THESIS - EE185401

THE COORDINATION OF DUAL SETTING DIRECTIONAL OVERCURRENT RELAY IN PT. PUPUK SRIWIDJAJA RING SYSTEM USING ADAPTIVE MODIFIED FIREFLY ALGORITHM

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2020

APPROVAL SHEET

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STATEMENT OF THESIS ORIGINALITY

I hereby declare that the entire content of my Thesis entitled "**THE COORDINATION OF DUAL SETTING DIRECTIONAL OVERCURRENT RELAY IN PT. PUPUK SRIWIDJAJA RING SYSTEM USING ADAPTIVE MODIFIED FIREFLY ALGORITHM**" is truly the attainment of independent intellectuals, completed without the use of unauthorized materials, and not the work of others that I claim as my own.

All references cited or referred have been fully written in the bibliography. If this statement is not true, I am willing to accept sanctions in accordance with applicable regulations.

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THE COORDINATION OF DUAL SETTING DIRECTIONAL OVERCURRENT RELAY IN PT. PUPUK SRIWIDJAJA RING SYSTEM USING ADAPTIVE MODIFIED FIREFLY ALGORITHM

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ABSTRACT

Directional Overcurrent Relays (DOCRs) play an essential role in the power system protection to guarantee the reliability, speed of relay operation and avoiding mal-trip in the primary and backup relays when unintentional fault conditions occur in the system. Moreover, the dual setting protection scheme is more efficient protection schemes for offering fast response protection and providing flexibility in the coordination of relay.

The Adaptive Modified Firefly Algorithm (AMFA) is used to determine the optimal coordination of dual setting DOCRs in the ring distribution system. The AMFA is completed by choosing the minimum value of the pickup current (I_p) and time dial setting (TDS). On the other hand, dual setting DOCRs protection scheme also proposed for operating in both forward and reverse directions that consisted of individual time current characteristics (TCC) curve for each direction.

The AMFA method is applied to the ring distribution system network of PT. Pupuk Sriwidjaja by considering the fault on each bus. Then, the result is illustrated that the AMFA within dual setting protection scheme is significantly reaching the optimized coordination and the relay coordination is certain for all simulation scenarios with the minimum value of the total operating time (TOP). The CTI of each pairs relay is no less than 0.2s. Also, the comparison of converges iteration shown that the AMFA method is faster than the original FA method. The AMFA has been successfully implemented in MATLAB 2018b software and the relay coordination can be verified by using ETAP 12.6.0.

Keywords: (Directional Overcurrent Relay, Dual Setting Protection Scheme, Time Dial Setting, Pickup Current, Adaptive Modified Firefly Algorithm)

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KOORDINASI RELE ARUS LEBIH TERARAH UNTUK SISTEM RING PT. PUPUK SRIWIDJAJA MENGGUNAKAN ADAPTIVE MODIFIED FIREFLY ALGORITHM

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ABSTRAK

Directional Overcurrent Relays (DOCRs) memainkan peran penting dalam perlindungan sistem tenaga untuk menjamin keandalan, kecepatan operasi rele dan menghindari mal-trip pada rele primer dan cadangan saat kondisi gangguan yang tidak disengaja terjadi dalam system. Selain itu, skema perlindungan pengaturan ganda adalah skema perlindungan yang lebih efisien untuk menawarkan perlindungan respons cepat dan memberikan fleksibilitas dalam koordinasi rele.

Algoritma Adaptive Modified Firefly (AMFA) digunakan untuk menentukan koordinasi optimal DOCRs dalam sistem distribusi cincin. AMFA diselesaikan dengan memilih nilai minimum Pickup Current (I_p) dan Time Dial Setting (TDS). Di sisi lain, skema perlindungan DOCR juga diusulkan untuk beroperasi di arah maju dan mundur yang terdiri dari kurva individu Time Current Characteristics (TCC) untuk setiap arah.

Metode AMFA diterapkan pada jaringan sistem distribusi cincin PT. Pupuk Sriwidjaja dengan mempertimbangkan kesalahan pada setiap bus. Kemudian, hasilnya diilustrasikan bahwa AMFA dalam skema perlindungan pengaturan ganda secara signifikan mencapai koordinasi optimal dan koordinasi rele pasti untuk semua skenario simulasi dengan nilai minimum Total Operating Time (*TOP*). *CTI* dari masing-masing pasangan relay tidak kurang dari 0,2s. Juga, perbandingan iterasi konvergen menunjukkan bahwa metode AMFA lebih cepat daripada metode FA asli. AMFA telah berhasil diimplementasikan dalam perangkat lunak MATLAB 2018b dan koordinasi rele dapat diverifikasi dengan menggunakan ETAP 12.6.0.

Kata kunci: (Directional Overcurrent Relay, Dual Setting Protection Scheme, Time Dial Setting, Pickup Current, Adaptive Modified Firefly Algorithm)

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PREFACE

This thesis represents the clue of optimal coordination of dual setting directional overcurrent relay in the ring distribution system by using the adaptive modified firefly algorithm (AMFA). This is a very interesting topic for nowadays research in the field of Smart Grid. In my thesis research, I hope it will help other researchers to solve the problem in optimal relay protection coordination

The AMFA is one of the most command Nature-Inspire Algorithm that modified from the original firefly algorithm (FA). It can deal with a multi-objective function optimization problem and fast to converge than another algorithm. The objective of this thesis research is to define the optimum value of the time dial setting (*TDS*) to minimize the total operating time of directional overcurrent relays (DOCR). Then, the selection of the IEC TCC curves to guarantee the relay protection coordination is presented.

I would like first to say thank you to my supervisors **Dr. Ir. Margo Pujiantara, MT** and **Dr. Eng. Ardyono Priyadi, ST., M.Eng** for their excellent guidance, invaluable technical advice, brilliance idea, encouragement and support during my research study. Without his advice, this thesis could not complete on time and has a high quality of research.

I would like to express my deepest appreciation to my family. Especially, my parents who give my birth and always support me the finance to study, guidance, the best advice, motivation and confidence in me. Without both of them, I could not have today.

A very special thank you to and sincere appreciation to **KNB scholarship**, **Institut Teknologi Sepuluh Nopember (ITS)** and **ITS Global Engagement** for continuously offering financial support during my master's degree.

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Surabaya, 1 July 2020

Kimhok Chheng

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CHAPTER 1

INTRODUCTION

1.1 Background

Protection coordination plays a significant role in power systems design to ensure the relay can distinguish abnormal or undesirable conditions and then sends a signal to the circuit breaker to disconnect that part from the remaining operating system. The protection is naturally achieved by coordinating relay settings based on load flow and short-circuit analysis. A properly coordinated protection system can cope with interference quickly, precisely and efficiently to protect the system performance.

The protection system equipment is commonly overcurrent relay, overcurrent relay is divided into 2 types based on the operating time, namely inverse time overcurrent relay (ANSI 51 code) and instantaneous or definite relay (ANSI 50 code). Inverse time overcurrent relays are used to protect the system from overloaded equipment with a long duration of time, while instantaneous or definite relays are used to secure short circuit fault currents with a short duration of time.

In the protection system, a primary relay is not enough to localize an interruption, so a backup relay is needed if the main relay fails to secure a source of interference. Therefore, we need coordination between relays to avoid protection failure. In the determination of coordination between relays, several parameters must be considered such as the type of time current characteristic curve of each relay, pickup current (I_P), time dial setting (*TDS*), and coordination time interval (*CTI*). The *TDS* parameter can be found with a certain value to get optimal coordination. In practice, the *TDS* value is determined through manual calculations to get the minimum *TDS* value, then the shifting of the TCC curve in coordination with other relays to get the *CTI* value is appropriate. But the problem is that it takes time and impractical. Therefore, the Adaptive Modified Firefly Algorithm method is used to get optimal values of *TDS*, to get a minimum operating time, and without coordination errors.

Adaptive Modified Firefly Algorithm (AMFA) is one of the Nature-Inspire Algorithm that modified from the original Firefly Algorithm. The AMFA can deal with multi-objective function optimization problems more naturally and efficiently. Actually, as in [1] is demonstrated that the firefly algorithm is much more efficient in finding global optima as well as all the local optima simultaneously in a very effective manner. Furthermore, AMFA is close to the optimum value and fast convergence than another metaheuristic algorithm such as particle swarm optimization (PSO), and genetic algorithm (GA) [1]–[3].

PT Pupuk Sriwidjaja is a large industry in the field of urea fertilizer produce in Indonesia. Therefore, PT Pupuk Sriwidjaja has required continuity of power supply to support the production. When a disturbance occurs in the system, the power supply will be cut off which caused the products to become discard or damage. Therefore, the company will be stuck and lost a lot of benefits.

PT Pupuk Sriwidjaja is needing to expand the system by adding the load P2B and distributed generator STG-1. In expansion, several conditions will be met. First, each load must have at least two sources from the old and new expansion generator. Second, the expansion factory has its generator STG-1, when one of the generators in the old factory is cut off, it will disturb the stability of the old factory system. So, the old factory required supply from the distributed generator STG-1. These conditions resulting in the establishment of a ring system with a protection system based on dual setting DOCR. Because of that reason, it is a problem to determine the relay settings in the ring distribution system because it is difficult to calculate manually. Consequently, this proposed research will be discussing the protection coordination in the ring system by proposing the new method to optimize the total operating time of dual setting DOCRs and applying the dual setting protection coordination scheme.

1.2 Problem Formulation

The main problem that needs to solve in this research study is presented in the following:

- The optimum value of the *TDS* relay parameter in the ring distribution system using AMFA when the fault located on each bus.
- Selecting the best inverse time current characteristic curve that consists of the minimum value of overall total operating time.
- Applying the obtained result of *TDS* from the applied method in PT Pupuk Sriwidjaja ring system using ETAP 12.6.0 to verify the protection coordination.

1.3 Objectives

The main objective of this research is to find out the optimum value of the time dial setting to minimize the total operating time of directional overcurrent relays in the real electrical system of PT Pupuk Sriwidjaja ring system by using Adaptive Modified Firefly Algorithm (AMFA) and applied the novel protection coordination scheme base on dual setting DOCRs. Then, the selection of the best IEC TCC curve for ensuring protection coordination is presented.

1.4 Scope

The scope of this proposal is descript as follows:

- The optimal coordination of DOCRs and dual setting protection coordination schemes perform in the PT Pupuk Sriwidjaja ring system in level voltage 13.8kV.
- The AMFA is implemented in MATLAB 2018b software programming to determine the optimum value of the *TDS* of each DOCRs.
- The protection coordination scheme is based on dual setting DOCRs.
- The protection coordination problem is solved by considering the three-phase short circuit current of 0.5 cycles that occur on each bus of the ring distribution system.

- The protection coordination is used relays 51 and 67.
- Selecting one of the best time current characteristic (TCC) curves that suitable for protection coordination.
- The optimum results that got from AMFA will validate in ETAP 12.6.0 of the ring distribution system with dual setting DOCRs.

1.5 Contribution

Due to the rising of the research article, many approaches have been proposed on the protection coordination of DOCRs in the looped and ring distribution system network. Nevertheless, no article proposed to determine the optimal coordination of dual setting DOCRs in the ring distribution system by using the Adaptive Modified Firefly Algorithm (AMFA) when the fault is located on the bus of the system. The novel method is applied in the real plan of PT Pupuk Sriwidjaja ring distribution system to minimize the total operating time of the DOCRs. To achieve the minimum total operating time of DOCRs, two parameters needed to define the minimum value. Those parameters are pickup current (I_P) and time dial setting (*TDS*).

1.6 Research Methodology

To succeed in this research. There are nine steps of the research methodology as the description in the following:

1. The Deeply Understand about Literature Review and The Proposed Objective Function

It is the initial process for collecting references such as journal articles, paper and other documents that discussion related to the ring distribution system and be able to apply in this case study. After collecting the most interesting references, trying to understand deeply about those references and conducted the contribution and the objective function of the research topic. Those references are related to overcurrent relay protection coordination, dual setting protection scheme, inverse time current characteristic of DOCRs, the instruction manual of the relay, firefly algorithm, and adaptive modified firefly algorithm.

2. Data Collection

It is a step for collecting the data related to the distribution system of PT Pupuk Sriwidjaja ring distribution system. Those data are single line diagrams of the electrical of PT Pupuk Sriwidjaja and other electrical equipment such as distributed generators, transformer parameters, bus level, cable data, relay manufacturer, nominal current and load data.

3. Simulation of PT Pupuk Sriwidjaja Ring Distribution System in ETAP 12.6.0 Software

In this step, the simulation of the electrical of PT. Pupuk Sriwidjaja ring distribution system is using ETAP 12.6.0 software by applying the data collected from the previous step 2. After that, it is assumed that the three-phase short circuit current occurs on each bus of the ring distribution system.

4. Calculation of Three Phase Short Circuit Current in ETAP 12.6.0 for All Fault Location

It is assuming that all three-phase short circuit is located on every bus of the ring distribution system. From the simulation in ETAP, the value of the short circuit current on each bus is determined for all fault location.

5. Adaptive Modified Firefly Algorithm (AMFA)

The AMFA is used for finding the optimal value of the total operating time of DOCRs. To optimize the value of total operating time, the value of the time dial setting (TDS) and pickup current (I_P) are needed to determine by using AMFA with the input data of nominal current, short circuit current, and primary and backup relay pair. On the other hand, AMFA is needed to set the initial value of TDS and I_P for the first optimization. Moreover, the result from AMFA has to follow some of the coordination criteria (relay operating time, time dial and pickup current setting, and coordination time interval). Besides, if the optimum value of TDS and I_P from AMFA have a large error so the algorithm will redefine the new optimal value with the small error and following the constraint. Furthermore, it also analyzes the number of iterations and algorithm convergence. The AMFA method is carried out in MATLAB R2018b software programming.

6. Applying Dual Setting DOCRs Protection Coordination Scheme

The result of each relay that optimized from applying AMFA in MATLAB 2018b is contained in two pairs of setting for the forward and reverse direction. Those two different pairs of the setting are TDS_{fw} and $I_{P_{fw}}$ for primary protection (the forward direction) and another pair is TDS_{rev} and $I_{P_{rev}}$ for backup protection (the reverse direction). So, those results are inputted in all relay to verify the relay protection coordination scheme.

7. The Comparison Result of Each Time Current Characteristic Curve

The proposed research is applied to 4 different curves of time current characteristic. The result of applying AMFA in each curve is needed to compare for selecting the best time current characteristic curve with the minimum value of the total operating time and satisfy the relay protection coordination.

8. Analyzing the Result and Discussion for All Case Study

It is the step to analyze the results after selecting the best IEC TCC curve that suitable for protection coordination. The result of all case studies can be analyzed base on the CTI value, operating time of each DOCRs, total operating time of each type IEC TCC curve, and the updating value of the randomization parameter α. Then, the optimal result will be applied in ETAP 12.6.0 to guarantee the relay protection coordination.

9. Making the Conclusion

Draw a conclusion based on the analysis of the result after implemented in ETAP 12.6.0. It is accompanied by advice and recommendations on the coordination protection of the ring system.

CHAPTER 2
LITERATURE REVIEW

The distribution system network will modify from the radial nature toward a looped or meshed structure according to the rising penetration of DG. It's caused a bidirectional power flow and increases the short circuit levels. Normally, the addition of DG has different impacts on distribution systems and the protection system. The impact of DG integration on the protection scheme depends on the type of DG as well as the nature of the distribution system. To protect the various parts of the power system and the whole system, protective relaying is necessary.

In the looped and ring system networks consist of bidirectional flow of current that DOCRs are preferred for their protection. There are two important parameters of DOCRs protection settings, namely pickup current (I_P) and time dial settings (*TDS*) that are determined using analytical methods or optimization techniques for effective coordination between primary and backup relays.

The rest of this chapter is organized as follows: Subsection 2.1 is introduced about the related research study. Subsection 2.2 is explained about the basic theory of optimal and protection coordination of DOCRs.

2.1 Related Research Study

In the last few years, several solution techniques are proposed to solve the coordination problem by minimizing the operating time of DOCRs following a set of coordination constraints. In the references [4]–[8] are presented a communication assisted dual-setting relay protection scheme for a microgrid with grid-connected and islanded capacity is proposed instead of the conventional inverse time current characteristics for optimal determine to minimize the overall operation time for the primary and backup operation. As a result, the protection coordination with dual-setting relay reaches the optimal value of the total directional overcurrent relays operating time.

However, another complex nonlinear optimization problem has been solved by using a variant of evolutionary optimization techniques name Firefly

Algorithm (FA). In addition, the optimal coordination of inverse definite minimum time (IDMT) directional overcurrent relays in the meshed distribution system is definite by considering the impact of the transmission line series compensation (SC) [9], [10]. Destina S. Lesstari et al [11] are proposed Firefly Algorithm (FA) and Artificial Neural Network (ANN) are used to obtain the optimal coordination on a modified IEEE 9 bus loop system with the addition of distributed generation (DG). Optimization using the firefly Algorithm will get the value of time Dial setting (*TDS*), Pickup current (I_P) and a total of the fastest operation time. The *TDS* and I_P values of FA optimization results are used as ANN training target data. Finally, the result of both methods shown that the FA-ANN is a suitable method to model the adaptive and optimal relay coordination system.

The coordination of directional overcurrent relays (DOCRs) problem has been solved in [12] using an adaptive directional overcurrent relay (ADOCR) of the meshed distribution system. the two-phase approach has been proposed to determine the optimal relay setting as follows (i) optimal current setting by using the adaptive fuzzy current setting module (ACSM) and (ii) optimal time setting is using an Optimization Algorithms (OA).

Optimization techniques [13] are successfully applied for the optimization of the DOCR coordination problem. This article applies Chaotic Firefly with a tent map algorithm (CFA) method to get the minimum overcurrent relays time operation using the inverse time current characteristic. This method verified in IEEE 9 bus with two distributed generations. The result of this method is faster than the firefly Algorithm method (FA).

Another nature inspire algorithm method is Cuckoo-Linear Optimization Algorithm and Linear Programming have been proposed to optimize the coordination protection of DOCRs in microgrid (Grid connected and island mode) and find the optimum value of Fault Current Limiter (FCL) at the Point of Common Coupling (PCC) [14],[15]. The proposed algorithm is utilized in the IEEE 14 bus network and compared with Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). The computational efficiency of the proposed COA-LP is better than PSO and GA in terms of speed and total operating time of DOCRs. Moreover, the setting of TCC of overcurrent relay in the real system application is obtained using serial computing Modified Particle Swarm optimization in [16].

In [3], [17] and [18], the authors have proposed the method for improving the firefly algorithm and optimize coordination of OCRs in power system protection when DG is presented in the radial or loop distribution system. The optimum value of PS and TMS from the AMFA will cause the total operating time of OCR protection coordination is minimum also. From the comparison between AMFA and FA, the result demonstrates that the proposed AMFA can achieve the optimized coordination of OCRs in all test cases. In this study, AMFA has a better performance by achieving more convergence and obtaining a faster of coordinated relay operating time value. Therefore, in this final project will use AMFA to calculate the value of the *TDS* relay protection system of PT Pupuk Sriwidjaja ring system.

2.2 Basic Theory

Protection coordination of relay is becoming more efficient in the ring distribution system. Moreover, a protection coordination scheme is also vital to operating as a primary and backup relay on the system. Therefore, the directional overcurrent relay is described in subsection 2.2.1. The inverse-time characteristic of dual-setting DOCRs is shown in subsection 2.2.2. In the subsection 2.2.3 is presented about dual setting versus conventional DOCRs. Then, the type of short circuit current is explained in subsection 2.2.4. The formulation problem in optimized DOCRs coordination descript in subsection 2.2.5. For the last subsection 2.2.6 is express about the adaptive modified firefly algorithm (AMFA).

2.2.1 Directional Overcurrent Relay (Device 67)

2.2.1.1 Application of Directional Overcurrent Relay in Power System Protection

Directional overcurrent relay is a protective device that used to provide sensitive tripping of fault current in one direction. There are many typical applications of this relay as described in following [19]:

- Protection of the distribution line but not for the radial distribution line as in Figure 2.1.
- Detection of uncleared faults on the unity line where fault current can be back through from the second unity line.
- Sensitive high-speed ground fault protection of transformers and generators.
- Applied in parallel transformers with a closed secondary bus tie circuit breaker by the article of the NEC.
- In other applications to distinguish the direction of current flow.

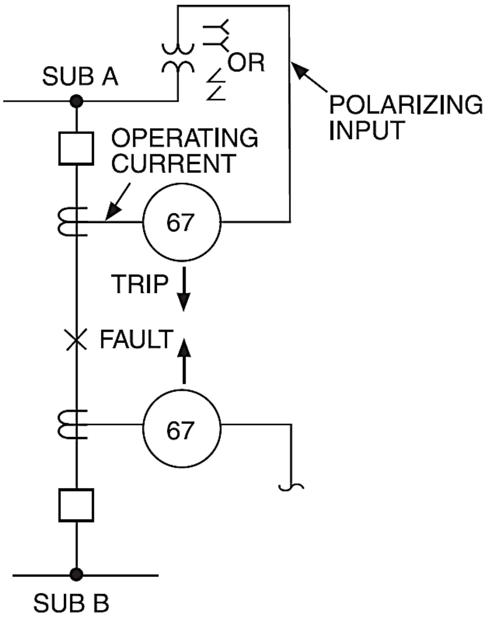


Figure 2.1 Line Protection Using Directional Overcurrent Relay [19]

2.2.1.2 Operation Principle of Directional Overcurrent Relay

Directional overcurrent relay contains two functions. The first function is overcurrent function and another one is the directional function. The directional function can control the operation of the overcurrent function and define the direction of its operation by using the input from polarizing. The polarizing input of directional overcurrent relay can be performed of current or voltage or both. The electromechanical induction disk element and an instantaneous directional power element of directional overcurrent relay are depicted in Figure 2.2 [19]. It is established that the directional overcurrent function will enable the overcurrent function to operate when presented of flowing current in tripping direction (forward direction) and the current is higher than its tap setting. In contrast, the directional function will be desirable the overcurrent function and prevented the operation when the fault current has flowed in the reverse direction.

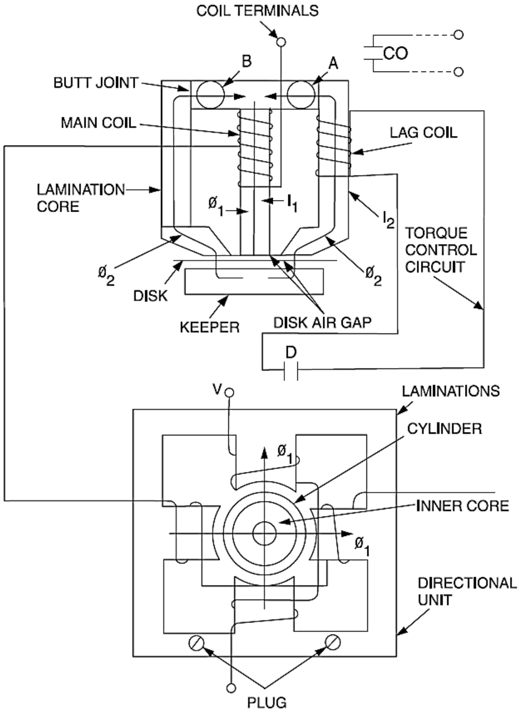


Figure 2.2 Directional Overcurrent Relay [19]

The directional element consisted of an operating current coil and a polarizing coil. The characteristic of a directional element is presented in Figure 2.3. The directional element can be tripped the system when the fault occurred by produced the maximum positive torque. The maximum positive torque has happened when the angle between the operating coil current and the polarizing coil quantity is equal to the maximum torque angles of the relay. However, the operation of the directional instantaneous overcurrent element is controlled by the directional element for using in the time overcurrent element [19].

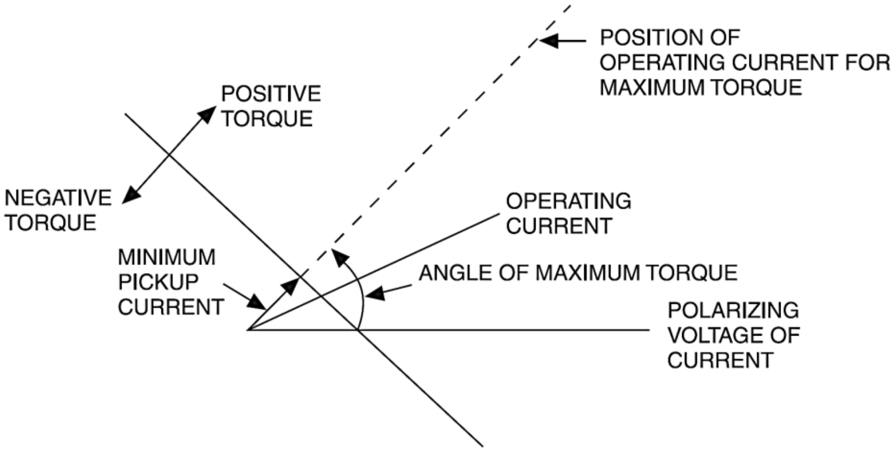


Figure 2.3 The Characteristic of a Directional Element [19]

2.2.2 Inverse Time Current Characteristic of Dual Setting DOCRs

Dual setting directional overcurrent relay can operate in forward and reverse direction when the fault appears in the system. The operating time DOCRs is calculated from the inverse function of the short circuit current crossing through it. From the literature review, the operating time of the DOCRs is formulated as a linear programming problem when the pickup current setting is predefined. One more thing, it can be in the form of a nonlinear programming problem when the time dial and pickup current setting to be a continuous variable. But also, the operating time of DOCR allows to formulating as a mixed-integer nonlinear programming problem by considering the pickup current setting to be a discrete variable. Generally, the DOCRs time-current characteristic can be formulated in (2.1) as follow [4].

$$t_{ij} = TDS_i * \frac{A}{\left(\left(\frac{I_{SC_{ij}}}{I_{p_i}}\right)^B - 1\right) * \beta} \tag{2.1}$$

$$TAP = \frac{I_{P_i}}{CT_{pri}} \tag{2.2}$$

Where

i : is the relay identifier.

j : is the fault location identifier.

t_{ij} : is the tripping time (in seconds) of relay i for a fault at location j.

$t_{SC_{ij}}$: is the short circuit current measure at the secondary winding of the current transformer of relay i for a fault at location j.

I_{P_i} : is the pickup current of the relay i.

TDS_i : is the time dial setting of relay i.

CT_{pri} : is the primary current of the current transformer

TAP : is the pickup setting of directional overcurrent relay

According to the International Electrotechnical Commission (IEC) standard inverse time overcurrent relay characteristic, there are four types of inverse time current characteristic curve. Those curves are Normal Inverse, Very Inverse, Long Time Inverse, and Extremely Inverse as illustrated in Figure 2.4. The constant A, B, and β are based on the IEC standard inverse curve and the instruction manual of the relay Eaton EDR-5000 as an expression in Table 2.1.

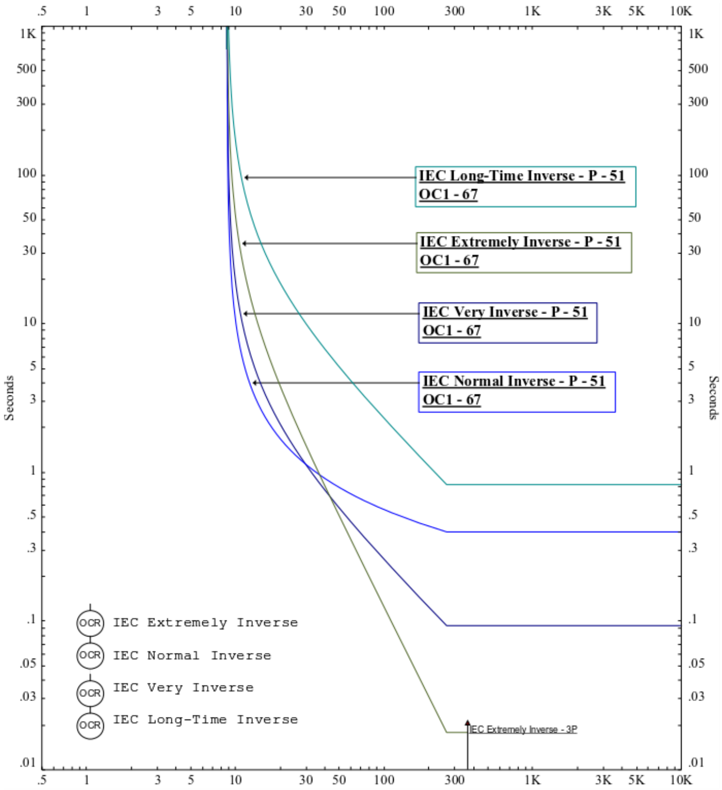


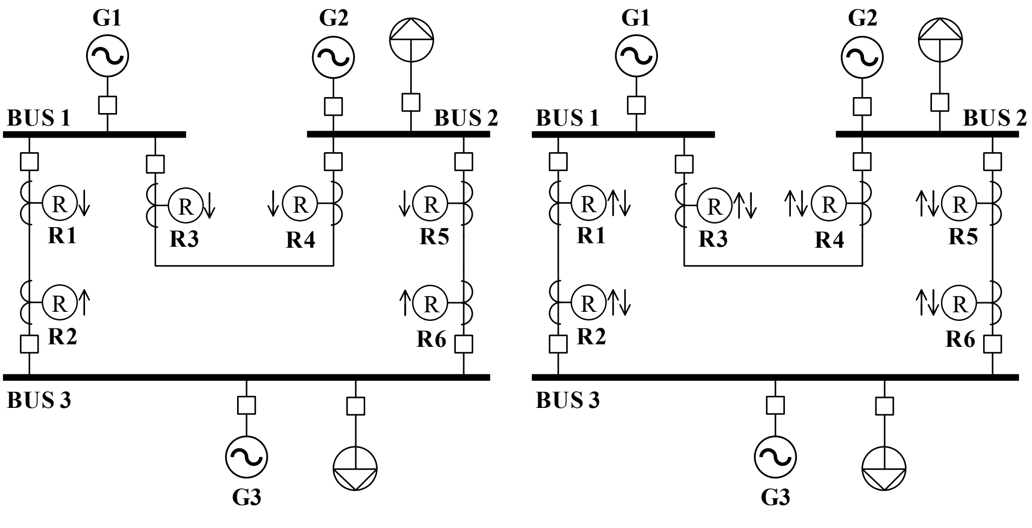
Figure 2.4 IEC Inverse Time Current Characteristic Curve

Table 2.1 Coefficient Value of IEC Inverse Time Current Characteristic Curve

IEC Time Current Characteristic Curve	**Coefficient Value**		
	A	**B**	β
IEC Normal Inverse	014	0.12	1
IEC Very Inverse	13.5	1	1
IEC Long Time Inverse	120	1	1
IEC Extremely Inverse	80	2	1

2.2.3 Dual Setting DOCRs Versus Conventional DOCRs

In the ring distribution system, directional overcurrent relay is become an interesting device according to the bidirectionality of fault current. Especially, each dual setting directional overcurrent relays device can be used with different settings for forward and reverse direction. The main benefit of dual setting DOCRs is that a single relay can perform in both directions of relays. Therefore, each DOCRs is consist of two pair of setting for both possible directions: two values of time dial setting (*TDS*) and two pickup current (I_P) setting [6], [7].



(a) (b)

Figure 2.5 The Protection Coordination Scheme of Dual Setting and Conventional, (a) Conventional Protection Scheme and (b) Dual Setting Protection Scheme

To understand the protection coordination scheme between conventional and dual setting DOCRs, an example is established to explain as in Figure 2.5.

Otherwise, Figure 2.5 (a) is presented about the three-bus ring distribution system with six DOCRs that considering in the conventional protection scheme. In the conventional scheme case, all relays in this system are operated only in one direction. The time current characteristics curve of the conventional DOCRs will be established in Figure 2.6.

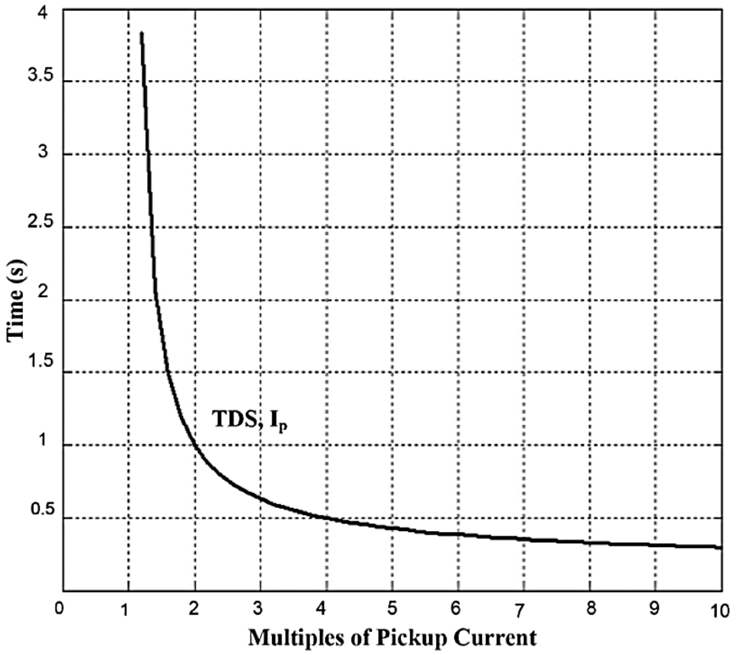


Figure 2.6 Time Current Characteristic of Conventional DOCR [8]

Additionally, If the short circuit appears at BUS 1, relay R2 will be the act as the primary relay and R5 will be the backup relay if the relay R2 fails to operate. In the same case of a fault, the relay R4 is a primary relay and the relay R6 act as a backup relay when the relay R4 fails to operate. When all fault location is applied to each bus of the ring distribution system, the conventional protection coordination scheme is offered in Table 2.2.

Figure 2.5 (b) shown about dual setting protection coordination scheme in the ring distribution system which consisted of the time current characteristic curve as shown in Figure 2.7. For the fault location BUS1, the relay R1 will operate as the primary protection in case the direction of fault current in the forward direction and the relay R2 is operate as the backup protection for a fault current flowing in the reverse direction. Each relay contained two pairs of setting to represent the primary (TDS_{fw}, $I_{P_{fw}}$) and backup (TDS_{rv}, $I_{P_{rv}}$) protection operation. The protection coordination scheme of the dual setting relay is shown in Table 2.2.

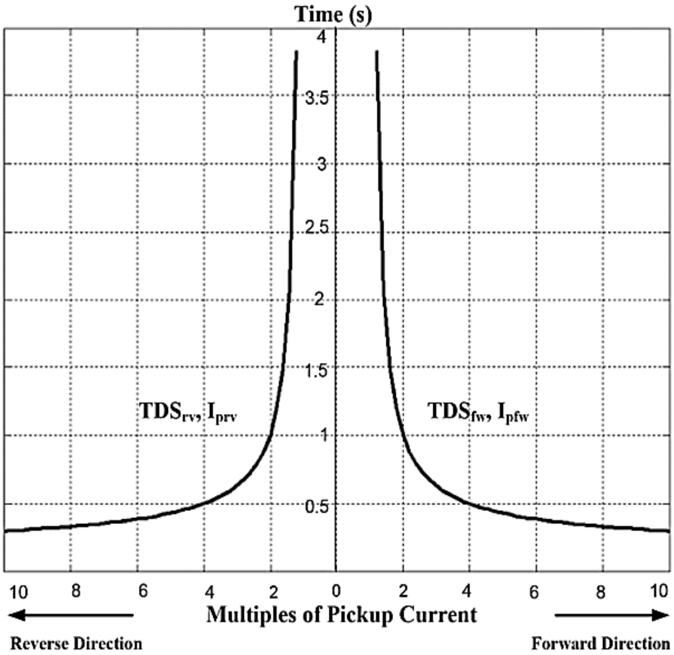


Figure 2.7 Time Current Characteristic of Dual Setting DOCR [8]

Table 2.2 Protection Coordination Scheme of the Primary and Backup Relay Pair Base on Conventional and Dual Setting DOCRs for Three Bus System

Primary Protection Relay	**Backup Relay Base on Conventional DOCRs**	**Backup Relay Base on Dual Setting DOCRs Scheme**
R1	R4	R2
R2	R5	R1
R3	R2	R4
R4	R6	R3
R5	R3	R6
R6	R1	R5

From the example of the conventional and dual setting DOCR protection scheme. the weakness of the conventional DOCRs is that each relay operated only in one direction and the operating time of each relay is long which causes the problem of damage to the equipment in the system. For this reason, the proposed dual setting DOCRs is benefited from the flexibility and capability of the available dual setting directional relay.to reduce the total operating time of the relays.

