Design and Performance Evaluation of a High-Impedance REF Scheme for MV/LV Transformers

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***Abstract*—This paper presents the detailed engineering study conducted to design a high-impedance restricted earth fault (REF) scheme for four 11/0.415-kV, Dyn11, and 2500-kVA power transformers in an industrial power system. Analytical calculations carried out to specify the components constituting the REF scheme and to determine the appropriate relay settings are provided. The proposed REF scheme is evaluated using reliable Alternative Transients Program–Electromagnetic Transients Program simulations. The obtained results validate the adequacy of the design and highlight the advantages of using such a protection, such as fast and reliable operation even under severe current transformer saturation conditions.**

***Index Terms*—Alternative Transients Program–Electromagnetic Transients Program (ATP–EMTP), current transformer (CT) saturation, high impedance, protective relaying, restricted earth fault (REF) protection.**

NOMENCLATURE

CTR	Turns ratio of current transformer.
I_{arc}	RMS value of arcing current.
I_e	Current transformer leakage current at relay setting voltage V_S.
$I_{F\mathrm{ext}}$	Maximum current transformer secondary current for external fault.
$I_{F\mathrm{int}}$	Maximum current transformer secondary current for internal fault.
I_N	Relay nominal current.
I_{OP}	Primary relay operating current.
I_S	Relay setting current.
L	Length of the lead wire (in m).
n	Number of current transformers in parallel with relay.
R_{arc}	Time-varying arc resistance.
R_B	Relay burden (in ohms).
R_{CT}	Secondary resistance of current transformer.
R_L	Total secondary loop lead resistance (between current transformer and relay connection point).
R_S	Value of stabilizing resistor.
R_W	Lead wire resistance (in ohms/m).
S_N	Relay burden (in VA).
V_F	Theoretical voltage across the relay circuit under internal fault conditions.
V_K	Knee-point voltage of current transformer.
V_P	Peak voltage across relay circuit under maximum internal fault conditions.
V_S	Stability voltage setting.

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I. INTRODUCTION

RESTRICTED earth fault (REF) protection on a transformer is a subject for which there has been little attention, and compared with other types of protection, very little literature exists [1]. REF is a sensitive protection applied to protect star winding of transformers against phase-to-ground faults. REF works on the differential principle. It compares summated line currents against neutral current on the same side of the protected transformer.

Recent developments in computer relaying have made this protection available in multifunctional digital relays for transformer application. In such implementations, a low-impedance principle is used for REF protection to complement differential protection in detecting transformer earth faults [2]. Low-impedance REF protection is so named because the differential relay current inputs have low impedance to the flow of current transformer (CT) secondary current. However, these implementations are relatively expensive and typically fitted to HV/MV transformers rated above 5 MVA due to the value of the asset.

In most industrial applications for small-megavoltampere and low-cost MV/LV distribution transformers (less than 3.5 MVA), ground fault protection in the area covering the transformer secondary and unloading tails is provided either by feeder overcurrent relays or by fuses associated with primary side transformer protection or by simplistic standby earth fault (SBEF) relays supplied via a CT mounted on the transformer neutral-to-earth conductor. In the majority of these applications, ground faults in the transformer secondary cannot be detected by primary protection, whereas SBEF relays must be set to coordinate with downstream relays resulting in a time-delayed breaker trip. This, however, may lead to the transformer being no longer serviceable in case of an earth fault.

On the other hand, high-impedance REF is a relatively cost-effective and traditionally reliable way to protect LV transformer windings and interconnecting cables between the transformer secondary and the LV switchboard (SWBD) incomer circuit

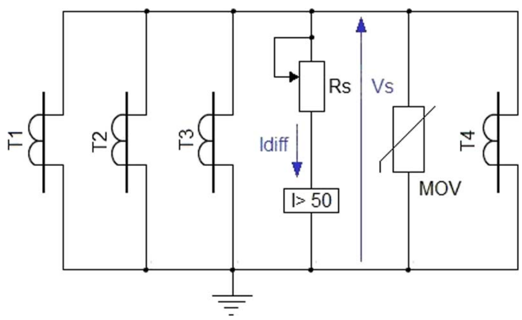

Fig. 1. Typical high-impedance REF protection scheme.

breaker (CB). It is a fast-acting differential protection and can isolate winding faults and cable earth faults very quickly, thereby limiting transformer damage and consequently repair costs [3].

In the remainder of this paper, the detailed analysis carried out for designing a high-impedance REF scheme for four 11/0.415-kV, Dyn11, and 2500-kVA power transformers in a gas treatment plant is presented. All possible realizations of the REF schemes that were investigated in terms of construction constraints and cost benefits are presented. Analytical calculations for class-PX CTs' sizing; selection of the related equipment comprising the high-impedance REF scheme, e.g., stabilizing resistor, metal–oxide varistor (MOV), and protective relay; and the relay settings are given. Moreover, analytical guidelines for verifying the scheme performance using detailed Alternative Transients Program–Electromagnetic Transients Program (ATP–EMTP) simulations are provided. Finally, the transient simulation results are used to assess the relay performance under CT saturation conditions for internal faults in the REF zone of protection, as well as for external faults.

II. High-Impedance REF Protection Principle

High-impedance REF protection is a bright and simple technique that requires that all CTs used in the protection scheme (line side CTs and transformer neutral CT) have relatively high knee-point voltage, similar magnetizing characteristic, and the same ratio [4]. In high-impedance REF protection, all CTs shall be connected in parallel, as shown in Fig. 1.

From the CT junction points, a measuring branch is connected. The measuring branch is a series connection of one fixed or variable setting resistor R_S and an overcurrent relay $(I > 50)$. Thus, the high-impedance REF protection responds to a current flowing through the measuring branch. However, this current is a result of a differential voltage caused by the parallel CT connection across the measuring branch. These current and voltage are interrelated by Ohm's law.

Hence, there are two types of high-impedance REF relays that are met in commercial realizations [5]. The first type has internal resistors and a voltage setting. In this type, the resistors are effectively switched in and out to change the setting and, therefore, the value of the stabilizing voltage. The second type has an external resistor where the setting is calculated in ohms and applied either by changing the resistance of a variable resistor or by preselecting a fixed resistor value. In this case, the REF relay is a current-operated relay with a resistor in series that provides stabilization.

During internal faults, the high-impedance relay circuit constitutes an excessive burden to the CTs. A very high voltage develops across the relay circuit and the CTs, which may cause damage to the insulation of CT secondary winding and relay. To avoid such a condition, in most cases, a MOV or voltage-limiting nonlinear resistor (Metrosil) is connected across the parallel connection of the CTs and relay to clamp the voltage to a safe limit, without affecting relay operation. Sufficient current still flows through the relay to ensure operation.

The procedure typically applied for deriving the characteristics of the REF relay is described in the following [6], [7]. The extreme case for the stability of the REF scheme will be if one CT in Fig. 1 is completely saturated in case of a through-fault condition, and the other CTs remain unaffected. The applied voltage V_R across the relay for this specific condition is

$$V_R = I_{F\mathrm{ext}}(R_{\mathrm{CT}} + R_L). \tag{1}$$

The stabilizing resistor in series with the relay circuit is used to improve the stability of the relay under through-fault conditions. This resistor will limit the spill (differential) current to less than the relay setting I_S by allowing a part of it to flow through the "healthy" CTs (phase and/or neutral) not carrying primary fault current. The general stability requirement can be achieved when having

$$V_S = I_S(R_S + R_B) \geq K \cdot I_{F\mathrm{ext}}(R_{\mathrm{CT}} + R_L) \tag{2}$$

where K is the stability factor that is influenced by the ratio V_K/V_S, which, in turn, governs the stability of the REF protection element for through faults.

