

Relay Protection Coordination of a Hybrid Renewable Energy Network for Safe and Reliable Operation in Salvation Ministries Cathedral Power Network

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Abstract

This study develops and evaluates a relay protection coordination scheme for a 11.5 MW hybrid power system comprising 5 MW solar photovoltaic (PV), 2 MW wind, and a 4.5 MW diesel generator, interconnected with the utility grid at Salvation Ministries Cathedral, Rivers State, Nigeria. The protection design addresses key challenges in distributed generation, including bidirectional power flow, low fault current contribution from inverter-based sources, and operation under both grid-connected and islanded modes (PV Sources). Current transformer (CT) ratios were selected based on load and fault analyses as 200/1 A (33 kV), 800/1 A (11 kV), and 3500/1 A (transformer protection). Initial relay settings followed IEEE C37.112 inverse-time characteristics, with pickup currents at 125% of full-load current and a grading margin of 0.3 s. However, simulations using ETAP 19.0.1 revealed significant coordination challenges due to unequal fault current contributions, ranging from approximately 1.7 kA (PV) to over 5 kA (grid), with overall fault levels of 17.5 kA (33 kV), 19.2 kA (11 kV) and 52.6 kA (0.415 kV). The results showed that load-based pickup settings led to poor relay sensitivity for inverter-based sources and delayed operation for grid-connected protection. A revised approach based on minimum fault current levels, with non-uniform pickup settings and optimized time grading, improved coordination and selectivity. The study concludes that effective protection of hybrid systems requires fault-based relay setting methodologies and, for busbar faults, fast tripping schemes beyond conventional grading.

Keywords- Relay Protection Coordination, Overcurrent Relay, CT Sizing, Time-Current Characteristic, Selectivity, Hybrid Renewable Energy, IEEE 50/51, ETAP, Protection Settings, Plug Setting Multiplier, Time Multiplier Setting

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I. INTRODUCTION

The integration of renewable energy sources into conventional power systems presents significant and multifaceted challenges for protection engineers worldwide. Unlike traditional synchronous generators that have been the backbone of power systems for over a century, inverter-based resources such as solar photovoltaic (PV) systems, wind turbines, and battery energy storage systems exhibit fundamentally different electrical characteristics during both normal operation and fault conditions. During fault conditions, grid-connected inverters typically limit their output current to approximately 1.2 to 1.5 times the rated current through sophisticated control algorithms, compared to synchronous generators which can contribute fault currents of 6 to 10 times the rated current due to their inherent physical properties and the dynamics of electromagnetic energy conversion. This substantially reduced fault current magnitude fundamentally complicates protection coordination, particularly when renewable sources are integrated with conventional grid-connected systems that rely on high fault current levels for reliable protective relay operation.

The protection challenges are further exacerbated in hybrid renewable energy systems that combine multiple generation technologies with different fault current characteristics. Solar PV systems contribute limited fault current through their inverter interfaces, wind turbines may use either doubly fed induction generators or full-converter synchronous generators with varying fault responses, battery storage systems provide controlled

current output, and conventional diesel generators offer traditional high fault current contributions. This diversity of fault current sources creates complex protection coordination scenarios where traditional relay settings based on maximum fault current may not provide adequate sensitivity for faults supplied primarily by inverter-based sources, while settings optimized for inverter contributions may result in slow operation or failure to operate for faults with high synchronous generator contribution.

Salvation Ministries Cathedral Project (SMCP) located in Igwuruta, Rivers State, Nigeria, presents a compelling and representative case study for protection coordination in hybrid renewable energy systems. The facility operates a 11.5 MW hybrid generation system comprising 5 MW of solar photovoltaic arrays, 2 MW of wind turbine capacity and 4.5 MW of diesel generator backup, all interconnected with the utility grid at 33 kV through a comprehensive distribution network with multiple voltage transformation levels. The protection system must ensure safe, reliable, and selective operation under various operating modes including grid-connected with renewable export, grid-connected with renewable curtailment, islanded mode with diesel generation providing voltage and frequency reference, and transition states between these operating conditions. Furthermore, the protection scheme must coordinate across multiple voltage levels (33 kV, 11 kV, and 0.415 kV) with different fault current characteristics and protection requirements at each level.

The primary objectives of this comprehensive protection coordination study are:

- i. to design a robust and comprehensive protection scheme that ensures selective fault clearance under all operating conditions.
- ii. to calculate appropriate CT ratios for accurate fault detection, measurement, and relay operation across all voltage levels.
- iii. to determine optimal relay settings for phase overcurrent protection (50/51) that coordinate properly across the entire network.
- iv. to develop and verify time-current characteristic curves that demonstrate proper selectivity with adequate grading margins.
- v. to analyze protection performance under different operating modes including grid-connected and islanded operation.
- vi. to verify protection coordination through detailed simulation using ETAP 19.0.1 software with comprehensive fault scenarios.

This paper is organized as follows: Section II provides detailed definitions of key terminologies related to protection coordination. Section III presents a comprehensive review of relevant literature on protection challenges in renewable energy systems and established coordination methodologies. Section IV describes the materials and methods including system configuration, fault analysis methodology, and protection philosophy. Section V presents detailed protection design calculations including CT sizing, relay settings calculations with complete mathematical derivations, and coordination analysis. Section VI presents results and discussion including TCC curves, coordination verification, and performance analysis. Section VII provides conclusions and practical recommendations for protection engineers.

DEFINITION OF KEY TERMINOLOGIES

Protection Coordination

Protection coordination is the systematic engineering discipline of arranging protective devices in a power system such that faults are cleared by the protective device nearest to the fault location, while all other protective devices remain inoperative and unaffected. Proper coordination ensures minimum disruption to the power system, maintains service continuity to healthy sections of the network, provides backup protection in case of primary protection failure, and minimizes equipment damage and safety hazards. The coordination process involves selecting appropriate relay types, calculating pickup settings, determining time-current characteristics, and verifying grading margins between successive protection levels. Effective protection coordination requires detailed knowledge of system configuration, fault current magnitudes under various operating conditions, equipment ratings, and protection device characteristics.

Overcurrent Relay (50/51)

Overcurrent relays are fundamental protective devices that operate when the electrical current exceeds a predetermined threshold value. The IEEE device number 50 represents instantaneous overcurrent protection, which operates without intentional time delay when the measured current exceeds a set pickup value. This element provides rapid clearing of high-magnitude faults close to the relay location. Device number 51 represents time-overcurrent protection, which incorporates an intentional time delay that varies inversely with the magnitude of the current exceeding the pickup threshold. The time delay characteristic follows standardized mathematical curves (inverse, very inverse, extremely inverse) that allow coordination with downstream devices. The combined 50/51 relay provides comprehensive protection with instantaneous operation for high-

magnitude faults and time-delayed operation for lower magnitude faults, overload conditions, and coordination purposes. Modern microprocessor-based relays offer programmable characteristics, multiple setting groups, and advanced features such as cold load pickup, inrush restraint, and harmonic restraint.

Current Transformer (CT)

A current transformer is an instrument transformer that produces a secondary current accurately proportional to the primary current flowing in the power circuit. CTs are essential for reducing high power system currents to standardized secondary levels (typically 1A or 5A) suitable for protective relays, measuring instruments, and control devices. The CT ratio is selected based on maximum load current, maximum fault current magnitude, connected burden, and relay input requirements. CT accuracy class (such as 5P20, 10P10, or TPX) indicates the maximum composite error at the rated accuracy limit primary current and defines the CT's performance during fault conditions. Protection CTs must maintain accuracy under high fault currents to ensure reliable relay operation. Important CT parameters include: continuous thermal rating, short-time thermal rating, accuracy class, accuracy limit factor (ALF), knee-point voltage for class X CTs, and secondary winding resistance.

Time-Current Characteristic (TCC) Curve

A time-current characteristic curve is a graphical representation of the operating time of a protective device as a function of the applied fault current magnitude. TCC curves are plotted on logarithmic coordinates with current (expressed as multiples of pickup current) on the horizontal axis and operating time on the vertical axis. Standard curve types defined by IEEE and IEC include: Standard Inverse (SI), Very Inverse (VI), Extremely Inverse (EI), Long Time Inverse, and Definite Time characteristics. Each curve type follows a specific mathematical equation that determines the relationship between current magnitude and operating time. Proper coordination requires that downstream device curves lie entirely below upstream device curves with adequate time margin (grading margin) across the entire range of fault currents. TCC curves are essential tools for visualizing and verifying protection coordination in power system protection studies.

Selectivity and Grading Margin

Selectivity is the fundamental principle of protection coordination that ensures only the protective device closest to a fault operates to isolate the faulted section, while all other protective devices remain inactive to maintain power supply to healthy network sections. The grading margin is the minimum intentional time difference between the operating time of two protective devices in series for the same fault current. A typical grading margin of 0.3 to 0.4 seconds accounts for circuit breaker operating time (typically 0.08 to 0.12 seconds), relay over-travel time (typically 0.05 to 0.10 seconds), safety factor, and measurement errors. Proper selectivity ensures minimum service interruption, reduces equipment stress from through-faults, and provides clear indication of fault location for maintenance personnel. Selectivity can be achieved through time grading, current grading, or a combination of both, depending on system configuration and protection requirements.

