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Parameterization of a Coordinated Protection Scheme for a 400/110 kV Power Transformer using a Multifunction Digital Relay SEL-787

Tento článok predstavuje komplexnú metodiku parametrizácie schémy ochrán pre výkonový transformátor 250 MVA, 400/110 kV, ktorý je kľúčovým prvkom v elektrických staniciach. Ochrana je realizovaná pomocou moderného multifunkčného digitálneho relé SEL-787 od spoločnosti Schweitzer Engineering Laboratories (SEL). Ochrana výkonových transformátorov je zásadná, keďže ich poruchy môžu viesť k významnej nestabilite sústavy a veľkým ekonomickým stratám. Táto práca podrobne opisuje analytický proces nastavenia kľúčových ochranných funkcií, vrátane primárnej percentuálnej diferenčnej ochrany (ANSI 87) a záložnej nadprúdovej ochrany s nezávislou charakteristikou (ANSI 50). Ďalej je riešená parametrizácia dôležitých doplnkových funkcií, ako sú ochrana proti tepelnému preťaženiu (ANSI 49), frekvenčná ochrana (ANSI 81) a podpätová ochrana (ANSI 27). Prezentovaný je kompletný a skoordinovaný súbor výpočtov a výsledných nastavení, ktoré sú odvodené z detailných parametrov sústavy a sú v súlade s princípmi definovanými v príslušných normách IEC a IEEE. Štúdia slúži ako praktická prípadová štúdia, ktorá demonštruje aplikáciu modernej filozofie ochrán s cieľom zabezpečiť spoľahlivosť aj bezpečnosť prevádzky vysokonapäťových výkonových transformátorov.

Kľúčové slová: vysokonapäťový transformátor, digitálna ochrana, SEL-787

This paper presents a comprehensive methodology for the parameterization of a protection scheme for a critical 250 MVA, 400/110 kV power transformer, a vital asset in electrical substations. The protection is implemented using a modern Schweitzer Engineering Laboratories (SEL) SEL-787 multifunction digital relay. The critical importance of robust power transformer protection is underscored, as failures can lead to significant grid instability and economic loss. This work details the analytical process for setting key protection functions, including the primary percentage-restrained differential protection (ANSI 87) and the backup time-independent overcurrent protection (ANSI 50). Furthermore, the parameterization of essential ancillary functions such as thermal overload (ANSI 49), frequency (ANSI 81), and undervoltage (ANSI 27) is addressed. A complete, coordinated set of calculations and final settings is presented, derived from detailed system parameters and aligned with the principles outlined in relevant IEC and IEEE standards. The study serves as a practical case study, demonstrating the application of modern protection philosophy to ensure both the dependability and security of high-voltage power transformers.

Keywords: power transformer, multifunction digital relay, SEL-787

I. INTRODUCTION

Large power transformers are among the most critical and capital-intensive components in electrical power systems. They perform the essential function of stepping voltage levels up or down, enabling efficient bulk power transfer over long distances at extra-high voltages (EHV) and subsequent distribution at lower voltage levels. The strategic importance of a 400/110 kV transformer, for instance, lies in its role as a key interface between the transmission grid and sub-transmission or major industrial networks. Due to their bespoke design, high cost, and long manufacturing and replacement lead times, an unplanned outage of such a transformer can have severe consequences, including prolonged supply interruptions, significant economic losses, and a reduction in overall grid reliability [1]. Consequently, the design and implementation of a comprehensive, reliable, and secure protection system is not merely a technical requirement but a fundamental necessity for ensuring the operational integrity of the power system.

Evolution of Protection Philosophy

The philosophy and technology of power system protection have undergone a profound evolution over the past several decades. Early protection schemes relied on discrete electromechanical relays, each designed to perform a single, specific function. These were later superseded by static relays using analog electronic circuits, which offered faster operating times and reduced maintenance. The contemporary standard, however, is the microprocessor-based digital relay, often referred to as an Intelligent Electronic Device (IED). This technological leap has precipitated a paradigm shift in protection philosophy [2].

