) mode

5.1.1. Purpose and connections

The Master/Follower mode can be used exclusively in cases where all parallel power transformers have the same ratings and the tap changers have the same step voltages. The Master/Follower mode means that all parallel transformers operate as one unit. The Master regulates all the Followers simultaneously with Raise and Lower commands. Basically, an unlimited number of followers can be used with this operation mode. For a simple Master/Follower voltage regulation only voltage measurement is required.

When the M/F mode is used, it is recommended to transfer tap-changer position information from the Followers to the Master, either via an analogue signal, or over LON communication. This will automatically enable the *out-of-step* function, which means that the Master can regulate a separate Follower, if its tap position is different from that of the Master. The out-of-step function also requires that the Raise and Lower commands sent to Followers are obtained from the FLLW_CTRL output of the Master's COLTC function block. The out-of-step function enables a maximum of four parallel transformers to be used.

Fig. 5.1.1.-1 shows an example of a configuration that can be used for both Master and Follower. The tap changer position information of the own transformer is connected to RTD1_6_AI1 and transmitted via the RTD1_6_AO1 output as a mA signal. The same signal is connected to the RTD1_6_AI2 input of parallel units. In this configuration it makes no difference which one is the Master and which one is a Follower.

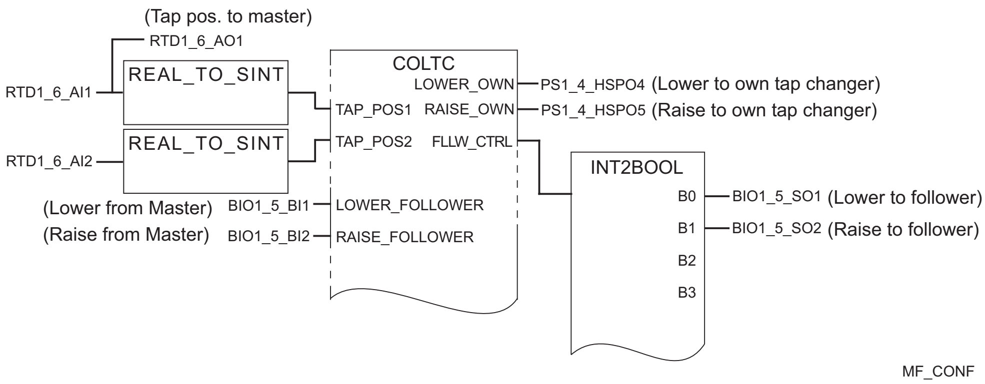

Fig. 5.1.1.-1 Example of Master/Follower configuration with out-of-step function

5.1.2. Settings

The same principle of setting the AVR parameters as for a single transformer can be used in the Master/Follower mode (refer to Section 4.2. Settings).

The operation mode can either be set to be fixed for the Master and Follower, or selectable via binary inputs. Table 5.1.2-1 shows the operation mode at different input values of the COLTC function block. See the configuration example in Fig. 5.-1.

Table 5.1.2-1 Operation mode of the AVR at different settings

Operation mode parameter	PARAL_MODE	AUTO_MAN	PARALLEL	Actual operation mode
Op. mode input	0 or 1 or 2	0	0	Manual
Op. mode input	0 or 1 or 2	1	0	Automatic single
Op. mode input	0	1	1	Automatic master
Op. mode input	0	0	1	Automatic follower
Autom. Single	NA	NA	NA	Automatic single
Autom. Master	NA	NA	NA	Automatic master
Autom. Follower	NA	NA	NA	Automatic follower
Other setting	NA	NA	NA	According to Operation mode parameter

It should be noted that there can be only one Master in the Master/Follower operation mode.

Functions such as LDC and RSV can also be used in the Master/Follower mode. In M/F mode only the regulation settings of the Master are effective. A Follower(s) will operate according to the Raise and Lower commands given by the Master.

When LDC is used, the calculations made in the COLTC function block are based on the total current of all parallel transformers. Therefore, the number of followers must be known to the COLTC function block. Since the parallel transformers are identical, the total current is calculated by multiplying the current of one transformer by the total number of parallel transformers. The Master COLTC function block can conclude the number of parallel transformers from the tap-changer position inputs connected to it. If there are no tap changer position signals connected to the function block, the number of Followers must be set with the parameter *Parallel trafos*. The correct setting is important for the LDC function.

5.1.3. Example: Master/Follower with LON communication

Instead of wiring the Raise and Lower signals to all Followers and the tap position information to the Master, an option is to use LON communication between the RET 54_ terminals. If there are only one Master and one Follower, LON communication can be established by using only one RER 103 for each RET 54_ terminal and connecting them together through optical fibres. If more than two units are run in parallel, a star coupler RER 111 is required.

