1   Introduction

Generator rotor winding and its associated dc supply electric circuit is typically fully insulated from the earth (i.e. ground). Therefore single connection of this circuit to earth will not cause flow of any substantial current. However if second earth fault appears in this circuit circumstances can be quit serious. Depending on the location of these two faults such operating condition may cause:

- Partial or total generator loss of field

- Large dc current flow through rotor magnetic circuit

- Rotor vibration

- Rotor displacement sufficient to cause stator mechanical damage

Therefore practically all bigger generators have some dedicated protection which is capable to detect the first earth fault in the rotor circuit and then, depending on the fault resistance, either just to give an alarm to the operating personnel or actually to give stop command to the machine.

Rotor earth fault protection can be integrated in REG670/REG650 among all other protection functions typically required for generator protection. How this is achieved by using COMBIFLEX® injection unit RXTTE4 is described in this document.

2   Injection unit

The injection unit RXTTE4 is used to inject a fundamental frequency AC voltage signal (i.e. either 50Hz or 60Hz depending on the actual machine rating) to the rotor winding and its associated electrical circuit. Principal internal RXTTE4 drawing is shown in Figure 1.
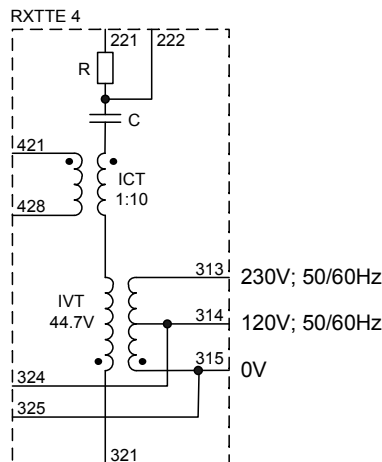

Figure 1: Voltage injection unit RXTTE4 with its main internal components

Internal components within RXTTE4 unit have the following nominal values:

- Resistor R=220Ω; 10W

- Capacitor C=6.8µF

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- Internal current transformer (i.e. ICT) has ratio 1:10

- Internal voltage transformer (i.e. IVT) will produce 44.7V on the secondary side when it is supplied from either 120V AC or 230V AC source as shown in Figure 1; if supply voltage magnitude is different from these values, induced secondary voltage magnitude will also vary accordingly. Note that it is preferred to have injection voltage close to above stated values otherwise the resultant injection current can be too small to be measured.

The injection unit RXTTE 4 shall be connected between one of the two rotor poles (i.e. either plus or minus) and the earth. The resultant injected current signal is then connected to an analog current input of REG IED and the injected voltage signal is connected to an analog voltage input of REG IED, as shown in Figure 2. Due to quite low level of the injected current signal it is recommended to use 1A rated analog current input in REG 670 and sensitive current input in REG650 for this protection. Note that REG IED will actually measure ten times bigger current than the real injected rotor current due to selected ICT ratio of 1:10.

RXTTE4 can be connected directly to the rotor winding as shown in Figure 2, or via a protective external resistor mounted close to the generator as shown in Figure 3.
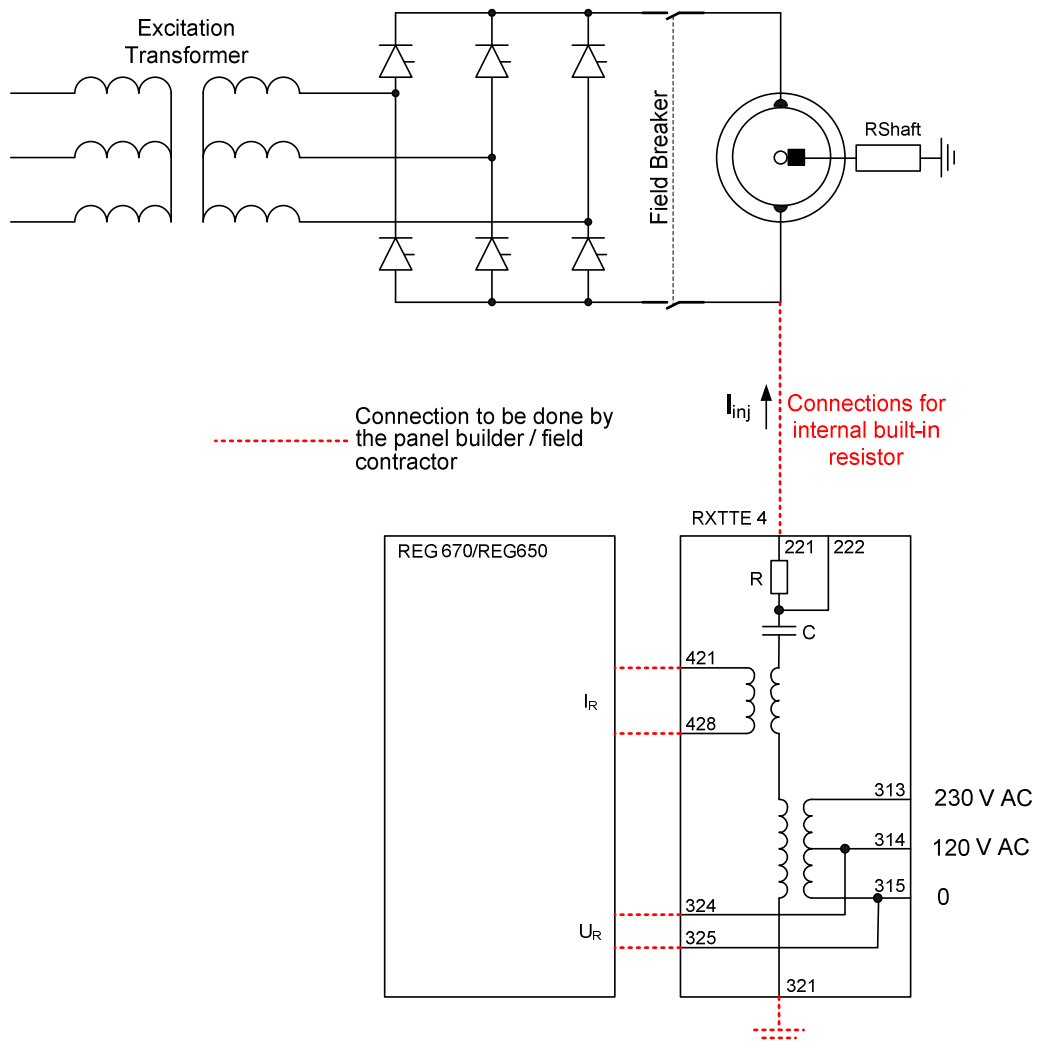