2.2.4 Short Circuit Current

The power system will massive destruction when the short circuit current happened. The magnitude of the short circuit current is greater than the load current. The high magnitude of the short circuit current can be affected by the normal operation of the system. Additional heating on the conductor is caused by the high magnitude of short circuit current. It can cause various problems such as mechanical forces on the conductor, breaking of the insulator, distort transformer winding and other physical damage. The flowing of the high magnitude of short circuit current along the system impedance can be caused by low voltages and forced the equipment to shut down [19].

2.2.4.1 The Nature of Short Circuit Current

Power system protection almost always requires protection against short-circuits wherever there is an electrical discontinuity. The short circuit current must be calculated at each bus in the system in view of determining the characteristics of the equipment required to resist or break the fault current. In normal conditions, the equivalence circuit of the system impedance is depicted in Figure 2.8. Z_S , Z_c and Z_l are the impedance of the source, circuit and the load, respectively. It can be used to determine the load current and the flow of current along with those three impedances. A short circuit can be considered as a conductor that shorts form an impedance to other impedance. So, Figure 2.9 is shown the equivalence circuit of system impedance when the short circuit happened. It is shown that Z_S and Z_c are became an impedance that restrict the flow of current. Then, the calculation of the short circuit current will be defined form the voltage sources and both impedances [19], [20].

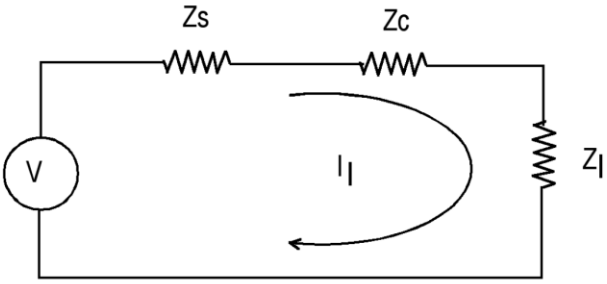


Figure 2.8 Equivalent Circuit of Impedances in a Normal Condition [19]

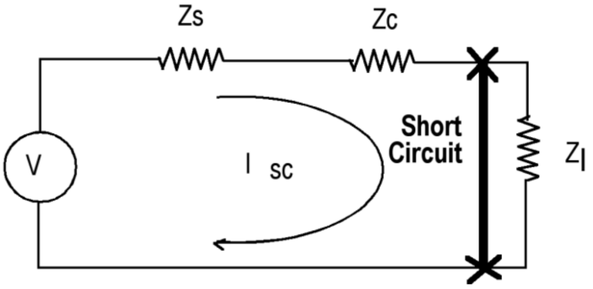


Figure 2.9 Equivalent Circuit of Impedance when a Short Circuit Happened [19]

For example, Figure 2.10 is showed a short circuit happens in the simplified system after the switch is off. The current of the source (I_S) will flow forward along the line after the switch is off. Then, it is assumed the fault occurs between the node A and B. The short circuit current (I_{SC}) is developed under the transient condition depending on the reactance X and the resistance R. Therefore, the impedance of the short circuit current is Z_{SC} expressed in (2.3).

$$Z_{SC} = \sqrt{R^2 + X^2} \tag{2.3}$$

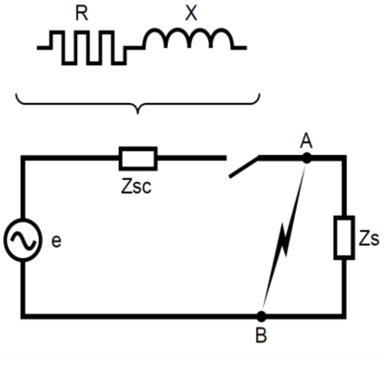


Figure 2.10 The Short Circuit Current Happen in Simplified System Network [20]

The primary characteristics of short circuit current are:

- Duration (self-extinguishing, transient and steady-state)
- Origin:
    - Mechanical (break in a conductor, accidental electrical contact between two conductors via a foreign conducting body such as a tool or an animal).
    - Internal or atmospheric overvoltage.
    - Insulation breakdown due to heat, humidity or a corrosive environment
- Location (inside or outside a machine or an electrical switchboard).

2.2.4.2 Types of Short Circuit Current

The value of the short circuit current (I_{SC}) can be calculated depending on the different types of short circuit happening. There are four main types of short circuit current [20]:

- Three Phase Short Circuit

The three phases short circuit is involved in all three phases (5% of initial faults). The direction of the current when three short circuits happen is shown in Figure 2.11 and the impedances of the power sources and the lines presented in Figure 2.12. The calculation of short circuit current I_{SC_3} is defined in (2.4).

$$I_{SC_3} = \frac{U}{\sqrt{3} * Z_{SC}} \tag{2.4}$$

Where

U : is the phase to phase voltage corresponds to the transformer no-load voltage which is 3 to 5 % greater than the no-load voltage across the terminal.

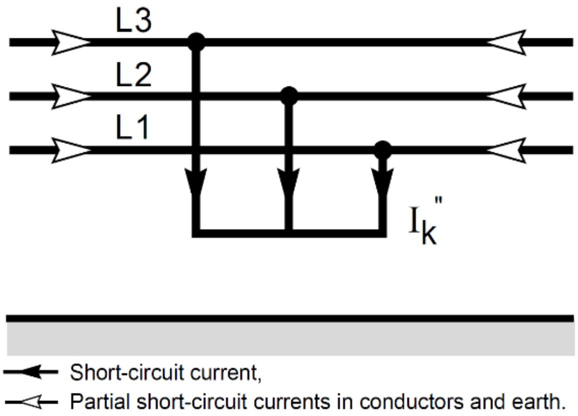


Figure 2.11 The Direction of Current in Three Phase Short Circuit [20]

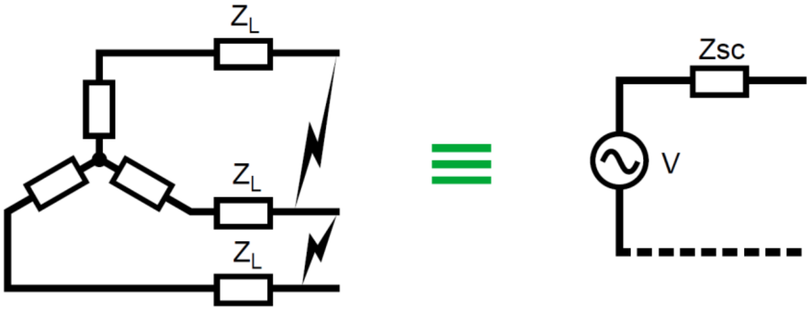


Figure 2.12 The Impedance of the Sources and the Line of Three Phase Short Circuit [20]

- Phase to Phase Short Circuit Clear of Earth

This fault is the fault between two phases with the supply from the phase to phase voltage U (15% of faults). This type of fault can be transformed into three phases short circuit. Figure 2.13 is shown in the direction of the current when the fault happens in the system. The equivalence circuit of the source and line impedance is expressed in Figure 2.14. The value of the short circuit current I_{SC_2} is smaller than the three-phase short circuit current in the previous case. The formulation of phase to phase short circuit current is stated as in (2.5).

$$I_{SC_2} = \frac{\sqrt{3}}{2} * I_{SC_3} = 0.868 * I_{SC_3} \tag{2.5}$$

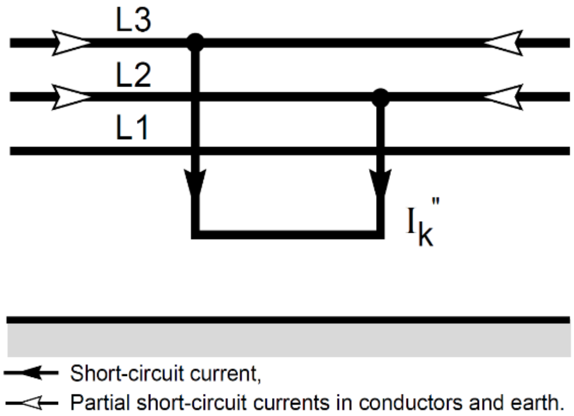


Figure 2.13 The Direction of Current in Phase to Phase Short Circuit Clear of Earth [20]

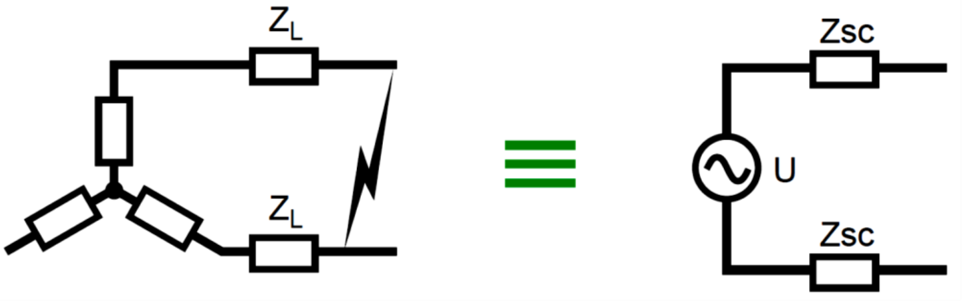


Figure 2.14 The Impedance of the Sources and the Line of Phase to Phase Short Circuit Clear of Earth [20]

– Phase to Neutral Short Circuit Clear of Earth

It is the fault between one phase to the neutral with the supply of a phase to neutral voltage in. The direction of the short circuit current is established in Figure 2.15 and the impedance of the source and the line is shown in Figure 2.16. The calculation of the short circuit current I_{SC_1} is performed as in (2.6).

$$I_{SC_1} = \frac{U}{\sqrt{3} * (Z_{SC} + Z_{Ln})} \tag{2.6}$$

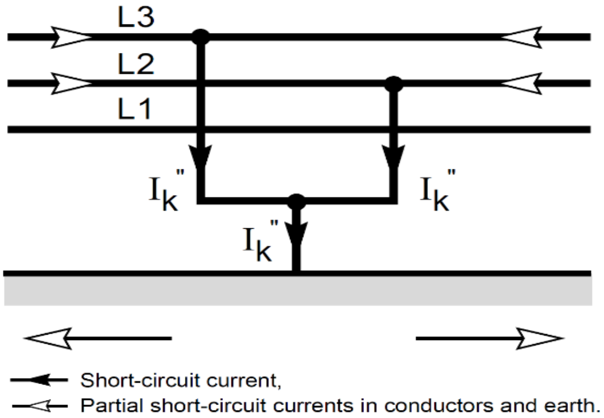


Figure 2.15 The Direction of Current in Phase to Neutral Short Circuit Clear of Earth [20]

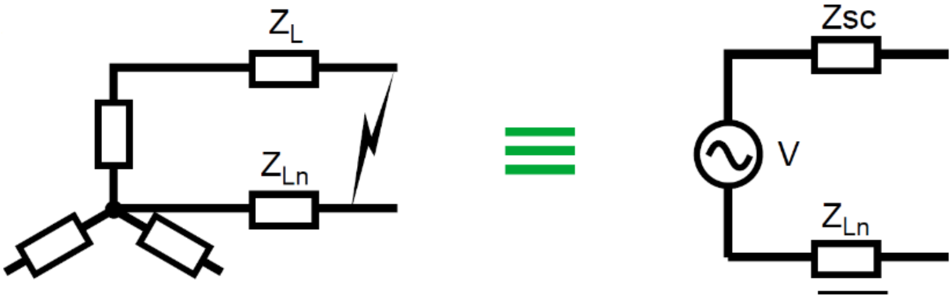


Figure 2.16 The Impedance of the Sources and the Line of Phase to Neutral Short Circuit Clear of Earth [20]

- Phase to earth fault (one or two phases)

In this fault, the zero-sequence impedance Z_0 is required to define the value of the short circuit current. When the rotating machines are involved, the zero-sequence impedance will be reduced. The value of this short circuit current I_{SC_0} is less than a three-phase fault. The neutral system is important for the calculation of I_{SC_0} setting thresholds for the zero sequence (HV) or earth fault (LV) protection devices. The direction of the short circuit current shown in Figure 2.17 and the equivalence circuit impedance is presented in Figure 2.18. The formulation of short circuit current I_{SC_0} can be defined in (2.7).

$$I_{SC_0} = \frac{U}{\sqrt{3}*(Z_{SC}+Z_0)} \tag{2.7}$$

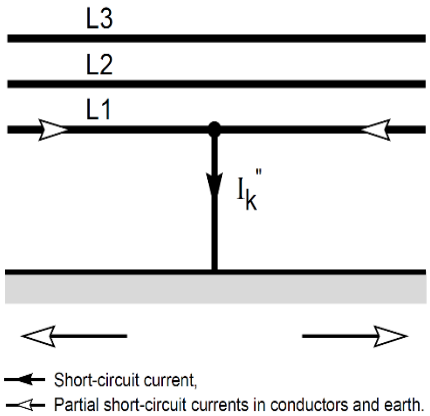


Figure 2.17 The Direction of Current in Phase to Earth Fault (One or Two Phases) [20]

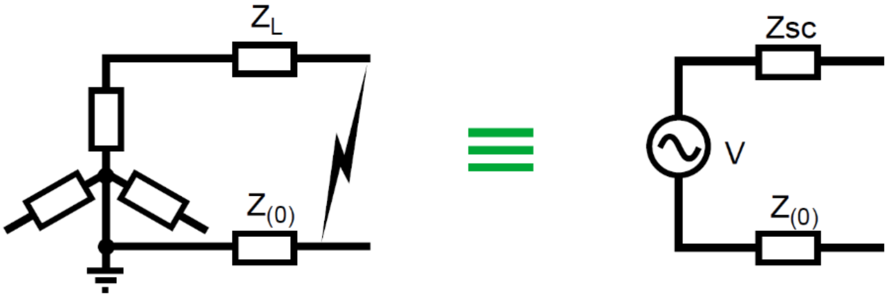


Figure 2.18 The Impedance of the Sources and the Line of Phase to Earth Fault (One or Two Phases) [20]

2.2.5 Formulation Problem in Optimized DOCRs Coordination

The typically of Protection coordination in the ring distribution system is optimum the total operating time of relay and eliminates the miss-coordination between primary and backup relays that formulated as an optimization problem. Otherwise, the optimal coordination of directional overcurrent relays in the ring distribution system should satisfy the objective function as in subsection 2.2.5.1, the relay operating time is presented in subsection 2.2.5.2, in subsection 2.2.5.3 is shown the constraint of time dial setting and pickup current setting, and the last subsection 2.2.5.4 is talked about the coordination time interval.

2.2.5.1 Objective Function of Optimal Coordination

The major optimization problem in this case study is the coordination protection of DOCRs. The main optimization objective is to minimize the total operating time of primary and backup relay while sustaining the conditions of protection coordination. Therefore, the objective function of optimal coordination is formulated by the sum of primary and backup operating time as expressed in (2.8). To minimum the operating time of the relay, the main variable that needed to optimize for the protection coordination is the time dial setting of both directions.

$$Minimise\ (TOP) = \sum_{j=1}^{M}\left(\sum_{i=1}^{N} t_{fwij} + \sum_{i=1}^{N} t_{rvkj}\right) \tag{2.8}$$

Where

N : represents the total number of relays.

M : denote the total number of fault locations across all buses.

i and k : are the relay ID.

t_{fwij} and t_{rvkj} : are the operation time of relay i and k for a fault at location j.

The variables of t_{fwij} and t_{rvkj} can be formulated in (2.9) and (2.10) as following:

$$t_{fwij} = TDS_{fwi} * \frac{A}{\left(\left(\dfrac{I_{SC_{fwij}}}{I_{p_{fwi}}}\right)^{B} - 1\right) * \beta} \tag{2.9}$$

$$t_{rvkj} = TDS_{rvk} * \frac{A}{\left(\left(\dfrac{I_{SC_{rvkj}}}{I_{p_{rvk}}}\right)^{B} - 1\right) * \beta} \tag{2.10}$$

Where

TDS_{fwi} and TDS_{rvk} : are the time dial setting of relay i and k in the forward and reverse direction, respectively.

$I_{P_{fwi}}$ and $I_{P_{rvk}}$: represented the pickup current setting of relay i and k for forward and reverse direction.

$I_{SC_{fwij}}$: a fault current at location j passing through relay i in the forward direction.

$I_{SC_{rvkj}}$: a fault current at location j passing through relay k in the reverse direction.

2.2.5.2 Relay Operating Time

The operating time of the relay is related to the time dial and pickup current when the fault existing. To guarantee the safety of the proposed protection approach, the operating of each DOCRs must follow the constraint according to its minimum and maximum operating time as in (2.11).

$$t_{ij,\min} \le t_{fwij}, t_{rvkj} \le t_{ij,\max} \tag{2.11}$$

Where

$t_{ij,min}$ and $t_{ij,max}$: Are the minimum and maximum operating time of the relay i for a fault location at j.

2.2.5.3 Time Dial and Pickup Current Setting

The time dial setting is the time delay before the relay operated when the fault current equal or bigger than the pickup current setting. The time dial setting of each relay is constraint by the maximum and minimum value as shown in (2.12). Also, the pickup current is following the lower and upper bounds that assume between $1.1 \times I_{FLA}$ to $1.5 \times I_{FLA}$ as presented in (2.13).

$$TDS_{i,\min} \le TDS_{fwi}, TDS_{rvi} \le TDS_{i,\max} \tag{2.12}$$

$$I_{pi\_\min} \le I_{pfwi}, I_{prvi} \le I_{pi\_\max} \tag{2.13}$$

Where

$TDS_{i,min}$ and $TDS_{i,max}$: are the minimum and maximum limitation of TDS for the relay i.

$I_{P_i,min}$ and $I_{P_i,max}$: are the minimum and maximum limitation of IP for the relay i.

2.2.5.4 Coordination Time Interval

The coordinating time interval is the minimum time between the operating characteristics of two series devices. The protection coordination of relays must avoid miscoordination when the fault appears in the system. The backup relay unit should operate after the primary relay is missing operating. The time interval between primary and backup relay is called coordination time interval (*CTI*) where the *CTI* with values from 0.2 to 0.5s. Thus, the coordination time interval must verify with the constraint as (2.14) in the following.

$$t_{rvkj} - t_{fwij} \geq CTI \tag{2.14}$$

Where

t_{rvkj} and t_{fwij} : are the operating time of relay k and i at fault location j in the forward and reverse direction, respectively.

The field calibrated should be considered in all devices setting to reduce the *CTI* value by 0.05s as compared between *CTIs* with and without field calibration in Table 2.3 and Table 2.4. From a comparison of both cases, the minimum of *CTIs* can be summarized in Table 2.5 for industrial application in the condition of field tested and calibrated [19].

Table 2.3 *CTIs* without Field Calibration

Components	*CTI* without field testing	
	Electromechanical	Static
Circuit breaker opening time (5 cycles)	0.08 s	0.08 s
Relay overtravel	0.10 s	0.00 s
Relay tolerance and setting errors	0.17 s	0.17 s
Total CTI	0.35 s	0.25 s

Table 2.4 *CTIs* with Field Calibration

Components	*CTI* with field testing	
	Electromechanical	Static
Circuit breaker opening time (5 cycles)	0.08 s	0.08 s
Relay overtravel	0.10 s	0.00 s

Components	*CTI* with field testing	
	Electromechanical	Static
Relay tolerance and setting errors	0.12 s	0.12 s
Total CTI	0.30 s	0.20 s

Table 2.5 The Minimum of *CTIs* for Industrial Application

Downstream	Upstream			
	Fuse	Low voltage breaker	Electromechanical relay	Static relay
Fuse	$CS^{b,c}$	CS	0.22s	0.12s
Low-voltage circuit breaker	CS^{c}	CS	0.22s	0.12s
Electromechanical relay (5 cycles)	0.20s	0.20s	0.30s	0.20s
Static relay (5 cycles)	0.20s	0.20s	0.30s	0.20s

Where

CS^b : Clear space between curves with upstream minimum-melting curve adjusted for pre-load.

CS^c : Some manufacturers may also recommend a safety factor. Consult manufacturers' time-current curves.

2.2.6 Adaptive Modified Firefly Algorithm (AMFA)

Adaptive Modified Firefly Algorithm is one of the novel Natures-Inspire Algorithm (NIA) developed from the Firefly Algorithm by Anang Tjahjono et el [3]. It is energized by the social behavior of a firefly that generates a flashing light to attract another mating partner (communication) and to attract potential prey. On the other hand, the light intensity of the firefly will decrease or increase according to the distance of the firefly. In addition, the AMFA is based on three idealized rules as follows [21]:

- Firstly, one firefly will be attracted to other fireflies regardless of their sex because all fireflies are unisex.

- Secondly, the attractiveness of fireflies is proportional to their brightness. So, from the example of the attractiveness between two flashing fireflies show that the less bright firefly will move toward to the brighter firefly one. When the distance of both flashing fireflies is increased, the attractiveness of both fireflies will be decreasing. The particular firefly will move randomly when there is no brighter one.
- Lastly, the brightness of the firefly will be defined by the formulation of the objective function. So, the brightness of the firefly is the objective function of the optimized problem.

According to the three idealized rule of firefly algorithm, the degree of the attractiveness *β(r)* between each firefly is formulated in (2.15) as follow:

$$\beta(r) = \beta_0 e^{-\gamma r^m}, \qquad (m \geq 1) \tag{2.15}$$

Where

r : is the distance between the two fireflies.

β_0 : is the attractiveness of fireflies when the distance r=0.

γ : is a coefficient of light absorption.

m : is the number of fireflies.

The light intensity *I(r)* is varied to the inverse square law in (2.16) and the distance r with a fixed light absorption coefficient γ in (2.17). so, the combination effect of both the inverse square law and absorption can be approximated as the following gaussian form (2.18).

$$I(r) = \frac{I_s}{r^2} \tag{2.16}$$

$$I = I_0 e^{-\gamma r} \tag{2.17}$$

$$I(r) = I_0 e^{-\gamma r^2} \tag{2.18}$$

Where

I_s : is the intensity at the source.

I_0 : is the original light intensity.

The distance of fireflies i^{th} to j^{th} at spatial coordinate X_i and X_j is determined by (2.19) as follow:

$$r_{ij} = \left\| X_i - X_j \right\| = \sqrt{\sum_{m=1}^{k} \left(x_{i,m} - x_{j,m} \right)^2} \tag{2.19}$$

$$X_i = \left[x_{i,1}, x_{i,2}, x_{i,3}, \cdots, x_{i,m} \right] \tag{2.20}$$

$$X_j = \left[x_{j,1}, x_{j,2}, x_{j,3}, \cdots, x_{j,m} \right] \tag{2.21}$$

Where

$x_{i,m}$: is the m^{th} component of the spatial coordinate of the i^{th} fireflies.

$x_{j,m}$: is the m^{th} component of the spatial coordinate of the j^{th} fireflies.

k : is the number of dimensions.

The movement of the low brightness firefly i is attracted to another brighter firefly j is demonstrated in (2.22).

$$X_i = X_i + \beta_0 e^{-\gamma r^m} \left(X_j - X_i \right) + \alpha \varepsilon_i \tag{2.22}$$

Where

α : is the randomization parameter with the value from 0 to 1.

ε_i : is the vector of random number draw from a gaussian distribution or uniform distribution.

The parameter that needed to improve for making the firefly algorithm fast converge and getting the optimal value is the random movement factor α. As in equation (2.22), the randomization parameter α is essential to control the diversity of the solution. The value of α can be tuned while iteration process, so it is varying with the iteration of the algorithm. Moreover, when the randomization parameter α isn't controlled or unimprovement, it will take a long time to convergence and get stuck in the local optima. Especially, the optimal value will be not reaching the minimum value.

Many approaches have been proposed to improve the randomization parameter. In reference [9] is proposed the modified firefly algorithm (MFA) to improve the firefly algorithm by updating value α with decreasing every iteration. Another article has been approached by using a combination of the original firefly and chaotic algorithm [13]. Firstly, the author also uses the initial value of α but after that, the author uses the tent map function to determine the chaotic distribution and subsequent α instead of using a random number of α. However, in reference [17] is improved the firefly algorithm on self-adaptive weight and experience-based learning strategy. the self-adaptive weight is implemented to filter the quality of the brighter fireflies and the lesser fireflies by slightly improves its value. The experience-based learning strategy can improve the convergence rate and enhances the exploitation ability of the algorithm

Consequently, this research is applied adaptive modified firefly algorithm (AMFA) by controlling the value of the randomization parameter (α) in every iteration as established in (2.23) and ensure fast convergence to reach the optimum value. If the value of α didn't manage, it will be slow to reach the converged result. The updating value of the randomization parameter α of each iteration is established as follows.

$$\alpha^{k+1} = \alpha^{k} * \left(\frac{k_{\max}}{2} \right)^{\frac{1}{k_{\max}+1}} \tag{2.23}$$

Where

k : is the sequence of iteration.
k_{max} : is the maximum iteration.

From the basic formulation, three idealized rules and the updated value of the randomization parameter (α) of the Firefly Algorithm (FA), the pseudo code of the AMFA algorithm expressed in the following:

Algorithm Pseudo Code for the AMFA Algorithm

```
1. Objective function $f(x)$, $x=(x_1,..., x_d)^T$
2. Initialize population of fireflies $x_i(i=1,2,...,n)$
3. Calculate the light intensity $I_1$ at $x_i$ is determine by $f(x_i)$
4. Define the light intensity coefficient $\gamma$
```

```
While (t<Maximum iteration)
    For i, j=1:n all n fireflies
        If $(I_j>I_i)$, move firefly i toward firefly j in all directions base on the formulation (2.22)
        End for If
        Update value of $\alpha$ of each iteration base on equation (2.23)
        Evaluation of new solution and update the light intensity
    End for i
    End for j
    Arrange the best fireflies and find the best solution
    Accept the new solution if it is better than the old one and follow all constraints as in (2.11), (2.12), (2.13), and (2.14)
End for While
Display the best result of fireflies
```

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CHAPTER 3
RESEARCH METHODOLOGY

3.1 Electrical System of PT. Pupuk Sriwidjaja Ring Distribution System

The dual setting DOCRs protection scheme along with the AMFA is proposed on the PT. Pupuk Sriwidjaja expansion ring distribution system. Figure 3.1 depicts a single line diagram of the PT. Pupuk Sriwidjaja expansion ring system in the level voltage 13.8kV. Firstly, this system is a radial distribution system that consists of 4 generators connected with the synchronous bus. It is becoming the ring distribution system by adding the load P2B and distributed generator STG-1 at bus SG-61 and STG-1, to secure all the load without cut off when one of the generators in the radial distribution system is offline. So, PT. Pupuk Sriwidjaja has a total of 5 units of the distributed generator for supplying the factories. The capacity of each distributed generator is presented in Table 3.1. The synchronous bus SYN BUS OLD is connected to SYN BUS NEW by using the transformer TR#SB-1 and TR#SB-2. The data of both transformers are displayed in Table 3.2. The ring distribution system is connected to lump load as in Table 3.3. The line parameters of the bus connection are specified in Table 3.4. The current transformer ratio connected to the DOCRs is shown in Table 3.5.

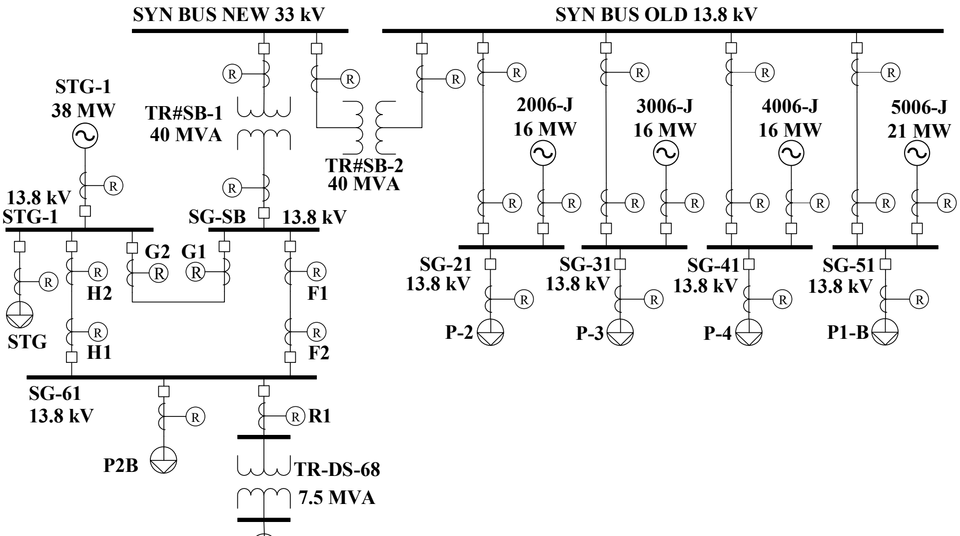


Figure 3.1 The Single Line Diagram of the PT. Pupuk Sriwidjaja Ring System

Table 3.1 The Capacity of Each Distributed Generator

No	Generator ID	Voltage (kV)	Capacity (MW)
1	STG-1	13.8	38
2	2006-J	13.8	16
3	3006-J	13.8	16
4	4006-J	13.8	16
5	5006-J	13.8	21

Table 3.2 The Data of Both Transformers

No	ID	Capacity (MVA)	Voltage (kV)	%Z	Connection
1	TR#SB-1	40	33/13.8	12.5	Delta-Wye
2	TR#SB-2	40	33/13.8	12.5	Wye-Delta

Table 3.3 Lump Load Data

No	ID	BUS	Rating (MVA)	Voltage Rating (kV)	Power Factor (%)
1	P2B	SG_61	16.643	13.8	84.59
2	STG	STG_1	17.393	13.8	85.26
3	Lump2	Bus18	1.2	13.8	85

Table 3.4 Line Impedances Parameter

No	From	To	Length (km)	Impedance Z (Ω/km)	
				$Z_1=Z_2$	Z_0
1	STG_1	SG-61	0.73	0.0742+j0.143	0.233+j0.0.352
2	STG_1	SC-SB	1.3	0.0742+j0.143	0.233+j0.0.352
3	SG-SB	SG-61	0.7	0.0742+j0.143	0.233+j0.0.352

Table 3.5 Current Transformer Ratio

NO	ID	CT Ratio (A)
1	CT1	2000/5
2	CT23	2000/5
3	CT7	2000/5
4	CT6	2000/5
5	CT4	2000/5
6	CT21	2000/5

3.2 The Protection System of PT. Pupuk Sriwidjaja Ring System

3.2.1 Relay Eaton EDR-5000

Eaton's EDR-5000 distribution protection relay is one of the protection relays that can operate a multi-functional, microprocessor-based relay for feeder circuits of all voltage levels. It can be used as the primary or as backup protection on the feeder, transformers, high voltage lines, and differential protection. It is the most commonly used on medium voltage switchgear applications. The protection features of Eaton's EDR-5000 distribution protection relay on the phase overcurrent element is described as follow:

- Three instantaneous elements with timers (50P [1], 50P [2], and 50P [3]).
- Three inverse time overcurrent elements (51P [1], 51P [2], and 51P [3]).
- 11 standard curves
- Instantaneous or time delay reset
- Voltage Restraint (51P [2] and 51P [3]).
- Directional Control (All Elements)

In PT. Pupuk Sriwidjaja ring system, it is equipped with 6 DOCRs of the relay manufacturer Eaton EDR-5000 as presented in Table 3.6. Eaton EDR-5000 consists of three groups of the inverse time overcurrent elements control in each. The ability of this relay is that a relay can be enabled all groups in simultaneously but different settings. The inverse time current characteristics can be defined by using (2.1) with the constant value of the coefficient parameter as in Table 2.1 and follow the Maximum/Minimum and the step of *TDS* for all type IEC TCC curves as in Table 3.7.

Table 3.6 Manufacturing and Installed Relay in the Ring Distribution System

No	ID Relay	Relay Manufacturing
1	F1	Eaton EDR-5000
2	F1	Eaton EDR-5000
3	G1	Eaton EDR-5000
4	G1	Eaton EDR-5000
5	H1	Eaton EDR-5000
6	H2	Eaton EDR-5000

Table 3.7 The Step of *TDS* Value of Directional Overcurrent Relay Eaton EDR-5000 for All Types of IEC TCC

Type of curve	Manufacture relay	Min TDS	Max TDS	Step TDS	Step TAP
IEC Normal Inverse	Eaton EDR 5000	0.02	2	0.01	0.01
IEC Long time Inverse	Eaton EDR 5000	0.02	2	0.01	0.01
IEC Very Inverse	Eaton EDR 5000	0.02	2	0.01	0.01
IEC Extremely Inverse	Eaton EDR 5000	0.02	2	0.01	0.01

3.2.2 The Primary and Backup Relay Pairs of PT. Pupuk Sriwidjaja Ring System

In relay protection, the backup relay protection is needed to avoid the failure of the primary relay protection and protected the system from the damage of the electrical equipment in the system. It can be defined as the primary and backup relay pairs by the direction of the short circuit current when the fault or disturbance occurs in the system. In this situation, the primary and backup relay pairs of the electrical system of PT. Pupuk Sriwidjaja ring system is presented in Table 3.8 when the short circuit current happen on each bus.

Table 3.8 The Primary and Backup Relay Pairs of PT. Pupuk Sriwidjaja Ring Distribution System when Short Circuit Happen on Each Bus

Bus Fault	**Primary Relay**	**Backup Relay**
STG-1	H2 OC1	H1 OC2
	G2 OC1	G1 OC2
SG-61	H1 OC1	H2 OC2
	F2 OC1	F1 OC2
SG-SB	G1 OC1	G2 OC2
	F1 OC1	F2 OC2

From Table 3.8, it can be seen that the primary relay H1 OC1 and F2 OC1 can't operate at 0.1s like the other primary relay if the relay R1 is considered. when the short circuit happened on the load side (Lump 2), the relay H1 OC1 and F2 OC1 will be acted as the backup relay of the primary relay R1. So, the calculation of the operating time of relay H1 OC1 and F1 OC1 will consider with the relay R1.

3.3 Coordination Constraint Parameter

The coordination of DOCRs in the PT. Pupuk Sriwidjaja Ring System can be done by following all of the coordination constraints. According to the instruction manual of the relay Eaton EDR-5000, the minimum and maximum value of *TDS* is assumed to 0.02s to 2s, respectively. The minimum and maximum operating time of each DOCRs are 0.1s and 2.5s [22], [23], respectively. In optimization, the operating time target of all primary relay is 0.1s and 0.3s for all backup relay protection. In addition, the selection of the pickup current is $1.1 * I_{FLA}$ that is followed the constraint of $1.1 * I_{FLA}$ to $1.5 * I_{FLA}$. The value of full load ampere (I_{FLA}) flowing across all relay is specified in Table 3.9. Typically, the *CTI* is assumed between 0.2s to 0.5s. Therefore, the value of *CTI* is 0.2s for all cases study. The constant-coefficient value of A, B, and β of each time overcurrent curve is based on Table 2.1.

Table 3.9 The Value of Full Load Ampere Across All DOCRs

ID Relay	H2	G2	G1	F1	F2	H1
I_{FLA} (A)	788	788	788	788	788	788

3.4 AMFA Input Data

To optimize the value of *TDS* by using the AMFA, some input parameter of the AMFA is needed to contribute as in Table 3.10.

