

Power System Studies for Industrial Electrical Network Using ETAP

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Abstract: This paper presents a detailed study on relay coordination and arc flash hazard analysis for a 27-bus industrial electrical network using ETAP. In complex industrial systems, ensuring proper coordination between protective devices and minimizing arc flash risks are critical for both system reliability and personnel safety. The work begins with modelling the network and performing short-circuit analysis to determine fault levels at various buses. Based on these results, overcurrent relay settings are calculated for different protection stages, including both phase and ground faults, using definite minimum time (DMT) and inverse definite minimum time (IDMT) characteristics. Time-current coordination (TCC) curves are then developed to verify the selectivity and proper sequence of operation between upstream and downstream devices, including low-voltage breakers. The coordination process ensures that faults are cleared by the nearest protective device without unnecessary tripping of the entire system. Following this, an arc flash study is carried out to evaluate key parameters such as arc flash boundary (AFB), fault clearing time (FCT), incident energy, and working distance. The analysis helps in identifying critical sections of the network where higher incident energy levels pose safety concerns. It is observed that fault clearing time and relay coordination significantly influence arc flash severity. Based on the results, arc flash labels are generated to provide practical safety information for field implementation. Overall, the study demonstrates that optimized relay coordination not only improves protection performance but also plays a vital role in reducing arc flash hazards in industrial power systems.

Keywords: ETAP, IDMT, DMT, Incident Energy, FCT.

I. INTRODUCTION

Modern industrial power systems are becoming increasingly complex due to the integration of multiple loads, distributed sources, and long transmission distances. In such systems, the role of protection schemes is crucial to ensure system stability, equipment safety, and uninterrupted operation. Protective devices such as overcurrent relays and circuit breakers must operate in a coordinated manner so that faults are isolated quickly and selectively without affecting the healthy part of the network. However, improper relay coordination can lead to delayed fault clearing or unnecessary tripping, which may result in equipment damage and reduced system reliability. In addition to protection challenges, arc flash hazards have emerged as a major safety concern in industrial electrical networks. Arc flash events can produce extremely high temperatures and energy levels, posing serious risks to personnel and equipment. Parameters such as incident energy, arc flash boundary, and fault clearing time play a significant role in assessing the severity of such events. Therefore, it is essential not only to design an effective protection scheme but also to evaluate the system from a safety perspective.

With the advancement of simulation tools like ETAP, it has become possible to perform detailed analysis of power systems, including load flow, short-circuit, relay coordination, and arc flash studies within a single platform. While several studies focus either on relay coordination or arc flash analysis independently, limited work has been carried out to integrate both aspects for a comprehensive assessment of industrial systems. This paper presents a combined study of relay coordination and arc flash hazard analysis for a 27-bus industrial electrical network. The work includes calculation of overcurrent relay settings for different fault conditions using definite minimum time (DMT) and inverse definite minimum time (IDMT) characteristics, along with verification through time-current coordination (TCC) curves. Furthermore, an arc flash analysis is performed to evaluate critical parameters and identify high-risk zones within the system. The objective of this study is to improve protection reliability while minimizing arc flash hazards, thereby enhancing overall system safety and performance.

II. SYSTEM DESCRIPTION

The analysis in this work is performed on a 27-bus industrial electrical network modelled using ETAP. The system represents a practical industrial power distribution arrangement, comprising both high-voltage (HT) and low-voltage (LT) levels, along with multiple load centres and standby generation.

The main supply to the plant is received from an 11 kV utility source. This source is connected via an approximately 7 km-long feeder, which introduces noticeable impedance into the system and results in relatively weak grid conditions. The incoming supply is terminated at the HT switchgear, from where power is fed to the main transformer rated at 3.5 MVA with a voltage rating of 11/0.433 kV. This transformer steps down the voltage to the LT level for further distribution.

At the LT side, power is distributed through the main LT PCC bus to several downstream buses and panels. These include multiple motor control centres (IMCCs), main power distribution boards (MPDBs), and dedicated panels for different plant utilities such as boiler systems, fire hydrant systems, HVAC loads (including chillers and VRF units), RO plant, and lighting loads. The connected loads vary in size and are generally operating at an average power factor close to 0.85. To improve system reliability and ensure continuity of supply during outages, two diesel generator (DG) units of 1600 kW each are connected at the LT level. Bus couplers are also provided between different sections of the PCC to allow flexibility in operation and load sharing during abnormal conditions.

The network is protected using a combination of HT and LT protective devices, including circuit breakers, molded case circuit breakers (MCCBs), and numerical relays. These devices are installed at incoming feeders, outgoing feeders, and major load points. Appropriate current transformer (CT) ratios are used to support protection and measurement functions across different voltage levels.

