



THESIS - EE185401

OPTIMIZING THE COORDINATION OF OVERCURRENT RELAY WITH TIME CURRENT CURVE SELECTION FOR RADIAL-INDUSTRIAL SYSTEM USING FIREFLY ALGORITHM

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MASTER PROGRAM
POWER SYSTEM ENGINEERING
ELECTRICAL ENGINEERING DEPARTMENT
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di

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STATEMENT OF THESIS ORIGINALITY

I hereby declare that the entire content of my Thesis entitled **“OPTIMIZING THE COORDINATION OF OVERCURRENT RELAY WITH TIME CURRENT CURVE SELECTION FOR RADIAL-INDUSTRIAL SYSTEM USING 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.

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Surabaya, 06 July 2020



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OPTIMIZING THE COORDINATION OF OVERCURRENT RELAY WITH TIME CURRENT CURVE SELECTION FOR RADIAL-INDUSTRIAL SYSTEM USING FIREFLY ALGORITHM

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ABSTRACT

Overcurrent relay (OCR) is the primary protection in the industrial distribution system. The advantages of OCR in the protection system is the ability to work coordinately in time, current, time-current grading. To attain the coordination setting of OCRs, it requires a proper minimum operating time (TOP) and satisfied coordination time interval (CTI). However, attaining the coordination of OCR is quite challenging when distributed generations (DGs) are presented in the power system. The presence of DGs gives additional fault current contribution to the fault location.

In this thesis research, Firefly Algorithm (FA) is proposed to solve the coordination of OCR. The FA will be used to obtain time dial setting (TDS) with an objective to minimize the TOP and constraint of satisfying CTI for all possible network topologies and DGs operation. The proposed method is tested in a radial distribution system of Tanjung Harapan, a composite network of PT. Pupuk Kalimantan Timur industrial petrochemical plant, with two different study cases. For study case 1, the FA is applied for the radial distribution system of Tanjung Harapan without connection of DG. For study case 2, the FA is applied for the radial distribution system of Tanjung Harapan with connection of DG.

The result of FA optimization for each study case is compared in different curve characteristics according to the IEC Standard 60255 in order to select the best curve with smallest overall operating time for protection coordination of OCRs in Tanjung Harapan electrical system.

Key words: overcurrent relay (OCR), firefly algorithm (FA), distributed generation (DG), radial distribution system, optimal protection coordination

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OPTIMASI KOORDINASI PERLINDUNGAN OVERCURRENT RELAY DENGAN PEMILIHAN TIME CURRENT CURVE UNTUK SISTEM RADIAL-INDUSTRI MENGUNAKAN FIREFLY ALGORITHM

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ABSTRAK

Overcurrent relay (OCR) adalah perlindungan utama dalam sistem distribusi industri. Kelebihan OCR dalam sistem perlindungan adalah kemampuan untuk bekerja secara terkoordinasi dalam waktu, saat ini, penilaian waktu-saat ini. Untuk mencapai pengaturan koordinasi OCR, diperlukan *operating time (TOP)* minimum yang tepat dan *coordination time interval (CTI)* puas. Namun, mencapai koordinasi OCR cukup menantang ketika *distributed generation (DG)* disajikan dalam sistem tenaga. Kehadiran DG memberikan kontribusi arus gangguan tambahan ke lokasi gangguan.

Dalam penelitian tesis ini, *firefly algorithm (FA)* diusulkan untuk menyelesaikan koordinasi OCR. FA akan digunakan untuk mendapatkan *time dial setting (TDS)* dengan tujuan untuk meminimalkan TOP dan kendala memuaskan CTI untuk semua topologi jaringan yang mungkin dan operasi DG. Metode yang diusulkan diuji dalam sistem distribusi radial Tanjung Harapan, jaringan komposit PT. Pabrik petrokimia industri Pupuk Kalimantan Timur, dengan dua studi berbeda. Untuk studi kasus 1, FA diterapkan untuk sistem distribusi radial Tanjung Harapan tanpa koneksi dari DG. Untuk studi kasus 2, FA diterapkan untuk sistem distribusi radial Tanjung Harapan dengan koneksi DG.

Hasil optimasi FA untuk setiap studi kasus dibandingkan dalam karakteristik kurva yang berbeda sesuai dengan Standar IEC 60255 untuk memilih kurva terbaik dengan *overall operating time* terkecil untuk koordinasi perlindungan OCR di sistem kelistrikan Tanjung Harapan.

Kata kunci: overcurrent relay (OCR), firefly algorithm (FA), distributed generation (DG), radial distribution system, optimal protection coordination

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PREFACE

This thesis is made as a completion of the master education in Power System Protection. This thesis is the product of the master period, which is the last part of the Power System Protection study at Institut Teknologi Sepuluh Nopember (ITS), Electrical Engineering Department.

Several persons and institutions have contributed academically, practically and with support to this master thesis. I would like to express my gratitude from the bottom of my heart toward to **KNB scholarship, International Office (IO)** and **Institut Teknologi Sepuluh Nopember (ITS)** for financial support, help and provide good education system; without this financial support and scholarship I could not have a chance to continue my master degree in such a good institution.

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Surabaya, 06 July 2020



Punleu Chhun

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CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, electrical power plays important roles in everyday life of humans in term of creating something new which makes their lives being easier, modern, fashionable, and comfortable. Many businessmen have caught this opportunity and formed their own industry to manufacture their products depending upon company vision. However, their product lines would not run well last long; the product lines, sometimes, may be stuck due to damages of electrical equipment caused by fault current. Repairment or replacement of damaged electrical equipment requires additional cost and much time to achieve reoperation of product lines as usual. It is very inconvenient because the company will lose its benefit due to getting stuck of the product lines during repairment or replacement of the damaged equipment. To come up with this problem, electrical equipment running in product lines should be protected.

Overcurrent relay (OCR) is well known as the important protection device in distribution system as well as productive industry while it is projected to save electrical equipment by isolating the fault part from the power system. OCR should operate as fast as possible when current flow through its sensor exceeds the pickup current setting. Because of its important responsibility in protecting electrical equipment, protection coordination of OCR is the most concern to be considered and optimized in order to provide a good system protection with proper operation. Mathematically, OCR setting parameters, consisting of pickup setting PS , time dial setting TDS and operating time TOP , can be determined by using numerical method or artificial intelligent method (AI). Recent years, AI method is quite popular used by many authors in optimization problems because of its fast-computational time in solving complex problem. The first firefly algorithm (FA) published by Xin-She Yang for continuous optimization in late 2007 and 2008 at Cambridge University, which is one of AI methods, is a natural inspired algorithm based on the flashing patterns and behavior of fireflies [1], [2]. FA is one of the swarm intelligence

algorithms; hence, it has similar advantages that other swarm intelligence algorithms have. As discussed in [1], the results shown that FA saved about 86% and 74% compared with Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), respectively, of overall computational efforts. In [3], the result is also shown that FA is better than PSO in term of the time taken for the optimum or near optimum values.

PT. Pupuk Kalimantan Timur is an industrial of Indonesia government which does business in fertilizer. Since established in 1977, eight generators have been operated (two generators in KALTIM-1: 16MW (Off) and 11MW (Off), one generator in KALTIM-2: 36.4MW, one generator in KALTIM-3: 30MW, one generator in KALTIM-4: 21.6MW, one generator in KDM: 34MW, one generator in KANIBUNGAN: 30MW, and one generator in TAJUNG HARAPAN: 30MW). As shown in Figure 1.1, each generator is integrated through a ring bus network at level voltage of 33 kV to supply electrical power to the factory loads of PT. Fertilizer Kalimantan Timur (KALTIM-1, KALTIM-2, KALTIM-3, KALTIM-4, KDM, KANIBUNGAN, TAJUNG HARAPAN, TURSINA LOAD, and SS4).

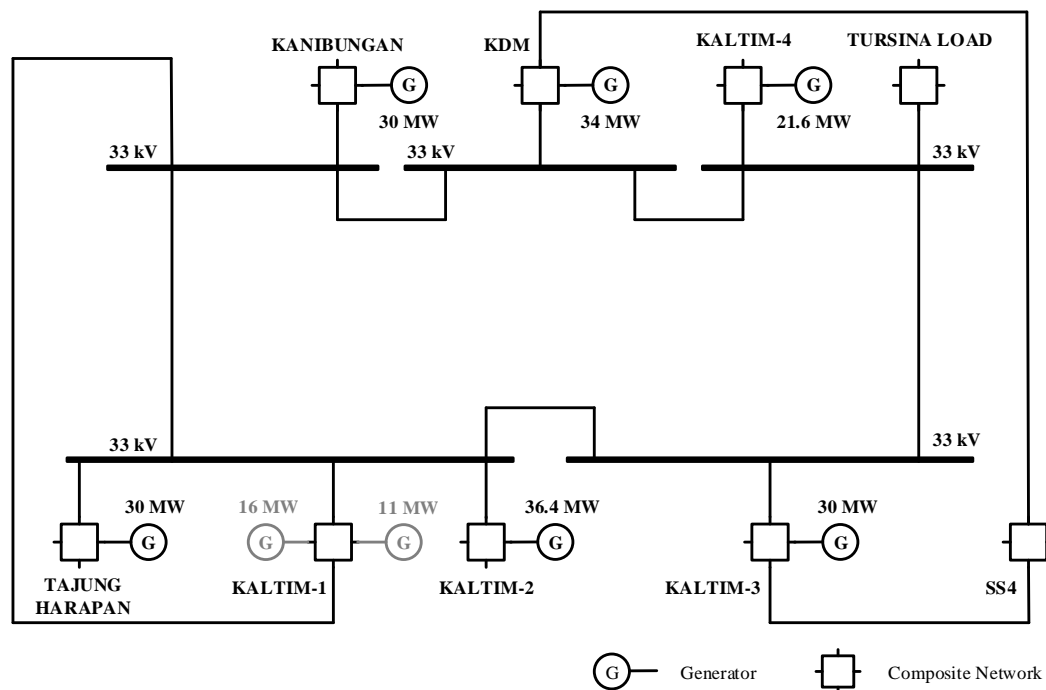


Figure 1.1 Single Line Diagram of PT. Pupuk Kalimantan Timur

1.2 Problem Statement

The presence of distributed generation (DG) causes some problems in protection coordination due to its high current penetration to the system when a fault occurs. Dealing with this problem, researchers have used some different methods: using a fault current limiter (FCL) to limit current penetration from DG to fault location, and using a remote bus marching practice (RBMP) technique that combining fuse, CB and reactor to limit the current distributing to the fault location. By using these kinds of method, the OCR protection coordination can still work correctly; but it is not commonly used because of the requirement of the additional cost on equipment. Avoiding this additional cost, the improvement of existing OCR is, therefore, applied in this thesis research. In the progress of the improvement of existing OCR, the operating time can be minimized unless time current characteristic (TCC) of OCR has been selected. TCCs of OCR existing of standard inverse (SI), very inverse (VI) and extremely inverse (EI), which are commonly used, represent the sensitivity of OCR in isolating the faulted network from the system. It is the challenging in order to select the most appropriate TCC of OCR for protection coordination; and this challenging will be done in this thesis research.

1.3 Objectives

The objective of this thesis research is to acquire the optimal protection coordination of OCR with acceptable coordination time interval (CTI) between primary and backup relay for all possible network topologies. The operating time (TOP) of OCR is decreased or increased linearly depend upon the decrease or increase of time dial setting (TDS); hence, *TDS* should be minimized in order to obtain minimum *TOP*. In this thesis research, firefly algorithm (FA) is applied to determine the minimum *TDS* with related constraints. The FA is tested in Tanjung Harapan electrical system with two different study cases: 1) without the presence of DG and 2) with the presence of DG. However, minimizing *TOP* of OCR with single selecting of TCC is not enough to obtain the minimum overall operating time of OCRs; three scenarios of using different curves for each study cases, using IEC-EI curve, IEC-SI curve and IEC-VI curve, will be done and compared to select the most appropriate TCC with the smallest overall operating time.

1.4 Scope

There are many composite networks with large number of loads and generators in PT. Pupuk Kalimantan Timur as shown in Figure 1.1. It is not option to study in completed system. The limitations of the thesis research that will be discussed are described as following:

- This study is only focus on TANJUNG HARAPAN composite network that is a radial system of PT. Pupuk Kalimantan Timur.
- The faulted interference is tested only on the buses.
- Data used for calculating the *TDS* values and selecting TCC curves will be taken from the electrical system of PT. Pupuk Kalimantan Timur in ETAP 12.6.0.
- The study investigates on two study cases. Study case 1, TANJUNG HARAPAN composite network operates without DG penetration. Study case 2, TANJUNG HARAPAN composite network operates with DG penetration.
- For each study case, there are three different scenarios. Scenario 1, the TCC of each OCR is IEC extremely inverse (EI). Scenario 2, the TCC of each OCR is IEC standard inverse (SI). Scenario 3, the TCC of each OCR is IEC very inverse (VI).
- Pickup current I_p is fixed from 1.05 to 1.4 times full load amps *FLA*.
- FA is conducted by using MATLAB to obtain minimum *TDS*, minimum value of overall operating time *TOP* for each study case, and then select TCC curve which provides the smallest overall *TOP*.
- The result will be validated in the studied system by using ETAP 12.6.0 to prove the correctness of the used method.

1.5 Contribution

Optimizing protection coordination of OCR has been achieved in this thesis research with acceptable *CTI* between primary relay and its backup relay for all possible network topologies. Moreover, the most appropriate TCC curve, which provides the smallest overall *TOP*, has been selected successfully. The optimized results of protection coordination have been succeeded in ETAP 12.6.0 validation.

1.6 Research Methodology

In the process of conducting the thesis research, some stages of research are conducted and carried out as following:

- Literature review study

A literature review is a comprehensive summary of previous research on a topic. The literature review studies scholarly articles, books, and other sources related to a specific area of research. To achieve this thesis research, some literature reviews, such as protection coordination of overcurrent relay (OCR), fault current limiter (FLC), remote bus marching practice (RBMP) technique, and some natural inspired algorithms including firefly algorithm (FA), etc., are conducted to find out research gap and what method can be applied in this thesis research.

- Data acquisition

Applying FA method in this thesis research, some data are required such as completed electrical system with providing of specific data, fault current, and full load amps (FLA). Needed data is collected from a real industrial system of PT. Pupuk Kalimantan Timur.

- Protection coordination constraints

In solving optimization problem, some protection coordination constraints are needed such as constraint of time grading or coordination time interval (CTI), constraint of operating time of OCR, constraint of time dial setting (TDS), and constraint of pickup setting (PS). The constraints mentioned above are basically occupied from instruction manual of OCR modeled “Sepam 40”.

- Division of study case

The thesis research investigates on two study cases: study case I, the studied system is not connected to a distributed generation (DG). Study case II, the studied system is connected to a distributed generation (DG). For each study case, there are three different scenarios in term of the use of time current characteristics which are IEC extremely inverse (EI), IEC standard inverse (SI), and IEC very inverse (VI).

