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Mitigating Maloperations of Generator Protection in Oil and Gas Facilities: A Coordination Strategy for Overcurrent and Overcurrent Voltage Restrained Relays

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Abstract

The oil and gas industry requires a highly reliable and adaptive electrical protection system to prevent maloperation and ensure operational continuity. Unlike conventional industrial systems, electrical configurations in oil and gas facilities often feature short electrical distances between generators and loads, with some connected directly and others through transformers. This condition increases the risk of miscoordination in overcurrent relays (50/51 and 50/51V), potentially leading to widespread blackouts that may disrupt production processes and cause significant financial losses. Such maloperations are often linked to improper relay settings. Inaccurate modelling of time–current characteristic (TCC) curves and misadjustment of 50/51V relays can result in non-selective tripping, where the 50/51V relay operates before the 50/51 relay as the primary protection. This study proposes relay coordination strategies for three representative power system configurations in the oil and gas sector, which are evaluated through relay coordination simulations using power system simulation software. The approach considers for the unique characteristics of the 50/51V relay and equipment damage curves, using power system simulation software for evaluation. The results demonstrate that the proposed scheme avoids maloperation by maintaining IEEE standard coordination margins (0.2–1 s), ensuring relay curves remain below electrical equipment damage thresholds, preserving selectivity and preventing relay coordination maloperations. These findings provide practical guidelines for engineers in designing selective and reliable protection systems, thereby reducing blackout risks and supporting continuous operation in oil and gas facilities.

Keywords: *coordination protection; overcurrent relay; voltage restrained; generator; oil and gas industry.*

Introduction

The oil and gas industry are characterized by a unique electrical system topology, where electricity demand is supplied by autonomous power plants or systems that operate independently from external power networks (standalone). A standalone power system is defined as an autonomous system capable of supplying electricity without being connected to an external grid (Boccaletti et al., 2007). The advantages of autonomous power generation include avoiding disturbances from external networks, maintaining system reliability, achieving full control over frequency and enabling more operational cost efficiency. Additionally, the electrical systems in the oil and gas industry are dominated by large motor loads with varying capacities and configurations. These configurations are based on technical and operational requirements to ensure motors receive adequate power, maintain system safety and stabilize voltage. Industrial operations typically require large energy equipment such as induction motors (Salam et al., 2025)(de Almeida et al., 2024). These motors must operate optimally under voltage variations of ±10% and frequency variations of ±5%.

Due to the complexity and high-power demand, the electrical systems in the oil and gas industry must not only ensure optimal power supply but also prioritize system reliability. These systems must be economically designed for continuous operation, ensure equipment safety, allow ease of maintenance, minimize power losses, and accommodate load growth (Makani & Daniel Chowdhury, 2017). Reliability is a critical factor in maintaining continuous oil and gas production. Therefore, a reliable electrical protection system is essential to safeguard equipment from disturbances caused by various factors illustrated in Figure 1. A protection system is considered effective if it meets five key criteria: selectivity, sensitivity, speed, reliability and stability (Blackburn & Domin, 2014). Electrical faults in rotating equipment such as motors or generators include dielectric failure, over/under voltage, stator damage, earthing faults, reverse phase sequence, short circuits, unbalanced voltage supply, and voltage fluctuations (Abbasi, 2025).

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Such disturbances can be detected through overcurrent relays (OCR) or 50/51 relays. However, protection is not limited to 50/51 relays, but the 50/51V relay also serves as backup protection. Proper relay coordination improves reliability, sensitivity, cost efficiency, and power quality (Unluturk & Ozer, 2025). The 50/51V relay is generally used as backup protection for generators and operates when the 50/51 relay fails to function. In oil and gas industrial power systems have unique electrical system topologies, whereas the short electrical distance between the generator and the load without through transformer causes coordination maloperations between the 50/51V and 50/51 relays. The maloperation refers to incorrect and non-selective tripping, where the 50/51V backup relay trips before the primary 50/51 relay. Furthermore, overly sensitive 50/51V relays may cause maloperation if there is poor coordination between upstream and downstream relays. Improper modelling of the time-current characteristic (TCC) coordination between 50/51 and 50/51V relays can result in non-selective tripping, where relays outside the fault zone operate prematurely. This condition leads to a blackout in the industrial power system, thereby disrupting the production process. Blackouts pose significant risks to industrial supply chains by disrupting logistics and supply simultaneously, causing shutdowns in operations, triggering unpredictable customer behaviors and ultimately threatening both the performance and long-term viability of the entire industrial ecosystem (Ivanov, 2025).

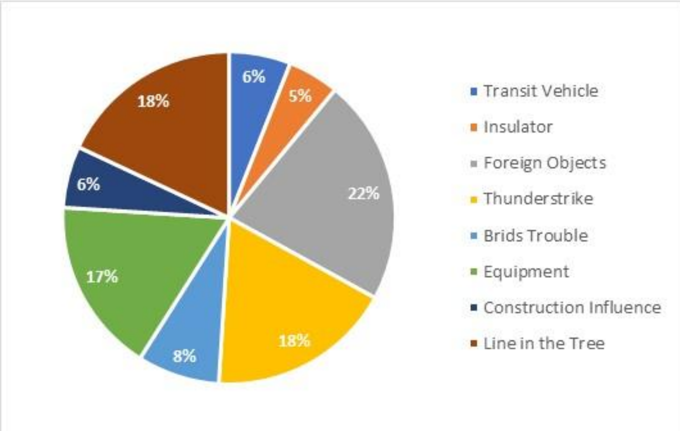

Figure 1 Disturbance statistics on electrical system elements (Bai et al., 2017).

Existing research on the application of 50/51 and 50/51V relays typically focuses on distribution systems with various bus configurations (e.g., 30-bus, 9-bus, and 135-bus systems) (Mishra et al., 2025) (Saleh & Ayad, 2021) (Reiz et al., 2024), distribution systems integrated with PV (Mishra et al., 2021) and microgrids with distributed generation (Saad et al., 2021). Table 1 showed an overview of literature review related to research on 50/51 and 50/51V relay coordination. According to previous studies, relay coordination analyses typically do not incorporate equipment damage curves and rarely provide a detailed explanation of the relay 50/51V setting strategy, despite its unique protective characteristics. Based on these studies, the use of 50/51 and 50/51V relays as recommendations for electrical protection systems specifically for the oil and gas industry has not yet been carried out.

Table 1 An overview of the research literature review.

References	Case Study	Relay Coordination Considering Equipment Damage Curve	50/51V relay setting strategy
Mishra et al., 2025	IEEE 30 – Bus	×	✓
Saleh & Ayad, 2021	IEEE 9 – Bus	×	×
Reiz et al., 2024	IEEE 135 – Bus	×	✓
Mishra et al., 2021	distribution systems integrated with PV	×	✓
Saad et al., 2021	microgrids with distributed generation	×	✓
Current Work	Oil and gas industry system	✓	✓

Furthermore, existing electrical protection standards for the oil and gas industry remain general, focusing on protection in hazardous areas (IEC/IEEE, 2015), instructions related to the classification of hazard areas and electrical protection installations for oil and gas environments (API, 2014) and electrical protection systems for offshore facilities (API, 2008). Meanwhile, the standard use of 50/51 and 50/51V relays is only described for general electrical system conditions and has not yet provided specific recommendations for the electrical protection systems of the oil and gas industry, as stated in recommendations (IEEE/IEC, 2018) and (IEEE, 2001).

Therefore, this paper presents specific recommendations for electrical system protection in the oil and gas industry with considering the use of 50/51 and 50/51V relays based on short-circuit fault contribution currents in the system. It presents a systematic protection approach based on short-circuit fault contribution analysis and refined time-current characteristic (TCC) curve modeling, which are critical in preventing non-selective tripping. This study proposes relay coordination strategies for three different power system configurations commonly found in the oil and gas industry. Furthermore, coordination relay settings also consider voltage conditions and the damage curves of electrical equipment. By combining oil and gas industry electrical system configurations and fault scenarios, this paper provides a technically robust and practically applicable reference for protection engineers. The proposed methodology aims to enhance system reliability, mitigate blackout risks and bridge the gap between theoretical protection frameworks and field implementations in complex oil and gas industrial environments.

Theoretical Foundation and Protection Device Characteristic

Overcurrent Protection Relays: 50/51 and 50/51V

According to ANSI standards, 50/51 refers to an overcurrent relay, where number of 50 represents instantaneous overcurrent protection and number of 51 indicates time-delayed overcurrent protection (time overcurrent). The relay operates when an overcurrent fault exceeding the pickup current limit is detected through measurements by the current transformer (CT). Generally, the 50/51 relay is used to protect equipment such as transformers, lines and generators from short-circuit faults. Overcurrent protection for generators is important and critical causes failure condition in disconnection may lead to thermal and mechanical damage. Therefore, the relay operating characteristics depend on the type of time-current characteristic (TCC) curve such as standard inverse, very inverse and extremely inverse types. Each curve type has a different operation time and can be determined through Eq. (1) in accordance with the IEEE C37.112 standard (IEEE, 2018). Table 2 presents the values of k, β, and α for each curve type, where the constant value is used as a differentiator of each type of relay curve. The steepness of the relay curve indicates the ability of the relay speed to trip when a fault occurs, as shown in Figure 2. The TMS value represents the minimum timing of the relay curve.