Figure 2: Direct connection of RXTTE4 to the rotor winding

Note that connecting cable between rotor and RXTTE4 shall follow the insulation requirements/levels specified for the generator rotor winding.
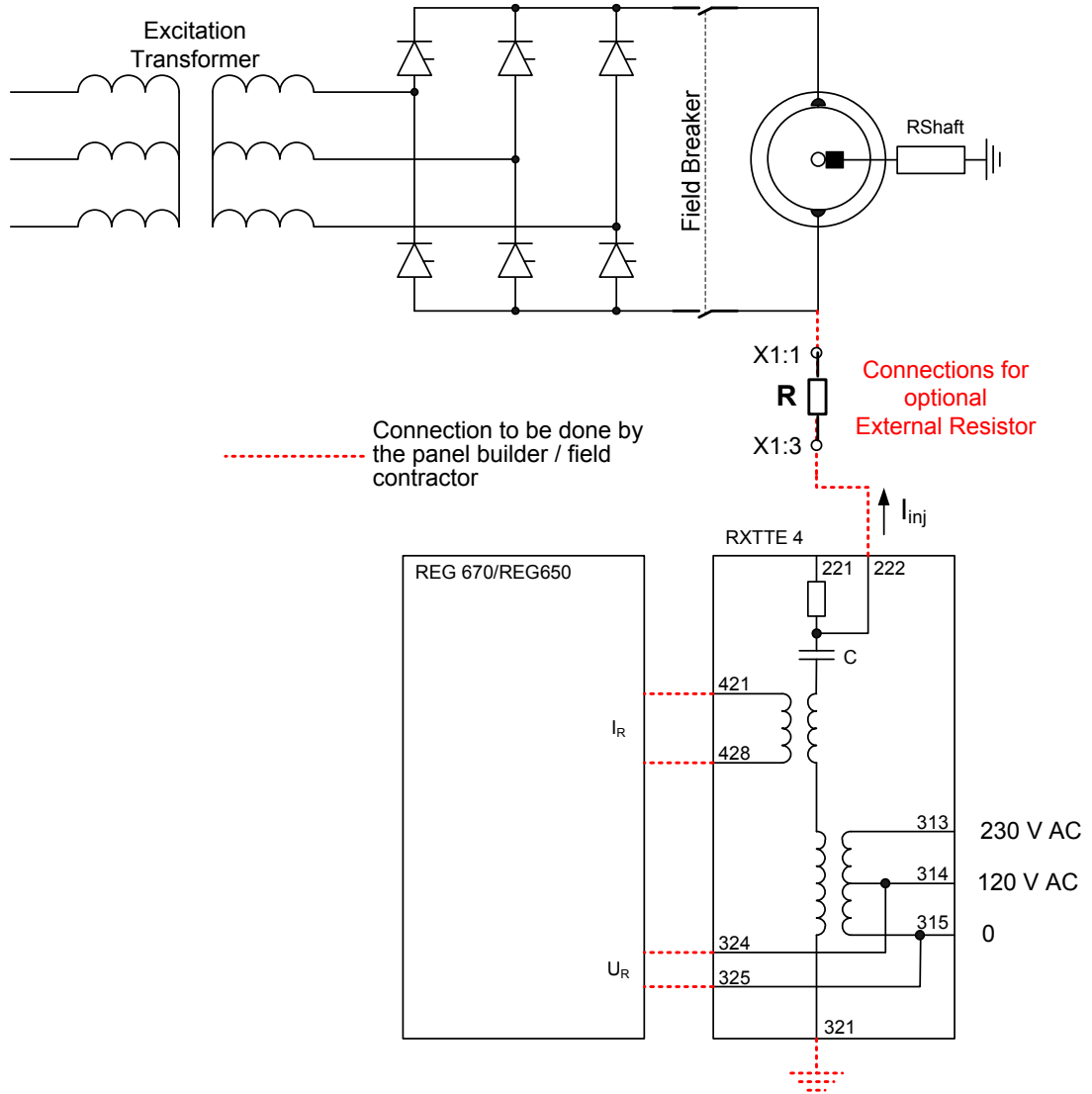
Figure 3: Connection of RXTTE4 to the rotor winding via protecting resistor

The second type of installation is used when either there is end-user requirement to minimize physical exposure of the field circuit or when high harmonic content of the total injection current can cause overheating of the built-in RXTTE4 resistor (see Section 3).

All internal calculations in the REG IED are performed in primary amperes and primary volts. Therefore it is also necessary to set CT and VT ratio for the two analogue inputs used for rotor earth-fault protection. It is recommended to set the primary rated CT current to 1000A and the secondary rated CT current to 1A. By doing so, the displayed service value for the primary current (i.e. called I_R in further text) both from the function and from the TRM channel will directly correspond to mA value of the injected current I_R measured by the REG IED. Parameter *CTearthing* shall be set to the value "FromObject" in order to use setting "Forward" for directional protection function used for rotor earth fault protection (see Section 4.1 for more details). However this shall be verified during commissioning.

The voltage input into REG IED is always taken directly from the 120 V input tap on the RXTTE4, as shown in Figure 2 and Figure 3. It is recommended to set the primary rated VT voltage to 100 kV and the secondary rated VT voltage to 100 V. By doing so, the displayed service value for the primary voltage (i.e. called U_R in further text), both from the function and from the TRM channel will directly correspond to the injected voltage in volts on the 120 V tap.