In addition, reactive power compensation is provided through automatic power factor correction (APFC) panels, which help maintain the system power factor and support voltage levels. The system also includes cables of different lengths and sizes, which influence voltage drop and fault current distribution across the network.

Overall, the modelled system reflects a realistic industrial electrical setup with multiple interconnected buses, diverse load types, and detailed protection arrangements. This provides a suitable platform for carrying out relay coordination and arc flash hazard analysis.

III. RELAY COORDINATION

In modern industries, electrical power systems have become increasingly large and complex. Due to this complexity, faults occur more frequently, which can lead to system instability, damage to expensive equipment, and serious safety risks to both personnel and infrastructure. To address these challenges, protective relays are used to detect abnormal operating conditions within the system. Once a fault is identified, the relay initiates the isolation of the faulty section, ensuring that the healthy part of the system continues to operate without interruption. This also helps in preventing the fault from propagating throughout the network. Therefore, relay coordination plays a critical role in ensuring the reliable and safe operation of power systems. Proper coordination ensures that only the nearest protective device operates during a fault, minimizing disruption and equipment damage. With ETAP software, relay coordination studies can be performed effectively, enabling engineers to determine accurate relay settings and evaluate system performance under fault conditions.

The electrical network under study is divided into two main sections: high-voltage (HT) and low-voltage (LT) systems. At the LT level (0.415 kV), circuit breakers are typically equipped with in-built protection, known as release units, while in some cases additional external relays are used. In contrast, HT breakers rely entirely on external numerical relays for fault detection and isolation. LT protection is commonly based on L–S–I–G functions. Long-time (L) protection handles overload conditions by allowing a delay before tripping, preventing unnecessary interruptions during temporary overcurrent. Short-time (S) protection is designed for short-circuit faults and operates with a definite time delay to ensure coordination with downstream devices. Instantaneous (I) protection provides rapid tripping for severe faults with minimal or no delay. Ground fault (G) protection detects earth faults and typically operates with a controlled time delay for selective isolation.

IV. RELEASE SETTING CALCULATION

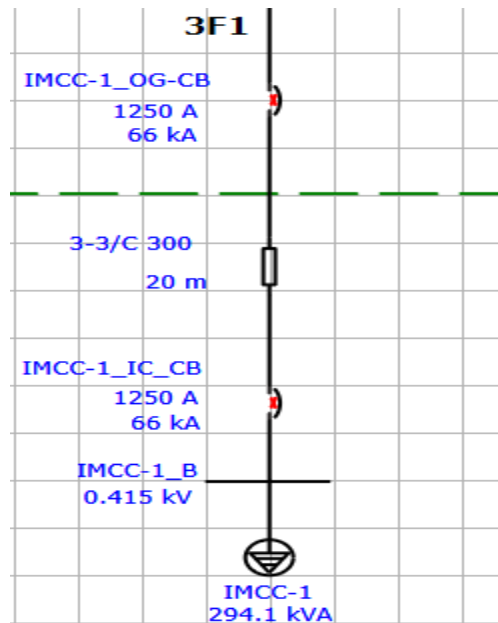


FIG-1 IMCC-1 FEEDER

1. Long-time Settings

$$I_r = 1.1 \text{ or } 1.2 \times \text{FLA} = 1.1 \times 409.2 = 450.12$$

$$= 450.12 / 1250 = 0.36 \sim 0.4$$

@6x I_r curve (Taking Reference from Release Manual)

$$I^2 t = K$$

For $t_r = 3$

$$6^2 \times (3) = K = 108$$

Now, $I^2 t = K = 108$

$$t = 108 / (1.1)^2 = 89.2 \text{ sec}$$

Here, for $t_r = 3$, $t = 89.2$ sec is between 80-100 sec, then the time setting for $t_r = 3$ and pick-up setting is $I_r = 1.1$

2. Short-term Setting:

$$\text{FLA} = 409.2 \text{ A}$$

$$409.2 \times 2 = 818.4$$

$$I_s = 818.4 / 1250 = 0.65 \sim 0.6$$

It is set to $0.6 I_n$

As per the defined time grading, in this case, it should be 200 msec.

3. Instantaneous setting:

As a time, delay is not available in this protection element; this protection should be kept OFF to avoid maloperations where an instantaneous setting is not required.

As per the requirements, either the short circuit setting or the instantaneous setting is used. Only one setting can be activated at a time. If both are activated simultaneously, the relay may malfunction.