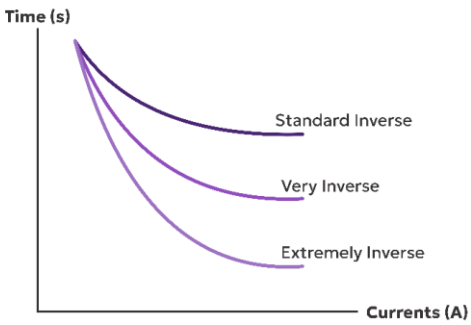

Figure 2 Type of trip curve of relay 50/51 in time current characteristic.

Table 2 Constant values of k and α for each type of relay working curve 50/51.

Curve Type	α	k	β
Standard Inverse	0.14	0.02	2.97
Very Inverse	13.5	1	1.5
Extremely Inverse	80	2	0.808

$$t_d = TMS \frac{k}{\left(\left(\frac{I}{I_{pickup}}\right)^{\alpha} - 1\right) \cdot \beta} \quad (1)$$

The 50/51V relay has the same working principle as the 50/51 relay, but the 50/51V relay will be more sensitive when there is a voltage drop condition. The 50/51V relay is used as backup protection for generators in case the 50/51 relay fails to operate. This relay is essential for generator protection because in fault conditions located far from the generator, the fault current contribution from the generator becomes small. The small current may cause the 50/51 relay to fail to operate, as the current does not exceed the set pickup level. If this is left unaddressed it can lead to the accumulation of thermal stress and resulting in permanent damage of generator. Hence, the use of the 50/51V relay is necessary. The 50/51V relay operates under two principles: voltage-controlled and voltage-restrained. The voltage-controlled principle reduces the pickup current to a fixed value when voltage drops, whereas the voltage-restrained

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principle reduces the pickup current proportionally with the voltage. Figure 3 illustrates the two types working principles of 50/51V relay.

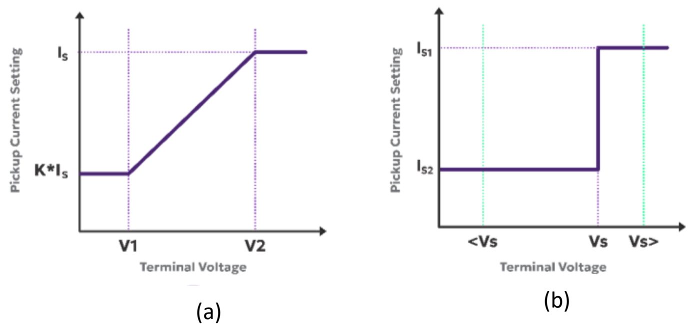

Figure 3 50/51V relay working principle, a.) voltage – restrained, b.) voltage – controlled.

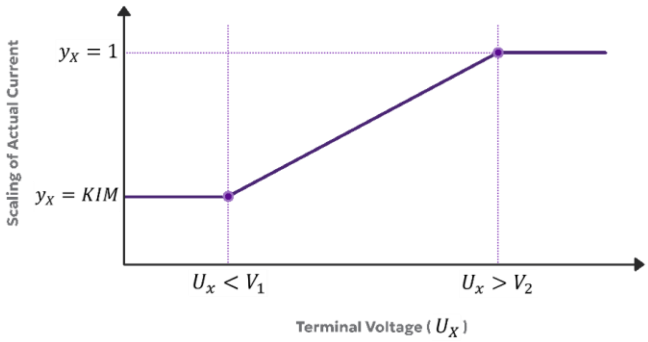

Figure 4 illustration of equation 5 for work principles of 50/51V relay (voltage – restrained).

In the power system simulations conducted using DIgSILENT PowerFactory 2021, the operating principle of the 50/51V relay of the voltage-restrained type is controled by the software logic represented in Eqs. (2), (3), and (4). These equations adjust the relay response by scaling the measured current to a higher value, thereby increasing its sensitivity. The logic is activated when the voltage condition enters a specific range, determined by the voltage transformer reading represented by the value of U_x. The voltage range is bounded by upper and lower voltage thresholds, where V_1 is the lower threshold and V_2 is the upper threshold. The value of KIM defines the minimum current scaling to avoid infinite current readings under extremely low-voltage conditions. The parameters U_x, V_1 and V_2 are used to determine the value of y_x, or the actual current scaling factor as defined by Equation 2. The actual current scaling is performed using a voltage interpolation function as shown in Eq. (2). Eq. (3) is used to determine the value of y_x based on the condition of U_x relative to the lower and upper thresholds, V_1 and V_2, respectively. y_x value increases linearly and represents a voltage-based scaling function as illustrated in Figure 4.

$$y_X = \left(KIM + (1 - KIM) \cdot \frac{U_X - V_1}{V_2 - V_1}\right) \tag{2}$$

$$y_x = \begin{cases} 1, & U_x > V_2 \\ KIM + (1 - KIM) \cdot \frac{U_X - V_1}{V_2 - V_1}, & V_1 < U_x < V_2 \\ KIM, & U_x < V_1 \end{cases} \tag{3}$$

$$I_X^{adj} = \frac{I_X}{y_x} \tag{4}$$

Finally, the actual current I_X entering the 50/51V relay logic is scaled and normalized as described in Equation 4. As a result, the actual current measured by the current transformer through the 50/51V relay appears increased, as represented by the value of I_X^{adj}. Figure 5 illustrates the operation of the 50/51V relay under normal condition (figure 5.a) and voltage restrained conditions (figures 5.b and 5.c). The 50/51V relay can respond to voltage – restrained conditions through two distinct mechanisms by amplifying the actual current magnitude linear with voltage reduction (figure 5.b) and dynamically shifting the TCC curve to reflect a more sensitive operating region (figure 5.c). Figure 5.c also shows that the 50/51V relay works the same as the 50/51 relay by shifting the relay curve. Despite the differences in these approaches, both mechanisms produce the same tripping time under identical fault conditions.

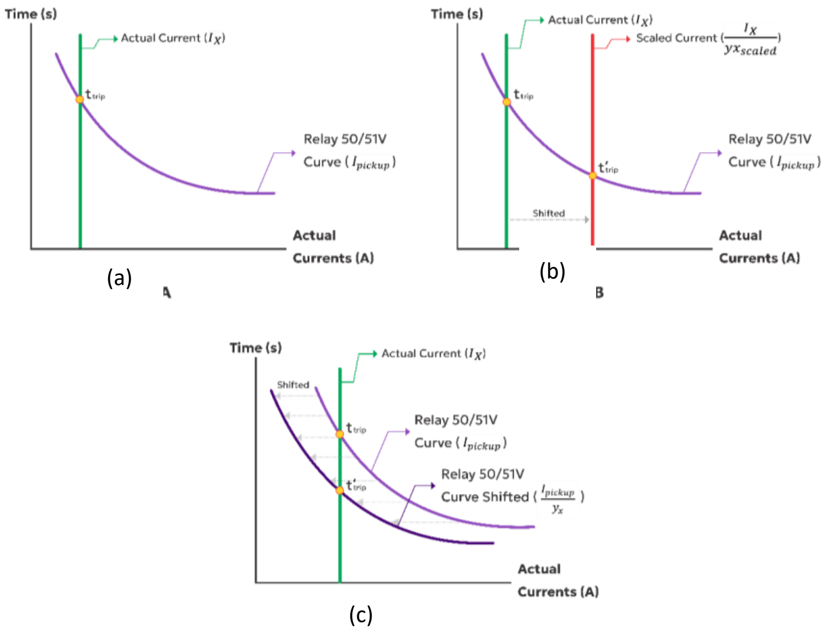

Figure 5 illustration of 50/51V relay working for normal condition and voltage restrained condition, a.) normal voltage condition, b.) voltage restrained condition (scaled current), c.) voltage restrained condition (shifted curve).

Equipment Damage Curves

The damage curve is a graph representing the thermal limit of equipment particularly generators and in relation to overcurrent as a function of time. The curve indicates the ability of the equipment to withstand fault currents before sustaining damage. In protection systems, the damage curve plays a crucial role to ensuring that protection relays operate quickly enough to prevent such damage. Within the time-current characteristic, the relay operating curve must lie below the damage curve of the protected equipment (Taheri et al., 2023). This ensures that the relay operates promptly to isolate the network from the fault before the current reaches the damage threshold. Therefore, relay settings must consider a safety margin between the relay curve and the damage curve as illustrated in Figure 6.

$$k = I^2 t \quad (5)$$

The primary purpose of combining the two curves is to ensure that the protection relay design is not only reliable but also within the operational limits of the equipment. The standard used to define the thermal limits of generator damage curves is IEEE C37.102 (IEEE, 2018). Damage curves can be mathematically modelled in the form of an exponential function with a variable *k*, as shown in Eq. (5).