LON communication also requires mapping of LON nodes in each RET 54_ terminal. For this purpose the Lon Network Tool (LNT 505) is used.

When LON communication is configured in the CAP Relay Configuration Tool, only two COMM_IN_ and COMM_OUT_ are needed between the Master and the Follower: one for transferring the Raise and Lower commands and one for tap-changer position information.

Fig. 5.1.3.-1 shows a Master/Follower configuration example with LON communication between two RET 54_ terminals. The configuration of COMM_IN_ and COMM_OUT_ is identical for the Master and the Follower, so it makes no difference, which one of them is set to run as the Master. The basic principle is that e.g. COMM_OUT1 of the Master is connected to COMM_IN1 of the Follower, etc.

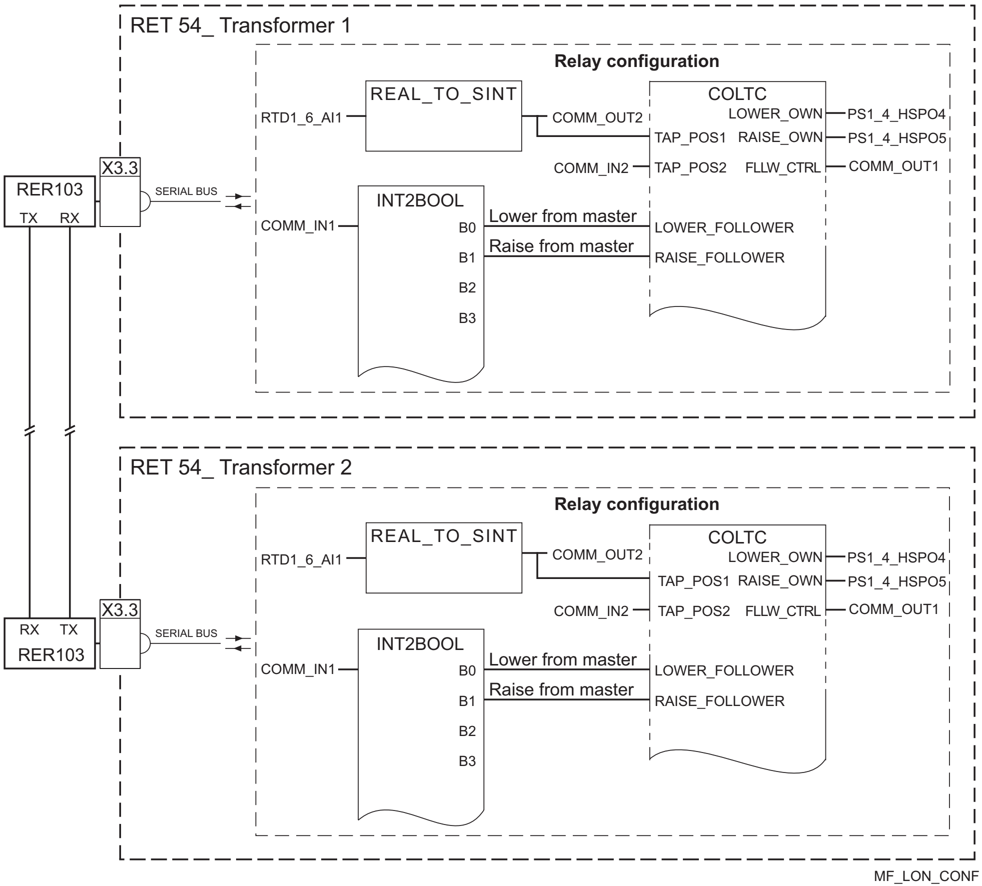

Fig. 5.1.3.-1 Configuration for sending Raise and Lower commands and tap position information between Master and Follower.

In this example, external switches connected to the binary inputs of the RET 54_ terminals are used for selecting the operation mode. The binary inputs are configured to the AUTO_MAN and PARALLEL input of the COLTC function block (refer to Fig. 5.1.1.-1). When Master/Follower operation is used, the PARAL_MODE input is set to "0".

Instead of using external switches for selecting the operation mode, the auxiliary contacts of the CB can be used.