As a general rule of thumb, a value of $K = 1$ can be safely used for $V_K/V_S \leq 16$, whereas for $V_K/V_S > 16$ a value of $K = 1.2$ is deemed more suitable [8].

The appropriate value of series resistance R_S required to ensure stability is calculated as follows:

$$R_S = V_S/I_S - R_B. \tag{3}$$

The knee-point voltage V_K of the CT is defined as the point on the magnetization curve at which a 10% increase in excitation voltage produces a 50% increase in excitation current. The knee-point voltage must be significantly higher than the stability voltage V_S in order for the REF relay to ensure stability for through faults and operation in less than 40 ms for internal faults. A ratio of 2 is typically applied, but a ratio of 4 or 5 would be more appropriate; thus,

$$V_K \geq 4V_S. \tag{4}$$

For a solidly earthed system, as it is typical for the secondary of MV/LV transformers, the relay setting I_S shall provide an effective operating current between 10% and 60% of LV-winding-rated current. For a resistance earthed star winding, where the fault current linearly varies as a function of fault position from neutral, since the resistor is the dominant impedance, a typical setting for REF protection shall be 10%–25% of minimum earth fault current for a fault at transformer terminals. For both

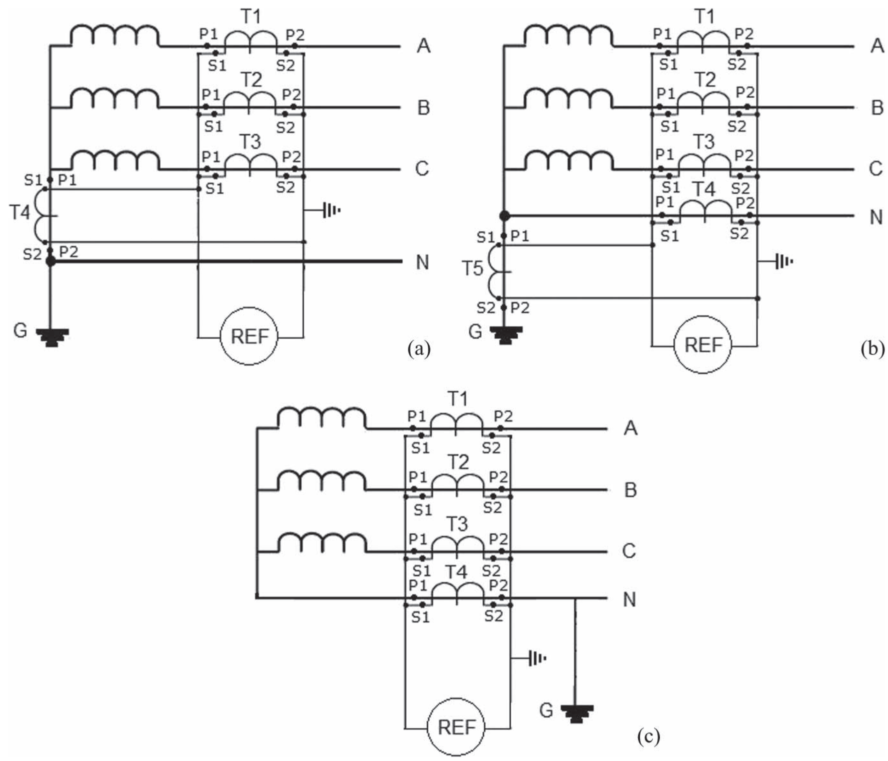

Fig. 2. Possible REF scheme arrangements for MV/LV power transformers.

earthing arrangements, the primary operating current I_{OP} is calculated as follows:

$$I_{OP} = \mathrm{CTR} \cdot (I_S + nI_e). \tag{5}$$

From (5), it is made clear that the magnetizing current of the CTs I_e is a major desensitizing factor for high-impedance REF protection.

A nonlinear resistor (Metrosil) is required to limit the CT output voltage under an internal fault if the magnitude of peak voltage V_P is higher than 3 kV. The voltage spike V_P due to CT saturation is calculated from

$$V_P = 2\sqrt{2V_K(V_F - V_K)} \tag{6}$$

where

$$V_F = I_{F\mathrm{int}}(R_{\mathrm{CT}} + 2R_L + R_S + R_B). \tag{7}$$

Fig. 3. Physical mounting of transformer neutral CT before the bifurcation point.

III. High-Impedance REF Application Example

This section covers the practical aspects encountered for designing a high-impedance REF scheme for four 11/0.415-kV power transformers in a stand-alone gas processing facility with in-house captive power generation to meet the total plant electrical load requirement.

In the initial protection system philosophy, a REF scheme had not been specified for MV/LV transformers. The only element available to provide protection against ground faults in the transformer LV windings and backup protection for ground faults in downstream 0.4-kV feeders was a time–overcurrent element by means of an SBEF relay.

However, two sequential ground faults occurred in the LV cables connecting the secondaries of two power transformers with the main incoming CBs, which, due to the prolonged clearing time of the SBEF relay, resulted in one transformer becoming unserviceable and caused long-term downtime. These faults were attributed to inappropriate cable sizing and placement with respect to the installation conditions, as well as to bonding the cable armors at both ends. This had caused extreme overheating of the cable due to the circulating currents in the cable armors, which resulted into cable failures by means of ground faults [9]. Therefore, it was decided to provide a form

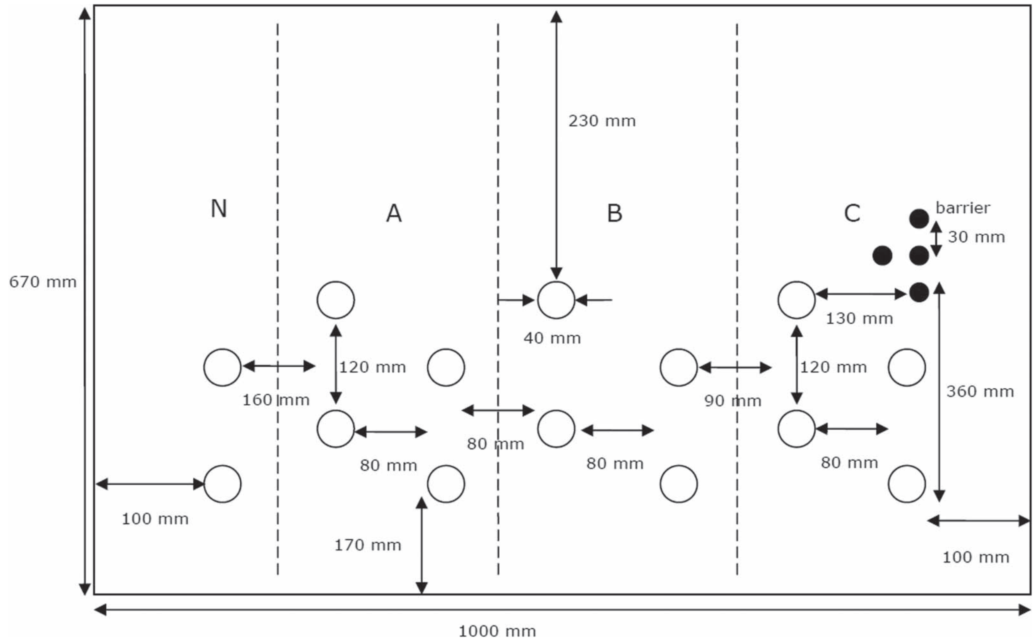

Fig. 4. Bottom view of the cable entry gland plate for the main incomer from MV/LV transformer: type I.

of instantaneous protection for this specific transformer zone. High-impedance REF protection was acknowledged as the most effective technoeconomical solution for this purpose.