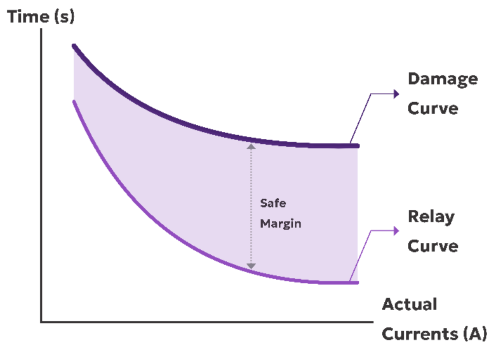

Figure 6 Relay position against equipment damage curve.

Challenges and Maloperations of 50/51 and 50/51V Relay Coordination

The unique configuration of electrical systems in the oil and gas industry, which often rely on standalone generation units or generators as the primary power source, requires coordination between 50/51 and 50/51V relays critical and necessitates the avoidance of any maloperation. Maloperation may occur when the coordination between relays lacks selectivity, such as when the 50/51V relay operates prior to the 50/51 relay and results in a total system blackout. If left

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unaddressed, such conditions may significantly disrupt industrial oil and gas production process. Figure 7.a shows a single line diagram of the oil and gas industry electrical system, where the electrical system components include generators, lines and motor loads. Figure 7.b illustrates the TCC curves from one of the protective schemes implemented in an oil and gas electrical system that experienced maloperation.

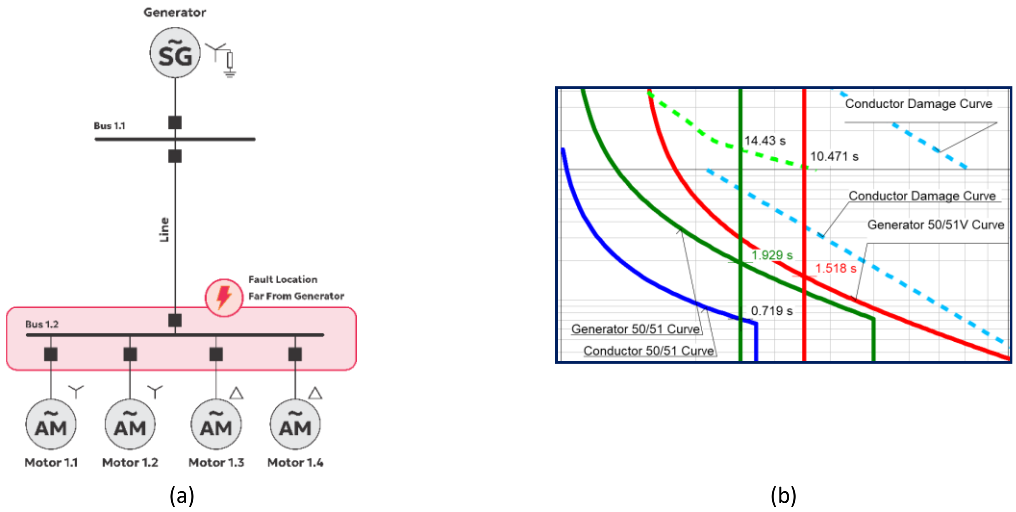

Figure 7 Maloperation case illustration, a) The single-line diagram used in the analysis, b) The simulation results showing miscoordination between the 50/51 and 50/51V relays.

Based on Figure 7, it was found that the 50/51V relay tripped first in response to a fault occurring at the load side accompanied by a voltage drop at the generator terminal. The simulation results confirm that the relay coordination was not selective, thereby emphasizing the need for strategic guidelines and recommendations for the coordination of 50/51 and 50/51V protective relays in safeguarding generator systems within oil and gas industrial facilities. back-up relaying must wait for primary relaying to complete its operation and must not replace the primary relaying function (Paithankar & Bhide, 2007) (Rizwan et al., 2024).

Protection Coordination Overview and Considerations

Generator protection coordination recommendations using 50/51 and 50/51V relays proposed in this paper are briefly illustrated in Figure 8. The initial step involves conducting power flow simulation and analysis of the electrical system in oil and gas industries to validate the system model and determine the full load current (FLA) of each equipment. This is followed by a three-phase short-circuit simulation to obtain the minimum fault current contribution, which serves as a primary parameter in relay setting configuration. The next step is to determine the relay installation locations based on the protection zones and the position of critical equipment that must be protected. Subsequently, the relay characteristics are configured by considering the FLA values, minimum fault current contribution, the type of relay characteristic curve and trip time settings. The final stage is the coordination analysis of the 50/51 and 50/51V relays, which includes evaluating the relay operating characteristics and calculating the time margins between curves to ensure selectivity and prevent miscoordination. Figure 8 shows the flowchart of the recommended guide for coordination of 50/51 and 50/51V relay protection. The subsequent section will present detailed information regarding the protection coordination recommendations for 50/51 and 50/51V relays applied to generators in oil and gas industrial facilities.

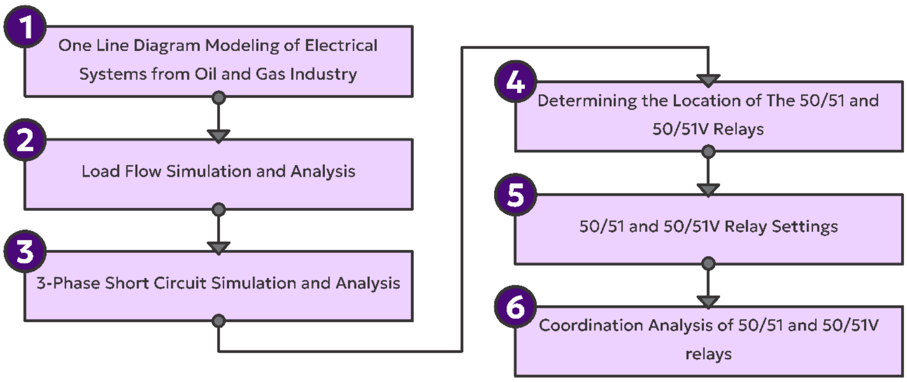

Figure 8 Flowchart guide recommendation for coordination of 50/51 and 50/51V relay protection.

Power Protection System Modeling of Oil and Gas Industry

Simulation – based Modeling of Power Protection System in Oil and Gas Industry

Figure 9 shows three types of single line diagrams that represent the oil and gas industry. These figures exhibit unique characteristics and a variety of system configurations. Table 3 provides detailed information on the components in each single line diagram. The modelling was carried out using power system simulation. The validation of the developed model considers actual conditions such as motor loads operating at 80% of installed capacity, the absence of overloaded equipment and busbar voltage maintained within standard limits (5% undervoltage and 10% overvoltage).

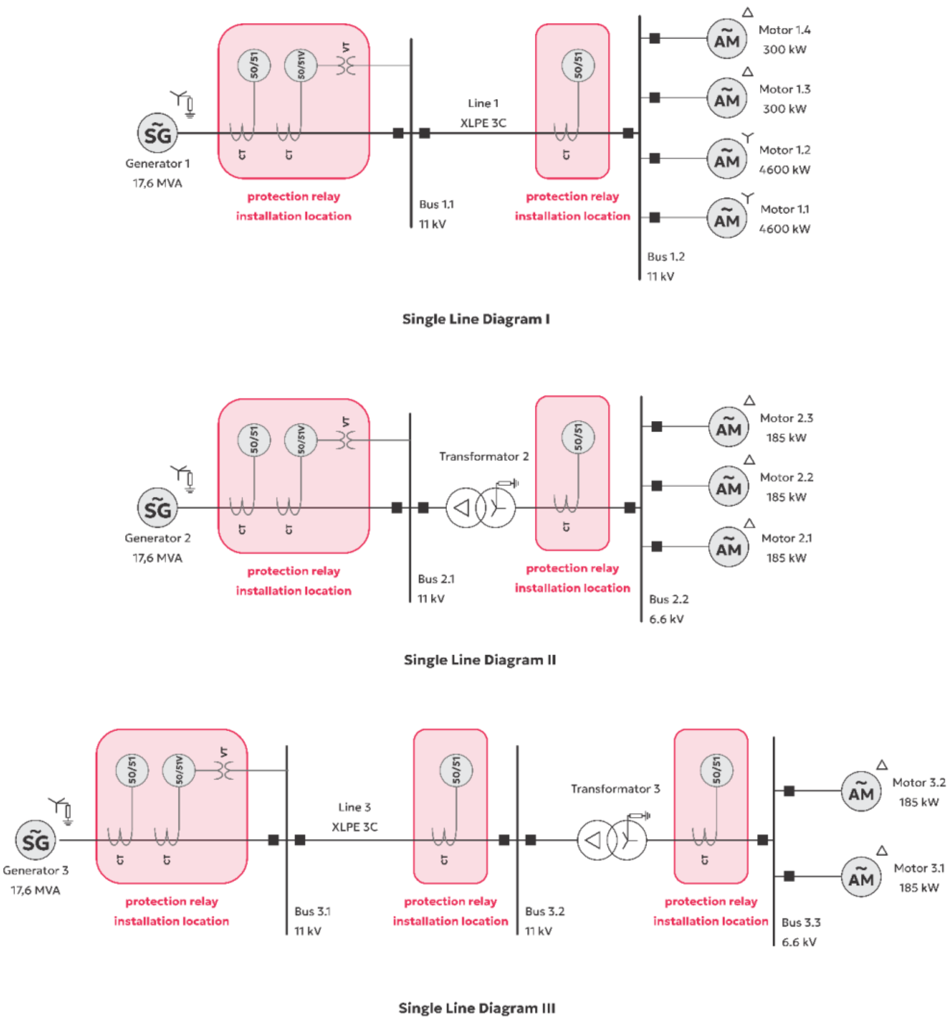

Figure 9 Single line diagram representing the oil and gas industry.