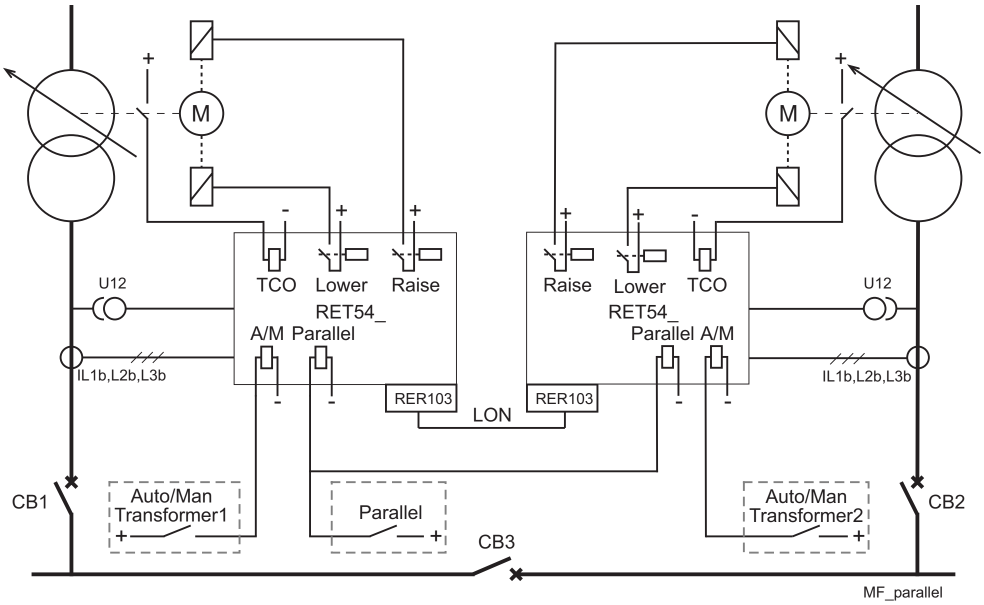

Fig. 5.1.3.-2 Wiring for two voltage regulators running in parallel with Master/Follower operation mode.

Three switches are used to control the operation mode of the two AVRs. Table 5.1.3-1 shows how the operation mode of the AVRs is affected by the position of the control switches. The *Operation mode* parameter has to be set to *Op. mode input*.

Table 5.1.3-1 Selection of operation mode with control switches

Control switches			Operation mode	
AVR 1 Auto/Man	**AVR 2 Auto/Man**	**Parallel**	**AVR 1**	**AVR 2**
0	0	0	Man	Man
1	0	0	Auto	Man
0	1	0	Man	Auto
1	1	0	Auto	Auto
1	0	1	Master	Follower
0	1	1	Follower	Master
1	1	1	Two Masters (not allowed)	

5.2. Minimizing Circulating Current (MCC) mode

5.2.1. Purpose and connections

The MCC mode can be used when the power transformers have the same or different ratings and the tap changers have different step voltages. The MCC mode is also the best solution for the control of parallel transformers with varying reactive loads.

The purpose of the MCC mode is to control the load voltage and minimize the circulating current between parallel transformers. The circulating current is a reactive current appearing when parallel transformers have different voltages, e.g. at different tap positions. The magnitude of the circulating current depends on the voltage difference and the impedance of the parallel transformers. The circulating current does not serve any useful purpose. It increases transformer heating and so also the losses.

Besides voltage and current measurement on the LV side of the transformer, LON communication is required between the RET 54_ terminals. Amplitude and phase angle data, which are required for calculating the circulating current for each power transformer, are transferred over LON communication.

5.2.2. Settings

The same principle of setting the AVR parameters as that used for a single transformer can be used in the MCC mode (refer to Section 4.2. Settings).

The MCC mode requires that all parallel AVRs are in the MCC operation mode. The MCC operation mode can be set to be fixed in all parallel AVRs or selectable e.g. via binary inputs. Fig. 5.2.2.-1 shows a configuration example where the operation mode is selected via the binary inputs BI9 and BI10. The indication of the operation mode can be obtained from the OPER_MODE output. In this example, the operation mode is displayed in the MIMIC and also connected to two output relays.

In addition, the CONN_STATUS input has to be activated in the MCC mode. This input is used to verify that the transformer is connected to the network. In Fig. 5.2.2.-1 BI11 is configured as CONN_STATUS input. The COLTC function block will not transfer information to other parallel AVRs until the CONN_STATUS input is activated.