A. REF Protection Scheme Setup

The first and most important matter was to establish the high-impedance REF scheme arrangement. In the majority of LV systems, the neutral is distributed and the criterion for REF configuration is the actual location of the neutral-to-earth connection. Fig. 2 depicts all possible secure implementations of the REF scheme. Moreover, Fig. 2 illustrates two additional points that are critical for the proper operation of REF protection and are related with common field problems encountered with REF schemes: (a) the CT polarity markings; and (b) the earthing point of CT secondary circuit (only at one place).

In Fig. 2(a), a four-CT REF scheme is shown. CT T4 is mounted before the neutral-to-earth bifurcation point. The neutral current flows through CT T4 and balances against the summated line currents. Hence, REF will not pick up during unbalanced load conditions. However, mounting of CT T4 in many installations may not be feasible due to constructional difficulties.

Fig. 2(b) depicts a five-CT REF scheme to counteract the difficulties encountered for mounting a neutral CT before bifurcation. In this arrangement, the neutral-end CT is mounted in the grounding conductor (T5) and an additional CT on the neutral conductor within the LV SWBD side (T4) is used to avoid nuisance tripping during unbalanced conditions. During an unbalanced condition (unequally loaded phases at transformer LV side), unbalanced current flows back through the neutral conductor CT. Since current through this CT is in opposite direction as that of phases, it avoids nuisance tripping of the REF relay. If this CT is not provided, then the relay may trip during an unbalance. During an earth fault within the REF zone, current flows back to transformer star point through the CT on transformer neutral (T5). This way, the REF relay detects the fault and trips the system. If a fault is outside the zone, fault current flows through the phase CT and the transformer neutral CT. Current through transformer neutral flows in opposite direction as that of phase CT. Thus, REF relay blocks nuisance tripping.

In Fig. 2(c), contrary to Fig. 2(a) and (b), the neutral-to-ground connection is not in the transformer side but in the LV SWBD side. Thus, a four-CT REF scheme, as shown in Fig. 2(c), is deemed adequate in terms of security and dependability for handling all three possible conditions, namely, unbalanced current flowing in the neutral conductor, internal earth faults, and external earth faults.

In the specific installation under study, the neutral is earthed at the transformer. Moreover, the existence of a riser pole for connecting the distributed neutral conductors with the transformer neutral terminal makes feasible the mounting of the neutral CT before the bifurcation point, as shown in Fig. 3. Thus, a four-CT REF scheme, as shown in Fig. 2(a), was selected, which also improves the effective operating current in (5).

B. CT Installation Requirements

Class-PX CTs are typically used for high-impedance REF applications. To specify a special class-PX CT, the following data must be provided according to IEC 60044-1 [10]:

a) turns ratio;
b) knee-point voltage V_K;
c) maximum exciting current at V_K, i.e., I_e;
d) CT secondary resistance at 75 °C;
e) rated power-frequency withstand voltage for 60 s;
f) physical limiting dimensions and aperture dimensions.

Parameters a)–e) are specified using relay manufacturers' formulas and characteristics of the application. Analytical

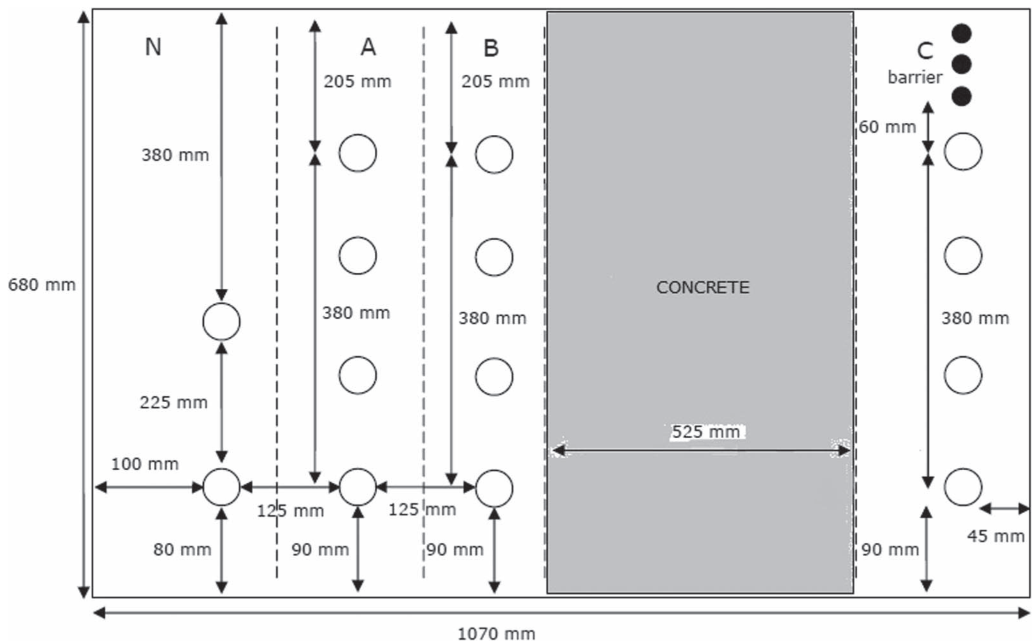

Fig. 5. Bottom view of the cable entry gland plate for the main incomer from MV/LV transformer: type II.

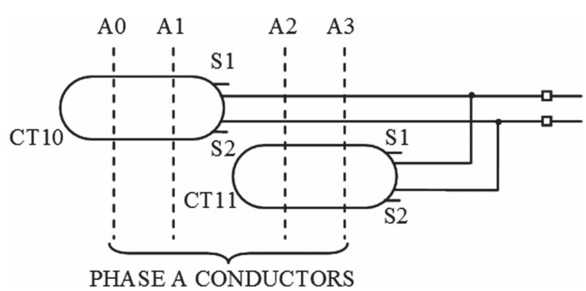

Fig. 6. Grouping circuit conductors in more than one CT.

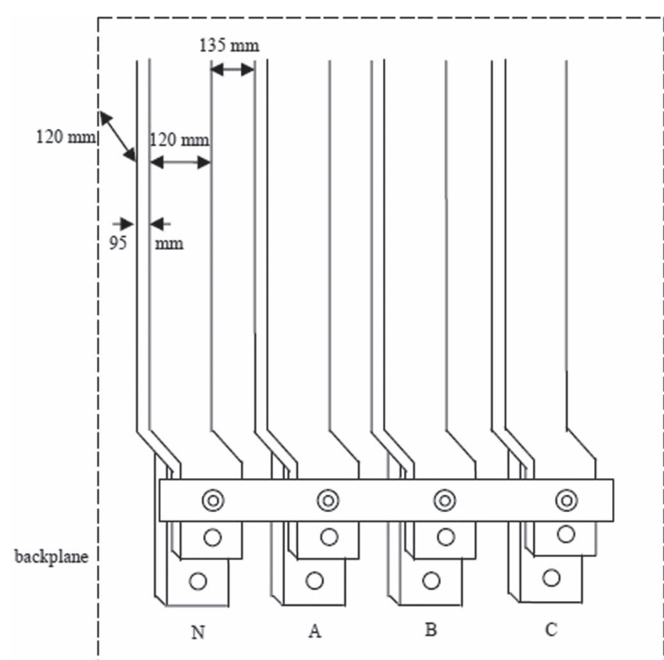

Fig. 7. LV incomer busbar chamber: cable entry compartment.

calculations are provided in the next paragraph. Parameter f) is related to physical installation constraints and is critical for an efficient and cost-effective CT design [11]. Typical indoor-type CTs are categorized as taped, plastic case, or resin encapsulated models based on the material employed and as ring, square, or stadium style based on their shape. For the specific application under study, all possible class-PX CT designs and locations for mounting these CTs inside the LV SWBD were considered.