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Table 3 Component details on each single line diagram.

Single Line Diagram I	Single Line Diagram II	Single Line Diagram III
- Generator - Line - Motor Load	- Generator - Transformer - Motor Load	- Generator - Line - Transformer - Motor Load

The simulation scenarios represent four voltage conditions derived from the operating principle of the voltage-restrained 50/51V relay. Figure 10 illustrates the relationship between the relay's operating principle diagram and the applied scenarios, while Table 4 provides detailed descriptions of the scenarios used in the relay coordination simulations for 50/51 and 50/51V.

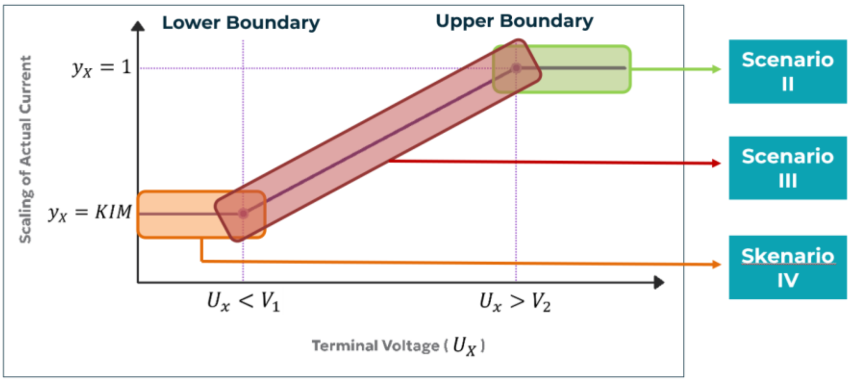

Figure 10 Ilustration of simulation scenarios.

Table 4 50/51 and 50/51V relay protection coordination scenarios in the oil and gas industry.

Simulation Scenario	Description	Generator Voltage Condition
I	Normal condition without a three-phase fault at the load bus. The generator nominal voltage is maintained at 11 kV.	Voltage remains unchanged (normal condition).
II	Three-phase fault occurs at the load bus, and the generator nominal voltage decreases from 11 kV to 10 kV.	Voltage decreases but has not yet entered the voltage restrained operating range.
III	Three-phase fault occurs at the load bus, and the generator nominal voltage decreases from 11 kV to 9.5, 9, and 8.5 kV.	Voltage decreases and has already entered the voltage restrained operating range.
IV	Three-phase fault occurs at the load bus, and the generator nominal voltage decreases from 11 kV to 7.8 and 7.5 kV.	Voltage decreases and falls below the lower threshold of the voltage restrained operating range.

Investigation on Three Phase Fault Short Circuit Current Contribution

The investigation of fault contribution current is conducted using a three-phase fault type. This type of fault is considered a disturbance in the power system as it produces the maximum short-circuit current. The selection of a three-phase fault for contribution current analysis represents the worst case scenario when a fault occurs in the system. Additionally, the three-phase fault contribution current is more representative for 50/51 relay settings compared to other fault types. According to the IEC 60909 standard (IEC, 2001), the three-phase fault current can be expressed as in Eq. (6), where U_N is the nominal system voltage, Z_k is the total impedance at the fault point and c is a correction factor with a value range of 1.0–1.1.

$$I_k'' = \frac{cU_N}{\sqrt{3}Z_k} \tag{6}$$

Short-circuit fault simulations are conducted using the features of power system simulation software. The objective of the fault contribution current analysis is to determine the amount of short-circuit current generated by equipment, particularly from generators. The calculated fault contribution current is used as a basis for setting the 50/51 and 50/51V relays for ensuring selective relay operation and avoiding false trips.

The three-phase short-circuit fault simulation scenarios are divided into two conditions: faults occurring near the source (generator) and faults occurring far from the source (load busbar). Figure 11 illustrates the fault location scenarios for the three types of oil and gas electrical systems. The contribution current generated by the generator is then observed. The simulation results of the short-circuit faults are presented in Figure 12.

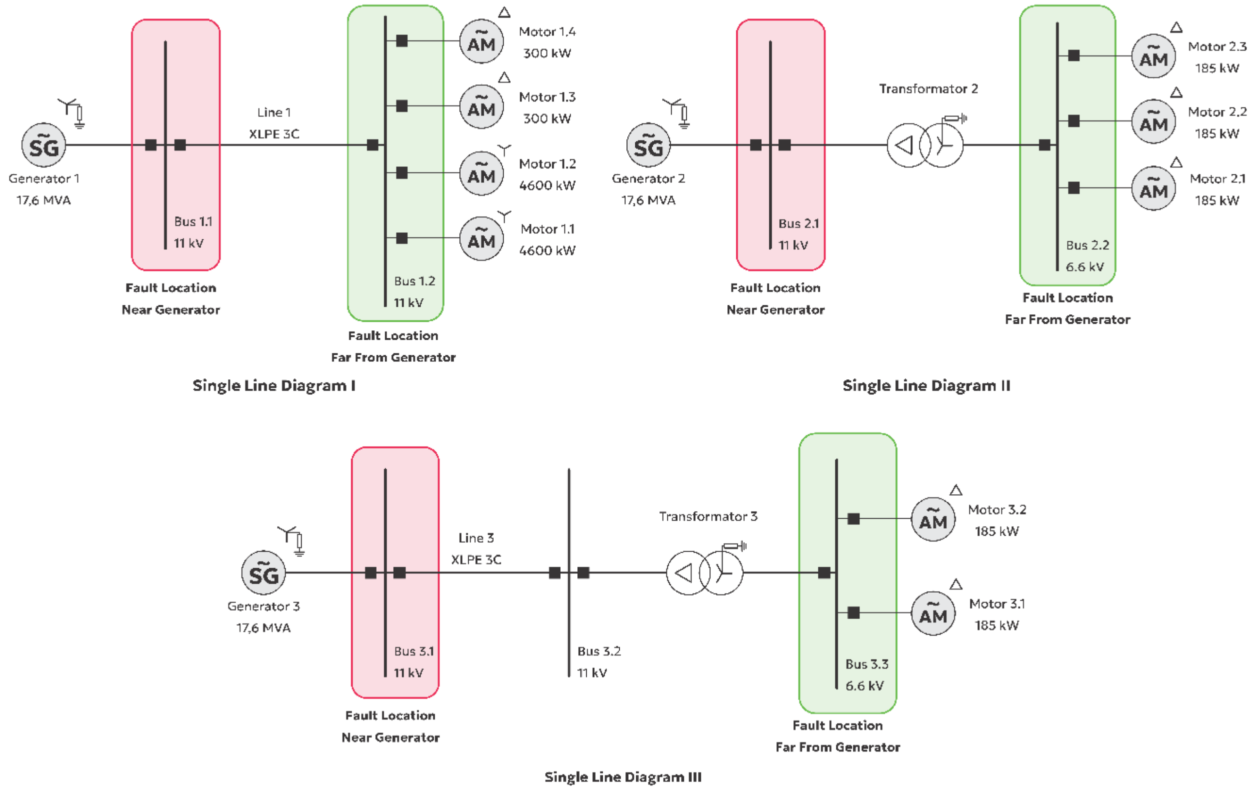

Figure 11 3-phase short circuit fault scenarios on each single line diagram of oil and gas industry type.