The transition from discrete, single-function hardware to integrated, multifunction IEDs like the SEL-787 represents a fundamental change from coordinating separate physical devices to coordinating logical functions within a single, software-driven platform [3]. In a conventional scheme, differential, overcurrent, and thermal protection would each be implemented in separate physical relays, requiring complex external wiring for power, measurement, and trip signaling. Coordination involved meticulously matching the time-current characteristics of these independent hardware components. With a modern IED, these diverse protection elements exist as software algorithms within one device. The output of the differential element can serve as a direct logical input to the breaker failure scheme within the same relay, eliminating external wiring and its associated points of failure. This centralization of functionality redefines the role of the protection engineer, where proficiency in software configuration, logic programming, and communication protocols becomes as critical as traditional short-circuit analysis [4].

Challenges in Transformer Protection

The primary objective of a transformer protection system is to balance two conflicting requirements: dependability and security. Dependability is the ability of the protection to operate correctly and rapidly for all internal faults. Security is the ability to refrain from operating during conditions that are not internal faults. Several transient phenomena present significant challenges to achieving this balance [2]:

Magnetizing Inrush: During the energization of a transformer, a transient, high-magnitude current flows into one winding, which is rich in harmonic components, particularly the second harmonic. This current appears as a "false" differential current to the protection relay and can cause an unwanted trip if not properly addressed [2], [5], [6].

Overexcitation: This occurs when the ratio of voltage to frequency (U/Hz) exceeds the transformer's design limits, causing the magnetic core to saturate. This saturation leads to a sharp increase in excitation current, rich in odd harmonics (especially the fifth), which can also manifest as a false differential current and cause dangerous overheating in non-laminated components [3], [6].

External Faults with Current Transformer (CT) Saturation: A high-magnitude fault outside the transformer's zone of protection (a "through-fault") can cause the CTs to saturate. CT saturation results in a severe distortion of the secondary current waveform, leading to a significant measurement error. This can create a spurious differential current, potentially causing the relay to maloperate for a fault it should ignore [2], [5].

II. SYSTEM MODEL AND PARAMETERS

A precise and accurate model of the protected asset and its associated instrumentation is the foundation of any reliable protection scheme. All subsequent calculations are directly derived from the parameters of the power transformer and the current transformers.

Transformer Specifications

The subject of this study is a three-winding power transformer manufactured by Siemens, installed at the U.S. Steel Košice facility and fed from the Lemešany substation. The transformer serves to step down voltage from the 400 kV transmission level to the 110 kV sub-transmission level, with a tertiary winding providing power at 10.72 kV. The detailed nameplate data, which forms the basis for all fault and protection calculations, is presented in TABLE I [6].

TABLE I
Transformer Nameplate Data [6]

Parameter	Value
Manufacturer	Siemens
Type	1 ARZd 250 000-420/C
Rated Power (S_n)	250/250/80 MVA (HV/MV/LV)
Rated Voltage, Primary (HV)	400 kV
Rated Voltage, Secondary (MV)	121 kV (±8 x 1.5% taps)
Rated Voltage, Tertiary (LV)	10.72 kV
Vector Group	YNa0d1
Short-Circuit Voltage (u_k), HV-MV	13.36%
Short-Circuit Voltage (u_k), HV-LV	51.13%
Short-Circuit Voltage (u_k), MV-LV	35.44%
No-Load Losses	90 kW
Load Losses	520 kW
Rated Current, HV ($I_{n,HV}$)	360.8 A
Rated Current, MV ($I_{n,MV}$)	1192.9 A
Rated Current, LV ($I_{n,LV}$)	4308.6 A
Rated Frequency	50 Hz
Cooling Type	ODAF (3 coolers + 1 backup)

Instrumentation: Current Transformer Specifications

The accurate measurement of primary currents is performed by current transformers (CTs) located on each of the transformer's terminals. The selection and specification of these CTs are critical, as their performance directly impacts the reliability of the protection scheme, particularly the differential protection. The specifications of the CTs used in this application are detailed in TABLE II. The accuracy class "5p20" is significant; it indicates that the CT will maintain a composite error of less than 5% at up to 20 times its rated current, a crucial performance characteristic for through-fault conditions [6], [7].