Setting calculations

$$\text{FLA} = 409.2 \text{ A}$$

$$409.2 \times 10 = 4092$$

$$I_{st} = 4092 / 1250 = 3.2$$

I_{st} is set to $3.2 I_n$

0 sec. Trip Time

4. Ground element Setting:

$$I_g = 0.2-0.5 \times \text{FLA}$$

$$0.2 \times 409.2 = 81.84$$

$$I_g = 81.84/1250 = 0.065 \sim 0.1$$

Time tg: As per defined time grading, in this case, it should be 200 msec.

V. SETTING CALCULATION FOR TRANSFORMER FEEDER

TRANSFORMER DETAILS:

Rating	: 3.5 MVA
Voltage ratio	: 11/0.433 kV
FLA	: 183.7/4667 A
%Z	: 7.85%
CT Ratio	: 250/1

SECONDARY SIDE - IDMT Phase Over Current Protection (51)

Fault Current (I_f) at 0.415 kV bus : 20.44 Ka (Calculate by ETAP)

Pickup : $(1.1 \times \text{FLA}) / \text{CTR} = (1.1 \times 4667) / 6000 = 0.85$

Hence, adopted approx. setting : **0.85 x CT Sec (5100 Amps)**

Operating Characteristic : IEC Extremely Inv.

We have required minimum Time Dial set such as a relay will be operated as per time grading (0.6 sec) for fault in 433 V network.

Operating Characteristics for IEC Extremely inverse

$$T_{op} = \frac{80}{\left(\frac{I_{\text{fault}}}{I_s}\right)^2 - 1} \times \text{TMS}$$

$$\text{TMS} = \frac{\left(\frac{I_{\text{fault}}}{I_s}\right)^2 - 1}{80} \times T_{op} = \frac{\left(\frac{20.44}{5100}\right)^2 - 1}{80} \times 0.6 = 0.1$$

So, we adopt **TMS = 0.1**

DMT Phase Over Current Protection (50-1)

Pickup : 110% to 130% of DMT Protection stage pickup of the Downstream release

Time Delay : 0.60 seconds (As per required time grading)

Down Stream DMT stage pick up is 6.3kA so need to

Pickup : $(6300 \times 1.3)/6000 = 1.3$ (**8190 A**)

Time Delay : 0.60 seconds (As per required time grading)

Instantaneous Phase Over Current Protection (50-2)

When fault occurs near the load, 19 kA current flows, so set pick up according to this reference

Pickup : $(4.24 \times \text{FLA}) / \text{CTR}$

: $(4.24 \times 4667) / 6000 = 3.3 \times \text{CT Sec} =$ (**19800A**)

Time Delay : 0.05 seconds (As per required time grading)

Earth fault Protection:

The system at 11 kV is Solid Grounded, so Earth fault protection will be set at 20% of Transformer FLA

IDMT Earth Fault Protection (51G)

Pickup : (0.2 x Transformer FLA) / CT Ratio
 : (0.2 x 4667) / 6000 = 0.16 x CT Sec

Characteristics : IEC Very Inverse

TMS : 0.16 (According to L-G fault current 25.54 A)

DMT Earth Fault Protection (50G)

Pickup = Set 1.3 Times of Downstream Release Ground Pick-up current
 = (756 x 1.3)/6000 = select = 0.16 (996 A)
 = 0.6 Sec Time Grading