Plug Setting Multiplier (PSM) and Time Multiplier Setting (TMS)

The Plug Setting Multiplier (PSM), also known as the multiple of pickup, is the ratio of the actual fault current to the relay pickup current setting, expressed mathematically as;

$$PSM = \frac{I_{Fault}}{I_{Pickup}} \quad (1)$$

The PSM determines the position on the time-current characteristic curve and thus the operating time for inverse-time relays.

The Time Multiplier Setting (TMS), also known as Time Dial Setting (TDS), is an adjustable multiplier that scales the operating time obtained from the standard characteristic curve. The actual operating time is calculated as:

$$t = \frac{\alpha \times TSM}{(PSM)^\beta - 1} \quad (2)$$

The TMS allows coordination engineers to adjust relay operating times to achieve proper grading margins while maintaining the same characteristic curve shape. Typical TMS values range from 0.025 to 1.0 for electromechanical relays and 0.00 to 1.00 for microprocessor-based relays with finer resolution.

II. LITERATURE REVIEW

The protection of power systems with high penetration of renewable energy sources has been extensively studied in the technical literature over the past two decades. The fundamental challenge arises from the fundamentally different fault current contribution characteristics of inverter-based resources compared to conventional synchronous generators. According to IEEE Std 1547-2018, grid-connected inverters must cease to

energize the area electric power system within specified clearing times during abnormal voltage or frequency conditions. This anti-islanding requirement fundamentally limits the fault current contribution from renewable sources and creates protection coordination challenges that do not exist in conventional power systems dominated by synchronous generation.

Al-Nasseri et al. (2006) conducted pioneering research on protection coordination issues in distribution systems with distributed generation, highlighting that bidirectional power flow can cause several protection problems including protection blinding (failure to detect faults due to current division), sympathetic tripping (unnecessary operation for faults outside the protected zone), and failed reclosing (unsuccessful automatic restoration due to continued generation in the isolated section). The study recommended adaptive protection schemes that adjust relay settings based on real-time generation availability and system configuration. This work established the foundation for understanding protection challenges in systems with distributed generation.

Brahma (2011) proposed an innovative fault location and protection scheme specifically designed for multi-source power systems with distributed generation. The research emphasized the need for communication-assisted protection in systems with distributed generation, where traditional overcurrent protection may not provide adequate selectivity due to variable fault current contributions from multiple sources. The proposed scheme used synchronized measurements from multiple locations to accurately identify fault location and isolate only the faulted section. This work demonstrated that advanced protection techniques beyond conventional overcurrent protection are necessary for complex systems with multiple generation sources.

Zamani et al. (2012) presented a comprehensive and influential review of protection challenges specific to microgrids, identifying four key technical issues: (1) reduced fault current levels from inverter-based sources affecting overcurrent relay sensitivity and reach; (2) bidirectional power flow causing incorrect directional decisions in directional overcurrent relays designed for unidirectional flow; (3) varying fault current contributions depending on operating mode (grid-connected versus islanded) requiring different protection settings; and (4) protection coordination complexity in islanded mode where fault currents are significantly lower than in grid-connected mode. The authors recommended a combination of conventional overcurrent protection, differential protection, and communication-based schemes for effective microgrid protection across all operating modes.

Sortomme et al. (2011) conducted detailed analysis of the impact of photovoltaic generation on protective device coordination in distribution systems using both simulation and field data. The study demonstrated that PV penetration levels above 30% can significantly alter fault current magnitudes and directions throughout the distribution network, potentially causing miscoordination of existing protection schemes that were designed assuming unidirectional power flow and specific fault current levels. The authors proposed a microprocessor-based adaptive protection system that modifies relay settings in real-time based on generation data and system configuration. This work highlighted the need for flexible protection systems that can adapt to changing generation patterns in systems with high renewable penetration.

For current transformer and voltage transformer sizing in renewable energy applications, IEEE C57.13 and IEC 61869 standards provide comprehensive guidelines that must be carefully applied. CT selection criteria include: (1) continuous thermal rating factor (typically 1.0 or 1.3 for protection applications); (2) accuracy class requirements (5P, 10P, or TP for protection applications); (3) accuracy limit factor (ALF) that defines the multiple of rated current at which the CT maintains specified accuracy; and (4) transient performance requirements for applications with high DC offset fault currents. VT selection criteria include: (1) voltage ratio matching the system voltage and connected device requirements; (2) burden capability exceeding the total connected load including relay voltage circuits and any metering devices; (3) accuracy class (0.3, 0.6, or 1.2 for metering; 3P or 6P for protection); and (4) thermal and voltage factor ratings for abnormal conditions.

Overcurrent relay setting calculations follow well-established methodologies documented in IEEE C37.112 and IEC 60255 standards. The pickup current for phase overcurrent elements is typically set at 125% to 150% of maximum load current to prevent nuisance tripping during normal overload conditions and cold load pickup. Time dial settings are determined through coordination studies to achieve proper selectivity with adequate grading margins. For renewable energy systems, additional considerations include: (1) inverter current limiting effects on fault current magnitude that may require more sensitive settings; (2) harmonic content from power electronic converters that can affect relay accuracy and may require harmonic filtering; (3) varying generation profiles affecting load current calculations; and (4) different fault contributions in grid-connected versus islanded modes that may require multiple setting groups.

Recent advanced studies by Hooshyar and Iravani (2017) and Jia et al. (2018) have explored innovative protection techniques specifically designed for inverter-dominated power systems. These include traveling wave protection that uses high-frequency components of fault transients, frequency-based protection that detects faults through analysis of system frequency response, and machine learning approaches for fault detection and classification. While these advanced techniques show promise for future applications, conventional overcurrent protection with proper coordination remains the most practical and economically viable solution for many

current applications, particularly in developing countries with limited communication infrastructure and technical resources. This research focuses on practical protection coordination using established techniques that can be implemented with readily available equipment and expertise.

III. MATERIALS AND METHODS

System Configuration and Network Topology

The SMCP hybrid renewable energy system comprises multiple generation sources interconnected through a comprehensive 33/11/0.415 kV distribution network. The single-line diagram of the protection study network includes the following key components:

- (1) Grid interconnection at 33 kV with 1000 MVA short-circuit capacity representing the utility connection;
- (2) Two 7.5 MVA, 33/11 kV step-down transformers (designated TR-800 and TR-801) with 8.35% impedance and ONAN cooling;
- (3) 5 MW solar photovoltaic arrays connected through 2.5 MVA inverter transformers with 600V DC input and 11 kV AC output;
- (7) Two 1 MW wind turbines connected through a 2.5 MVA, 0.69/11 kV step-up transformer; (5) 4.5 MW diesel generator capacity comprising two 2.25 MW units operating at 0.415 kV;
- (8) Distribution feeders at 11 kV and 0.415 kV supplying various facility loads including lighting, HVAC, and sound systems.

The system is designed to operate in multiple modes depending on grid availability and load requirements: (1) Grid-connected mode with renewable sources exporting excess power to the utility; (2) Grid-connected mode with renewable generation less than load, importing power from utility; (3) Islanded mode with diesel generators providing voltage and frequency reference; (4) Islanded mode with battery storage providing grid-forming function; and (5) Transition modes during grid connection and disconnection sequences. The protection coordination must account for all operating modes with varying fault current contributions from each source and ensure reliable protection across the entire range of operating conditions.

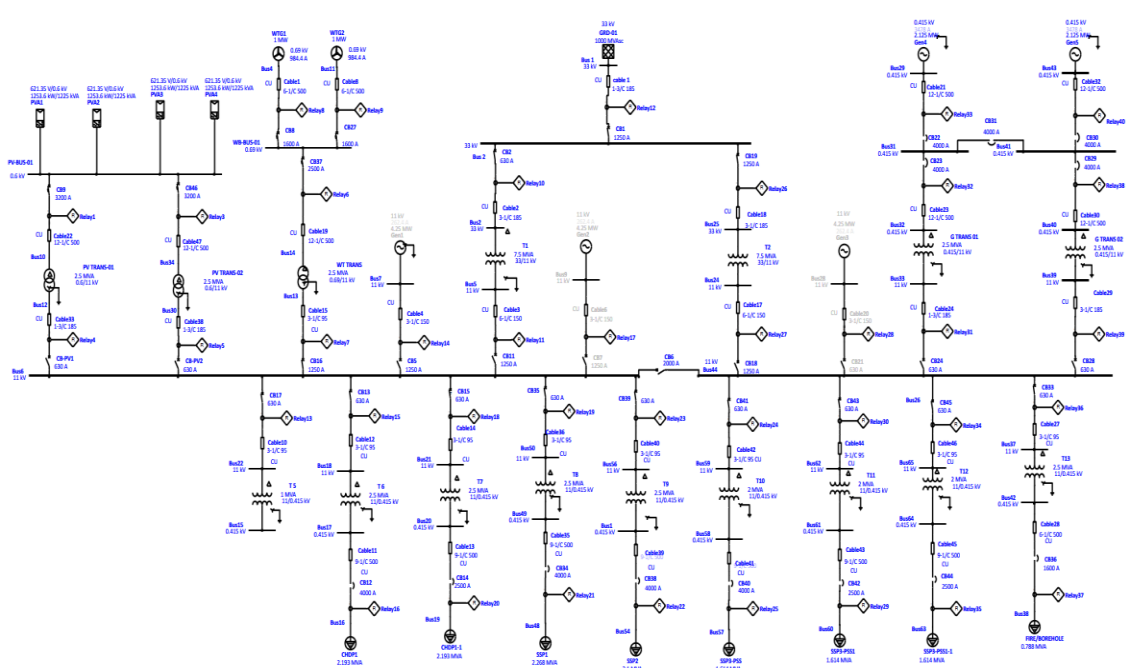


Figure 1: Salvation Ministries Proposed Power Network

Generation Source Characteristics and Fault Current Contributions

Source	Capacity	Voltage	Fault Current	X/R Ratio
Grid	1000 MVAsc	33 kV	11.25 kA	45
Solar PV	5 MW	600 V DC	1.2 x rated	-
Wind	2 MW	690 V	1.2 x rated	-
Diesel	4.5 MW	0.415 kV	6-8 x rated	25

Battery	500 kWh	600 V DC	1.2 x rated	-
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Table 1: Generation Source Characteristics and Fault Current Contributions

Load Flow Analysis Using Newton Raphson Technique

Load flow analysis was carried out in ETAP using Newton Raphson method to evaluate the steady state performance of the network, including Voltage profiles, Active and Reactive power distribution and Amperage loading of the system as show below.