Table 3.10 The Initiation Input Parameter of the AMFA

No	**Parameters**	**Abbreviations**	**Values**
1	Maximum iteration	MaxIt	100
2	Number of firefly populations	nPop	30
3	Light absorption coefficient	gamma	1
4	Attraction coefficient base value	beta0	1
5	Randomization parameter	alpha	0.2
6	Randomness reduction	delta	0.99

3.5 Protection Coordination Using Adaptive Modified Firefly Algorithm

The optimum value of the Time Dial setting (*TDS*) of the electrical system PT. Pupuk Sriwidjaja ring system can be calculated by using AMFA for facing various problems. The flowchart of optimal the value of *TDS* using the AMFA is established in Figure 3.2. Hence, the explanation of the AMFA is presented as follows:

The main objective function of optimal coordination in electrical PT. Pupuk Sriwidjaja ring system is the minimum of the total operating time of 6 DOCRs as in (2.8). To get the minimum of the total operating time of each relay, the *TDS* parameter is needed to minimize first. The *TDS* parameter can be defined by using (2.1). The objective function must follow many constraints such as relay operating time, time dial and pickup current setting, and coordination time interval. The first step, the AMFA needed to input the initiation parameter, those parameters are the population of the firefly, the maximum iteration, the initiation of the randomization parameter α, the full load current flow, relay parameters (the maximum, minimum and the step of *TDS*) Table 3.7, the coefficient value of each IEC curve in Table 2.1, CT ratio, three phases short circuit current calculated by using ETAP 12.0.6 program, the primary and backup relay pair, *CTI* target value. After getting the input value, the AMFA will be randomized to the position of the firefly population. In this research, the maximum of the firefly population is 30. The position of each firefly is presented of the value of the *TDS* of each relay. The random value of the *TDS* is increased base on the *TDS* step and in the rank of the minimum and maximum *TDS*. Then, the first iteration is started to find the light intensity (the operating time value) as (2.18) and the absorption coefficient of each firefly (2.15). After that, the light intensity of each firefly population will be compared and move toward to the firefly that consisted of the lightest intensity (the smallest operating time) by using equation (2.22). So, the position of the firefly is updated after the movement of the low light intensity firefly to the highest light intensity firefly. Next, the value of the randomization parameter α will be updated base on equation (2.23) in every iteration. If it has not reached the maximum iteration or not converge to the target value, the program will be returned to the randomization of the firefly position again. At the end of the iteration, the best position of the firefly (the *TDS* Value) with the brightest light intensity (the operating time value) is obtained. So, it means that the operating time that we got is closest to the operating time target. Finally, the program will be defined and shown all the pickup current of each primary and backup relay, the *TDS* value, the total overall operating time of each IEC TCC curve and selected the suitable curve for the electrical PT. Pupuk Sriwidjaja ring system.

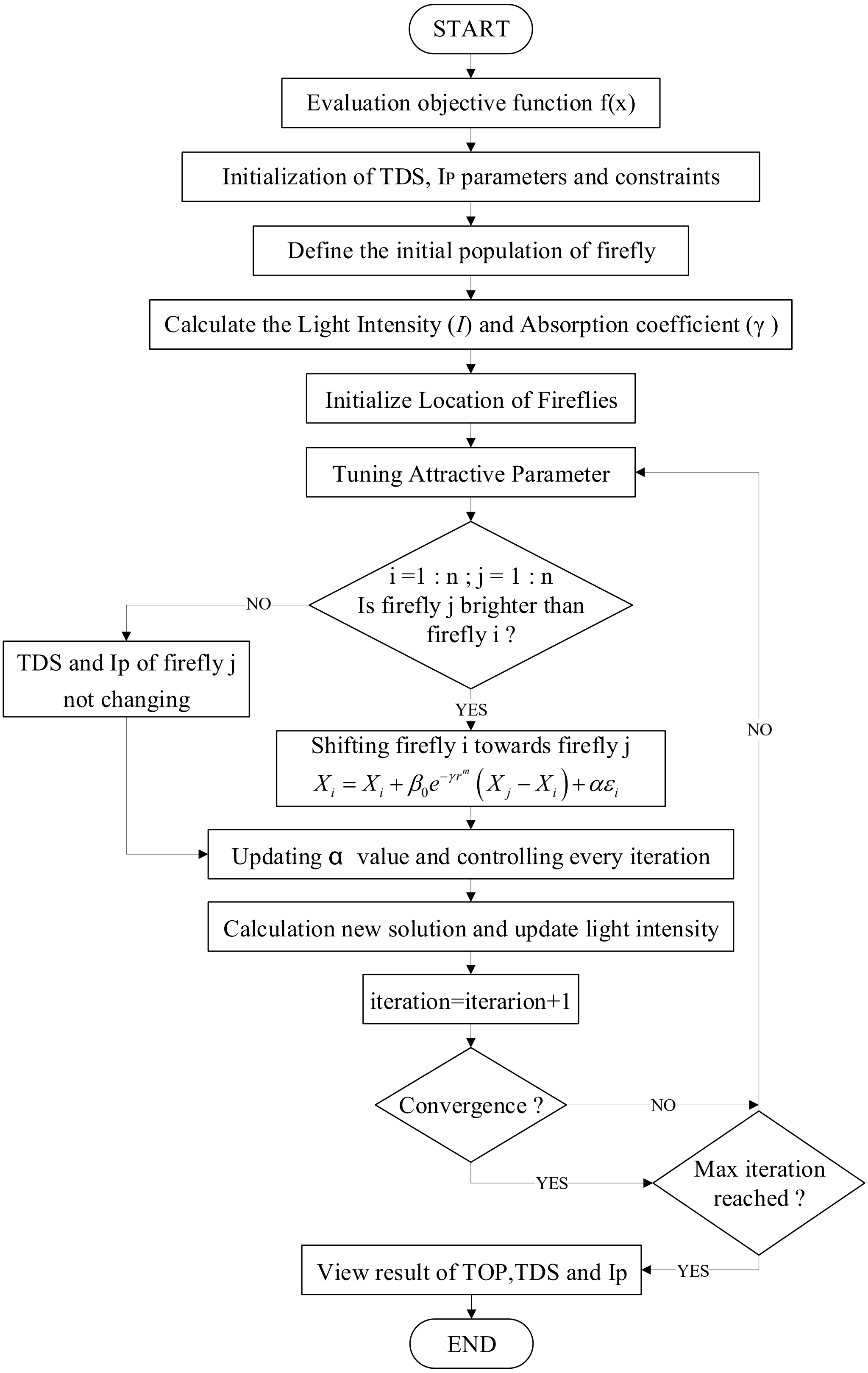


Figure 3.2 The Flowchart of the Optimal Value of the *TDS* Value

CHAPTER 4
RESULTS AND DISCUSSION

The protection coordination of the PT. Pupuk Sriwidjaja ring distribution system will be modeled by using ETAP 12.6.0 software (Electrical Transient and Analysis Program) to perform the short circuit current and the protection coordination. The optimization of the TDS parameter is completed using AMFA and employed in MATLAB 2018b software programming. This chapter will be studied on the short circuit current, the protection coordination and selecting the best time current characteristic curve. Then, the relay setting results are implemented in the real system of the PT. Pupuk Sriwidjaja ring system to verify the relay protection coordination. The protection coordination in the PT. Pupuk Sriwidjaja ring system is divided into two main case studies that will be discussed in the following subsection.

4.1 Short Circuit Current and Relay Operating Protection Scheme

This research is studied under 3 different cases when the fault exists on the bus of the ring distribution system. The value of short circuit current is calculated using ETAP 12.6.0 software programming. Those case studies are described in the following:

- Case 1: All distributed generators connected
- Case 2: Distributed generator (5006-J) disconnected

The value of short circuit current in each case when the fault happened on each bus of the ring distribution system is defined in Table 4.1 and Table 4.2.

Table 4.1 Short Circuit and Relay Operating Protection Scheme for Case Study 1

Fault Location	**Fault Current (kA)**	**Primary Relay**	**Fault Current (A)**	**Backup Relay**	**Fault Current (A)**
STG-1	23.92	H2 OC1	5130	H1 OC2	5130
		G2 OC1	3530	G1 OC2	3530

Fault Location	**Fault Current (kA)**	**Primary Relay**	**Fault Current (A)**	**Backup Relay**	**Fault Current (A)**
SG-SB	23.18	G1 OC1	8570	G2 OC2	8570
		F1 OC1	9760	F2 OC2	9760
SG-61	23.37	F2 OC1	7440	F1 OC2	7440
		H1 OC1	11940	H2 OC2	11940

Table 4.2 Short Circuit and Relay Operating Protection Scheme for Case Study 2

Fault Location	**Fault Current (kA)**	**Primary Relay**	**Fault Current (A)**	**Backup Relay**	**Fault Current (A)**
STG-1	23.69	H2 OC1	5020	H1 OC2	5020
		G2 OC1	3410	G1 OC2	3410
SG-SB	22.94	G1 OC1	8570	G2 OC2	8570
		F1 OC1	9760	F2 OC2	9760
SG-61	23.14	F2 OC1	7270	F1 OC2	7270
		H1 OC1	11890	H2 OC2	11890

4.2 Case Study 1: All Distributed Generators Connected

In this case, the Optimal coordination of DOCRs using the AMFA method is applied in the ring distribution system when all distributed generators connected. In this condition, the value of the three-phase short circuit current (0.5 cycles) is bigger than other conditions as declared in Table 4.1. Four types of IEC time current characteristic curve needed to optimal coordination protection and selected the best curve for the system with the minimum value of the total operating time relay.

4.2.1 The Randomize Position of Time Dial Setting (*TDS*) in Case Study 1

The AMFA program will be started to randomize the position of time dial setting after applied the initiation parameters. The initiation parameter consisted of the relay parameter, short circuit current, the AMFA parameter, the coefficient of each IEC TCC and the full load current across each relay. So, the randomized position of *TDS* and *TOP* of the primary H2 OC1 and backup H1 OC2 relay in the case of the IEC extremely inverse (EINV) curve is described in Table 4.3 and Table 4.4. It consisted of 30 firefly populations that are randomized for the first iteration of the AMFA. The *TDS* value of each DOCR is represented to the firefly population of the AMFA method. Thus, the randomization population of the primary and backup relay is presented in Figure 4.1 and Figure 4.2.

Table 4.3 The Randomized Position of *TDS* and *TOP* of Primary Relay H2 OC1 in Case of IEC EINV Curve for Case Study 1

Populations	***TDS (s)***	***TOP (s)***	**Populations**	***TDS (s)***	***TOP (s)***
1	1.6	3.881	16	1	2.425
2	1.13	2.741	17	1.78	4.317
3	1.36	3.299	18	0.69	1.674
4	1.88	4.560	19	1.3	3.153
5	0.48	1.164	20	0.95	2.304
6	0.41	0.994	21	0.27	0.655
7	0.5	1.213	22	0.09	0.218
8	1.56	3.784	23	1.41	3.420
9	0.79	1.916	24	1.84	4.463
10	1.22	2.959	25	1.13	2.741
11	0.31	0.752	26	1.53	3.711
12	0.27	0.655	27	0.17	0.412
13	1.76	4.269	28	0.29	0.703
14	2	4.851	29	0.94	2.280
15	1.9	4.608	30	0.35	0.849

Table 4.4 The Randomized Position of *TDS* and *TOP* of Backup Relay H1 OC2 in Case of IEC EINV Curve for Case Study 1

Populations	***TDS (s)***	***TOP (s)***	**Populations**	***TDS (s)***	***TOP (s)***
1	1.06	2.571	16	1.63	3.953
2	1.69	4.099	17	0.29	0.703
3	1.75	4.245	18	0.71	1.722
4	0.05	0.121	19	1.31	3.177

Populations	***TDS (s)***	***TOP (s)***	**Populations**	***TDS (s)***	***TOP (s)***
5	1.21	2.935	20	0.09	0.218
6	0.49	1.188	21	0.99	2.401
7	1.4	3.396	22	1.98	4.802
8	1.02	2.474	23	0.07	0.170
9	0.91	2.207	24	0.75	1.819
10	0.18	0.437	25	0.19	0.461
11	2	4.851	26	0.05	0.121
12	1.48	3.590	27	1.04	2.522
13	1.72	4.172	28	0.63	1.528
14	0.8	1.940	29	1.38	3.347
15	1.92	4.657	30	1.2	2.911

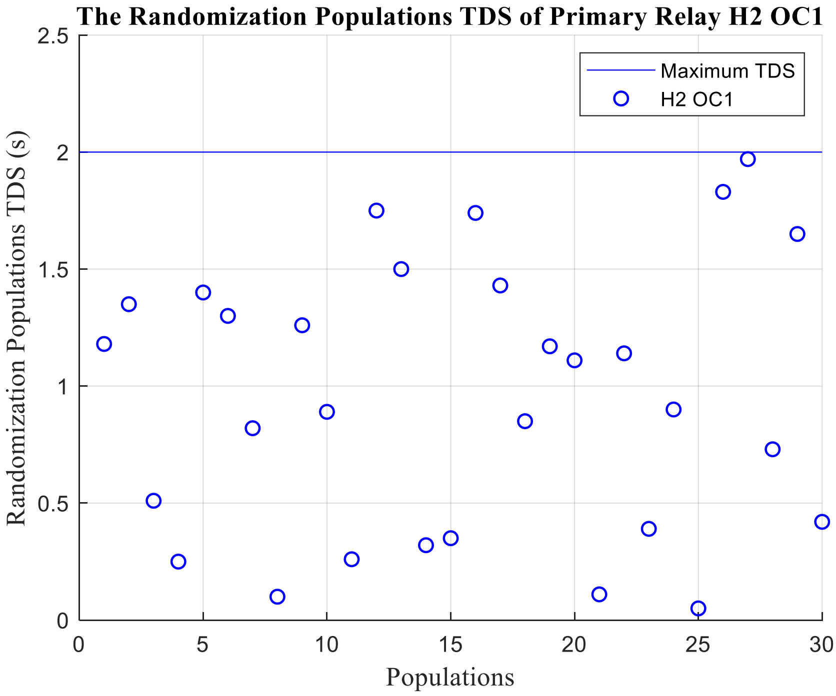


Figure 4.1 The Randomization Population *TDS* of Primary Relay H2 OC1 for Case Study 1

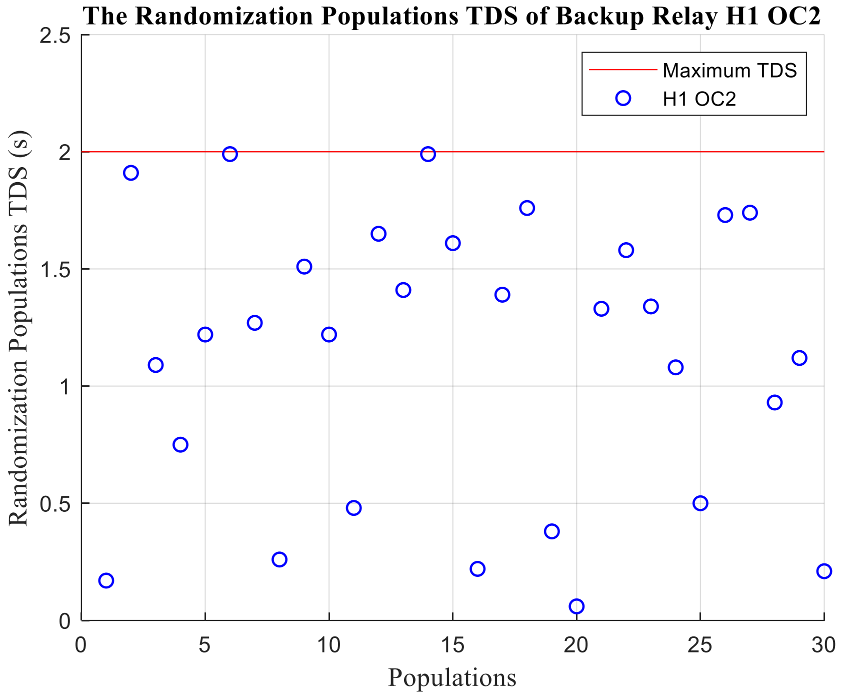


Figure 4.2 The Randomization Population *TDS* of Backup Relay H1 OC2 for Case Study 1

The randomized position of *TDS* and *TOP* will become the input of the main loop of the AMFA that running from iteration 1 to 100. The main loop of the AMFA is the place where each population of *TDS* is compared and moved toward the population of *TDS* that consisted of the minimum value of operating time. So, the new population of *TDS* and *TOP* of primary relay H2 OC1 and backup relay H1 OC2 in the IEC extremely inverse curve condition of the first iteration of the main loop is presented in Table 4.5 and Table 4.6.

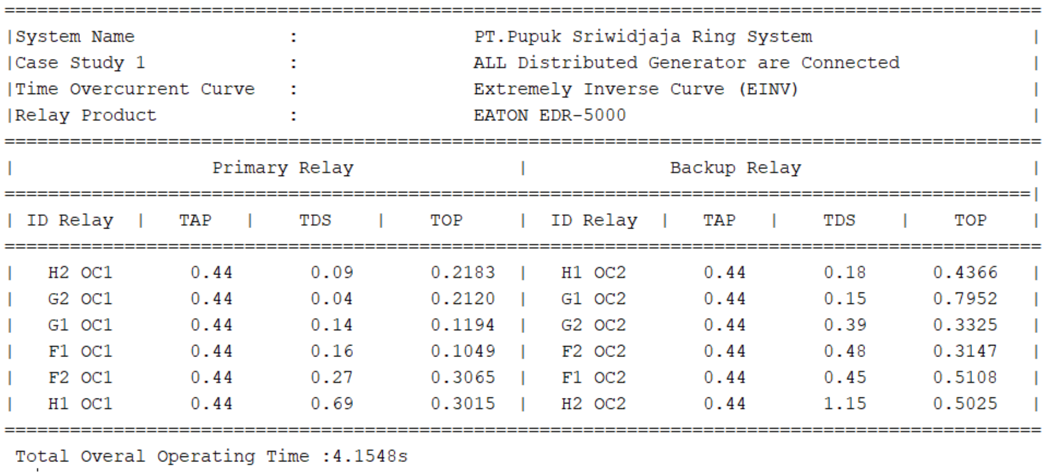
Table 4.5 The New Population of *TDS* and *TOP* of Primary Relay H2 OC1 in IEC EINV Curve of The First Iteration for Case Study 1

New Populations	***TDS (s)***	***TOP (s)***	**New Populations**	***TDS (s)***	***TOP (s)***
1	1.18	2.862	16	0.49	1.188
2	0.9	2.183	17	1.03	2.498
3	0.81	1.965	18	0.28	0.679
4	1.17	2.838	19	0.48	1.164

New Populations	***TDS (s)***	***TOP (s)***	**New Populations**	***TDS (s)***	***TOP (s)***
5	0.55	1.334	20	0.85	2.062
6	0.37	0.897	21	0.3	0.728
7	0.66	1.601	22	0.3	0.728
8	1.36	3.299	23	0.83	2.013
9	0.67	1.625	24	1.82	4.414
10	0.53	1.285	25	0.99	2.401
11	0.45	1.091	26	1.18	2.862
12	0.24	0.582	27	0.02	0.049
13	1.59	3.856	28	0.4	0.970
14	1.61	3.905	29	0.98	2.377
15	0.99	2.401	30	0.53	1.285

Table 4.6 The New Population of *TDS* and *TOP* of Backup Relay H1 OC2 in Case of IEC EINV Curve of The First Iteration for Case Study 1

New Populations	***TDS (s)***	***TOP (s)***	**New Populations**	***TDS (s)***	***TOP (s)***
1	0.47	1.140	16	1.2	2.911
2	1.66	4.026	17	0.03	0.073
3	1.59	3.856	18	0.67	1.625
4	0.2	0.485	19	1.36	3.299
5	1.35	3.274	20	0.26	0.631
6	0.23	0.558	21	0.87	2.110
7	1.24	3.008	22	1.89	4.584
8	0.94	2.280	23	0.02	0.049
9	0.52	1.261	24	0.61	1.480
10	0.52	1.261	25	0.24	0.582
11	2	4.851	26	0.66	1.601
12	1.43	3.468	27	0.7	1.698
13	1.44	3.493	28	0.15	0.364
14	0.84	2.037	29	1.23	2.983
15	1.8	4.366	30	0.91	2.207



```
=====================================================================================
|System Name              :              PT.Pupuk Sriwidjaja Ring System            |
|Case Study 1             :              ALL Distributed Generator are Connected    |
|Time Overcurrent Curve   :              Extremely Inverse Curve (EINV)             |
|Relay Product            :              EATON EDR-5000                             |
=====================================================================================
|                  Primary Relay                 |              Backup Relay        |
====================================================================================|
| ID Relay  |   TAP   |    TDS    |    TOP    | ID Relay  |   TAP   |   TDS   |   TOP   |
=====================================================================================
|   H2 OC1       0.44       0.09       0.2183  |  H1 OC2      0.44      0.18     0.4366  |
|   G2 OC1       0.44       0.04       0.2120  |  G1 OC2      0.44      0.15     0.7952  |
|   G1 OC1       0.44       0.14       0.1194  |  G2 OC2      0.44      0.39     0.3325  |
|   F1 OC1       0.44       0.16       0.1049  |  F2 OC2      0.44      0.48     0.3147  |
|   F2 OC1       0.44       0.27       0.3065  |  F1 OC2      0.44      0.45     0.5108  |
|   H1 OC1       0.44       0.69       0.3015  |  H2 OC2      0.44      1.15     0.5025  |
=====================================================================================
 Total Overal Operating Time :4.1548s
```

Figure 4.3 The Operating Time of All DOCR in Case of IEC Extremely Inverse Curve of the First Iteration for Case Study 1

As we can see the result of time dial setting and operating time of all DOCR in case of IEC Extremely inverse curve of the first iteration in the main loop of AMFA in Figure 4.3. The program has shown the result of the value of operating time of primary relay H2 OC1 in the first iteration is 0.2183s with the time dial setting 0.09s that is the position 22 of the 30 firefly populations as classified in Table 4.3. For the backup relay, the value of operating time and the time dial setting in the first iteration is 0.4366s and 0.18s, respectively. It is the 10 position of the 30 firefly populations. The result of another pairs relay in the first iteration is depicted in Figure 4.3.

4.2.2 The Time Dial Setting (*TDS*) and Relay Operating Time Results in Case Study 1

After finished running the program in of all IEC TCC curve with 100 of maximum iteration, the result of *TDS* and the minimum operating time of all DOCR in the PT. Pupuk Sriwidjaja ring distribution system is summarized in Table 4.7, Table 4.8, Table 4.9, and Table 4.10.

Table 4.7 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC NINV Curve for Case Study 1

IEC Normal Inverse Curve (NINV)									
Primary Relay					**Backup Relay**				
Relay ID	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**	**Relay ID**	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**
H2 OC1	880	0.44	0.03	0.117	H1 OC2	880	0.44	0.09	0.351
G2 OC1	880	0.44	0.03	0.149	G1 OC2	880	0.44	0.08	0.398
G1 OC1	880	0.44	0.04	0.120	G2 OC2	880	0.44	0.11	0.331
F1 OC1	880	0.44	0.04	0.114	F2 OC2	880	0.44	0.12	0.341
F2 OC1	880	0.44	0.10	0.321	F1 OC2	880	0.44	0.17	0.546
H1 OC1	880	0.44	0.12	0.314	H2 OC2	880	0.44	0.20	0.523
Objective Function					3.6234s				

Table 4.8 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC VINV Curve for Case Study 1

IEC Very Inverse Curve (VINV)									
Primary Relay					**Backup Relay**				
Relay ID	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**	**Relay ID**	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**
H2 OC1	880	0.44	0.04	0.112	H1 OC2	880	0.44	0.12	0.335
G2 OC1	880	0.44	0.03	0.134	G1 OC2	880	0.44	0.08	0.359
G1 OC1	880	0.44	0.07	0.108	G2 OC2	880	0.44	0.20	0.309
F1 OC1	880	0.44	0.08	0.107	F2 OC2	880	0.44	0.23	0.308
F2 OC1	880	0.44	0.17	0.308	F1 OC2	880	0.44	0.29	0.525
H1 OC1	880	0.44	0.28	0.301	H2 OC2	880	0.44	0.47	0.505
Objective Function					3.4109s				

Table 4.9 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC LTINV Curve for Case Study 1

IEC Long-Time Inverse Curve (LTINV)									
Primary Relay					**Backup Relay**				
Relay ID	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**	**Relay ID**	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**
H2 OC1	880	0.44	0.02	0.497	H1 OC2	880	0.44	0.03	0.745
G2 OC1	880	0.44	0.02	0.797	G1 OC2	880	0.44	0.03	1.195
G1 OC1	880	0.44	0.02	0.275	G2 OC2	880	0.44	0.04	0.549
F1 OC1	880	0.44	0.02	0.238	F2 OC2	880	0.44	0.04	0.476
F2 OC1	880	0.44	0.02	0.322	F1 OC2	880	0.44	0.04	0.644
H1 OC1	880	0.44	0.04	0.382	H2 OC2	880	0.44	0.07	0.668
Objective Function					6.7884s				

Table 4.10 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC EINV Curve for Case Study 1

IEC Extremely Inverse Curve (EINV)									
Primary Relay					**Backup Relay**				
Relay ID	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**	**Relay ID**	***I_P* (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**
H2 OC1	880	0.44	0.05	0.121	H1 OC2	880	0.44	0.14	0.304
G2 OC1	880	0.44	0.02	0.106	G1 OC2	880	0.44	0.06	0.318
G1 OC1	880	0.44	0.12	0.102	G2 OC2	880	0.44	0.36	0.307
F1 OC1	880	0.44	0.16	0.105	F2 OC2	880	0.44	0.47	0.308
F2 OC1	880	0.44	0.27	0.306	F1 OC2	880	0.44	0.45	0.511
H1 OC1	880	0.44	0.69	0.301	H2 OC2	880	0.44	1.15	0.502
Objective Function					3.3284s				

From the result in Table 4.7 to Table 4.10, all primary and backup relay in case IEC NINV, VINV, and EINV curve are operated at operating time 0.1s and 0.3s, respectively, as the operating time constraint target in AMFA program but except primary relay F2 OC1 and H1 OC1 are selected to operate at 0.3s when the fault happens on the bus SG-61 because these two relays are considered as the backup of the relay R1 when the fault occurs on the bus of the load side. In the case, IEC LTINV curve, the primary and backup relay result shown that the operating time value does not follow the operating time constraint target. So, it cannot compare with another IEC TCC curve.

4.2.3 The Result of Coordination Time Interval (*CTI*) in Case Study 1

According to the *CTI* constraint setting in AMFA, the *CTI* between the primary and backup relay must be in the constraint of 0.2s to 0.5s. So, the *CTI* target in this case study is assumed to be 0.2s between each relay pairs. From the optimal result of all type IEC TCC curves in Table 4.7 to Table 4.10, the *CTI* value of all relay pairs for all types of IEC TCC curves is presented in Table 4.11.

Table 4.11 The Coordination Time Interval of All IEC TCC for Case Study 1

IEC TCC	**Pairs Relay**		***CTI* (s)**
	Primary Relay	**Backup Relay**	
Normal Inverse	H2 OC1	H1 OC2	0.234
	G2 OC1	G1 OC2	0.248
	G1 OC1	G2 OC2	0.210
	F1 OC1	F2 OC2	0.227
	F2 OC1	F1 OC2	0.225
	H1 OC1	H2 OC2	0.209
Very Inverse	H2 OC1	H1 OC2	0.224
	G2 OC1	G1 OC2	0.224
	G1 OC1	G2 OC2	0.201
	F1 OC1	F2 OC2	0.201
	F2 OC1	F1 OC2	0.217

IEC TCC	**Pairs Relay**		***CTI* (s)**
	Primary Relay	**Backup Relay**	
	H1 OC1	H2 OC2	0.204
Long-Time Inverse	H2 OC1	H1 OC2	0.248
	G2 OC1	G1 OC2	0.398
	G1 OC1	G2 OC2	0.275
	F1 OC1	F2 OC2	0.238
	F2 OC1	F1 OC2	0.322
	H1 OC1	H2 OC2	0.286
Extremely Inverse	H2 OC1	H1 OC2	0.218
	G2 OC1	G1 OC2	0.212
	G1 OC1	G2 OC2	0.205
	F1 OC1	F2 OC2	0.203
	F2 OC1	F1 OC2	0.204
	H1 OC1	H2 OC2	0.201

4.2.4 Selecting the Best IEC TCC Curve with Minimum Value of Total Operating Time (*TOP*) in Case Study 1

The result of 4 different types of IEC TCC in Table 4.7 to Table 4.10 is shown that the IEC extremely inverse curve (EINV) consists of the minimum value of the total operating time within the coordination of relay protection. In addition, the comparison result of the total operating time of all IEC TCC is presented in the bar graph of Figure 4.4. The comparison result in the bar graph is displayed that the minimum value of the total operating time of the EINV curve is 3.32843s which is the smallest value among the IEC TCC curve. Thus, the suitable curve for relay protection coordination in the PT. Pupuk Sriwidjaja ring system is IEC extremely inverse curve.

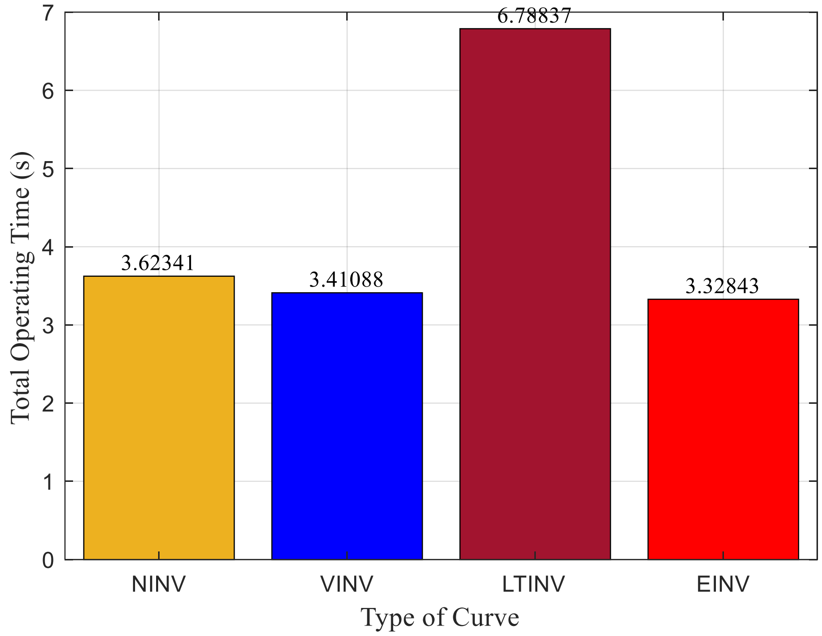


Figure 4.4 The Comparison of Total Operating Time for All IEC TCC Curve for Case Study 1

4.2.5 Result of Updating the Randomization Parameter α of Selecting Curve in Case Study 1

After selecting the IEC EINV curve is the best curve to guarantee the protection coordination of PT. Pupuk Sriwidjaja ring system. Consequently, the optimal result of this curve is done by updating the value of the randomization parameter α in every iteration of the AMFA program. The updating of the randomization parameter α of all primary and backup relay in case IEC EINV curve is presented in Figure 4.5 and Figure 4.6.

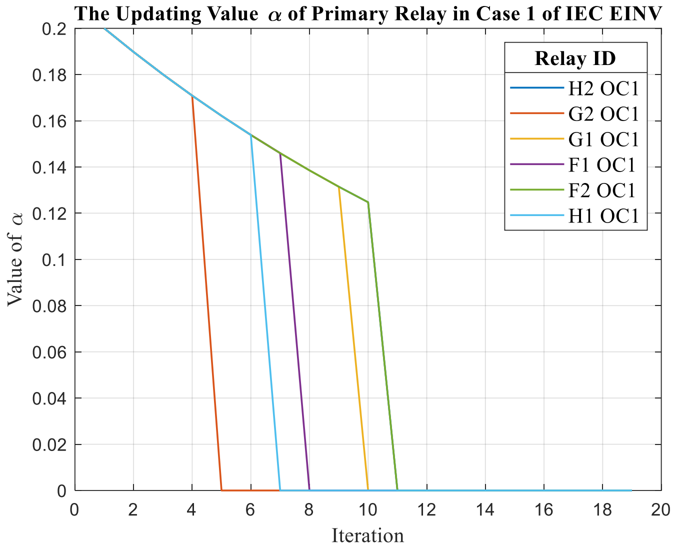


Figure 4.5 The Updating Value α of Primary Relay in Case IEC EINV Curve for Case Study 1

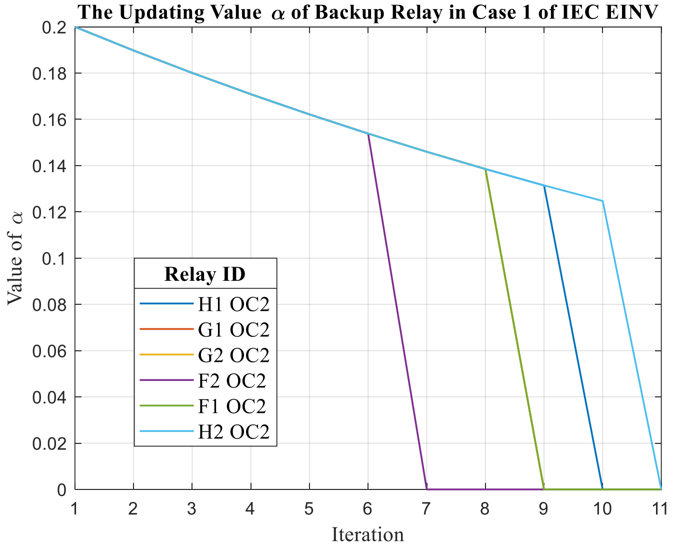


Figure 4.6 The Updating Value α of Backup Relay in Case IEC EINV Curve for Case Study 1

From Figure 4.5 and Figure 4.6, each curve is shown the updating value alpha in every iteration of the primary and backup relay. Moreover, it described the converge iteration of each primary and backup relay operating time. The primary and backup relay operating time is converged when the updating value alpha is equal to 0. As an example of primary relay G2 OC1, the updating of alpha value is equal to 0 in iteration 5, so the operating time is converged in the iteration 4. For backup relay H1 OC2, the operating time is converged in the iteration 9 of the maximum iteration. In some cases, the curve of updating value alpha is not displayed on both figures. It means that those curves are having the same value and iteration of other primary or backup relays. Like the primary relay H2 OC1 in Figure 4.5, the updating value alpha and the iteration are the same as the primary relay F2 OC1. For the backup relay G1 OC2 and G2 OC2 in Figure 4.6, the curve of updating alpha value is the same as the backup relay F1 OC2.

From the result of updating value α in Figure 4.5 and Figure 4.6 of the AMFA method, it can be compared to the converge iteration with the original FA method in Table 4.12. The result of comparison iteration is shown that the updating value α in every iteration of the AMFA method is faster than the fixed value α of the original FA method. Moreover, by running both algorithms in 30 times with the same computer's processor speed and RAM. The results of processing time are not permanent and keep on varying depending upon the computer's processor speed and RAM. Hence, the comparison of the average processing time for calculated the optimal value is presented in Table 4.13.