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Sometimes it may be required that one RXTTE4 injection unit shall supply two REG IEDs (i.e. Main 1 and Main 2 protections) in order to have redundant rotor earth fault protection. This can be achieved by using connection shown in Figure 4. Note that only one RXTTE4 can be used and that only measurement part of the rotor earth fault protection is made redundant by such connation.
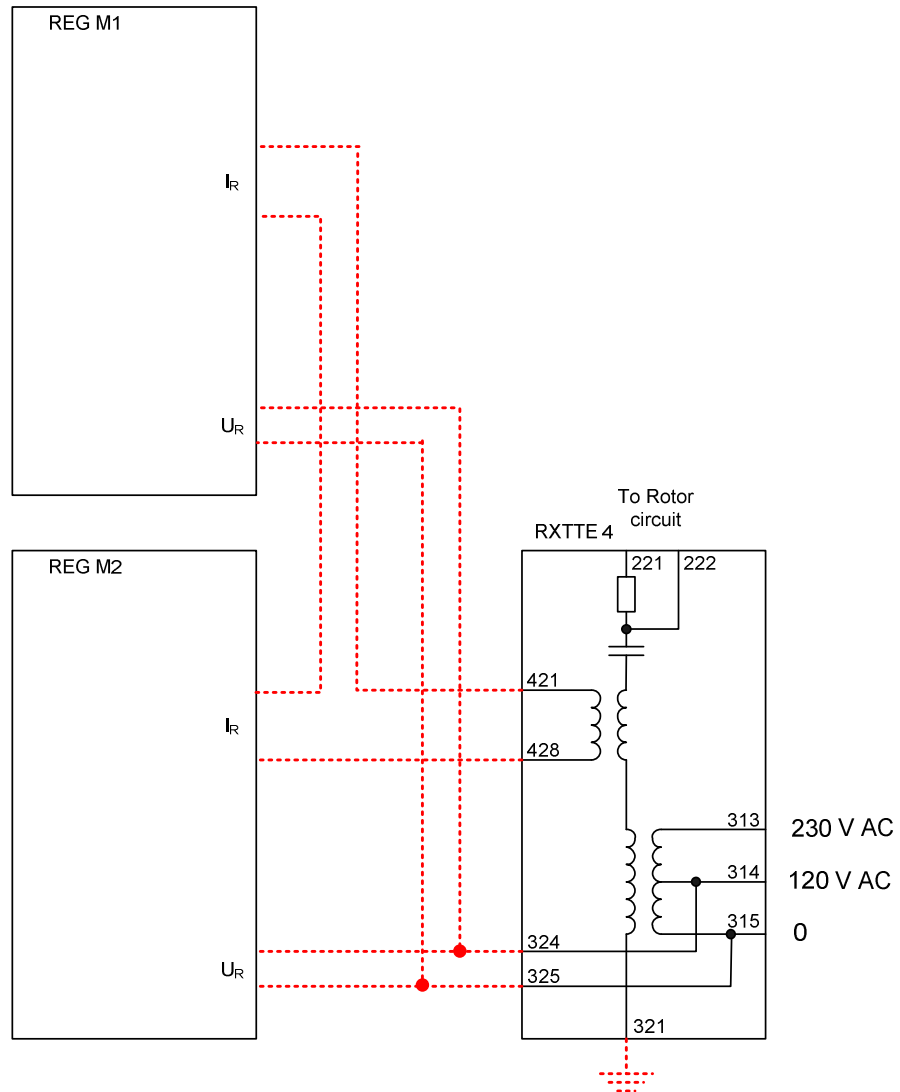

Figure 4: Connection of RXTTE4 in order to obtain redundant measurement

Some generators are equipped with rotating exciter. In such applications RXTTE4 shall be connected as shown in Figure 5.
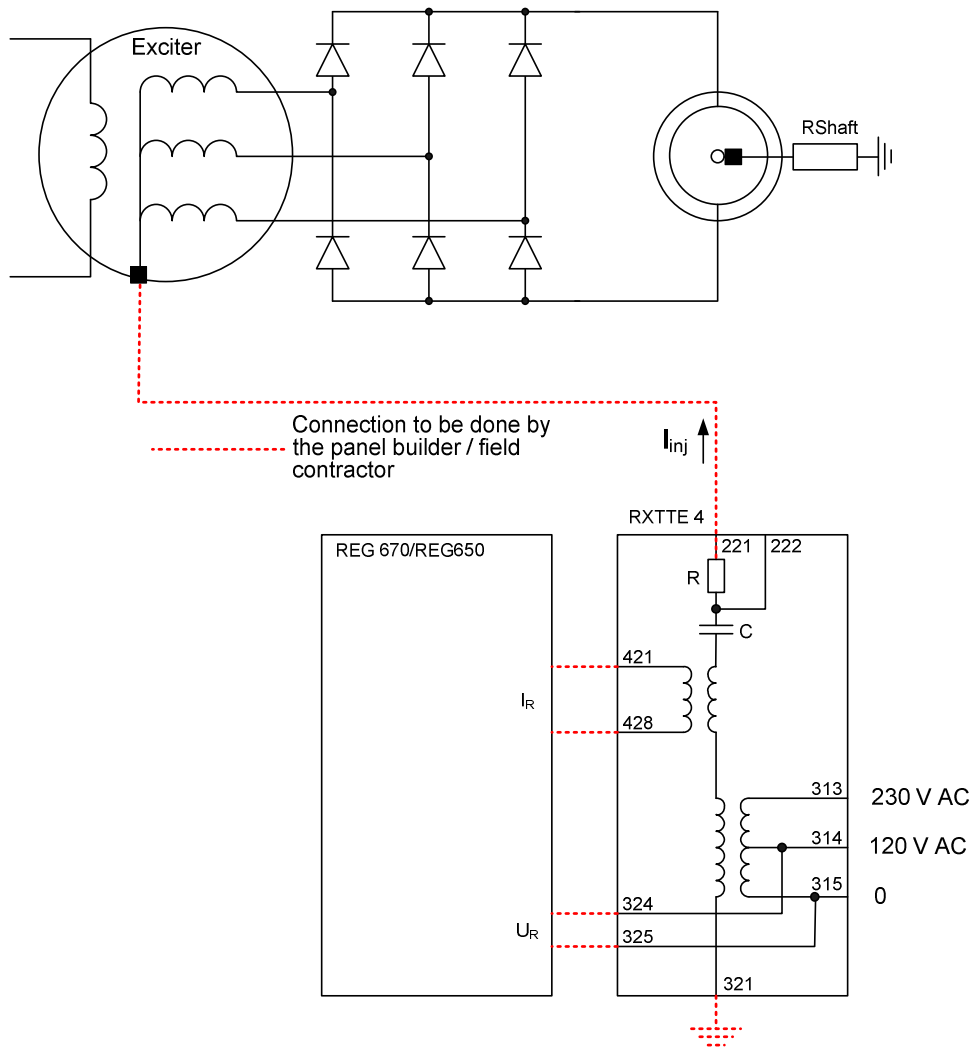
Figure 5: Connection of RXTTE4 to rotating exciter

2.1 Selection of injected voltage source

RXTTE4 need a reliable source of fundamental frequency 120V or 230V voltage signal. The following two solutions are typically used in practice:

1. One phase-to-phase VT voltage from the generator terminal is used as source of supply for the injection circuit. By using such connection injection voltage is automatically removed from the rotor circuit when generator is at standstill which may be desirable from the personal safety point if view. As a consequence rotor earth fault protection is disabled until generator is almost at full speed and excitation is applied. However note that injection voltage from RXTTE4 is in order or 40V and do not pose direct danger to the personnel.