Figs. 4 and 5 show a bottom view of the cable gland entry plate in the main LV incomers' compartment. This was the first location examined for mounting the LV SWBD CTs. However, due to the conductor arrangement in the gland plate, the barriers involved, and the tight space limitations, this location was initially conceived as inappropriate for manufacturing and mounting a CT. Even the case of splitting the conductors of each circuit in more than one CT, as shown in Fig. 6, was investigated, but it was abandoned due to the additional costs required and the difficulties imposed on passing the conductors as nearly as possible to the CT window center to avoid false operation due to inaccuracies.

On the other hand, installation of the CTs in the main LV incomer busbar chamber, just after the cable entry box, was deemed more suitable for delivering a compact and cost-effective CT design and for extending the area covered by REF protection to include also some portion of the busbar since the limits of REF protection zone are defined by the location of CTs. Therefore, Fig. 7 was provided to CT manufacturers along with the required CT characteristics a)–e) in order to be used as a guide for manufacturing a CT for this specific application. However, it should be mentioned that this CT placement would entail dismantling a section of the busbars, which might result in much downtime in order to ensure the integrity of CT connections and its correct installation.

TABLE I
ANALYTICAL CALCULATIONS FOR SPECIFYING REF SCHEME PARAMETERS

Step	Description	
1	Installation Details	
	Transformer Rating: 2.5 MVA Nominal Voltage: 0.415 kV Rated Current: 3478 A Nominal Frequency: 50 Hz Rated Short Circuit Current: 80 kA/ 1 sec Transformer Impedance: 6.8 % Maximum Internal Earth Fault Current (I_{Fint}): 52 kA Maximum Through Earth Fault Current (I_{Fext}): 36 kA (considering the presence of four parallel LV power cables 4x1x500 mm2 XLPE/PVC/AWA/PVC 0.6/1 kV)	
2	Details of CT (Data Requested from the CT Manufacturer)	
	Type of CT: Class PX Transformation Ratio: 4000/5 A, $I_e \leq 8$mA (at $V_K/4$) CT Resistance (R_{CT}): 1 Ohm at 75^0 C Number of CTs: 3 for REF protection	CTs Mounted at the LV SWBD
	Type of CT: Class PX Transformation Ratio: 4000/5 A, $I_e \leq 8$mA (at $V_K/4$) CT Resistance (R_{CT}): 0.75 Ohm at 75^0 C Number of CTs: 1 for REF protection	CT Mounted at the Transformer Neutral Bushing
3	Details of Relay	
	Type: Overcurrent Relay Nominal Current (I_N): 5A Relay Burden (S_N): 0.16 VA	
4	Calculation of Burden Connected to the CT Core	
	Length of Cable (L1): 3 m Area of Cross Section: 4 mm2 Lead Resistance (R_{W1}): 0.0046 Ohm/m	CTs Mounted at the LV SWBD
	CT Loop Lead Resistance (R_{L1}): $2\cdot R_{W1}\cdot L1=2\cdot 0.0046\cdot 3=0.0276$ Ohm Relay Burden (R_B): $S_N/I_N^2=0.16/25=0.0064$ Ohm Total Connected Burden ($R_{L1}+R_B$): 0.034 Ohm CT Internal Resistance (R_{CT1}): 1 Ohm	
	Length of Cable (L2): 50 m Area of Cross Section: 6 mm2 Lead Resistance (R_{W2}): 0.003 Ohm/m CT Loop Lead Resistance (R_{L2}): $2\cdot R_{W2}\cdot L2=2\cdot 0.003\cdot 50=0.3$ Ohm Relay Burden (R_B): $S_N/I_N^2=0.16/25=0.0064$ Ohm Total Connected Burden ($R_{L2}+R_B$): 0.3064 Ohm CT Internal Resistance (R_{CT2}): 0.75 Ohm	CT Mounted at the Transformer Neutral Bushing
5	Stability Voltage Setting	
	$V_S>V_{Smin}$ Knee Point Voltage $V_K \geq 4\cdot V_S$ (according to relay manufacturer) $V_S>K\cdot I_{Fext}\cdot(I_{CTs}/I_{CTp})\cdot(R_{CT1}+R_{L1})$ => $Vs>1\cdot 36000\cdot(5/4000)\cdot(1+0.0276)=46.242$ V (Stability factor K is taken as 1 for Vk/Vs less or equal to 16) Minimum Stability Voltage (V_{Smin})=50 V Hence, actual stability voltage setting **Vs=50 V**	
6	Calculation of Maximum Sensitivity	
	CT Transformation Ratio: 4000/5A Number of CTs (n): 4 Selected Magnetizing Current of CT (I_e): 0.008 A Relay Setting $\mathbf{I_S}$ (IE>): $0.1xI_N=$**0.5 A** Primary Operating Current (I_{OP}): $I_{OP}=CTR\cdot(I_S+n\cdot I_e)=800\cdot(0.5+4\cdot 0.008)=425.6$ A Thus, the relay actual operating current is almost 12% of the transformer rated current.	
7	Calculation of Stabilizing Resistor	
	Stabilising Resistor: $R_S=V_S/I_S-R_B=50/0.5-0.0064\approx 100$ Ohm Power Rating of R_S: $16\cdot V_S^2/R_S=400$ W Hence, $\mathbf{R_S=100}$ **Ohm**	

TABLE I
(Continued.) ANALYTICAL CALCULATIONS FOR SPECIFYING REF SCHEME PARAMETERS

8	CT Requirements for High Impedance REF
	As per relay manufacturer application notes, to obtain high speed operation for internal faults (less than 40 ms), the knee point voltage of the CT V_K must fulfil the following relation: $V_K \geq 4\cdot I_S\cdot R_S=4\cdot 0.5\cdot 100=200$ V Thus, accepted CT knee point voltage for LV SWBD CTs: $V_K \geq 200$ V
9	Calculation of MOV (Metrosil)
	Maximum peak voltage across CT secondary wiring shall not exceed 3 kV, otherwise a non-linear Metrosil resistor shall be provided to limit the voltage developed to 3 kV or less. Prospective voltage that would be produced for an internal fault if CT saturation did not occur (V_F): $V_F=I_{Fint}\cdot(I_{CTs}/I_{CTp})\cdot(R_{CT1}+R_{L1}+R_B+R_S)=52000\cdot(5/4000)\cdot(1+0.034+100)$ $=6567$ V Voltage Across Relay (V_P): $V_P=2\sqrt{2\cdot V_K\cdot(V_F-V_K)}=3192$ V > 3 kV Hence, Metrosil is required.
10	Selection of Metrosil
	For a 5A CT with maximum internal secondary fault current of (52000/800)=65 A and relay setting voltage V_S=50 V, Metrosil type 600A/S2/P/S1217 (C=470/540) 35 mA rms shall be used. a) Checking the maximum permissible leakage $I_{RMS}=0.52x((V_{RMS}\sqrt{2})/C)^{1/b}$ Using minimum C value for this Metrosil type and b of 0.25: $I_{RMS}=0.52x((50\sqrt{2})/470)^{1/0.25}=2.6641\cdot 10^{-4}$ A rms < 35mA rms b) Checking the maximum protection voltage $V_{PEAK}=1.09xCxI_{RMS}^{b}$ Using maximum C and b of 0.25 (and I_{RMS}=65 A): $V_{PEAK}=1.09x540x65^{0.25}=1671$ V < 1730 V Thus, Metrosil type 600A/S2/P/S1217 (C=470/540) 35 mA rms is deemed adequate for the application.