- Choosing configuration of protection coordination

Choosing configuration of protection coordination is quite important to guarantee the correction of the protection coordination of OCR. Configuration of

protection coordination means the direction of coordination of OCR as shown in Figure 1.2. For instance, if configuration C2 is chosen, it means the coordination setting of backup OCR named R06-OC1 is calculated based on primary OCR named R10-OC1. The CTI between backup OCR and primary OCR for all possible network topologies must be greater than minimum CTI.

- Computing *TDS* and *TOP* using FA

In the objective of optimizing the protection coordination of OCR, FA is applied for solving optimization problem in this thesis research to determine minimum *TDS* and then *TOP* of OCRs.

- Selecting the most appropriate TCC for protection coordination

The most appropriate TCC for protection coordination can be selected by comparing IEC curves including extremely inverse (EI), standard inverse (SI), and extremely inverse (VI). The curve type, which provides the smallest total operating time of all primary and backup relays, will be selected as the most appropriate TCC for the studied system.

- Validating the results in studied system using ETAP 12.6.0

The results getting from FA will be implemented in ETAP 12.6.0 to demonstrate the correctness of the results.

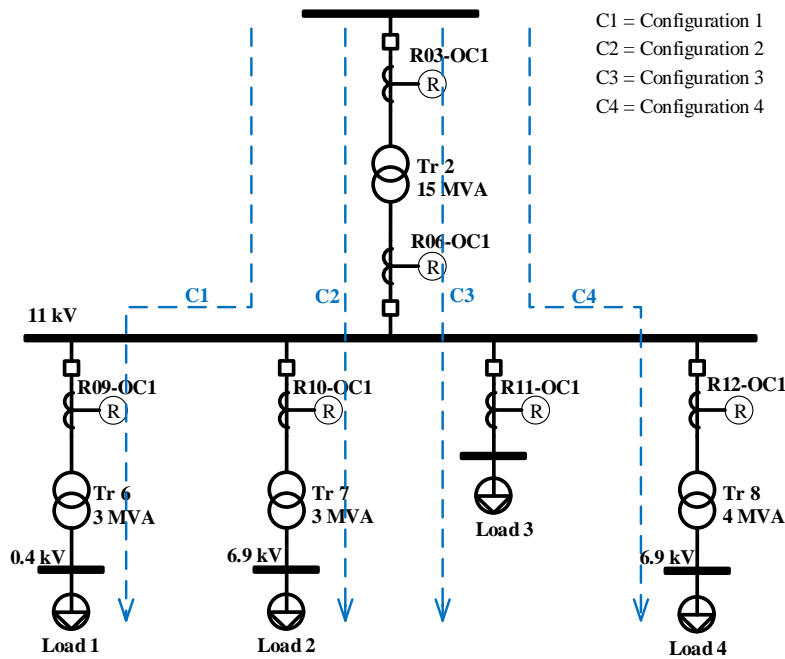


Figure 1.2 Configuration of Protection Coordination

CHAPTER 2

LITERATURE REVIEW

Overcurrent relay is very well known as a protection device in the electrical power system, especially in feeder protection, with a purpose to secure the electrical equipment by isolating the fault part and minimizing the impacted area [4]. Because of its important responsibility in protecting electrical equipment, the coordination of OCR needs to be considered in order to provide a resilient protection system with proper operation.

2.1 Related Research Study

The presence of DG causes some problems in protection coordination due to its high current penetration to the system when a fault occurs [5], [6]. Dealing with this problem, researchers have used some different methods. In [7], the authors proposed fault current limiter (FCL) to limit current flow from DG to fault location. The author in [8] proposed a remote bus marching practice (RBMP) technique that combines fuse, CB, and reactor to limit the current. By using this kind of equipment, the OCR protection coordination can still work correctly but not commonly used because of the requirement of the additional cost.

On the other hand, the improvement of existing OCR is applied by many researchers because it does not require any capital investment. Many methods, such as conventional and heuristic techniques, have been applied to optimize the protection coordination of OCR [9]. Typically, the conventional techniques implement the trial and error approach to determine the coordination of OCR. This approach produces a slow convergence rate because it needs many iterations to reach the optimal coordination value of OCR [10]. Despite conventional techniques, a natural inspired algorithm (NIA) can conduct the optimization with faster convergence. Some of the NIAs have been conducted to determine the optimal coordination of OCR with only single inverse-time current curve characteristic, such as hybrid GA optimizer [11], gravitational search algorithm [12], particle swarm optimization (PSO) [13], and hybrid PSO-DE algorithm [14].

2.2 Basic Theory

Investigating in this thesis research, many related theories and information are required to reach the objective presented in Section 1.3 of Chapter 1. The related theories are listed and explained in below subsections.

2.2.1 Fundamental of Protection Relay

Protection relay is a smart protective device that receives data from its sensors in the form of current, voltage, resistance, or temperature. By comparing the received data with reference values, the protection relay may decide to maintain reliability of the system by isolating faulted network from the main system or displaying visible information in the form of indicator lights, control warning, and alarm. The diagram shown in Figure 2.1 answers the question what the protection relay is [15].

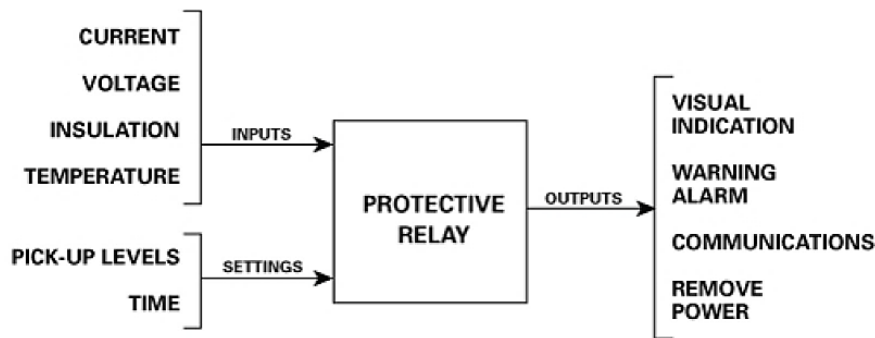


Figure 2.1 Basic Block Diagram of Protective Relay Inputs and Outputs [15]

2.2.2 Overcurrent Relay

Overcurrent relay (OCR) is one of protection relays which takes action when current flowing through its sensor is greater than pickup current setting. In principle, there would be a current coil inside an overcurrent relay. When current flows through this coil in normal condition, the magnetic effect generated by the coil is not sufficient to move the moving element of the relay, as in this condition the restraining force is greater than deflecting force. But when the current flowing through the coil increases, the magnetic effect increases. After a certain level of current, the deflecting force generated by the magnetic effect of the coil crosses the

restraining force. As a result, the moving element starts moving to change the contact position in the relay [16].

Figure 2.2 shows the basic diagram and principle work of overcurrent relay. When there is a fault F in the network, relay coil may sense high current flowing through the current transformer (CT), and relay coil may generate enough force to move the moving element of the relay. After connecting DC circuit of the relay, trip coil is energized by the DC power supply and starts to generate pulling force to open the circuit breaker (CB).

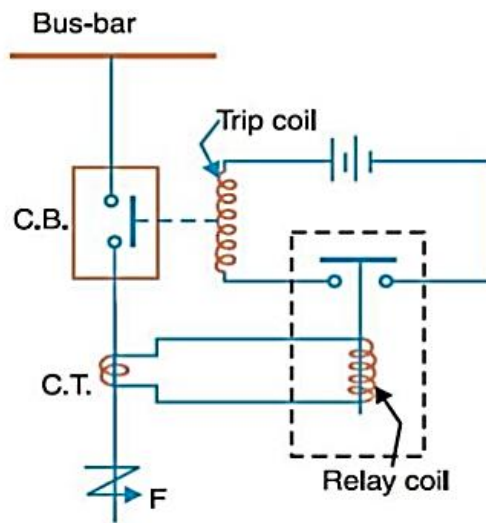


Figure 2.2 Principle Block Diagram of Overcurrent Relay

Depending upon the operating characteristic, overcurrent relay may be categorized as three types such as instantaneous overcurrent relay, definite time overcurrent relay and inverse time overcurrent relay. Each type of OCRs operates with different characteristics due to curvature of time current characteristic of OCR.

2.2.2.1 *Instantaneous Overcurrent Relay*

The overcurrent relay operating with instantaneous time-current characteristic takes action instantly without time delay when current flowing through its sensor exceeds the setting value. Using this characteristic, current threshold or pickup current, the current at which the relay trips, can be adjusted. In contrast, operating time of the relay cannot be adjusted; it works with fixed and

minimal operating time when current is greater the preset value, as shown in Figure 2.3.

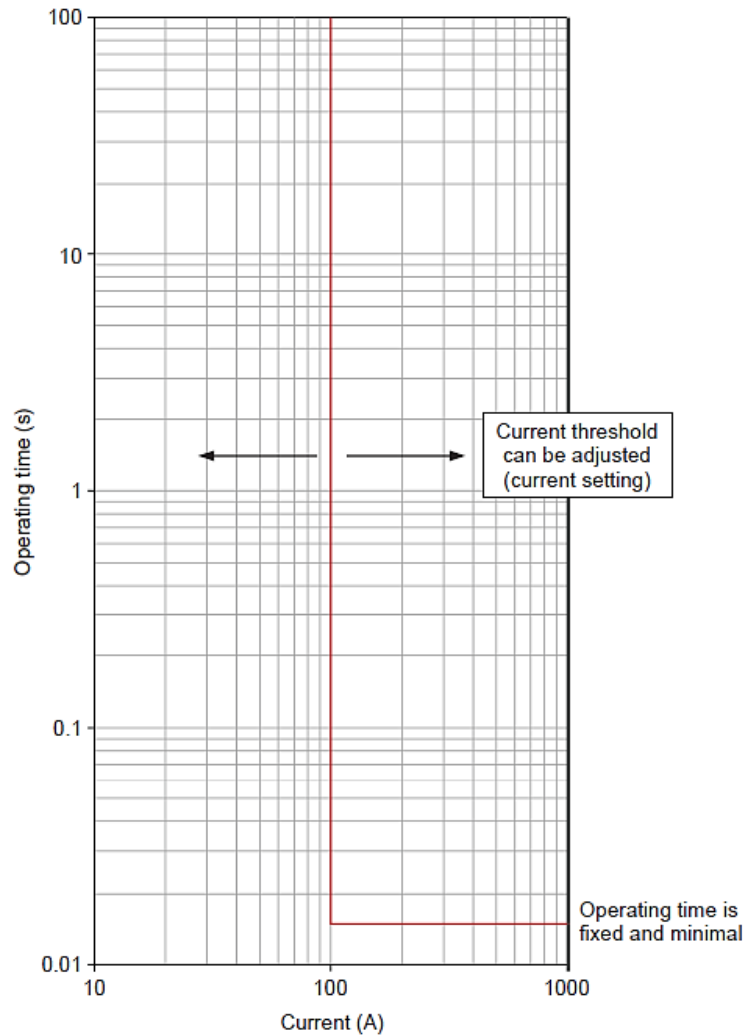


Figure 2.3 Time-Current Characteristic of Instantaneous Overcurrent Relay [17]

2.2.2.2 *Definite Time Overcurrent Relay*

The overcurrent relay operating with definite time-current characteristic is more likely to the operating with instantaneous time-current characteristic which the current threshold or pickup current can be adjusted; but definite time overcurrent relay can operate with adjustable operating time. As shown in Figure 2.4, both current threshold and operating time can be adjusted to values higher than the minimum values.

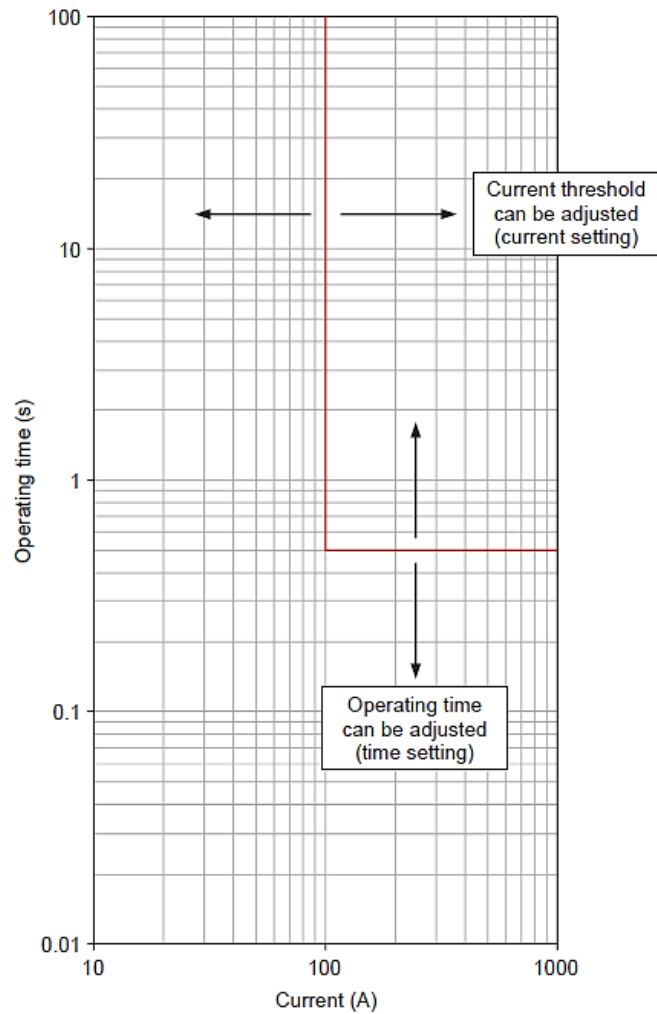


Figure 2.4 Time-Current Characteristic of Definite Time Overcurrent Relay [17]

2.2.2.3 Inverse Time Overcurrent Relay

An overcurrent relay with an inverse time-current characteristic is possible to operate with adjustable setting value of current and operating time. Using this characteristic, the operating time is inversely changed based on the change of current. As shown in Figure 2.5, operating time decreases when current increases; it means that the relay operates faster if current is getting higher.