2. Independent AC supply from the station auxiliary supply is used as source of supply for the injection circuit. Advantage of this approach is that rotor earth fault protection is active whenever this AC supply is connected to the injection unit.

Which of these two methods shall be used may depend on national safety standards and/or end-user operating practices.

3   External Resistor for RXTTE4

The external resistor is used when either there is a need to minimize physical exposure of the field circuit or when high harmonic content of the total injection current can cause overheating of the built-in RXTTE4 resistor.

The external resistor is delivered mounted on an insulated plate with overall dimensions Height=160mm, Width=135mm suitable for wall mounting, see Figure 6. It actually consists of two resistors (i.e. R1 and R2) which are on delivery connected in series.
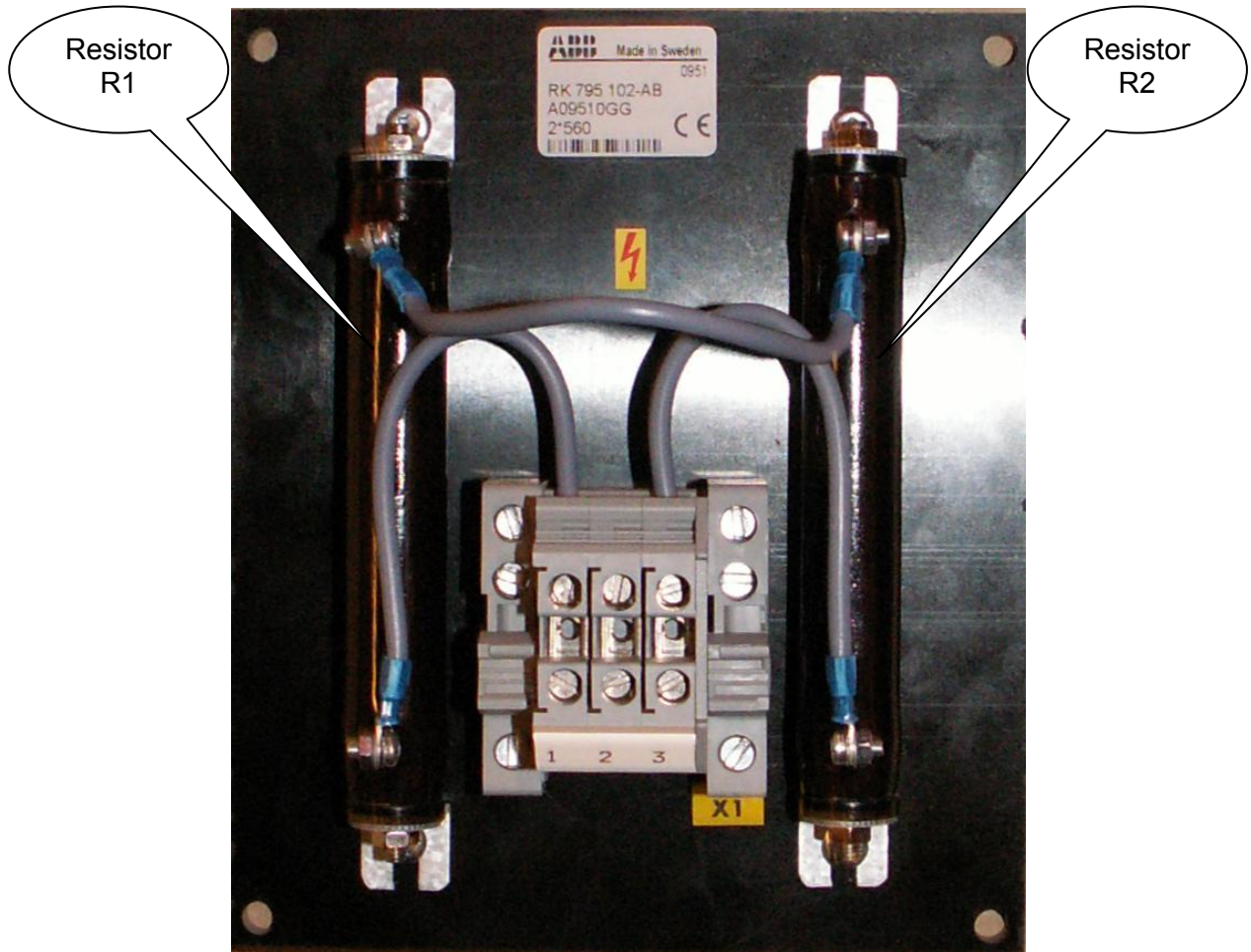

Figure 6: External resistor mounted on a plate

It is possible to order two different types of the external resistor as shown in Table 1:

Table 1: Ordering details and properties for external resistor

	Order Number for Complete Plate	R1 properties	R2 Properties
1	RK795102-AD	100Ω; 50W	120Ω; 50W
2	RK795102-AB	560Ω; 50W	560Ω; 50W

The first type (i.e. with ordering number RK795102-AD) has exactly the same ohmic value of 220Ω as the internal RXTTE4 resistor. It shall be used in cases where only physical exposure of the field circuit shall be limited.

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The second type (i.e. with ordering number RK795102-AB) has different ohmic value than internal RXTTE4 resistor. It shall be used in installations where current with high harmonic content is pushed back onto the RXTTE4 injection unit by the rotor circuit, see Section 5.1 for more information. Typically such installations are characterized by:

1. Small rotor capacitance to ground (i.e. C_R<2µF, see Figure 7)
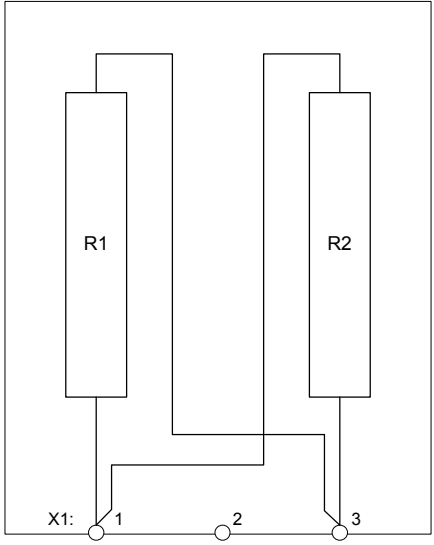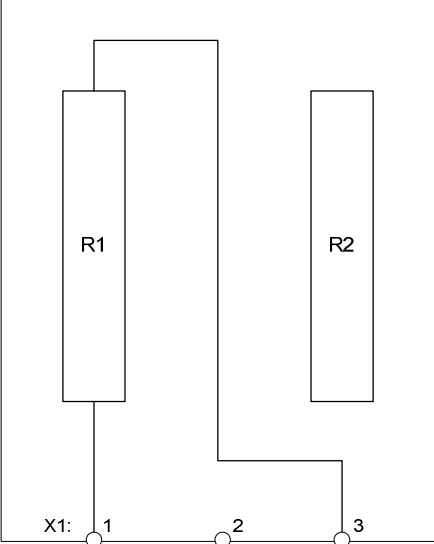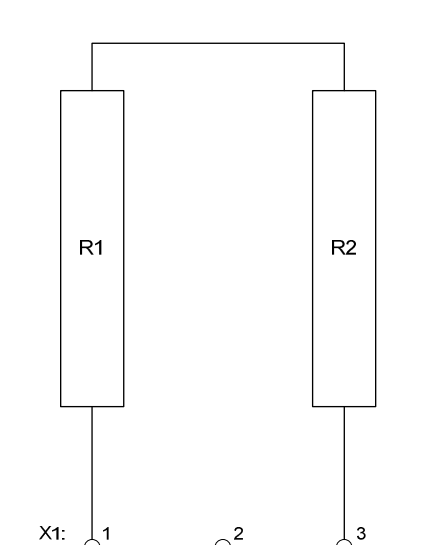
2. Static excitation equipment

In such installation it is preferable to use the second type of the external resistor because it actually offer possibility to change its ohmic value by simple using serial or parallel connection of the R1 and R2 resistors on the delivered plate. Note that three different ohmic values of 280Ω or 560Ω or 1120Ω are viable (see Table 2 for more details).

The following rules shall be used to decide when to switch to the external resistor and then how to select its ohmic value:

1. Total injected current I_{inj} (i.e. including all harmonic components) which flows through the RXTTE4 into the rotor must be smaller than 115mA in order to use the internal resistor. In practice it might be easier to measure voltage across the internal 220 Ω resistor instead (i.e. between terminals 221 and 222 on the RXTTE4 injection unit, see Figure 1). If this voltage is bigger than 25V external resistor must be used. Note that the used voltmeter shall be able to measure the total RMS voltage (i.e. including all harmonic components).

2. When external resistor shall be used its ohmic value should be the smallest one from the three values shown in Table 2, for which the total injected current (i.e. including all harmonic components, which flows through the RXTTE4 into the rotor) is smaller than 200mA. This limit is set in order to prevent internal RXTTE4 capacitor from overheating. In practice it might be easier to measure voltage across the external resistor instead (between terminals X1:1 and X1:3, see Table 2 and Figure 6) and then the following voltages shall not be exceeded:
   - 56V in order to use 280Ω external resistor
   - 112V in order to use 560Ω external resistor
   - 224V in order to use 1120Ω external resistor

   Once more please note that used voltmeter shall be able to measure the total true RMS voltage (i.e. including all harmonic components).

Table 2: Different ohmic values with RK795102-AB depending on used connections

External resistor ohmic value	Required connection for R1 and R2
280Ω * (parallel connection of R1 & R2)	
560Ω * (use just R1)	
1120Ω (serial connection of R1 & R2)	

* Requires wiring change of the factory delivered external resistor

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4 Relay Operating Principles and Settings

A fundamental frequency voltage (i.e. 50Hz or 60Hz) is injected via the injection unit RXTTE4 into the generator field winding circuit. Typically the injected voltage towards the rotor circuit is around 40V. This voltage forms a small current I_{inj} (see Figure 2) which flows via internal capacitor C and resistor R into the connected rotor circuitry. The internal current transformer (ICT) of the RXTTE4 then amplifies this current with its ratio 1:10 to a measurable level by the selected current input on the REG IED. Note that current I_{inj} has its path via rotor winding isolation resistance and rotor winding capacitance to rotor axle.

The rotor axle is grounded either via turbine (e.g. contact between turbine blades and water for the hydro units) or via dedicated grounding brush on to the rotor axle. The grounding brush is connected to earth either directly or via an additional shaft resistance (see RShaft in Figure 2 and Figure 7). When RXTTE4 is used condition $RShaft \leq 200\Omega$ shall be fulfilled. The following equivalent circuit can then be drawn for the RXTTE4:
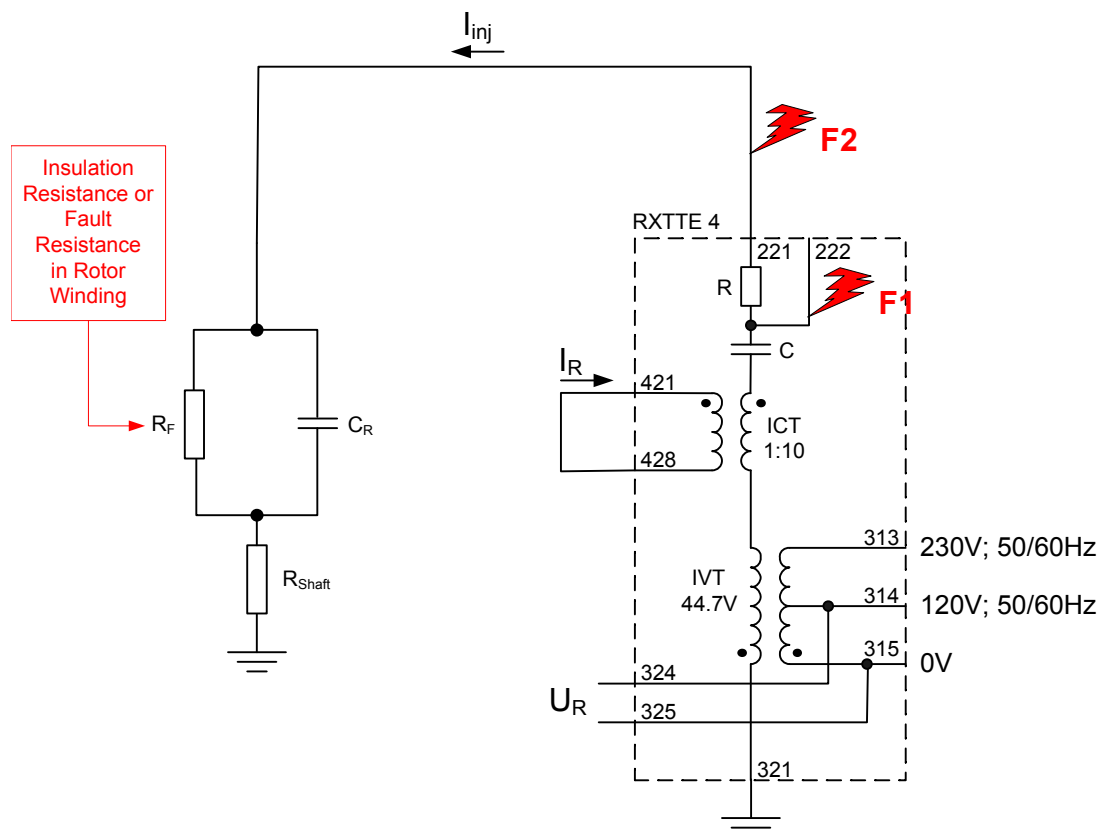