C. Relay Installation and Trip Scheme Selection

REF relay shall be located in the LV SWBD side since it provides protection in the area covering the transformer secondary windings and the interconnecting cables between the transformer and the LV SWBD. The relay shall be made to trip not only the LV side but also the MV side breaker. It should isolate the source of supply to the transformer (typically, the MV side). The LV breaker may trip on undervoltage (caused by the MV trip) or by an intertrip signal from the MV breaker or directly from the REF relay. Alternately, the REF relay may trip the LV breaker and the MV breaker may be made to trip on an intertrip arrangement, wherein, for any fault trip of the LV breaker, the associated MV breaker would trip.

D. Analytical Calculations

This section covers the analytical calculations carried out to specify the components comprising the high-impedance REF scheme, as well as the associated relay settings. These calculations are shown in Table I with a step-by-step explanation. It should be noted that these calculations have been done according to the fundamental high-impedance REF principles presented in paragraph III but considering also the specific guidelines set by the relay manufacturer, which was selected for this application.

One critical aspect to ensure REF scheme stability, as indicated in Table I, is to balance the total loop impedance from the relay to the LV SWBD CTs and the neutral-end

TABLE II
EQUIPMENT SIZING FOR HIGH-IMPEDANCE REF PROTECTION

Item	Description	Characteristics	Nos	Unit Cost
1	LV SWBD CTs	Class: PX I_{CTP}: 4000 A I_{CTS}: 5 A f_N: 50 Hz V_K: ≥ 200 V R_{CT}: ≤ 1 Ohm I_e @ V_K/4: ≤ 8 mA Type: Indoor type – Taped model Shape: Ring Dimensions (mm): 160 ID/250 OD/65 AL	3	170$
2	Transformer Neutral CT	Class: PX I_{CTP}: 4000 A I_{CTS}: 5 A f_N: 50 Hz V_K: ≥ 208 V R_{CT}: ≤ 0.75 Ohm I_e @ V_K/4: ≤ 8 mA Type: Indoor Type – Taped Model Shape: Ring Dimensions (mm): 145 ID/252 OD/65 AL	1	210$
3	Voltage Limiting Non-linear Resistor	Metrosil Type (600A/S2/P/S1217, C=470/540, 35 mA rms, 1730 V peak) Short Time Rating: 100 A rms for 1 sec Max. Continuous Voltage Rating: 230 V rms	1	350$
4	Stabilizing Resistor	Wire Wound Resistor (Porcelain or Ceramic Tube), 100 Ohm, 400 W	1	220$
5	REF Relay	Single-phase | Earth Fault Overcurrent Relay	1	750$
		Total Estimated Cost		**2040$**

CT, respectively. This entails knowing in detail the physical distances and routing paths between the relay and the CTs for selecting the appropriate wiring size and specifying accordingly the CT secondary resistance. Another important issue is to order the REF CTs from the same manufacturer to ensure proper coordination in the manufacturing process of the CTs. Finally, since this protection, when operates, brings high voltage and heat dissipation in the relay cubicle, good integrity and reliability of the selected equipment are very important.

Table II shows a list with the equipment specified for purchase for the REF scheme. Moreover, budgetary costs per component are included as provided by different vendors. It can be seen that, although the high-impedance REF requires intensive engineering forces to be designed properly, it is a cost-effective solution compared with the asset value and other commercial multifunction transformer relay packages.

IV. HIGH-IMPEDANCE REF MODELING AND ANALYSIS RESULTS

Fig. 8 shows a part of the electrical system of the specific industrial installation simulated in ATP–EMTP for evaluating the performance of the proposed high-impedance REF scheme. The synchronous generator is rated 11 kV, 11 MVA, and 0.80 pf, and its characteristics are shown in Table III. The incoming and outgoing MV feeder cables were modeled with three-phase symmetrical PI equivalents, and their parameters are presented in Table IV. The characteristics of the 11/0.42-kV 2.5-MVA power transformer are shown in Table I and was modeled as a saturable transformer in ATP–EMTP.

The underground LV cables ($4 \times 1 \times 500$ mm^2 Ph. $+2 \times 1 \times 500$ mm^2 N 0.6/1-kV XLPE/PVC/AWA/PVC) were modeled using the cable constants routine in ATP–EMTP, which requires the geometrical and material characteristics of the cable as an input (see Table V). The homogeneous PI-circuit modeling was used so that the cable model reflects the actual grounding conditions of the cable system (parallel connection of all 14 numbers of single-core cables' armors and bonding at each cable end).

The three-phase load in the LV SWBD was expressed in terms of linear components. It is connected in a wye configuration and represented by a parallel resistor and induction per phase, whose values are shown in Table VI. This way, an unbalanced load is formed, which allows current flowing in the neutral that helps checking the REF scheme stability during normal operating conditions.

The CTs used are those depicted in Table II, whose models were reported in [12]–[14]. The resistances of CTs' secondary circuit and its cables are $R_{\mathrm{CT4}} = 0.75\ \Omega$ and $R_{L4} = 0.3\ \Omega$ for the CT located at the transformer neutral terminal and $R_{\mathrm{CT1,2,3}} = 1\ \Omega$ and $R_{L1,2,3} = 0.0276\ \Omega$ for the CTs located at the LV SWBD, respectively. The CT saturation characteristic was modeled using the excitation curve data shown in Figs. 9 and 10 for LV SWBD and transformer neutral CT, respectively. Curve B in these figures illustrates with better resolution the lowest part of the CT magnetization curve (up to 0.30 per unit scaling of I_e).

The representations of the R_S and MOV elements of the high-impedance REF relay were made as a resistance and nonlinear resistance (type 92) in ATP–EMTP, respectively [15]. The R_S value was taken as 100.0064 Ω (including R_B), and the MOV reference voltage was taken as 1.0 kV. The MOV voltage versus current characteristic was the one defined by the Metrosil manufacturer in Table II (step 10) and is shown in Fig. 11.

The fault waveforms captured from ATP–EMTP were post-processed in MATLAB in a similar manner that a digital relay manipulates the input signals from instrument transformers. Fig. 12 shows the content of the relay model implemented in MATLAB. Initially, the input current signal was filtered against antialiasing using a third-order Butterworth low-pass filter tuned at 560 Hz and conditioned. Afterward, it was sampled at a rate of 16 samples per cycle and forwarded as a data window of signal samples to the digital filter used for phasor estimation. Three commonly applied orthogonal finite impulse response (FIR) filters used for protective relay applications were implemented and tested, i.e., full-cycle discrete Fourier transform (FCDFT), half-cycle discrete Fourier transform (HCDFT), and cosine filter [16], [17]. The properties of the used filter types in terms of speed and noise cancelation are shown in Table VII.

A. Event 1: Internal REF Fault

A single-line-to-ground fault was simulated across the secondary terminals of the power transformer involving phase A and ground (see fault point FL1 in Fig. 8).