Table 4.12 The Comparison of Converge Iteration of the AMFA to the Original FA for Case Study 1

Relay ID	***TDS* (s)**		***TOP* (s)**		**Iteration**	
	AMFA	**FA**	**AMFA**	**FA**	**AMFA**	**FA**
H2 OC1	0.05	0.05	0.121	0.121	10	13
G2 OC1	0.02	0.02	0.106	0.106	4	7
G1 OC1	0.12	0.12	0.102	0.102	9	15
F1 OC1	0.16	0.16	0.105	0.105	7	8
F2 OC1	0.27	0.27	0.306	0.306	10	10
H1 OC1	0.69	0.69	0.301	0.301	6	10
H1 OC2	0.14	0.14	0.340	0.340	9	11
G1 OC2	0.06	0.06	0.318	0.318	8	10
G2 OC2	0.36	0.36	0.307	0.307	8	10
F2 OC2	0.47	0.47	0.308	0.308	6	12

Relay ID	***TDS* (s)**		***TOP* (s)**		**Iteration**	
	AMFA	**FA**	**AMFA**	**FA**	**AMFA**	**FA**
F1 OC2	0.45	0.45	0.511	0.511	8	8
H2 OC2	1.15	1.15	0.502	0.502	10	12

Table 4.13 The Comparison of Processing Time Between the AMFA and the Original FA for Case Study 1

Number of Running	**AMFA**	**FA**
1	1.513	1.803
2	1.596	2.214
3	1.545	1.828
4	1.562	1.686
5	1.43	1.705
6	1.59	1.682
7	1.548	1.973
8	1.411	1.649
9	1.543	1.719
10	1.568	1.719
11	1.448	1.726
12	1.753	1.737
13	1.585	1.639
14	1.487	1.754
15	1.597	1.887
16	1.536	1.577
17	1.624	1.544
18	1.575	1.745
19	1.517	1.69
20	1.575	1.682
21	1.559	1.67
22	1.571	1.696
23	1.542	1.492
24	1.818	1.686

Number of Running	AMFA	FA
25	1.563	1.561
26	1.603	1.709
27	1.615	1.632
28	1.596	1.569
29	1.467	1.605
30	1.699	1.74
Average Processing Time (s)	1.567	1.710

4.2.6 Protection Coordination Analysis Using the AMFA Result in Case Study 1

The result of protection coordination is analyzed by plotting the IEC TCC of the selecting curve in the MATLAB 2018b programming and the ETAP 12.6.0 software. The plotting of the TCC curve can be established the operating time of each relay and the coordination time interval of each pairs relay. To plotting the IEC extremely inverse curve that is the selecting curve for the system, three locations of three phases short circuit current on the bus is presented. For the TCC of IEC normal and very inverse which is not selected for the system is presented in APPENDIX A and APPENDIX B.

- Three phases short circuit current on bus STG_1

The relay H2 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus STG_1 and the relay H1 OC2 is the backup relay. For another pairs relay, the relay G2 OC1 is the primary relay of the backup relay G1 OC2. So, the tripping sequence of DOCRs in ETAP 12.6.0 while faulting on the bus STG_1 is displayed in Figure 4.7. Figure 4.8 and Figure 4.10 are the TCC curve of pairs relay that plotted by MATLAB 2018b. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.9 and Figure 4.11. The blue line is represented the primary relay and the green line is represented the backup relay. The red line is presented the value of the three-phase short circuit current on the bus STG_1. It can be seen that the operating time of both primary relay H2 OC1 and G2 OC1 are 0.121s and 0.106s, respectively, while both backup relay H1 OC2 and G1 OC2 are 0.339s and 0.317s, respectively. So, the coordination time interval (*CTI*) of pairs relay (H2 OC1/H1 OC2) is 0.218s and 0.211s for another pairs relay (G2 OC1/G1 OC2). Because the result of *CTI* value is not perfectly at 0.2s as the *CTI* constraint in the AMFA program. Then, the *CTI* error of both pairs relay is 0.018s and 0.011s, respectively. Therefore, both pairs relay is coordinated because the operating time is larger than 0.1s for both primary pairs relay and larger than 0.3s for both backup pairs relay. Also, the *CTI* value is larger than 0.2s.

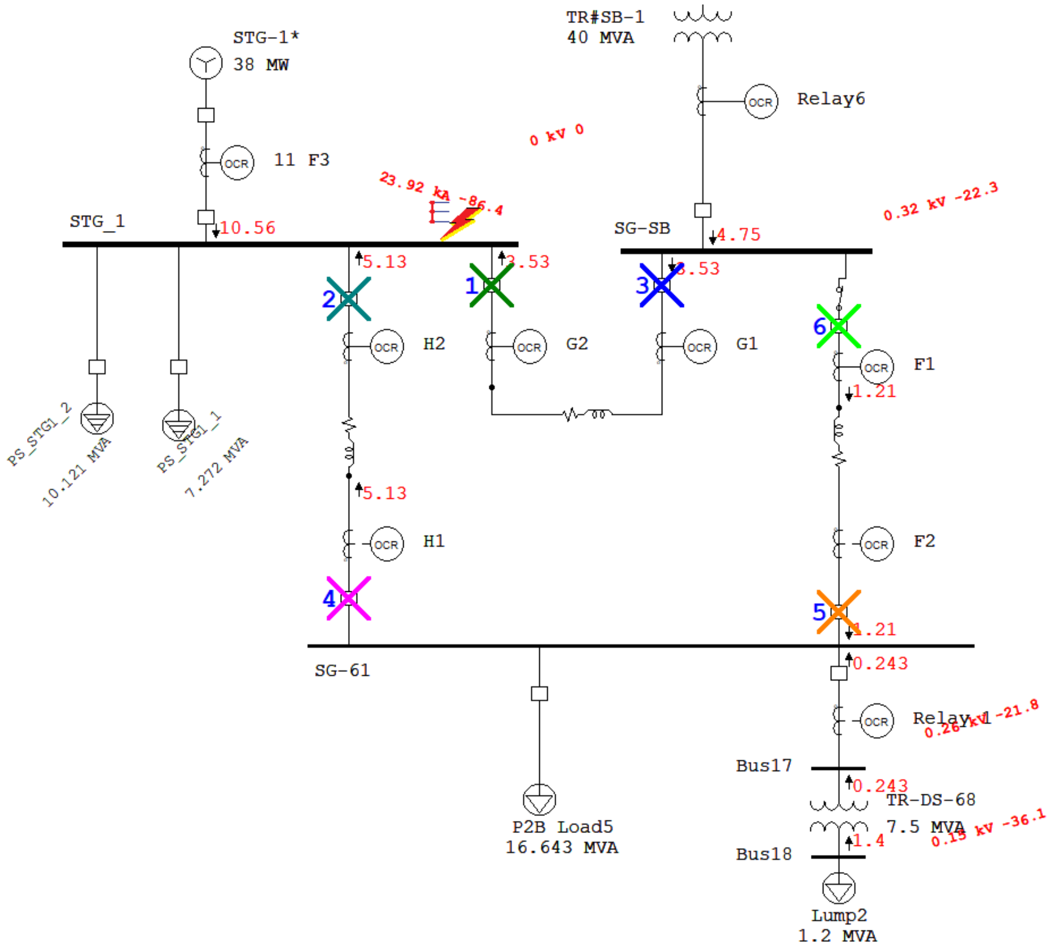


Figure 4.7 Tripping Sequence in ETAP While Faulting on the Bus STG_1 for Case Study 1

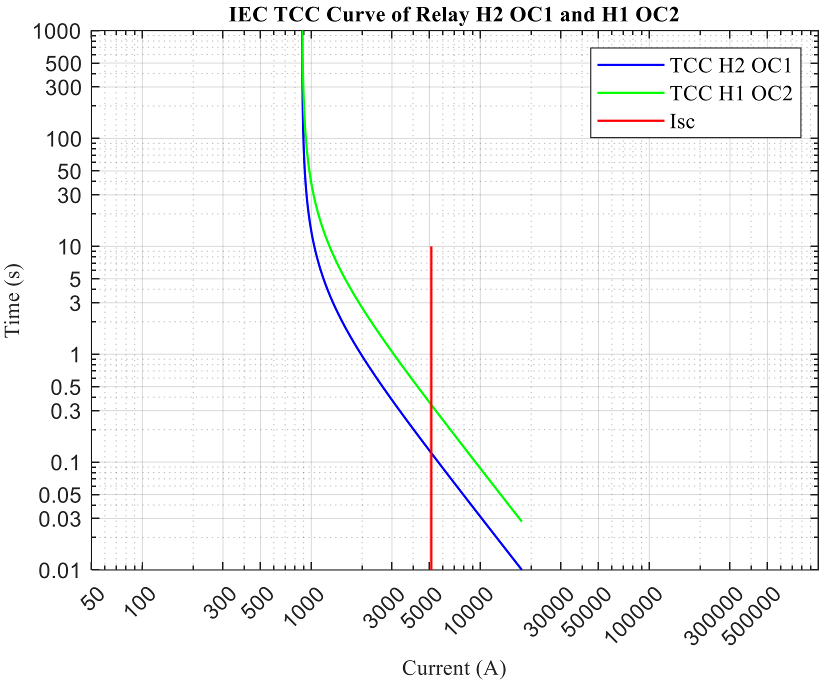


Figure 4.8 The TCC Curve of Relay H2 OC1 and H1 OC2 for Case Study 1 Using MATLAB 2018b

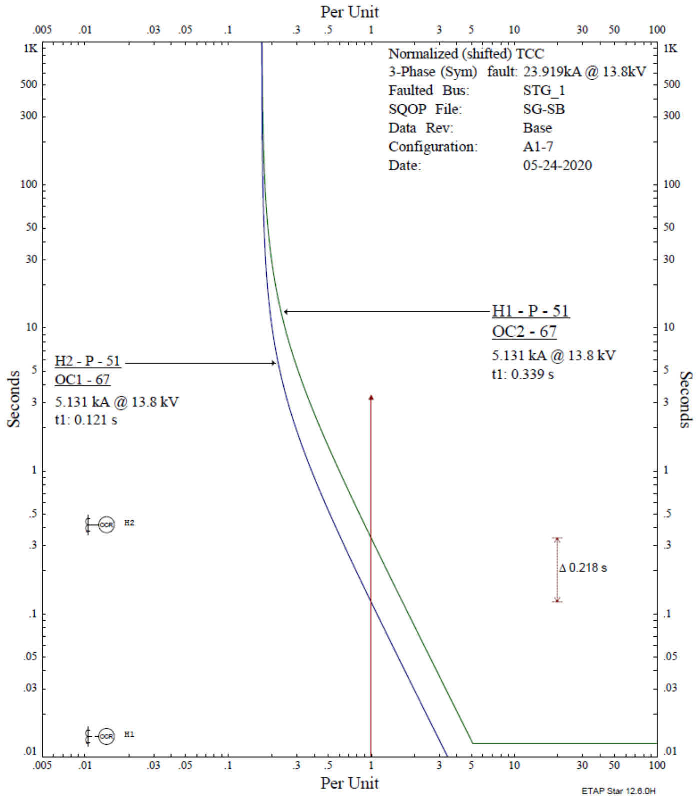


Figure 4.9 The TCC Curve of Relay H2 OC1 and H1 OC2 for Case Study 1 Using ETAP 12.6.0

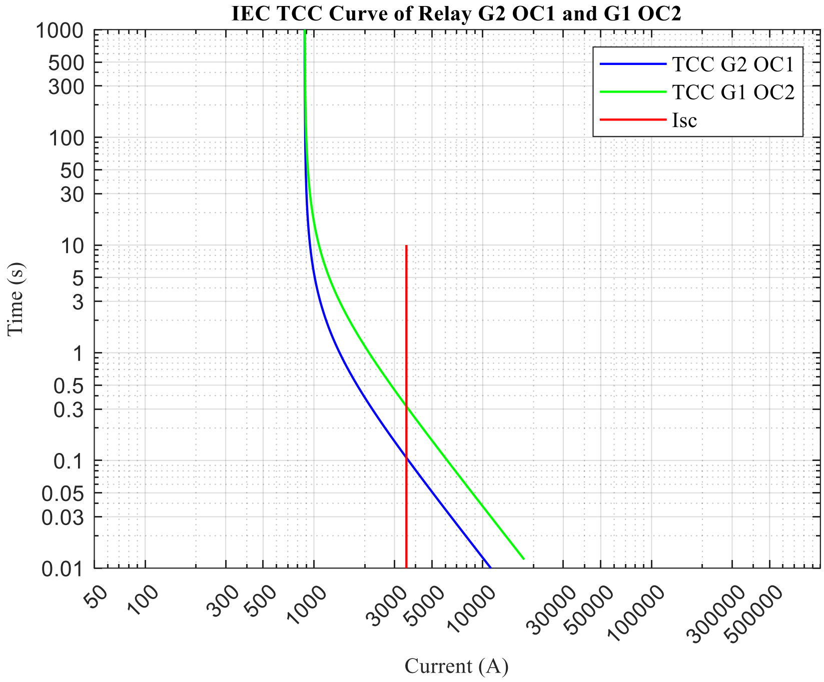


Figure 4.10 The TCC Curve of Relay G2 OC1 and G1 OC2 for Case study 1 Using MATLAB 2018b

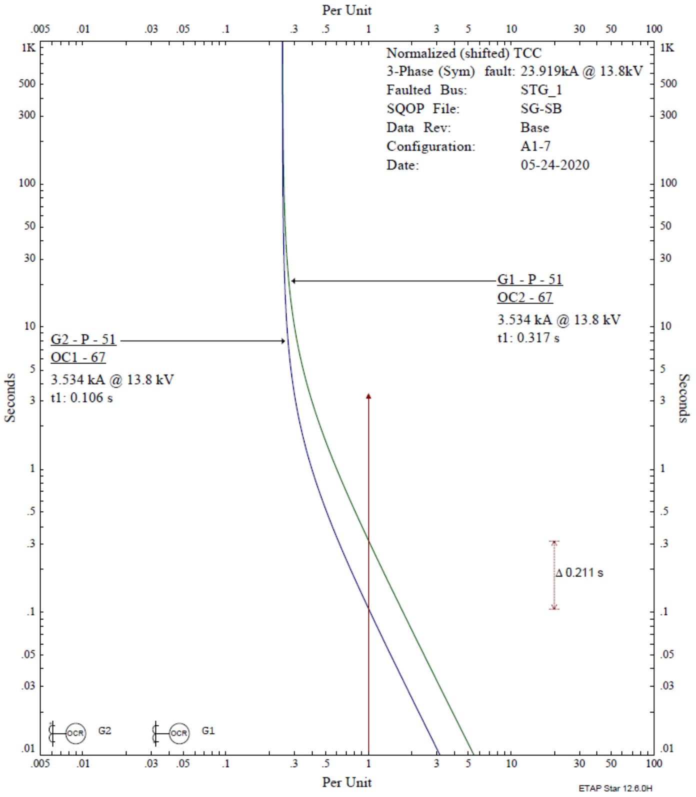


Figure 4.11 The TCC Curve of Relay G2 OC1 and G1 OC2 for Case Study 1 Using ETAP 12.6.0

– Three phases short circuit current on bus SG-61

The relay H1 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus STG-61 and the relay H2 OC2 is the backup relay. For another pairs relay, the relay F2 OC1 is the primary relay of the backup relay F1 OC2. So, the tripping sequence of DOCRs in ETAP 12.6.0 while faulting on the bus SG_61 is displayed in Figure 4.12. Figure 4.13 and Figure 4.15 are the TCC curve of pairs relay that plotted by MATLAB 2018b. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.14 and Figure 4.16. The blue line is represented the primary relay and the green line is represented the backup relay. The red line is presented the value of the three-phase short circuit current on the bus SG_61. It can be seen that the operating time of both primary relay H1 OC1 and F2 OC1 are 0.301s and 0.306s, respectively, while both backup relay H2 OC2 and F1 OC2 are 0.502s and 0.511s, respectively. In this point, both primary relays are selected to follow the relay operating time at 0.3s because both primary relays will become the backup of Relay R1 when the short circuit current happened the bus of the load P2B. So, both backup relays will be selected to operate at 0.5s for verifying the *CTI* constraint. Then, the coordination time interval (*CTI*) of pairs relay (H1 OC1/H2 OC2) is 0.201s and 0.205s for another pairs relay (F2 OC1/F1 OC2). Because the result of *CTI* value is not perfectly at 0.2s as the *CTI* constraint in the AMFA program. Then, the *CTI* error of both pairs relay is 0.001s and 0.005s, respectively. Therefore, both pairs relay is coordinated because the operating time is larger than 0.1s for both primary pairs relay and larger than 0.3s for both backup pairs relay. Also, the *CTI* value is larger than 0.2s.

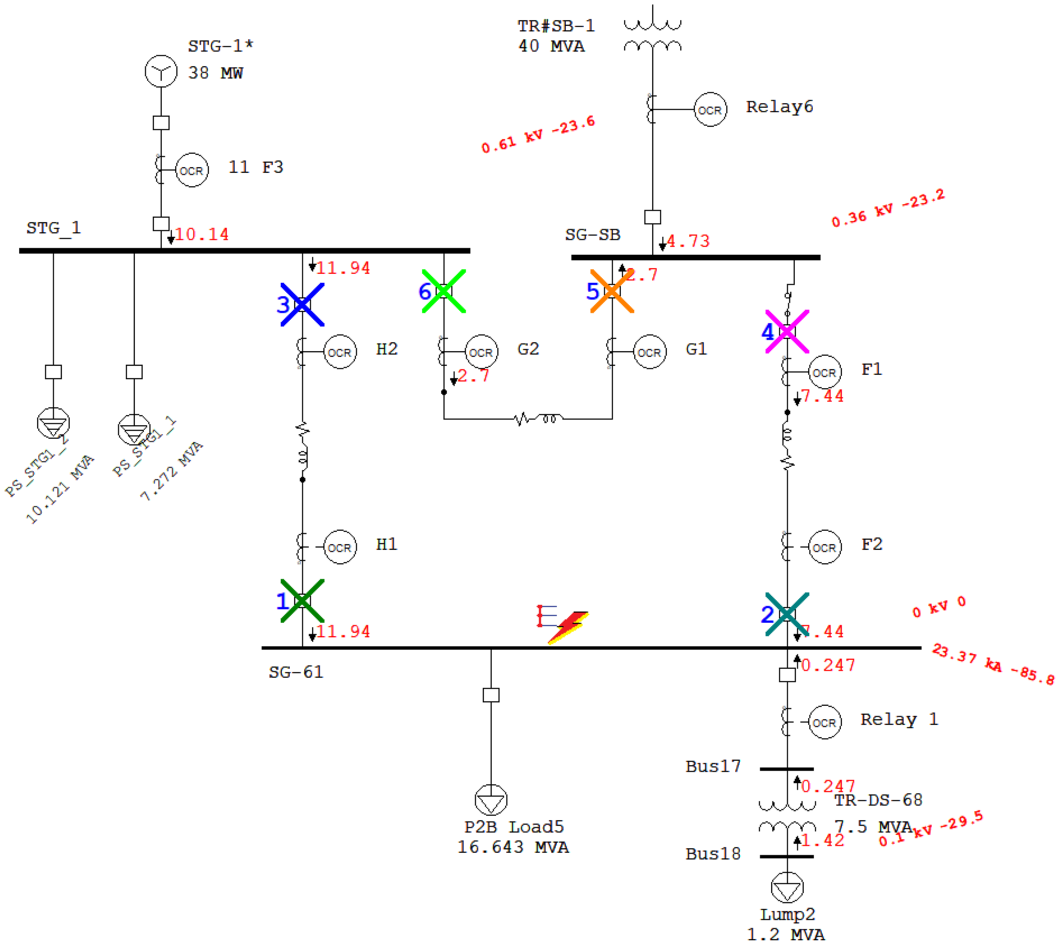


Figure 4.12 Tripping Sequence in ETAP While Faulting on the Bus SG_61 for Case Study 1

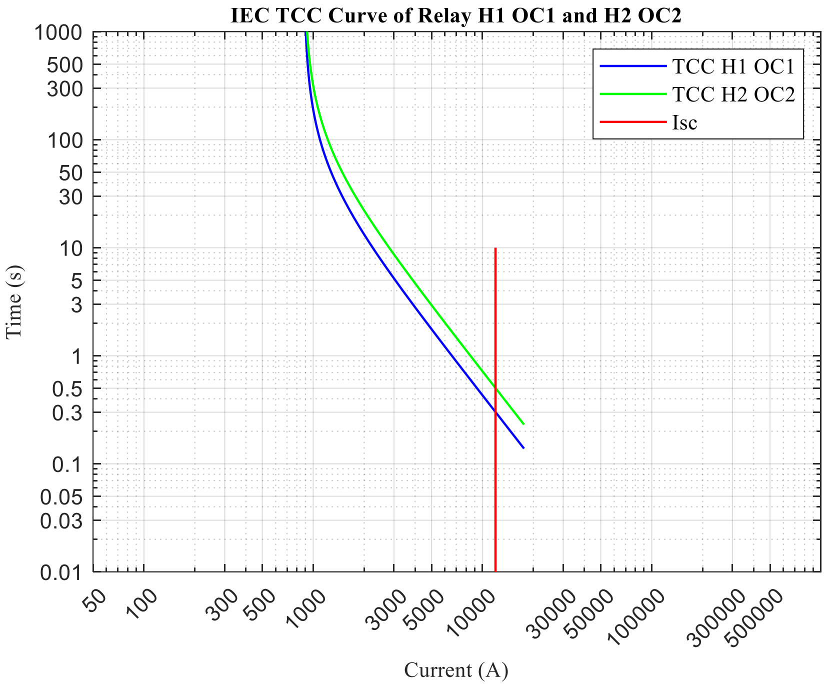


Figure 4.13 The TCC Curve of Relay H1 OC1 and H2 OC2 for Case Study 1 Using MATLAB 2018b

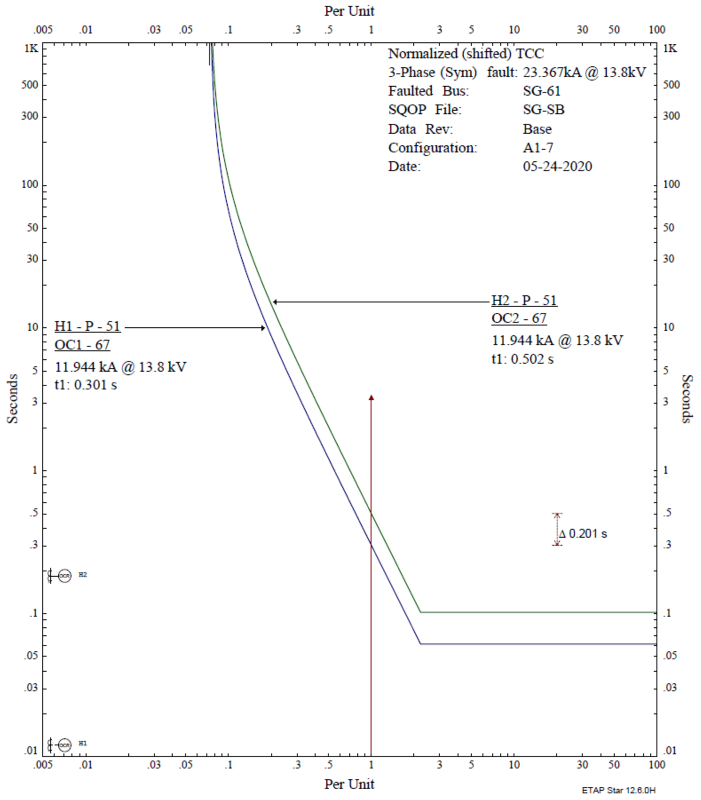


Figure 4.14 The TCC Curve of Relay H1 OC1 and H2 OC2 for Case Study 1 Using ETAP 12.6.0

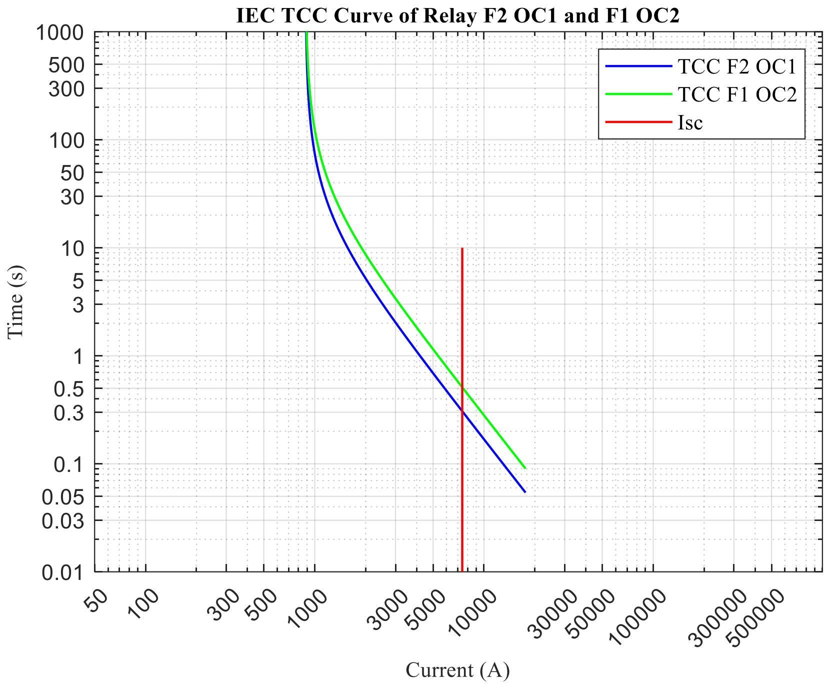


Figure 4.15 The TCC Curve of Relay F2 OC1 and F1 OC2 for Case Study 1 Using MATLAB 2018b

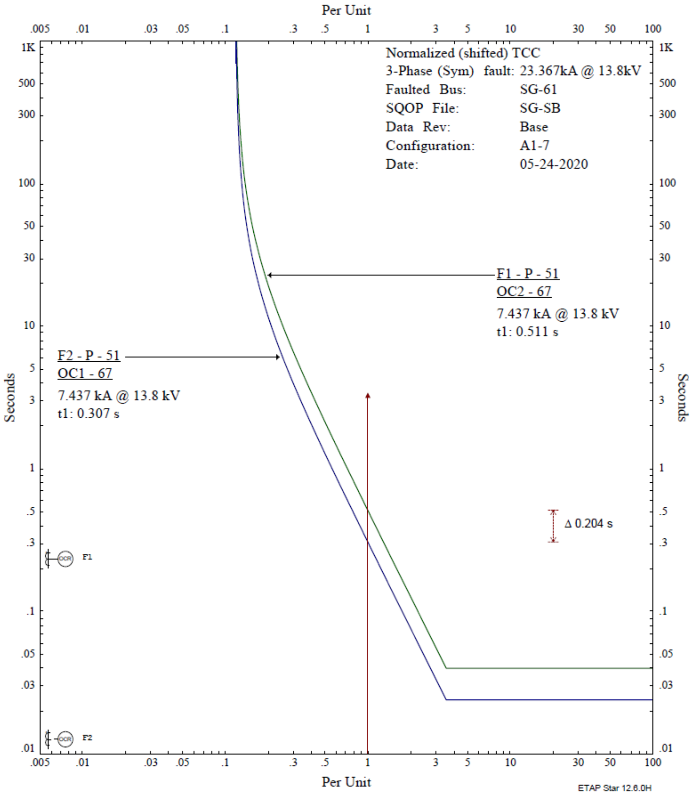


Figure 4.16 The TCC Curve of Relay F2 OC1 and F1 OC2 for Case Study 1 Using ETAP 12.6.0

- Three phases short circuit current on bus SG-SB

The relay F1 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus SG-SB and the relay F2 OC2 is the backup relay. For another pairs relay, the relay G1 OC1 is the primary relay of the backup relay G2 OC2. So, the tripping sequence of DOCRs in ETAP 12.6.0 while faulting on the bus SG_SB is displayed in Figure 4.17. Figure 4.18 and Figure 4.20 are the TCC curve of pairs relay that plotted by MATLAB 2018b. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.19 and Figure 4.21. The blue line is represented the primary relay and the green line is represented the backup relay. The red line is presented the value of the three-phase short circuit current on the bus SG_SB. It can be seen that the operating time of both primary relay F1 OC1 and G1 OC1 are 0.105s and 0.102s, respectively, while both backup relay F2 OC2 and G2 OC2 are 0.308s and 0.307s, respectively. So, the coordination time interval (CTI) of pairs relay (F1 OC1/F2 OC2) is 0.203s and 0.205s for another pairs relay (G1 OC1/G2 OC2). Because the result of *CTI* value is not perfectly at 0.2s as the *CTI* constraint in the AMFA program. Then, the *CTI* error of both pairs relay is 0.003s and 0.005s, respectively. Therefore, both pairs relay is coordinated because the operating time is larger than 0.1s for both primary pairs relay and larger than 0.3s for both backup pairs relay. Also, the *CTI* value is larger than 0.2s.

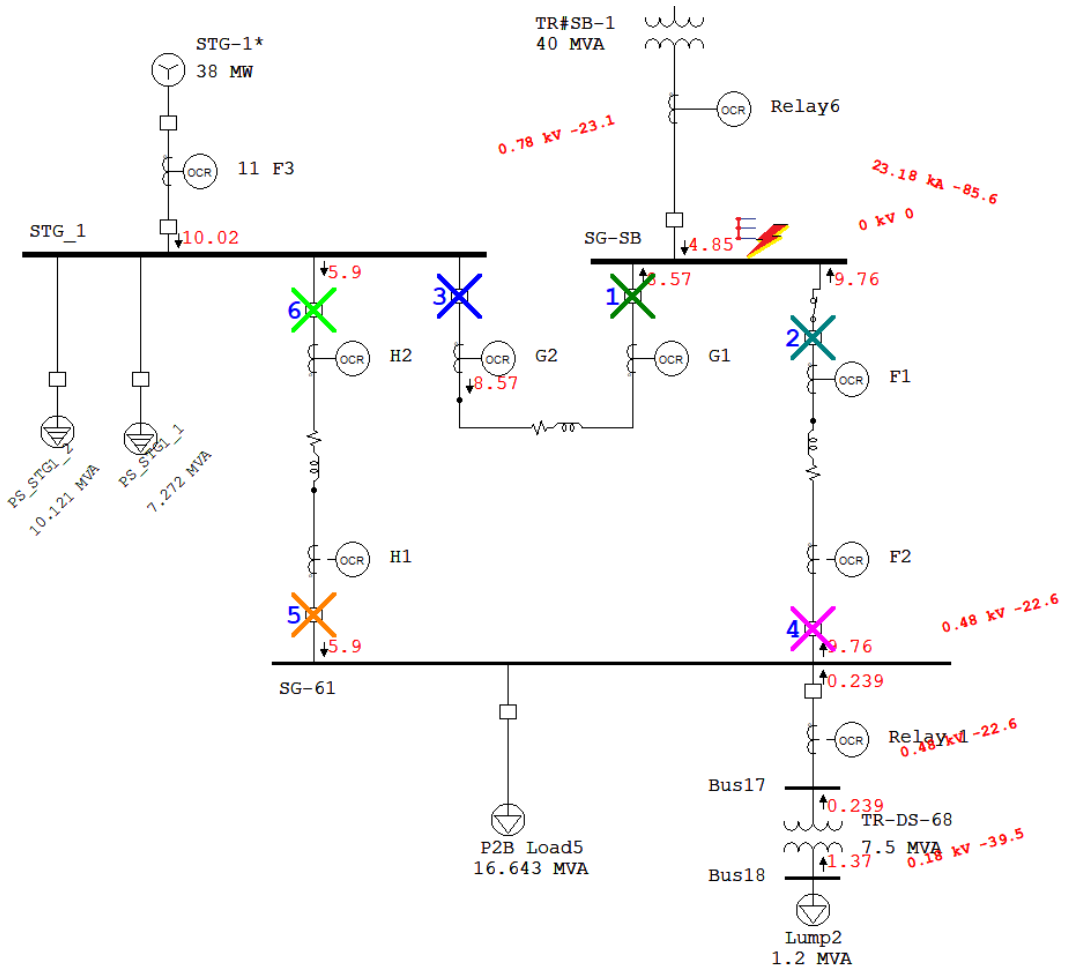


Figure 4.17 Tripping Sequence in ETAP While Faulting on the Bus SG_SB for Case Study 1

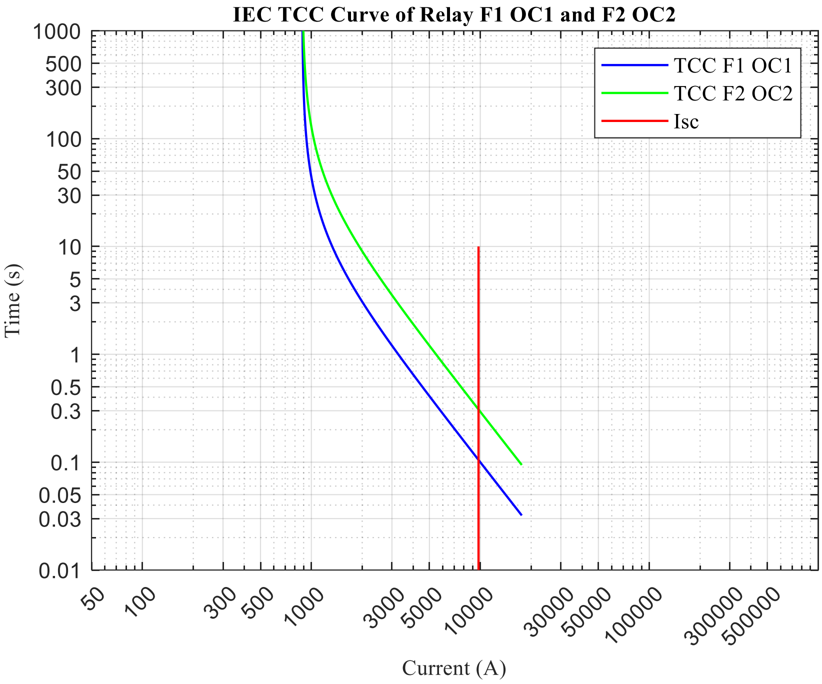


Figure 4.18 The TCC Curve of Relay F1 OC1 and F2 OC2 for Case Study 1 Using MATLAB 2018b

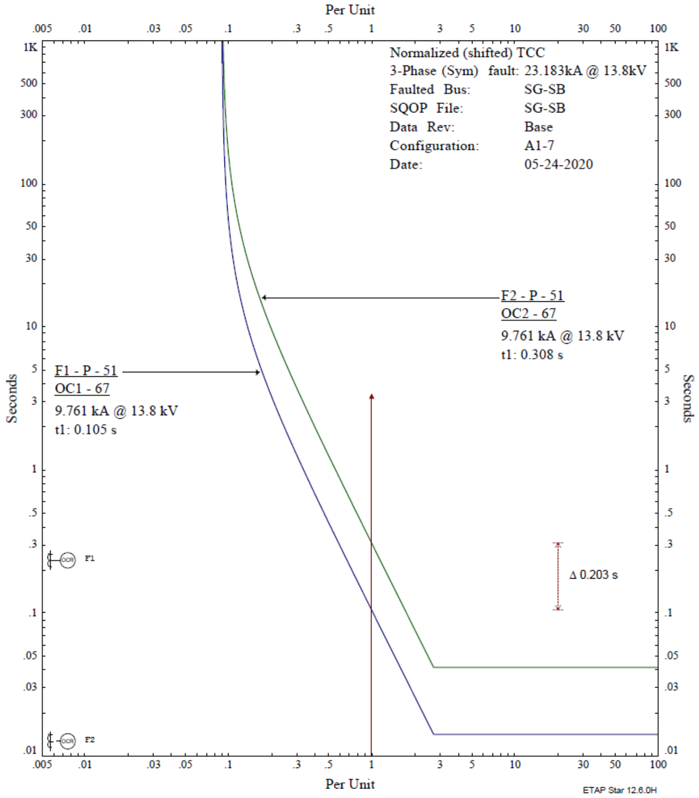


Figure 4.19 The TCC Curve of Relay F1 OC1 and F2 OC2 for Case Study 1 Using ETAP 12.6.0