VI. RELAY COORDINATION STUDY RESULTS & DISCUSSION

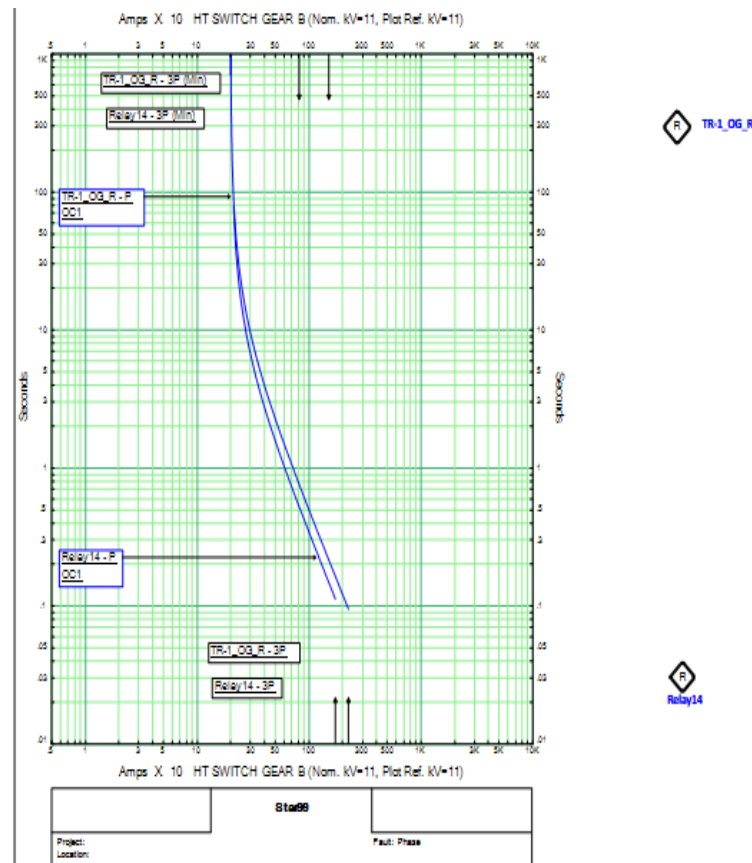


FIG.2 OC-51 TCC CURVE

TABLE I SEQUENCE OF OPERATION

ID	IF (kA)	TIME (ms)	T1 (ms)	CONDITION
IMCC-1_IC	19.148	220	180	Phase
IMCC-1_OG	19.148	220	180	Phase
BUS COUPLER	19.148	440	360	Phase
RELAY-14	19.148	630	600	Phase-OC1-50
TR-1_IC_CB1			30	Trip by Relay 14
TR-1_OG_R	0.763	840	800	Phase-OC1-50
TR-1_OG_CB			40	Trip by TR-1_OG_R
HT_SWGR_R	0.763	1322	1282	Phase-OC1-51
HT_SWGR_CB			40	Trip by HT_SWGR_R
ICOG_PNL_R	0.763	3914	3874	Phase-OC1-51
ICOG_PNL_CB			40	Trip by ICOG_PNL_R

The relay coordination was checked using TCC curves, and the results show clear separation between the relay characteristics. There is no overlapping observed, which confirms that the relays are properly coordinated. A sufficient time gap is maintained between downstream and upstream devices to ensure smooth operation.

During fault conditions, it is observed that the relay closest to the fault operates first, while the upstream relays respond with a delay and act as backup. This indicates that the sequence of operation is correct and faults are cleared selectively without affecting the healthy part of the system.

VII. ARC FLASH HAZARD ANALYSIS

Arc flash is a critical safety concern in industrial power systems, caused by electrical faults that release high thermal energy within a short duration. The severity of an arc flash event primarily depends on the available fault current and the fault clearing time, making protection system performance a key factor in determining system safety. In coordinated protection schemes, relay operating time directly influences the magnitude of incident energy. Faster fault clearance reduces arc flash hazards, while delayed operation increases the risk to equipment and personnel. Therefore, it is essential to evaluate arc flash behaviour in conjunction with relay coordination. In this study, an arc flash analysis is performed on a 27-bus industrial electrical network modelled using ETAP. The analysis utilizes fault current levels and relay operating times derived from the developed coordination scheme. The objective is to assess incident energy levels, determine arc flash boundaries, and identify critical locations within the network. The results of this study provide insight into the relationship between protection coordination and arc flash severity and support the development of safer and more reliable industrial power systems.

VIII. ARC FLASH STUDY METHODOLOGY

The arc flash analysis is carried out using ETAP based on the operating conditions of the 27-bus industrial network. The study utilizes fault current values obtained from short-circuit analysis and relay operating times derived from the coordination study. Key input parameters considered for the analysis include system voltage levels, available fault current, working distance, and protective device clearing time. The clearing time of protective devices plays a significant role in determining the severity of arc flash, as it directly affects the duration of the fault. The analysis is performed in accordance with standard industry practices, where arc flash parameters such as incident energy and arc flash boundary are calculated for different buses in the network. This approach enables evaluation of system safety under fault conditions and identification of high-risk locations.

IX. ARC FLASH STUDY PARAMETERS

Arc flash analysis involves the evaluation of key parameters that determine the severity of an arc fault and its impact on personnel and equipment.

Incident Energy (cal/cm²) represents the thermal energy released at a specific working distance from the arc source. It is the primary factor used to assess the level of hazard and to determine the required personal protective equipment (PPE).

Arc Flash Boundary (AFB) is defined as the distance from the arc source at which the incident energy reduces to a safe level. This boundary indicates the minimum distance at which a worker can be exposed without suffering serious injury.

Fault Clearing Time (FCT) is the total time required for the protective device to detect and clear the fault. It is one of the most critical parameters, as higher clearing time results in increased incident energy.

Working Distance refers to the typical distance between the worker and the energized equipment during operation or maintenance activities. This parameter is considered while calculating incident energy and evaluating safety conditions. These parameters collectively help in assessing arc flash hazards and identifying critical locations within the electrical network.