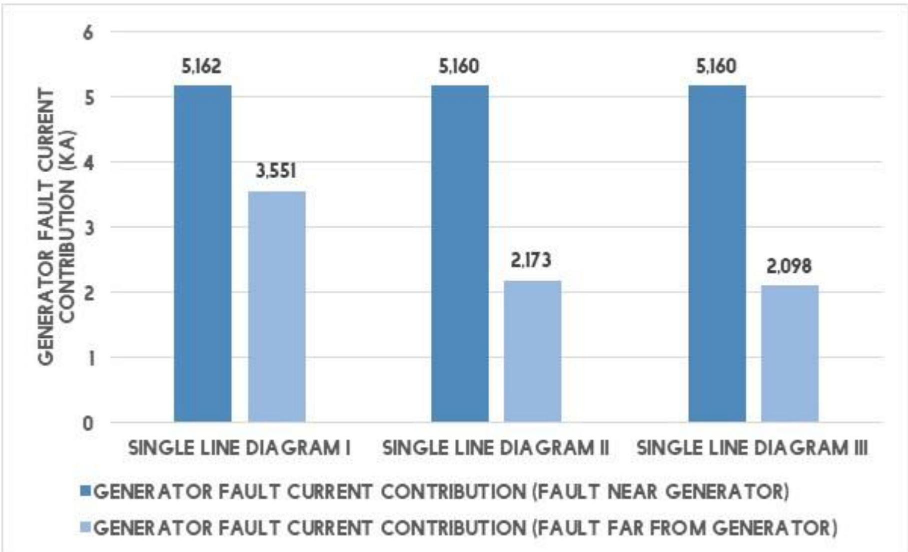

Figure 12 3-phase fault contribution currents.

Based on the results shown in Figure 12, it is observed that the highest contribution current from the generator occurs when the fault is located at the generator busbar compared to faults located at the load busbar. The difference in fault current contribution may occur due to the system impedance between the generator and the fault point which is influenced by distance, thereby limiting the fault current flow from the generator. This implies that as the distance to the three-phase fault location increases and the total impedance becomes greater. As a result, the fault current contribution from the generator becomes smaller.

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Table 5 The short-circuit simulation results when the generator voltage drops to 9.9 kV for 50/51V relay setting.

Single Line Diagram	Generator Fault Current Contribution (kA)	Three – Phase Fault Impedance (Ohm)
Single line diagram I	2.171	1.2
Single line diagram II	1.457	1.15
Single line diagram III	1.432	1.05

Figure 12 illustrates that a low fault current contribution is difficult to detect by the 50/51 relay when a fault occurs at a location far from the generator. Therefore, the 50/51V relay is required as a backup protection in case the 50/51 relay fails to operate. To ensure accurate operation of the 50/51V relay, the fault current value must be obtained through short-circuit simulation when the voltage reaches the upper limit of the voltage-restrained range by adjusting the three – phase fault impedance. The nominal generator voltage in the three types of single line diagrams is 11 kV; thus, the applied voltage-restrained range is from 9.9 kV to 8 kV. A voltage of 9.9 kV represents the upper limit of the voltage-restrained condition. Table 5 presents the short-circuit simulation results when the generator voltage drops to 9.9 kV. These results serve as a reference for determining the pickup current setting of the 50/51V relay.

Coordination and Settings Strategy of 50/51 and 50/51V Relay

As shown in Figure 9, 50/51 relays are installed at the generator outgoing side, line, and low voltage transformer side, while the 50/51V relay is placed at the generator outgoing side as a backup element. The placement strategy ensures selective protection and fast disturbance isolation without affecting the entire system. Both 50/51 and 50/51V relays apply the very inverse time-current characteristic curve. The pickup current and time dial value for each relay are configured to ensure proper coordination sequence and remain within the equipment safety margin. The pickup current is determined by considering the full load ampere (FLA) of the equipment and the lowest fault contribution current as illustrated in Figure 13 (Paithankar & Bhide, 2007). Therefore, the parameters relay for each type of single line diagram that represents the oil and gas industry electrical system are obtained by Tables 6, 7, 8 and 9.

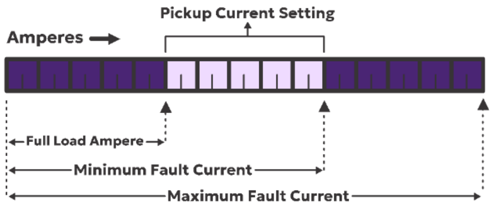

Figure 13 Illustration of pickup current setting.

Table 6 50/51 relay setting for single line diagram I.

Relay Installation Location	Relay Curve	Relay Curve Type	Pickup Current (p.u.)	Time Dial Settings (s)
Outgoing Generator	Curve 1	IEC Class A (Standard Inverse)	1.18	0.07
	Curve 2	Definite Time	3.2	0.13
	Curve 3	Non Active		
	Curve 4	Non Active		
Downstream equipment (Line)	Curve 1	IEC Class A (Standard Inverse)	0.96	0.05
	Curve 2	Definite Time	30	0.08
	Curve 3	Non Active		
	Curve 4	Non Active		

Table 7 50/51 relay setting for single line diagram II.

Relay Installation Location	Relay Curve	Relay Curve Type	Pickup Current (p.u.)	Time Dial Settings (s)
Outgoing Generator	Curve 1	IEC Class A (Standard Inverse)	1.15	0.06
	Curve 2	Non active		
	Curve 3	Non Active		
	Curve 4	Non Active		
Downstrem Equipment (HV Side of Transformer)	Curve 1	IEC Class A (Standard Inverse)	0.2	0.54
	Curve 2	Definite Time	2	1.2
	Curve 3	Definite Time	2.5	0.4
	Curve 4	Definite Time	4	0.09

Table 8 50/51 relay setting for single line diagram III

Relay Installation Location	Relay Curve	Relay Curve Type	Pickup Current (p.u.)	Time Dial Settings (s)
Outgoing Generator	Curve 1	IEC Class A (Standard Inverse)	1.1	0.09
	Curve 2	Definite Time	14	0.1
	Curve 3	Non Active		
	Curve 4	Non Active		
Downstream Equipment (Line)	Curve 1	IEC Class A (Standard Inverse)	1.05	0.07
	Curve 2	Definite Time	9	0.08
	Curve 3	Non Active		
	Curve 4	Non Active		
Downstrem Equipment (HV Side of Transformer)	Curve 1	IEC Class A (Standard Inverse)	0.2	0.6
	Curve 2	Definite Time	5	0.2
	Curve 3	Definite Time	12	0.06
	Curve 4	Non Active		

Table 9 50/51V relay setting

50/51V Relay Setting Type	Single Line Diagram I	Single Line Diagram II	Single Line Diagram III
Pickup Current (p.u.)	2.1	1.45	1.44
Time Dial Settings (s)	0.1	0.2	0.25
KIM	0.4	0.4	0.4

Specifically for the 50/51V relay, several logic settings are applied. The aim is to ensure that the 50/51V relay operates under voltage-restrained conditions. voltage-restrained conditions are modelled when the voltage drops in the range of 9.9 kV to 8 kV. Table 10 presents the logic settings of the 50/51V relay for voltage-restrained operation. Setting the time dial and pickup current for 50/51 and 50/51V relays in the power system software will form a curve in time-current characteristic (TCC) curve. Based on the relay setting strategies for 50/51 and 50/51V, the resulting relay coordination design is illustrated on the time–current characteristic (TCC) curve, as shown in Figure 14.

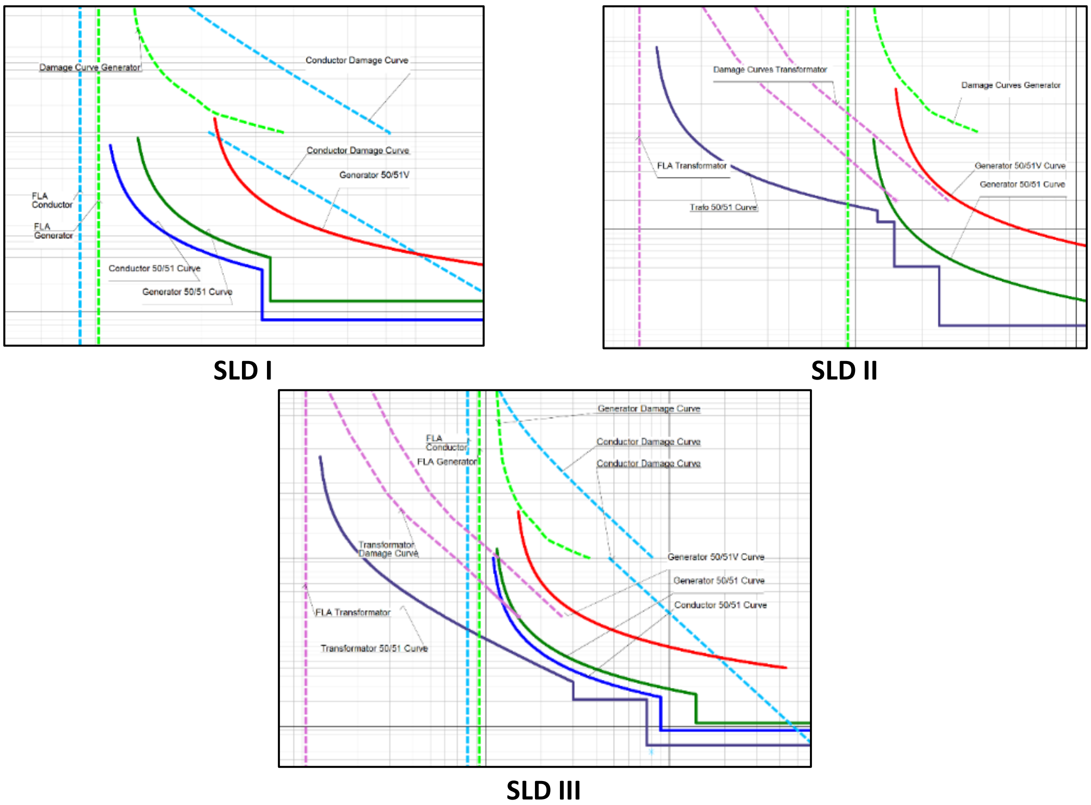

Figure 14 The time–current characteristic (TCC) curve of the relay coordination strategy is constructed based on the 50/51 and 50/51V relay setting strategies presented in Tables 6, 7, 8, 9, and 10.

