Protecting Harmonic Filters in a ±600 kV HVDC Installation

Eduardo Brandi
Furnas

Ricardo Abboud and Fernando Calero
Schweitzer Engineering Laboratories, Inc.

Presented at the
42nd Annual Western Protective Relay Conference
Spokane, Washington
October 20–22, 2015

Protecting Harmonic Filters in a ±600 kV HVDC Installation

Eduardo Brandi, *Furnas*
Ricardo Abboud and Fernando Calero, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Many power electronic applications use harmonic filters to filter out harmonics generated by the conversion process. As a part of the Madeira River Interconnection, two long bipolar 600 kV high-voltage direct current transmission lines connect the Porto Velho and Araraquara stations over a distance of 2,400 km. This paper presents the protective relaying philosophy adopted for the protection of the harmonic filters present in this application.**

Specifically, we describe a scheme that protects the harmonic filters at each of these two substations associated with the bipolar transmission lines. The scheme protects each of the harmonic filter components individually. The innovative protective relaying functions presented include the thermal protection of the filter reactors, which are able to calculate the heating effects associated with harmonics up to the 49th. To detect the loss of filter characteristics due to element failures, we apply "filter detuning" protection. This function operates by monitoring fundamental frequency currents in various elements of the filter.

I. Introduction

The large Santo Antônio (3,150 MW) and Jirau (3,300 MW) hydroelectric power plants located on the Madeira River, in the Rondônia state in Brazil, are connected to the Brazilian National Interconnected System (SIN – Sistema Interligado Nacional). The bipolar 600 kV high-voltage direct current (HVDC) transmission line originates at the Porto Velho rectifier station in the state of Rondônia and terminates at the Araraquara inverter station in the state of São Paulo (2,400 km away), as shown in Fig. 1.

The Madeira River HVDC system comprises a total of 7,100 MW of converter capacity. This system transmits power from the hydroelectric plants of Santo Antônio and Jirau (located on the Madeira River, close to Porto Velho) to the Araraquara inverter station, which is close to the load centers in southeastern Brazil.

This is the first project to take advantage of the hydroelectric potential of the Amazon River [1]. Two bipolar dc transmission lines (denoted as Bipole 1 and Bipole 2), which are 2,400 km long, transport power from the two previously mentioned power plants in Rondônia to the load centers in São Paulo, as shown in Fig. 1. For economic reasons, HVDC transmission lines were selected for this project. However, the rectifier and inverter stations are sources of harmonics in the power system. This is due to the switching and commutation of the thyristors. Therefore, it is essential to use and apply harmonic filters to decrease the harmonics injected by the rectification and inversion process in the Brazilian power system (SIN). This will guarantee that the harmonic levels do not compromise the power quality, as established by Brazilian standards and the Operator of the National Electricity System (ONS – Operador Nacional do Sistema Elétrico) [2]. However, a major disadvantage of HVDC converters is that they require reactive power for the commutation process. Thyristor-based converters always absorb reactive power, behaving in the same way as a shunt reactor.

The conversion process (both rectification and inversion) requires reactive power, and harmonic filters are sources of reactive power when voltage is present in the busbar. Without a reactive power source, the conversion process cannot occur; therefore, the harmonic filter protective relaying must be secure and reliable.

Fig. 1. 2,400 km bipolar 600 kV HVDC transmission lines connect the Porto Velho rectifier station and the Araraquara inverter station

Fig. 2 shows the simplified system diagram of the two bipoles [3]. The Interligação Elétrica do Madeira (IE Madeira) project consists of Bipole 2 and the ac filters, which are highlighted by blue ellipses in the figure. The protection of these ac filters is the focus of this paper. Bipole 1 and the other components are part of a different project.

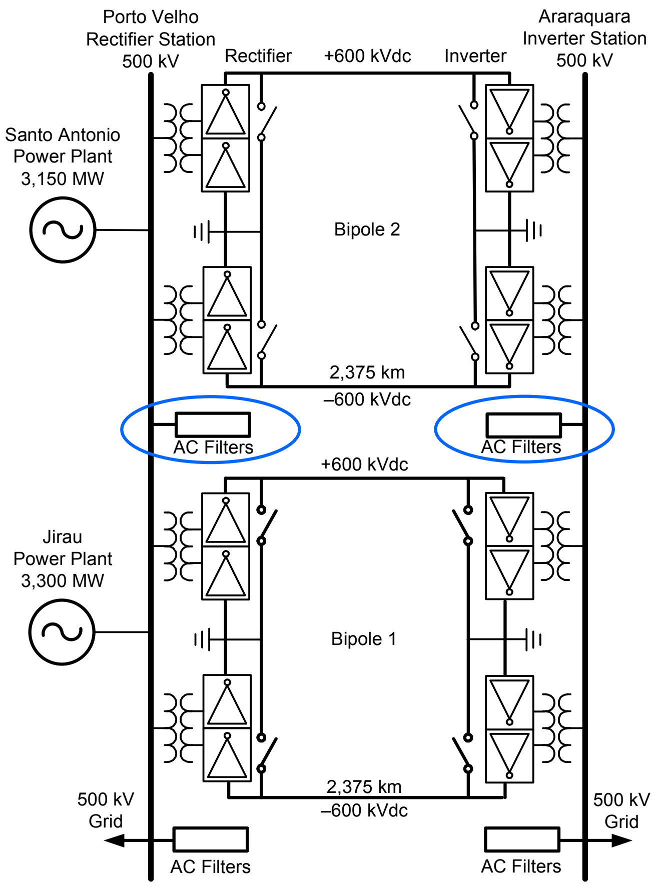

Fig. 2. System diagram of the IE Madeira project

The two power plants, Santo Antônio and Jirau, send power to the Porto Velho rectifier station via 500 kV transmission lines. The ac filters are located on the 500 kV side. Similarly, at the Araraquara inverter station, harmonic filters are located on the 500 kV busbar.

Because this is an extra-high voltage (EHV) application (500 kV) with a very high power flow, the harmonic filters have complex arrangements. The harmonic filters consist of a combination of capacitors in an "H-bridge" configuration, reactors, resistors, and additional auxiliary capacitor units. Each of these components is designed specifically for the application. In the case of the capacitors, they are made of individual units that are connected appropriately to achieve the required capacitance. Physically, there are three filters, one per phase, that are located several meters apart. This greatly reduces the possibility of a phase-to-phase fault. The main faults to be considered are ground faults and overloads.

The arrangement of harmonic filters in the IE Madeira project consists of six harmonic filters in the Araraquara inverter station and five in the Porto Velho rectifier station. The nominal power and the harmonic order, which these filters are tuned to, are different for each of the filter banks. The different configurations and types of filter banks are shown in Section II.

II. Technical Data and Filter Arrangement

At the Porto Velho rectifier station, there are two Type A, two Type B, and one Type C harmonic filter banks, each rated at 247 MVAR. Type A filters are tuned to filter out the 3rd, the 13th, and the 40th harmonics. Type B filters are tuned to filter out the 5th, the 11th, and the 23rd harmonics. The Type C filter is tuned to filter out the 13th and the 31st harmonics. Fig. 3 illustrates the arrangement and the technical data for these filters in the Porto Velho rectifier station [4].