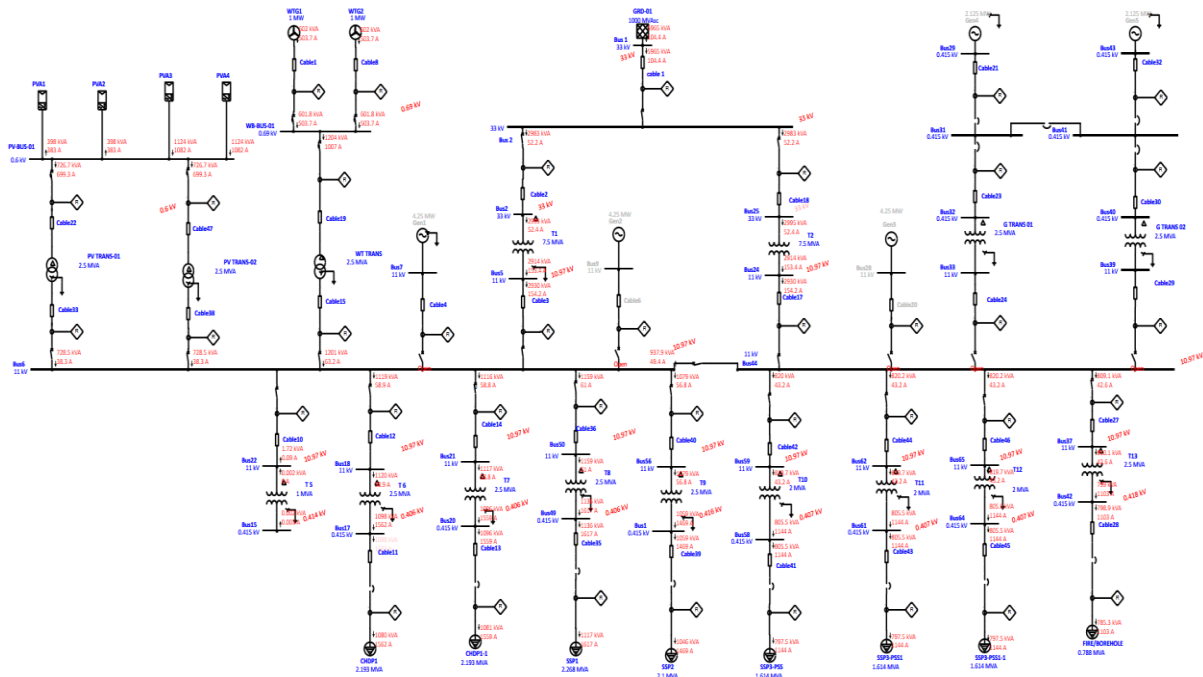


Figure 2: Load flow Analysis of Salvation Ministries Proposed Power Network

Table 2: Load flow Results at Key Network Locations

Location	Nominal KV	Voltage %	MW Loading	Mvar Loading	Amp Loading
33 kV Bus	33	100	3.809	2.297	104.3
11 kV Bus	11	99.74	4.549	2.232	266.7
0.415 kV Bus	0.415	99.71	0.672	0.433	1103
Solar PCC	0.6	100	2.249	0.0399	2164
Wind PCC	0.69	99.96	1.199	0.1	1007

Fault Analysis Methodology and Calculation Approach

Comprehensive fault analysis was conducted using ETAP 19.0.1 software following IEC 60909 standards for short-circuit current calculation. Three-phase (L-L-L), line-to-ground (L-G), line-to-line (L-L), and double line-to-ground (L-L-G) fault currents were calculated at critical locations throughout the network including 33 kV bus, 11 kV buses, 0.415 kV switchgear, and points of common coupling for renewable sources. The analysis considered both maximum and minimum fault current levels in the network for proper selection of protective devices and relay settings.

For inverter-based sources including solar PV, wind turbines, and battery storage, fault current contribution was modeled based on manufacturer specifications with current limiting typically set at 1.2 times rated current. The

inverter fault current model assumes the inverter operates as a controlled current source with fast current limiting response.

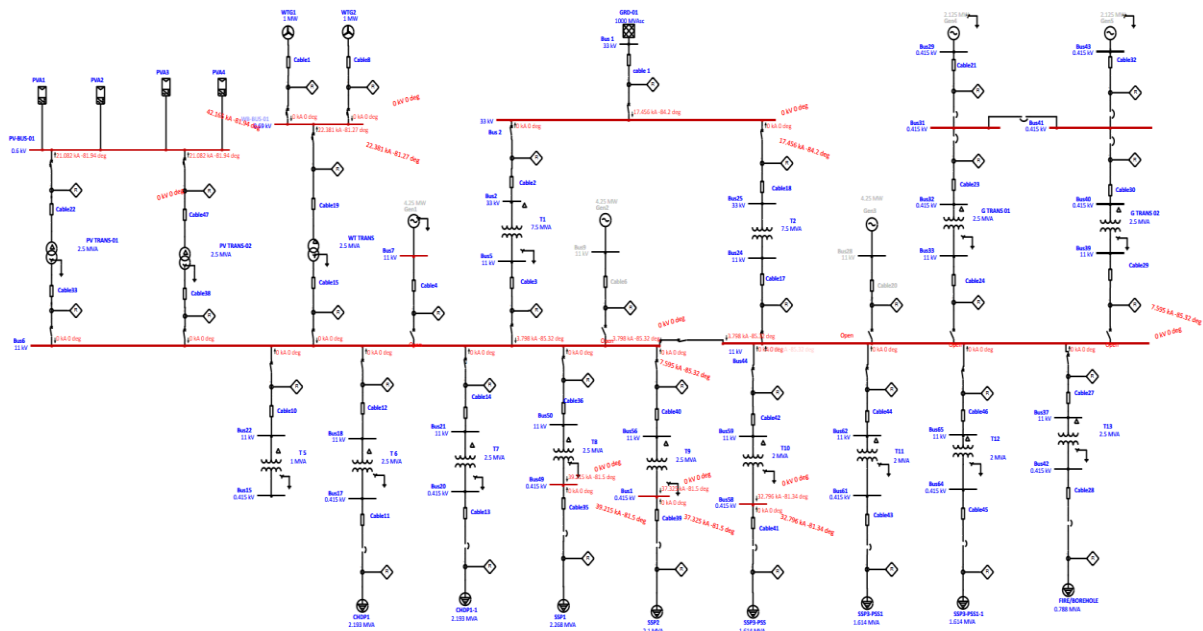


Figure 3: Minimum short Circuit Current Analysis of Salvation Ministries Proposed Power Network

Table 3: Minimum short Circuit Current Results at Key Network Locations

Bus ID	3 Phase Fault			Line-to-Ground Fault				Line-to-Line Fault				Line-to-Line-to-Ground Fault			
	I''k	ip	Ik	I''k	ip	Ib	Ik	I''k	ip	Ib	Ik	I''k	ip	Ib	Ik
33 kV Bus	17.5	43.0	17.5	17.4	42.9	17.4	17.4	15.1	37.3	15.1	15.1	17.5	43.0	17.5	17.5
11 kV Bus	7.6	19.2	7.6	9.5	24.1	9.5	9.5	6.6	16.6	6.6	6.6	9.3	23.4	9.3	9.3
0.415 kV Bus	32.8	76.1	32.8	34.9	80.9	34.9	34.9	28.4	65.9	28.4	28.4	34.1	79.2	34.1	34.1
Solar PCC	42.2	99.0	42.2	0.00	0.00	0.00	0.00	36.5	85.8	36.5	36.5	36.5	85.8	36.5	36.5
Wind PCC	22.4	51.9	22.4	0.00	0.00	0.00	0.00	19.4	44.9	19.4	19.4	19.4	19.4	19.4	19.4