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Table 10 Voltage restrained logic settings for 50/51V relays

Voltage Limit	Nominal Voltage (p.u.)	Nominal Voltage V in Line to Line (kV)	Nominal Voltage V in Line to Neutral (kV)	Voltage read by VT (V)
Upper Limit	0.9 p.u.	9.9 kV	5.71 kV	51.9 V
Lower limit	0.72 p.u.	8 kV	4.61 kV	41.9 V

Results of the 50/51 and 50/51V Relay Coordination Simulation

The results of Simulation Scenario I show the expected outcome, in which neither the 50/51 nor the 50/51V relay operates, since no fault is present in the system. This condition is illustrated in Figure 15, where the current measured by the CT does not intersect with any relay curve. Such behaviour satisfies the fundamental criterion of relay coordination, namely that relays should only operate under fault conditions and remain inactive during normal operating states.

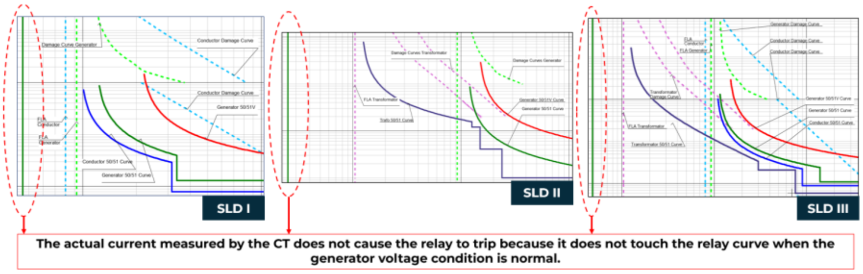

Figure 15 Results of relay coordination simulation for scenario I.

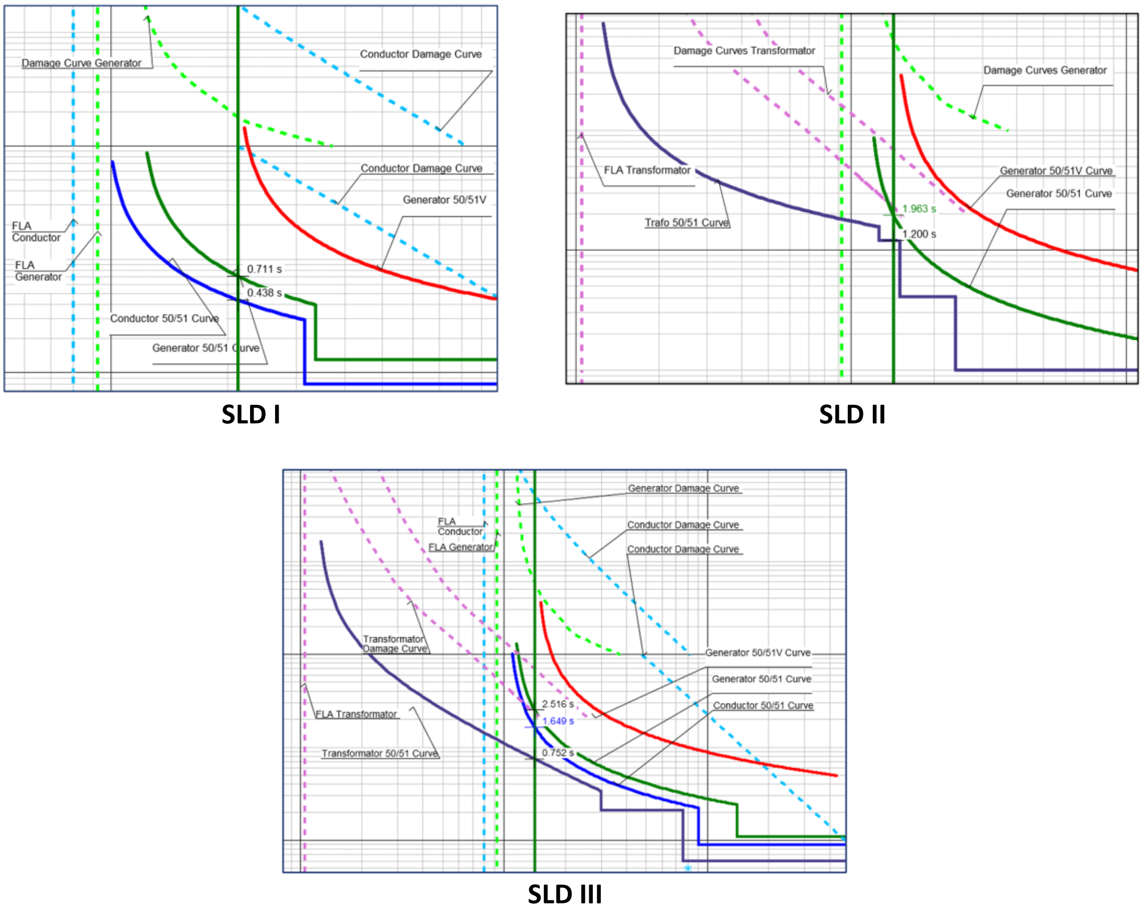

Figure 16 The results of relay coordination simulation for Scenario II are shown, where the actual current line (green line) touching the relay curve indicates that only the 50/51 relay is operating.

The simulation results for Scenario II demonstrate proper coordination between the 50/51 and 50/51V relays. When the system voltage decreases but has not yet entered the *voltage restrained* range, the 50/51V relay remains inactive. As shown in Figure 16, only one actual current line is present, intersecting solely with the 50/51 relay curve, indicating that the 50/51 relay operates as the primary protection. Furthermore, the coordination among the 50/51 relays is selective, operating below the equipment damage curve and within the IEEE-standard trip time, as summarized in Table 11, 12 and 13.

Table 11 Relay coordination trip time for scenario II (SLD I).

The sequence of relay operation	Relay	Tripping Time (s)
1	Line I 50/51 relay curve	0.438
2	Generator I 50/51 relay curve	0.830

Table 12 Relay coordination trip time for scenario II (SLD II).

The sequence of relay operation	Relay	Tripping Time (s)
1	Trafo II 50/51 relay curve	1.2
2	Generator II 50/51 relay curve	1.963

Table 13 Relay coordination trip time for scenario I (SLD III).

The sequence of relay operation	Relay	Tripping Time (s)
1	Trafo III 50/51 relay curve	0.752
2	Line III 50/51 relay curve	1.649
3	Generator III 50/51 relay curve	2.516

In Simulation III, under the scenario of voltage reduction within the voltage-restrained range, the 50/51V relay was activated in each single-line diagram. This was evidenced by the appearance of a red line on the TCC curve, representing the actual current that had been magnified through the 50/51V relay logic. The designed coordination strategy effectively prevented maloperation during voltage restrained, ensured that the relay tripping times complied with the IEEE standard and maintained relay selectivity. These results are illustrated in Figure 17, while the cumulative tripping times are summarized in Tables 14, 15 and 16. Furthermore, Table 17 presents the scaling factors applied by the 50/51V relay logic to shift the actual current curve.