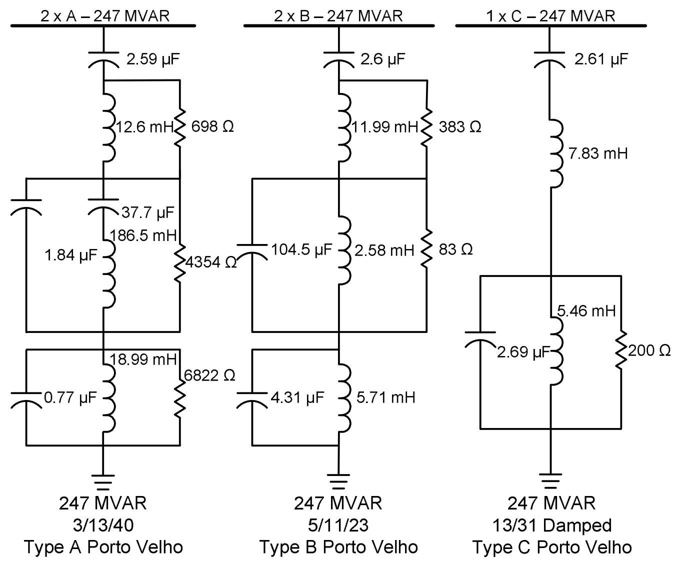

Fig. 3. Filter data in the Porto Velho rectifier station

At the Araraquara inverter station, there are four Type D harmonic filter banks and two Type E shunt capacitor banks. The Type D filters (305 MVAR) are tuned at the 12th and the 24th harmonics in order to filter out the 11th, the 13th, and the 23rd harmonics. The Type E (316 MVAR) shunt capacitor banks are designed with shunt capacitors and a small inductor. Fig. 4 shows the arrangement and the technical data for the filters at the Araraquara inverter station [4].

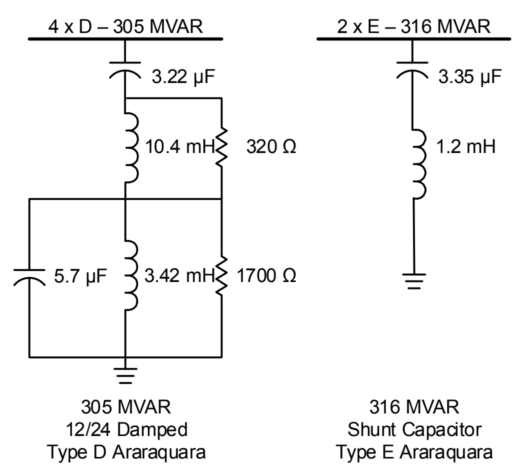

Fig. 4. Filter data in Araraquara inverter station

The discussion that follows concentrates on the Type A filters located at the Porto Velho rectifier station. This type of filter consists of the highest number of components, as shown in Fig. 3. The philosophy and techniques used in the protection of each element of this filter can be extended to others in both the Porto Velho rectifier station and the Araraquara inverter station.

III. Protective Relaying Connections and Functions

The protective relaying philosophy requires that each filter bank have a system to monitor the current and temperature of each component. This system must provide adequate protection and alert the operating personnel to any abnormal operating conditions in a timely manner so that appropriate action can be taken to prevent component damage [1].

To accomplish this requirement, a dedicated protective intelligent electronic device (IED) was installed for each of the main components of the filter, such as main capacitor banks, reactors, and resistors. Fig. 5 illustrates the connections and locations of the measurements for the IEDs implementing the protection functions for the Type A filters in the Porto Velho rectifier station. The figure shows only the main protection functions in each IED. For example, IED F61C1 is responsible for protecting the C1 capacitor bank. This IED also detects capacitive element failure (61) and provides breaker failure protection (50BF), overvoltage protection (59), and overcurrent backup protection (51RMS). IEDs F49R1, F49R2, and F49R3 protect resistors R1, R2, and R3, respectively. IEDs F49L1, F49L2, and F49L3 protect reactors L1, L2, and L3, respectively. The main protective function in these last six IEDs is the thermal replica (49).

The auxiliary capacitors (C2, C2a, and C3) in Fig. 5 are also included in the protection scheme. We discuss the protection of these elements in Section IV. These components are protected with a dedicated real-time automation controller that uses measurements provided by the IEDs described above. This controller is denoted as P1 in Fig. 5 and also includes an ambient temperature sensor input, denoted as P2. Communication between the IEDs and the real-time automation controller occurs through an Ethernet network, applying IEC 61850 manufacturing message specification (MMS) and IEC 61850 Generic Object-Oriented Substation Event (GOOSE) protocols.

To improve the protection system reliability, the IEDs provide backup protection for adjacent components. Table I summarizes the protective functions in each IED provided for protection of the Type A harmonic filters at the Porto Velho rectifier station.

Reference [4] provides details about the harmonic performance and rating of the harmonic filters. This topic is outside the scope of this paper; however, it is worth noting that each component in the filter has a test report with its characteristics defined at different harmonic frequencies. The test reports are provided by the manufacturers of the individual filter bank components. The frequency response of each component is taken into consideration when proposing the protection schemes.

It is important to note that the IEDs implement frequency tracking. The power system rarely operates at its nominal frequency (60 Hz in Brazil) and deviations should be measured. The fundamental frequency and its harmonics are not set; therefore, executing frequency tracking is an important characteristic of the IEDs, especially those implementing the thermal replica (49) protection that measures the harmonics.

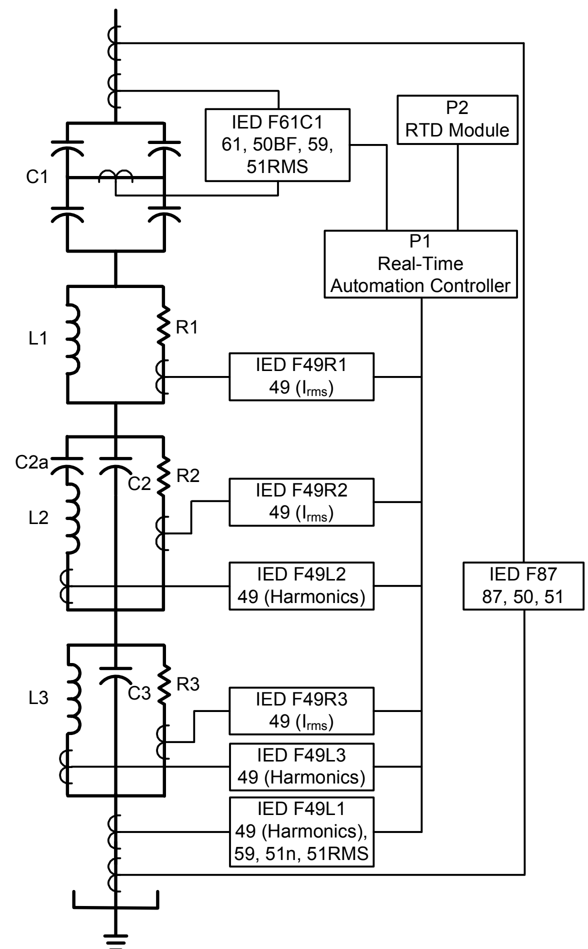

Fig. 5. Single-line diagram showing the principal functions of each IED for the Type A filter in the Porto Velho rectifier station

TABLE I
PROTECTIVE RELAYING FUNCTIONS IN THE SCHEME IEDS

IED	Protection Functions
F87	Differential element (87). Instantaneous overcurrent (50). Time-delayed overcurrent (51).
F61C1	Phase current unbalance for the C1 capacitor bank (61). Breaker failure (50BF). Overvoltage (59). I_{rms} overcurrent backup protection for Reactor L1 (51RMS).
F49L1	Thermal replica (49) for the L1 reactor (considering harmonic content). I_{rms} overcurrent backup protection for the entire filter (51RMS). Time-delayed residual overcurrent (51N). Overvoltage (59).
F49R1	Thermal replica (49) for the R1 resistor and backup for the L1 reactor.
F49L2	Thermal replica (49) for the L2 reactor (considering harmonic content).
F49R2	Thermal replica (49) for the R2 resistor and backup for the L2 reactor.
F49L3	Thermal replica (49) for the L3 reactor (considering harmonic content).
F49R3	Thermal replica (49) for the R3 resistor and backup for the L3 reactor.
P1	Provides "filter detuning" protection and detects faults in the auxiliary capacitors. Receives current and voltage measurements from the other IEDs through communication. Sends the values of the ambient temperature to all IEDs that implement the thermal replica function in order to compensate for the variations of the ambient temperature.
P2	Measures the ambient temperature using resistance temperature detector (RTD) sensors, Type PT100. This measurement is sent to P1 to be distributed to the IEDs that implement the thermal replica function in order to compensate for the variations of the ambient temperature.