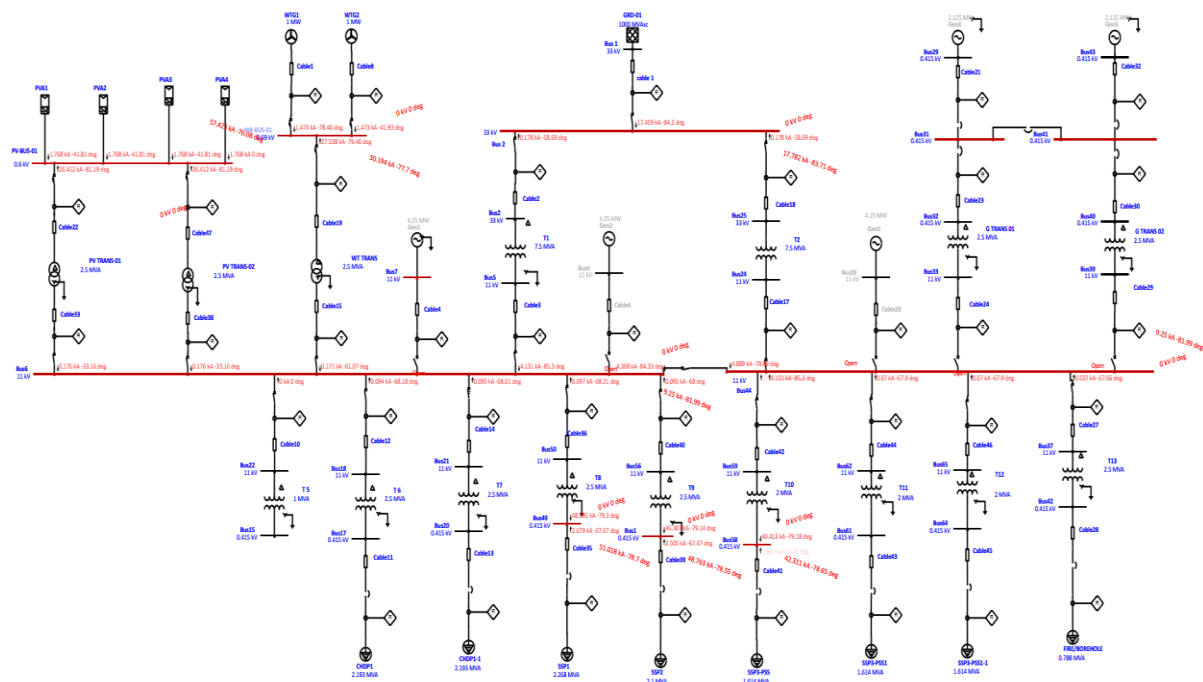


Figure 4: Maximum short Circuit Current Analysis of Salvation Ministries Proposed Power Network

Table 3: Maximum short Circuit Current Results at Key Network Locations

Bus ID	3 Phase Fault			Line-to-Ground Fault				Line-to-Line Fault				Line-to-Line-to-Ground Fault			
	I''k	ip	Ik	I''k	ip	Ib	Ik	I''k	ip	Ib	Ik	I''k	ip	Ib	Ik
33 kV Bus	18.3	44.8	17.7	17.9	43.9	17.9	17.9	15.9	38.7	15.9	15.9	18.2	44.4	18.2	18.2
11 kV Bus	11.6	27.2	8.9	13.6	31.9	13.6	13.6	9.9	23.3	9.9	9.9	13.2	30.9	13.2	13.2
0.415 kV Bus	52.9	116.8	40.2	51.5	113.7	51.5	51.5	45.8	101.2	45.8	45.8	52.9	116.8	52.9	52.9
Solar PCC	61.1	147.1	60.8	0.00	0.00	0.00	0.00	51.7	124.4	51.7	51.7	51.7	124.4	51.7	51.7
Wind PCC	31.3	69.2	32.2	0.00	0.00	0.00	0.00	26.6	58.9	26.6	26.6	26.6	58.8	26.6	26.6

PROTECTION PHILOSOPHY AND COORDINATION STRATEGY

The protection scheme follows a hierarchical three-level coordination strategy designed to ensure selective fault clearance with adequate backup protection: (1) Primary protection at the feeder level (11 kV and 0.415 kV distribution feeders) using 50/51 phase overcurrent relays (2) Backup protection at the bus and transformer level with time-delayed overcurrent, (3) Tertiary protection at the interconnection level including high-set instantaneous overcurrent for bus faults.

The coordination principles applied in this study include: (1) Minimum 0.3 second grading margin between successive protection levels to account for breaker operating time, relay over-travel, and safety factors; (2) Relay pickup settings set above maximum load current with 25% safety margin to prevent nuisance tripping during normal overload conditions; (3) Instantaneous overcurrent elements (50) set above maximum through-fault current seen by the relay for external faults; (4) Time-overcurrent elements (51) coordinated using Very inverse (SI) characteristics for consistent coordination across the network.

PROTECTION DESIGN CALCULATIONS

Current Transformer Sizing Calculations

Current transformer sizing follows IEEE C57.13 and IEC 61869-2 standards with comprehensive analysis of all relevant factors. The primary rating is selected based on the maximum continuous current considering a thermal rating factor of 1.3 for protection CTs. The accuracy class is selected based on the maximum fault current and connected burden to ensure accurate relay operation under all fault conditions.

Table 3: Current Transformer Sizing and Specifications

Location	CT Ratio	$I_{FL}(A)$	$I_f(KA)$	Thermal Rating Factor	ALF	Class
33 kV Feeder	200/1	131.2	18.3	1.3	20	5P20
11 kV Feeder	800/1	393.6	11.6	1.3	20	5P20
0.415 KV Feeder	3500/5	3478	52.9	1.3	20	5P20
Solar Inverter	3200/1	2406	61.1	1.3	20	5P20
Wind Turbine	1500/1	984.4	15.8	1.3	20	5P20

Overcurrent Relay Settings Calculations (50/51)

In order to coordinate a relay properly it is important to choose the appropriate PSM and TSM values so that the relay can operate at a predetermined time, t.

$$t = \frac{\alpha \times TMS}{(PSM)^\beta - 1}$$

$$PSM = \frac{I_f}{I_p}$$

Where;

α = Constant

β = Constant

I_f = Fault Current in relay

I_p = Relay Pick up current

t= Relay operating time

From the equation above two constant values α and β are seen. These constant values depend on the relay curve type. Different relay curve types are available on ETAP relay properties. The values for α and β are shown for different curve types on table

Table. IEC Constants Values for Relay Curve types

Curve Type	α	β
Standard Inverse	0.14	0.02
Very Inverse	13.5	1.0
Extremely Inverse	80.0	2.0
Long-time Inverse	120.0	1.0

Calculating Pickup Current I_p

Overcurrent relay settings

are calculated following IEEE C37.112 standard using standard inverse time-current characteristics. The pickup current for phase overcurrent elements is set at 125% of maximum load current to prevent operation during normal overload conditions while ensuring sensitivity for fault detection.

$$Pickup\ current, I_p = 125\% \times FLA$$

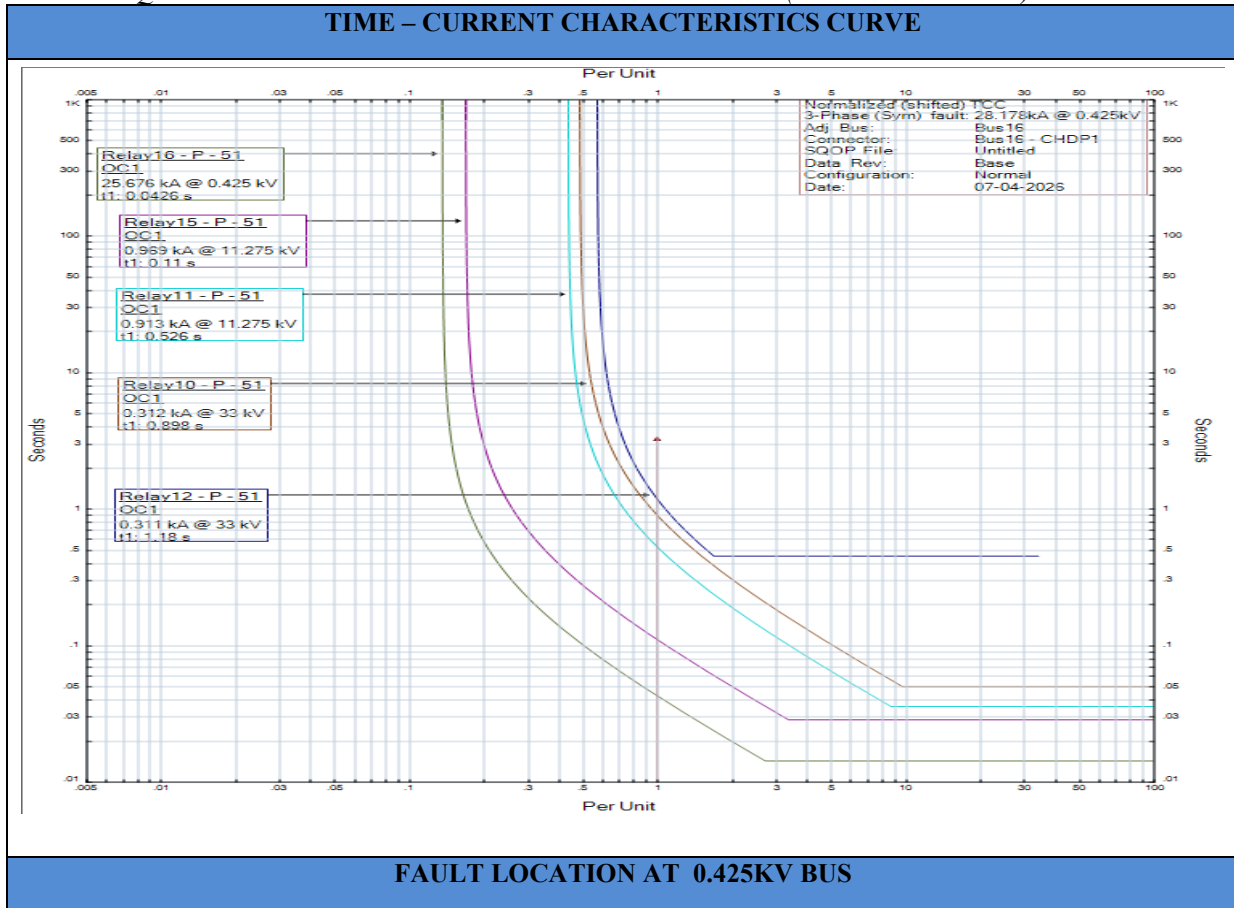
$$Pickup\ current\ in\ relay = \frac{125\% \times FLA}{CT\ Ratio}$$