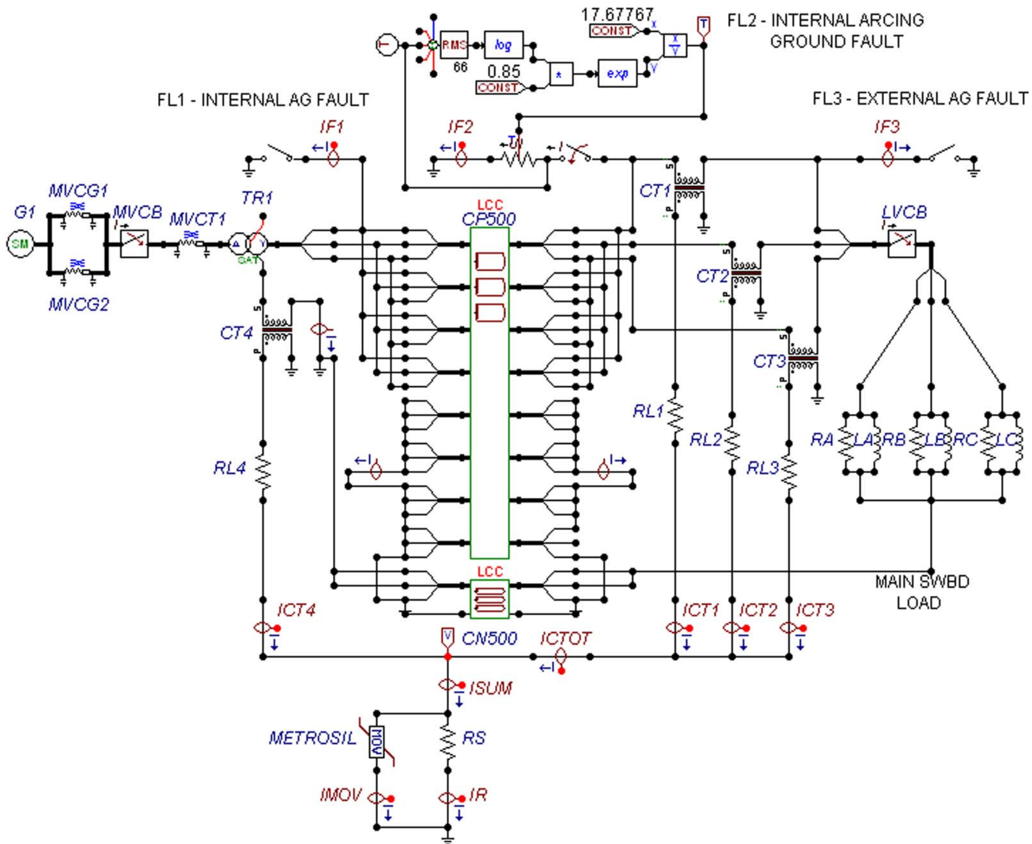

Fig. 8. Simulated power system in ATP–EMTP.

TABLE III
SYNCHRONOUS GENERATOR PARAMETERS

f (Hz)	Ra (pu)	Xl (pu)	X0 (pu)	Rn (*) (pu)	Xd (pu)	Xq (pu)	X'd (pu)
50	0.0036	0.0437	0.046	11.5455	1.87	1.049	0.186
X'q (pu)	X"d (pu)	X"q (pu)	T'do (s)	T'qo (s)	T"do (s)	T"qo (s)	WR^2 (kg-m^2)
1.049	0.153	0.288	9.621	0	0.096	0.3	1584

(*) generator neutral grounding resistor

TABLE IV
MV CABLES' PARAMETERS

ID	R1 (Ohm/km)	L1 (mH/km)	C1 (μF/km)	R0 (Ohm/km)	L0 (mH/km)	Length (km)
MVCG1	0.0800	0.3342	0.5061	0.1300	0.8594	0.1600
MVCG2	0.0800	0.3342	0.5061	0.1300	0.8594	0.1600
MVCT1	0.0800	0.3342	0.5061	0.1300	0.8594	0.0550

TABLE V
LV CABLE CHARACTERISTICS IN ATP–EMTP

Layer	Rin (m)	Rout (m)	Rho (Ohm·m)	mu	mu (ins)	eps (ins)
Core	0.0000	0.0131	1.9732e-8	1	1	3.3780
Sheath/ Armor	0.0163	0.0168	3.2840e-8	1	1	0.1600
Earth Resistivity Rho (Ohm·m)					50	
Total Cable Radius R5 (m)					0.019	
Total Cable Length (m)					50	

TABLE VI
LUMPED R_L LOAD DATA

R_A (Ohm)	L_A (mH)	R_B (Ohm)	L_B (mH)	R_C (Ohm)	L_C (mH)
0.1469	0.7543	0.1430	0.7345	0.1509	0.7753

Fig. 13(a) and (b) shows the secondary currents of the CTs at the LV SWBD side and at the transformer neutral side, respectively. It is shown that, due to the high secondary current at CT4, the CTs at the LV SWBD side (even those associated with the healthy phases) are forced into saturation. This "sympathetic" saturation is caused by the significant voltage drop across the LV SWBD CTs due to the parallel CT connections and the high-impedance principle of the REF relay.

Fig. 13(c) shows the current that flows through the relay. It is shown that this current is extremely nonsinusoidal in its nature due to the MOV effect, which acts to clamp [see Fig. 13(d)] the voltage across the relay clipping every half-cycle the voltage spikes. Moreover, it is shown that saturation somehow limits the maximum current seen by the relay. Fig. 13(e) shows the results of measuring the waveform in Fig. 13(c) with a full-cycle DFT, a half-cycle DFT, and a full-cycle cosine digital filter, respectively. The magnitude of the filter output exceeds the pickup setting (0.5 As) in each case. Thus, a trip signal is issued by the REF relay. Due to its nature, the half-cycle DFT filter provides faster response compared with classical DFT and the cosine filter. However, it is subjected to a higher offset, which has the form of a ripple around the actual signal amplitude in Fig. 13(e), since it does not eliminate dc offset and

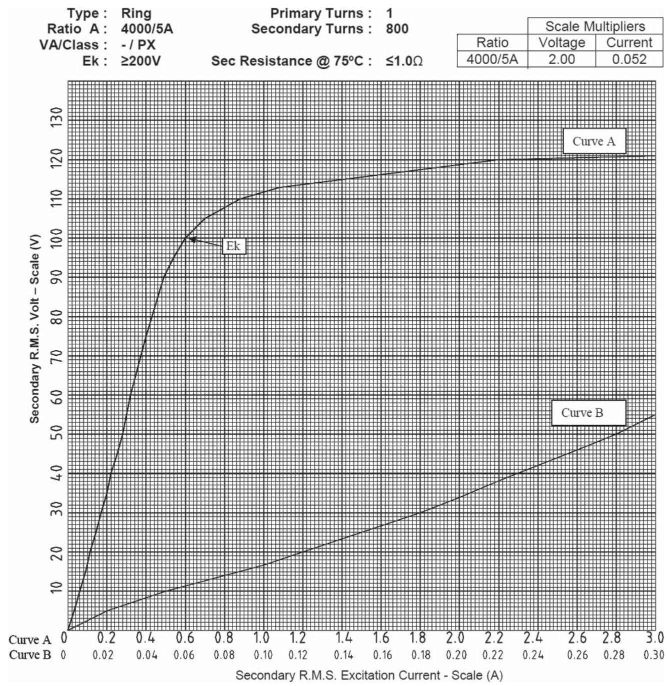

Fig. 9. Magnetization curve for LV SWBD CTs.