IV. PROTECTIVE RELAYING SETTINGS PHILOSOPHY

A. Main Capacitor Bank Protection

The protection scheme for the main capacitor bank (C1) of the harmonic filter is the current unbalance (60 or 61) protection for the three phases.

The main capacitors for the filters at the Porto Velho and Araraquara stations are configured as an H-bridge (i.e., as four arms, two series, two parallel, connected at the center), as shown in Fig. 6.

The values $C1_A$, $C1_B$, $C1_C$, and $C1_D$ are chosen such that, in a normal operating condition, the current flowing through the current transformer (CT), I_{UNB}, is zero. For this situation, the equivalent capacitance values are chosen to meet the relationship in (1), in which the principle is the same as that of the Wheatstone bridge [5].

$$\frac{X_{C1A}}{X_{C1B}} = \frac{X_{C1C}}{X_{C1D}} \tag{1}$$

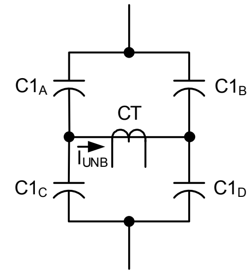

Fig. 6. H-bridge connection

Provided that all branches are balanced, according to (1), no current will flow through the CT. If a capacitive element fails, some current will flow through the midpoint CT. The unbalance protection for this capacitor bank relies on the measurement of the unbalance current of the midpoint CT.

A CT with a very low transformation ratio (5:1), allows the monitoring of the unbalance in the C1 capacitor bank. The H-bridge configuration, as shown in Fig. 6, allows the monitoring of the middle connection of the "H" section. Under normal conditions of operation, the measured currents should be zero. Failure of the capacitive elements in the capacitor bank will generate unbalance currents in that middle point. This unbalance will be detected by the associated protective IED that is measuring this unbalance. In fact, because of the construction tolerances in the characteristics of the capacitive elements, there may exist a "natural" current unbalance under steady-state conditions. The unbalance protection should have the ability to compensate for this natural current unbalance, in order to be as sensitive as possible.

The F61C1 IED provides unbalance protection (60) and automatically compensates for the natural current unbalance, avoiding misoperations and at the same time maintaining sensitivity to detect internal faults in the capacitor bank. This compensation eliminates the effect of the natural current unbalance in the protective scheme.

The objective of this protection scheme is to disconnect the capacitor bank prior to catastrophic failure while avoiding nuisance tripping because of occasional random failures. Failures in the capacitive elements result in a modification in the impedance of the branch, causing an unbalance within the bank and an increase in the voltage across some of the remaining elements [6]. A continuous overvoltage above the limit on any unit shall be prevented, and the filter must be tripped. According to IEEE C37.99-2000, abnormal operating conditions must be limited to 110 percent of the rated root-mean-square (rms) terminal voltage [7].

The F61C1 IED provides three stages of unbalance protection: the first stage is intended for alarming purposes, the second stage is a delayed trip, and the third stage is a fast trip. The alarm is triggered if two elements (capacitor cans) fail; the failure of a single element does not cause any significant change in the capacitor bank operation. Furthermore, the detection of one failed element is not practical. The delayed-trip setting is set to operate if there is a chance that the voltages across an element will exceed 150 percent of the nominal operating voltage. This is in accordance with 110 percent of the rated voltage. The rated voltage far exceeds the maximum fundamental frequency voltages under normal conditions. The fast-trip setting is designed to detect flashover events; therefore, for security, it will have a time delay of 80 milliseconds.

Table II lists the unbalance secondary current values for the number of faulted capacitive elements in the capacitor bank, and Table III presents the settings proposed for the protective element. The study and determination for these unbalance levels was conducted by the filter manufacturer according to previously mentioned criteria, which are in agreement with recommendations found in [7].

TABLE II
UNBALANCE CURRENTS FOR A NUMBER OF CAPACITIVE ELEMENTS IN A CAPACITOR BANK

Faulted Capacitive Elements	Unbalance Current (mA sec)
1	5–10
2	13–21
3	23–35
4	36–53
5	52–75
6	73–105
7	102–145
8	144–205
9	213–301
10	342–481

TABLE III
PROPOSED SETTINGS FOR THE CURRENT UNBALANCE FUNCTION (60)

Level/Stage	Number of Faulted Capacitive Elements	Pickup Current (mA sec)	Time Delay (s)
Alarm	2	12	300
Trip	5	52	7,200
Fast trip	7	103	0.08

B. Harmonic Filter Reactor Protection

The reactors in the filters are protected, ensuring that they operate within their thermal capability. The main functionality of the F49L1, F49L2, and F49L3 IEDs is to implement the overload thermal protection using a thermal replica (49). The objective of this protection function is to detect operating conditions that could damage the filter performance over time.

As backup protection, the IEDs connected to the CTs protecting the filter resistors (F49R1, F49R2, and F49R3) also implement the thermal protection of the reactors using a compensation factor. This is discussed in Section IV, Subsection G.

Because of the conductor's skin effect, the resistance of the reactor is not constant at different frequencies and it increases as the frequency of the through current increases. This relates to the diminishing area of conduction in the conductor at higher frequencies. The increase of the resistance value at higher frequencies because of the skin effect has been considered when implementing the thermal replica of the reactor. The different resistance values are taken into account when calculating the thermal effect of the higher harmonics, which is proportional to I^2R.

Thirteen harmonic frequency components have been considered for the thermal replica (49) protection of each reactor. These harmonics represent the most relevant harmonics that can be measured based on the conversion process of the HVDC installation. These harmonics were identified using simulations and computational techniques that replicate the conversion process. This study is described in [4].

The F49Ln (n = 1, 2, or 3) IEDs measure harmonics and conform to IEC 61000-4-30 [8]. The IEDs are able to measure individual harmonics up to the 63rd order. Table IV shows the most relevant harmonics for each reactor for the Type A harmonic filters in the Porto Velho rectifier station.

TABLE IV
RELEVANT HARMONICS FOR THE REACTORS IN THE TYPE A HARMONIC FILTERS AT THE PORTO VELHO RECTIFIER STATION

Reactor L1	Reactor L2	Reactor L3
1	1	1
2	2	3
3	3	11
7	4	13
9	5	15
11	6	17
13	7	19
15	8	23
17	9	25
35	10	35
37	11	37
47	13	47
49	15	49

The reactor temperature is not measured directly; however, it is emulated using a first-order thermal model. The temperature is determined by establishing the heat balance equation (i.e., heat input minus the heat losses). The model is explained in [9] and [10]. In this application, the harmonic currents are measured individually and the heat produced by each one is calculated taking into account the dependence of the resistance to the frequency. The frequency tracking capability in the IEDs is important to this protective function.