TABLE II
Current Transformer Specifications [6]

Location	CT Ratio, Burden, Accuracy Class
Primary Side (400 kV)	400/1/1, 30/30VA, 5p20, FS10
Secondary Side (110 kV)	1200/1/1, 30/30VA, 5p20, FS10
Tertiary Side (10 kV)	4000/1/1, 30/30VA, 5p20, FS10
Neutral Point	400/1

III. DIFFERENTIAL PROTECTION SCHEME (ANSI 87)

The percentage-restrained differential protection (ANSI device number 87) is the primary protection for a power transformer. It offers fast, sensitive, and selective detection of internal faults, such as winding-to-winding or winding-to-ground short circuits [2], [8].

Principle of Operation

The fundamental principle of differential protection is an application of Kirchhoff's Current Law. Under normal operating conditions or for an external fault, the sum of the currents entering the protected zone (the transformer) is equal to the sum of the currents leaving it. A digital relay measures the currents from the CTs on all windings and calculates their phasor sum. For an internal fault, this equilibrium is disturbed, and the phasor sum will be non-zero, creating a differential or "operate" current (I_{op}). However, to prevent maloperation due to the challenges like CT errors or saturation, a restraining quantity (I_{res}) is also calculated. This is typically a scalar sum or average of the magnitudes of the measured currents, representing the total through-fault current. Relay trips only if the operating current exceeds a certain percentage of the restraining current, making the scheme less sensitive at higher through-fault currents where measurement errors are more likely [9].

Parameterization and Calculations

The parameterization of the SEL-787 differential element involves several key steps to configure its operating characteristic, which is graphically represented by a dual-slope curve.

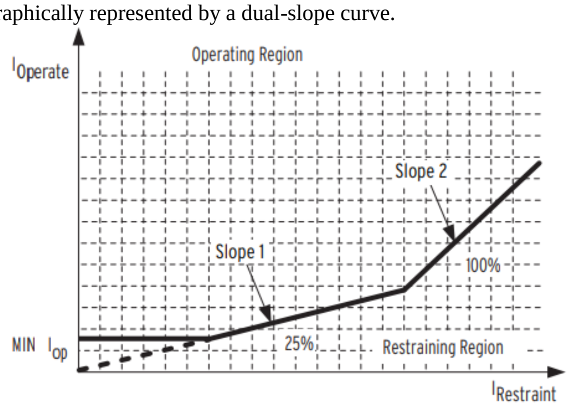

FIg. 1 Dual-Slope Restrained Differential Characteristic [3]

Current Normalization (TAP Settings)

The currents from the different windings have vastly different magnitudes and are measured by CTs with different ratios. To compare them on a common basis, the relay normalizes them using a compensation factor, or TAP setting, for each winding. The TAP is calculated to bring all measured currents to a common per-unit base relative to the transformer's rated power. The formula is [3], [6], [9]:

$$TAP = \frac{S \cdot 1000}{\sqrt{3} \cdot V_{WDG} \cdot CTR} \cdot C \tag{1}$$

where: S is the rated power of the transformer (250 MVA), V_{WDG} is the line-to-line voltage of the winding (in kV), CTR is the current transformer ratio for that winding, C is a connection compensation factor (1 for Wye connections).

Dual-Slope Characteristic Setting

The dual-slope characteristic is an engineered compromise designed to resolve the conflict between sensitivity for internal faults and security against external disturbances.

Minimum Pickup (087P): This is the minimum differential current, expressed as a multiple of the TAP value, required to cause operation. It must be set low enough to detect minor internal faults but high enough to ride through normal steady-state errors from CT inaccuracies and transformer magnetizing current. A typical setting is between 0.2 and 0.3 per unit. A value of 0.3 is selected, providing a good balance of sensitivity and security [3], [6], [9].