Based on IEC standard 60255 for phase overcurrent protection, time-current characteristic of inverse time overcurrent relay is mainly divided into three types including standard inverse curve (SI), very inverse curve (VI), and extremely inverse curve (EI). However, the operating time of the three inverse time

characteristics can be defined with the same equation which is formulated as following [18]:

$$t = \frac{k \times TDS}{(PSM^\alpha - 1) \times \beta} \quad (2.1)$$

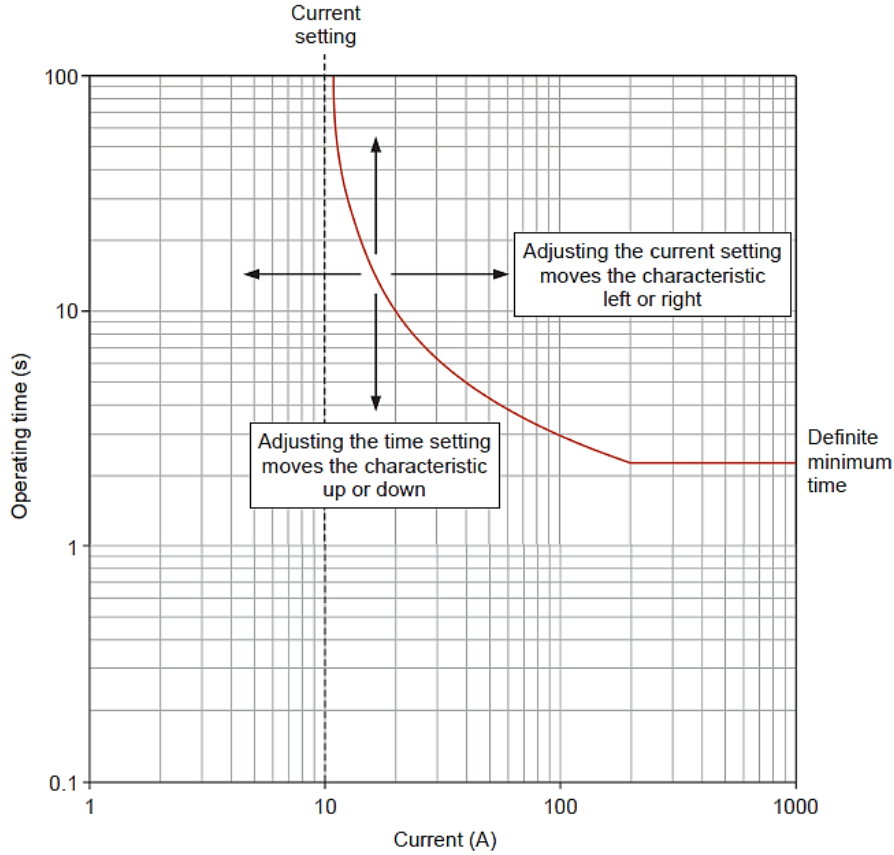


Figure 2.5 Time-Current Characteristic of Inverse Time Overcurrent Relay [17]

where TDS denotes the time dial setting of OCR. k , α and β are coefficients of inverse-time current curves shown in Table 2.1. PSM is called plug setting multiplier, which is formulated as following:

$$PSM = \frac{I_f}{I_p} \quad (2.2)$$

where I_p and I_f represent the pickup and fault current sensed by relay, respectively. When PSM is greater than 20, fault current is 20 times larger than pickup current, a significant error of CT in measuring fault current value is occurred because CTs that feed the inputs of any overcurrent relays no longer operate linearly if they are

subjected to high current levels [17]. In [17], [19], to avoid errors in the relay operating time at high current levels, the operating time t in equation (2.1) should not decrease anymore or should be in saturation point when PSM is greater than 20 ($PSM > 20$).

Table 2.1 Coefficient Values of IEC Characteristic Curves [18]

Type of curve	k	α	β
Standard Inverse (SI)	0.14	0.02	2.97
Very Inverse (VI)	13.5	1	1.5
Extremely Inverse (EI)	80	2	0.808

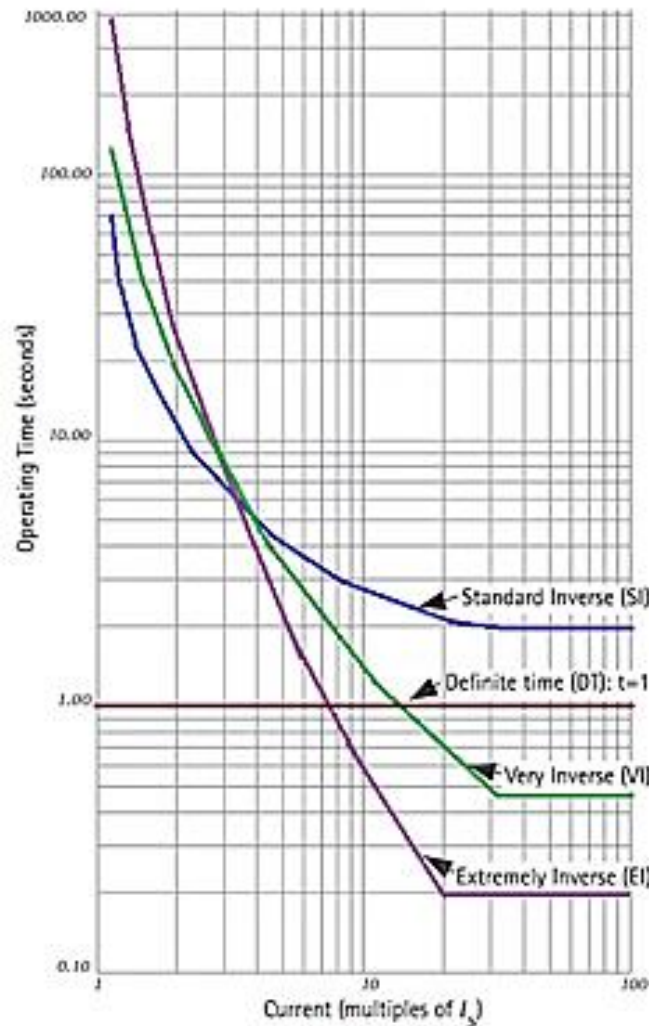


Figure 2.6 Time Current Characteristic of IEC Standard 60255 [20]

2.2.3 Coordination Time Interval

The primary and backup relays can sense the fault current simultaneously. Without time delay between the primary relay and backup relay called time grading, both relays may operate at the same time. Hence, a time grading or coordination time interval (CTI), which is the sum of the operating time of primary relay, circuit breaker, and overshoot time, is needed to guarantee the proper tripping time of the backup relay when the primary relay fails to isolate the fault from the system.

2.2.4 Motor Starting Characteristic

An electrical motor is an electrical machine that converts electrical energy into mechanical energy. Motor starting current is a current needed to run the motor during startup condition. The star-delta principal of starting assumed that motor draws several times of its full load current and causes sudden voltage sag in its terminal/neighbor buses for a short time period [21], [22]. Figure 2.7 shows the illustration of the motor starting process. The IEC extremely inverse (EI) should be used to protect electrical motor with capability to compensate the direct-online starting process as the motor needs high starting current with the range from 6 to 8 times of the nameplate current rating [23].

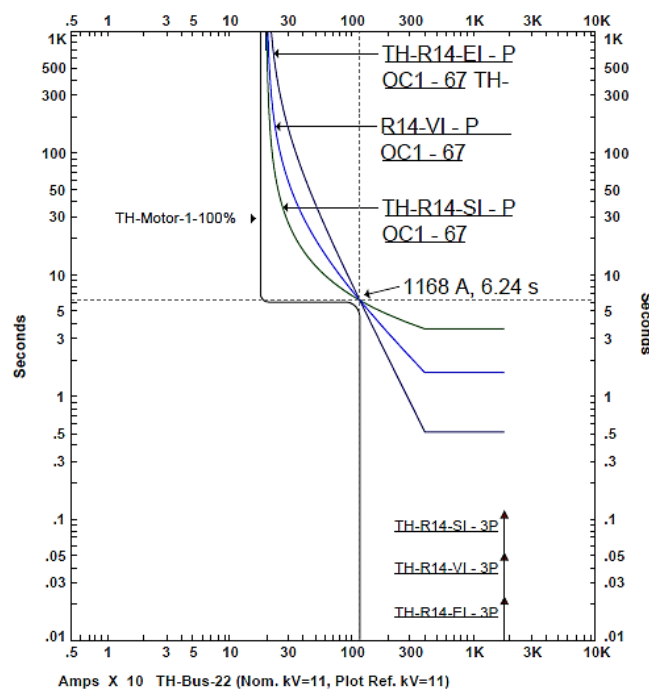


Figure 2.7 Time-Current Characteristic of IEC Standard 60255 and Motor Starting

2.2.5 Formulation of Objective Function

Optimizing protection coordination of OCR is the main scope of this thesis research to be approached. Before approaching this scope, mathematical equation of objective function and related theories must be carried out. The optimal protection coordination problem can be achieved with a specific objective function and a certain related constraint. To have a minimum operating time (TOP) of each OCR, the objective function of the optimization shall minimize the operating time of all primary and backup OCRs. The objective function can be expressed as following:

$$\text{Minimize (OF)} = \sum_{i=1}^N \left(t_i + \sum_{j=1}^M t_{j,i} \right) \quad (2.3)$$

where i and j is the primary relay and backup relay of i -relay, respectively. t is denoted as the relay operating time. The t follows the IEC Standard 60255 with equation formulated in (2.1).

2.2.6 Formulation of Protection Coordination Constraints

In order to investigate the optimization of the objective function, some related constraints must be defined clearly and carried out in the below subsections.

2.2.6.1 Constraint of Time Grading

The constraint of time grading or coordination time interval between primary and backup relay can be expressed as following:

$$t_{j,i} - t_i \geq CTI \quad (2.4)$$

where t_i represents the operating time of primary relay i . $t_{j,i}$ represents the operating time of backup relay j when relay i works as primary. CTI is the time grading between primary and backup relay with the values from 0.2 to 0.5 s [10]. In this study, CTI is considered equal to 0.2 s.

2.2.6.2 Constraint of Operating Time

The operating time of OCR has its constraint due to the limitation of sampling time. It can be expressed as following:

$$t_{i,\min} \leq t_i \leq t_{i,\max} \quad (2.5)$$

where $t_{i,\min}$ and $t_{i,\max}$ represent the minimum and maximum operating time of relay i , respectively. According to [24], the permissible operating time of OCR should be between 0.1 s and 2.5 s in order to assure the security of the proposed protection strategy.

2.2.6.3 Constraint of Time Dial Setting

Time dial setting (TDS) in (2.1) is a constant that can give a multiplier effect to the t . In this study, TDS is optimized to get minimum operating time. However, the optimized value of TDS must be within the acceptable ranges. The constraint of TDS can be defined as following:

$$TDS_{i,\min} \leq TDS_i \leq TDS_{i,\max} \quad (2.6)$$

where $TDS_{i,\min}$ and $TDS_{i,\max}$ is the minimum and maximum allowable time dial setting of relay i . The acceptable time dial setting of OCR is from 0.1 to 12.5 s, according to user's manual of the OCR model "Sepam Series 40" [18].

2.2.6.4 Constraint of Pickup Setting

OCR operates when current flowing through its sensor exceeds the pickup setting (PS). The boundaries of PS shown in the following expression.

$$PS_{i,\min} \leq PS_i \leq PS_{i,\max} \quad (2.7)$$

where $PS_{i,\min}$ and $PS_{i,\max}$ represent the lower and upper bound of pickup setting. The value of PS can be defined as following:

$$PS = \frac{I_P}{I_{CT,prim}} \quad (2.8)$$

where I_P and $I_{CT,prim}$ denote the pickup current and primary current rating of the current transformer (CT). In [18], PS value is between 0.1 to 2.4.

2.2.7 Firefly Algorithm

Firefly Algorithm (FA) was first developed by Xin-She Yang, which was based on the flashing patterns and behavior of fireflies. FA follows three important rules [1], [25].

- 1) A firefly is not attracted by other fireflies because of gender.
- 2) Attractiveness is related to the brightness, and both attractiveness and brightness decrease as their distance increases. Therefore, the less bright firefly will move towards the brighter firefly. If there is no brighter one, the firefly will move randomly.
- 3) Brightness of a firefly is determined by the landscape of the objective function.

2.2.7.1 *Light Intensity*

The light intensity $I(r)$ varies with the distance r monotonically and exponentially; hence it can be defined by:

$$I = I_0 e^{-\gamma r} \quad (2.9)$$

where the original light intensity is denoted by I_0 and γ is the light absorption coefficient.

2.2.7.2 *Attractiveness*

Since the attractiveness of firefly is proportioned to the light intensity, the attractiveness β can be formulated as following:

$$\beta = \beta_0 e^{-\gamma r^2} \quad (2.10)$$

where β_0 denotes the attractiveness at $r = 0$. It is worth indicating that the exponent γr can be replaced by γr^m , where $m > 0$.

2.2.7.3 *Distance*

The light intensity and attractiveness of a firefly can be achieved unless the distance between fireflies is known. The distance r_{ij} between two fireflies can be formulated as the following expression.

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (2.11)$$

where (x_i, y_i) and (x_j, y_j) represent the positions of firefly i and j respectively.

2.2.7.4 Movement

The movement of a firefly i attracted to another more attractive (brighter) firefly j is determined by [1]:

$$x_i^{t+1} = x_i^t + \beta_0 e^{-\gamma r_{ij}^2} (x_j^t - x_i^t) + \alpha_t \varepsilon_i^t \quad (2.12)$$

where the second term represents the attraction between firefly i and j . The third term, $\alpha_t \varepsilon_i^t$, represents the randomization.

2.2.7.5 Firefly Algorithm Pseudo Code

Firefly Algorithm (FA) can be summarized in the pseudo code, shown in Figure 2.6. First, objective function of the optimization must be defined. Then, population of fireflies is initialized. After giving initialized population of fireflies, the light absorption coefficient may be defined. The light intensity $I(r)$ of all possibilities between fireflies can be calculated by equation (2.9). And then, compare the light intensity between fireflies to defined the brightest firefly and move the less bright fireflies towards the brighter firefly. The loop of the above steps may be conducted until the solution is found or maximum iteration is reached.

Firefly Algorithm Pseudo Code [25]:

```

Objective function  $f(x)$ ,  $x = (x_1, \dots, x_d)^T$ 
Initialize a population of fireflies  $x_i = (i = 1, 2, \dots, n)$ 
Define light absorption coefficient  $\gamma$ 
while ( $t < \text{MaxGeneration}$ )
    for  $i = 1: n$  all  $n$  fireflies
        for  $j = 1: i$  all  $n$  fireflies
            Light intensity  $I_i$  at  $x_i$  is determined by  $f(x_i)$ 
            if ( $I_j > I_i$ )
                Move firefly  $i$  towards  $j$  in all  $d$  dimensions
            end if
            Attractiveness varies with distance  $r$  via  $e^{-\gamma r}$ 
            Evaluate new solutions and update light intensity
        end for j
    end for i
    Rank the fireflies and find the current best
end while
Postprocess results and visualization

```

CHAPTER 3

OPTIMAL PROTECTION COORDINATION OF OVERCURRENT RELAY USING FIREFLY ALGORITHM

In this chapter, important data of the electrical system of PT. Pupuk Kalimantan Timur is acquired from single line diagram modelled in ETAP 12.6.0. In addition, firefly algorithm using in optimization problem of protection coordination is briefly explained.

3.1 Electrical System Under Study

PT. Pupuk Kalimantan Timur covered six factories at once which produce Urea and Ammonia (for Factory 1A, Factory 2, Factory 3, Factory 4 and Factory 5), and NPK (for NPK Factory) [26]. Studying the whole electrical system of PT. Pupuk Kalimantan Timur is quite complicated due to its large-scale system. Therefore, electrical system of Tanjung Harapan, a composite network of PT. Pupuk Kalimantan Timur, is investigated in this thesis research.