X. ARC FLASH STUDY RESULT & DISCUSSION

TABLE II ARC FLASH RESULT

ID	KV	FINAL FCT (sec)	TOTAL ENERGY (cal/cm ²)	WORKING DISTANCE (m)	AFB (sec)	ENERGY LEVEL
HTMC_PANEL_B	11	0.3	0.816	91.4	0.714	LEVEL 0
ICOG_PANEL_B	11	0.19	0.516	91.4	0.534	LEVEL 0
HT_SWG_B	11	0.13	0.352	91.4	0.418	LEVEL 0
MPDB-1_B	0.415	0.04	1.909	45.7	0.611	LEVEL 1
MPDB-2_B	0.415	0.22	6.521	45.7	1.318	LEVEL 2
LT_PCC_BUS-A	0.415	0.44	19.914	61	3.534	LEVEL 3
LT_PCC_BUS-B	0.415	0.63	28.514	61	4.424	LEVEL 4

The arc flash study indicates that the HT side panels, including the HTMC Panel, ICOG Panel, and HT Switchgear, have very low incident energy and are categorized under Level 0, reflecting minimal hazard. On the LT side, MPDB-1 and MPDB-2 fall within Level 1 and Level 2, indicating moderate risk levels where standard arc-rated PPE is sufficient. In contrast, LT PCC Bus-A and Bus-B show much higher incident energy, falling under Level 3 and Level 4, mainly due to longer fault-clearing times. These findings suggest that arc flash risk becomes more severe at downstream LT buses. Therefore, improving fault-clearing speed and implementing advanced protection measures are essential to reduce incident energy and enhance overall safety.

XI. RECOMMENDATION FOR ARC FLASH STUDY

PPE CLOTH: PPE selection should be based on the arc flash incident energy level to ensure personnel safety. For Level 0, basic non-melting clothing with standard safety equipment is sufficient. Level 1 and Level 2 require arc-rated clothing with face protection and essential protective gear. For Level 3, a complete arc flash suit with a hood is necessary to handle higher energy exposure. At Level 4, full-body arc-rated protection with insulated gloves and maximum coverage is required.

ARC FLASH REALY: For locations with **Level 3 and Level 4 arc flash energy**, such as LT PCC Bus-A and LT PCC Bus-B, implementation of **high-speed arc flash protection** is strongly recommended. Dedicated **arc flash relays** should be installed to detect and clear faults within milliseconds.

ERMS: The use of an Energy Reduction Maintenance Switch (ERMS) is an effective approach to reduce arc flash hazards by enabling faster fault clearing. During maintenance, an additional instantaneous stage can be applied to the LT PCC Bus-B upstream relay, set at approximately **1.67× CT secondary (≈10.8 kA)** with an operating time of **0.05 s**, coordinated with the downstream short-time pickup of **6300 A**. This significantly lowers incident energy levels. However, such fast tripping may lead to unwanted plant interruptions during normal operation. Therefore, ERMS and instantaneous settings should be used only during maintenance, while proper PPE and dedicated arc flash relays remain The preferred and more reliable solution for regular operation.

XII. CONCLUSION

This study presents a comprehensive analysis of relay coordination and arc flash hazard assessment for a 27-bus industrial electrical network using ETAP. The results obtained from load flow and short-circuit analysis indicate that the system operates under weak grid conditions due to the presence of a long incoming feeder, resulting in reduced voltage levels and lower fault currents at the high-voltage side.

Based on these conditions, relay settings were calculated using both definite minimum time (DMT) and inverse definite minimum time (IDMT) characteristics for phase and earth fault protection. The coordination study, verified through time-current characteristic (TCC) curves, confirms that proper time grading is achieved between downstream and upstream protective devices. This ensures that faults are cleared selectively by the nearest device, while upstream relays operate as backup with appropriate delay.

The analysis also highlights the impact of transformer configuration on fault current distribution, where limited transfer of zero-sequence current to the high-voltage side makes relay coordination more sensitive. Proper selection of pickup values and time delays is therefore essential to maintain coordination without compromising system protection.

Furthermore, the arc flash analysis demonstrates that fault clearing time plays a critical role in determining incident energy levels. Faster operation of protective devices significantly reduces arc flash hazards, thereby improving personnel safety and equipment protection. The study identifies critical locations within the network where higher incident energy levels require attention and appropriate safety measures.

Overall, the integrated approach of relay coordination and arc flash analysis improves system reliability, selectivity, and safety. The results emphasize that optimized protection settings not only ensure effective fault isolation but also contribute to minimizing arc flash risks in industrial power systems

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