Low-Set Slope (SLP1): The first slope defines the relay's sensitivity at low to moderate through-currents. Its setting must account for the cumulative effect of several potential sources of current mismatch, including CT ratio errors and the full range of the transformer's on-load tap changer (LTC). The setting is calculated by summing the maximum expected errors from each source, plus a safety margin [3], [6], [9].

$$SLP1 = 4\% + 3 \cdot 3\% + 10\% + 5\% + 5\% = 33\% \tag{2}$$

A setting of 30% is chosen to provide a robust margin, ensuring security against false differential currents caused by tap-changer operation during heavy load or external fault conditions [6].

High-Set Slope (SLP2): The second, steeper slope is activated at high through-current levels, as defined by the breakpoint setting (IRS1). Its primary purpose is to prevent maloperation during severe external faults where one or more CTs may be saturated. When a CT saturates, its secondary output is diminished and distorted, creating a large false differential current. The steeper slope effectively desensitizes the relay under these specific conditions, prioritizing security over sensitivity precisely when CT saturation is most probable. A common practice is to set SLP2 to approximately double the value of SLP1. Therefore, a setting of 60% is selected [3], [6].

Harmonic Restraint for Magnetizing Inrush

Transformer inrush current is characterized by a high percentage of second-harmonic content, a signature that is largely absent in internal fault currents. The SEL-787 measures the ratio of the second-harmonic component to the fundamental component in the differential current. If this ratio exceeds a predefined threshold (typically 15-20%), the relay's operating logic is restrained, preventing a trip. This allows the transformer to be energized without causing a false operation of its most sensitive protection. The setting for the second-harmonic blocking threshold (PCT2) is set to 15% [3], [6].

Harmonic Blocking for Overexcitation

Similarly, overexcitation results in core saturation that generates a high level of odd harmonics, particularly the fifth. The relay can be configured to block tripping if the fifth-harmonic content exceeds a set threshold, providing security against this specific abnormal operating condition while allowing an alarm to be raised. The setting for the fifth-harmonic blocking threshold (PCT5) is set to 35% [3], [6].

TABLE III
Differential Protection Settings (87) [6]

Function	Description	Setting
TAP1	Compensation Factor, Winding 1 (400 kV)	0.90 A
TAP2	Compensation Factor, Winding 2 (110 kV)	0.99 A
TAP3	Compensation Factor, Winding 3 (10 kV)	3,37 A
O87P	Minimum Pickup Level	0,3 x TAP
O87AP	Differential current alarm value	0,15 x TAP
87AD	Differential current alarm delay	5 s
SLP1	Slope 1	30%
SLP2	Slope 2	60%
IRS1	Breaking point	2,5 x TAP
U87P	Unrestrained Differential Pickup	10 x TAP
PCT2	Second-Harmonic Blocking Threshold	15%
PCT4	Fourth-Harmonic Blocking Threshold	15%
PCT5	Fifth-Harmonic Blocking Threshold	35%
TH5P	Fifth harmonic alarm setting	OFF
HBLK	Harmonic Blocking Enable	YES

IV. BACKUP OVERCURRENT PROTECTION SCHEME (ANSI 50)

Role and Philosophy

While differential protection is the primary means of detecting internal faults, a robust scheme must include independent backup protection. Time-independent overcurrent protection (ANSI device number 50), also known as instantaneous overcurrent, serves this critical role. It is designed to operate for high-magnitude faults within the transformer that might not be correctly cleared by the differential relay due to issues such as CT circuit failure, relay malfunction, or DC power supply loss. It also provides fast clearance for faults on the busbars immediately adjacent to the transformer terminals, which may lie just outside the differential zone of protection. The coordination philosophy is to set the pickup current to be sensitive enough to detect faults but high enough to remain stable during normal and transient operating conditions [2], [9].

Short-Circuit Analysis

The symmetrical components ($Z_{(1)}$, $Z_{(2)}$, $Z_{(0)}$) are calculated for each voltage level. For a transformer, the positive and negative sequence impedances are equal ($Z_{(1)} = Z_{(2)}$). The zero-sequence impedance ($Z_{(0)}$) depends on the core construction and winding connections [6].