Fig. 7 shows an analog electrical circuit for the thermal element. The major components of the model are as follows:

- Heat source. Heat flow from the source is $\sum R_n I^2_n$ watts, where n is the harmonic order.
- Thermal capacity (C_T). Represents a reactor that has the capacity (C_T) to absorb heat from the heat source.
- Thermal resistance to ambient (TRA). Represents the heat dissipated by a reactor to its surroundings.

- Ambient temperature (T_A). The measured ambient temperature.
- Comparator. Compares the calculated reactor per unit temperature with a preset value based on the reactor manufacturer's data.

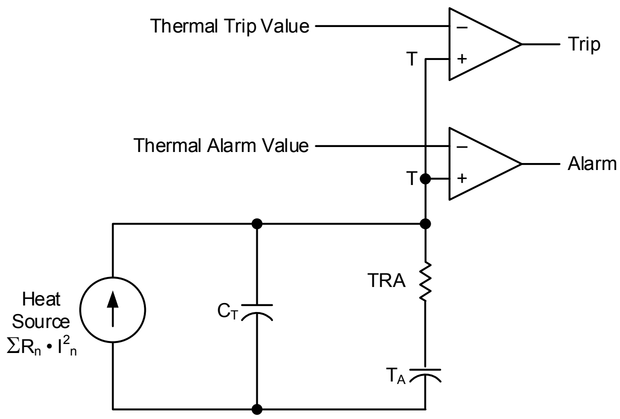

Fig. 7. Analog electrical circuit representing the thermal model of the filter reactors

Equation (2) shows the formula that is implemented in the IEDs, which represents the temperature T from Fig. 7:

$$T_j = \frac{\sum R_n \bullet I_n^2 \bullet N_{CT}^2}{C_T} \bullet \Delta t + T_{j-1} - \frac{T_{j-1} - T_A}{TRA \bullet C_T} \bullet \Delta t \qquad (2)$$

where:

T_j and T_{j-1} are the temperatures calculated in the process at j and a step before j–1 (°C).

R_n is the resistance of the "n" harmonic (Ω), based on Table V.

I_n is the measured current of the "n" harmonic (A sec).

N_{CT} is the CT ratio.

C_T is the estimated thermal capacity (kJ/°C).

Δt is the processing interval in the F49Ln (n = 1, 2, or 3) IEDs, which is 8 milliseconds.

T_A is the ambient temperature measured and provided by P1 and P2 in Fig. 5 (°C).

TRA is the thermal resistance to the ambient temperature, provided by the reactor's manufacturer (°C/kW).

The reactor's manufacturer supplied the resistor values of the reactor for each harmonic. Table V lists the reactor resistance variation at different harmonics. These values were used to implement the thermal model (49) protection function in the F49Ln (n = 1, 2, or 3) IEDs. The manufacturer also supplied all necessary data to implement the thermal model, including the thresholds for alarm and trip.

TABLE V
RESISTANCE VALUES AT DIFFERENT HARMONICS FOR THE CONDUCTORS OF EACH REACTOR

Order	**Reactor L1 R (mΩ)**	**Reactor L2 R (mΩ)**	**Reactor L3 R (mΩ)**
1	60	172	51
2	61	185	54
3	64	206	59
4	68	235	66
5	73	270	75
6	79	312	85
7	85	357	97
8	92	404	111
9	100	451	127
10	108	497	144
11	116	548	162
13	135	661	204
15	156	790	252
17	179	934	307
19	205	1,093	369
21	234	1,267	437
23	265	1,456	512
25	314	1,720	605
27	366	2,006	705
29	422	2,315	814
31	482	2,645	930
33	546	2,997	1,054
35	615	3,372	1,185
37	687	3,768	1,325
39	763	4,186	1,472
41	844	4,627	1,626
43	928	5,089	1,789
45	1,016	5,573	1,959
47	1,109	6,080	2,137
49	1,205	6,608	2,323

The thermal constants of the reactor, according to (2), are shown in Table VI.

TABLE VI
REACTOR DATA USED IN THE THERMAL REPLICA (49) PROTECTION

	Unit	Reactor L1	Reactor L2	Reactor L3
Inductance	mH	12.6	186.5	18.99
Specific heat – C_T	kJ/°C	319.0	3,162.0	965.3
Thermal resistance – TRA	°C/kW	6.64	2.56	3.08

Table VII shows the threshold temperatures used in the final settings. Two levels are considered, one for alarm and the other for tripping. The thresholds are based on the maximum operating temperature, which was calculated by the reactor's manufacturer.

TABLE VII
ALARM AND TRIP THRESHOLD LEVELS – REACTOR THERMAL REPLICA (49) PROTECTION

	Unit	Reactor L1	Reactor L2	Reactor L3
Temperature alarm	°C	120.6	129.8	118.3
Temperature trip	°C	130.6	139.8	128.3

When the calculated temperature reaches the trip threshold, the F49Ln (n = 1, 2, or 3) IEDs open the breakers associated with the harmonic filter. There is a 10°C hysteresis programmed. The trip signal does not reset immediately when the currents have been removed. Re-energizing the filter is not allowed until the reactor cools down sufficiently.

The thermal model algorithm maintains its execution even with the breaker open and will emulate the cooling of the reactor (i.e., the calculated temperature starts to decrease according to (2), considering that the current is zero).

The reactor thermal model algorithm was implemented in the F49Ln (n = 1, 2, or 3) IEDs using the available programmable logic functions.

The F49L1 IED does not measure the current of reactor L1 directly; however, as shown in Fig. 5, it measures the total current of the filter. This approach is possible because the reactor L1 current is very close to the total current of the filter. Table VIII shows the relationship of I_{L1}/I_{TOTAL} for several harmonic orders. For practical purposes, the total filter current is that of the L1 reactor.

TABLE VIII
RELATIONSHIP BETWEEN REACTOR L1 CURRENT AND THE TOTAL CURRENT OF THE FILTER

Harmonic	I_{L1}/I_{TOTAL}
1	0.99998
2	0.99991
3	0.99979
4	0.99963
5	0.99942
6	0.99917
7	0.99887
8	0.99852
9	0.99813
10	0.99769
11	0.99721
12	0.99668
13	0.99611
14	0.99549
15	0.99483
16	0.99412
17	0.99337
18	0.99258
19	0.99174
20	0.99086
40	0.96489

C. Harmonic Filter Resistor Protection

The protective relaying of the filter resistors follows the same principle used in the protection of the reactors. The main function of the F49R1, F49R2, and F49R3 IEDs is the thermal replica (49) protection for the Type A filter resistors at the Porto Velho rectifier station. The functionality implements the overload protection of these resistors. The objective of this protection function is to detect operating conditions that could damage or degrade the operation of the filter over time.

In the case of the resistors, as opposed to the discussion on the reactors in the previous section, the resistance variation for the different harmonic components is insignificant. The variation estimated is in the range of milliohms, compared to the actual value of the resistor, which is in hundreds of ohms. It is, therefore, possible to consider a single value of resistance. This value was provided by the resistor's manufacturer and is used in the thermal model for the filter resistor. In this protective scheme, it was unnecessary to consider the different harmonics and the rms measurement of the currents used to estimate the heating effect, instead of the individual harmonics. The rms current measurement performed by the IEDs (F49R1, F49R2, and F49R3) includes all harmonics up to the 63rd, which is the maximum capability of each IED.

Equation (3) shows the formula used to estimate the temperature of the filter resistors, which is similar to the one used for the inductors.

$$T_j = \frac{R \bullet I_{rms}^2 \bullet N_{CT}^2}{C_T} \bullet \Delta t + T_{j-1} - \frac{T_{j-1} - T_A}{TRA \bullet C_T} \bullet \Delta t \qquad (3)$$

where:

T_j and T_{j-1} are the temperatures calculated in the process at j and a step before j–1 (°C).