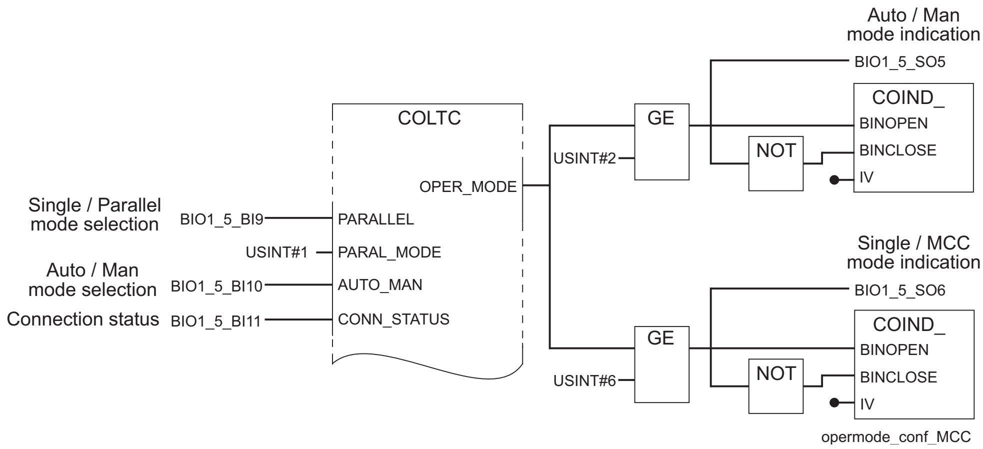

Fig. 5.2.2.-1 Configuration for switching between manual, automatic and MCC mode

The actual operation mode is presented in Table 5.2.2-1. Please note that the PARAL_MODE input must have the value 1 when MCC mode is used.

Table 5.2.2-1 Selection of operation mode with control switches

Operation mode parameter	PARAL_MODE	AUTO_MAN	PARALLEL	Actual operation mode
Op. mode input	1	0	0	Manual
Op. mode input	1	1	0	Automatic single
Op. mode input	1	0 or 1	1	MCC
MCC	NA	NA	NA	MCC
Other setting	NA	NA	NA	According to Operation mode parameter

LDC and RSV can also be used in MCC mode. When the LDC function is used, the calculations are based on the total current of all transformers connected in parallel. The COLTC function block can determine the number of parallel transformers via the LON communication and, therefore, no settings need to be changed if one transformer is taken out of service.

A *Stability* setting parameter is used to adjust the regulation sensitivity. A higher stability value provides a more sensitive regulation. At too high a setting value the regulator may give control pulses too frequently or have difficulty finding a stable position.

To find a suitable setting for the stability parameter, start by setting the stability of all voltage regulators to 10%. Then set all voltage regulators into MCC mode and wait until they are in a stable position. Check if the stability parameter is sufficient by setting one voltage regulator into manual mode and increasing or decreasing the tap position by one step. When the voltage regulator is returned to automatic mode, it should turn back into its initial position. Should the tap changer not return to its initial position, increase the stability parameter value. Repeat the same procedure for all parallel voltage regulators.

The *Circ. curr. limit* setting parameter is used to block the regulation, if the calculated circulating current exceeds the set value.

5.2.3. LON configuration

When the MCC mode is used, LON communication is required between the units. At least the COMM_CURR and COMM_ANGL outputs of COLTC must be mapped to the parallel units. Fig. 5.2.3.-1 shows a configuration and wiring example with LON communication between two RET 54_ terminals. If there are three or four RET 54_terminals connected in parallel, a star coupler RER 111 equipped with a SFIBER card is required.