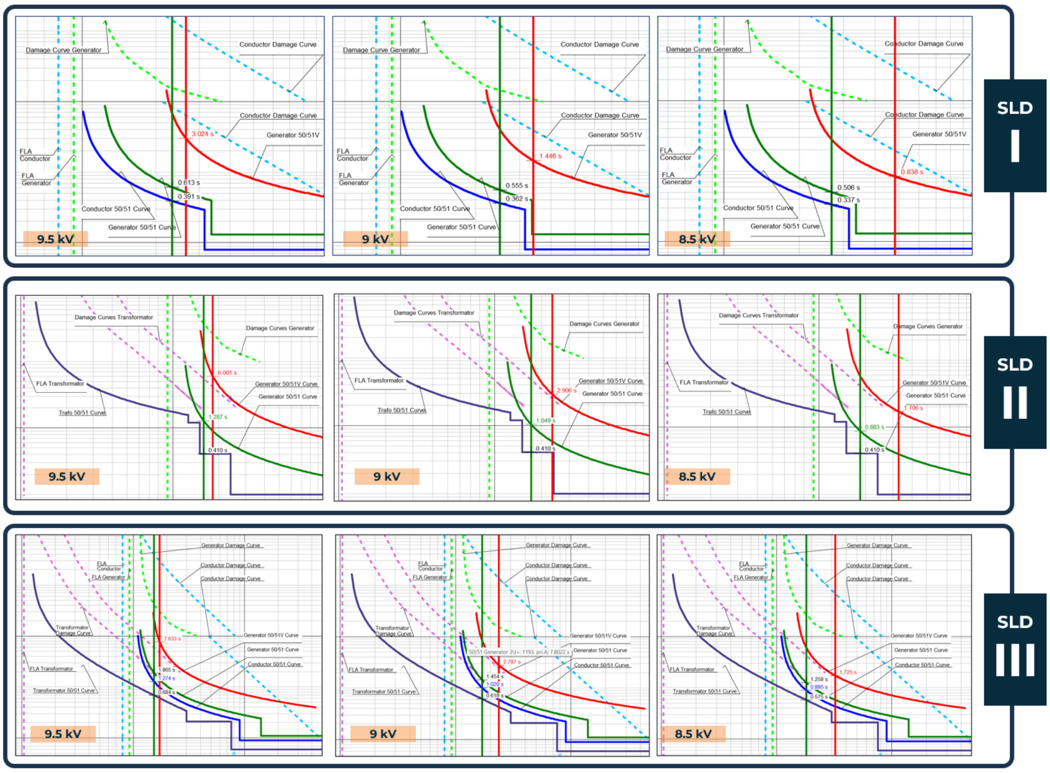

Figure 17 The results of relay coordination simulation for Scenario III are shown, where the increase in the actual current value due to the 50/51V relay logic (red line) is observed and this current increase is proportional to the voltage drop.

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Table 14 Relay coordination trip time for scenario III (SLD I).

The sequence of relay operation	Role of Relay	Relay	Tripping Time (9.5 kV)	Tripping Time (9 kV)	Tripping Time (8.5 kV)
1	Primary	Relay Curve 50/51 Line I	0.391	0.362	0.337
2	Primary	Relay Curve 50/51 Generator I	0.761	0.647	0.590
3	Backup	Relay Curve 50/51V Generator I	2.721	1.032	0.337

Table 15 Relay coordination trip time for scenario III (SLD II).

The sequence of relay operation	Role of Relay	Relay	Tripping Time (9.5 kV)	Tripping Time (9 kV)	Tripping Time (8.5 kV)
1	Primary	Relay Curve 50/51 Transformer II	0.410	0.410	0.410
2	Primary	Relay Curve 50/51 Generator II	1.287	1.049	0.883
3	Backup	Relay Curve 50/51V Generator II	6	2.906	1.706

Table 16 Relay coordination trip time for scenario III (SLD III).

The sequence of relay operation	Role of Relay	Relay	Tripping Time (9.5 kV)	Tripping Time (9 kV)	Tripping Time (8.5 kV)
1	Primary	Relay Curve 50/51 Transformer III	0.684	0.618	0.575
2	Primary	Relay Curve 50/51 Line III	1.274	1.02	0.875
3	Primary	Relay Curve 50/51 Generator III	1.864	1.454	0.128
4	Backup	Relay Curve 50/51V Generator III	7.633	2.787	1.725

The results of Simulation III indicate that the magnified actual current is represented by the appearance of a red current line on the TCC curve in Figure 17. This red line corresponds to the scaled version of the actual current (green line), resulting from the activation of the 50/51V relay logic under voltage-restrained conditions. The shift occurs due to the application of a scaling factor, as defined by Eqs. (2), (3) and (4). Table 17 summarizes the values of the scaling factors applied by the logic. When correlated with the simulated voltage reduction, these findings produce the operating principle curve of the voltage-restrained 50/51V relay, as illustrated in Figure 4 and with the evidence shown in Figure 18.

Table 17 Summarizes the values of scaling factors.

Single Line Diagram	Scale Factor Conditioned at 9.5 kV	Scale Factor Conditioned at 9 kV	Scale Factor Conditioned at 8.5 kV
SLD I	0.88	0.74	0.56
SLD II	0.87	0.73	0.56
SLD III	0.89	0.71	0.56

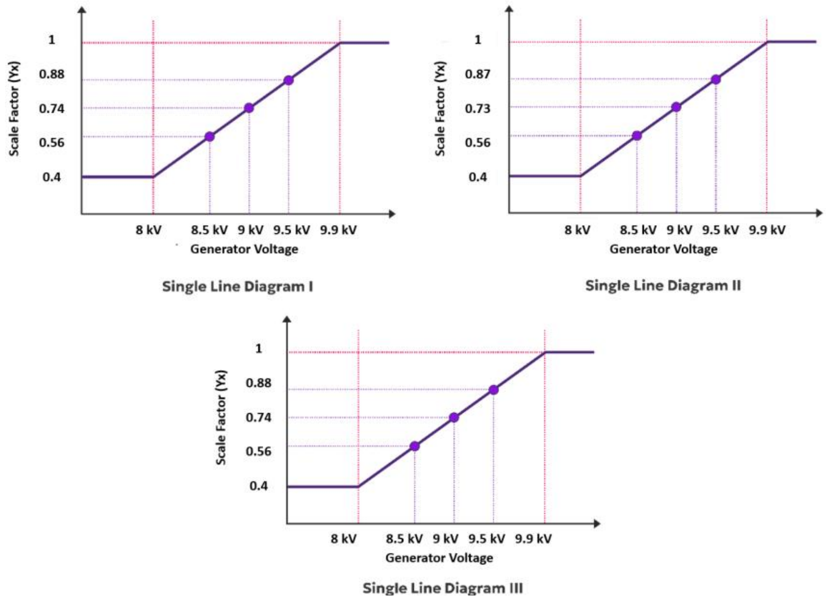

Figure 18 Graph of relationship between scale factor and voltage conditions from simulation results.

Scenario IV applies a voltage drop condition exceeding the lower limit of the voltage restrained setting, specifically at 7.8 kV and 7.5 kV. When the voltage on the generator busbar drops below the set lower limit of the voltage restrained, the scale factor does not decrease linearly as in the voltage restrained condition in scenario II. The results demonstrate that the 50/51V relay operates by applying a scaling factor, represented by the KIM value, as illustrated in Figure 19. The coordination between the 50/51 and 50/51V relays functions selectively, with no evidence of maloperation and the time margin between tripping events remains within the IEEE standard limits. The cumulative tripping time is summarized in Tables 18, 19 and 20.

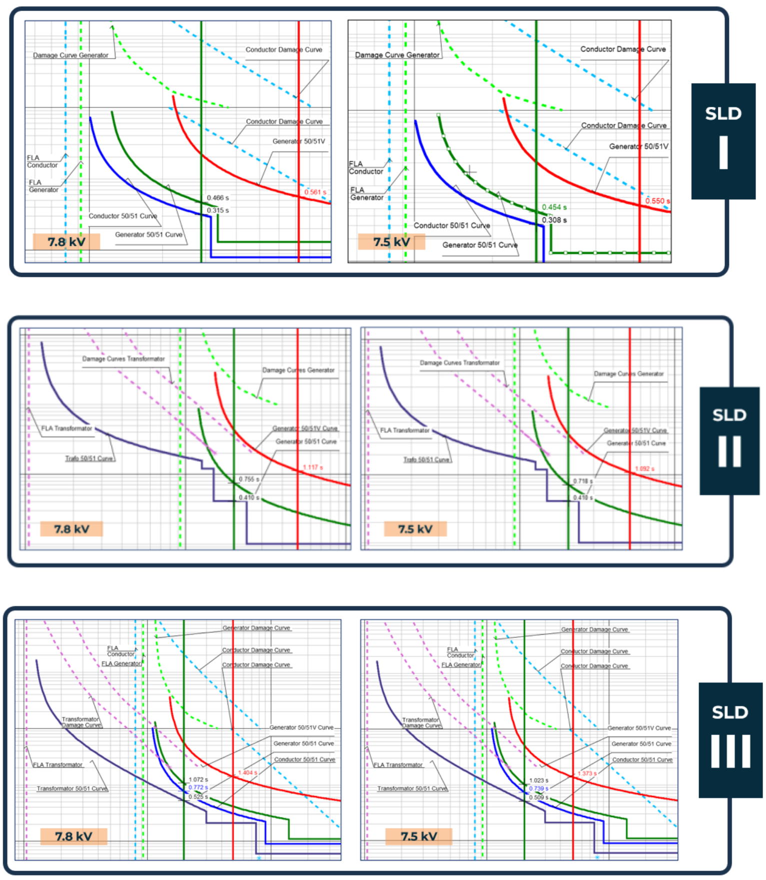

Figure 19 The results of relay coordination simulation for Scenario IV are presented, where when the voltage drops below the lower voltage threshold of the voltage-restrained logic, the sensitivity of the actual current is then determined by the KIM value.

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Table 18 Relay coordination trip time for scenario III (SLD I).