Figure 7: RXTTE4 equivalent circuit when internal resistor is used

Where new quantities are:

- C_R is rotor winding capacitance to ground
- R_F is fault resistance or rotor winding insulation resistance in fail-free situation
- R_{Shaft} is shaft grounding resistance (if existing)
- I_R is measured current by the REG IED
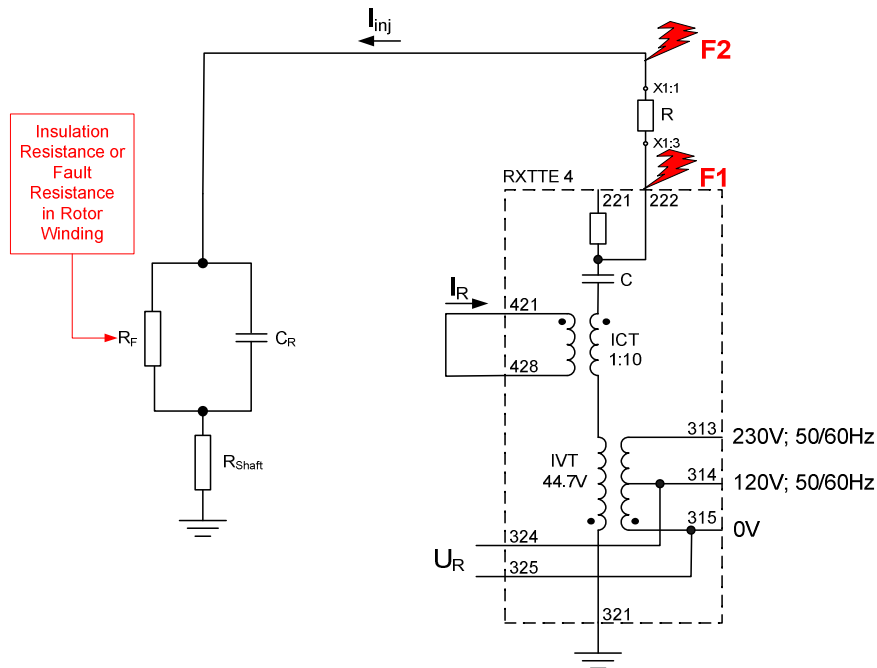- U_R is measured voltage by the REG IED

Figure 8: RXTTE4 equivalent circuit when external resistor is used

Because the equivalent circuit only contains resistive and capacitive elements, current measured by the IED will lead the injected voltage for angle β, as shown in Figure 9.
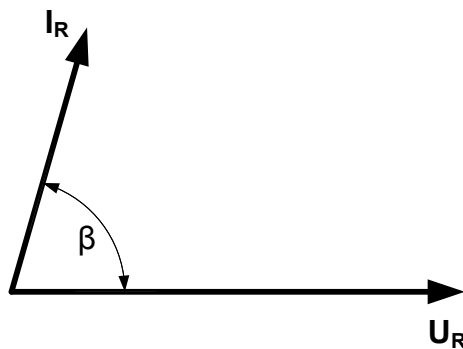

Figure 9: Phasor diagram of the measured quantities by the IED

During fault-free situation (i.e. normal operation) angle β will have value close to +90˚ (i.e. current will lead the voltage for this angle). This shall be verified during commissioning by using Measurement Menu on the IED built-in HMI. During fault conditions, the fault resistance R_F becomes smaller. Consequently the current I_R magnitude increases while the angle β decreases causing the active current component of the injected current (i.e. current in phase with the injected voltage; calculated as product $I_R \cdot \cos \beta$) to increase.

Thus a single phase, directional overcurrent protection function which operation is based on the fundamental frequency magnitude of the active component of the injected current (i.e. $I_R \cdot \cos \beta$) can be used to provide rotor earth fault protection. Note that injected voltage U_R is used as polarizing quantity. Typically two such directional stages are used. One stage is then used for alarm and the second stage for tripping. In REG670 either multipurpose function (i.e. CV GAPC) or four stage earth fault function (i.e. EF4 PTOC) can be used. In REG650 either sensitive earth fault function (i.e. SDE PSDE) or four stage earth fault function (i.e. EF4 PTOC) can be used. However in REG670 typically GF function is used because it offers additional features like under current stage (can be used for supervision of the integrity of the injection path on bigger generators) and under-voltage stage (can be used for supervision of the magnitude of the injection voltage).

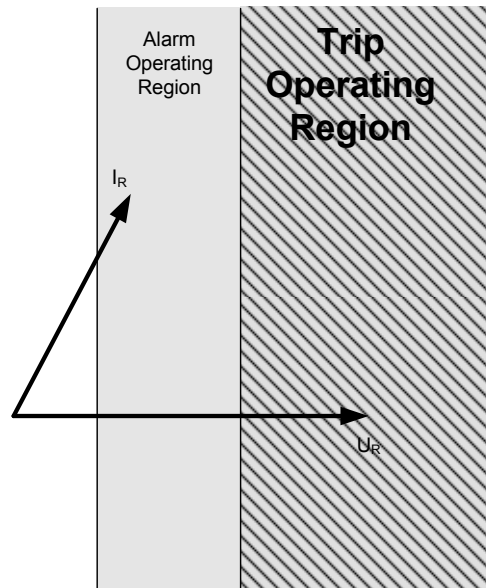Example of the operating characteristic for the directional overcurrent principle is shown in Figure 10.