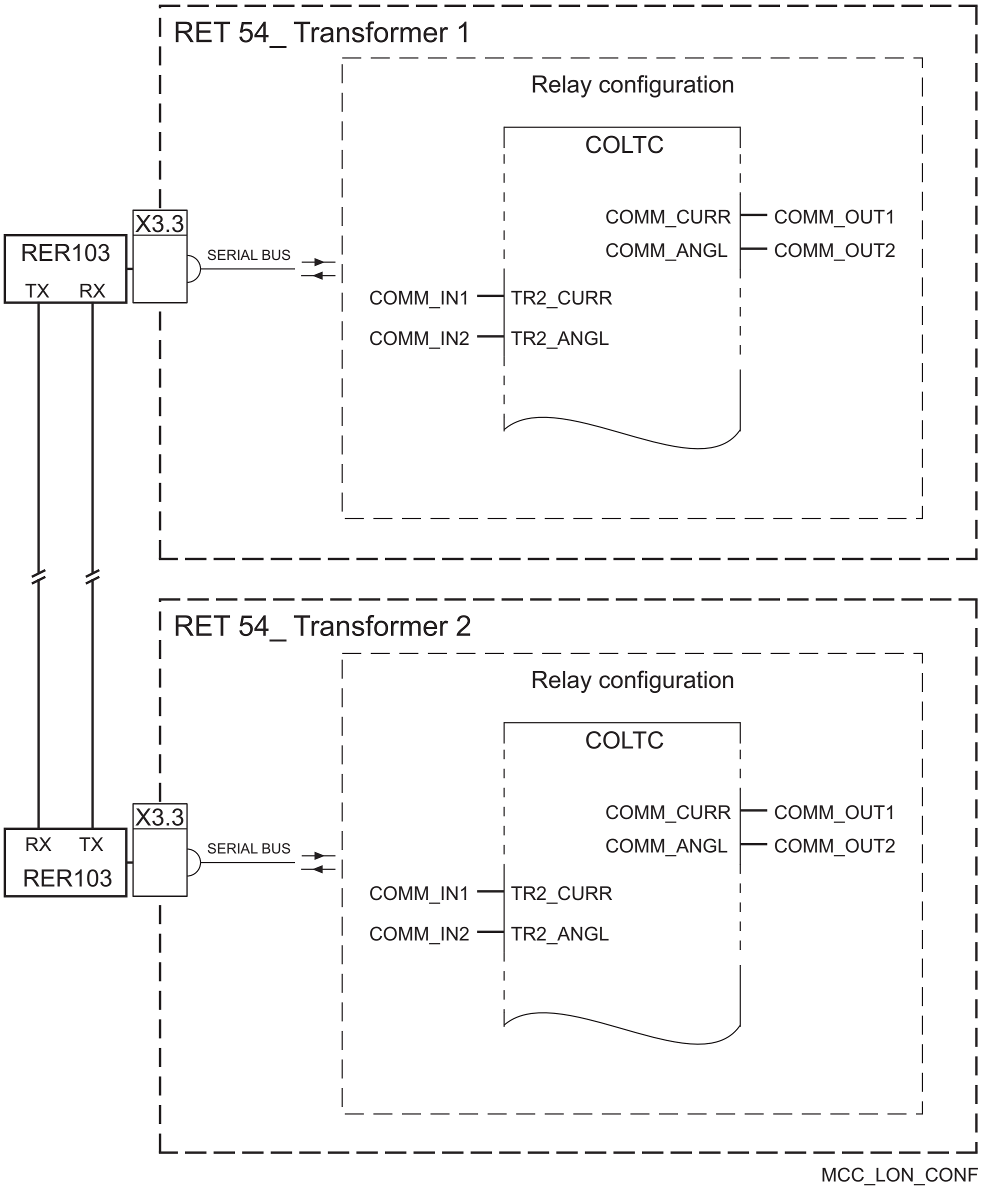

Fig. 5.2.3.-1 Configuration of LON communication for two voltage regulators operating in MCC mode

5.2.4. Example: Minimizing Circulating Current mode of operation

Fig. 5.2.4.-1 illustrates two transformers connected in parallel. The two AVRs operate in MCC mode. The operation mode of the AVRs is selected using three switches: Auto/Man Transformer 1, Auto/Man Transformer 2 and Parallel. The CONN_STATUS input is automatically activated, when the transformer is connected to the busbar. The configuration for selecting the operation mode is shown in Fig. 5.2.2.-1.

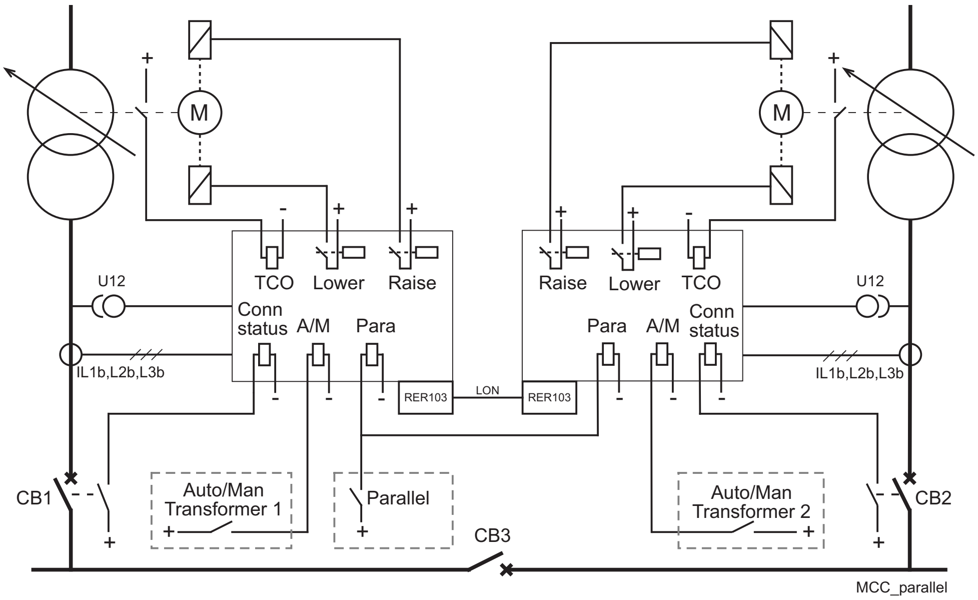

Fig. 5.2.4.-1 Wiring for two parallel voltage regulators operating in MCC mode.

In this example the same parallel switch is used for both AVRs. When more than two parallel AVRs are to be operating in MCC mode, the parallel mode should be separately selectable for each AVR. This will make it possible to select manual mode only for one AVR while the others are operating in parallel mode.