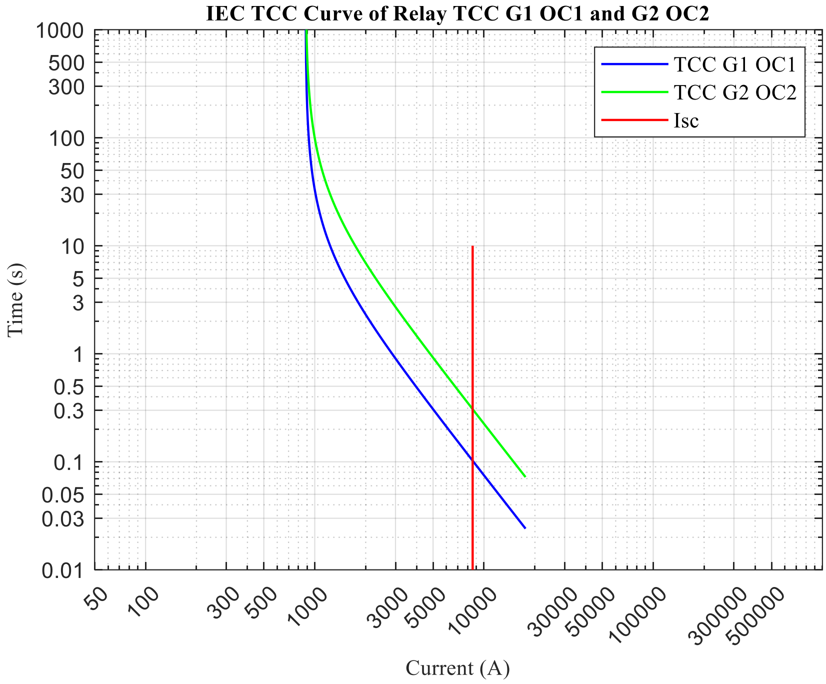


Figure 4.20 The TCC Curve of Relay G1 OC1 and G2 OC2 for Case Study 1 Using MATLAB 2018b

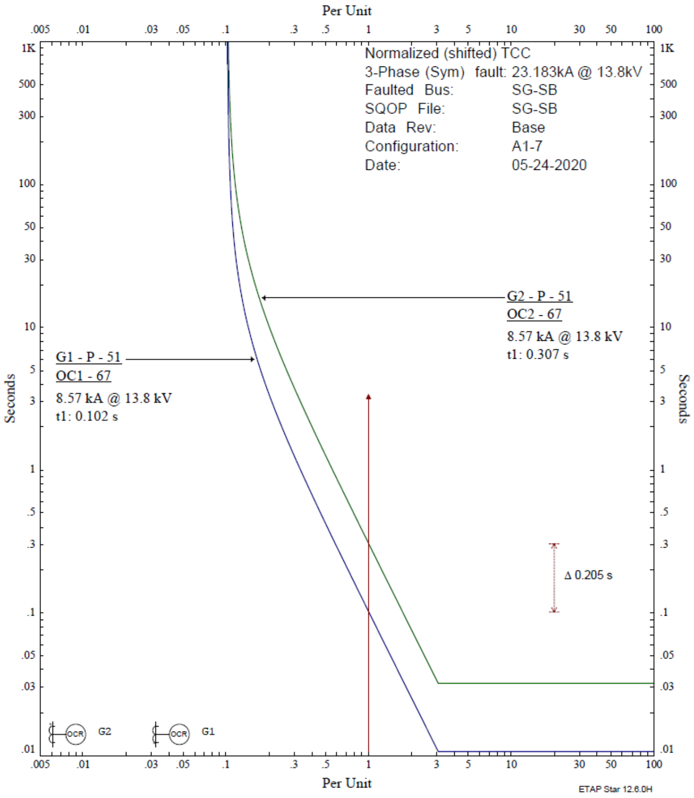


Figure 4.21 The TCC Curve of Relay G1 OC1 and G2 OC2 for Case Study 1 Using ETAP 12.6.0

4.2.7 Manual Calculation of *TDS* and *TOP* of DOCR for Case Study 1

The *TDS* and *TOP* of the primary and backup relay can calculate by the manual calculation to comparison with the AMFA as the following:

- **Relay H2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-2
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	5130 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{5130}{880}\right)^2 - 1\right)}{80} = 0.041\,\mathrm{s}$$

Because the TDS step is 0.01, the selected TDS is 0.05 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.05}{\left(\left(\frac{5130}{880}\right)^{2} - 1\right) * 1} = 0.121\,\text{s}$$

– **Relay G2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-1
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	3530 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^{B} - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^{B} - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1*1*\left(\left(\frac{3530}{880}\right)^2 - 1\right)}{80} = 0.018 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.02 s

- Operating Time Relay

$$t_{op} = \frac{80*0.02}{\left(\left(\frac{3530}{880}\right)^2 - 1\right)*1} = 0.106$$

– **Relay G1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	CB278
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	8570 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A*TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)*\beta}$$

$$TDS = \frac{t_{op}*\beta*\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1*1*\left(\left(\frac{8570}{880}\right)^2 - 1\right)}{80} = 0.117 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.12 s

- Operating Time Relay

$$t_{op} = \frac{80*0.12}{\left(\left(\frac{8570}{880}\right)^2 - 1\right)*1} = 0.102 \text{ s}$$

– **Relay F1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-TSTG1-01
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	9760 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A*TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)*\beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{9760}{880} \right)^2 - 1 \right)}{80} = 0.152 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.16 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.16}{\left(\left(\frac{9760}{880} \right)^2 - 1 \right) * 1} = 0.105 \text{ s}$$

- **Relay F2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I1(4)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	7440 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.3s.

$$TDS = \frac{0.3 * 1 * \left(\left(\frac{7440}{880}\right)^2 - 1\right)}{80} = 0.264 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.27 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.27}{\left(\left(\frac{7440}{880}\right)^2 - 1\right) * 1} = 0.306 \text{ s}$$

– **Relay H1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I2(6)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	11940 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

866.8< *Iset Pickup* <1182

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.3s.

$$TDS = \frac{0.3 * 1 * \left(\left(\frac{11940}{880}\right)^2 - 1\right)}{80} = 0.686\,\mathrm{s}$$

Because the TDS step is 0.01, the selected TDS is 0.69 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.69}{\left(\left(\frac{11940}{880}\right)^2 - 1\right) * 1} = 0.301\,\mathrm{s}$$

– **Relay H1 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I2(6)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	5130 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes
- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. H1 OC2 is the backup of relay H2 OC1, so the selection of operating time is 0.121+0.2=0.321s.

  $$TDS = \frac{0.321 * 1 * \left(\left(\frac{5130}{880}\right)^2 - 1\right)}{80} = 0.132 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.14 s
- Operating Time Relay

  $$t_{op} = \frac{80 * 0.14}{\left(\left(\frac{5130}{880}\right)^2 - 1\right) * 1} = 0.340 \text{ s}$$

– **Relay G1 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	CB278
CT	2000/5 A
FLA	788 A
Pickup Step	0.01

Data Specification	
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	3530 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes
- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. G1 OC2 is the backup of relay G2 OC1, so the selection of operating time is 0.106+0.2=0.306s.

$$TDS = \frac{0.306 * 1 * \left(\left(\frac{3530}{880}\right)^2 - 1\right)}{80} = 0.057 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.06 s
- Operating Time Relay

$$t_{op} = \frac{80 * 0.06}{\left(\left(\frac{3530}{880}\right)^2 - 1\right) * 1} = 0.318 \text{ s}$$

– **Relay G2 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000

Data Specification	
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-1
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	8570 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes
- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. G2 OC2 is the backup of relay G1 OC1, so the selection of operating time is 0.102+0.2=0.302s.

  $$TDS = \frac{0.302 * 1 * \left(\left(\frac{8570}{880}\right)^2 - 1\right)}{80} = 0.354\ \text{s}$$

  Because the TDS step is 0.01, the selected TDS is 0.36 s
- Operating Time Relay

  $$t_{op} = \frac{80 * 0.354}{\left(\left(\frac{8570}{880}\right)^2 - 1\right) * 1} = 0.307\ \text{s}$$

- **Relay F2 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I1(4)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	9760 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. F2 OC2 is the backup of relay F1 OC1, so the selection of operating time is 0.105+0.2=0.305s.

$$TDS = \frac{0.305 * 1 * \left(\left(\frac{9760}{880}\right)^2 - 1\right)}{80} = 0.465\,\text{s}$$

Because the TDS step is 0.01, the selected TDS is 0.47 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.47}{\left(\left(\frac{9760}{880}\right)^2 - 1\right) * 1} = 0.308\ \text{s}$$

- **Relay F1 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-TSTG1-01
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	7440 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. F1 OC2 is the backup of relay F2 OC1, so the selection of operating time is 0.306+0.2=0.506s.

$$TDS = \frac{0.506 * 1 * \left(\left(\frac{7440}{880} \right)^2 - 1 \right)}{80} = 0.445 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.45 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.45}{\left(\left(\frac{7440}{880} \right)^2 - 1 \right) * 1} = 0.511 \text{s}$$

- **Relay H2 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-2
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	11940 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. H2 OC2 is the backup of relay H1 OC1, so the selection of operating time is 0.301+0.2=0.501s.

$$TDS = \frac{0.501 * 1 * \left(\left(\frac{11940}{880} \right)^2 - 1 \right)}{80} = 1.146\,\mathrm{s}$$

Because the TDS step is 0.01, the selected TDS is 1.15 s

- Operating Time Relay

$$t_{op} = \frac{80 * 1.15}{\left(\left(\frac{11940}{880} \right)^2 - 1 \right) * 1} = 0.502\,\mathrm{s}$$

4.2.8 Protection Coordination of Single Setting Directional Overcurrent Relay

The time dial and operating time setting of primary and backup directional overcurrent relay can be calculated in the following:

- **Three Phase Short Circuit Current on Bus STG_1**
  - **Primary Relay H2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-2
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	5130 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{5130}{880}\right)^2 - 1\right)}{80} = 0.041\ \text{s}$$

  Because the TDS step is 0.01, the selected TDS is 0.05 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.05}{\left(\left(\frac{5130}{880}\right)^2 - 1\right) * 1} = 0.121\ \text{s}$$

- **Primary Relay G2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-1
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01

Data Specification	
Constraint TDS	0.02-2
IscMax	3530 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes
- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

  $$TDS = \frac{0.1 * 1 * \left(\left(\frac{3530}{880}\right)^2 - 1\right)}{80} = 0.018 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.02 s
- Operating Time Relay

  $$t_{op} = \frac{80 * 0.02}{\left(\left(\frac{3530}{880}\right)^2 - 1\right) * 1} = 0.106$$

– **Backup Relay F2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I1(4)

Data Specification	
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	9760 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes
- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. F2 OC1 is the backup of relay H2 OC1 and G2 OC1. The time dial setting of the backup relay is the same as the primary relay H2 OC1 Because F2 OC1 is the single setting DOCR.

  $$TDS = \frac{0.3 * 1 * \left(\left(\frac{7440}{880}\right)^2 - 1\right)}{80} = 0.264 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.27 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.27}{\left(\left(\frac{1214}{880}\right)^{2} - 1\right) * 1} = 23.91\,\text{s}$$

– **Three Phase Short Circuit Current on Bus SG_SB**

- **Primary Relay G1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	CB278
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	8570 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^{B} - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^{B} - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{8570}{880} \right)^2 - 1 \right)}{80} = 0.117 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.12 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.12}{\left(\left(\frac{8570}{880} \right)^2 - 1 \right) * 1} = 0.102 \text{ s}$$

- **Primary Relay F1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-TSTG1-01
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	9760 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1*1*\left(\left(\frac{9760}{880}\right)^2-1\right)}{80} = 0.152\text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.16 s

- Operating Time Relay

$$t_{op} = \frac{80*0.16}{\left(\left(\frac{9760}{880}\right)^2-1\right)*1} = 0.105\text{ s}$$

- **Backup Relay H1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I2(6)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	5130 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A*TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B-1\right)*\beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. H1 OC1 is the backup of relay G1 OC1 and F1 OC1. The time dial setting of this backup relay is the same as the primary relay H1 OC1 Because H1 OC1 is the single setting DOCR.

$$TDS = \frac{0.3 * 1 * \left(\left(\frac{11940}{880} \right)^2 - 1 \right)}{80} = 0.686\,\mathrm{s}$$

Because the TDS step is 0.01, the selected TDS is 0.69 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.69}{\left(\left(\frac{5900}{880} \right)^2 - 1 \right) * 1} = 1.25\,\mathrm{s}$$

– **Three Phase Short circuit current on bus SG_61**

- **Primary Relay F2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I1(4)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	7440 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.3s.

$$TDS = \frac{0.3 * 1 * \left(\left(\frac{7440}{880}\right)^2 - 1\right)}{80} = 0.264 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.27 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.27}{\left(\left(\frac{7440}{880}\right)^2 - 1\right) * 1} = 0.306 \text{ s}$$

- **Primary Relay H1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I2(6)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	11940 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.3s.

  $$TDS = \frac{0.3 * 1 * \left(\left(\frac{11940}{880}\right)^2 - 1\right)}{80} = 0.686\,\mathrm{s}$$

  Because the TDS step is 0.01, the selected TDS is 0.69 s

- Operating Time Relay

  $$t_{op} = \frac{80 * 0.69}{\left(\left(\frac{11940}{880}\right)^2 - 1\right) * 1} = 0.301\,\mathrm{s}$$

- **Backup Relay G1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	CB278
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01

Data Specification	
Constraint TDS	0.02-2
IscMax	3530 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. G1 OC1 is the backup of relay F2 OC1 and H1 OC1. The time dial setting of this backup relay is the same as the primary relay G1 OC1 Because G1 OC1 is the single setting DOCR.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{8570}{880}\right)^2 - 1\right)}{80} = 0.117 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.12 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.12}{\left(\left(\frac{2700}{880}\right)^2 - 1\right) * 1} = 1.14 \text{ s}$$

The result of *TDS* and *TOP* of all primary and backup relay will be applied in the ETAP 12.6.0 software to validate the protection coordination. The TCC of all primary and backup relay is presented in the following figure.

- Three phases short circuit current on bus SG_SB

The relay G1 OC1 and F1 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus SG_SB and H1 OC1 will be the backup relay. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.22. It can be seen that the operating time of both primary relay G1 OC1 and F1 OC1 are 0.102s and 0.105s, respectively, while the backup relay H1 OC1 is 1.25s. Thus, the coordination time interval (*CTI*) between the primary relay F1 OC1 and backup relay H1 OC1 is 1.14s. It is not less than 0.2s but larger than 0.5s of the *CTI* constraint. So, the relay protection coordination when the fault happens on bus SG_SB will be missed the coordination. Form this point of view, it showed that the single setting DOCR contained the maximum operation. It is not useful in the ring distribution system which consisted of multi-sources.

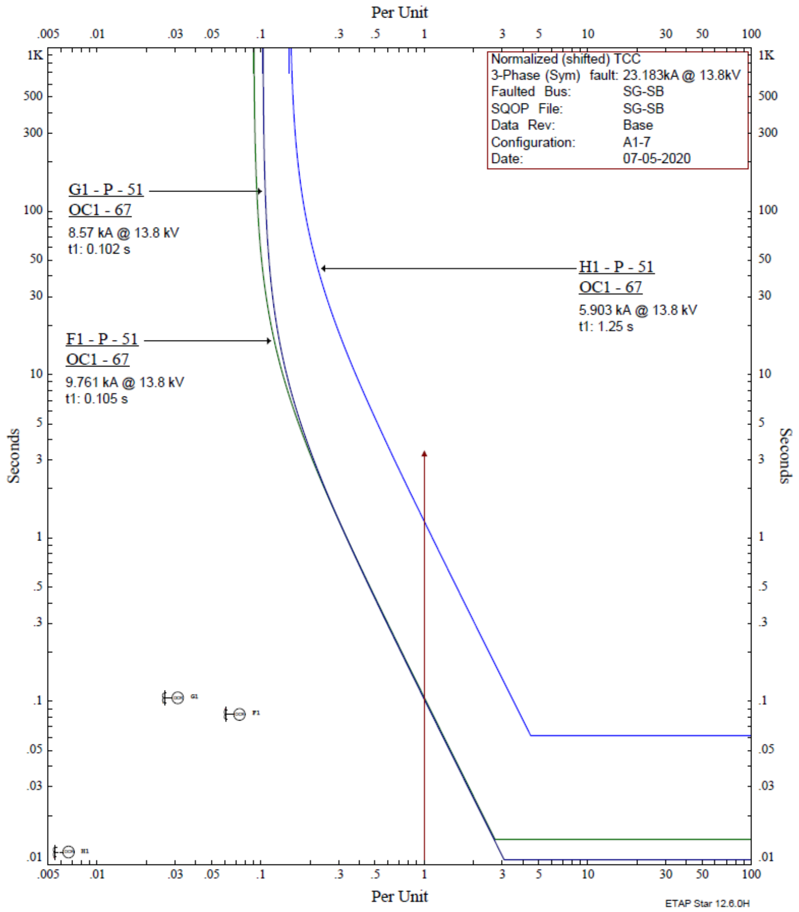


Figure 4.22 The TCC Curve of Single Setting DOCR F1 OC1 and H1 OC1 for Case Study 1 Using ETAP 12.6.0

- Three phases short circuit current on bus SG_61

The relay H1 OC1 and F2 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus SG_61 and G1 OC1 will be the backup relay. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.23. It can be seen that the operating time of both primary relay H1 OC1 and F2 OC1 are 0.301s and 0.307s, respectively, while the backup relay G1 OC1 is 1.14s. Thus, the coordination time interval (*CTI*) between the primary relay F2 OC1 and backup relay G1 OC1 is 0.83s. It is not less than 0.2s but larger than 0.5s of the *CTI* constraint. So, the relay protection coordination when the fault happens on bus SG_61 will be missed the coordination. Form this point of view, it showed that the single setting DOCR contained the maximum operation. It is not useful in the ring distribution system which consisted of multi-sources.

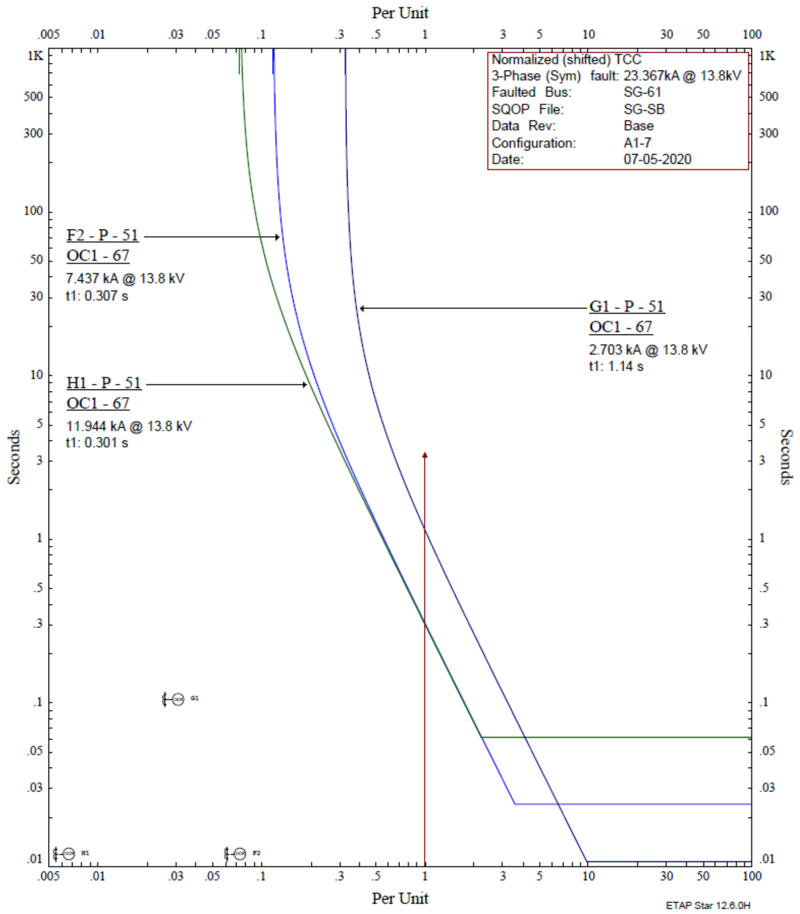


Figure 4.23 The TCC Curve of Single Setting DOCR F2 OC1 and G1 OC1 for Case Study 1 Using ETAP 12.6.0

– Three phases short circuit current on bus STG_1

The relay H2 OC1 and G2 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus STG_1 and F2 OC1 will be the backup relay. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.24. It can be seen that the operating time of both primary relay H2 OC1 and G2 OC1 are 0.121s and 0.106s, respectively, while the backup relay F2 OC1 is 23.9s. Thus, the coordination time interval (*CTI*) between the primary relay H2 OC1 and backup relay F2 OC1 is 23.77s. It is not less than 0.2s but larger than 0.5s of the *CTI* constraint. So, the relay protection coordination when the fault happens on bus STG_1 will be missed the coordination. Form this point of view, it showed that the single setting DOCR contained the maximum operation. It is not useful in the ring distribution system which consisted of multi-sources.

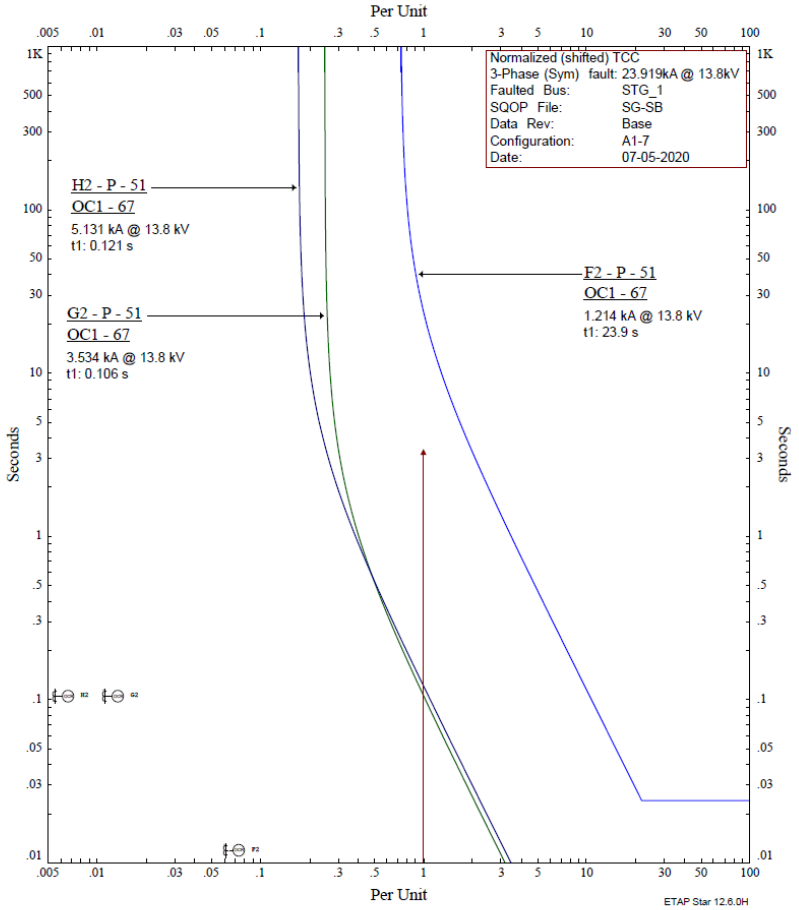


Figure 4.24 The TCC Curve of Single Setting DOCR H2 OC1 and F2 OC1 for Case Study 1 Using ETAP 12.6.0

4.3 Case Study 2: Distributed Generator (5006-J) Disconnected

In this case study 2, the Optimal coordination of DOCRs using the AMFA method is investigated in the ring distribution system when distributed generator (5006-J) disconnected. In this condition, the value of the three-phase short circuit current (0.5 cycles) is smaller than the first conditions as stated in Table 4.2. Four types of IEC TCC curve that needed to optimal coordination protection and selected the best IEC TCC curve for the system with the minimum value of the total operating time relay.

4.3.1 The Randomize Position of Time Dial Setting (*TDS*) in Case Study 2

The AMFA program will be started to randomize the position of time dial setting before starting the main loop. So, an example of the randomized position of TDS and TOP of the primary H2 OC1 and backup H1 OC2 relay in case of the IEC extremely inverse (EINV) curve is defined in Table 4.14 and Table 4.15. It consisted of 30 firefly populations that are randomized for the first iteration of the AMFA. The *TDS* value of each DOCR is represented to the firefly population of the AMFA method. Thus, the randomization population of the primary and backup relay is presented in Figure 4.25 and Figure 4.26.

Table 4.14 The Randomized Position of *TDS* and *TOP* of Primary Relay H2 OC1 in Case of IEC EINV Curve for Case Study 2

Populations	***TDS (s)***	***TOP (s)***	**Populations**	***TDS (s)***	***TOP (s)***
1	0.62	1.573	16	0.49	1.243
2	0.64	1.623	17	1.71	4.337
3	1.24	3.145	18	0.81	2.054
4	0.18	0.457	19	0.31	0.786
5	0.33	0.837	20	0.61	1.547
6	0.49	1.243	21	1.73	4.388
7	1.63	4.134	22	0.25	0.634
8	0.94	2.384	23	1.83	4.641
9	0.97	2.460	24	1.82	4.616
10	1.2	3.044	25	0.92	2.333

Populations	***TDS (s)***	***TOP (s)***	**Populations**	***TDS (s)***	***TOP (s)***
11	0.11	0.279	26	1.19	3.018
12	1.87	4.743	27	1.73	4.388
13	1.44	3.652	28	1.86	4.718
14	0.91	2.308	29	0.32	0.812
15	0.71	1.801	30	0.94	2.384

Table 4.15 The Randomized Position of *TDS* and *TOP* of Backup Relay H1 OC2 in Case of IEC EINV Curve for Case Study 2

Populations	***TDS (s)***	***TOP (s)***	**Populations**	***TDS (s)***	***TOP (s)***
1	0.18	0.457	16	1.62	4.109
2	1.05	2.663	17	0.08	0.203
3	1.39	3.525	18	1.86	4.718
4	1.53	3.881	19	0.6	1.522
5	0.74	1.877	20	1.6	4.058
6	0.12	0.304	21	0.51	1.294
7	0.24	0.609	22	0.61	1.547
8	0.68	1.725	23	1.83	4.641
9	0.82	2.080	24	1.66	4.210
10	0.65	1.649	25	0.94	2.384
11	0.04	0.101	26	0.95	2.409
12	0.8	2.029	27	1.63	4.134
13	1.33	3.373	28	0.75	1.902
14	1.41	3.576	29	1.91	4.844
15	0.75	1.902	30	0.75	1.902

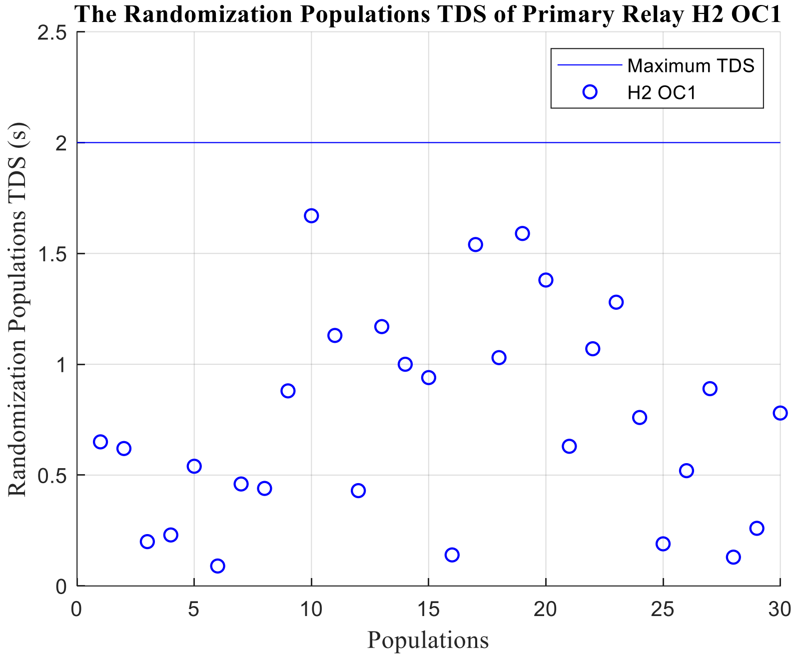


Figure 4.25 The Randomization Population *TDS* of Primary Relay H2 OC1 for Case Study 2

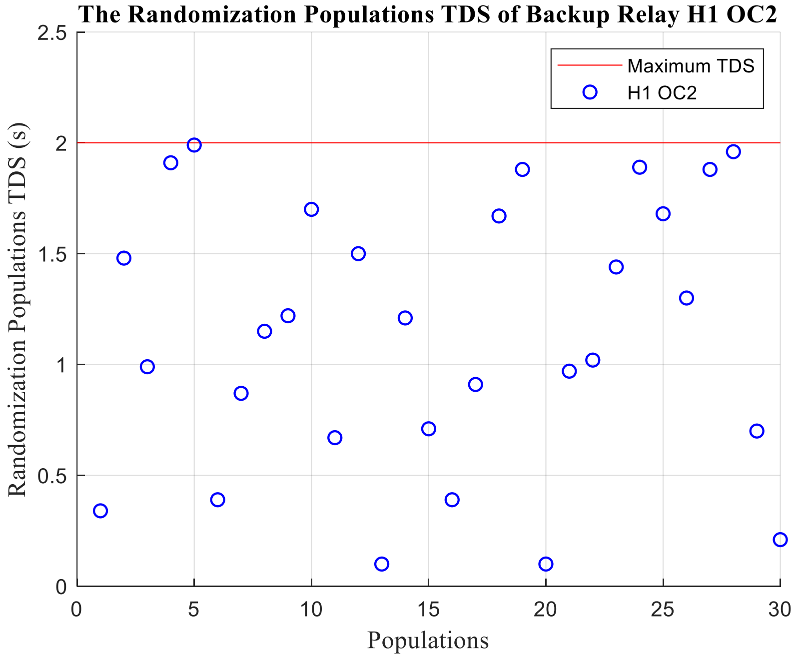


Figure 4.26 The Randomization Population *TDS* of Backup Relay H1 OC2 for Case Study 2

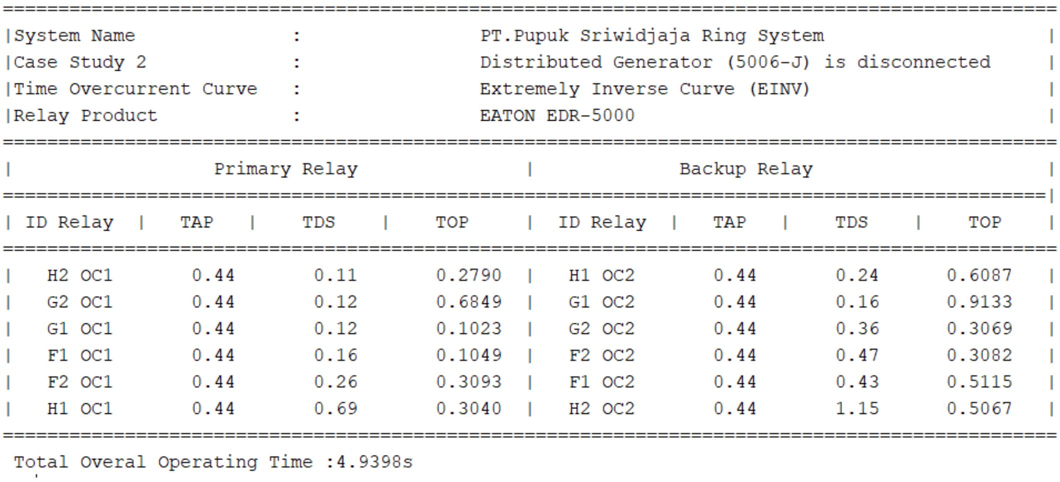
The randomized position of *TDS* and *TOP* will become the input of the main loop of the AMFA that running from the first iteration to 100 of maximum iteration. The main loop of the AMFA is the place where each population of *TDS* is compared to each other and moved toward the population of *TDS* that consisted of the minimum value of operating time. Thus, the new population of *TDS* and *TOP* of primary relay H2 OC1 and backup relay H1 OC2 in the IEC extremely inverse curve condition of the first iteration of the main loop is offered in Table 4.16 and Table 4.17.

Table 4.16 The New Population of *TDS* and *TOP* of Primary Relay H2 OC1 in IEC EINV Curve of the First Iteration for Case Study 2

New Populations	***TDS (s)***	***TOP (s)***	**New Populations**	***TDS (s)***	***TOP (s)***
1	0.41	1.040	16	0.22	0.558
2	0.36	0.913	17	1.48	3.754
3	0.88	2.232	18	0.7	1.775
4	0.18	0.457	19	0.41	1.040
5	0.23	0.583	20	0.41	1.040
6	0.25	0.634	21	1.38	3.500
7	1.28	3.246	22	0.2	0.507
8	0.92	2.333	23	1.38	3.500
9	1.06	2.688	24	1.14	2.891
10	1.16	2.942	25	0.86	2.181
11	1.16	2.942	26	0.93	2.359
12	1.75	4.439	27	1.4	3.551
13	1.1	2.790	28	1.68	4.261
14	0.82	2.080	29	0.19	0.482
15	0.28	0.710	30	0.71	1.801

Table 4.17 The New Population of *TDS* and *TOP* of Backup Relay H1 OC2 in IEC EINV Curve of the First Iteration for Case Study 2

New Populations	***TDS* (s)**	***TOP* (s)**	**New Populations**	***TDS* (s)**	***TOP* (s)**
1	0.26	0.659	16	1.41	3.576
2	1.12	2.841	17	0.6	1.522
3	0.84	2.131	18	1.26	3.196
4	1.23	3.120	19	0.58	1.471
5	0.46	1.167	20	1.49	3.779
6	0.16	0.406	21	0.6	1.522
7	0.16	0.406	22	0.51	1.294
8	0.87	2.207	23	0.91	2.308
9	0.81	2.054	24	1.37	3.475
10	0.48	1.217	25	0.95	2.409
11	0.04	0.101	26	0.82	2.080
12	0.65	1.649	27	1.39	3.525
13	0.84	2.131	28	0.83	2.105
14	0.83	2.105	29	1.69	4.286
15	0.76	1.928	30	0.83	2.105



```
===============================================================================
|System Name              :              PT.Pupuk Sriwidjaja Ring System          |
|Case Study 2             :              Distributed Generator (5006-J) is disconnected     |
|Time Overcurrent Curve   :              Extremely Inverse Curve (EINV)           |
|Relay Product            :              EATON EDR-5000                           |
===============================================================================
|                Primary Relay                |              Backup Relay          |
==============================================================================|
| ID Relay |   TAP   |    TDS    |    TOP    | ID Relay |   TAP   |    TDS    |    TOP    |
===============================================================================
|   H2 OC1      0.44       0.11       0.2790  |  H1 OC2     0.44       0.24       0.6087   |
|   G2 OC1      0.44       0.12       0.6849  |  G1 OC2     0.44       0.16       0.9133   |
|   G1 OC1      0.44       0.12       0.1023  |  G2 OC2     0.44       0.36       0.3069   |
|   F1 OC1      0.44       0.16       0.1049  |  F2 OC2     0.44       0.47       0.3082   |
|   F2 OC1      0.44       0.26       0.3093  |  F1 OC2     0.44       0.43       0.5115   |
|   H1 OC1      0.44       0.69       0.3040  |  H2 OC2     0.44       1.15       0.5067   |
===============================================================================
 Total Overal Operating Time :4.9398s
```

Figure 4.27 The *TDS* and *TOP* of all DOCR in Case of IEC Extremely Inverse Curve of the First Iteration for Case Study 2

As we can see the result of *TDS* and operating time of all DOCR in case of IEC Extremely inverse curve of the first iteration in the main loop of AMFA in Figure 4.27. The program has shown the result of the value of operating time of primary relay H2 OC1 in the first iteration is 0.2790s with the time dial setting 0.11s that is the position 11 of the 30 firefly populations as classified in Table 4.14. For the backup relay, the value of operating time and the time dial setting in the first iteration is 0.6087s and 0.24s, respectively. It is the 7 position of the 30 firefly populations. The result of another pairs relay in the first iteration is depicted in Figure 4.27.

4.3.2 The Time Dial Setting (*TDS*) and Relay Operating Time Results in Case Study 2

After finished running the AMFA program in of all IEC TCC curve with 100 of maximum iteration, the result of *TDS* and the minimum operating time of all DOCR in the PT. Pupuk Sriwidjaja ring distribution system is demonstrated in Table 4.18, Table 4.19, Table 4.20 and Table 4.21.