Figure 10: Relay operating characteristic

Note that due to internal CV GAPC function convention reported service value for angle between current and voltage from the function will be shown with a negative sign (e.g. -84˚) when measured current leads the measured voltage.

4.1 Settings and commissioning procedure when multipurpose function (i.e. CV GAPC) is used

Typically rotor earth fault alarm and trip values are specified as fault resistance (e.g. R_{Alarm}=5kΩ and R_{Trip}=500Ω). These two values can be converted to directional overcurrent function pickup settings only during commissioning. The reason is that they are dependent on actual site condition like magnitude of the injected voltage, rotor capacitance and used value of series resistor in RXTTE4.

The following procedure shall be used during commissioning to determine the final function current pickup settings:

1) Check that used CT and VT inputs in the IED have set ratio of 1000A/1A and 100kV/100V respectively.

2) Set function parameters as follows:
   In group *General / setting Group 1:*
   > *Current input*   = phase1
   > *IBase*   =1000A
   > *Voltage input*   = phase1
   > *UBase*   =100kV
   > *RCADir*   = 0 degrees
   In group *OCn / Setting group 1:*
   > *DirMode_OCn*   =Forward   (n=1 or 2)
   > *DirPrinc_OCn*   =IcosPhi&U   (n=1 or 2)

3) When RXTTE4 is prepared (i.e. fundamental frequency supply connected and rotor winding connected but machine at standstill) write down U_R, I_R, β and $I_R \cdot \cos β$ during fault-free condition. All four values are actually directly available as service values from the function. Make sure that the current lead the voltage for almost 90°. Note that the angle service value from the CV GAPC function will be shown with a minus sign (e.g. as -85°).

4) Connect the required alarm fault resistance (e.g. 5kΩ) between the connection point of the injection cable to the rotor circuit and the ground (i.e. fault point F2 in Figure 7 or Figure 8). Write down U_R, I_R, β and $I_R \cdot \cos β$ values.

5) Set the pickup value of the directional overcurrent alarm stage 2% under obtained value $I_R \cdot \cos β$ from the previous point. Set desired alarm time delay (e.g. ten seconds). Make sure that this stage now operates and give alarm signal in accordance with the protection scheme design.

6) Instead of the alarm resistance connect now the required trip fault resistance (e.g. 500Ω) to the same point. Write down U_R, I_R, β and $I_R \cdot \cos β$ values.

7) Set the pickup value of the directional overcurrent tripping stage 2% under obtained value $I_R \cdot \cos β$ from the previous point. Set desired alarm time delay (e.g. two seconds). Make sure that the trip stage now operates and give required trip signal in accordance with the protection scheme design.

8) Remove the trip fault resistance from the circuit. Write down U_R, I_R, β and $I_R \cdot \cos β$ values. Make sure that they are the same as under point 3) above.

Rotor earth fault protection is now set in accordance with the fault resistance settings.

It is also recommended to calculate the maximum possible fault current which will be obtained for earth fault in locations F1 and F2 as shown in Figure 7 and Figure 8. This maximum fault current magnitude can be estimated by using the following equation:

$$I_{F\_Max}[mA] = \frac{1000 \cdot U_R[kV]}{K};$$ with leading phase angle β in respect to injected voltage.

Where:

- I_{F_Max} [mA] maximum fault current magnitude in mA

- U_R [kV] injected voltage magnitude in kV as measured by the IED during fault-free operating condition

- K constant dependent on used resistor and injected frequency (see Table 3)

- βm is angle for which will the maximum fault current leads the injected voltage

Table 3: Parameters to estimate maximum feasible fault current measured by the IED

Used Resistor	Fault at point	f=50Hz	f=60Hz
Any (i.e. Not Relevant)	F1*	K= 125.7 & βm=+90°	K= 104.7 & βm=+90°
R=220 Ω	F2*	K= 138.9 & βm=+64.8°	K= 120.3 & βm=+60.6°
R=280 Ω	F2*	K= 146.5 & βm=+59.1°	K= 129 & βm=+54.3°
R=560 Ω	F2*	K= 196 & βm=+39.9°	K= 183.3 & βm=+34.9°
R=1120 Ω	F2*	K= 326 & βm=+22.7°	K= 318.5 & βm=+19.2°

* Fault point as shown in Figure 7 or Figure 8

Make sure that set alarm and trip current levels are smaller than the product $I_{F\_Max} \cdot \cos(\beta m)$ for the fault at F2 relevant for your installation (see Table 3 above).

5 External influencing quantities

5.1 Harmonics posed by the rotor circuit onto RXTTE4

Static excitation supply to the rotor circuit can cause quite complex rotor winding voltage patterns. Measured rotor voltage to ground in one installation is shown in Figure 11.
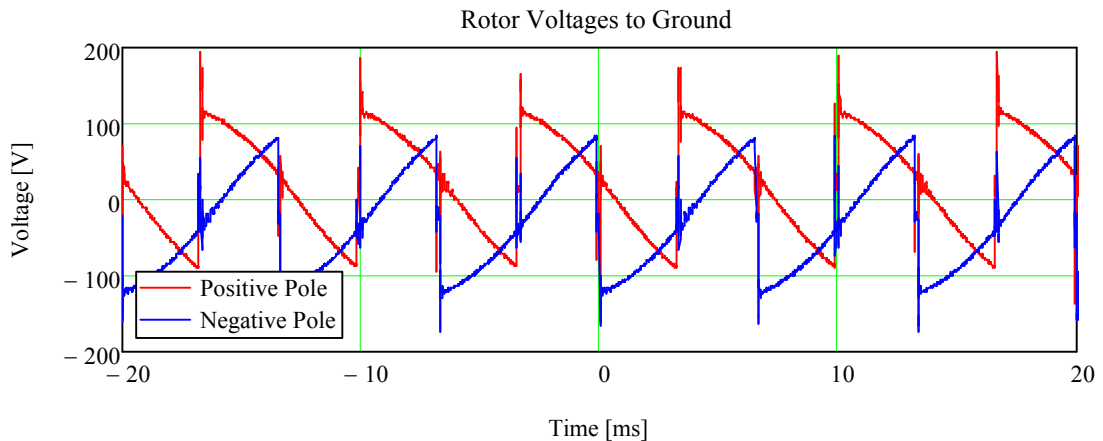
Figure 11: Example of Rotor Voltage to Ground for 50Hz Static Excitation Supply

Note that the magnitude of these two voltages may also depend on the design of the R-C filter circuit which is typically present in the static excitation system. This filter is typically called "shaft voltage suppressor".