For the 400 kV winding (based on HV-MV impedance):

$$Z_{(1)400\text{kV}} = \frac{u_{\text{k,HV-MV}}}{100} \cdot \frac{U_{\text{n,HV}}^2}{S_\text{n}} = \frac{13{,}36}{100} \cdot \frac{(400\ \text{kV})^2}{250\ \text{MVA}} = 85{,}504\ \Omega \tag{3}$$

$$Z_{(2)400\text{kV}} = Z_{(1)400\text{kV}} = 85{,}504\ \Omega \tag{4}$$

$$Z_{(0)400\text{kV}} = 0{,}85 \cdot Z_{(1)400\text{kV}} = 72{,}678\ \Omega \tag{5}$$

For the 110 kV winding (based on HV-MV impedance):

$$Z_{(1)110\text{kV}} = \frac{u_{\text{k,HV-MV}}}{100} \cdot \frac{U_{\text{n,MV}}^2}{S_\text{n}} = \frac{13{,}36}{100} \cdot \frac{(121\ \text{kV})^2}{250\ \text{MVA}} = 7{,}824\ \Omega \tag{6}$$

$$Z_{(2)110\text{kV}} = Z_{(1)110\text{kV}} = 7{,}824\ \Omega \tag{7}$$

$$Z_{(0)110\text{kV}} = 0{,}85 \cdot Z_{(1)110\text{kV}} = 6{,}650\ \Omega \tag{8}$$

For the 10.72 kV winding (based on MV-LV impedance):

$$Z_{(1)10\text{kV}} = \frac{u_{\text{k,HV-LV}}}{100} \cdot \frac{U_{\text{n,LV}}^2}{S_{\text{n,LV}}} = \frac{35{,}44}{100} \cdot \frac{(10{,}72\ \text{kV})^2}{80\ \text{MVA}} = 0{,}509\ \Omega \tag{9}$$

$$Z_{(2)10\mathrm{kV}} = Z_{(1)10\mathrm{kV}} = 0{,}509\ \Omega \tag{10}$$

$$Z_{(0)10\mathrm{kV}} = 0{,}85 \cdot Z_{(1)10\mathrm{kV}} = 0{,}433\ \Omega \tag{11}$$

Fault Current Calculations

Using these impedances, the initial symmetrical short-circuit currents (I''_{k}) are calculated for three-phase (I''_{k3}), two-phase (I''_{k2}), and single-phase (I''_{k1}) faults. The voltage factor *c* is taken as 1.1 for maximum fault calculations and 1.0 for minimum fault calculations per IEC 60909 [6], [10].

At the 400 kV terminals:

$$I''_{\mathrm{k3,max}} = \frac{c \cdot U_{\mathrm{n}}}{\sqrt{3} \cdot \left|Z_{(1)400\mathrm{kV}}\right|} = \frac{1{,}1 \cdot 400\ \mathrm{kV}}{\sqrt{3} \cdot |85{,}504\ \Omega|} = 2971\ \mathrm{A} \tag{12}$$

$$I''_{\mathrm{k2,min}} = \frac{c \cdot U_{\mathrm{n}}}{\left|Z_{(1)400\mathrm{kV}} + Z_{(2)400\mathrm{kV}}\right|} = \frac{1 \cdot 400\ \mathrm{kV}}{|85{,}504 + 85{,}504|} = 2339\ \mathrm{A} \tag{13}$$

At the 110 kV terminals:

$$I''_{\mathrm{k3,max}} = \frac{c \cdot U_{\mathrm{n}}}{\sqrt{3} \cdot \left|Z_{(1)110\mathrm{kV}}\right|} = \frac{1{,}1 \cdot 121\ \mathrm{kV}}{\sqrt{3} \cdot |7{,}824\ \Omega|} = 9822\ \mathrm{A} \tag{14}$$

$$I''_{\mathrm{k2,min}} = \frac{c \cdot U_{\mathrm{n}}}{\left|Z_{(1)110\mathrm{kV}} + Z_{(2)110\mathrm{kV}}\right|} = \frac{1 \cdot 400\ \mathrm{kV}}{|7{,}824\ \Omega + 7{,}824\ \Omega|} = 7733\ \mathrm{A} \tag{15}$$