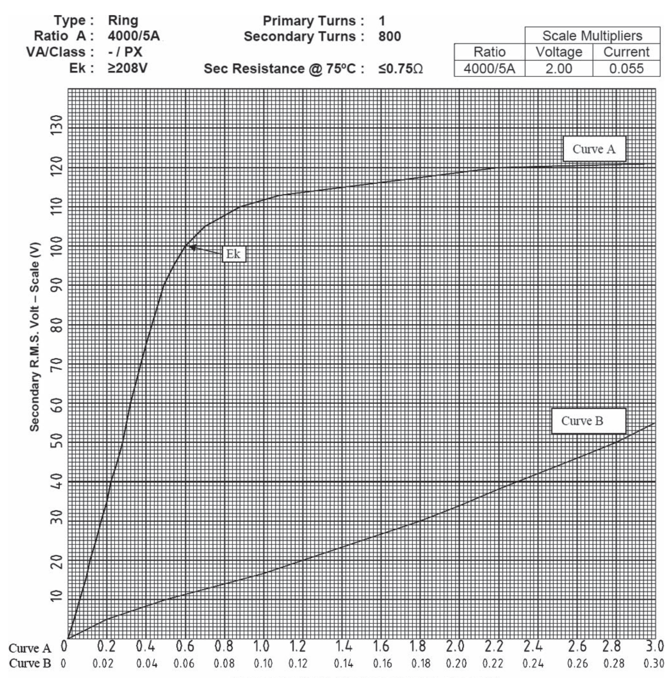

Fig. 10. Magnetization curve for transformer neutral CT.

even harmonics. Thus, it is the duty of the protection design engineer to judge between speed and security and to select a REF relay with the desired phasor estimation method.

B. Event 2: Internal REF Fault With Variable Rf

A line-to-ground arcing fault initiated from the end of phase A vertical busbar to the grounded metal-enclosed cubicle, just prior to LV SWBD CTs within the REF zone of protection, was simulated (see fault point FL2 in Fig. 8).

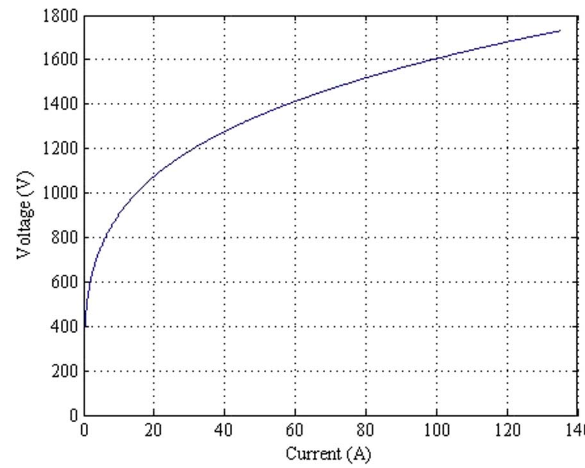

Fig. 11. V–I characteristic of the MOV (Metrosil).

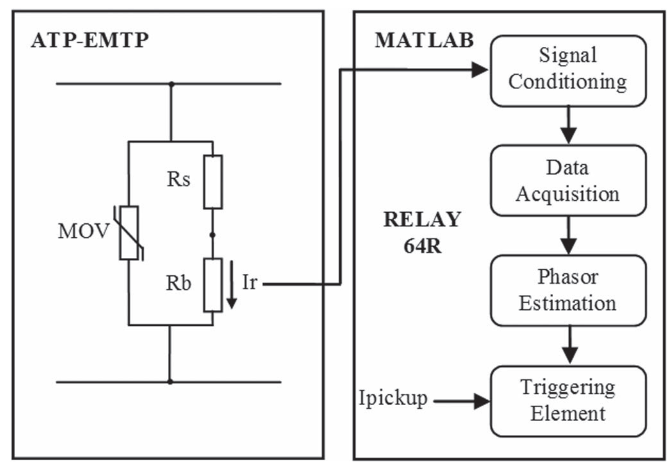

Fig. 12. High-impedance REF relay model.

TABLE VII
ORTHOGONAL FIR FILTERS' CHARACTERISTICS

Filter Type	Properties
FCDFT	- Bandpass response (about system frequency) - Odd and even harmonics attenuation - One cycle response time
HCDFT	- Bandpass response (about system frequency) - Odd harmonics attenuation and partial even harmonics rejection - Half cycle response time
COSINE	- Bandpass response (about system frequency) - Odd and even harmonics attenuation - Decaying DC rejection - 1 ¼ cycle response time

The characteristics of the fault arc were represented by using Fisher's equation for arc resistance [18], [19]

$$R_{\mathrm{arc}} = \frac{25\sqrt{g}}{I_{\mathrm{arc}}^{0.85}} \tag{8}$$

where $g = 2(1/2)$ in is the arc length, which corresponds to through air spacing from busbar to cubicle.

A type-91 transient analysis of control systems (TACS)-controlled resistor and a time-controlled switch were used for

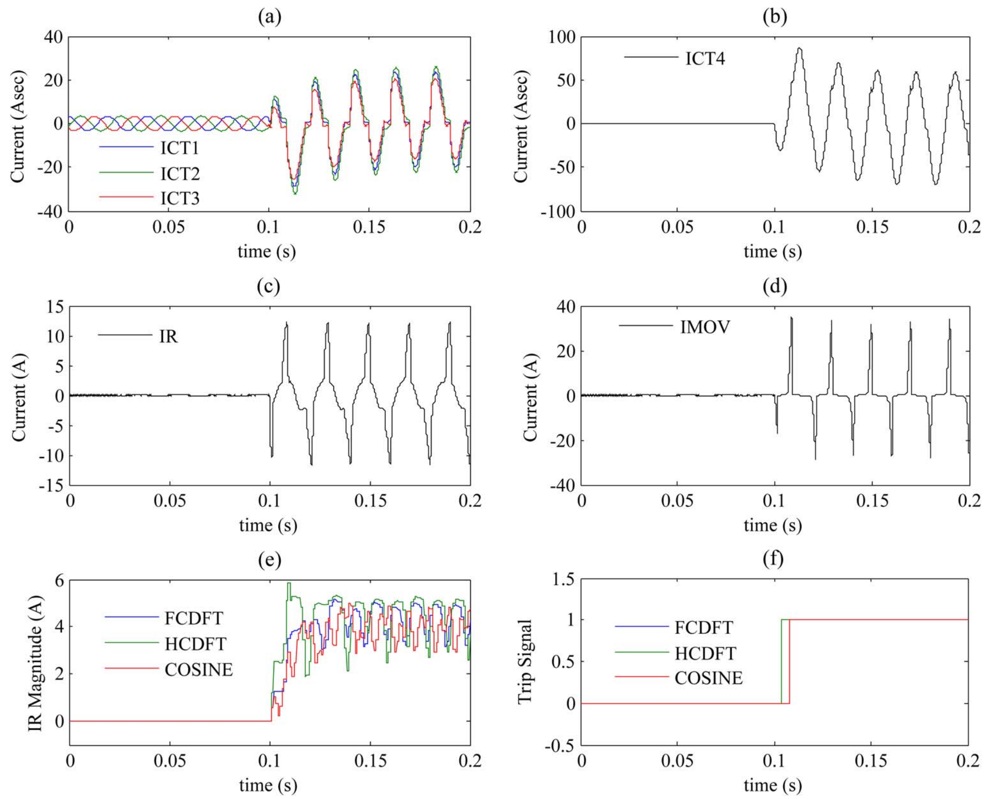

Fig. 13. REF scheme performance for an internal fault (Event 1): (a) CTs' secondary current in the LV SWBD. (b) CT secondary current at the transformer neutral. (c) Differential current through the relay. (d) Current through Metrosil. (e) Relay current magnitude. (f) REF relay trip signal.