3.1.1 Apparatus Data of Electrical System of Tanjung Harapan

In electrical system of Tanjung Harapan, there are many electrical equipment such as generator, transformer, motor load, lumped load, overcurrent relay (OCR), circuit breaker (CB) and current transformer (CT) as shown in Figure 3.1. This composite network gains electrical power from two sources: a main source with voltage level of 33 kV, and a 30 MW capacity-generator with voltage level of 11 kV. Eight-distributed transformers are used to step-up or step-down voltage to different levels such as 33 kV, 11 kV, 6.9 kV, 0.4 kV, and 0.525 kV. Sixteen-overcurrent relays are used to protection electrical equipment in Tanjung Harapan from over-load and over-current caused by over load demand or fault (short circuit). In below subsections, primary and technical data of those apparatuses are carried out. The acquired data is very important in optimization of protection coordination of OCR while optimized method needs this data as the input values.

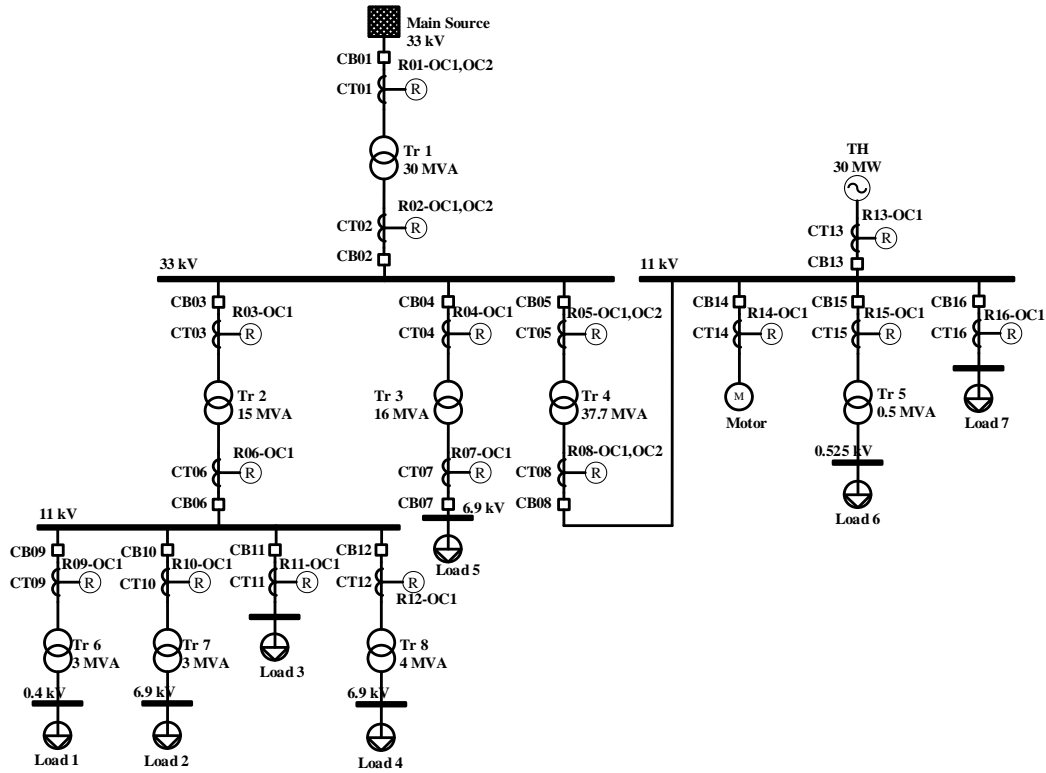


Figure 3.1 Tanjung Harapan Composite Network Under Study

3.1.1.1 Generator and Load Data of Electrical System of Tanjung Harapan

Under normal operating condition, a 30 MW (37.5 MVA with power factor %PF = 80%) distributed generator (DG), named TH, can supply power to various load connected to different buses. Table 3.1 shows more detail information of generator and load data of electrical system under study.

Table 3.1 Generator and Load Data of Electrical System of Tanjung Harapan

Type	ID	MW	Mvar	MVA	%PF	%Eff	Bus kV
Generator	TH	30	22.5	37.5	80	95	11
Lumped Load	Load 1	1.7	1.054	2	85	-	0.4
Lumped Load	Load 2	1.7	1.054	2	85	-	6.9
Lumped Load	Load 3	5.1	3.161	6	85	-	11
Lumped Load	Load 4	3	1.86	3.53	85	-	6.6
Lumped Load	Load 5	14.45	8.955	17	85	-	6.9
Lumped Load	Load 6	0.3775	0.2202	0.4441	85	-	0.525
Lumped Load	Load 7	10.2	6.321	12	85	-	11
Motor Load	Motor	2798	1975.3	3425	86	95	11

3.1.1.2 Transformer Data of Electrical System of Tanjung Harapan

Eight-distributed transformers are used to step-up or step-down voltage to different levels and data of those transformers are presented in Table 3.2.

Table 3.2 Transformer Data of Electrical System of Tanjung Harapan

ID	Capacity (MVA)	Voltage (kV)
Tr 1	30	33/33
Tr 2	15	33/11
Tr 3	16	33/6.9
Tr 4	37.7	33/11
Tr 5	0.5	11/0.525
Tr 6	3	11/0.4
Tr 7	3	11/6.9
Tr 8	4	11/6.6

3.1.1.3 Current Transformer (CT)

A current transformer (CT), a type of instrument transformer, is designed to produce an alternating current in its secondary winding which is proportional to the current being measured in its primary. The current transformer is used reduce a high current to a much lower value that offers a suitable way in measuring and monitoring methods. The current transformer is one of the significant elements in power system protection since it provides the main source of information to the protective relays and most kind of protective devices [27]. Table 3.3 shows the primary data of CTs that are used in electrical system of Tanjung Harapan.

Table 3.3 Ratio of Current Transformer Used for Each Overcurrent relay

Relay ID	CT ID	CT Ratio	Relay ID	CT ID	CT Ratio
R01-OC1	CT01	800/5	R11-OC1	CT11	800/5
R02-OC1	CT02	800/5	R12-OC1	CT12	600/5
R03-OC1	CT03	400/5	R13-OC1	CT13	2500/5
R04-OC1	CT04	400/5	R14-OC1	CT14	200/5
R05-OC1	CT05	800/5	R15-OC1	CT15	100/5
R06-OC1	CT06	2000/5	R16-OC1	CT16	1200/5
R07-OC1	CT07	2000/5	R01-OC2	CT01	800/5
R08-OC1	CT08	2000/5	R02-OC2	CT02	800/5
R09-OC1	CT09	1200/5	R05-OC2	CT05	800/5
R10-OC1	CT10	1200/5	R08-OC2	CT08	2000/5

3.1.1.4 Technical Data of Overcurrent Relay

The relay used in this thesis research, one of the Schneider Electric's products, is Sepam Series 40 shown in Figure 3.2. There are some main protection functions which are available in this relay model such as [18]:

- Phase protection and earth fault protection with adjustable reset time, with switching of the active group of settings and logic discrimination
- Earth fault protection insensitive to transformer switching
- RMS thermal overload protection that takes into account external operating temperature and ventilation operating rates
- Directional earth fault protection suitable for all isolated, compensated or impedance neutral systems
- Directional phase overcurrent protection with voltage memory
- Voltage and frequency protection functions (under/over, etc.).



Figure 3.2 Protective Relay Named Sepam Series 40

Phase overcurrent protection is the main objective of this thesis research. Therefore, phase overcurrent protection function of the relay modelled “Sepam Series 40” is used. In Table 3.4, setting characteristics of phase overcurrent relay are presented.

Table 3.4 Setting Characteristics of Phase Overcurrent Relay [18]

Is set point		
Setting	Definite time	$0.1 I_n \leq I_s \leq 24 I_n$ expressed in Amps
	IDMT	$0.1 I_n \leq I_s \leq 2.4 I_n$ expressed in Amps
Accuracy		$\pm 5\%$ or $\pm 0.01 I_n$
Time delay (T) or time dial setting (TDS)		
Setting	Definite time	inst., $50 \text{ ms} \leq T \leq 300 \text{ s}$
	IDMT	$100 \text{ ms} \leq T \leq 12.5 \text{ s}$
Accuracy	Definite time	$\pm 2\%$ or from -10 ms to $+25 \text{ ms}$
	IDMT	Class 5 or from -10 ms to $+25 \text{ ms}$

3.1.2 Important Data Using in Optimal Protection Coordination

In optimization of protection coordination of OCR, the most important data that need to be acquired before applying the optimization method are full load amps of the protected equipment, and maximum short circuit current caused by fault at any location of the system network. These important data are carried out in below subsections.

3.1.2.1 Full Load Amps and Pick up Current

In this study, pick up current (I_p) is 1.05 times full load amps (FLA). The data of full load amps and pick up current that can flow through each OCR without the presence of distributed generator (DG) are presented in Table 3.5.

Table 3.5 Full Load Amps for Each Overcurrent Relay without DG

Relay ID	FLA (A)	I_p (A)	Relay ID	FLA (A)	I_p (A)
R01-OC1	524.9	551.145	R09-OC1	157.5	165.375
R02-OC1	524.9	551.145	R10-OC1	157.5	165.375
R03-OC1	262.4	275.52	R11-OC1	314.9	330.645
R04-OC1	279.9	293.895	R12-OC1	209.9	220.395
R05-OC1	699.8	734.79	R14-OC1	179.8	188.79
R06-OC1	787.3	826.665	R15-OC1	26.2	27.51
R07-OC1	1339	1405.95	R16-OC1	629.8	661.29
R08-OC1	2099	2203.95			

The data of full load amps and pick up current that can flow through each OCR with the presence of DG are presented in Table 3.6.

Table 3.6 Full Load Amps for Each Overcurrent Relay with DG

Relay ID	FLA (A)	Ip (A)	Relay ID	FLA (A)	Ip (A)
R01-OC1	524.9	551.145	R11-OC1	314.9	330.645
R02-OC1	524.9	551.145	R12-OC1	209.9	220.395
R03-OC1	262.4	275.52	R13-OC1	1968	2066.4
R04-OC1	279.9	293.895	R14-OC1	179.8	188.79
R05-OC1	699.8	734.79	R15-OC1	26.2	27.51
R06-OC1	787.3	826.665	R16-OC1	629.8	661.29
R07-OC1	1339	1405.95	R01-OC2	524.9	551.145
R08-OC1	2099	2203.95	R02-OC2	524.9	551.145
R09-OC1	157.5	165.375	R05-OC2	699.8	734.79
R10-OC1	157.5	165.375	R08-OC2	2099	2203.95

3.1.2.2 Maximum Short Circuit Current

The data of maximum short circuit current that can flow through each OCR without the presence of distributed generator (DG are presented in Table 3.7.

Table 3.7 Maximum Short Circuit Current without DG

Relay ID		Isc (A)	
<i>Primary</i>	<i>Backup</i>	<i>Primary</i>	<i>Backup</i>
R01-OC1	-	14770	-
R02-OC1	R01-OC1	3400	3400
R03-OC1	R02-OC1	5530	3390
R04-OC1	R02-OC1	5240	3390
R05-OC1	R02-OC1	4990	3270
R06-OC1	R03-OC1	5510	1840
R07-OC1	R04-OC1	8980	1880
R08-OC1	R05-OC1	7500	2500
R09-OC1	R06-OC1	7340	4860
R10-OC1	R06-OC1	7180	4860
R11-OC1	R06-OC1	6850	5510
R12-OC1	R06-OC1	6980	4880
R14-OC1	R08-OC1	9660	6860
R15-OC1	R08-OC1	11670	7450
R16-OC1	R08-OC1	7860	6740

The data of maximum short circuit current that can flow through each OCR with the presence of DG are presented in Table 3.8.

Table 3.8 Maximum Short Circuit Current with DG

Relay ID			Isc (A)		
<i>Primary</i>	<i>Backup</i>		<i>Primary</i>	<i>Backup</i>	
R01-OC1	-	-	14770	-	-
R02-OC1	R01-OC1	-	3400	3400	-
R03-OC1	R02-OC1	R05-OC2	6890	3390	2460
R04-OC1	R02-OC1	R05-OC2	6600	3390	2460
R05-OC1	R02-OC1	-	4990	3270	-
R06-OC1	R03-OC1	-	5900	1970	-
R07-OC1	R04-OC1	-	9700	2030	-
R08-OC1	R05-OC1	-	7500	2500	-
R09-OC1	R06-OC1	-	7640	5170	-
R10-OC1	R06-OC1	-	7480	5180	-
R11-OC1	R06-OC1	-	7190	5900	-
R12-OC1	R06-OC1	-	7280	5200	-
R13-OC1	-	-	10820	-	-
R14-OC1	R08-OC1	R13-OC2	17970	6300	9090
R15-OC1	R08-OC1	R13-OC2	22290	7410	10690
R16-OC1	R08-OC1	R13-OC2	15600	5980	8630
R01-OC2	R02-OC2	-	2130	2130	-
R02-OC2	R05-OC2	-	4250	2460	-
R05-OC2	R08-OC2	-	2460	7390	-
R08-OC2	R13-OC1	-	15000	10750	-

3.2 Firefly Algorithm in Optimal Protection Coordination

In this thesis research, firefly algorithm is used to solve optimization problem of protection coordination of OCR. The firefly algorithm solves this optimization problem by finding minimum time dial setting (TDS) which offers the minimum operating time (TOP) for each OCR. The optimization is investigated by following the procedure of the flowchart shown in Figure 3.3. The flowchart is divided into two blocks: the first block (at the left side) shows the procedure of methodology used to minimize *TDS* and *TOP* of downstream OCRs, and the second block (at the right side) shows the procedure of methodology used to minimize *TDS* and *TOP* of upstream OCRs.