At the 10.72 kV terminals:

$$I''_{\mathrm{k3,max}} = \frac{c \cdot U_{\mathrm{n}}}{\sqrt{3} \cdot \left|Z_{(1)10\mathrm{kV}}\right|} = \frac{1{,}1 \cdot 10{,}72\ \mathrm{kV}}{\sqrt{3} \cdot |0{,}509\ \Omega|} = 13375\ \mathrm{A} \tag{16}$$

$$I''_{\mathrm{k2,min}} = \frac{c \cdot U_{\mathrm{n}}}{\left|Z_{(1)10\mathrm{kV}} + Z_{(2)10\mathrm{kV}}\right|} = \frac{1 \cdot 10{,}72\ \mathrm{kV}}{|0{,}509\ \Omega + 0{,}509\ \Omega|} = 10530\ \mathrm{A} \tag{17}$$

Pickup Current Setting Methodology

The setting of an instantaneous overcurrent relay requires a careful balance. The pickup current must be set above the maximum possible load current and must also be secure against transformer magnetizing inrush current. Crucially, to ensure dependability, it must be set below the minimum fault current that the relay is expected to detect.

This selection of the *minimum* fault current as the basis for the setting is a deliberate and conservative design choice. While the three-phase fault often produces the highest current, a protection scheme must be guaranteed to operate for *all* fault types within its zone. The two-phase fault (I''_{k2}) often represents the lowest magnitude phase-to-phase fault current. By ensuring the pickup setting is below this worst-case value ($I_{\mathrm{r}} < I''_{\mathrm{k2,min}}$), the engineer guarantees that the protection will respond even to the least severe type of short circuit. This philosophy ensures robust and dependable backup protection: if the relay can detect the weakest fault, it will certainly detect all stronger ones [2], [10].

The pickup current (I_{r}) is set below the minimum two-phase fault current ($I''_{\mathrm{k2,min}}$). A safety margin is applied [6].

- **400 kV Winding:** $I_{\mathrm{r}} = 2250\ \mathrm{A}$ (which is $< 2339\ \mathrm{A}$). Secondary current: $I_{2\mathrm{r}} = \frac{2250\ \mathrm{A}}{400} = 5{,}63\ \mathrm{A}$
- **110 kV Winding:** $I_{\mathrm{r}} = 7600\ \mathrm{A}$ (which is $< 7733\ \mathrm{A}$). Secondary current: $I_{2\mathrm{r}} = \frac{7600\ \mathrm{A}}{1200} = 6{,}33\ \mathrm{A}$
- **10,72 kV Winding:** $I_{\mathrm{r}} = 102500\ \mathrm{A}$ (which is $< 10530\ \mathrm{A}$). Secondary current: $I_{2\mathrm{r}} = \frac{10250\ \mathrm{A}}{4000} = 2{,}56\ \mathrm{A}$

These settings are for the high-set instantaneous element ($I >>$). A lower-set element ($I >$) is also configured for overload conditions, set at approximately 1.2 to 1.4 times the nominal current with a significant time delay to allow for coordination with downstream devices [6].

TABLE IV
Overcurrent Protection Settings (50) [6]

Winding	Function	Description	Setting
Primary (400 kV)	50P11P ($I >$)	Overload Pickup	1.26 A
	50P11D ($t >$)	Overload Time Delay	4.5 s
	50P12P ($I >>$)	Short-Circuit Pickup	5.63 A
	50P12D ($t >>$)	Short-Circuit Time Delay	0.3 s
Secondary (110 kV)	50P21P ($I >$)	Overload Pickup	1.39 A
	50P21D ($t >$)	Overload Time Delay	4.5 s
	50P22P ($I >>$)	Short-Circuit Pickup	6.33 A
	50P22D ($t >>$)	Short-Circuit Time Delay	0.4 s
Tertiary (10 kV)	50P31P ($I >$)	Overload Pickup	1.29 A
	50P31D ($t >$)	Overload Time Delay	4.5 s
	50P32P ($I >>$)	Short-Circuit Pickup	2.56 A
	50P32D ($t >>$)	Short-Circuit Time Delay	0.3 s

V. ANCILLARY AND SYSTEM-BASED PROTECTION FUNCTIONS

The capabilities of a modern multifunction IED extend far beyond simple fault detection. The integration of ancillary protection functions transforms the relay from a reactive device into a comprehensive asset management and system stability tool. While ANSI 87 and 50 elements act to mitigate the effects of a catastrophic failure already in progress, functions like thermal, frequency, and voltage protection provide proactive asset preservation and system-level support [4], [9].