Table 5.2.4-1 Operation mode of the voltage regulator

AVR 1	AVR 2		Operation mode	
Auto/Man	**Auto/Man**	**Parallel**	**AVR 1**	**AVR 2**
0	0	0	Man	Man
1	0	0	Auto	Man
0	1	0	Man	Auto
1	1	0	Auto	Auto
0	0	1	MCC	MCC
1	0	1	MCC	MCC
0	1	1	MCC	MCC
1	1	1	MCC	MCC

Note! The AVRs will not calculate nor minimize the circulating current until the operation mode is set to MCC and CONN_STATUS is activated (both CB1 and CB2 are closed). The AVR will, however, send current and angle data as long as the CONN_STATUS input is active, even if the AVR is in manual mode.

5.3. Negative Reactance Principle (NRP) mode

5.3.1. Purpose and connections

The Negative Reactance Principle (NRP) operation mode can be used as an alternative to the MCC mode. The advantage of this operation mode is that no wiring or communication is needed between the RET 54_ terminals. The voltage regulators operate totally independently. Another advantage is that the ratings of the parallel transformers do not have to be identical. Because the NRP mode calculates the circulating current by comparing the measured phase angle with the *Load phase angle* setting, it is important that the phase angle of the load is stable. If the phase angle of the load deviates from the *Load phase angle* setting, the voltage will be higher or lower than expected. In addition to voltage measurement, current measurement is also required on the LV side.

5.3.2. Settings

The same principle as that used for setting the AVR parameters for a single transformer, can be used in the NRP mode (refer to Section 4.2. Settings). The operation mode can be set to be NRP permanently fixed or selectable, e.g. via binary inputs using the Operation mode parameter. Fig. 5.3.2.-1 shows a configuration example, where the operation mode is selectable via binary inputs. The indication of the operation mode can be obtained from the OPER_MODE output. In this example the operation mode is displayed on the MIMIC display and also brought to two output relays.

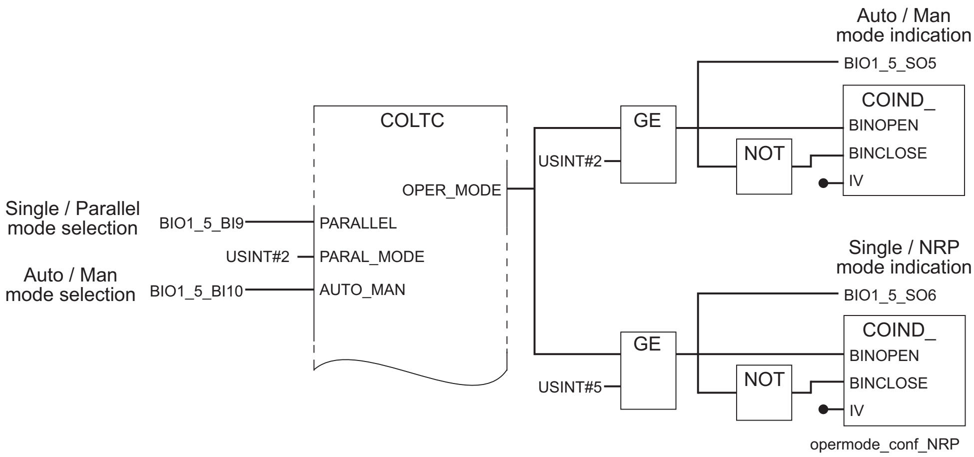

Fig. 5.3.2.-1 Configuration for switching between manual, automatic and NRP mode

The actual operation mode is presented in Table 5.3.2-1. Please note that the PARAL_MODE input must have the value 2 when NRP mode is used.

Table 5.3.2-1 Selection of operation mode with control switches

Operation mode parameter	PARAL_MODE	AUTO_MAN	PARALLEL	Actual operation mode
Op. mode input	2	0	0	Manual
Op. mode input	2	1	0	Automatic single
Op. mode input	2	0 or 1	1	NRP
NRP	NA	NA	NA	NRP
Other setting	NA	NA	NA	According to Operation mode parameter

The LDC and RSV functions can also be used in the NRP mode. When the LDC parameters U_r and U_x are calculated, the "I_{nT}" current used in the formula must be the sum of the rated currents of all transformers connected in parallel. To achieve the correct operation, it is important that the right values are used for the LDC calculation in the NRP mode.

The *Load phase angle* is set according to the phase angle of the load. A negative angle is used for a capacitive load, and a positive angle for an inductive load. To be able to maintain a stable voltage and a low circulating current, the Load phase angle must be correct and the phase angle of the load must be stable.

The *Stability* setting parameter is used to adjust the sensitivity of the regulation. A higher stability value will give a more sensitive regulation. Due to too high a setting the regulator may give too frequent control pulses or have difficulty finding a stable position. A suitable stability parameter value can be found the same way as in the MCC mode (refer to Section 5.2.2. Settings).