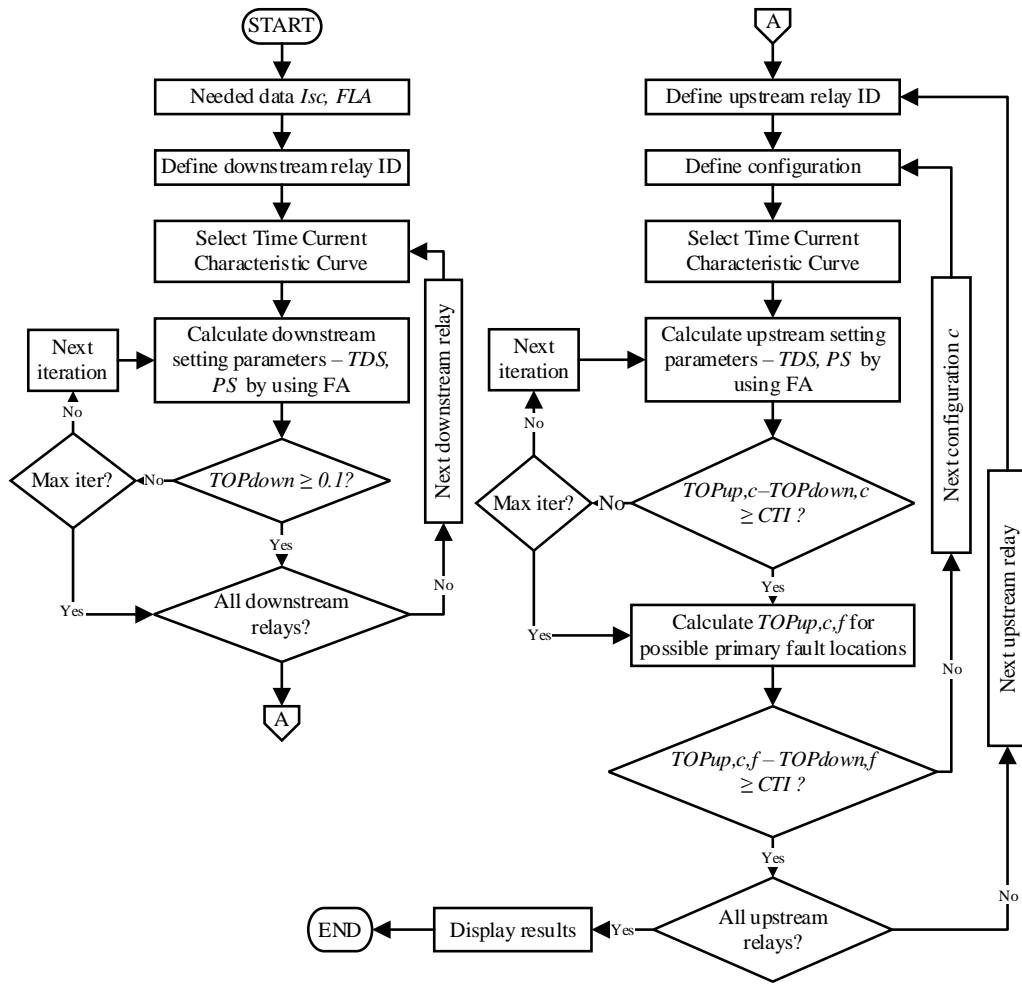


Figure 3.3 The Procedure of Protection Coordination of OCRs

CHAPTER 4

RESULTS AND DISCUSSION

In this thesis research, the proposed method, Firefly Algorithm, is investigated on a radial-industrial distribution system named Tanjung Harapan which is a composite network of PT. Pupuk Kalimantan Timur. The tested system is studied under two study cases: 1) a DG is not connected to the system of Tanjung Harapan, and 2) a DG is connected to the system of Tanjung Harapan.

4.1 Optimal Protection Coordination of OCRs of Tanjung Harapan Electrical System without DG

In study case 1, Tanjung Harapan Electrical System operates without connecting with a DG. In this case study, three scenarios are divided according to the use of different characteristic of IEC time-current curves. For scenario 1, IEC extremely inverse (IEC-EI) curves are selected to use for all overcurrent relays in the system under study. IEC standard inverse (IEC-SI) and IEC very inverse (IEC-VI) curves are used for scenario 2 and scenario 3, respectively. The results of each scenario found by proposed method are used in validating the correctness of developed program (Coded in MATLAB). The results are validated in ETAP and carried out in below subsections.

4.1.1 Scenario 1: Using IEC-EI

The FA is one of swarm intelligence algorithms which needs some initial population to process the optimization. In this optimization, the number of initial populations of *TDS* is 30 and the population values are carried out in Table 4.1.

Table 4.1 Initial TDS Population of Relay R02-OC1 for Case 1-Scenario 1

Population	TDS	Population	TDS	Population	TDS
1	8.13	11	1.83	21	10.31
2	2.18	12	10.75	22	9.24
3	9.43	13	0.95	23	1.04
4	4.39	14	2.50	24	9.14
5	3.11	15	7.70	25	5.65

Population	TDS	Population	TDS	Population	TDS
6	11.18	16	5.17	26	5.15
7	12.32	17	0.86	27	1.98
8	8.68	18	7.26	28	8.31
9	8.29	19	9.98	29	5.66
10	5.85	20	4.56	30	2.55

Figure 4.1 shows the dot plot of FA initial population (blue dot plot) and the best optimized solution of *TDS* (red dot plot) for relay R02-OC1. The red dot plots represent the values of *TDS* for the last iteration of FA when the best cost is reached.

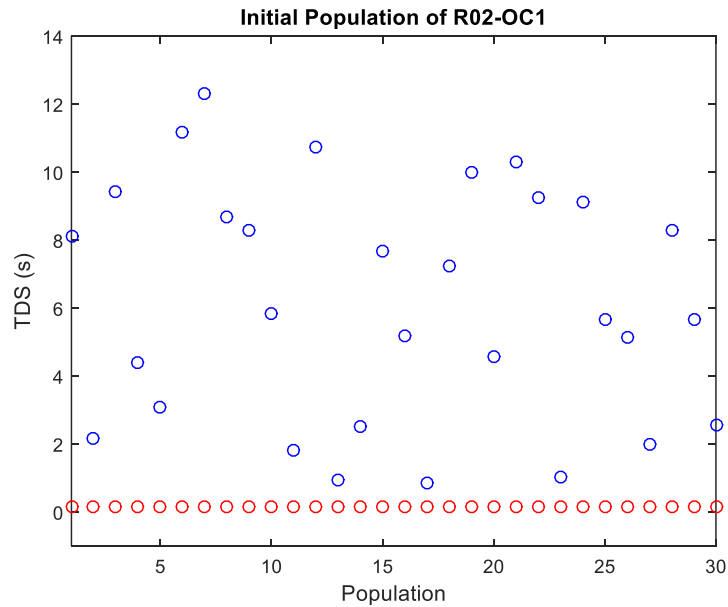


Figure 4.1 TDS Population of Relay R02-OC1 for Case 1-Scenario 1

Figure 4.2 shows the convergence of FA in optimization of operating time of relay R02-OC1 when it works as a backup relay of R05-OC1. The convergence is reached unless all *TDS* populations of FA (red dot plot) are equal as shown in Figure 4.1.

In scenario 1, IEC-EI curves are used for all OCRs. By applying the proposed method FA, the optimized values of PS, TDS, TOP for each primary and backup OCR, and the objective function (OF) are listed in Table 4.2.

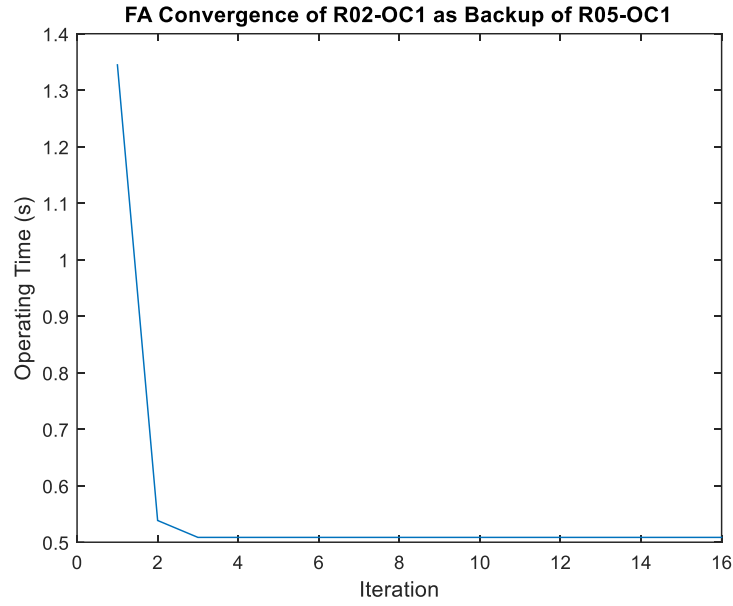


Figure 4.2 FA Convergence of Relay R02-OC1 for Case 1-Scenario 1

Table 4.2 Optimal Coordination of OCRs for Case 1-Scenario 1

Primary				Backup			
<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>	<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>
R01-OC1	0.70	0.41	0.1017	-	-	-	-
R02-OC1	0.70	0.17	0.4693	R01-OC1	0.70	0.41	0.4693
R03-OC1	0.70	0.40	0.1018	R02-OC1	0.70	0.17	0.4722
R04-OC1	0.80	0.27	0.1001	R02-OC1	0.70	0.17	0.4722
R05-OC1	1.00	0.11	0.2873	R02-OC1	0.70	0.17	0.5086
R06-OC1	0.50	0.10	0.3372	R03-OC1	0.70	0.40	0.3521
R07-OC1	0.80	0.10	0.3246	R04-OC1	0.80	0.27	0.3250
R08-OC1	1.20	0.10	1.1295	R05-OC1	1.00	0.11	1.2425
R09-OC1	0.20	0.41	0.1017	R06-OC1	0.50	0.10	0.4377
R10-OC1	0.20	0.41	0.1017	R06-OC1	0.50	0.10	0.4377
R11-OC1	0.50	0.30	0.1016	R06-OC1	0.50	0.10	0.3372
R12-OC1	0.40	0.41	0.1017	R06-OC1	0.50	0.10	0.4340
R14-OC1	1.00	2.08	0.5161	R08-OC1	1.20	0.10	1.3809
R15-OC1	0.30	0.41	0.1017	R08-OC1	1.20	0.10	1.1465
R16-OC1	0.60	0.12	0.1005	R08-OC1	1.20	0.10	1.4377
<i>OF</i>				13.4304 s			

Coordination Time Interval (*CTI*) represents the proper coordination of OCRs. The proper coordination must respect the constraint of *CTI* which is greater than 0.2 s. The *CTI* values of relay pairs are presented in Table 4.3.

Table 4.3 Coordination Time Interval of Relay Pair for Case 1-Scenario 1

Scenario 1: Using IEC-EI		
<i>Backup Relay</i>	<i>Primary Relay</i>	<i>CTI</i>
R02-OC1	R03-OC1	0.3704
	R04-OC1	0.3721
	R05-OC1	0.2212
R06-OC1	R09-OC1	0.3360
	R10-OC1	0.3360
	R11-OC1	0.2356
	R12-OC1	0.3322
R08-OC1	R14-OC1	0.8647
	R15-OC1	1.0448
	R16-OC1	1.3371

The results revealed in the above table are used to validate the correctness of proposed method. Figure 4.3 shows the IEC-EI time-current curves of relay pairs when *R02-OC1* works as a backup relay. The *CTI* values of relay pairs *R02-OC1/R03-OC1*, *R02-OC1/R03-OC1*, and *R02-OC1/R03-OC1* are 0.369 s, 0.369 s, and 0.221 s, respectively. It can be seen that the *CTI* values of relay pairs and *TOP* value of each OCR shown in Figure 4.3 are very close to the *CTI* and *TOP* values shown in Table 4.3 and Table 4.2. Time-current curve of more relay pairs are shown in APPENDIX B.

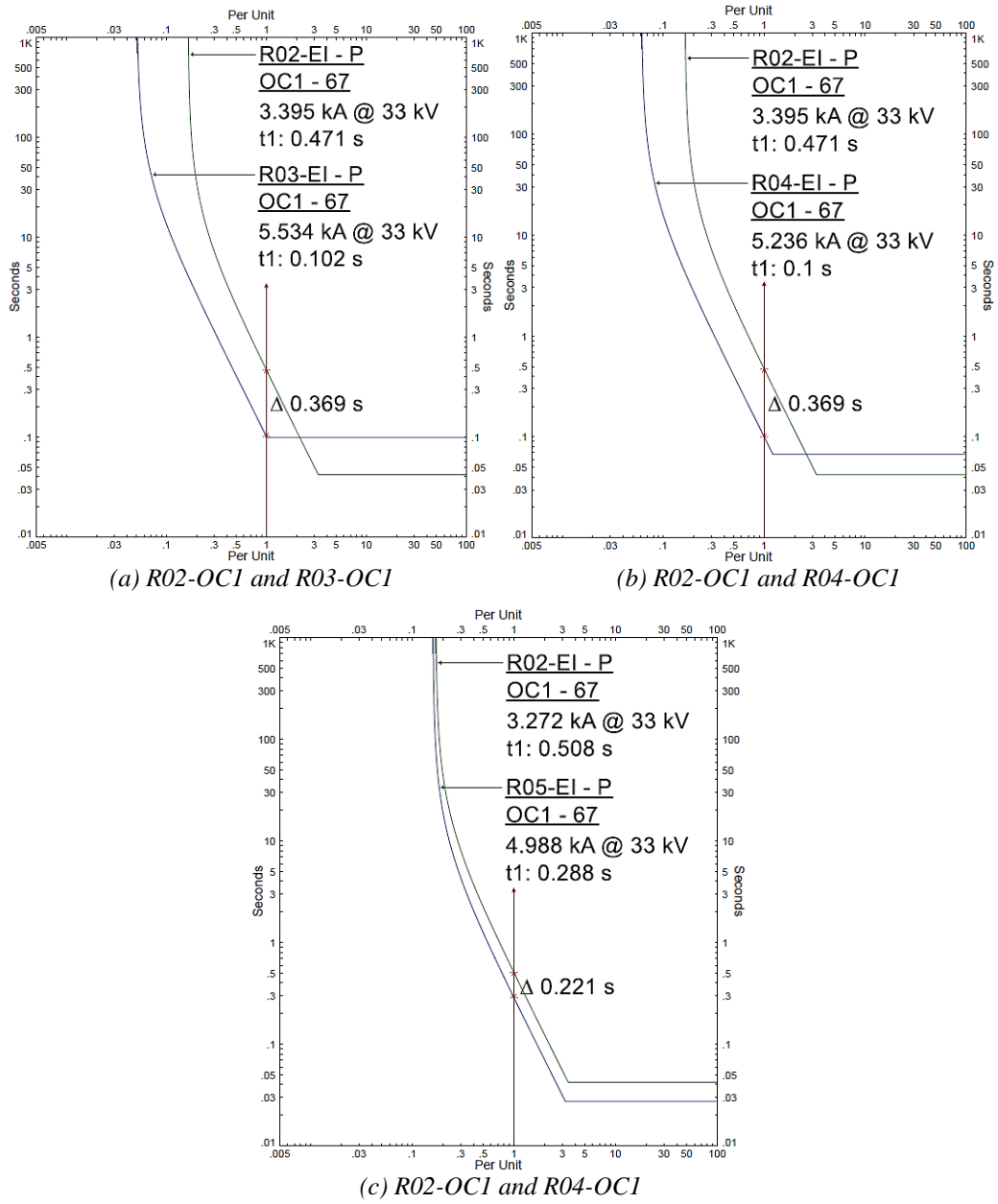


Figure 4.3 Time-Current Curves of Backup Relay Named R02-OC1 for Different Primary Relays for Case 1-Scenario 1

4.1.2 Scenario 2: Using IEC-SI

In this optimization, the number of initial populations of *TDS* is 30 and the population values are carried out in Table 4.4.

Table 4.4 Initial TDS Population of Relay R02-OC1 for Case 1-Scenario 2

Population	TDS	Population	TDS	Population	TDS
1	6.18	11	3.73	21	5.02
2	11.95	12	3.40	22	7.44
3	3.06	13	11.08	23	10.95
4	7.61	14	7.45	24	1.13
5	9.40	15	5.48	25	7.26
6	0.22	16	3.09	26	5.61
7	4.87	17	8.87	27	9.52
8	6.45	18	12.10	28	10.83
9	4.83	19	7.48	29	2.15
10	3.34	20	11.89	30	5.78

Figure 4.4 shows the dot plot of FA initial population (blue dot plot) and the best optimized solution of *TDS* (red dot plot) for relay R02-OC1. The red dot plots represent the values of *TDS* for the last iteration of FA when the best cost is reached.