Thermal Overload Protection (ANSI 49)

Sustained overloading, even at levels below the pickup of overcurrent protection, generates excess heat that accelerates the aging of the transformer's paper insulation. This thermal stress is the primary determinant of a transformer's operational lifespan. The thermal overload function (ANSI 49) protects against this gradual degradation. The SEL-787 uses inputs from Resistance Temperature Detectors (RTDs) placed in the transformer oil and windings to monitor temperatures directly [11]. The settings for alarm and trip thresholds are based on manufacturer recommendations and industry standards such as IEEE C57.91 and IEC 60076-7, which define the thermal limits for safe operation and acceptable loss of life [12]. This function is proactive; it acts to preserve the long-term health and value of the asset, not just prevent its immediate destruction.

Frequency Protection (ANSI 81)

The under-frequency protection element (ANSI 81) is not primarily designed to protect the transformer itself. Instead, it uses the transformer's connection point as a sensor to monitor the health of the entire interconnected power grid. A significant drop in system frequency indicates a severe imbalance between generation and load, a condition that can lead to a cascading blackout. Under-frequency relays are key components of grid defense plans. When frequency falls below a series of predetermined setpoints, these relays automatically shed blocks of load to restore balance. The tripping action of the ANSI 81 element in this scheme is therefore a deliberate, controlled sacrifice of the local load supplied by the transformer in order to help preserve the stability of the wider system. The settings are dictated by the transmission system operator's grid code requirements [9], [13].

Voltage Protection (ANSI 27)

The undervoltage protection element (ANSI 27) monitors for abnormally low system voltages. Sustained undervoltage can cause increased current draw and overheating in motor loads and can also be an indicator of a remote fault or unstable system conditions. The undervoltage function in this scheme serves to disconnect the transformer and its associated loads during severe voltage depressions, preventing potential damage to connected equipment and contributing to system stability by removing reactive power sinks [3], [9].

TABLE V
Ancillary Protection Settings [6]

Function	Description	Setting
Thermal (RTD)		
TRTMP1	Top Oil Trip Temperature	110 °C
ALTMP1	Top Oil Alarm Temperature	95 °C
TRTMP2	Winding Hot Spot Trip Temperature	125 °C
ALTMP2	Winding Hot Spot Alarm Temperature	113 °C
Frequency (81)		
81D1TP	Under-frequency Pickup	49.00 Hz
81D1TD	Under-frequency Time Delay	0.1 s
Undervoltage (27)		
27PP1P	Phase-to-Phase Undervoltage Pickup	85.0 V (secondary)
27PP1D	Undervoltage Time Delay	1.0 s

VI. SYSTEM INTEGRATION AND ADVANCED LOGIC

The full capability of a modern IED like the SEL-787 is realized not just through its individual protection functions, but through its ability to integrate into a larger automation system and execute complex, user-defined logic.

A modern protection relay is a key data acquisition point for Supervisory Control and Data Acquisition (SCADA) systems. The SEL-787 supports a wide array of industry-standard communication protocols, allowing for seamless integration into substation automation systems. These include [3]:

- **Ethernet Protocols**: IEC 61850, DNP3 LAN/WAN, and Modbus TCP/IP for high speed, network-based communication. These protocols enable the relay to transmit real-time metering data, event reports, and status information to a central SCADA master, and to receive remote commands [3].
- **Serial Protocols**: DNP3 Serial and Modbus RTU are also available for legacy systems or specific applications, typically communicating over EIA-232 or EIA-485 physical layers [3].

This communication capability allows operators to remotely monitor the transformer's status, acknowledge alarms, and analyze post-fault data without needing to be physically present at the substation, significantly improving operational efficiency and response times.