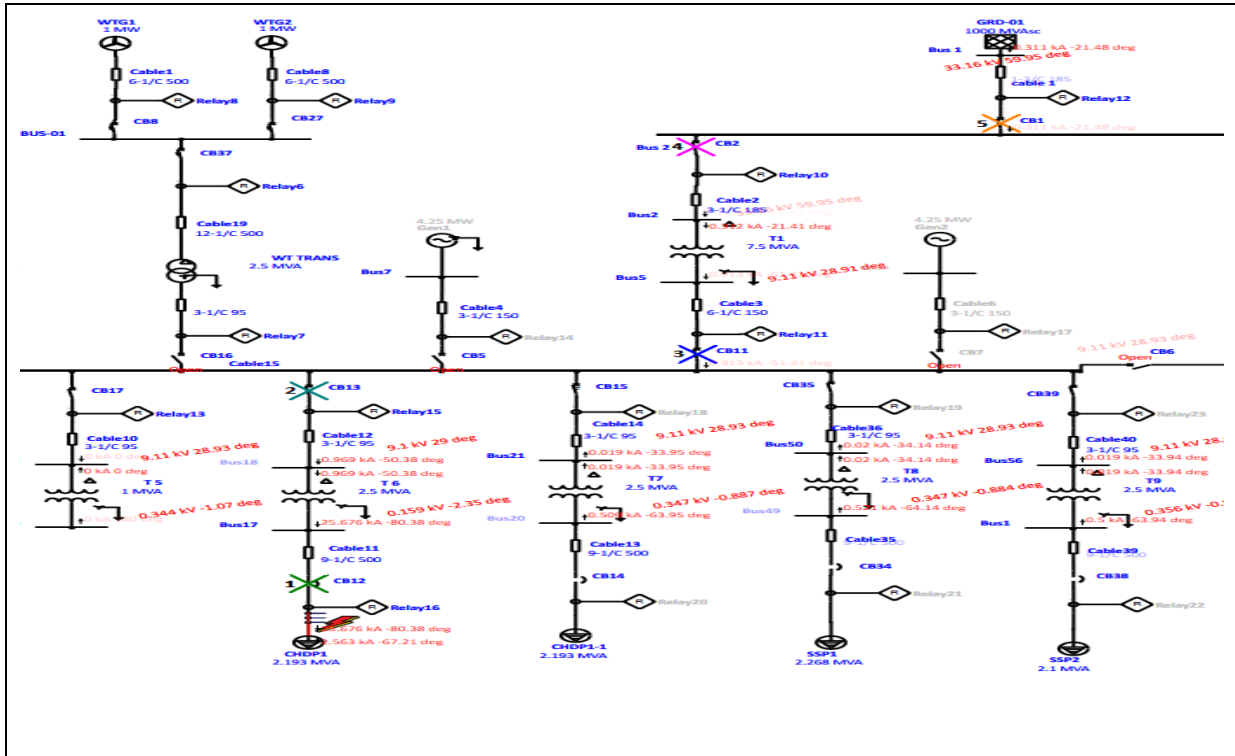
Table. Pickup Values for Relays Based on Full Load of Protected Equipment

Relays	Pick-up Current (A)	Pickup in relay
Relay10 & 26 Protecting T1& T2 HV side (33kv)	164	0.82
Relay11 & 27 Protecting T1 & T2 LV side (11kv)	393.6	0.615
Relay1 & 3 Protecting PV TRANS-01 & 02 HV side (11kv)	3007.5	0.94

Relay4 & 5 Protecting PV TRANS-01& 02 LV side (0.6kv side)	164	0.82
Relay8 & 9 Protecting WTG1 and WTG2	1230.5	0.82
Relay6 Protecting WT TRANS LV side (0.69kv)	2615	0.87
Relay7 Protecting WT TRANS HV side (11kv)	164	0.82
Relay15 & 16 Protecting Gen1, Gen2, & Gen3 (11kv)	328	0.66
Relay36 & 37 Protecting Gen4, & Gen5 (0.415kv)	4342.5	0.96

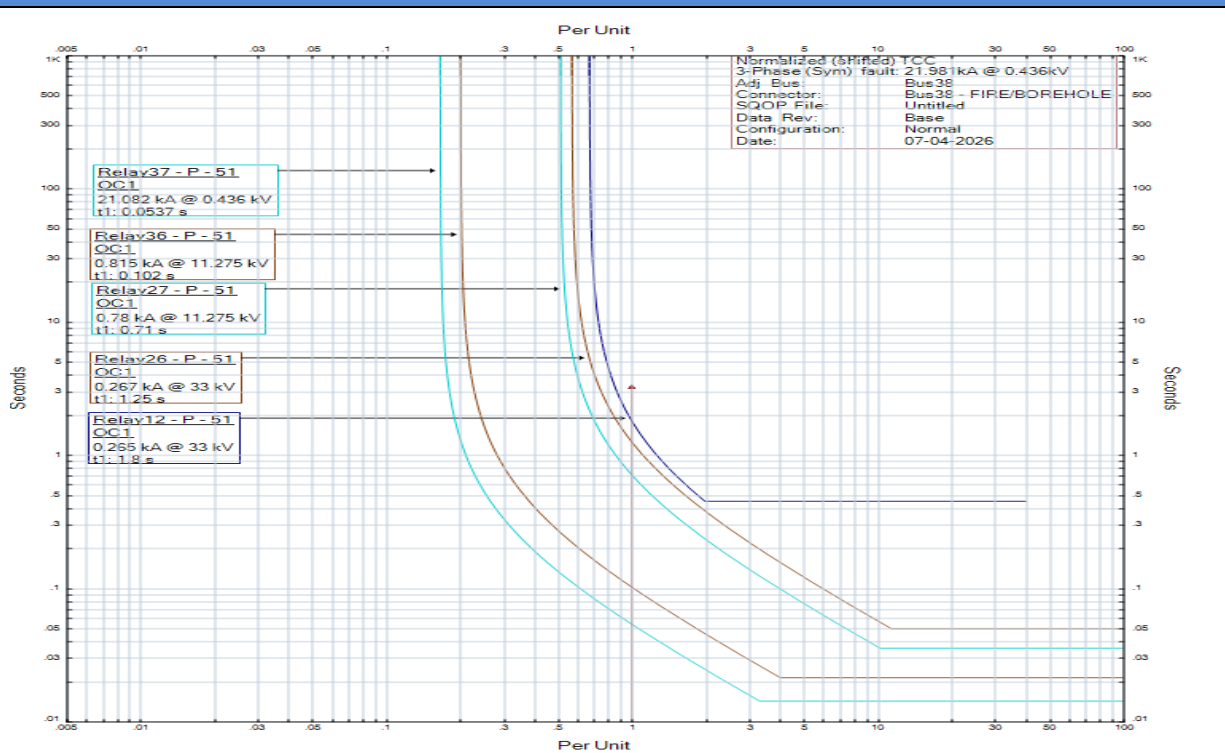
RELAY SEQUENCE OF OPERATION AFTER TCC CURVE FITTING (GRID CONNECTED)