Table 4.18 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC NINV Curve for Case Study 2

IEC Normal Inverse Curve (NINV)									
Primary Relay					**Backup Relay**				
Relay ID	**I_P (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**	**Relay ID**	**I_P (A)**	***TAP***	***TDS* (s)**	***TOP* (s)**
H2 OC1	880	0.44	0.03	0.119	H1 OC2	880	0.44	0.09	0.356
G2 OC1	880	0.44	0.02	0.102	G1 OC2	880	0.44	0.06	0.306
G1 OC1	880	0.44	0.04	0.120	G2 OC2	880	0.44	0.11	0.331
F1 OC1	880	0.44	0.04	0.114	F2 OC2	880	0.44	0.12	0.341
F2 OC1	880	0.44	0.10	0.325	F1 OC2	880	0.44	0.17	0.552
H1 OC1	880	0.44	0.12	0.314	H2 OC2	880	0.44	0.20	0.524
Objective Function					3.5016s				

Table 4.19 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC VINV Curve for Case Study 2

IEC Very Inverse Curve (VINV)									
Primary Relay					**Backup Relay**				
Relay ID	I_P **(A)**	***TAP***	***TDS*** **(s)**	***TOP*** **(s)**	**Relay ID**	I_P **(A)**	***TAP***	***TDS*** **(s)**	***TOP*** **(s)**
H2 OC1	880	0.44	0.04	0.115	H1 OC2	880	0.44	0.11	0.316
G2 OC1	880	0.44	0.03	0.141	G1 OC2	880	0.44	0.08	0.376
G1 OC1	880	0.44	0.07	0.108	G2 OC2	880	0.44	0.20	0.309
F1 OC1	880	0.44	0.08	0.107	F2 OC2	880	0.44	0.23	0.308
F2 OC1	880	0.44	0.17	0.316	F1 OC2	880	0.44	0.28	0.521
H1 OC1	880	0.44	0.28	0.302	H2 OC2	880	0.44	0.47	0.507
Objective Function					3.4247s				

Table 4.20 Optimized Coordination Protection Result of DOCRs Using AMFA and IEC LTINV Curve for Case Study 2

IEC Long-Time Inverse Curve (LTINV)									
Primary Relay					**Backup Relay**				
Relay ID	I_P **(A)**	***TAP***	***TDS*** **(s)**	***TOP*** **(s)**	**Relay ID**	I_P **(A)**	***TAP***	***TDS*** **(s)**	***TOP*** **(s)**
H2 OC1	880	0.44	0.02	0.510	H1 OC2	880	0.44	0.03	0.765
G2 OC1	880	0.44	0.02	0.835	G1 OC2	880	0.44	0.03	1.252
G1 OC1	880	0.44	0.02	0.275	G2 OC2	880	0.44	0.04	0.549
F1 OC1	880	0.44	0.02	0.238	F2 OC2	880	0.44	0.04	0.476
F2 OC1	880	0.44	0.02	0.331	F1 OC2	880	0.44	0.04	0.641
H1 OC1	880	0.44	0.04	0.384	H2 OC2	880	0.44	0.07	0.671
Objective Function					6.9463s				

Table 4.21 Optimized Coordination Protection Result of DOCRs using AMFA and IEC EINV Curve for Case Study 2

IEC Extremely Inverse Curve (EINV)									
Primary Relay					**Backup Relay**				
Relay ID	I_P **(A)**	***TAP***	***TDS*** **(s)**	***TOP*** **(s)**	**Relay ID**	I_P **(A)**	***TAP***	***TDS*** **(s)**	***TOP*** **(s)**
H2 OC1	880	0.44	0.04	0.101	H1 OC2	880	0.44	0.12	0.304
G2 OC1	880	0.44	0.02	0.114	G1 OC2	880	0.44	0.06	0.342
G1 OC1	880	0.44	0.12	0.102	G2 OC2	880	0.44	0.36	0.307
F1 OC1	880	0.44	0.16	0.105	F2 OC2	880	0.44	0.47	0.308
F2 OC1	880	0.44	0.26	0.309	F1 OC2	880	0.44	0.43	0.512
H1 OC1	880	0.44	0.69	0.304	H2 OC2	880	0.44	1.15	0.507
Objective Function					3.3163s				

From the result in Table 4.18 to Table 4.21, all primary and backup relay in case IEC NINV, VINV, and EINV curve are operated at operating time 0.1s and 0.3s, respectively, as the operating time constraint target in AMFA program but except primary relay F2 OC1 and H1 OC1 are selected to operate at 0.3s when the fault happens on the bus SG-61 because these two relays are considered as the backup of the relay R1 when the fault occurs on the bus of the load side. In the case, IEC LTINV curve, the primary and backup relay result shown that the operating time value does not follow the operating time constraint target. Therefore, it cannot choose to protect the ring system.

4.3.3 The Result of Coordination Time Interval (*CTI*) in Case Study 2

The CTI between the primary and backup relay must be in the constraint of 0.2s to 0.5s. So, the *CTI* target in this case study is assumed to be 0.2s between each relay pairs. From the optimal result of all type IEC TCC curves in Table 4.18 to Table 4.21, the *CTI* value of all pairs relay for all IEC TCC curves is presented in Table 4.22.

Table 4.22 The Coordination Time Interval of All IEC TCC for Case Study 2

IEC TCC	**Pairs Relay**		***CTI* (s)**
	Primary Relay	**Backup Relay**	
Normal Inverse	H2 OC1	H1 OC2	0.237
	G2 OC1	G1 OC2	0.204
	G1 OC1	G2 OC2	0.210
	F1 OC1	F2 OC2	0.227
	F2 OC1	F1 OC2	0.227
	H1 OC1	H2 OC2	0.210
Very Inverse	H2 OC1	H1 OC2	0.201
	G2 OC1	G1 OC2	0.235
	G1 OC1	G2 OC2	0.201
	F1 OC1	F2 OC2	0.201
	F2 OC1	F1 OC2	0.205
	H1 OC1	H2 OC2	0.205
Long-Time Inverse	H2 OC1	H1 OC2	0.255
	G2 OC1	G1 OC2	0.417
	G1 OC1	G2 OC2	0.275
	F1 OC1	F2 OC2	0.238
	F2 OC1	F1 OC2	0.331
	H1 OC1	H2 OC2	0.288
Extremely Inverse	H2 OC1	H1 OC2	0.203
	G2 OC1	G1 OC2	0.228
	G1 OC1	G2 OC2	0.205
	F1 OC1	F2 OC2	0.203
	F2 OC1	F1 OC2	0.202
	H1 OC1	H2 OC2	0.203

4.3.4 Selecting the Best IEC TCC Curve with Minimum Value of Total Operating Time (*TOP*) in Case Study 2

The result of 4 different types of IEC TCC in Table 4.18 to Table 4.21 is shown that the IEC extremely inverse curve (EINV) has consisted of the minimum value of the total operating time within the coordination of relay protection. Besides, the comparison result of the total operating time of all IEC TCC is presented in the bar graph of Figure 4.28. The comparison result in the bar graph is displayed that the minimum value of the total operating time of the EINV curve is 3.31631s which is the smallest value among the IEC TCC curve. Thus, the suitable curve for relay protection coordination in the PT. Pupuk Sriwidjaja ring system is IEC extremely inverse curve.

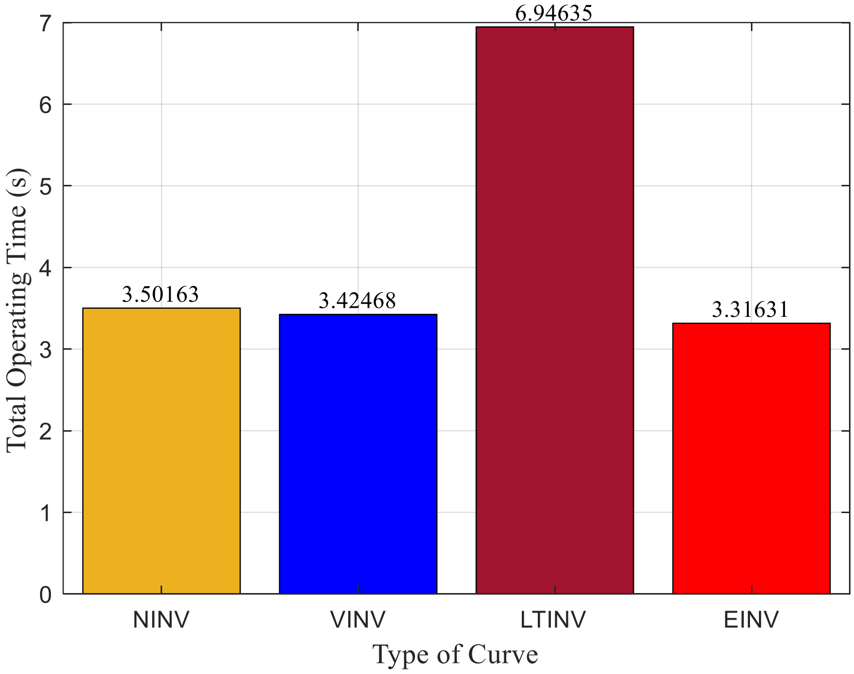


Figure 4.28 The Comparison of Total Operating Time for all IEC TCC Curve for Case Study 2

4.3.5 Result of Updating the Randomization Parameter α of Selecting Curve in Case Study 2

After selecting the IEC EINV curve is the best curve to guarantee the protection coordination of PT. Pupuk Sriwidjaja ring system. Consequently, the optimal result of this curve is done by updating the value of the randomization parameter α in every iteration of the AMFA program. The updating of the randomization parameter α of all primary and backup relay in case IEC EINV curve is presented in Figure 4.29 and Figure 4.30.

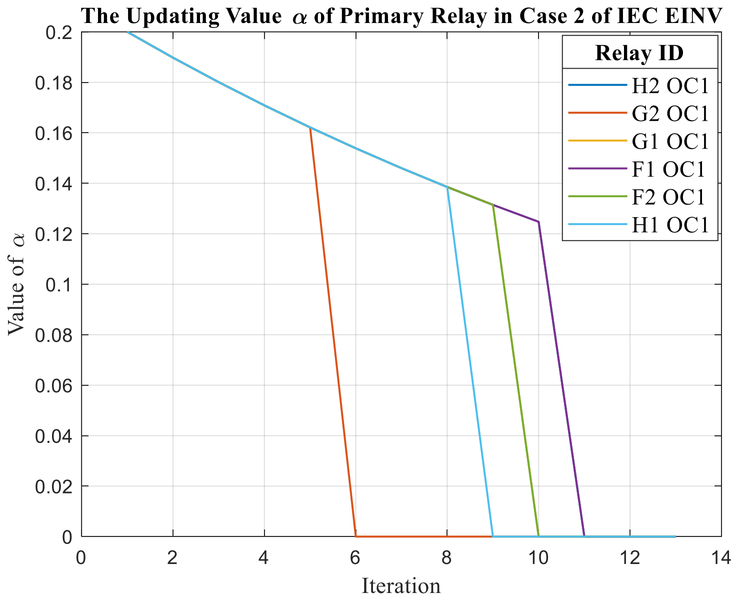


Figure 4.29 The Updating Value α of Primary Relay in Case IEC EINV Curve for Case Study 2

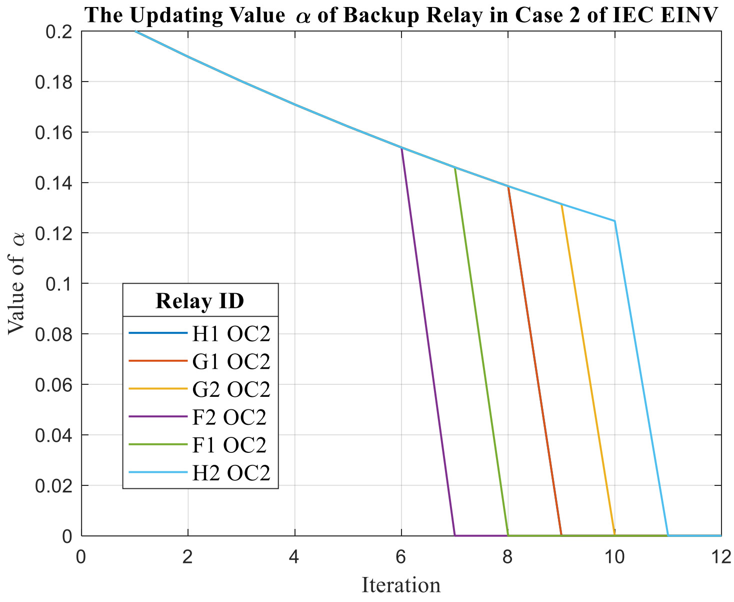


Figure 4.30 The Updating Value α of Backup Relay in Case IEC EINV Curve for Case Study 2

From Figure 4.29 and Figure 4.30, each curve is shown the updating value alpha in every iteration of the primary and backup relay. Moreover, it described the converge iteration of each primary and backup relay operating time. The primary and backup relay operating time is converged when the updating value alpha is equal to 0. As an example of primary relay G2 OC1, the updating of alpha value is equal to 0 in iteration 6, so the operating time is converged in the iteration 5. For backup relay F2 OC2, the operating time is converged in the iteration 6 of the maximum iteration. In some cases, the curve of updating value alpha is not displayed on both figures. It means that those curves are having the same value and iteration of other primary or backup relays. Like the primary relay G1 OC1 in Figure 4.29, the updating value alpha and the iteration are the same as the primary relay F2 OC1. For the backup relay H1 OC2 in Figure 4.30, the curve of updating alpha value is the same as the backup relay G1 OC2.

The result of updating value α in Figure 4.29 and Figure 4.30 of the AMFA method, it can be compared to the converge iteration with the original FA method in Table 4.23. The result of comparison iteration is shown that the updating value α in every iteration of the AMFA method is faster than the fixed value α of the original FA method. Moreover, by running both algorithms in 30 times with the same computer's processor speed and RAM. The results of processing time are not permanent and keep on varying depending upon the computer's processor speed and RAM. Hence, the comparison of the average processing time for calculated the optimal value is presented in Table 4.24.

Table 4.23 The Comparison of Converge Iteration of the AMFA to the Original FA for Case Study 2

Relay ID	***TDS (s)***		***TOP (s)***		**Iteration**	
	AMFA	**FA**	**AMFA**	**FA**	**AMFA**	**FA**
H2 OC1	0.04	0.04	0.101	0.101	10	12
G2 OC1	0.02	0.02	0.114	0.114	5	6
G1 OC1	0.12	0.12	0.102	0.102	9	12
F1 OC1	0.16	0.16	0.105	0.105	10	12
F2 OC1	0.26	0.26	0.309	0.309	9	12

Relay ID	*TDS (s)*		*TOP (s)*		Iteration	
	AMFA	FA	AMFA	FA	AMFA	FA
H1 OC1	0.69	0.69	0.304	0.304	8	10
H1 OC2	0.12	0.12	0.304	0.304	8	11
G1 OC2	0.06	0.06	0.342	0.342	8	10
G2 OC2	0.36	0.36	0.307	0.307	9	9
F2 OC2	0.47	0.47	0.308	0.308	6	11
F1 OC2	0.43	0.43	0.512	0.512	7	13
H2 OC2	1.15	1.15	0.507	0.507	10	10

Table 4.24 The Comparison of Processing Time Between the AMFA and the Original FA for Case Study 2

Number of Running	AMFA	FA
1	1.607	2.12
2	1.648	1.858
3	1.656	1.821
4	1.97	1.866
5	1.856	2.056
6	1.582	2.334
7	1.662	1.699
8	1.742	1.802
9	1.467	1.711
10	1.557	1.793
11	1.536	1.706
12	1.63	1.885
13	1.596	1.918
14	1.629	1.777
15	1.626	1.793
16	1.805	2.095
17	1.558	1.766
18	1.675	1.896
19	1.682	1.704

Number of Running	AMFA	FA
20	1.838	1.849
21	1.768	1.848
22	1.861	1.867
23	1.764	1.688
24	1.699	1.975
25	1.774	1.649
26	1.879	1.769
27	1.53	1.911
28	1.714	1.869
29	1.595	1.673
30	1.745	1.865
Average Processing Time (s)	1.688	1.852

4.3.6 Protection Coordination Analysis Using the AMFA Result in Case Study 2

The result of protection coordination is analyzed by plotting the IEC TCC of the selecting curve in the MATLAB 2018b programming and the ETAP 12.6.0 software. The plotting of the TCC curve can be established the operating time of each relay and the coordination time interval of each pairs relay. To plotting the IEC extremely inverse curve that is the selecting curve for the system, three locations of three phases short circuit current on the bus is presented. For the TCC of IEC normal and very inverse which is not selected for the system is presented in APPENDIX C and APPENDIX D.

– Three phases short circuit current on bus STG_1

The relay H2 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus STG_1 and the relay H1 OC2 is the backup relay. For another pairs relay, the relay G2 OC1 is the primary relay of the backup relay G1 OC2. So, the tripping sequence of DOCRs in ETAP 12.6.0 while faulting on the bus STG_1 is displayed in Figure 4.31. Figure 4.32 and Figure 4.34 are the TCC curve of pairs relay that plotted by MATLAB 2018b. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.33 and Figure

4.35. The blue line is represented the primary relay and the green line is represented the backup relay. The red line is presented the value of the three-phase short circuit current on the bus STG_1. It can be seen that the operating time of both primary relay H2 OC1 and G2 OC1 are 0.101s and 0.114s, respectively, while both backup relay H1 OC2 and G1 OC2 are 0.304s and 0.342s, respectively. So, the coordination time interval (*CTI*) of pairs relay (H2 OC1/H1 OC2) is 0.203s and 0.228s for another pairs relay (G2 OC1/G1 OC2). Because the result of *CTI* value is not perfectly at 0.2s as the *CTI* constraint in the AMFA program. Then, the *CTI* error of both pairs relay is 0.003s and 0.028s, respectively. Therefore, both pairs relay is coordinated because the operating time is larger than 0.1s for both primary pairs relay and larger than 0.3s for both backup pairs relay. Also, the *CTI* value is larger than 0.2s.

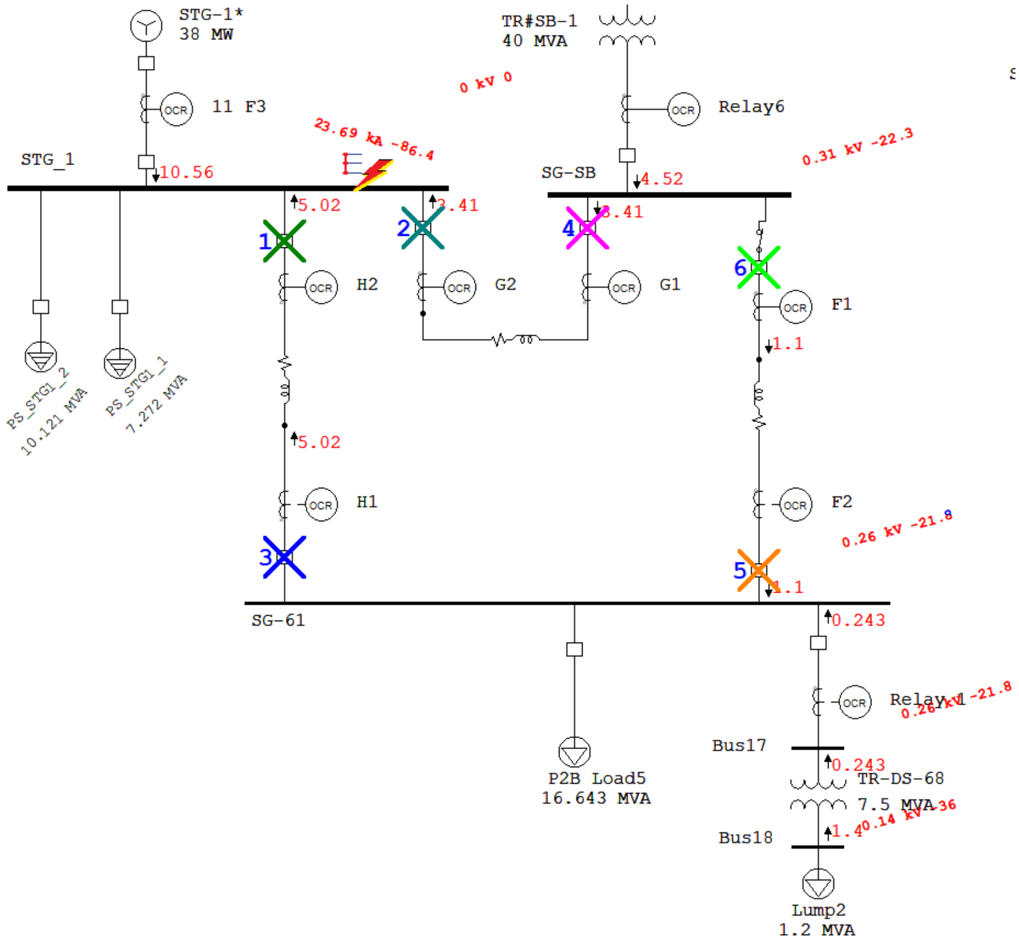


Figure 4.31 Tripping Sequence in ETAP While Faulting on the Bus STG_1 for Case Study 2

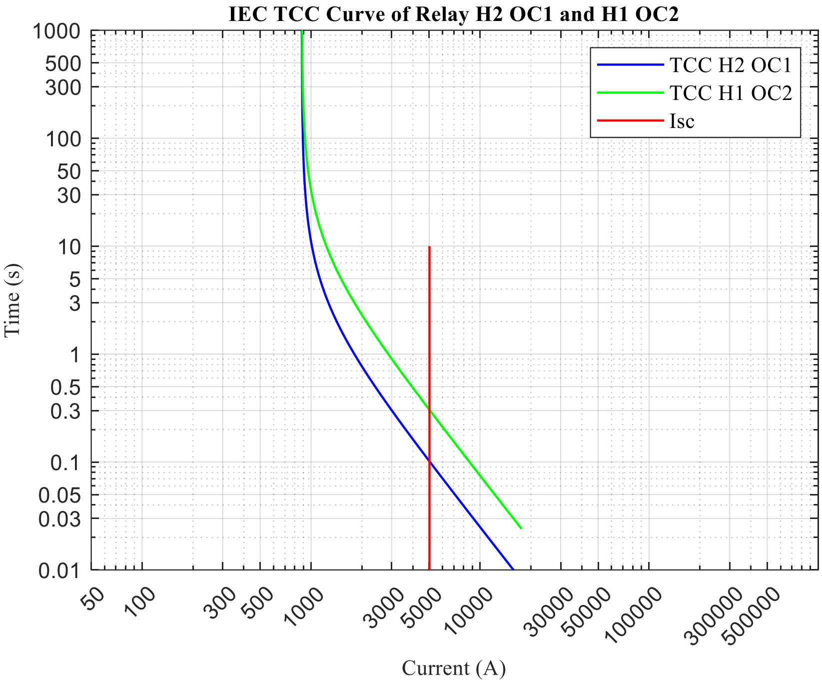


Figure 4.32 The TCC Curve of Relay H2 OC1 and H1 OC2 for Case Study 2 Using MATLAB 2018b

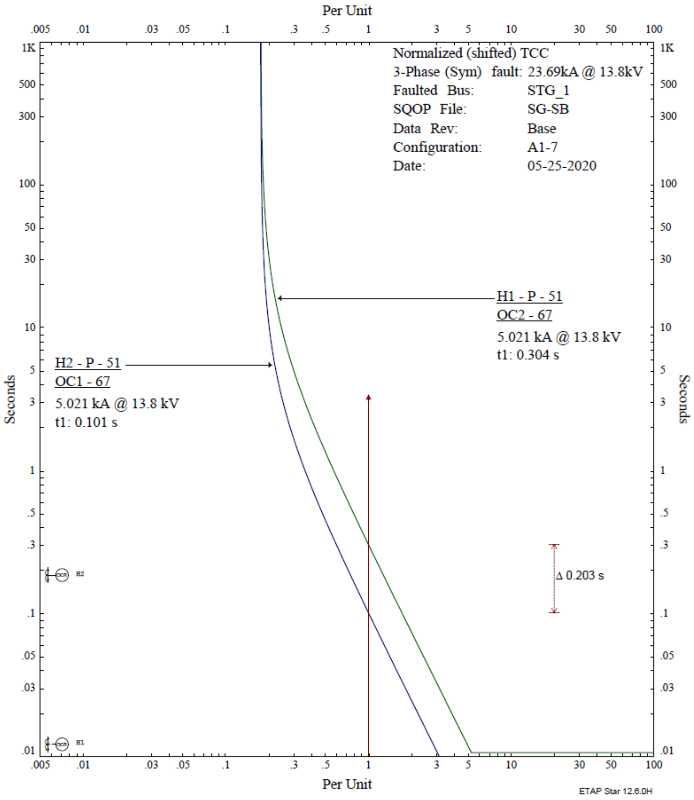


Figure 4.33 The TCC Curve of Relay H2 OC1 and H1 OC2 for Case Study 2 Using ETAP 12.6.0

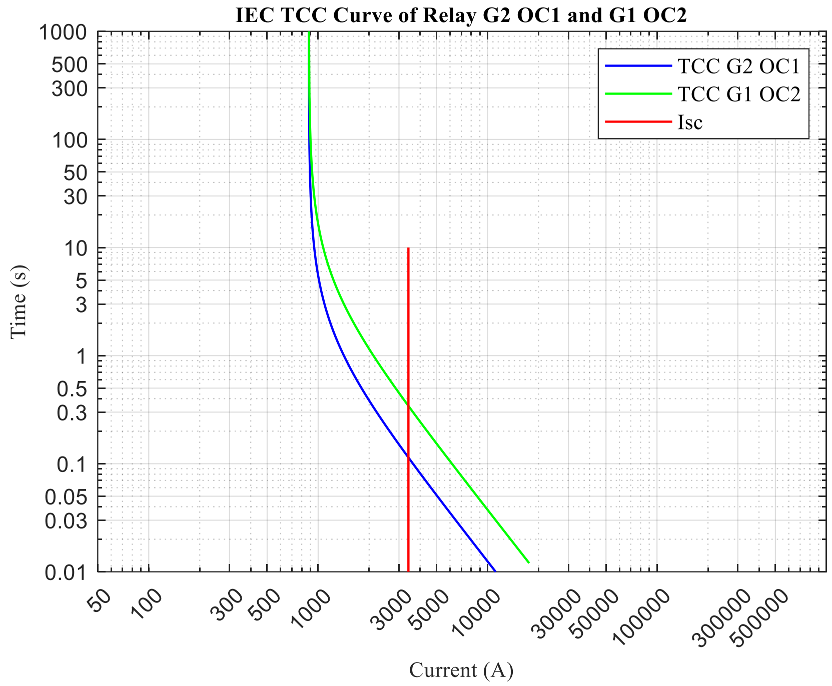


Figure 4.34 The TCC Curve of Relay G2 OC1 and G1 OC2 for Case Study 2 Using MATLAB 2018b

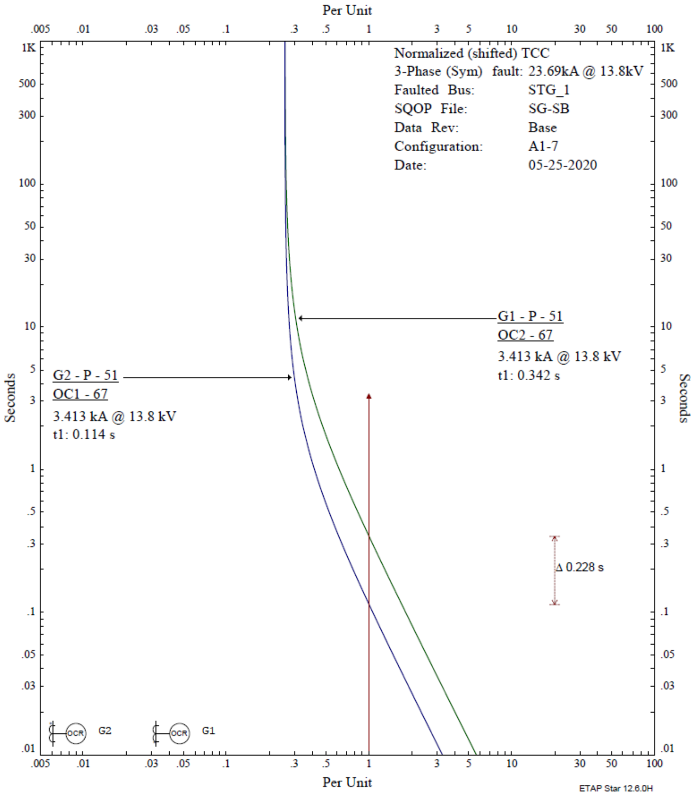


Figure 4.35 The TCC Curve of Relay G2 OC1 and G1 OC2 for Case Study 2 Using ETAP 12.6.0

- Three phases short circuit current on bus SG-61

The relay H1 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus STG-61 and the relay H2 OC2 is the backup relay. For another pairs relay, the relay F2 OC1 is the primary relay of the backup relay F1 OC2. So, the tripping sequence of DOCRs in ETAP 12.6.0 while faulting on the bus SG_61 is displayed in Figure 4.36. Figure 4.37 and Figure 4.39 are the TCC curve of pairs relay that plotted by MATLAB 2018b. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.38 and Figure 4.40. The blue line is represented the primary relay and the green line is represented the backup relay. The red line is presented the value of the three-phase short circuit current on the bus SG_61. It can be seen that the operating time of both primary relay H1 OC1 and F2 OC1 are 0.304s and 0.31s, respectively, while both backup relay H2 OC2 and F1 OC2 are 0.507s and 0.512s, respectively. In this point, both primary relays are selected to follow the relay operating time at 0.3s because both primary relays will become the backup of Relay R1 when the short circuit current happened the bus of the load P2B. So, both backup relays will be selected to operate at 0.5s for verifying the *CTI* constraint. Then, the coordination time interval (*CTI*) of pairs relay (H1 OC1/H2 OC2) is 0.203s and 0.202s for another pairs relay (F2 OC1/F1 OC2). Because the result of *CTI* value is not perfectly at 0.2s as the *CTI* constraint in the AMFA program. Then, the *CTI* error of both pairs relay is 0.003s and 0.002s, respectively. Therefore, both pairs relay is coordinated because the operating time is larger than 0.1s for both primary pairs relay and larger than 0.3s for both backup pairs relay. Also, the *CTI* value is larger than 0.2s.

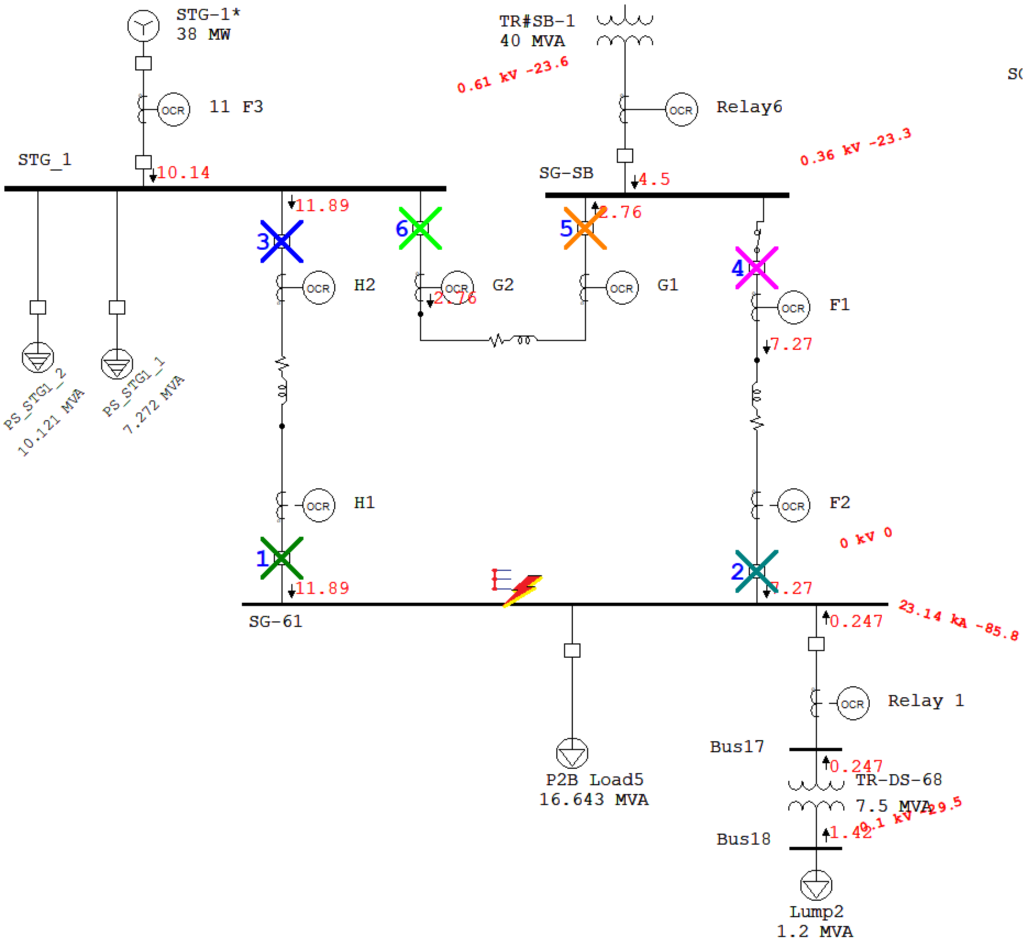


Figure 4.36 Tripping Sequence in ETAP While Faulting on the Bus SG_61 for Case Study 2

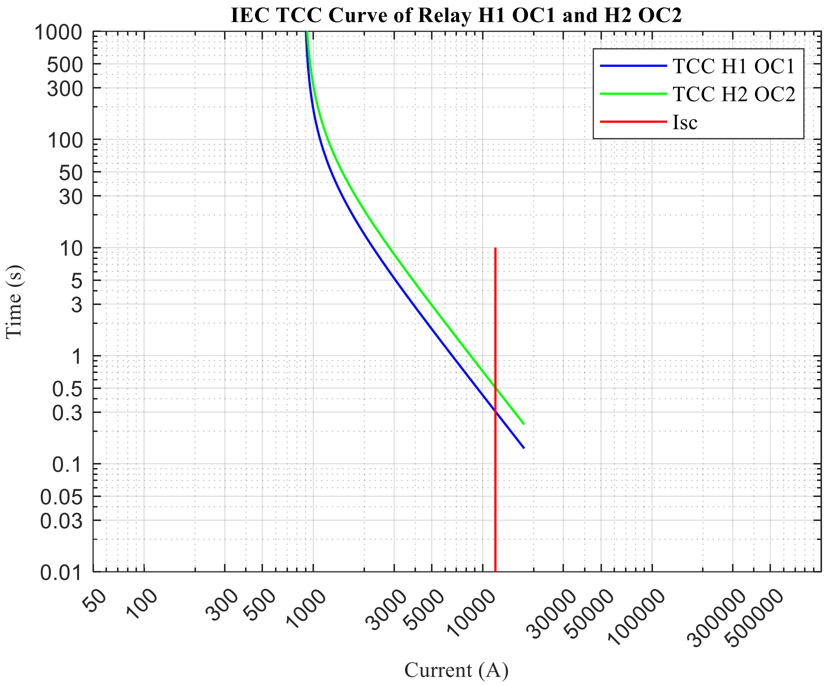


Figure 4.37 The TCC Curve of Relay H1 OC1 and H2 OC2 for Case Study 2 Using MATLAB 2018b