This rotor voltage to ground will cause additional current through the RXTTE4 injection unit which will be reach in harmonics. The frequency spectrum of the total injected current I$_{inj}$ from another RXTTE4 installation is shown in Figure 12:
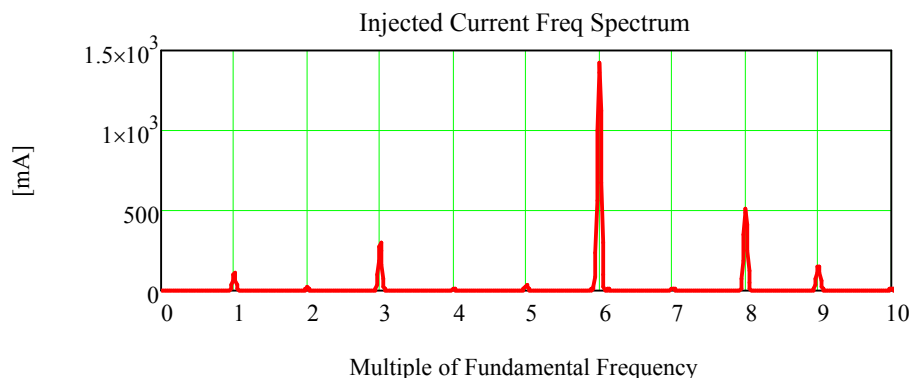
Figure 12: Frequency Spectrum of I$_{inj}$

Obviously the sixth harmonic current component is the most dominant one. It is couple of time bigger than the fundamental frequency current component caused by the RXTTE4 itself. Such high total RMS value of the injected current can be sufficiently high to overheat the RXTTE4. In such case external protective resistor must be used. Note that

these harmonic current components will not be visible as service value from REG IED. The reason is that REG IED is designed to measure and show only the fundamental frequency current component. For more information please refer to Section 3.

5.2 Earth faults on the AC side of the static excitation circuit

With static exciter it is possible to get earth fault either on a DC side or on an AC side of the rectifier bridge as shown in Figure 13.
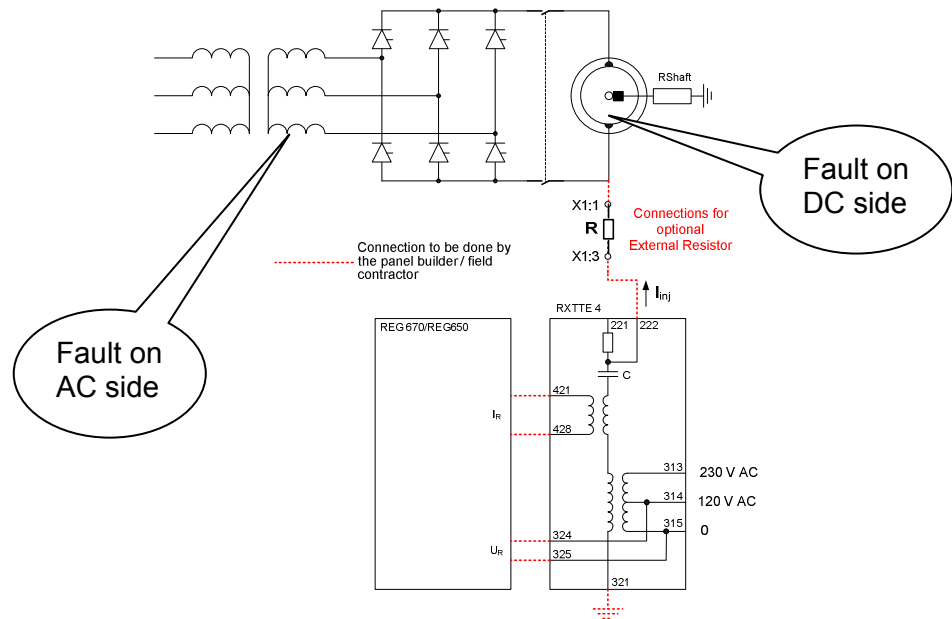

Figure 13: Connection of RXTTE4 to the rotor winding via protecting resistor

Note that for earth faults on the AC side an additional fundamental frequency voltage component will be superimposed onto the RXTTE4 circuit. Magnitude of this voltage component can vary from zero volts up to full phase-to-ground voltage depending on exact fault location point within the secondary winding of the excitation transformer. Thus, the resultant fundamental frequency current I_R measured by the IED can have any phase angle and magnitude much higher than injection current caused by the RXTTE4 itself.

Therefore typically third non-directional over-current protection stage (see Section 4.1) is used in order to trip for such condition. It setting shall be set 10% below the maximum fault current level calculated for fault at point F1 (see the second row in Table 3 for more information). To achieve this functionality separate CV GAPC function shall be used because each CV GAPC function has only two over-current stages. When EF4 PTOC function is used third over-current stage already available in this function shall be used for this purpose, but it shall be set as non-directional.

Note that it is strongly recommend to trip for faults on the AC side of the exciter because RXTTE4 design limits will be excited for such type of faults. If machine is not tripped promptly RXTTE4 components may be overheated and will consequently burn out.

6   Mounting of RXTTE4

Note that in order to mount injection unit RXTTE4 some COMBIFLEX accessories are required. First of all one COMBIFLEX terminal base type RX4 is needed in order to plug-in the RXTTE4 injection unit. This RX4 base can be rack, flash, case or DIN-rail mounted inside the panel. For any of these mounting alternatives, relevant COMBIFLEX accessories are needed. Finally, to wire the RX4 base, COMBIFLEX 10A and 20A contact sockets as well as COMBIFLEX crimping tool for attaching these sockets to leads are required. More information about all these COMBIFLEX accessories can be found in ABB document "Builder's Guide - COMBIFLEX®" with document number 1MRK 509 075-MEN.

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REVISION

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A		Document Created	P/ZG
B		Correction about CT earthing parameter	P/ZG
C		Final corrections for REG670	P/ZG
D		REG650 and RXTTE4 mounting added	P/ZG
E	P: 11; C: 4.1 2)	Added setting values for parameters Current input; Voltage input and RCADir.	PA/OW-E

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