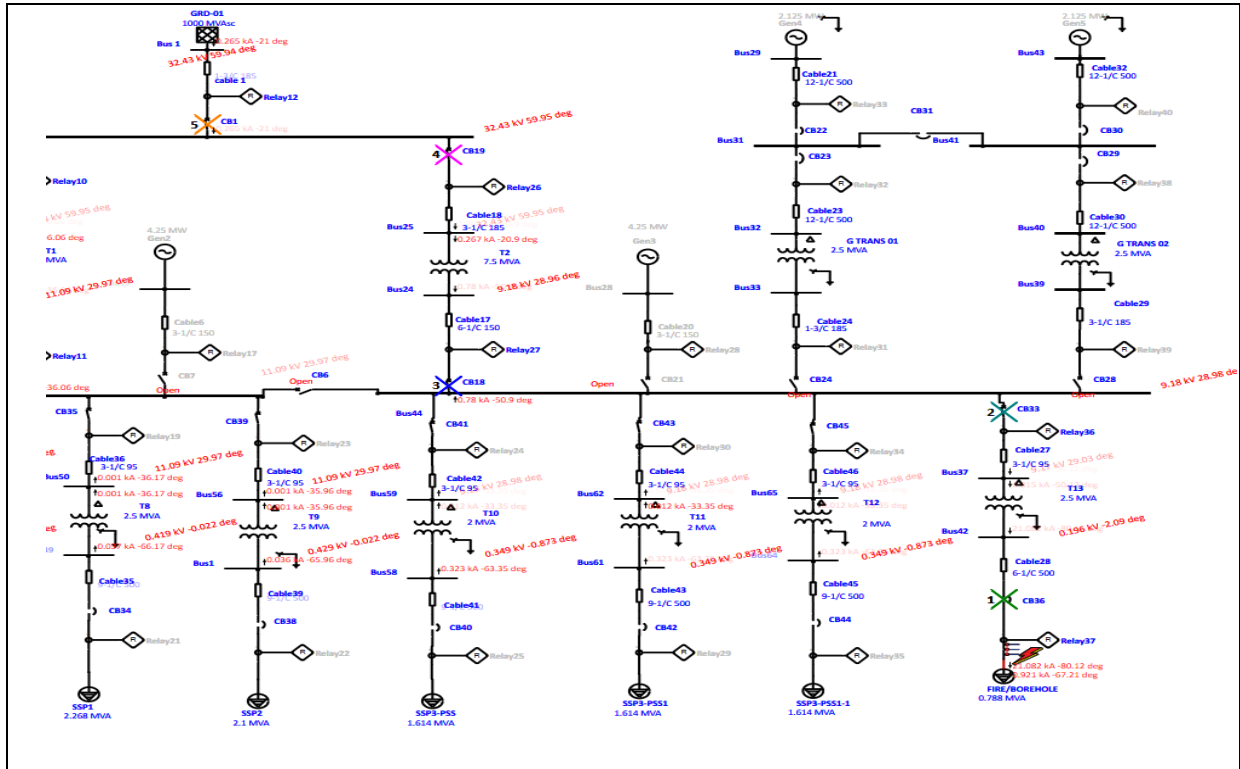


RELAY SEQUENCE OF OPERATION AFTER TCC CURVE FITTING (GRID CONNECTED)

TIME – CURRENT CHARACTERISTICS CURVE

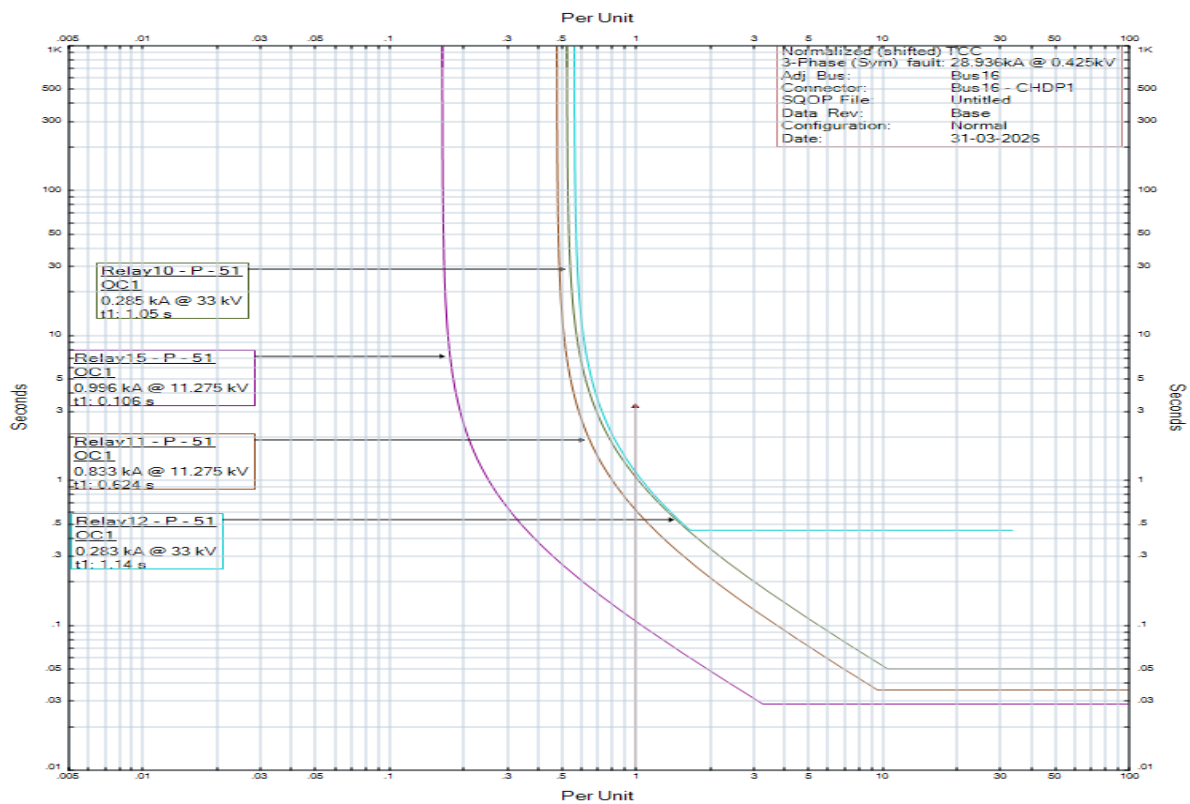


FAULT LOCATION AT 0.415KV BUS

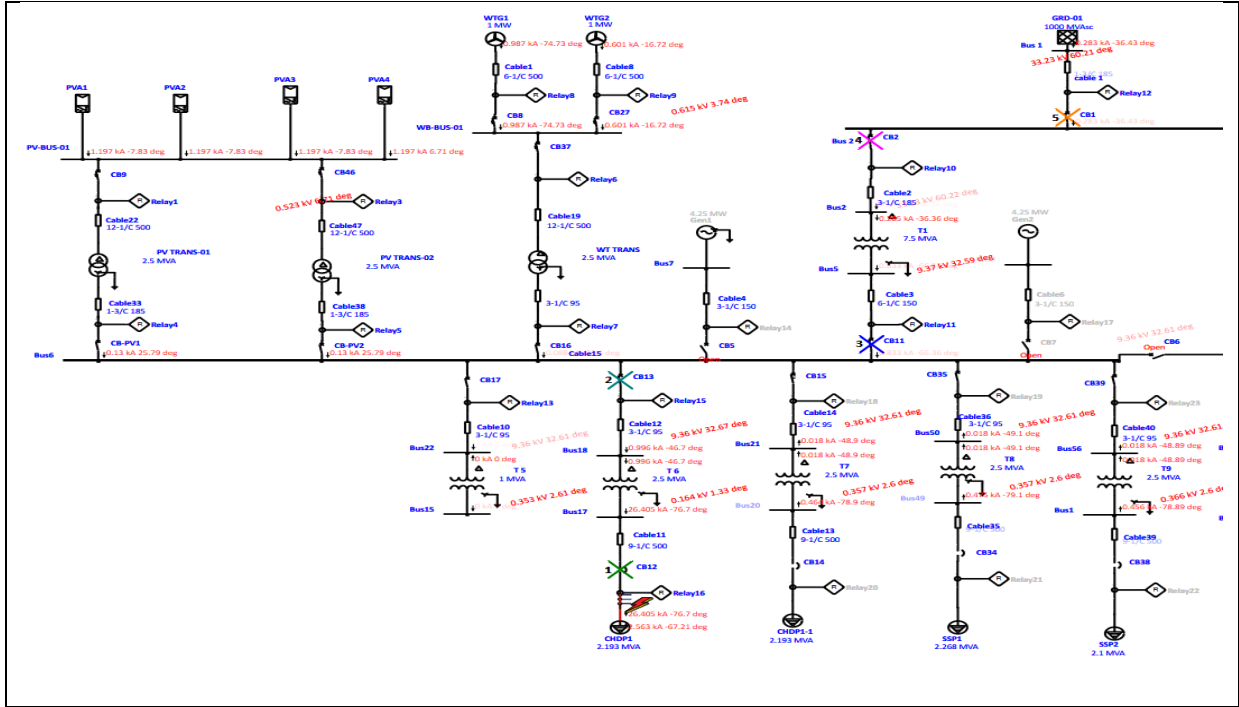


RELAY SEQUENCE OF OPERATION AFTER TCC CURVE FITTING (GRID AND HYBRID)