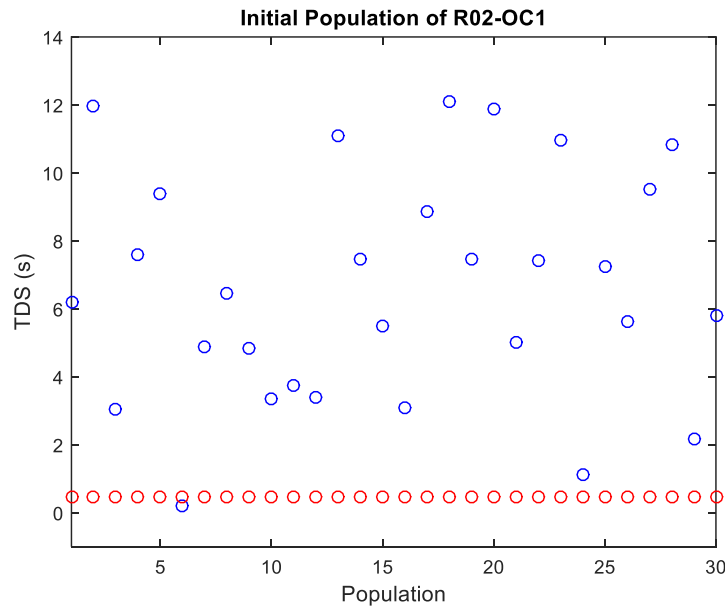


Figure 4.4 TDS Population of Relay R02-OC1 for Case 1-Scenario 2

Figure 4.5 shows the convergence of FA in optimization of operating time of relay R02-OC1 when it works as a backup relay of R05-OC1. The convergence

is reached unless all *TDS* populations of FA (red dot plot) are equal as shown in Figure 4.4.

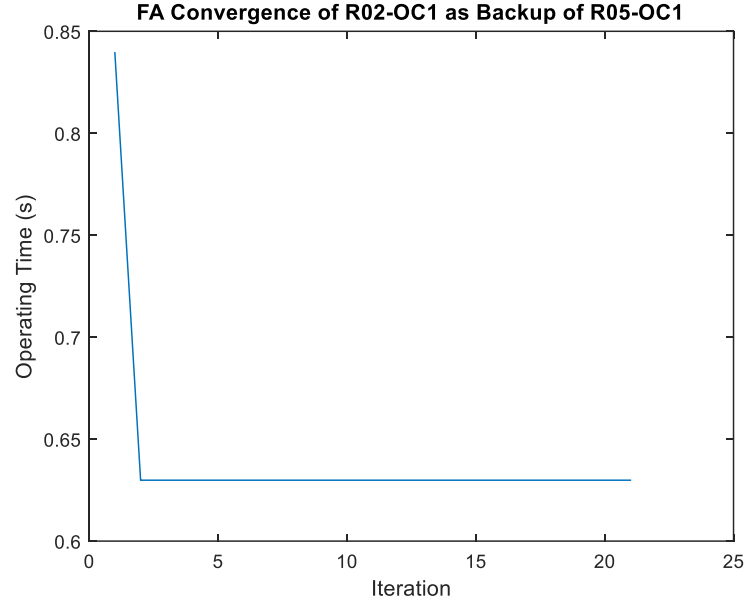


Figure 4.5 FA Convergence of Relay R02-OC1 for Case 1-Scenario 2

In scenario 2, IEC-SI curves are used for all OCRs excepts protection relay of motor named *R14-OC1* which uses IEC-EI curve. IEC-EI must be used for relay *R14-OC1* to compensate high starting current of the motor as explained in Chapter 2. By applying the proposed method FA, the optimized values of *PS*, *TDS*, *TOP* for each primary and backup OCR, and the objective function (*OF*) are listed in Table 4.5. The *CTI* values of relay pairs are presented in Table 4.6.

Table 4.5 Optimal Coordination of OCRs for Case 1-Scenario 2

Primary				Backup			
Relay ID	PS	TDS	TOP	Relay ID	PS	TDS	TOP
R01-OC1	0.70	0.48	0.3664	-	-	-	-
R02-OC1	0.70	0.48	0.6160	R01-OC1	0.70	0.48	0.6160
R03-OC1	0.70	0.26	0.1994	R02-OC1	0.70	0.48	0.6170
R04-OC1	0.80	0.13	0.1066	R02-OC1	0.70	0.48	0.6170
R05-OC1	1.00	0.33	0.4172	R02-OC1	0.70	0.48	0.6299
R06-OC1	0.50	0.23	0.3123	R03-OC1	0.70	0.26	0.3194
R07-OC1	0.80	0.10	0.1343	R04-OC1	0.80	0.13	0.1438
R08-OC1	1.20	0.33	0.6749	R05-OC1	1.00	0.33	0.6749
R09-OC1	0.20	0.14	0.1069	R06-OC1	0.50	0.23	0.3375

Primary				Backup			
<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>	<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>
R10-OC1	0.20	0.14	0.1069	R06-OC1	0.50	0.23	0.3375
R11-OC1	0.50	0.13	0.1048	R06-OC1	0.50	0.23	0.3123
R12-OC1	0.40	0.14	0.1069	R06-OC1	0.50	0.23	0.3366
R14-OC1	1.00	2.08	0.5161	R08-OC1	1.20	0.33	0.7328
R15-OC1	0.30	0.14	0.1069	R08-OC1	1.20	0.33	0.6789
R16-OC1	0.60	0.11	0.1059	R08-OC1	1.20	0.33	0.7455
<i>OF</i>				11.0803 s			

Table 4.6 Coordination Time Interval of Relay Pair for Case 1-Scenario 2

Scenario 1: Using IEC-SI		
<i>Backup Relay</i>	<i>Primary Relay</i>	<i>CTI</i>
R02-OC1	R03-OC1	0.4177
	R04-OC1	0.5105
	R05-OC1	0.2127
R06-OC1	R09-OC1	0.2306
	R10-OC1	0.2306
	R11-OC1	0.2074
	R12-OC1	0.2297
R08-OC1	R14-OC1	0.2167
	R15-OC1	0.5720
	R16-OC1	0.6396

Figure 4.6 shows the IEC-SI time-current curves of relay pairs when *R02-OC1* works as a backup relay. The *CTI* values of relay pairs *R02-OC1/R03-OC1*, *R02-OC1/R03-OC1*, and *R02-OC1/R03-OC1* are 0.418 s, 0.51 s, and 0.213 s, respectively. It can be seen that the *CTI* values of relay pairs and *TOP* value of each OCR shown in Figure 4.6 are very close to the *CTI* and *TOP* values shown in Table 4.6 and Table 4.5. Time-current curve of more relay pairs are shown in APPENDIX B.

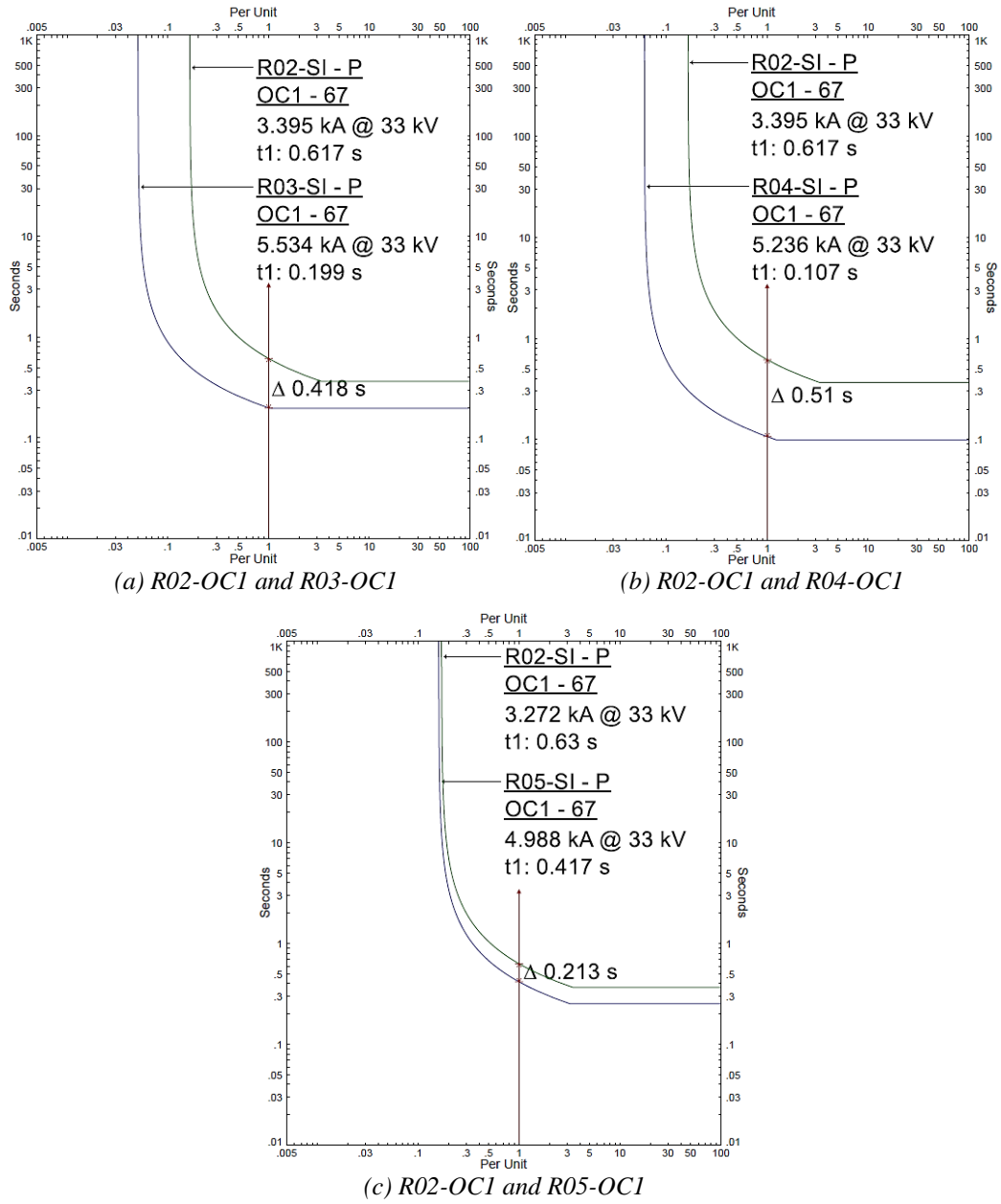


Figure 4.6 Time-Current Curves of Backup Relay Named R02-OC1 for Different Primary Relays for Case 1-Scenario 2

4.1.3 Scenario 3: Using IEC-VI

In this optimization, the number of initial populations of *TDS* is 30 and the population values are carried out in Table 4.7.

Table 4.7 Initial TDS Population of Relay R02-OC1 for Case 1-Scenario 3

Population	TDS	Population	TDS	Population	TDS
1	9.23	11	5.50	21	6.21
2	6.50	12	8.90	22	0.21
3	1.40	13	3.04	23	12.42
4	10.45	14	8.83	24	10.72
5	11.04	15	9.16	25	6.45
6	0.94	16	2.32	26	6.86
7	11.10	17	9.52	27	11.07
8	11.53	18	0.93	28	10.02
9	12.41	19	3.86	29	3.40
10	4.90	20	1.22	30	1.47

Figure 4.7 shows the dot plot of FA initial population (blue dot plot) and the best optimized solution of *TDS* (red dot plot) for relay R02-OC1. The red dot plots represent the values of *TDS* for the last iteration of FA when the best cost is reached.

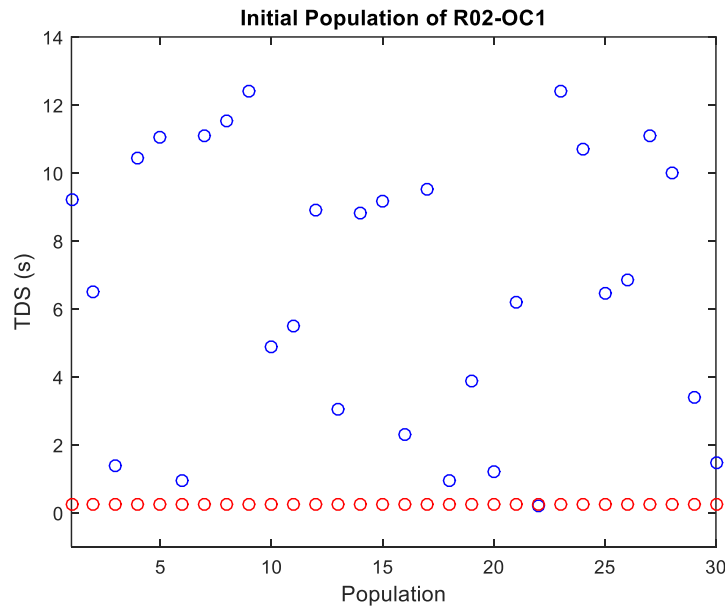


Figure 4.7 TDS Population of Relay R02-OC1 for Case 1-Scenario 3

Figure 4.8 shows the convergence of FA in optimization of operating time of relay R02-OC1 when it works as a backup relay of R05-OC1. The convergence

is reached unless all *TDS* populations of FA (red dot plot) are equal as shown in Figure 4.7.

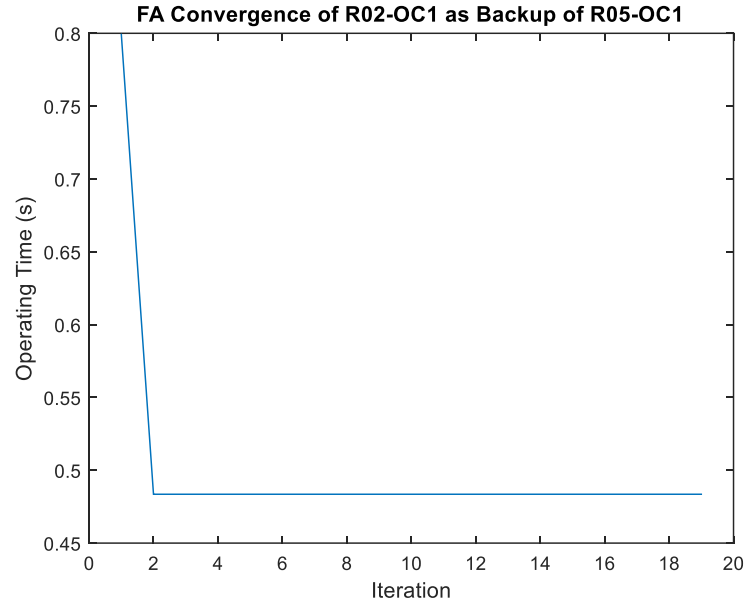


Figure 4.8 FA Convergence of Relay R02-OC1 for Case 1-Scenario 3

In scenario 3, IEC-VI curves are used for all OCRs excepts protection relay of motor named *R14-OC1* which uses IEC-EI curve. By applying the proposed method FA, the optimized values of *PS*, *TDS*, *TOP* for each primary and backup OCR, and the objective function (*OF*) are listed in Table 4.8. The *CTI* values of relay pairs are presented in Table 4.9.