The *Circ. curr. limit* setting parameter is used to block regulation, if the calculated circulating current exceeds the set value.

5.3.3. Example: Negative Reactance Principle

In the following example two transformers are connected in parallel. Because no wiring is needed between the parallel voltage regulators, they can even be located in separate substations. The operation mode for each AVR is selected using the two switches Auto/Man and Parallel. A configuration example for selecting the operation mode is shown in Fig. 5.3.3.-1.

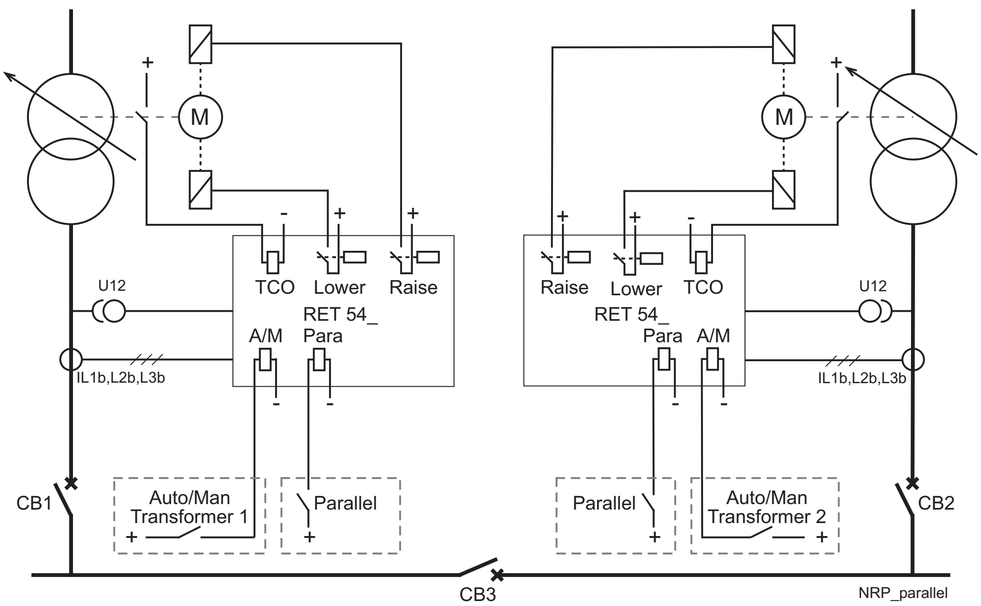

Fig. 5.3.3.-1 Wiring of two parallel voltage regulators operating in NRP mode.

The parallel switch is used to switch between the operation mode Automatic single and NRP of the separate AVRs. Additional parallel regulators with exactly the same configuration and connection can be added. It should be noted that to switch to the Manual operation mode both the Auto/Man and the Parallel switch have to be open.

Table 5.3.3-1 shows the operation mode of the voltage regulator according to the position of the switches.

Table 5.3.3-1 Operation mode of one AVR in NRP mode

AVR		AVR
Auto/Man	**Parallel**	**Operation mode**
0	0	Manual
1	0	Automatic single
0	1	NRP
1	1	NRP

5.4. Commissioning and troubleshooting

LON communication

The LON communication between parallel units can be easily tested by sending signals from one terminal to another. In this way the successful reception of signals can be verified.

First, make sure that the jumpers of the bus connection module RER 103 are in the positions "Light Off" and "Topology Star". Then set one of the RET 54_ terminals in test mode (HMI: `Tests/General/Test mode` = *Active*). Test the communication by setting a value to the mapped output (HMI: `Tests/LON SNVT/Comm. Outputs/COMM_OUT_`). The same value should then be seen on the corresponding input of the receiving unit(s) (HMI: `Status/LON SNVT/Comm. Inputs/COMM_IN_`)

Verifying the correct operation

Before commissioning a transformer provided with voltage regulation check the following:

First, set the voltage regulator into manual mode.

- Check that the COLTC function block measures the correct voltage and current (`Control/COLTC/Input data/Voltage U12 and Second. Current`)
- Check that the phase angle measured by the COLTC function block is correct (`Control/COLTC/Input data/Angle U1-IL1`). It should be close to 0 degrees.
- Check that no blockings are active (`Control/COLTC/Output data/`)
- Raise the tap changer manually and confirm that the voltage and tap position changes. Then, manually lower the tap changer and verify the changes.
- Set all parallel voltage regulators into the correct operation mode.
- If MMC mode is used, make sure that the CONN_STATUS input is active
- Check that the present operation mode is correct (`Control/COLTC/Output data/Output OPER_MODE`)
- If MCC mode is used, check that the LON communication between the units works. (`Control/COLTC/Output data/Communic. error` = *000000000000*)

- If MCC mode is used, check that the parameter "Parall. units MCC" corresponds to the number of parallel voltage regulators. (`Control/COLTC/Output data/`)
- If MCC mode is used, check the current and angle measurement values of the parallel voltage regulators (`Control/COLTC/Input data/Trafo _ current` and `Trafo _ angle`)
- Check that no alarms are active. (`Control/COLTC/Output data/Alarm reason` = *000*)
- In Master/Follower mode. Check for any failed followers from the Master. (`Control/COLTC/Output data/Failed followers` = *000*)

To resolve an abnormal situation or wrong measurement, check Table 5.4.-1 for a solution.