TIME – CURRENT CHARACTERISTICS CURVE

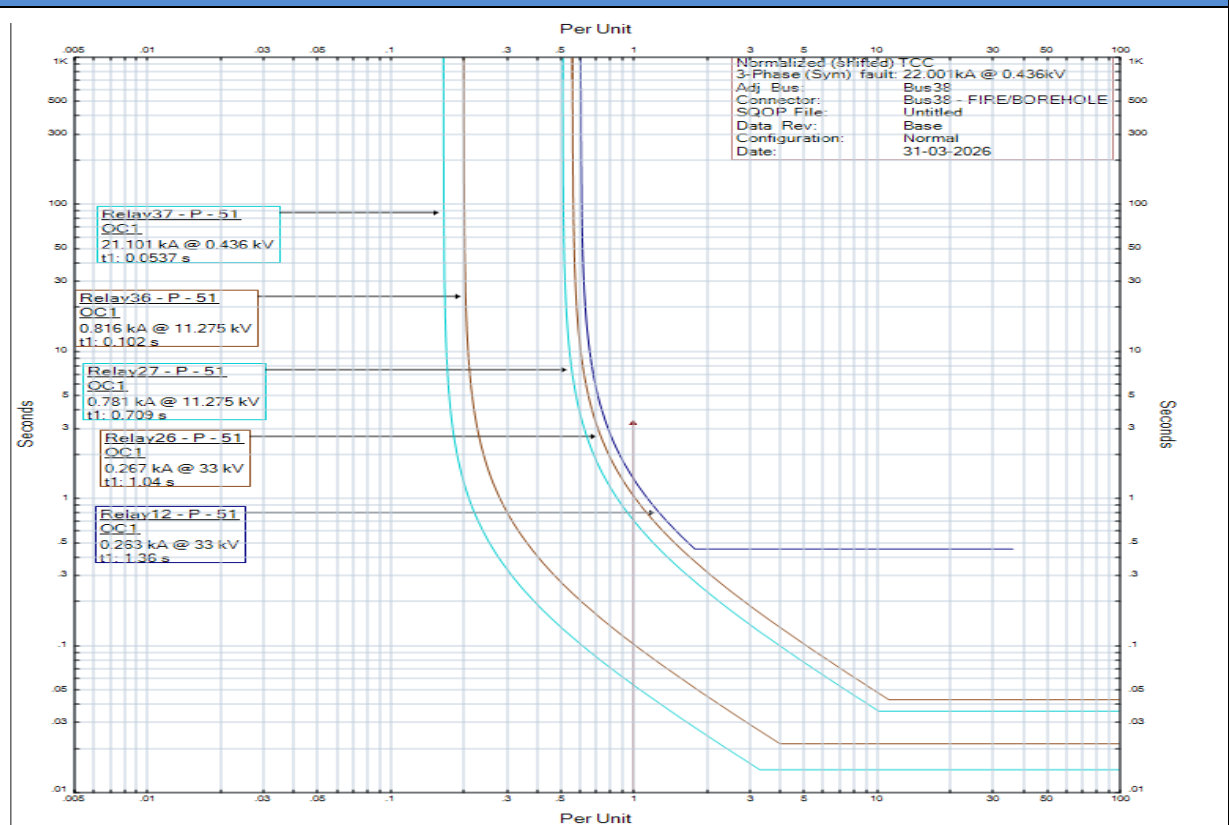


FAULT LOCATION AT 0.415KV BUS

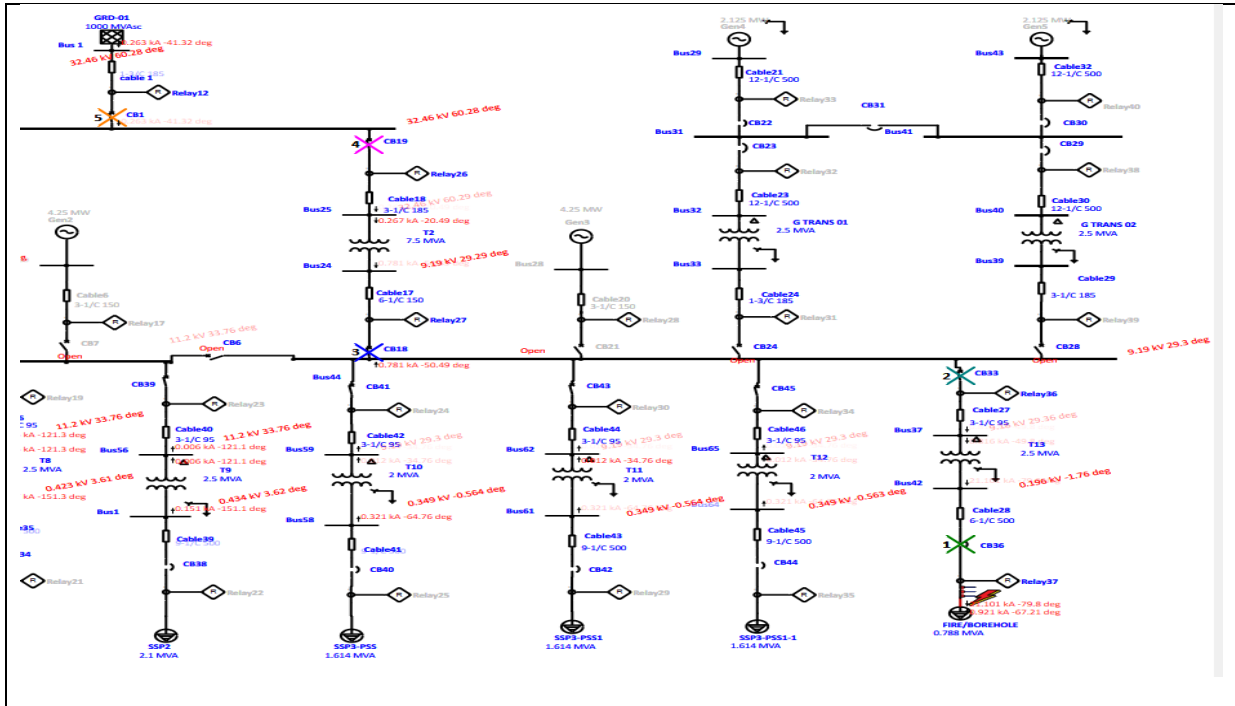


RELAY SEQUENCE OF OPERATION AFTER TCC CURVE FITTING (GRID AND HYBRID)