R is the resistive value of the resistor (Ω).

I_{rms} is the effective rms current (A sec).

N_{CT} is the CT ratio.

C_T is the estimated thermal capability (kJ/°C).

Δt is the processing interval in the F49Rn IEDs, which is 8 milliseconds.

T_A is the ambient temperature measured and provided by P1 and P2 in Fig. 5 (°C).

TRA is the thermal resistance to the ambient temperature, provided by the resistor's manufacturer (°C/kW).

The resistor's manufacturer supplied all necessary data to implement the thermal model, including the thresholds for alarm and trip.

Table IX shows the resistance values, as well as the particular thermal constants, according to (3), for each resistor (R1, R2, and R3) for the Type A filter.

TABLE IX
TECHNICAL DATA FOR THE PROTECTION OF THE TYPE A FILTER RESISTIVE COMPONENTS AT THE PORTO VELHO RECTIFIER STATION

	Unit	**R1 Resistor**	**R2 Resistor**	**R3 Resistor**
Resistance	Ω	698	4,354	6,822
Nominal power	kW	297	815	144
Specific heat – C_T	kJ/°C	37	55.5	16.5
Thermal resistance – TRA	°C/kW	1.3468	0.4294	3.4722

Table X shows the threshold temperatures used in the final settings. Two levels are considered, one for alarm and the other one for tripping. The thresholds are based on the maximum operating temperature, which is calculated by the resistor's manufacturer.

TABLE X
TRIP AND ALARM THRESHOLDS FOR THE THERMAL PROTECTION (49) OF THE FILTER RESISTORS

	Unit	**R1 Resistor**	**R2 Resistor**	**R3 Resistor**
Talarm	°C	430	380	530
Ttrip	°C	440	390	540

When the calculated temperature reaches the trip threshold, the F49Rn IEDs open the breakers associated with the harmonic filter. There is a 10ºC hysteresis programmed. The trip signal does not reset immediately when the currents have been removed. Re-energizing the filter is not allowed until the resistor cools down sufficiently.

The thermal model algorithm maintains its execution even with the breaker open and will emulate the cooling of the reactor (i.e., the calculated temperature starts to decrease according to (3), considering that the current is zero).

The resistor thermal model algorithm was implemented in the F49Rn (n = 1, 2, or 3) IEDs using the available programmable logic functions.

D. *Differential Protection*

The differential principle compares the outputs of the current transformers in all the circuits into and out of the protected area or zone [11]. Differential protection is one of the most effective means of protecting power equipment. In its simplest form, differential protection trips for a difference between the measured current entering and exiting the protected zone. The IED operates on the difference of the current instead of the total circuit current. This allows the IED with differential protection to have greater sensitivity to faults than other protection elements based on the measurement of total circuit current. The differential protection is highly selective because the zone of protection is precisely defined by the location of the CTs surrounding the protected zone. With high selectivity and sensitivity, a differential element can trip quickly without requiring any coordinating time interval.

As shown in Fig. 8, the F87 IED measures the current flowing in and out of each phase of the filter.

Differential protection is a fast and selective method of protection against short circuits; however, the application in a harmonic filter has some particularities. A phase-to-ground fault will cause current to decrease instead of increase with regard to the fundamental component as shown in Table XI. This decrease occurs because the total impedance from the busbar to the fault is larger than the total impedance of the filter.

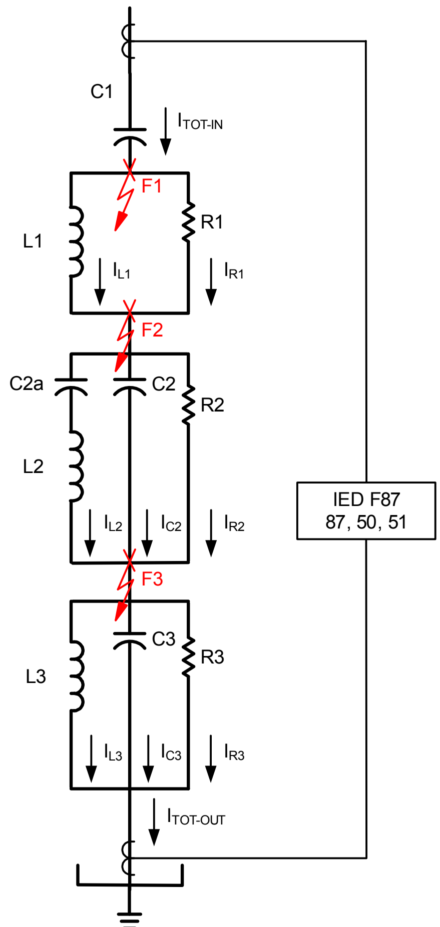

Fig. 8. Differential protection

During normal operation, the fundamental currents are I_{TOT-IN} = 281 A and $I_{TOT-OUT}$ = 281 A, which results in a differential current equal to zero. Table XI summarizes the current values for solid phase-to-ground faults at the different locations shown in Fig. 8.

TABLE XI
MEASURED FUNDAMENTAL CURRENT OF PHASE A BY THE DIFFERENTIAL PROTECTION FOR SOLID PHASE-TO-GROUND FAULTS AT DIFFERENT LOCATIONS

Location	IA_{TOT-IN} (A)	$IA_{TOT-OUT}$ (A)	IA_{DIF} (A)
Normal operation	281	281	0
F1	278	0	278
F2	172	0	172
F3	280	0	280

According to Table XI, the differential element must be sensitive enough to detect faults at location F2. In this specific application, the minimum setting of the F87 IED is 100 A, considering the CT ratio that has been applied; therefore, the F87 IED has enough sensitivity to detect faults at F2.

Short-circuit considerations are mainly for ground faults. The location of the filter components in the substation makes it very unlikely that a phase fault could happen; however, if this were the case, the differential protection provides the necessary protection.

E. Filter Detuning Protection

No specific capacitor unbalance protection is provided for the auxiliary capacitors. There are seven different auxiliary capacitor units supplied for the five filter types in this project. The detuning protection is required to detect major failures of the auxiliary capacitor units. The auxiliary capacitors are represented by C2, C2a, and C3 in Fig. 5.

The effects of failure in the elements of the auxiliary capacitors (C2, C2a, and C3 in the case of the Type A filter in the Porto Velho rectifier station) are summarized in Table XII.

TABLE XII
CAPACITANCE VARIATION BASED ON THE NUMBER OF FAULTED ELEMENTS IN THE AUXILIARY CAPACITORS

	Percentage Variation Compared to the Nominal Capacitance (%)		
Number of Failed Elements	**C2**	**C2a**	**C3**
1	1	2	3
2	2	4	6
3	3	8	9
4	5	14	13
5	7	29	16
6	9	–	20
7	12	–	24

There are no dedicated IEDs for detecting failures in the auxiliary capacitors; however, such failures can compromise the filter performance and defeat the effectiveness of filtering for the target harmonics, causing a detuning condition.

An innovative protection method was created specifically for this project to identify failed elements in the auxiliary capacitors. The method detects the detuning condition by measuring the proportion of resistor currents to the total filter current of the same specific harmonic order, selected according to filter characteristics.

The filter detuning protection function is based on the analysis and monitoring of variations in the ratios between circulating currents in the resistors and the total current of the filter at specific harmonic orders.