Programmable Logic and Inter-function Coordination

The SEL-787 includes a powerful programmable logic engine, known as SELogic, which allows engineers to create custom protection and control schemes using Boolean logic. This is a significant advancement over older systems that require complex external wiring between discrete relays to achieve similar results [3].

Using SELogic, the outputs of various protection elements can be combined with physical inputs (e.g., from breaker auxiliary contacts) and timers to create sophisticated logic. For example, a breaker failure scheme can be implemented entirely within the relay's software. If the differential element (87) issues a trip command, a SELogic timer starts. If the relay does not see the breaker's current interrupt or its auxiliary contact change state within a set time, the logic will assert a "breaker failure" output. This output can then be programmed to trip an upstream breaker, ensuring the fault is cleared. This internal, software-based coordination is faster, more reliable, and easier to document and test than traditional hardwired schemes [3], [14].

VII. SETTINGS VALIDATION AND COMMISSIONING

The calculation of protection settings is a critical first step, but it is not the final one. Before a relay is placed into service, its settings and logic must be rigorously tested and validated to ensure it will perform as expected under real-world conditions. This validation process is a cornerstone of commissioning and typically involves several methods:

Simulation: Advanced power system simulation software (e.g., EMTP, MATLAB/Simulink) can be used to create a detailed model of the transformer and the surrounding network. Various internal and external fault scenarios, as well as transient conditions like inrush, can be simulated. The resulting current and voltage waveforms are then played back into the relay through a test set to verify that it operates correctly and securely for each case [15].

Secondary Injection Testing: This is the most common form of relay testing, where a specialized test set (Omicron) is used to inject precise currents and voltages directly into the relay's terminals. This allows the engineer to verify the exact pickup points, operating times, and slope characteristics of each protection function, ensuring they match the calculated settings and the manufacturer's specifications [16].

End-to-End Testing: For unit protection schemes like differential, an end-to-end test is often performed. This involves injecting currents simultaneously at the locations of the different CTs in the scheme to verify the entire system, including the relay, wiring, and any communication channels involved.

VIII. CONCLUSION AND FUTURE ENHANCEMENTS

This paper has detailed the systematic parameterization of a comprehensive protection scheme for a 250 MVA, 400/110 kV power transformer, leveraging the multifunction capabilities of a SEL-787 digital relay. The primary contribution is the development of a complete, coordinated, and analytically justified set of protection settings designed to ensure the highest levels of dependability and security for this critical grid asset.

The key findings of this work are encapsulated in the final settings derived for the primary and backup protection functions. The differential protection scheme was configured with a dual-slope characteristic (30% and 60%) and harmonic restraint (15% for second harmonic), providing a robust balance that is sensitive to internal faults while remaining secure against the challenging transient conditions of magnetizing inrush and CT saturation. The backup time-independent overcurrent protection was set based on a rigorous short-circuit analysis, with pickup values carefully chosen to be below the minimum two-phase fault current at each terminal, guaranteeing operation even for the least severe fault scenarios. Furthermore, the integration of ancillary functions, advanced logic, and communication capabilities demonstrates the evolution of the protection relay into a holistic asset management and system stability tool.

For a truly comprehensive implementation, further enhancements could be considered to increase the depth of protection:

- **Distance Protection (ANSI 21):** While overcurrent provides effective backup, distance protection offers a more selective alternative. A distance relay measures the impedance to a fault and can be set to operate for faults on the connected transmission lines, providing fast, remote backup without the coordination challenges of time-delayed overcurrent relays. This improves overall system resilience by isolating external faults more rapidly [2], [16].

- **Frame Leakage Protection (ANSI 64):** This scheme, also known as tank ground protection, involves insulating the transformer tank from the main ground grid and connecting it via a single conductor that passes through a CT. This provides extremely sensitive and high-speed detection of any fault that involves the transformer's grounded structure, often operating faster than the differential protection for winding-to-ground faults. It offers an excellent supplement to the main differential scheme [9].

The methodology presented herein, however, provides a solid and reliable foundation for the protection of high-voltage power transformers in modern transmission networks. The subsequent validation and commissioning of these settings are crucial final steps to ensure the scheme's integrity before placing the asset in service.

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