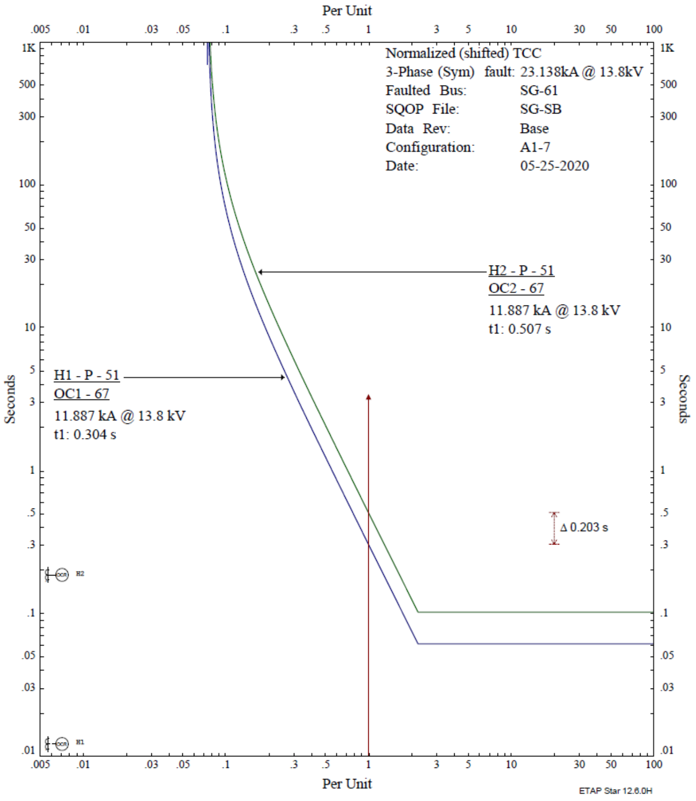


Figure 4.38 The TCC Curve of Relay H1 OC1 and H2 OC2 for Case Study 2 Using ETAP 12.6.0

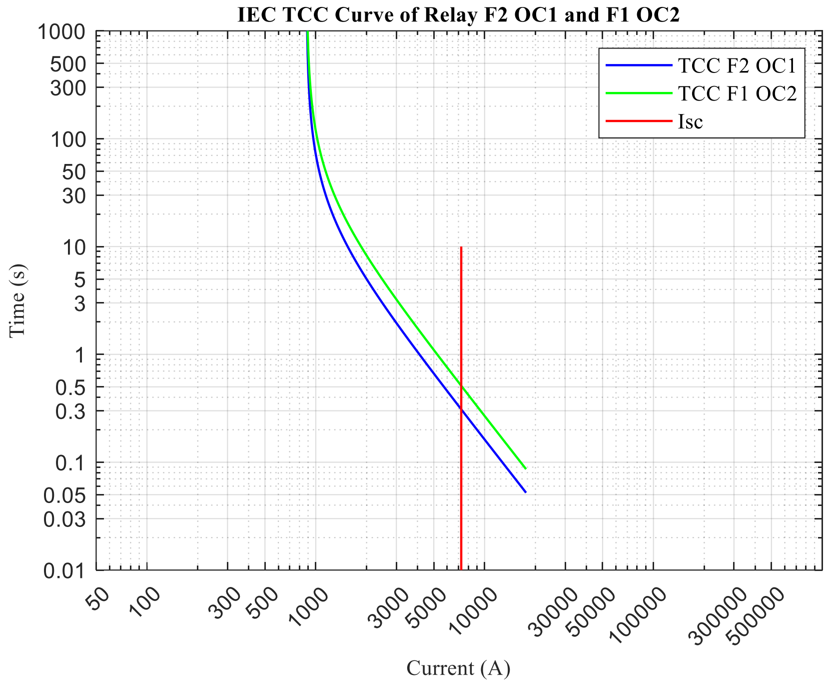


Figure 4.39 The TCC Curve of Relay F2 OC1 and F1 OC2 for Case Study 2 Using MATLAB 2018b

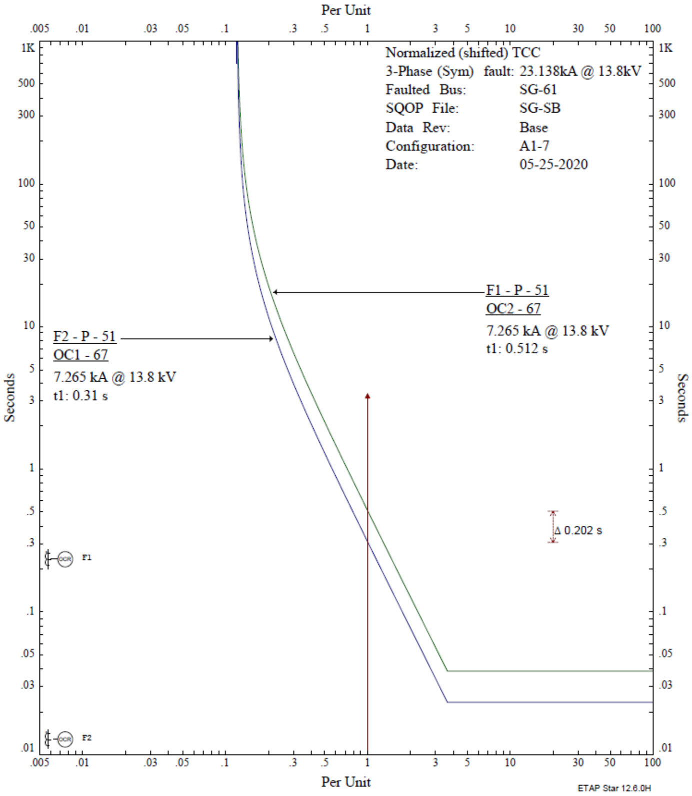


Figure 4.40 The TCC Curve of Relay F2 OC1 and F1 OC2 for Case Study 2 Using ETAP 12.6.0

- Three phases short circuit current on bus SG-SB

The relay F1 OC1 will be operated as the primary relay when the three-phase short circuit occurred on the bus SG-SB and the relay F2 OC2 is the backup relay. For another pairs relay, the relay G1 OC1 is the primary relay of the backup relay G2 OC2. So, the tripping sequence of DOCRs in ETAP 12.6.0 while faulting on the bus SG_SB is displayed in Figure 4.41. Figure 4.42 and Figure 4.44 are the TCC curve of pairs relay that plotted by MATLAB 2018b. The normalized TCC of pairs relay can be plotted by ETAP 12.6.0 software as in Figure 4.43 and Figure 4.45. The blue line is represented the primary relay and the green line is represented the backup relay. The red line is presented the value of the three-phase short circuit current on the bus SG-SB. It can be seen that the operating time of both primary relay F1 OC1 and G1 OC1 are 0.105s and 0.102s, respectively, while both backup relay F2 OC2 and G2 OC2 are 0.308s and 0.307s, respectively. So, the coordination time interval (*CTI*) of pairs relay (F1 OC1/F2 OC2) is 0.203s and 0.205s for another pairs relay (G1 OC1/G2 OC2). Because the result of *CTI* value is not perfectly at 0.2s as the *CTI* constraint in the AMFA program. Then, the *CTI* error of both pairs relay is 0.003s and 0.005s, respectively. Therefore, both pairs relay is coordinated because the operating time is larger than 0.1s for both primary pairs relay and larger than 0.3s for both backup pairs relay. Also, the *CTI* value is larger than 0.2s.

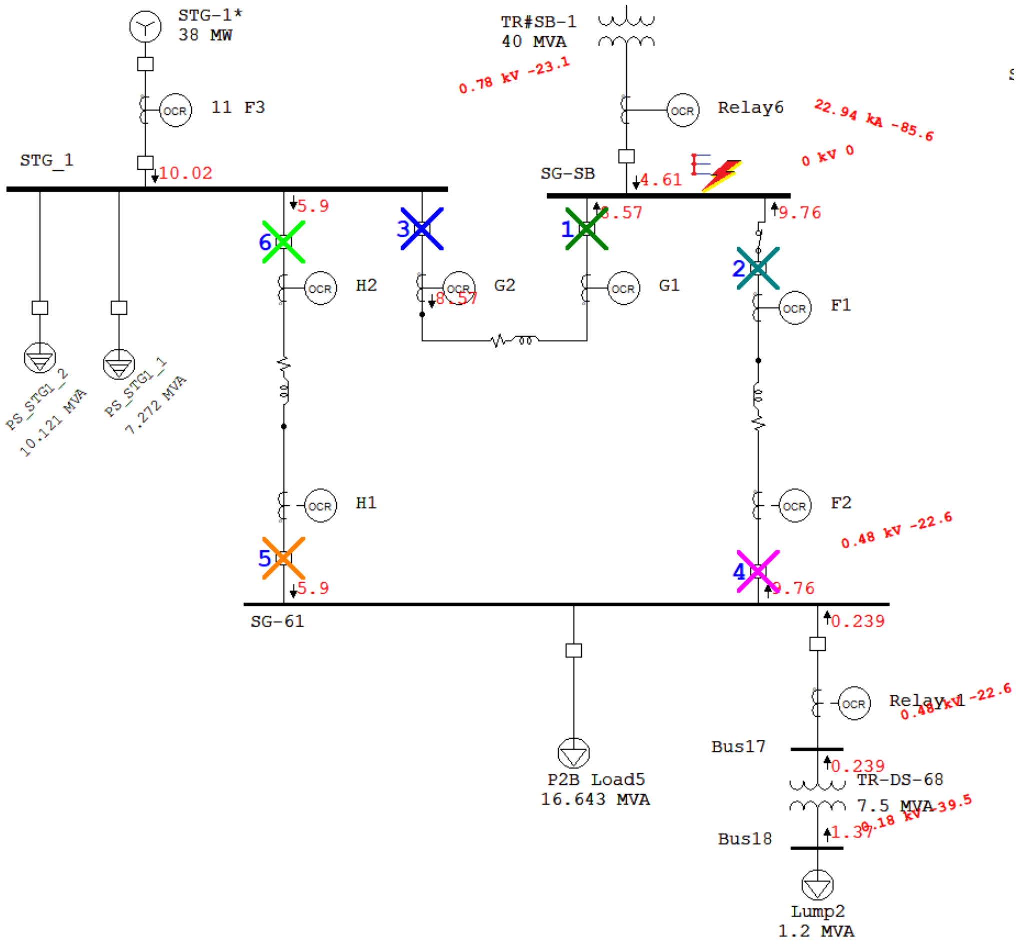


Figure 4.41 Tripping Sequence in ETAP While Faulting on the Bus SG_SB for Case Study 2

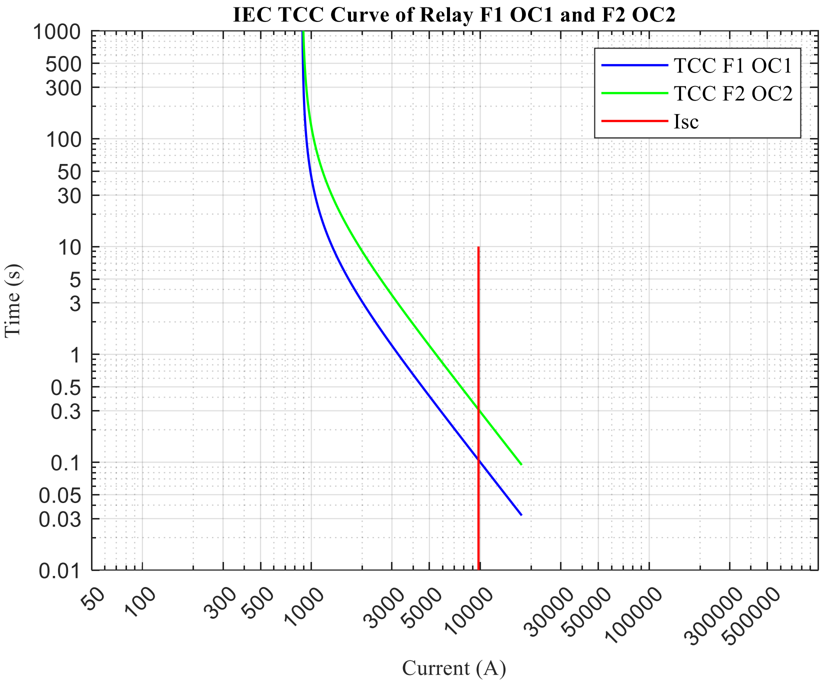


Figure 4.42 The TCC Curve of Relay F1 OC1 and F2 OC2 for Case Study 2 Using MATLAB 2018b

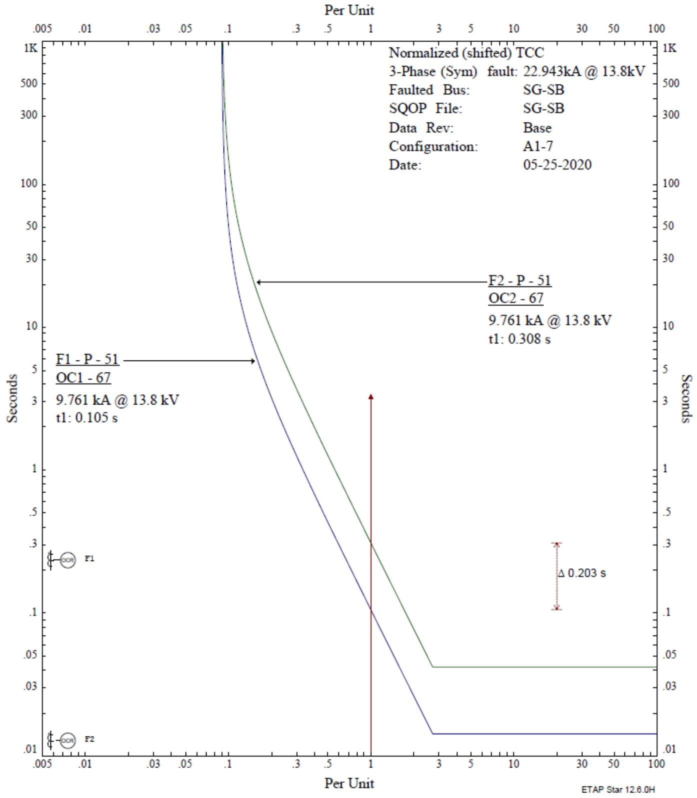


Figure 4.43 The TCC Curve of Relay F1 OC1 and F2 OC2 for Case Study 2 Using ETAP 12.6.0

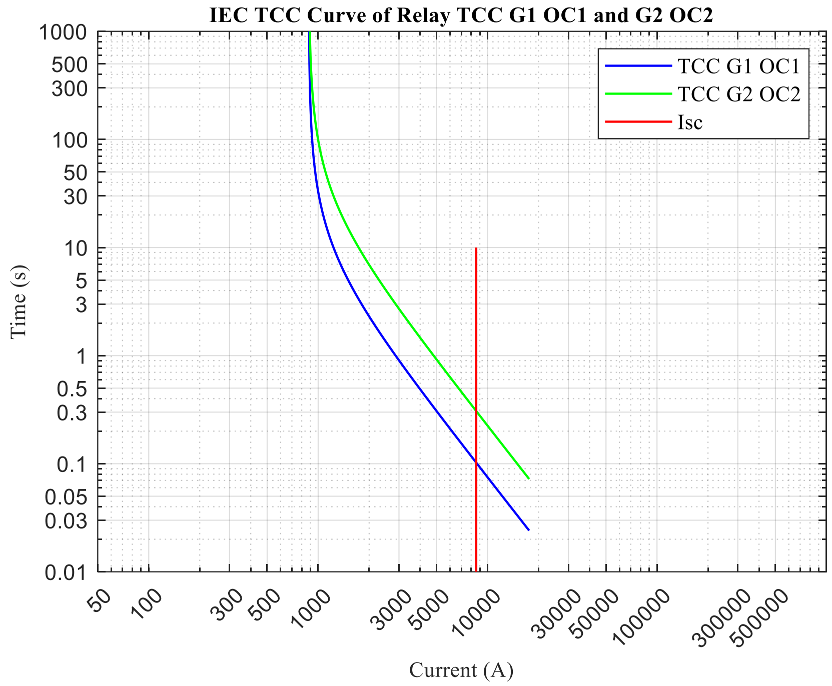


Figure 4.44 The TCC Curve of Relay G1 OC1 and G2 OC2 for Case Study 2 Using MATLAB 2018b

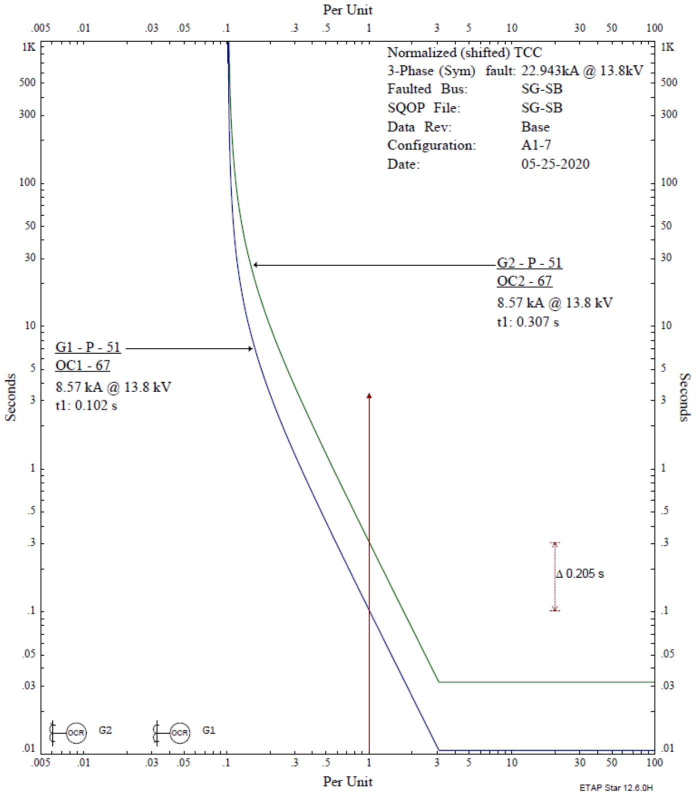


Figure 4.45 The TCC Curve of Relay G1 OC1 and G2 OC2 for Case study 2 Using ETAP 12.6.0

4.3.7 Manual Calculation of *TDS* and *TOP* of DOCR for Case Study 1

The *TDS* and *TOP* of the primary and backup relay can calculate by the manual calculation to comparison with the AMFA as the following:

- **Relay H2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-2
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	5020 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

  $$TDS = \frac{0.1 * 1 * \left(\left(\frac{5020}{880}\right)^2 - 1\right)}{80} = 0.039 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.04 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.04}{\left(\left(\frac{5020}{880}\right)^2 - 1\right) * 1} = 0.101\,\text{s}$$

– **Relay G2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-1
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	3410A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{3410}{880} \right)^2 - 1 \right)}{80} = 0.017\,\text{s}$$

Because the TDS step is 0.01, the selected TDS is 0.02 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.02}{\left(\left(\frac{3410}{880} \right)^2 - 1 \right) * 1} = 0.114\,\text{s}$$

- **Relay G1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	CB278
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	8570 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1*1*\left(\left(\frac{8570}{880}\right)^2 - 1\right)}{80} = 0.117 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.12 s

- Operating Time Relay

$$t_{op} = \frac{80*0.12}{\left(\left(\frac{8570}{880}\right)^2 - 1\right)*1} = 0.102 \text{ s}$$

- **Relay F1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-TSTG1-01
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	9760 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A*TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)*\beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.1s.

$$TDS = \frac{0.1 * 1 * \left(\left(\frac{9760}{880} \right)^2 - 1 \right)}{80} = 0.152 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.16 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.16}{\left(\left(\frac{9760}{880} \right)^2 - 1 \right) * 1} = 0.105 \text{ s}$$

- **Relay F2 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I1(4)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	7270 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.3s.

$$TDS = \frac{0.3 * 1 * \left(\left(\frac{7270}{880}\right)^2 - 1\right)}{80} = 0.252 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.26 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.26}{\left(\left(\frac{7270}{880}\right)^2 - 1\right) * 1} = 0.309 \text{ s}$$

– **Relay H1 OC1**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I2(6)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	11890 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1 and the operating time is 0.3s.

$$TDS = \frac{0.3 * 1 * \left(\left(\frac{11890}{880}\right)^2 - 1\right)}{80} = 0.681\,\text{s}$$

Because the TDS step is 0.01, the selected TDS is 0.69 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.69}{\left(\left(\frac{11890}{880}\right)^2 - 1\right) * 1} = 0.304\,\text{s}$$

- **Relay H1 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I2(6)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	5020 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

  $$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

  $$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. H1 OC2 is the backup of relay H2 OC1, so the selection of operating time is 0.101+0.2=0.301s.

  $$TDS = \frac{0.301 * 1 * \left(\left(\frac{5020}{880}\right)^2 - 1\right)}{80} = 0.118\ \text{s}$$

  Because the TDS step is 0.01, the selected TDS is 0.12 s

- Operating Time Relay

  $$t_{op} = \frac{80 * 0.12}{\left(\left(\frac{5020}{880}\right)^2 - 1\right) * 1} = 0.304\ \text{s}$$

– **Relay G1 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	CB278
CT	2000/5 A
FLA	788 A
Pickup Step	0.01

Data Specification	
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	3410 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes
- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. G1 OC2 is the backup of relay G2 OC1, so the selection of operating time is 0.114+0.2=0.314s.

$$TDS = \frac{0.314 * 1 * \left(\left(\frac{3410}{880}\right)^2 - 1\right)}{80} = 0.055 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.06 s
- Operating Time Relay

$$t_{op} = \frac{80 * 0.06}{\left(\left(\frac{3410}{880}\right)^2 - 1\right) * 1} = 0.342 \text{ s}$$

– **Relay G2 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000

Data Specification	
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-1
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	8570 A

- Pickup Current

  $1.1\times FLA < Iset\ Pickup < 1.5\times FLA$

  $1.1\times 788 < Iset\ Pickup < 1.5\times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

  The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. G2 OC2 is the backup of relay G1 OC1, so the selection of operating time is 0.102+0.2=0.302s.

$$TDS = \frac{0.302 * 1 * \left(\left(\frac{8570}{880}\right)^2 - 1\right)}{80} = 0.354 \text{ s}$$

  Because the TDS step is 0.01, the selected TDS is 0.36 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.354}{\left(\left(\frac{8570}{880}\right)^2 - 1\right) * 1} = 0.307 \text{ s}$$

- **Relay F2 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-SG-61-I1(4)
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	9760 A

- Pickup Current

  $1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

  $1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

  $866.8 < Iset\ Pickup < 1182$

  Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. F2 OC2 is the backup of relay F1 OC1, so the selection of operating time is 0.105+0.2=0.305s.

$$TDS = \frac{0.305 * 1 * \left(\left(\frac{9760}{880}\right)^2 - 1\right)}{80} = 0.465\,\text{s}$$

Because the TDS step is 0.01, the selected TDS is 0.47 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.47}{\left(\left(\frac{9760}{880}\right)^2 - 1\right) * 1} = 0.308 \text{ s}$$

– **Relay F1 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-TSTG1-01
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	7270 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P}\right)^B - 1\right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. F1 OC2 is the backup of relay F2 OC1, so the selection of operating time is 0.309+0.2=0.509s.

$$TDS = \frac{0.509 * 1 * \left(\left(\frac{7270}{880} \right)^2 - 1 \right)}{80} = 0.427 \text{ s}$$

Because the TDS step is 0.01, the selected TDS is 0.43 s

- Operating Time Relay

$$t_{op} = \frac{80 * 0.43}{\left(\left(\frac{7270}{880} \right)^2 - 1 \right) * 1} = 0.512 \text{ s}$$

– **Relay H2 OC2**

Data Specification	
Manufacture	Eaton
Type	EDR-5000
Voltage	13.8 kV
Output to Circuit Breaker	52-S-STG1-2
CT	2000/5 A
FLA	788 A
Pickup Step	0.01
Step TDS	0.01
Constraint TDS	0.02-2
IscMax	11890 A

- Pickup Current

$1.1 \times FLA < Iset\ Pickup < 1.5 \times FLA$

$1.1 \times 788 < Iset\ Pickup < 1.5 \times 788$

$866.8 < Iset\ Pickup < 1182$

Iset Pickup selected at 880 amperes

- Time Dial Setting

$$t_{op} = \frac{A * TDS}{\left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right) * \beta}$$

$$TDS = \frac{t_{op} * \beta * \left(\left(\frac{I_{SC}}{I_P} \right)^B - 1 \right)}{A}$$

The IEC Extremely inverse curve is selected. The coefficient value is according to Table 2.1. H2 OC2 is the backup of relay H1 OC1, so the selection of operating time is 0.304+0.2=0.504s.

$$TDS = \frac{0.504 * 1 * \left(\left(\frac{11890}{880} \right)^2 - 1 \right)}{80} = 1.143\,\mathrm{s}$$

Because the TDS step is 0.01, the selected TDS is 1.15 s

- Operating Time Relay

$$t_{op} = \frac{80 * 1.15}{\left(\left(\frac{11890}{880} \right)^2 - 1 \right) * 1} = 0.507\,\mathrm{s}$$

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CHAPTER 5
CONCLUSION

In conclusion, the applied AMFA method is studied in the ring distribution system to obtain the optimal protection coordination of dual setting DOCRs. The optimized overall operating time of the primary and backup relay attain by the minimum value of the *TDS*. On the other hand, the AMFA method is applied in 2 study cases and tested in 4 different curves of the IEC TCC to choose the appropriate curve that content the relay protection coordination with the minimum value of the total relay operating time.

The result of both study case shows that the optimal coordination protection using AMFA significantly gets the minimum value of the total overall operating time for all three-phase short circuit current on the bus. Additionally, the *CTI* value of pairs relay is not less than 0.2s. The iteration of the objective function using the AMFA method is faster to converge than the original FA method. Moreover, according to the comparison of total operating time for all type of IEC TCC curve shown that the IEC extremely inverse curve is the suitable curve to ensure the relay protection coordination of both study cases in PT. Pupuk Sriwidjaja ring system. The ETAP 12.6.0 software is used to plot the IEC TCC curve for verifying of the relay coordination.

The value of the objective function in case of IEC extremely inverse curve of the case study 1 is 3.327s and 3.316s for the case study 2. It can be concluded from the result of both study cases that the total operating time of the relay is varied to the configuration of the ring distribution system. Furthermore, the result of this research study is demonstrated that the AMFA is useful in the optimal protection coordination of relay. This algorithm can handle in the different case study, even though the distributed generator of the ring system is disconnected. Last but not least, the AMFA method is more advantageous for the researcher to find out the optimal setting of relay coordination in the ring distribution system.

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BIBLIOGRAPHY

[1] X.-S. Yang, “Firefly algorithms for multimodal optimization,” in *International symposium on stochastic algorithms*, 2009, pp. 169–178.

[2] I. Fister, I. Fister Jr, X.-S. Yang, and J. Brest, “A comprehensive review of firefly algorithms,” *Swarm Evol. Comput.*, vol. 13, pp. 34–46, 2013.

[3] A. Tjahjono *et al.*, “Adaptive modified firefly algorithm for optimal coordination of overcurrent relays,” *IET Gener. Transm. Distrib.*, vol. 11, no. 10, pp. 2575–2585, 2017.

[4] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, “Dual-setting characteristic for directional overcurrent relays considering multiple fault locations,” *IET Gener. Transm. Distrib.*, vol. 9, no. 12, pp. 1332–1340, 2015.

[5] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, “Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays,” *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 143–151, 2016.

[6] A. Yazdaninejadi, S. Golshannavaz, D. Nazarpour, S. Teimourzadeh, and F. Aminifar, “Dual-setting directional overcurrent relays for protecting automated distribution networks,” *IEEE Trans. Ind. Informatics*, vol. 15, no. 2, pp. 730–740, 2018.

[7] A. Yazdaninejadi, D. Nazarpour, and V. Talavat, “Optimal coordination of dual-setting directional over-current relays in multi-source meshed active distribution networks considering transient stability,” *IET Gener. Transm. Distrib.*, vol. 13, no. 2, pp. 157–170, 2018.

[8] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, and E. E.-D. A. El-Zahab, “Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays,” *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 115–123, 2014.

[9] A. Tjahjono, D. O. Anggriawan, A. K. Faizin, A. Priyadi, M. Pujiantara, and M. H. Purnomo, “Optimal coordination of overcurrent relays in radial system with distributed generation using modified firefly algorithm,” *Int. J. Electr. Eng. Informatics*, vol. 7, no. 4, p. 691, 2015.

[10] M. Zellagui, R. Benabid, M. Boudour, and A. Chaghi, “Application of firefly algorithm for optimal coordination of directional overcurrent protection relays in presence of series compensation,” *J. Autom. Syst. Eng.*, pp. 92–107, 2014.

[11] D. S. Lestari, M. Pujiantara, M. H. Purnomo, and D. Rahmatullah, “Adaptive DOCR coordination in loop distribution system with distributed generation using firefly algorithm-artificial neural network,” in *2018 International Conference on Information and Communications Technology (ICOIACT)*, 2018, pp. 579–584.

[12] D. S. Kumar, D. Srinivasan, A. Sharma, and T. Reindl, “Adaptive directional overcurrent relaying scheme for meshed distribution networks,” *IET Gener. Transm. Distrib.*, vol. 12, no. 13, pp. 3212–3220, 2018.

[13] M. P. Sari, G. E. Sulisityo, M. Pujiantara, and M. H. Purnomo, “Chaotic Firefly with Tent Map Algorithm for Overcurrent Relay in MeshedDistribution System,” in *2018 10th International Conference on Information Technology and Electrical Engineering (ICITEE)*, 2018, pp. 1–6.

[14] E. Dehghanpour, H. K. Karegar, R. Kheirollahi, and T. Soleymani, “Optimal coordination of directional overcurrent relays in microgrids by using cuckoo-linear optimization algorithm and fault current limiter,” *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1365–1375, 2016.

[15] M. Pujiantara, V. R. Mahindara, B. Fachrurriza, A. Priyadi, and M. H. Purnomo, “The Design of RBMP Technique to Limit The Fault Current and Voltage Dip in Medium Voltage Electrical System Application,” in *2019 International Seminar on Intelligent Technology and Its Applications*

(ISITIA), 2019, pp. 159–164.

[16] V. R. Mahindara, M. G. Istiqlal, M. Pujiantara, D. A. Asfani, A. Priyadi, and M. H. Purnomo, “Obtaining The Setting of Inverse-Curve Overcurrent Relay using Serial Computing Modified Particle Swarm Optimization in Real System Applications,” in *2018 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, 2018, pp. 187–192.

[17] T. Khurshaid, A. Wadood, S. G. Farkoush, C.-H. Kim, J. Yu, and S.-B. Rhee, “Improved firefly algorithm for the optimal coordination of directional overcurrent relays,” *IEEE Access*, vol. 7, pp. 78503–78514, 2019.

[18] R. M. Vincentius, A. W. Nugraha, P. S. Talitha, P. Margo, P. Ardyono, and H. P. Mauridhi, “Recognition of Electric Machines Boundary as The Constraint of Over Current Relay Coordination in Real Industrial Application with Serial Firefly Algorithm Optimization,” in *2019 IEEE 12th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, 2019, pp. 153–159.

[19] “IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book),” *IEEE Std 242-2001 (Revision of IEEE Std 242-1986) [IEEE Buff Book]*. pp. 1–710, 2001.

[20] B. de Metz-Noblat, F. Dumas, and C. Poulain, “Calculation of short-circuit currents,” *Cah. Tech.*, no. 158, 2005.

[21] X.-S. Yang, *Cuckoo search and firefly algorithm: Theory and applications*, vol. 516. Springer, 2013.

[22] A. Yazdaninejadi, D. Nazarpour, and S. Golshannavaz, “Dual-setting directional over-current relays: An optimal coordination in multiple source meshed distribution networks,” *Int. J. Electr. Power Energy Syst.*, vol. 86, pp. 163–176, 2017.

[23] A. Yazdaninejadi, M. S. Naderi, G. B. Gharehpetian, and V. Talavat, “Protection coordination of directional overcurrent relays: new time current characteristic and objective function,” *IET Gener. Transm. Distrib.*, vol. 12,

no. 1, pp. 190–199, 2017.

APPENDIX A

The TCC of Pairs Relay for IEC Normal Inverse Curve in Case Study 1.