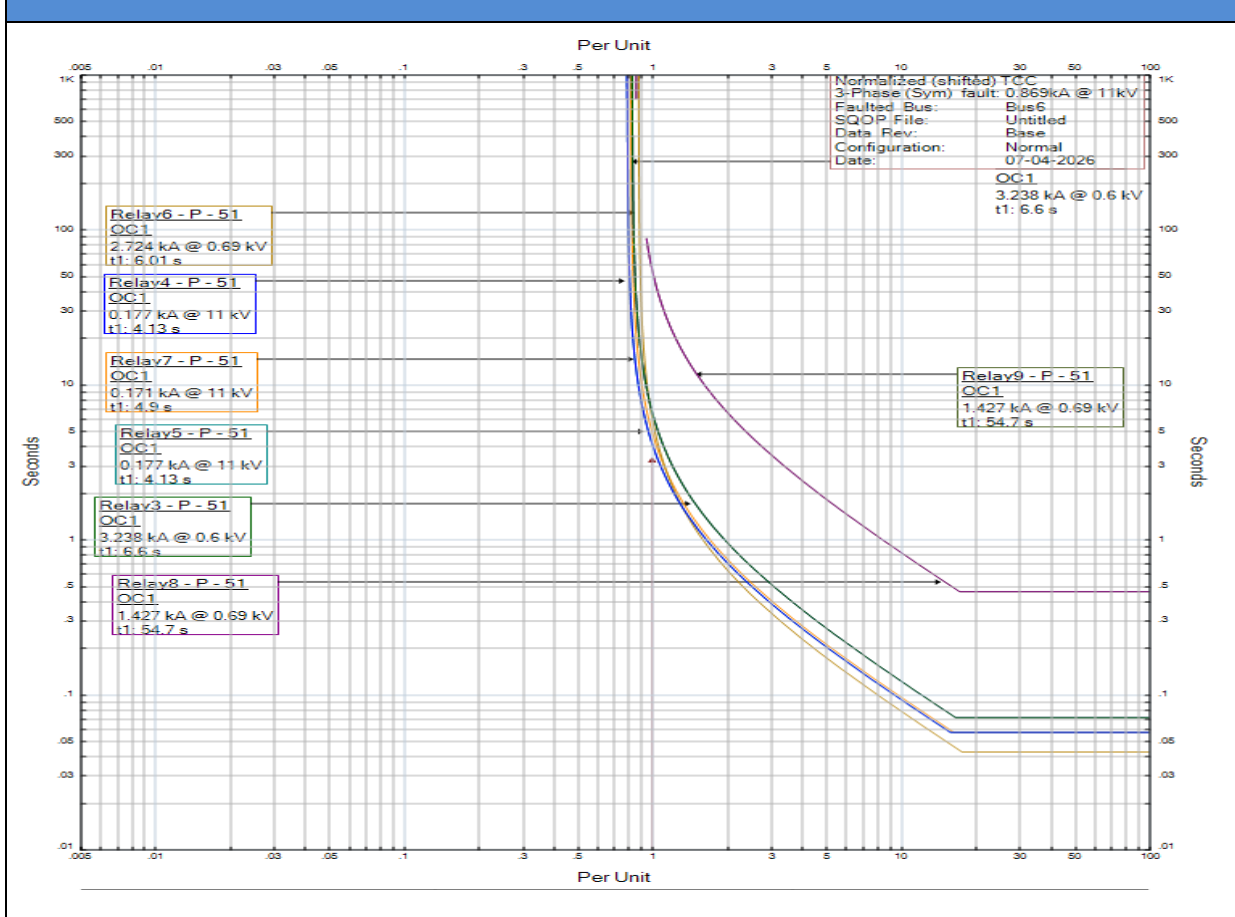
TIME – CURRENT CHARACTERISTICS CURVE

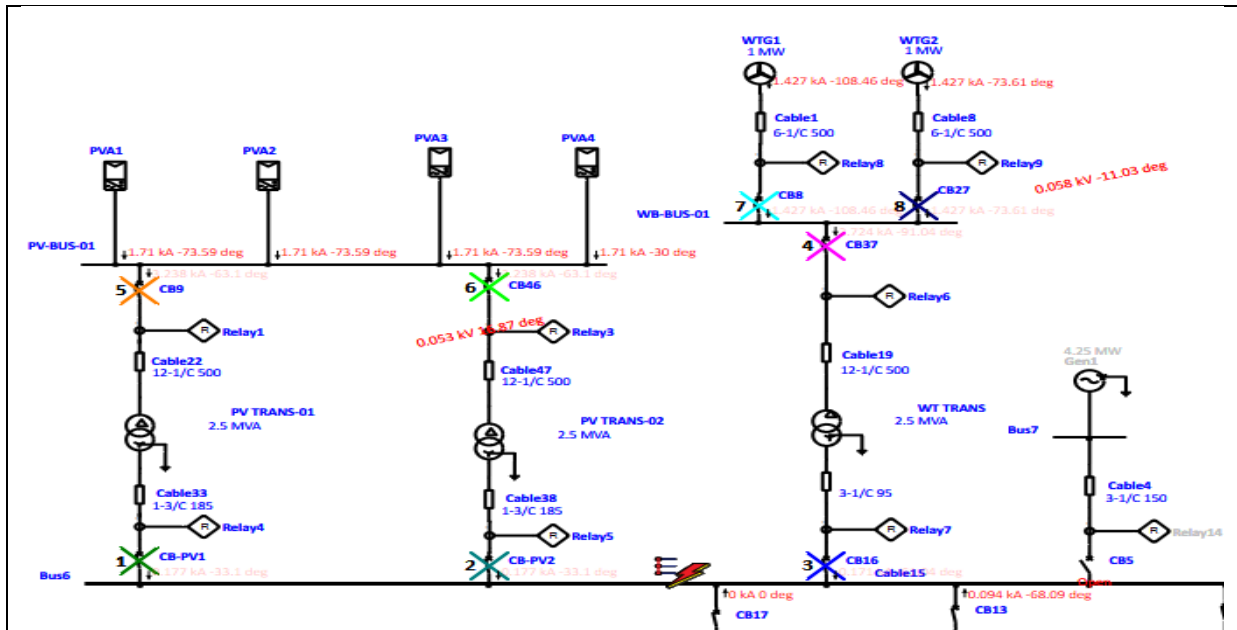


FAULT LOCATION AT 0.415KV BUS



TIME – CURRENT CHARACTERISTICS CURVE





IV. RESULTS AND DISCUSSION

Coordination Study Results and Verification

The protection coordination study was carried out using ETAP 19.0.1 Star Protective Device Coordination module. Multiple fault scenarios including three-phase, line-to-line, single line-to-ground, and double line-to-ground were simulated at strategic locations across the 33 kV, 11 kV, and low-voltage networks.

Initial coordination based on pickup settings of 125% of full-load current showed limitations in selectivity, particularly under conditions of unequal fault current contribution from different sources. Specifically, inverter-based sources (PV and wind) produced significantly lower fault currents compared to the grid, resulting in poor relay sensitivity and delayed or non-operation in some cases.

To address this, relay settings were revised using a fault-current-based approach, where pickup currents were derived from the minimum fault current seen at each relay location. This resulted in non-uniform pickup settings across PV, wind, and grid feeders, significantly improving relay responsiveness and discrimination. The updated time-current characteristic (TCC) curves demonstrated improved coordination with grading margins maintained at approximately 0.2–0.3 seconds between successive protection levels.

Selectivity Analysis and Fault Clearing Performance

Selectivity analysis confirmed that for feeder and downstream faults, the nearest protective device operates first, with upstream devices providing time-delayed backup. However, for faults occurring directly on the 11kV busbar, it was observed that conventional time grading alone is insufficient, as all sources contribute simultaneously to the fault. In such cases, closely coordinated operating times are required, or alternatively, high-speed busbar protection should be implemented for optimal performance.

The evaluated fault clearing times are summarized below:

Protective Device Settings - Relay													
Designated Bus	Relay ID	Manufacturer & Model	PT / CT Ratio	Device Function	Trip Element	Level /Stage	Curve	OCR (51, 51V), OLR (49, Acc.)			OCR (50), OLR (50, Jam)		
								Pickup	Prim. Amps	Time Delay	Pickup	Prim. Amps	Time Delay
PV-BUS-01	Relay1	Schneider Electric Sepam Series 10	3200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.840	2688.000	0.060	1.050	3360.00	0.15 s
PV-BUS-01	Relay3	Schneider Electric Sepam Series 10	3200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.840	2688.000	0.060	1.050	3360.00	0.15 s
Bus6	Relay4	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.700	140.000	0.050	0.800	160.00	0.1 s
Bus6	Relay5	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.700	140.000	0.050	0.800	160.00	0.1 s
WB-BUS-01	Relay6	Schneider Electric Sepam Series 10	3000:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.800	2400.000	0.060	1.000	3000.00	0.12 s
Bus6	Relay7	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.700	140.000	0.050	0.800	160.00	0.1 s
WB-BUS-01	Relay8	Schneider Electric P521	1500:1	Overcurrent	Phase	OC1	IEC - Very Inverse	0.820	1230.000	0.650	1.000	1500.00	0.11 s
WB-BUS-01	Relay9	Schneider Electric P521	1500:1	Overcurrent	Phase	OC1	IEC - Very Inverse	0.820	1230.000	0.650	1.000	1500.00	0.11 s
Bus6	Relay15	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.820	164.000	0.040	0.980	196.00	0.06 s
Bus16	Relay16	Schneider Electric Sepam Series 10	3500:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	1.000	3500.000	0.020	1.100	3850.00	0.05 s
Bus 2	Relay10	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.750	150.000	0.070	1.300	260.00	0.08 s
Bus6	Relay11	Schneider Electric Sepam Series 10	800:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.500	400.000	0.050	0.580	464.00	0.07 s
Bus 2	Relay12	Schneider Electric P441	200:1	Overcurrent	Phase	OC1	IEC V Inverse	0.800	160.000	0.065	2.810	562.00	0.09 s
Bus 2	Relay26	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.750	150.000	0.070	1.300	260.00	0.08 s
Bus44	Relay27	Schneider Electric Sepam Series 10	800:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.500	400.000	0.050	0.580	464.00	0.07 s
Bus44	Relay36	Schneider Electric Sepam Series 10	200:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	0.820	164.000	0.030	0.980	196.00	0.06 s
Bus38	Relay37	Schneider Electric Sepam Series 10	3500:1	Overcurrent	Phase	OC1	IEC Very Inverse Time VIT/B	1.000	3500.000	0.020	1.100	3850.00	0.05 s

Table 6: Protective Device Setting Report

Protection Performance Under Varying Operating Modes

The protection scheme was evaluated under different system conditions, including grid-connected operation with maximum and minimum renewable generation. Results show that fault current levels vary significantly depending on system configuration, with the grid contributing the highest fault levels and inverter-based sources contributing limited currents. Despite these variations, the revised relay settings maintained adequate sensitivity, with fault currents exceeding relay pickup thresholds by sufficient margins for reliable operation. However, the study highlights that hybrid systems require adaptive protection philosophies, as conventional load-based coordination methods are inadequate in systems with high penetration of inverter-based resources.

Key Observations

- Relay coordination based solely on load current is inadequate for hybrid systems
- Fault-current-based settings significantly improve selectivity and sensitivity
- Inverter-based sources require special consideration due to limited fault contribution
- Busbar faults demand fast tripping schemes beyond conventional grading

V. CONCLUSION

This study has presented the development and critical evaluation of a relay protection coordination scheme for a hybrid renewable energy system at Salvation Ministries Cathedral, Igwuruta, Rivers State, Nigeria. The system integrates solar PV, wind generation, battery storage, diesel backup, and utility grid supply across multiple voltage levels, introducing complexities such as bidirectional power flow and unequal fault current contributions. The study revealed that conventional protection design based solely on load current specifically the use of pickup settings at 125% of full-load current is insufficient for hybrid systems. Significant disparities in fault current contribution were observed, with inverter-based sources (PV and wind) contributing relatively low fault currents compared to the grid. This resulted in poor relay sensitivity and coordination challenges under initial settings. A key outcome of this work is the adoption of a fault-current-based coordination approach, where relay pickup settings are derived from the minimum fault current at each location rather than load current. This led to non-uniform but technically appropriate settings across different sources, significantly improving protection sensitivity and selectivity. Time-current coordination was achieved with grading margins of approximately 0.2–0.3 seconds for feeder protection, while recognizing that conventional grading alone is inadequate for busbar faults, which require fast and near-simultaneous tripping or dedicated busbar protection schemes. Simulation results obtained using ETAP 19.0.1 confirmed that the revised protection scheme provides reliable fault detection and isolation across varying operating conditions, including different generation levels. Fault clearing times remained within acceptable limits, ensuring system stability and equipment protection. This study demonstrates that effective protection of hybrid renewable systems requires a shift from traditional methods to adaptive, fault-oriented strategies that explicitly account for inverter-based resource behavior. The findings provide a practical framework for protection engineers designing similar systems, particularly in regions with increasing renewable energy penetration.

VI. RECOMMENDATIONS

Based on the findings and practical observations from this study, the following recommendations are proposed for effective protection coordination in hybrid renewable energy systems:

1. Perform detailed fault studies for all operating conditions, including grid-connected operation at maximum and minimum generation levels, as well as islanded mode. Particular attention should be given to determining the minimum fault current at each relay location, as this forms the basis for reliable protection settings in systems with inverter-based resources.
2. Adopt fault-current-based relay setting methodology rather than relying solely on load-based criteria. Relay pickup currents should be selected within a range of approximately 20–50% of the minimum fault current, while still remaining above maximum load current, to ensure both sensitivity and stability.
3. Select current transformer (CT) ratios based on a combination of maximum load current and fault current levels, ensuring adequate accuracy and saturation performance under high fault conditions, with allowance for future system expansion.
4. Implement proper time-current coordination using inverse-time characteristics, with grading margins in the range of 0.2–0.3 seconds between successive protection levels. However, excessive time grading should be avoided in multi-source systems to prevent delayed fault clearing.

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