The F49L1, F49R2, and F49R3 IEDs, shown in Fig. 9, measure the specific harmonic currents used in the detuning protection and transmit them to a real-time automation controller, P1. This controller calculates the relationship between these harmonic measurements from the R2 (I_{R2}) and R3 (I_{R3}) resistors and the total current of the filter (I_{TOT}) to identify a detuning condition, verifying that these relationships are within the expected values and tolerances. If the measurements are outside of the tolerances, the controller declares a detuning condition and sends an alarm signal to the operator. At this time, no considerations are being made to disconnect the filter from this element, leaving the operator with the decision to take the filter out of service in a programmed way.

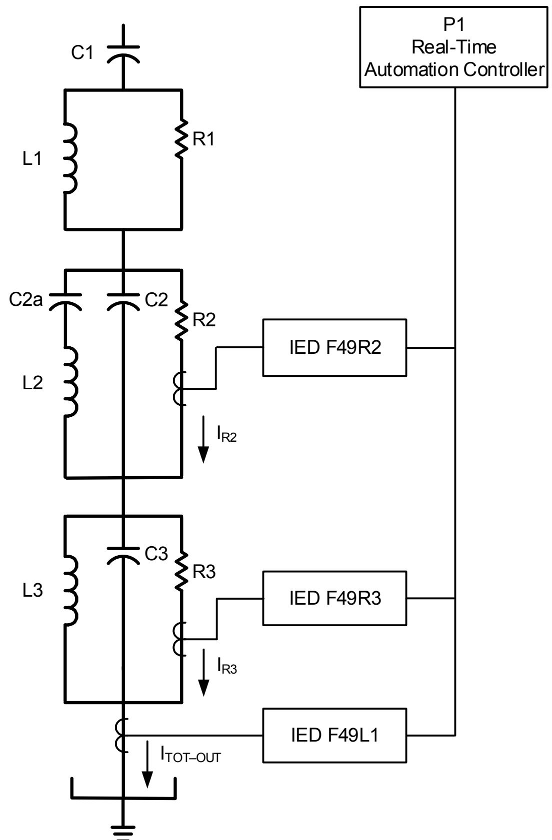

Fig. 9. Detuning protection

As previously mentioned, the detuning protection measures the proportion of resistor currents to the total filter current for some specific harmonic order. For variations in the auxiliary capacitors' impedances because of failed elements for the Type A filter in the Porto Velho rectifier station, Table XIII, Table XIV, and Table XV summarize the harmonic orders used in the detuning protection and the relationships of I_{R2}/I_{TOT} and I_{R3}/I_{TOT} for these harmonic orders.

TABLE XIII
VARIATIONS IN THE RELATIONSHIP OF THE R2 RESISTOR 5TH-HARMONIC CURRENT AND TOTAL 5TH-HARMONIC FILTER CURRENT FROM NOMINAL FOR FAILURES IN THE C2 AUXILIARY CAPACITOR

C2 auxiliary capacitor impedance variation from nominal (%)	5	10	20
I_{R2}/I_{TOT} 5th-harmonic variation from nonfailure condition	–21	–36	–56

TABLE XIV
VARIATIONS IN THE RELATIONSHIP OF THE R2 RESISTOR FUNDAMENTAL CURRENT AND TOTAL FILTER CURRENT FROM NOMINAL FOR FAILURES IN THE C2A AUXILIARY CAPACITOR

C2a auxiliary capacitor impedance variation from nominal (%)	5	10	20
I_{R2}/I_{TOT} fundamental current variation from nonfailure condition	133	267	537

TABLE XV
VARIATIONS IN THE RELATIONSHIP OF THE R3 RESISTOR 23RD-HARMONIC CURRENT AND TOTAL 23RD-HARMONIC FILTER CURRENT FROM NOMINAL FOR FAILURES IN THE C3 AUXILIARY CAPACITOR

C3 auxiliary capacitor impedance variation from nominal (%)	5	10	20
I_{R2}/I_{TOT} 23rd-harmonic current variation from nonfailure condition	–29	–46	–66

The I_{TOT} current in the previous tables is the total filter current measured by the F49FL1 IED. The I_{R2} current is measured by the F49R2 IED, which is the current through the R2 resistor. The I_{R3} current is measured by the F49R3 IED, which is the current through the R3 resistor. The comparison of the particular harmonics is shown in Table XIII, Table XIV, and Table XV. For the C2 capacitor in Table XIII, for example, the P1 controller compares the 5th harmonic measured in the R2 resistor to the same harmonic measured in the total current. A specific threshold is provided in order to detect failures in the elements of C2. For the case of C2a, the relationship between I_{R2} and I_{TOT} fundamental currents is monitored. For the case of C3, the relationship between I_{R3} and I_{TOT} 23rd-harmonic currents is monitored. Two levels of alarm were implemented for the C2 auxiliary capacitor in which the first and second levels detected four and seven failed elements, respectively. For the C2a auxiliary capacitor, the first and second levels detected three and four failed elements, respectively. For the C3 auxiliary capacitor, the first and second levels detected two and four failed elements, respectively. Examining Table XII and Table XIII shows that it is possible to define the thresholds for each level of alarm.

Fig. 10 shows the detuning protection logic programmed in the P1 real-time automation controller for the Level 1 alarm. The detuning protection logic for the Level 2 alarm is similar.

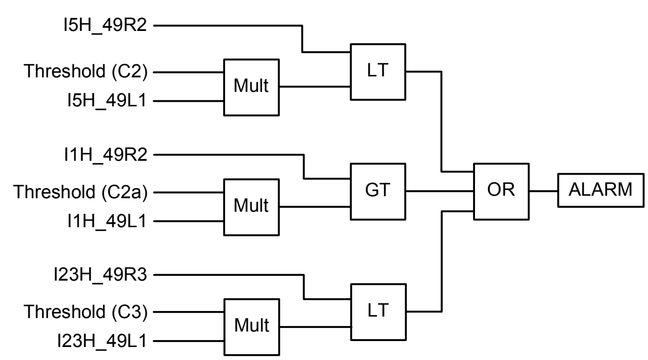

Fig. 10. Level 1 alarm for detuning element

The other filter types have similar logic with the appropriate threshold levels.

F. *Residual Overcurrent Protection*

The residual overcurrent protection works as a backup for the differential protection.

As shown in Fig. 11, the F49L1 IED measures the current flowing out of each phase of the filter and calculates the fundamental residual current ($I_{RES-OUT}$).

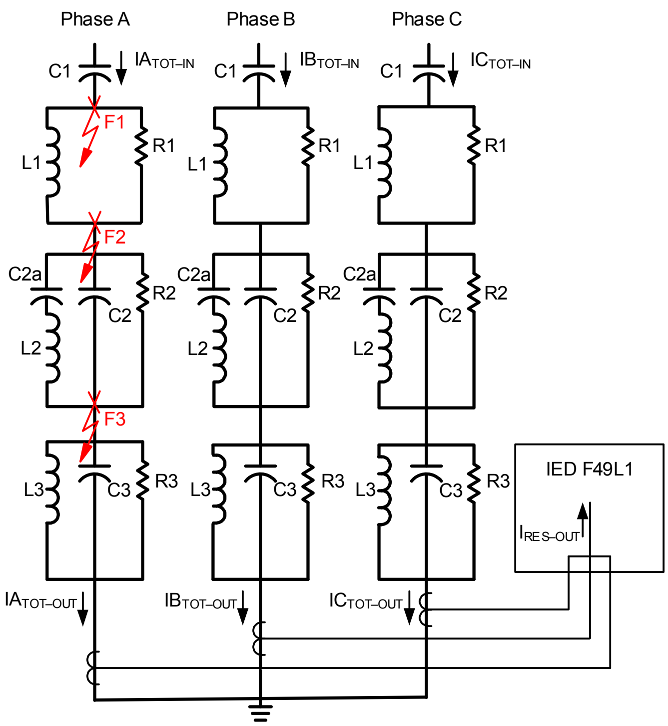

Fig. 11. Residual overcurrent protection

Residual overcurrent protection is a sensitive method of protection against single-phase faults; however, the application in a harmonic filter has some particularities. As previously mentioned, a phase-to-ground fault inside the filter will cause a current to decrease instead of increase. This occurs because the total impedance from the busbar to the fault is larger than the total impedance of the filter.