The sequence of relay operation	Role of Relay	Relay	Tripping Time (7.8 kV)	Tripping Time (7.5 kV)
1	Primary	Relay Curve 50/51 Line I	0.315	0.308
2	Primary	Relay Curve 50/51 Generator I	0.466	0.454
3	Backup	Relay Curve 50/51V Generator I	0.560	0.550

Table 19 Relay coordination trip time for scenario III (SLD II).

The sequence of relay operation	Role of Relay	Relay	Tripping Time (7.8 kV)	Tripping Time (7.5 kV)
1	Primary	Relay Curve 50/51 Transformer II	0.410	0.410
2	Primary	Relay Curve 50/51 Generator II	0.755	0.718
3	Backup	Relay Curve 50/51V Generator II	1.117	1.092

Table 20 Relay coordination trip time for scenario III (SLD III).

The sequence of relay operation	Role of Relay	Relay	Tripping Time (7.8 kV)	Tripping Time (7.5 kV)
1	Primary	Relay Curve 50/51 Transformer III	0.525	0.059
2	Primary	Relay Curve 50/51 Line III	0.772	0.739
3	Primary	Relay Curve 50/51 Generator III	1.072	1.023
4	Backup	Relay Curve 50/51V Generator III	1.404	1.373

Discussion and Protection Recommendations

Based on the simulation results, this study shows that the key aspect to preventing maloperation lies in the configuration of the 50/51V relay logic and its associated time dial settings. The voltage-restrained logic must be set by considering an appropriate voltage window, enabling the 50/51V relay to respond rapidly once the system voltage decreases. At the same time, the time dial of the 50/51V relay must be coordinated such that its operating curve consistently remains above the 50/51 relay curve, preventing the backup element from operating prior to the primary relay.

The proposed coordination strategy applied to various single line diagrams representing oil and gas industrial systems demonstrates consistently selective relay operation with tripping time margins that comply with IEEE standards. These findings are further validated under multiple voltage drop scenarios, confirming that the 50/51V relay performs effectively as backup protection to the 50/51 relay without introducing the risk of unintended generator disconnection.

Conclusion

The recommended protection strategy proves that selective coordination between relay 50/51 and 50/51V can effectively prevent maloperation and unnecessary generator isolation in oil and gas power systems. The relay sequence consistently prioritizes clearing faults closest to the disturbance location, before escalating protection upstream, thereby minimizing the risk of blackout.

This study also confirms that the 50/51V relay optimally functions as backup protection under voltage-restrained conditions and does not operate before the primary 50/51 relay. Under all simulated scenarios, the TCC curves remain below the equipment damage curves, ensuring both thermal and mechanical safety margins.

Overall, the coordinated use of relay 50/51 as primary protection and 50/51V as voltage-restrained backup demonstrably enhances the reliability of generator protection in oil and gas industrial power systems. The proposed design not only prevents maloperation and unnecessary generator isolation, but also provides adaptive response capability under voltage-varying fault conditions. Consequently, this coordination framework can serve as a practical reference for protection engineers in developing protection architectures that maintain selectivity while sustaining system continuity under diverse operating scenarios in the oil and gas sector.

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Compliance with ethics guidelines

The authors declare they have no conflict of interest or financial conflicts to disclose.

This article contains no studies with human or animal subjects performed by the authors.

References

Abbasi, A. R. (2025). Statistical techniques in power systems fault diagnostic: Classifications, challenges, and strategic recommendations. *Electric Power Systems Research, 239*, 111279. https://doi.org/10.1016/j.epsr.2024.111279

API. (2014). Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Division 1 and Division 2.

API. (2008). By Authority Of THE UNITED STATES OF AMERICA Legally Binding Document API RP 14F: Recommended Practice for Design and Installation of Electrical Systems for Offshore Production Platforms.

Bai, Y., Li, Y., Liu, Y., & Ma, Z. (2017). Short-term prediction of distribution network faults based on support vector machine. *2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA),* 1421–1426. https://doi.org/10.1109/ICIEA.2017.8283062

Blackburn, J. L., & Domin, T. J. (2014). Protective Relaying. CRC Press. https://doi.org/10.1201/b16518

Boccaletti, C., Fabbri, G., & Santini, E. (2007). Innovative solutions for stand alone system powering. *INTELEC 07 - 29th International Telecommunications Energy Conference, Rome, Italy*, 294–301. https://doi.org/10.1109/INTLEC.2007.4448786

IEC. (2001). Short-circuit currents in three-phase AC systems – Part 0: Calculation of currents.

de Almeida, A. T., Fong, J. A. C., & Ferreira, F. J. T. E. (2024). Energy-Efficient Industrial Motor-Driven Systems and Standards Toward Net Zero Carbon. *2024 IEEE/IAS 60th Industrial and Commercial Power Systems Technical Conference (I& CPS)*, 1–10. https://doi.org/10.1109/ICPS60943.2024.10563531

IEC/IEEE International Standard - Explosive atmospheres -- Part 30-1: Electrical resistance trace heating -- General and testing requirements. (2015). IEEE. https://doi.org/10.1109/IEEESTD.2015.7279035

IEEE recommended practice for protection and coordination of industrial and commercial power systems. (2001). Institute of Electrical and Electronics Engineers.

IEEE Standard for Inverse-Time Characteristics Equations for Overcurrent Relays. (2018). IEEE. https://doi.org/10.1109/IEEESTD.2019.8635630

IEEE/IEC International Standard - Measuring relays and protection equipment - Part 118-1: Synchrophasor for power systems - Measurements. (2018). IEEE. https://doi.org/10.1109/IEEESTD.2018.8577045

Ivanov, D. (2025). Blackout and supply chains: Cross-structural ripple effect, performance, resilience and viability impact analysis. *Annals of Operations Research, 348*(3), 1127–1143. https://doi.org/10.1007/s10479-022-04754-9

Makani, Z., & Daniel Chowdhury, S. P. (2017). Design of electrical power supply system in a typical petroleum refinery. *2017 52nd International Universities Power Engineering Conference (UPEC),* 1–6. https://doi.org/10.1109/UPEC.2017.8231942

Mishra, P., Pradhan, A. K., & Bajpai, P. (2021). Adaptive Voltage Restrained Overcurrent Relaying for Protection of Distribution System with PV Plant. *2021 9th IEEE International Conference on Power Systems (ICPS),* 1–5. https://doi.org/10.1109/ICPS52420.2021.9670077

Mishra, P., Pradhan, A. K., & Bajpai, P. (2025). Coordination of distance and positive sequence voltage-restrained overcurrent relays for protection of distribution systems with PV plants. *Electric Power Systems Research, 242,* 111432. https://doi.org/10.1016/j.epsr.2025.111432

Paithankar, Y. G. ., & Bhide, S. R. . (2007). Fundamentals of power system protection. Prentice-Hall of India.

Reiz, C., Leite, J. B., Gouveia, C. S., & Javadi, M. S. (2024). Protection system planning in distribution networks with microgrids using a bi-level multi-objective and multi-criteria optimization technique. *Electric Power Systems Research, 228*, 109966. https://doi.org/10.1016/j.epsr.2023.109966

Rizwan, M., Gao, C., Hong, L., Ahmad, S., Sayed, A. E., & Zaindin, M. (2024). An innovative dual-setting uni-directional hybrid characteristics for enhanced primary-backup relay coordination. *Electric Power Systems Research, 235,* 110545. https://doi.org/10.1016/j.epsr.2024.110545

Saad, Saad. M., Alasali, F., Naily, N. El, Elhaffar, A., Hussein, T., & Mohamed, F. A. (2021). Coordination of Mixed Overcurrent and voltage-Restrained Overcurrent Relays To Avoid Miscoordination Problems Considering IEC Time-Current Curve Limitations. *2021 12th International Renewable Energy Congress (IREC)*, 1–6. https://doi.org/10.1109/IREC52758.2021.9624932

Salam, S. M., Mohammad, N., & Rashid, M. M. (2025). Quantifying demand-side management in sustainable grid networks by industrial load flexibility with variable inertia flywheel induction motors. *E-Prime - Advances in Electrical Engineering, Electronics and Energy, 11*, 100890. https://doi.org/10.1016/j.prime.2024.100890

Saleh, K., & Ayad, A. (2021). Fault zone identification and phase selection for microgrids using decision trees ensemble. *International Journal of Electrical Power & Energy Systems, 132*, 107178. https://doi.org/10.1016/j.ijepes.2021.107178

Taheri, M. R., Mohammadi, R., & Ghotbi-Maleki, M. (2023). Optimal cable size selection in distribution network considering damage curve with variable fault clearing time of overcurrent relay. *Electric Power Systems Research, 225*, 109812. https://doi.org/10.1016/j.epsr.2023.109812

Unluturk, A., & Ozer, I. (2025). Optimization based control of overcurrent relays in distribution network considering real-time measurements: A case study. *Applied Energy, 377*, 124439. https://doi.org/10.1016/j.apenergy.2024.124439

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