- Three Phase Short Circuit Current on the Bus STG_1

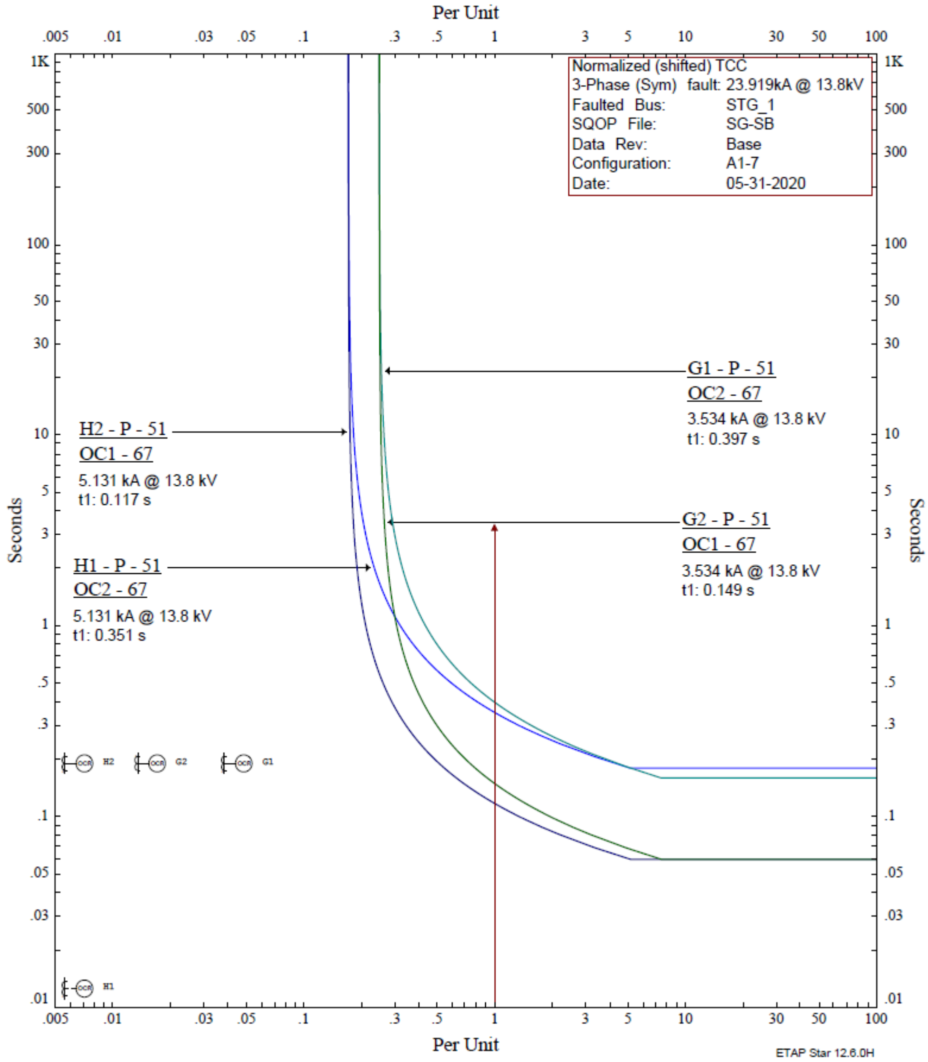

Figure 5.1 The IEC Normal Inverse Curve of Relay While Faulting on the Bus STG_1 for Case Study 1

- Three Phase Short Circuit Current on the bus SG_SB

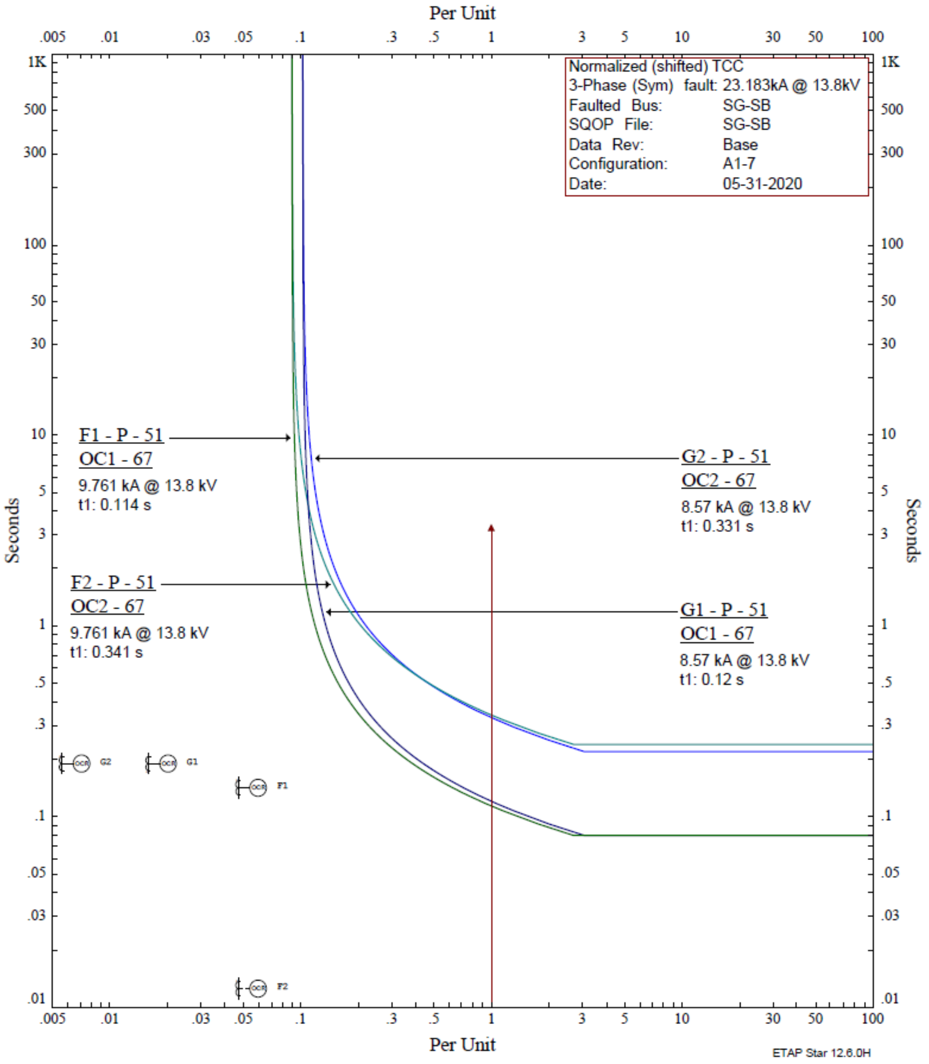

Figure 5.2 The IEC Normal Inverse Curve of Relay While Faulting on the Bus SG_SB for Case Study 1

- Three Phase Short Circuit Current on the bus SG_61

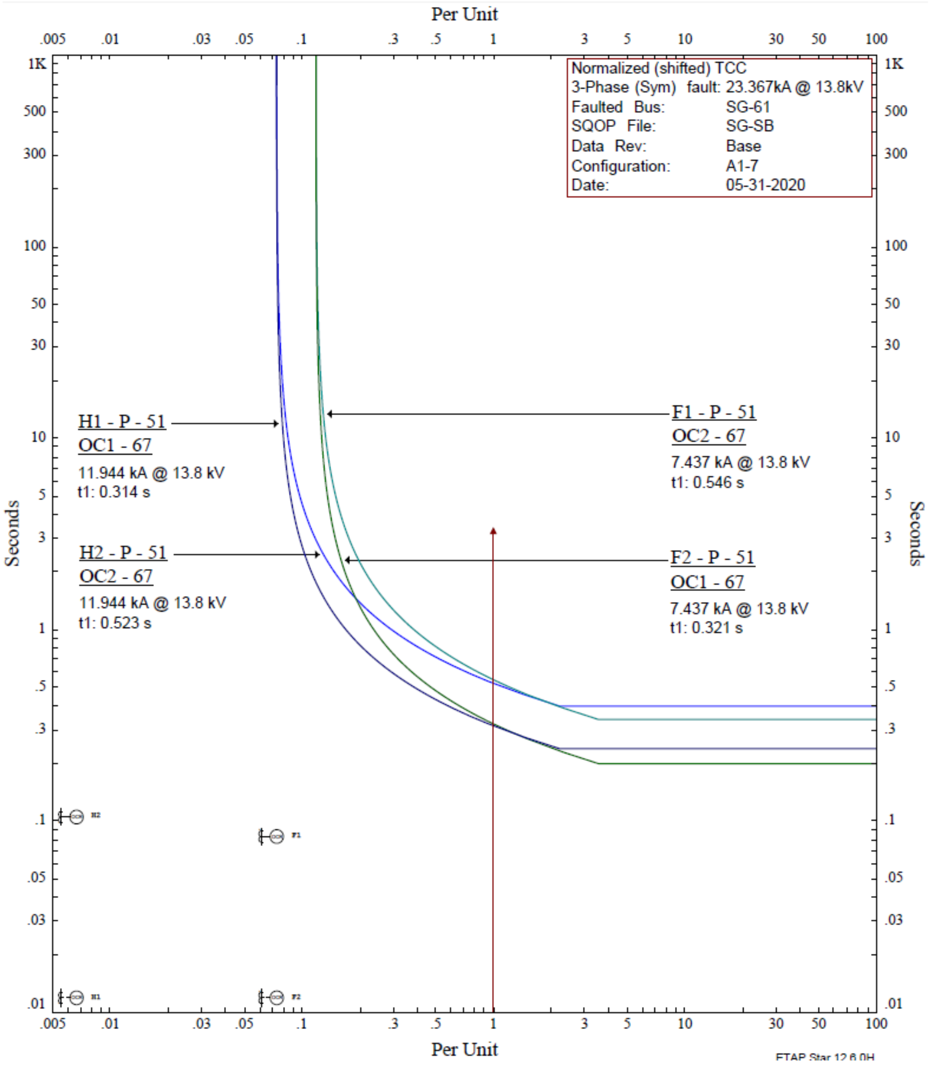

Figure 5.3 The IEC Normal Inverse Curve of Relay While Faulting on the Bus SG_61 for Case Study 1

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APPENDIX B

TCC of Pairs Relay for IEC Very Inverse Curve in Case Study 1.

- Three Phase Short Circuit Current on the Bus STG_1

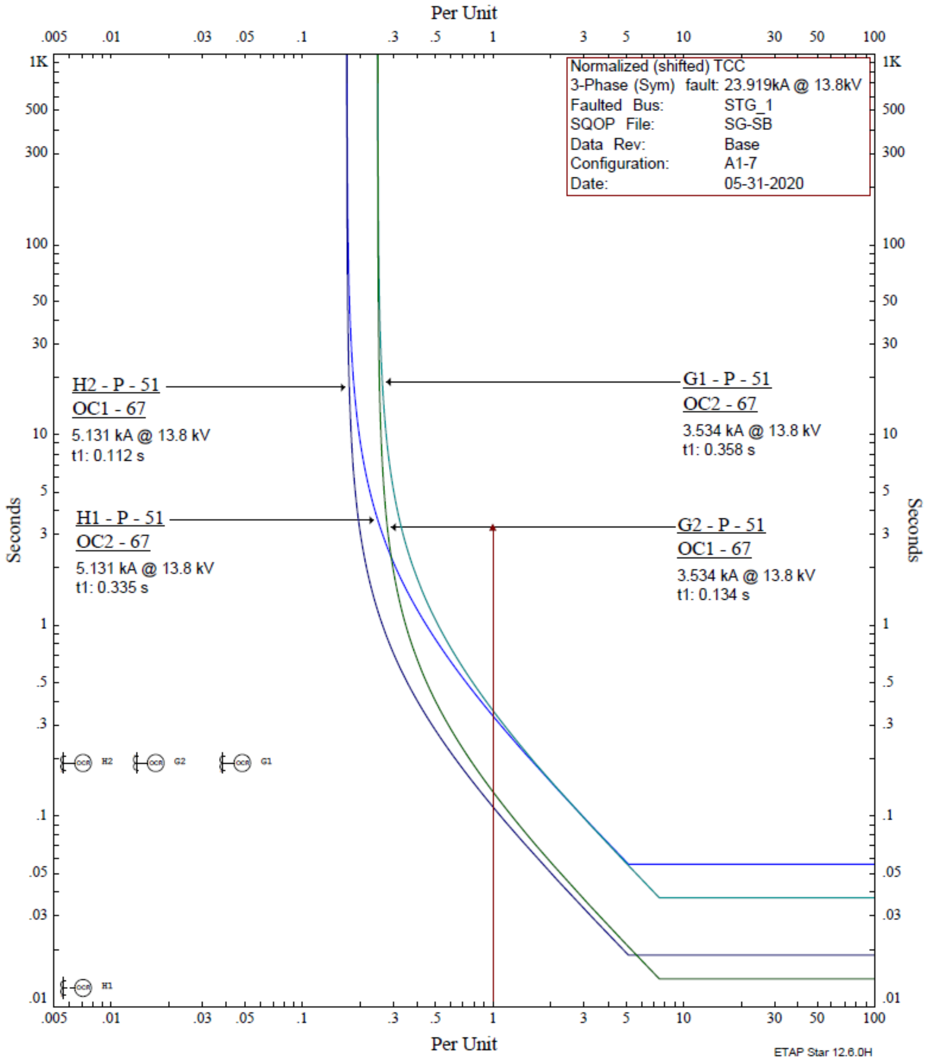

Figure 5.4 The IEC Very Inverse Curve of Relay While Faulting on the Bus STG_1 for Case Study 1

- Three Phase Short Circuit Current on the Bus SG_SB

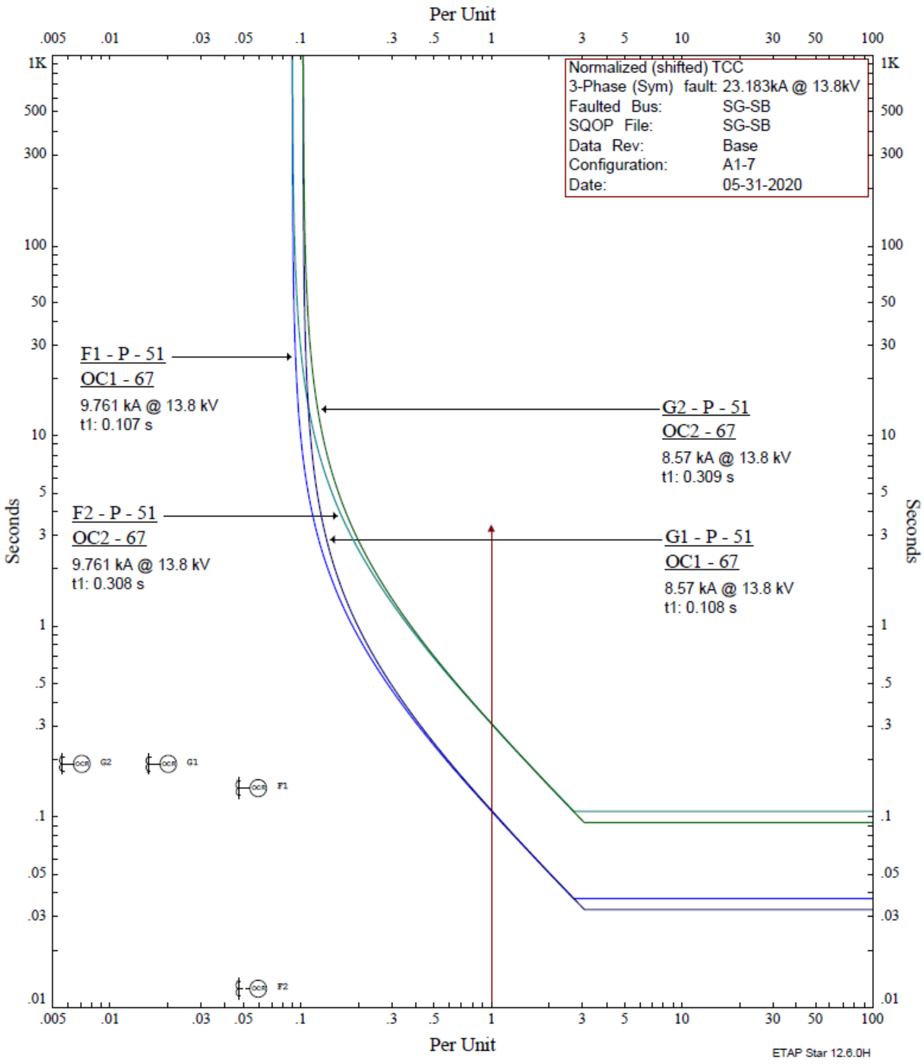

Figure 5.5 The IEC Very Inverse Curve of Relay While Faulting on the Bus SG_SB for Case Study 1

- Three Phase Short Circuit Current on the Bus SG_61

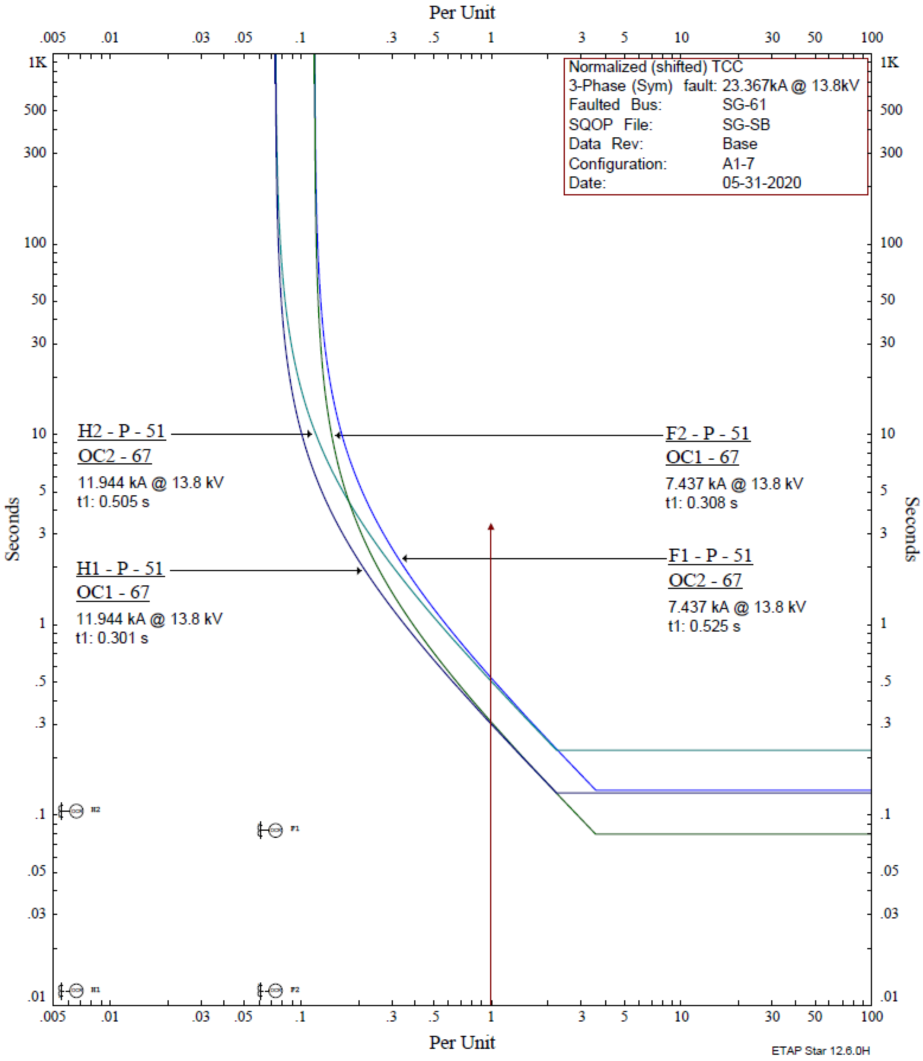

Figure 5.6 The IEC Very Inverse Curve of Relay While Faulting on the Bus SG_61 for Case Study 1

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APPENDIX C

The TCC of Pairs Relay for IEC Normal Inverse Curve in Case Study 2

- Three Phase Short Circuit Current on the Bus STG_1

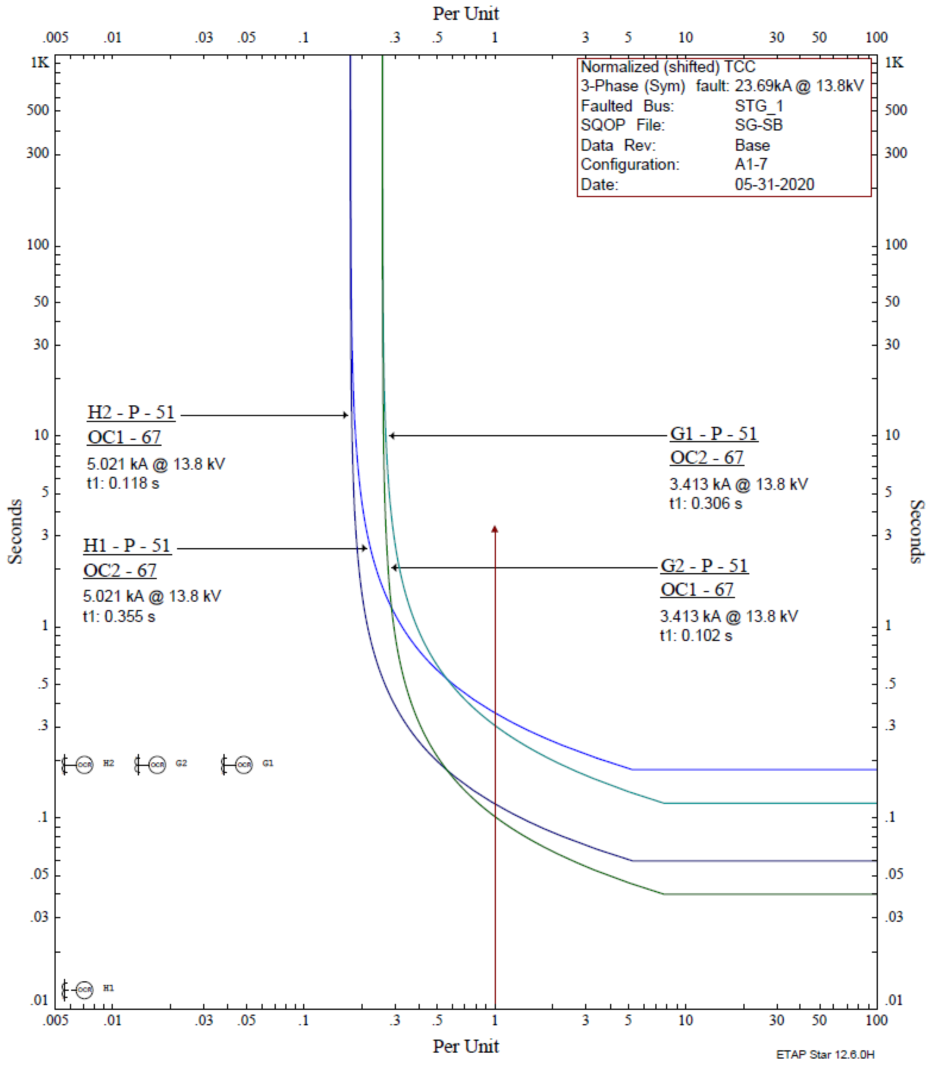

Figure 5.7 The IEC Normal Inverse Curve of Relay While Faulting on the Bus STG_1 for Case Study 2

- Three Phase Short Circuit Current on the Bus SG_SB

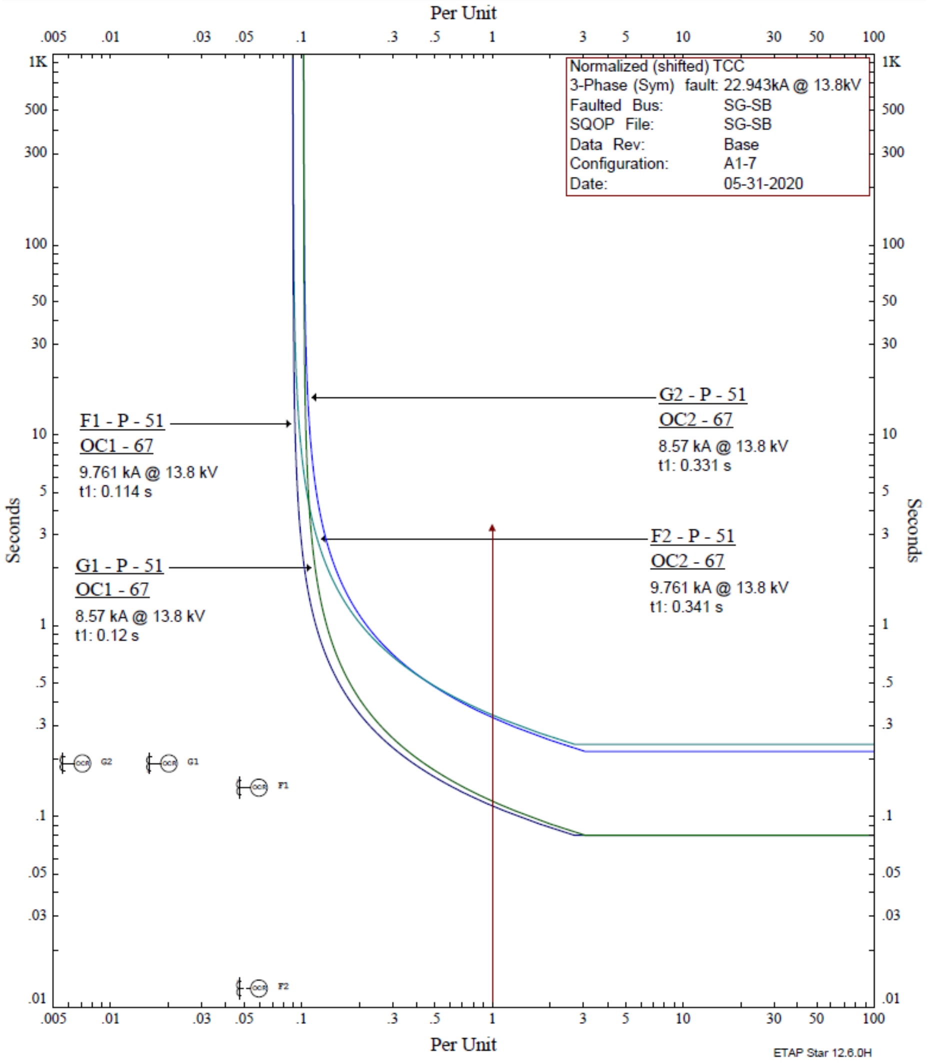

Figure 5.8 The IEC Normal Inverse Curve of Relay While Faulting on the Bus SG_SB for Case Study 2

- Three Phase Short Circuit Current on the Bus SG_61

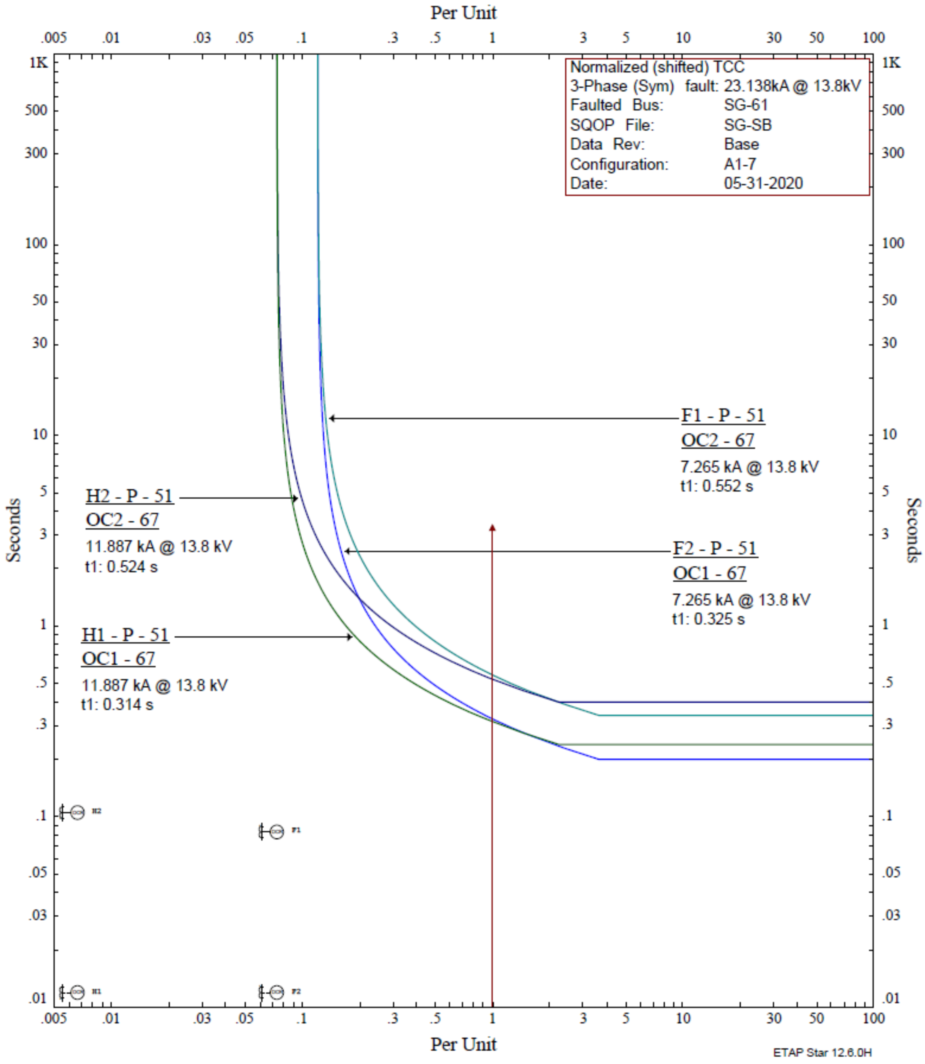

Figure 5.9 The IEC Normal Inverse Curve of Relay While Faulting on the Bus SG_61 for Case Study 2

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APPENDIX D

The TCC of Pairs Relay for IEC Very Inverse Curve in Case Study 2

- Three Phase Short Circuit Current on the Bus STG_1

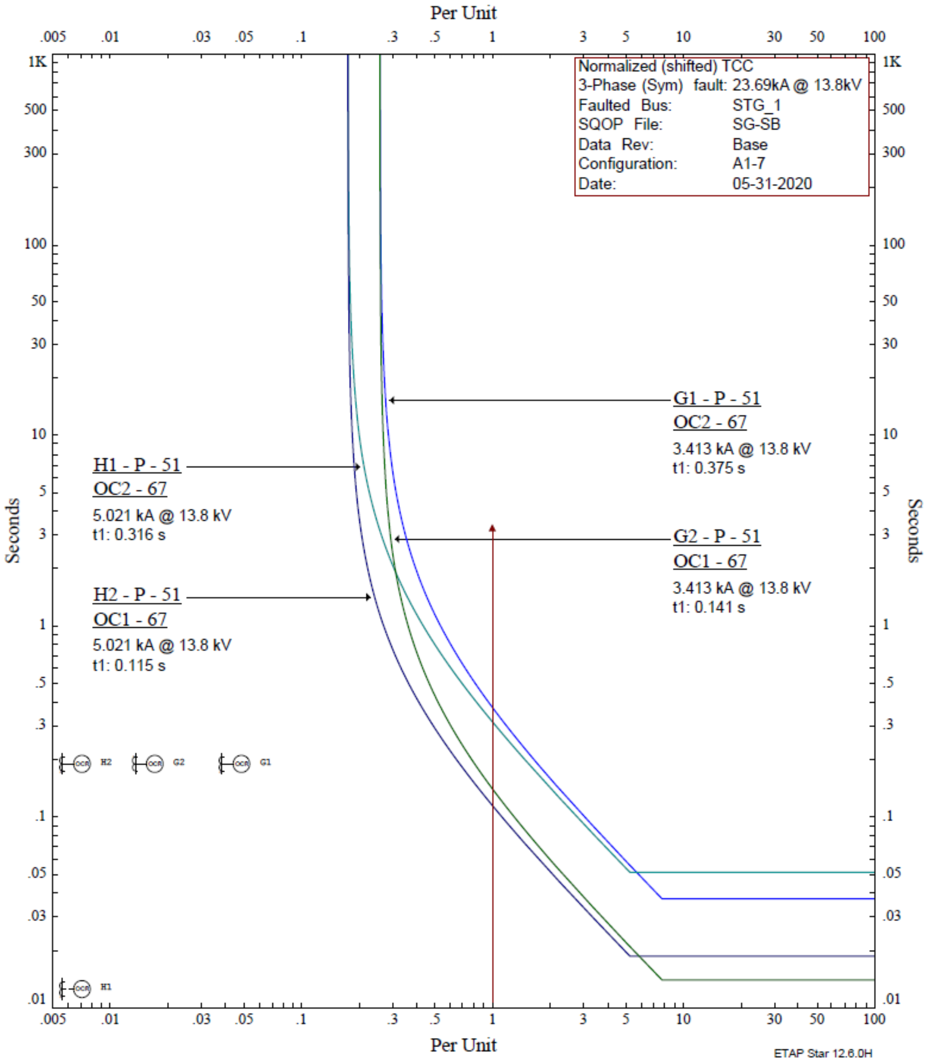

Figure 5.10 The IEC Very Inverse Curve of Relay While Faulting on the Bus STG_1 for Case Study 2

– Three Phase Short Circuit Current on the Bus SG_SB

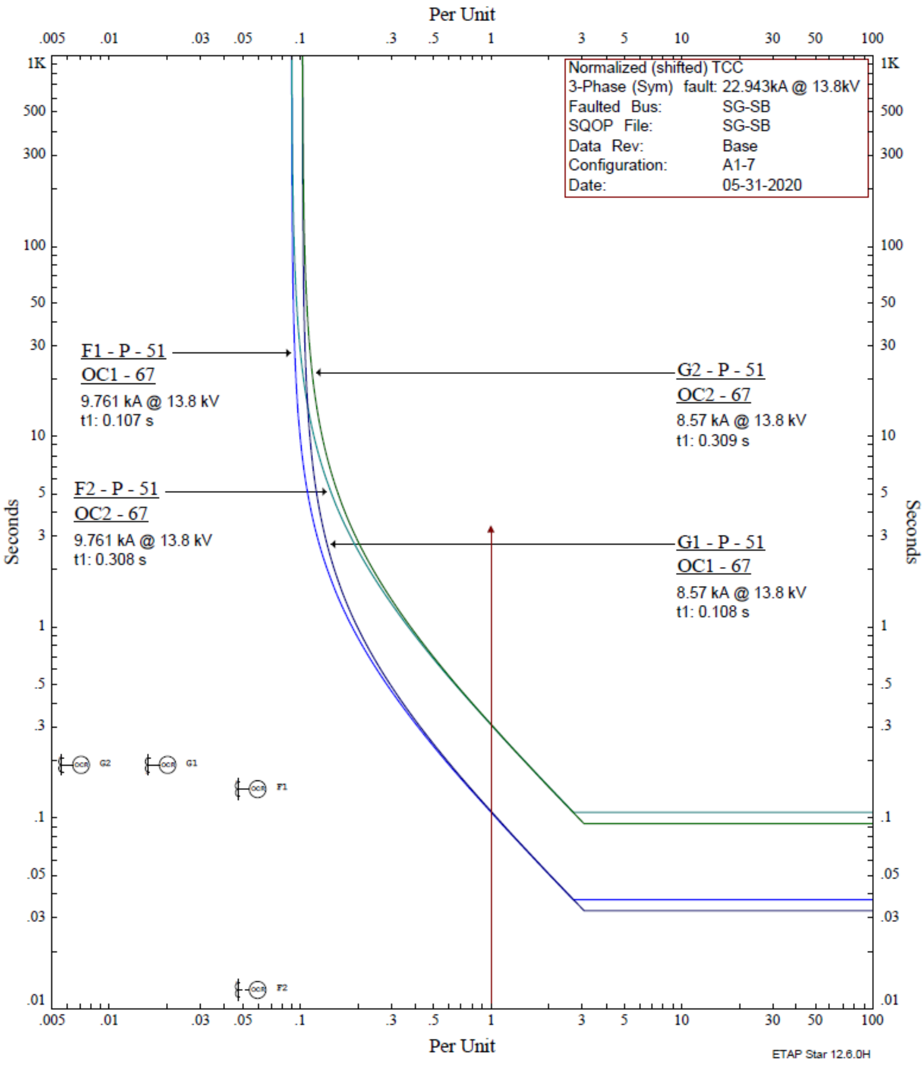

Figure 5.11 The IEC Very Inverse Curve of Relay While Faulting on the Bus SG_SB for Case Study 2

- Three Phase Short Circuit Current on the Bus SG_61

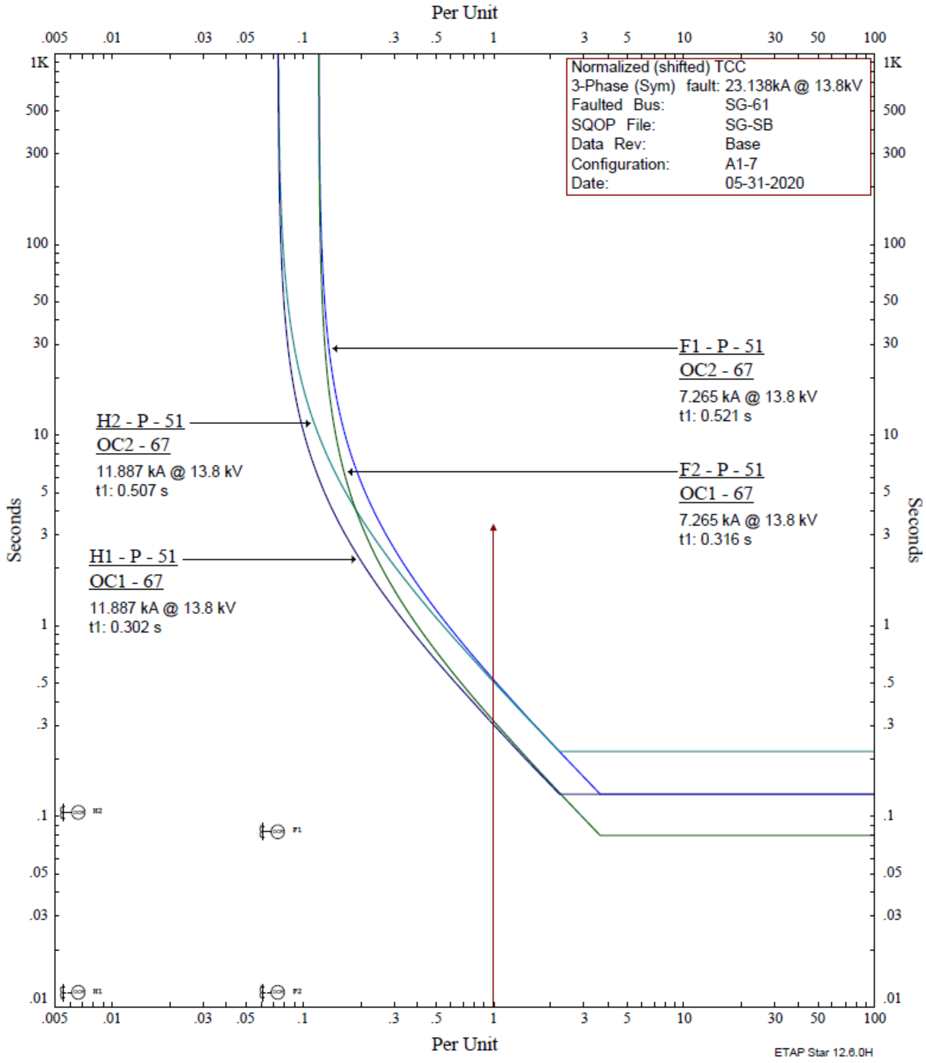

Figure 5.12 The IEC Very Inverse Curve of Relay While Faulting on the Bus SG_61 for Case Study 2

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