Table XVI summarizes the current values (in primary amperes) for solid phase-to-ground faults at the different locations shown in Fig. 12.

TABLE XVI
RESIDUAL CURRENTS FROM THE UPPER AND LOWER CTS FOR SOLID PHASE-TO-GROUND FAULTS AT DIFFERENT LOCATIONS

Location	I_{RES-IN} (A pri)	$I_{RES-OUT}$ (A pri)
F1	3	281
F2	223	281
F3	2	281

The values in Table XVI are the result of (4) and (5), where:

$$I_{RES-IN} = IA_{TOT-IN} + IB_{TOT-IN} + IC_{TOT-IN} \quad (4)$$

$$I_{RES-OUT} = IA_{TOT-OUT} + IB_{TOT-OUT} + IC_{TOT-OUT} \quad (5)$$

From Table XVI, it is clear that the residual current from the upper CTs is not suitable to be used for residual overcurrent protection because it is too low. The residual current from the neutral side CTs must be used for the residual overcurrent protection, and it must be sensitive enough to detect currents of around 281 amperes primary.

For a close-in single-phase-to-ground fault, or a double-phase-to-ground fault in the adjacent lines, the residual overcurrent ($I_{RES-OUT}$) will have the same value for the internal faults (i.e., 281 amperes primary). This is also true for faults in the busbar. For this reason, the protection must be coordinated with the line protection and the busbar protection; therefore, a time delay of 750 milliseconds was adopted.

G. Backup Protection for the Reactors L1, L2, and L3

The IEDs monitoring the resistors F49R1, F49R2, and F49R3, are also responsible for implementing a thermal replica algorithm that calculates the temperature in the reactors L1, L2, and L3, respectively. The algorithm and equation are the same as described in Section IV, Subsection B. The current magnitude used in the formula is calculated from the measured current through the resistor. The through current in the R1, R2, and R3 resistors is much lower than that through the reactors L1, L2, and L3, respectively.

The current in the resistors is directly proportional to its voltage drop. Because the resistors are in parallel with the reactors, a relationship can be determined between the current in the resistor and the current in the parallel reactor. Therefore, scaling factors can be determined to estimate the reactor currents for each harmonic component because the relationship of the voltage and current is linear in the resistors. The scaling factors are used to multiply the harmonics measured by the F49Rn IEDs and indirectly find the harmonic components of the current through the parallel reactors. With the resistor's currents and the scaling factors, it is possible to implement thermal models in the F49Rn IEDs, as described in Section IV, Subsection B and according to (2). The alarm and trip threshold levels are the same as in Table VII that were proposed for the reactors.

This method is not accurate for reactor L2 in the case of failures in the elements of capacitor C2a, because the relationship between the current in the R2 resistor and the current in the parallel reactor L2 will be different from the nominal.

H. Backup Protection for Harmonic Overload

One of the filter design steps is the rating studies that are conducted on the basis of predetermined system and components conditions. The filter is evaluated for continuous and short-term duty. For all continuous operating conditions including minimum power to maximum power, maximum and minimum voltages of the busbar, harmonic currents generated by the converters for different conditions, filter components tolerance, etc., the filters are rated to ensure that no reduction of power is required because of the different system conditions. Thus, the filter has its nominal characteristics defined during the design including the continuous maximum currents, fundamental, and harmonics allowed during different operating conditions.

Excess harmonics from the system can damage the filter components. The thermal models are intended to detect overloads in each specific component. As backup protection for the thermal models, an overload protection was implemented based on the amount of the harmonic currents in the F49L1 IED that is measuring the total current of the filter and calculating the total harmonic distortion (THD), considering the harmonics from the 2nd to the 63rd orders. The THD for current is the ratio of the harmonic only rms value of the current to the fundamental value of the current. Therefore, if the THD is multiplied by the fundamental value of the current, the result will be the fundamental frequency rms value as shown in (6).

$$IRMS_{HARM} = \sqrt{\sum_{2}^{n} I_n^2} = \frac{THD_{current} \cdot I_1}{100} \qquad (6)$$

where:

$IRMS_{HARM}$ is the harmonic only rms current (A).

I_n is the harmonic of order n (A).

I_1 is the fundamental value of the current (A).

$THD_{current}$ is the current total harmonic distortion (%).

n is 63 for the F49L1 IED.

The Type A filter of the Porto Velho rectifier station was designed considering a value of 240 A for $IRMS_{HARM}$. Therefore, an alarm threshold was implemented according to this value.

Excess harmonics from the system will affect all components of the filter; however, the resistors are the weakest components with respect to harmonic overload. Therefore, a trip threshold was implemented based on the resistor's supportability for the harmonic overload, which is 25 percent above the alarm threshold and has a time delay of 20 seconds.

V. Protection Philosophy for Other Filter Types

Based on the previous discussion, a similar protection philosophy can be applied for other filter types, as shown in Fig. 12 and Fig. 13.

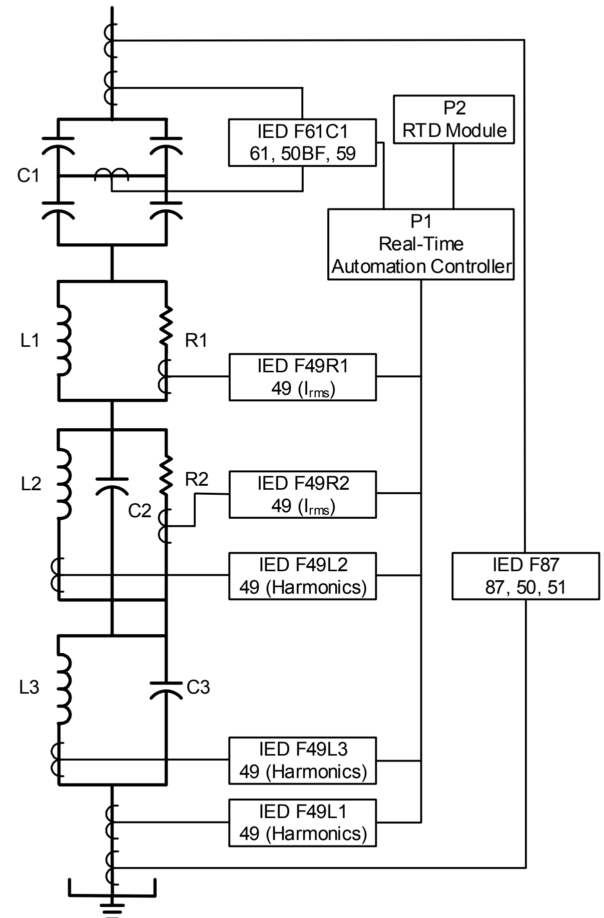

Fig. 12. Single-line diagram showing the principal functions of each IED for the Type B filter in the Porto Velho rectifier station