Table 4.8 Optimal Coordination of OCRs for Case 1-Scenario 3

Primary				Backup			
<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>	<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>
R01-OC1	0.70	0.26	0.1232	-	-	-	-
R02-OC1	0.70	0.26	0.4614	R01-OC1	0.70	0.26	0.4614
R03-OC1	0.70	0.21	0.1008	R02-OC1	0.70	0.26	0.4630
R04-OC1	0.80	0.18	0.1054	R02-OC1	0.70	0.26	0.4630
R05-OC1	1.00	0.16	0.2749	R02-OC1	0.70	0.26	0.4835
R06-OC1	0.50	0.16	0.3193	R03-OC1	0.70	0.21	0.3231
R07-OC1	0.80	0.10	0.1951	R04-OC1	0.80	0.18	0.2031
R08-OC1	1.20	0.15	0.6353	R05-OC1	1.00	0.16	0.6776
R09-OC1	0.20	0.22	0.1042	R06-OC1	0.50	0.16	0.3731
R10-OC1	0.20	0.22	0.1042	R06-OC1	0.50	0.16	0.3731

Primary				Backup			
<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>	<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>
R11-OC1	0.50	0.18	0.1005	R06-OC1	0.50	0.16	0.3193
R12-OC1	0.40	0.22	0.1042	R06-OC1	0.50	0.16	0.3711
R14-OC1	1.00	2.08	0.5161	R08-OC1	1.20	0.15	0.7265
R15-OC1	0.30	0.22	0.1042	R08-OC1	1.20	0.15	0.6416
R16-OC1	0.60	0.12	0.1089	R08-OC1	1.20	0.15	0.7465
<i>OF</i>				9.9837 s			

Table 4.9 Coordination Time Interval of Relay Pair for Case 1-Scenario 3

Scenario 1: Using IEC-VI		
<i>Backup Relay</i>	<i>Primary Relay</i>	<i>CTI</i>
R02-OC1	R03-OC1	0.3622
	R04-OC1	0.3577
	R05-OC1	0.2086
R06-OC1	R09-OC1	0.2688
	R10-OC1	0.2688
	R11-OC1	0.2188
	R12-OC1	0.2669
R08-OC1	R14-OC1	0.2103
	R15-OC1	0.5374
	R16-OC1	0.6376

Figure 4.9 shows the IEC-VI time-current curves of relay pairs when *R02-OC1* works as a backup relay. The *CTI* values of relay pairs *R02-OC1* and *R03-OC1*, *R02-OC1* and *R03-OC1*, *R02-OC1* and *R03-OC1* are 0.361 s, 0.356 s, and 0.208 s, respectively. It can be seen that the *CTI* values of relay pairs and *TOP* value of each OCR shown in Figure 4.9 are very close to the *CTI* and *TOP* values shown in Table 4.9 and Table 4.8. Time-current curve of more relay pairs are shown in APPENDIX B.

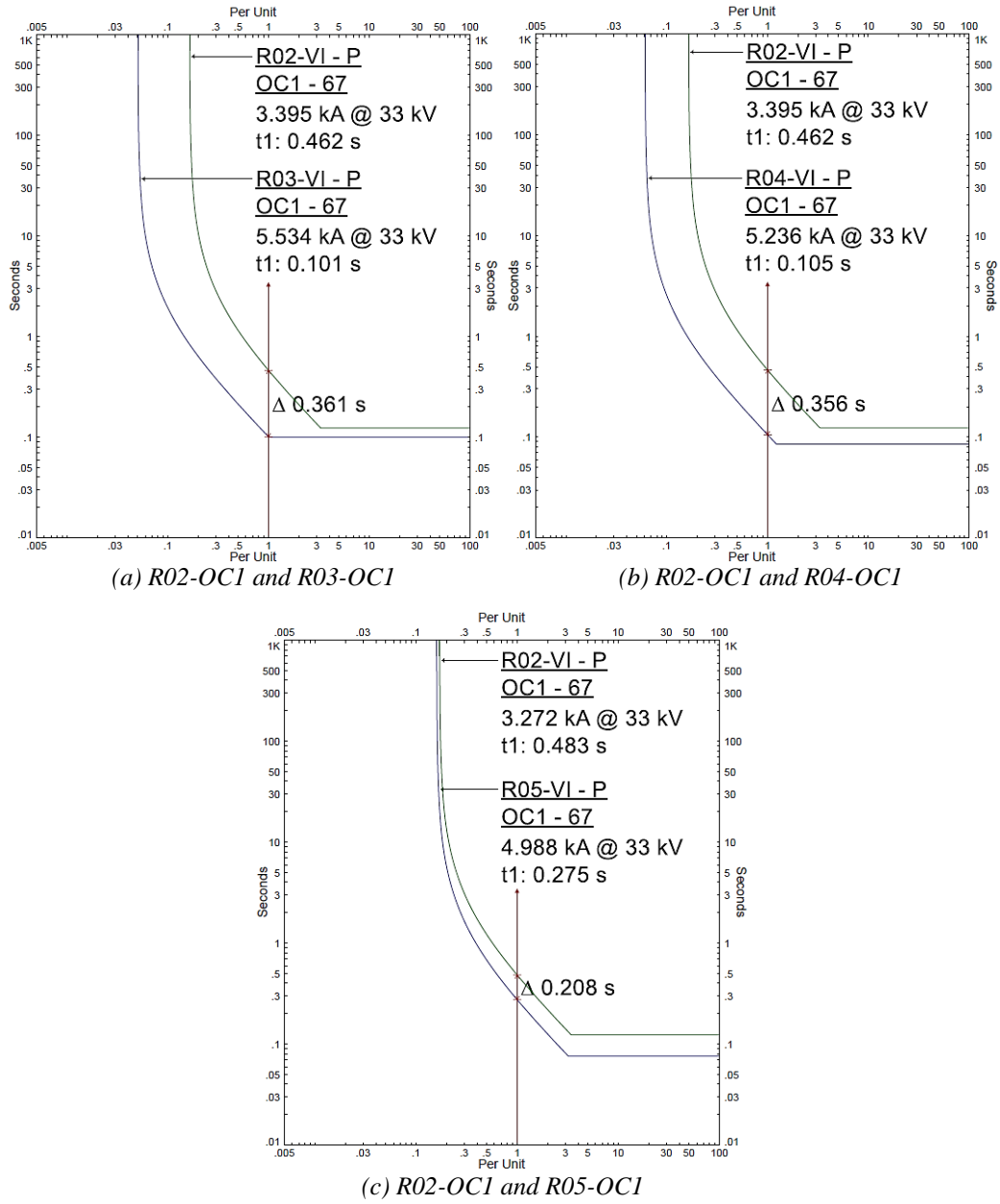


Figure 4.9 Time-Current Curves of Backup Relay Named R02-OC1 for Different Primary Relays for Case 1-Scenario 3

4.1.4 Discussion

Selecting the best curve for OCR is quite important to have a good protection coordination with minimum operating time. In study case 1, the objective functions of each scenario with different curves are 13.4304 s for scenario 1 which used IEC-EI curve, 11.0803 s for scenario 2 which used IEC-SI curve, and 9.9837 s for scenario 3 which used IEC-VI curve. As shown in Figure 4.10, the objective

function of scenario 3, which used IEC-VI curve, is the smallest value with 25.66% smaller than scenario 1 and 9.90% smaller than scenario 2. Therefore, scenario 3 using IEC-VI curve should be selected to use in protection coordination of OCRs for radial-industrial system, in case there is not a DG connected to the electrical system of Tanjung Harapan.

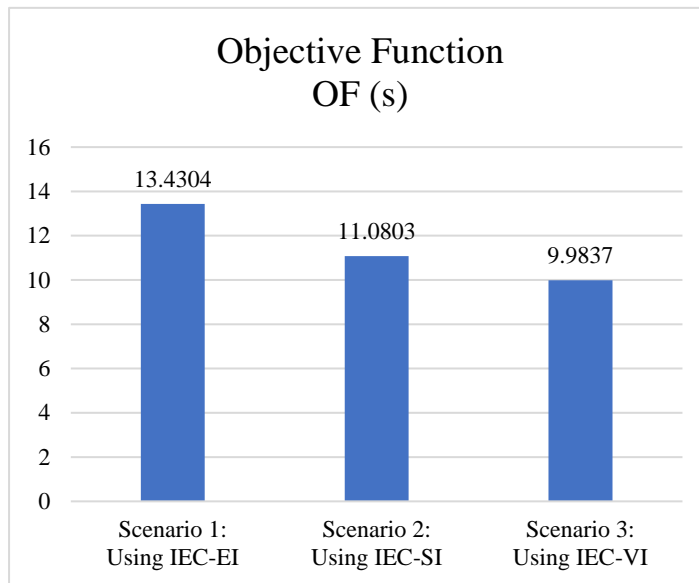


Figure 4.10 Objective Function Values for Study Case 1

4.2 Optimal Protection Coordination of OCRs of Tangung Harapan Electrical System with DG

In study case 2, Tangung Harapan Electrical System operates with the presence of a DG. Similar to study case 1, study case 2 is divided into three scenarios according to the use of different characteristic of IEC time-current curves. For scenario 1, IEC extremely inverse (IEC-EI) curves are selected to use for all overcurrent relays in the system under study. IEC standard inverse (IEC-SI) and IEC very inverse (IEC-VI) curves are used for scenario 2 and scenario 3, respectively.

4.2.1 Scenario 1: Using IEC-EI

In this optimization, the number of initial populations of *TDS* is 30 and the population values are carried out in Table 4.10.

Table 4.10 Initial TDS Population of Relay R02-OC1 for Case 2-Scenario 1

Population	TDS	Population	TDS	Population	TDS
1	0.30	11	12.41	21	3.92
2	4.37	12	10.37	22	5.23
3	10.67	13	6.58	23	6.08
4	10.48	14	8.57	24	2.50
5	1.59	15	6.30	25	8.66
6	3.88	16	10.43	26	5.07
7	1.66	17	0.90	27	3.09
8	11.75	18	2.59	28	9.16
9	5.33	19	4.47	29	6.47
10	3.89	20	5.63	30	5.29

Figure 4.11 shows the dot plot of FA initial population (blue dot plot) and the best optimized solution of *TDS* (red dot plot) for relay R02-OC1. The red dot plots represent the values of *TDS* for the last iteration of FA when the best cost is reached.

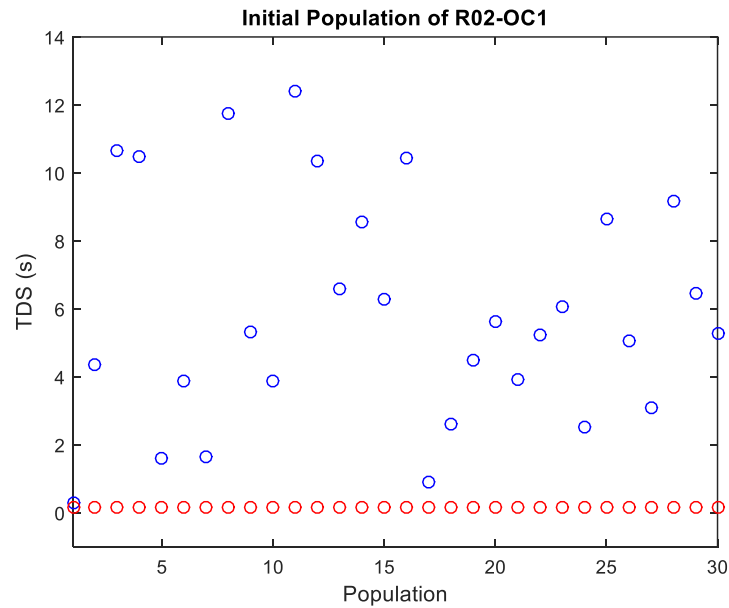


Figure 4.11 TDS Population of Relay R02-OC1 for Case 2-Scenario 1

Figure 4.12 shows the convergence of FA in optimization of operating time of relay R02-OC1 when it works as a backup relay of R05-OC1. The

convergence is reached unless all *TDS* populations of FA (red dot plot) are equal as shown in Figure 4.11.

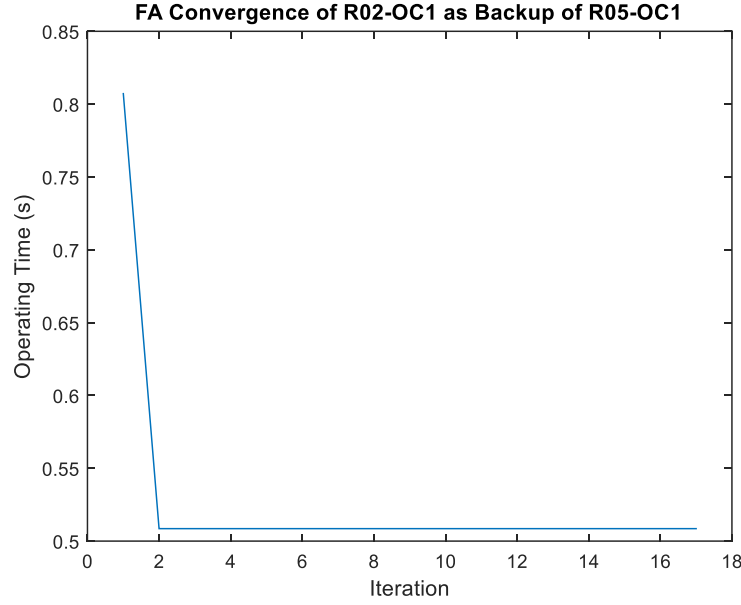


Figure 4.12 FA Convergence of Relay R02-OC1 for Case 2-Scenario 1

In scenario 1, IEC-EI curves are used for all OCRs. By applying the proposed method FA, the optimized values of *PS*, *TDS*, *TOP* for each primary and backup OCR, and the objective function (*OF*) are listed in Table 4.11. The *CTI* values of relay pairs are presented in Table 4.12.