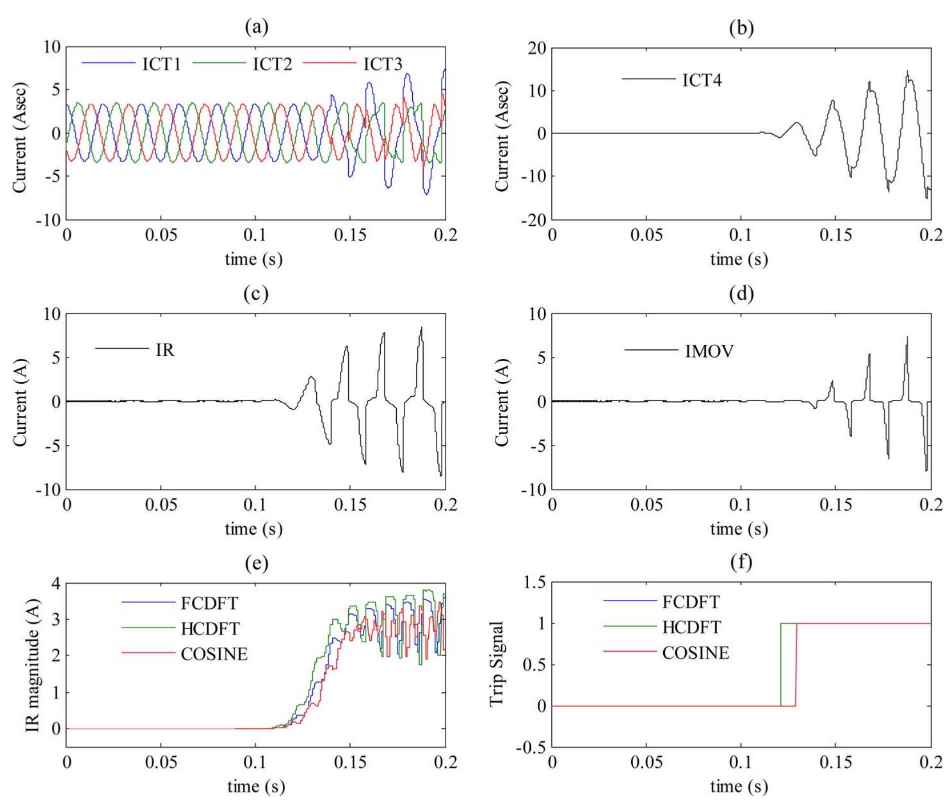

Fig. 14. REF scheme performance for an internal fault (Event 2): (a) CTs' secondary current in the LV SWBD. (b) CT secondary current at the transformer neutral. (c) Differential current through the relay. (d) Current through Metrosil. (e) Relay current magnitude. (f) REF relay trip signal.

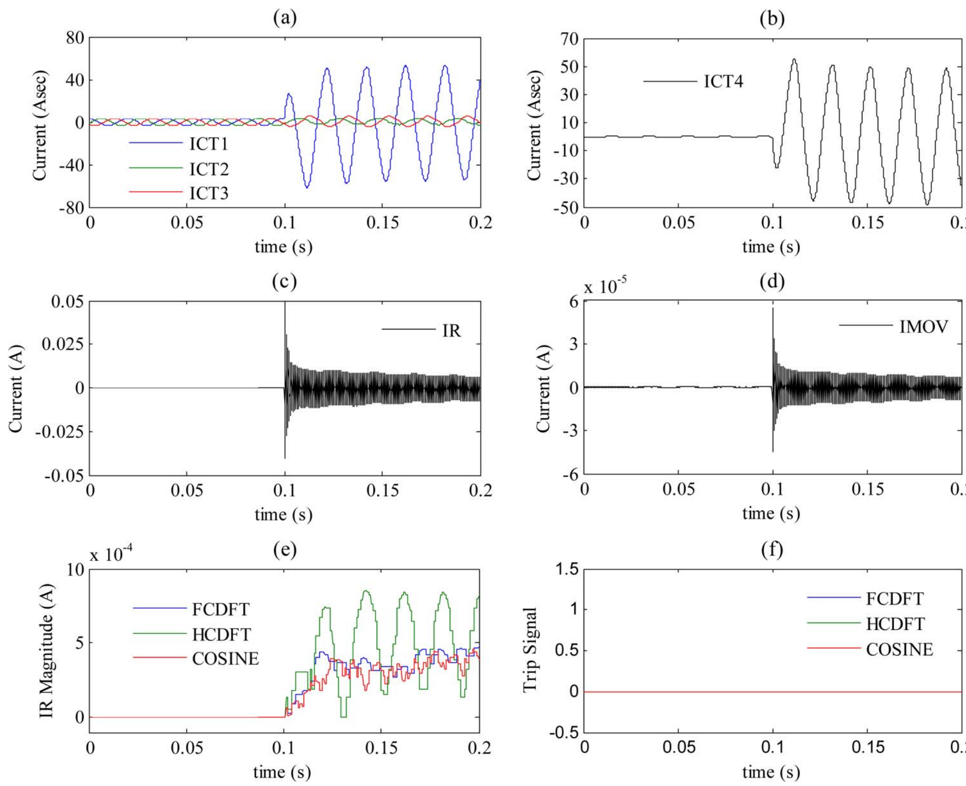

Fig. 15. REF scheme performance for an external fault (Event 3): (a) CTs' secondary current in the LV SWBD. (b) CT secondary current at the transformer neutral. (c) Differential current through the relay. (d) Current through Metrosil. (e) Relay current magnitude. (f) REF relay trip signal.

modeling the fault arc within ATP–EMTP. The value of the nonlinear resistance of the arc in (8) was computed by using TACS functions (e.g., TACS type-66 RMS meter) in a closed-loop manner, as illustrated in Fig. 8.

Fig. 14(a) and (b) shows the secondary currents of the CTs at the LV SWBD side and at the transformer neutral side, respectively. It is shown that, due to the fault location and the intervention of the arc resistance, the saturation of the CTs is not very severe and mainly affects the CTs associated with faulted phase A in the LV SWBD side and the neutral CT in the transformer side. The time-varying resistance of the arc is reflected in Fig. 14(b), where it can be observed that, in the first cycles of the fault, it dampens the short-circuit current and gradually decreases as the RMS value of the arcing current increases. Anyhow, a significant differential current flows through the relay [see Fig. 14(c)] whose characteristics are mainly dominated by the dynamics of CTs rather than the MOV since the voltage across the relay is limited compared with the bolted ground fault in Event 1, and thus, a less amount of current is conducted by the MOV [see Fig. 14(d)]. However, the magnitude of this current is adequate to activate the REF relay trip signal, as shown in Fig. 14(e) and (f).

C. Event 3: External REF Fault

A single-phase-to-ground fault involving phase A was simulated just outside the REF zone of protection after the LV SWBD CTs (see fault point FL3 in Fig. 8).

Due to the proper CT sizing and design, it can be deduced from Fig. 15(a)–(c) that no saturation was developed, leading to equal performance from the matched CTs, i.e., CT1 and CT4. Thus, there was very little differential current to flow in the high-impedance REF relay, as shown in Fig. 15(e) and (f).

In this case, the fault would have been detected and cleared by the downstream LV CB without opening the CB at the MV side, thus keeping the transformer energized.

V. Conclusion

This paper has presented the fundamental concepts of high-impedance REF protection and some practical guidelines for designing and applying such a protection scheme for MV/LV power transformers. The merits of the high-impedance REF protection have been demonstrated with a real-life application example and with an innovative approach for its modeling and simulation using the ATP–EMTP software and MATLAB.

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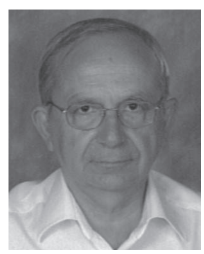

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