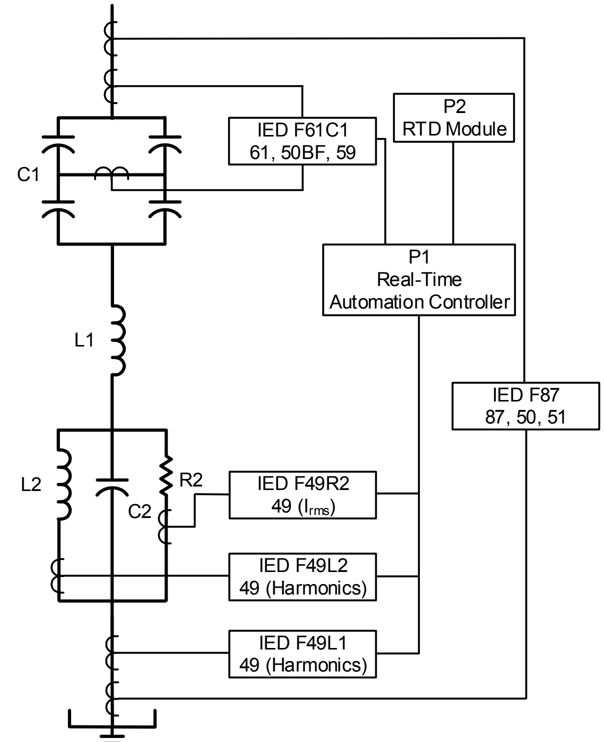

Fig. 13. Single-line diagram showing the principal functions of each IED for the Type C filter in the Porto Velho rectifier station

VI. Conclusions

In the conception process of the IE Madeira project, the companies of the consortium requested the design and operation of a protective relaying system that is robust, comprehensive, and extremely reliable. The request also considered individual protection IEDs for each of the filter components with sufficient backup protection.

In the protective relaying system provided, the sensitivity and security aspects were evaluated. The unbalance protective relaying for the capacitors that were connected in an H-bridge configuration, the thermal overload of the reactors with respect to relevant harmonics, and the detuning protective algorithm were provided to satisfy the requirements.

It is estimated that less than two percent of the full hydroelectric potential of the rivers in the Amazon region have been explored [12]. Because of the fundamental importance of new energy sources for the economic growth of Brazil, other similar projects are expected in the future, such as the IE Madeira and the Belo Monte power plant in northern Brazil.

The pertinent topic of protecting EHV harmonic filters has very few bibliographic references compared to other protection functions applied to transmission systems.

A protection philosophy was presented in this document that can serve as a support for new applications of EHV filters in general, and in the future, for projects related to the integration of the hydraulic potential of the Amazon region.

VII. References

[1] P. C. V. Esmeraldo, E. M. A. Araujo, and D. S. Carvalho, Jr., “HVDC Madeira Transmission System – Planning Development and Final Design,” proceedings of the CIGRE Session 2010, Paris, France, 2010.

[2] The Electric System National Operator (ONS – Operador Nacional do Sistema Elétrico), Procedimentos de Rede, Módulo 2, Submódulo 2.8. Available: http://www.ons.org.br/procedimentos/index.aspx.

[3] Agência Nacional de Energia Elétrica (ANEEL – Brazilian Electricity Regulatory Agency), Edital de Leilão No. 007/2008-ANEEL, Anexo 6F-CC, Lote LF-CC, Integração do Madeira, Vol. III-Fl.473 de 1276. Available: http://www.aneel.gov.br/aplicacoes/editais_transmissao/documentos/06_LOTE_LF_CC_Madeira.pdf.

[4] F. Jusan, L. Carijó, G. Luz, R. Gonçalves, M. Lima, M. Cavalheiro, and G. Oheidhin, “Sistema de Transmissão CCAT do Madeira – Estudos de Desempenho Harmônico e Rating dos Filtros CA do Bipolo 2,” proceedings of the XXI Brazilian National Seminar of Production and Transmission of Electrical Energy (SNPTEE), Florianópolis, Costã do Santinho, Brazil, 2011.

[5] W. Boyes (ed.), *Instrumentation Reference Book* (Fourth Edition). Butterworth-Heinemann (Elsevier Inc.), Burlington, MA, USA, 2010.

[6] S. Samineni, C. Labuschagne, and J. Pope, “Principles of Shunt Capacitor Bank Application and Protection,” proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

[7] IEEE Standard C37.99-2012, IEEE Guide for the Protection of Shunt Capacitor Banks.

[8] Brazilian Association of Technical Standards (ABNT) NBR IEC 61000-4-30:2011, Electromagnetic Compatibility – Part 4-30: Testing and Measurement Techniques – Methods of Measurement of Power Quality.

[9] E. Lebenhaft, “First Order Thermal Model Applied to Cyclic Loads,” proceedings of the 2007 IEEE-IAS/PCA Cement Industry Technical Conference, Charleston, SC, April 2007.

[10] G. Benmouyal, M. B. Bryson, and M. Palmer, “Implementing a Line Thermal Protection Element Using Programmable Logic,” proceedings of the 30th Annual Western Protective Relay Conference, Spokane, WA, October 2003.

[11] M. J. Thompson, “Percentage Restrained Differential, Percentage of What?” proceedings of the 64th Annual Conference for Protective Relay Engineers, College Station, TX, April 2011.

[12] Agência Nacional de Energia Elétrica (ANEEL – Brazilian Electricity Regulatory Agency), “Atlas de Energia Elétrica do Brasil, 3a Edição.” Available: http://www.aneel.gov.br.

VIII. Biographies

Eduardo de Medeiros Brandi received his BSEE from Universidade Gama Filho (1980), his MS in Energy Planning and Nuclear Engineering from COPPE/Universidade Federal do Rio de Janeiro (1986), and his MAB in Finance from COPPEAD/Universidade Federal do Rio de Janeiro (2005). Mr. Brandi worked for Furnas Centrais Eletricas from 1981 to 2013, serving in various departments such as maintenance, planning, engineering, and operations. He has extensive experience with transmission systems and Flexible AC Transmission (FACT), assuming roles in several phases of specification, design, implementation, and tests of control and protection for transmission systems. In 2014, Mr. Brandi worked as a consultant with the Interligação Elétrica do Madeira (IE Madeira) project. He is presently serving Belo Monte Transmissora de Energia as a consultant, working on the 800 kVdc bipole project. He has authored and coauthored several papers presented at national and international conferences.

Ricardo Abboud received his BSEE degree in electrical engineering from Universidade Federal de Uberlandia, Brazil in 1992. In 1993, he started work for CPFL Energia in Brazil as a protection engineer. Mr. Abboud’s responsibilities included maintenance, commissioning, specification, studies, and relay settings of power system protection. In 2000, he left CPFL and joined Schweitzer Engineering Laboratories, Inc. (SEL) as a field application engineer covering the entire country of Brazil. His responsibilities included training and assisting SEL customers in substation protection and automation efforts related to generation, transmission, distribution and industrial areas. In 2005, he became field engineering manager for SEL Brazil. Since 2014, Mr. Abboud has lead the engineering services branch in Brazil. In addition, he is an instructor with SEL University and instructs two specialization courses in Brazil. He has authored and coauthored several technical papers.

Fernando Calero received his BSEE in 1986 from the University of Kansas, his MSEE in 1987 from the University of Illinois (Urbana-Champaign), and his MSEPE in 1989 from the Rensselaer Polytechnic Institute, Troy, NY. From 1990 to 1996, Mr. Calero worked in Coral Springs, Florida, for the ABB relay division in the support, training, testing, and design of protective relays. Between 1997 and 2000, Mr. Calero worked for Itec Engineering, Florida Power & Light, and Siemens. Since 2000, Mr. Calero has worked for Schweitzer Engineering Laboratories, Inc. as an application engineer in international sales and marketing, providing training and technical assistance. He is presently a senior automation systems engineer in the International Technology Group.

20150914 • TP6714-01