Table 5.4.-1 Troubleshooting in MCC mode

Problem	**Solution**
Wrong phase angle measured in COLTC	• Check the polarity of the voltage and/or current connection. • Check that the phase currents are connected to the correct terminal.
Tap changer moves in wrong direction	• Check the *Min. volt. Tap* and *Max. volt. Tap* settings. • Check the Raise and Lower wiring. • Check the polarity of the voltage and current connection. • Check that the phase currents are connected to the correct terminals
Wrong tap-changer position indication	• Calibrate the tap-changer position signal with the Transducer Linearization Tool. • Check that *Linear curve* is “Enabled” in CAP under `Configuration/RTD1/Input _` • Make sure that the settings are stored and the relay restarted.
Communication works but no measurement from parallel voltage regulator	• Make sure that the CONN_STATUS input of the COLTC function block is active in all parallel RET 54_ units.
Delay times T1 and T2 are not according to setting	• Alarm activated. The Alarm reason parameter should be 000, otherwise *T1* and *T2* are doubled. Check which alarm is active from `Control/COLTC/Output data/Alarm reason` • Check that the correct setting group is active.
The voltage regulator does not increase the voltage even if the dU value is greater than the bandwidth setting.	• If the line drop compensation function is used, the *LDC limit* may have been reached and therefore the regulator is prevented from increasing the voltage • External blocking activated • The extreme tap changer position has been reached

Table 5.4.-1 Troubleshooting in MCC mode (Continued)

Problem	Solution
“Command error” alarm (Alarm reason = 001)	• The tap-changer position did not change within 20 seconds to a Raise or Lower command . • The position did not change at all, or changed more than one step. Re-calibrate the tap-changer position signal. • The tap changer moved in the wrong direction. The Raise and Lower wiring might be swapped.
“TCO signal does not fall" alarm (Alarm reason = 010)	• The TCO signal stays active for more than 15 seconds after a Raise or Lower command. • Possible tap-changer control failure
"Regulator pumping" alarm (Alarm reason = 100)	• Too many Raise and Lower commands during one hour. • Unstable regulation. The reason may be too small bandwidth setting values and/or T1, T2. • Check if *Controls per 1h setting* is within the permitted limit. (`Control/COLTC/Control setting/`)

To reset an alarm manually, press the **C** button for two seconds.

6. References

/1/ 1MRS755225
Transformer Terminal RET 54_. Technical Reference Manual, General

/2/ 1MRS755224
COLTC. Automatic or manual voltage control of transformers

/3/ 1MRS755530
Transformer Terminal RET 54_. Power transformer with tap changer and parallel operation with Master/Follower principle.

/4/ 1MRS755531
Transformer Terminal RET 54_. Power transformer with tap changer and parallel operation with Minimizing Circulating Current principle.

/5/ 1MRS751706-MUM
LON Network Tool 505 Operators manual

7. List of symbols

AVR	Automatic Voltage Regulator
BI	Binary Input
dU	Error voltage difference (Um-Up)
$I_{L1} \dots I_{L3}$	Phase currents (HV-side)
$I_{L1b} \dots I_{L3b}$	Phase currents (LV-side)
LDC	Line Drop Compensation
M/F	Master / Follower operation principle
MCC	Minimizing Circulating Current operation principle
NRP	Negative Reactance Principle
OLTC	On-Load Tap Changer
RSV	Reduce Set Voltage
RTD card	Analogue input / output card
T1	Operation delay timer 1
T2	Operation delay timer 2
TCO	Tap Changer Operating
TLT	Transducer Linearization Tool
ΔUs	Bandwidth
In	Rated current of the power transformer
$U_{12b} \dots U_{31b}$	Phase-to phase voltages (LV-side)
U_{12bs}	Virtual voltage (LV-side)
Uci	Compensation term for circulating current compensation
Um	Measured voltage
Un	Rated phase-to-phase voltage of the power transformer
Up	Control voltage
Ur	Resistive line drop compensation factor
Ursv	Compensation term for reduced set voltage function
Us	Reference voltage setting
Ux	Reactive line drop compensation factor
Uz	Compensation term for line drop compensation function

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