Table 4.11 Optimal Coordination of OCRs for Case 2-Scenario 1

Primary				Backup			
Relay ID	PS	TDS	TOP	Relay ID	PS	TDS	TOP
R01-OC1	0.70	0.41	0.1017	-	-	-	-
R01-OC2	0.70	0.10	0.7352	R02-OC2	0.70	0.10	0.7352
R02-OC1	0.70	0.17	0.4693	R01-OC1	0.70	0.41	0.4693
R02-OC2	0.70	0.10	0.1749	R05-OC2	1.00	0.10	1.1709
R03-OC1	0.70	0.41	0.1017	R02-OC1	0.70	0.17	0.4722
				R05-OC2	1.00	0.10	1.1709
R04-OC1	0.80	0.41	0.1017	R02-OC1	0.70	0.17	0.4722
				R05-OC2	1.00	0.10	1.1709
R05-OC1	1.00	0.11	0.2873	R02-OC1	0.70	0.17	0.5086
R05-OC2	1.00	0.10	1.1709	R08-OC2	1.20	0.11	1.2841
R06-OC1	0.50	0.11	0.3221	R03-OC1	0.70	0.41	0.3266

Primary				Backup			
Relay ID	PS	TDS	TOP	Relay ID	PS	TDS	TOP
R07-OC1	0.80	0.10	0.2769	R04-OC1	0.80	0.41	0.2775
R08-OC1	1.20	0.10	1.1295	R05-OC1	1.00	0.11	1.2425
R08-OC2	1.20	0.11	0.2861	R13-OC1	0.90	0.12	0.5443
R09-OC1	0.20	0.41	0.1017	R06-OC1	0.50	0.11	0.4233
R10-OC1	0.20	0.41	0.1017	R06-OC1	0.50	0.11	0.4216
R11-OC1	0.50	0.33	0.1014	R06-OC1	0.50	0.11	0.3221
R12-OC1	0.40	0.41	0.1017	R06-OC1	0.50	0.11	0.4182
R13-OC1	0.90	0.12	0.5370	-	-	-	-
R14-OC1	1.00	2.08	0.5161	R08-OC1	1.20	0.10	1.6808
				R13-OC1	0.90	0.12	0.7755
R15-OC1	0.30	0.41	0.1017	R08-OC1	1.20	0.10	1.1604
				R13-OC1	0.90	0.12	0.5507
R16-OC1	0.60	0.41	0.1017	R08-OC1	1.20	0.10	1.9010
				R13-OC1	0.90	0.12	0.8665
OF				25.1864 s			

Table 4.12 Coordination Time Interval of Relay Pair for Case 2-Scenario 1

Scenario 1: Using IEC-EI		
<i>Backup Relay</i>	<i>Primary Relay</i>	<i>CTI</i>
R02-OC1	R03-OC1	0.3705
	R04-OC1	0.3705
	R05-OC1	0.2212
R05-OC2	R02-OC2	0.9960
	R03-OC1	1.0692
	R04-OC1	1.0692
R06-OC1	R09-OC1	0.3216
	R10-OC1	0.3199
	R11-OC1	0.2207
	R12-OC1	0.3165
R08-OC1	R14-OC1	1.1647
	R15-OC1	1.0586
	R16-OC1	1.7992
R13-OC1	R08-OC2	0.2582
	R14-OC1	0.2593
	R15-OC1	0.4490
	R16-OC1	0.7648

Figure 4.13 shows the IEC-EI time-current curves of relay pairs when *R02-OC1* works as a backup relay. The *CTI* values of relay pairs *R02-OC1/R03-OC1*, *R02-OC1/R03-OC1*, and *R02-OC1/R03-OC1* are 0.369 s, 0.367 s, and 0.221 s, respectively. It can be seen that the *CTI* values of relay pairs and *TOP* value of each OCR shown in Figure 4.13 are very close to the *CTI* and *TOP* values shown in Table 4.12 and Table 4.11. Time-current curve of more relay pairs are shown in APPENDIX C.

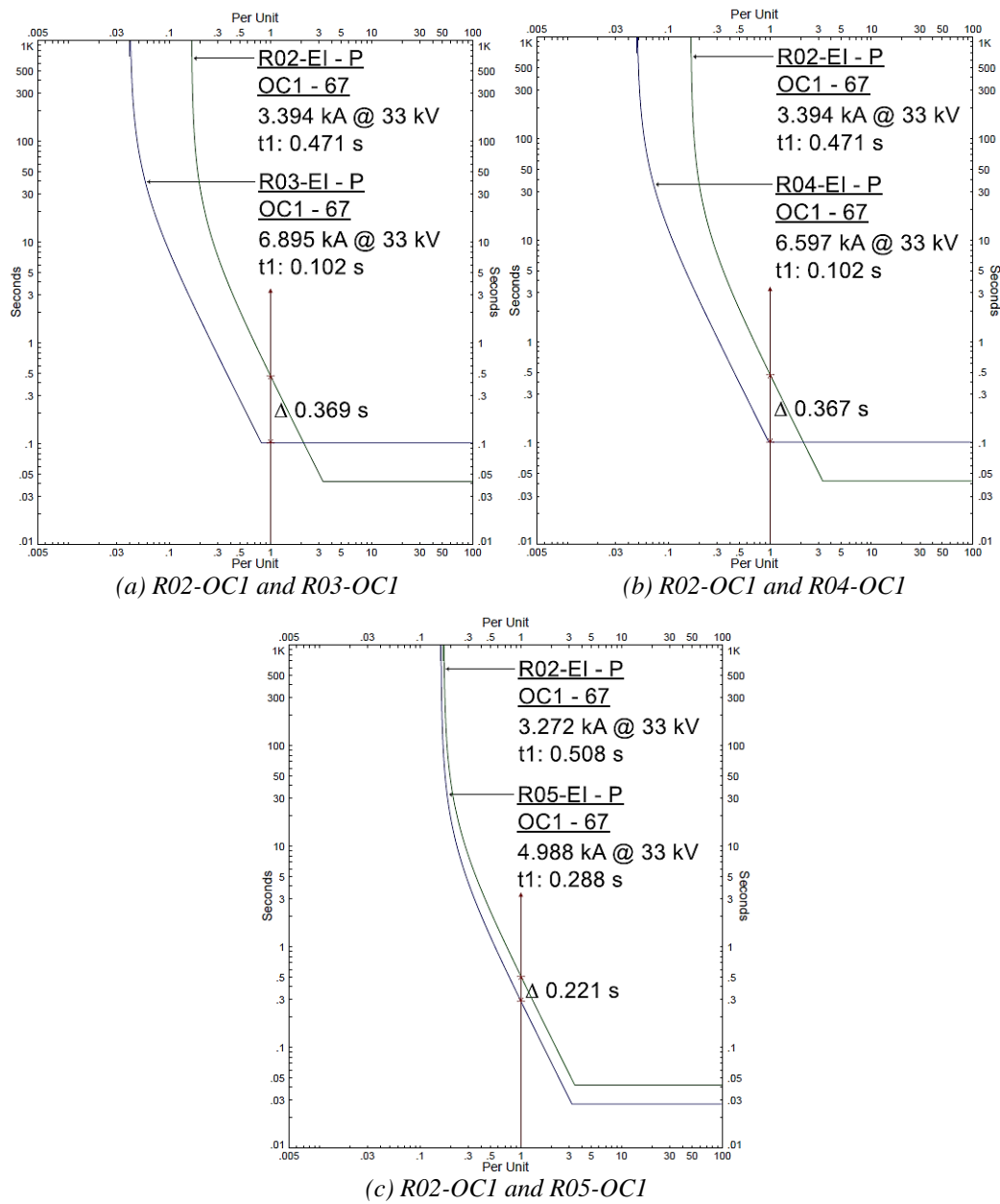


Figure 4.13 Time-Current Curves of Backup Relay Named *R02-OC1* for Different Primary Relays for Case 2-Scenario 1

4.2.2 Scenario 2: Using IEC-SI

In this optimization, the number of initial populations of *TDS* is 30 and the population values are carried out in Table 4.13.

Table 4.13 Initial *TDS* Population of Relay R02-OC1 for Case 2-Scenario 2

Population	TDS	Population	TDS	Population	TDS
1	8.90	11	4.20	21	11.74
2	8.47	12	2.90	22	10.24
3	4.42	13	2.25	23	6.25
4	2.92	14	8.20	24	2.94
5	1.91	15	7.93	25	12.09
6	2.96	16	4.60	26	4.47
7	4.97	17	10.41	27	5.00
8	11.84	18	10.79	28	3.70
9	8.32	19	5.77	29	12.39
10	10.61	20	7.77	30	4.01

Figure 4.14 shows the dot plot of FA initial population (blue dot plot) and the best optimized solution of *TDS* (red dot plot) for relay R02-OC1. The red dot plots represent the values of *TDS* for the last iteration of FA when the best cost is reached.

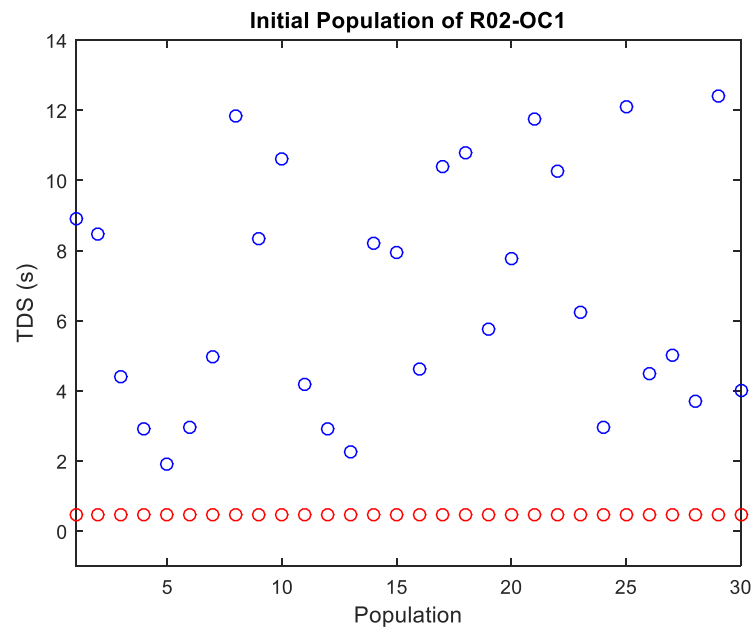


Figure 4.14 *TDS* Population of Relay R02-OC1 for Case 2-Scenario 2

Figure 4.15 shows the convergence of FA in optimization of operating time of relay R02-OC1 when it works as a backup relay of R05-OC1. The convergence is reached unless all *TDS* populations of FA (red dot plot) are equal as shown in Figure 4.14.

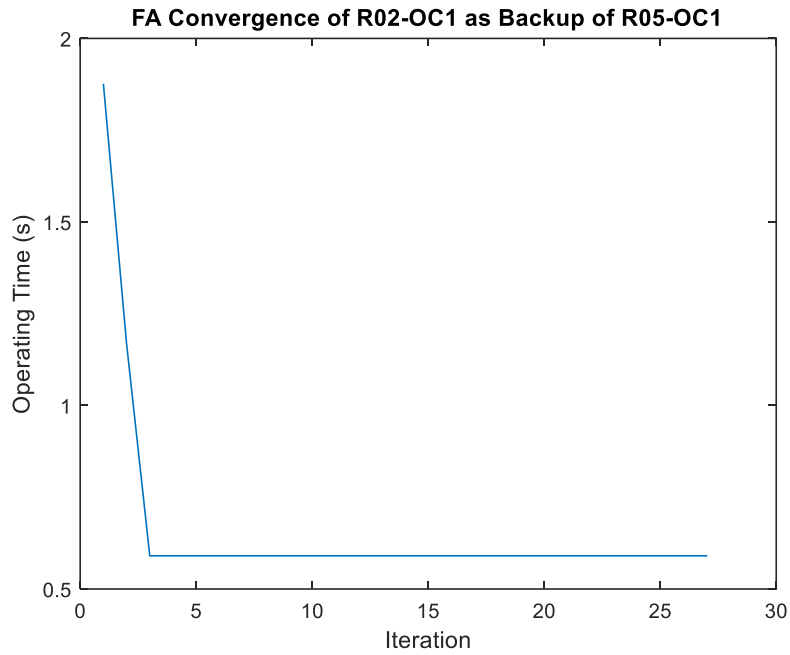


Figure 4.15 FA Convergence of Relay R02-OC1 for Case 2-Scenario 2

In scenario 2, IEC-SI curves are used for all OCRs excepts protection relay of motor named *R14-OC1* which uses IEC-EI curve. By applying the proposed method FA, the optimized values of *PS*, *TDS*, *TOP* for each primary and backup OCR, and the objective function (*OF*) are listed in Table 4.14. The *CTI* values of relay pairs are presented in Table 4.15.

Table 4.14 Optimal Coordination of OCRs for Case 2-Scenario 2

Primary				Backup			
<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>	<i>Relay ID</i>	<i>PS</i>	<i>TDS</i>	<i>TOP</i>
R01-OC1	0.70	0.45	0.3435	-	-	-	-
R01-OC2	0.70	0.10	0.1741	R02-OC2	0.70	0.10	0.1741
R02-OC1	0.70	0.45	0.5775	R01-OC1	0.70	0.45	0.5775
R02-OC2	0.70	0.10	0.1139	R05-OC2	1.00	0.20	0.4149
R03-OC1	0.70	0.27	0.2061	R02-OC1	0.70	0.45	0.5785
				R05-OC2	1.00	0.20	0.4149

Primary				Backup			
Relay ID	PS	TDS	TOP	Relay ID	PS	TDS	TOP
R04-OC1	0.80	0.14	0.1069	R02-OC1	0.70	0.45	0.5785
				R05-OC2	1.00	0.20	0.4149
R05-OC1	1.00	0.30	0.3792	R02-OC1	0.70	0.45	0.5905
R05-OC2	1.00	0.20	0.4149	R08-OC2	1.20	0.21	0.4352
R06-OC1	0.50	0.24	0.3131	R03-OC1	0.70	0.27	0.3199
R07-OC1	0.80	0.10	0.1284	R04-OC1	0.80	0.14	0.1378
R08-OC1	1.20	0.30	0.6135	R05-OC1	1.00	0.30	0.6135
R08-OC2	1.20	0.21	0.2652	R13-OC1	0.90	0.44	0.6528
R09-OC1	0.20	0.14	0.1069	R06-OC1	0.50	0.24	0.3387
R10-OC1	0.20	0.14	0.1069	R06-OC1	0.50	0.24	0.3383
R11-OC1	0.50	0.13	0.1030	R06-OC1	0.50	0.24	0.3131
R12-OC1	0.40	0.14	0.1069	R06-OC1	0.50	0.24	0.3375
R13-OC1	0.90	0.44	0.6500	-	-	-	-
R14-OC1	1.00	2.08	0.5161	R08-OC1	1.20	0.30	0.7256
				R13-OC1	0.90	0.44	0.7324
R15-OC1	0.30	0.14	0.1069	R08-OC1	1.20	0.30	0.6201
				R13-OC1	0.90	0.44	0.6551
R16-OC1	0.60	0.14	0.1069	R08-OC1	1.20	0.30	0.7674
				R13-OC1	0.90	0.44	0.7611
OF				16.9322 s			

Table 4.15 Coordination Time Interval of Relay Pair for Case 2-Scenario 2

Scenario 2: Using IEC-SI		
<i>Backup Relay</i>	<i>Primary Relay</i>	<i>CTI</i>
R02-OC1	R03-OC1	0.3723
	R04-OC1	0.4716
	R05-OC1	0.2113
R05-OC2	R02-OC2	0.3010
	R03-OC1	0.2088
	R04-OC1	0.3081
R06-OC1	R09-OC1	0.2318
	R10-OC1	0.2314
	R11-OC1	0.2100
	R12-OC1	0.2306
R08-OC1	R14-OC1	0.2095
	R15-OC1	0.5133
	R16-OC1	0.6606

Scenario 2: Using IEC-SI		
Backup Relay	Primary Relay	CTI
R13-OC1	R08-OC2	0.3876
	R14-OC1	0.2163
	R15-OC1	0.5483
	R16-OC1	0.6542

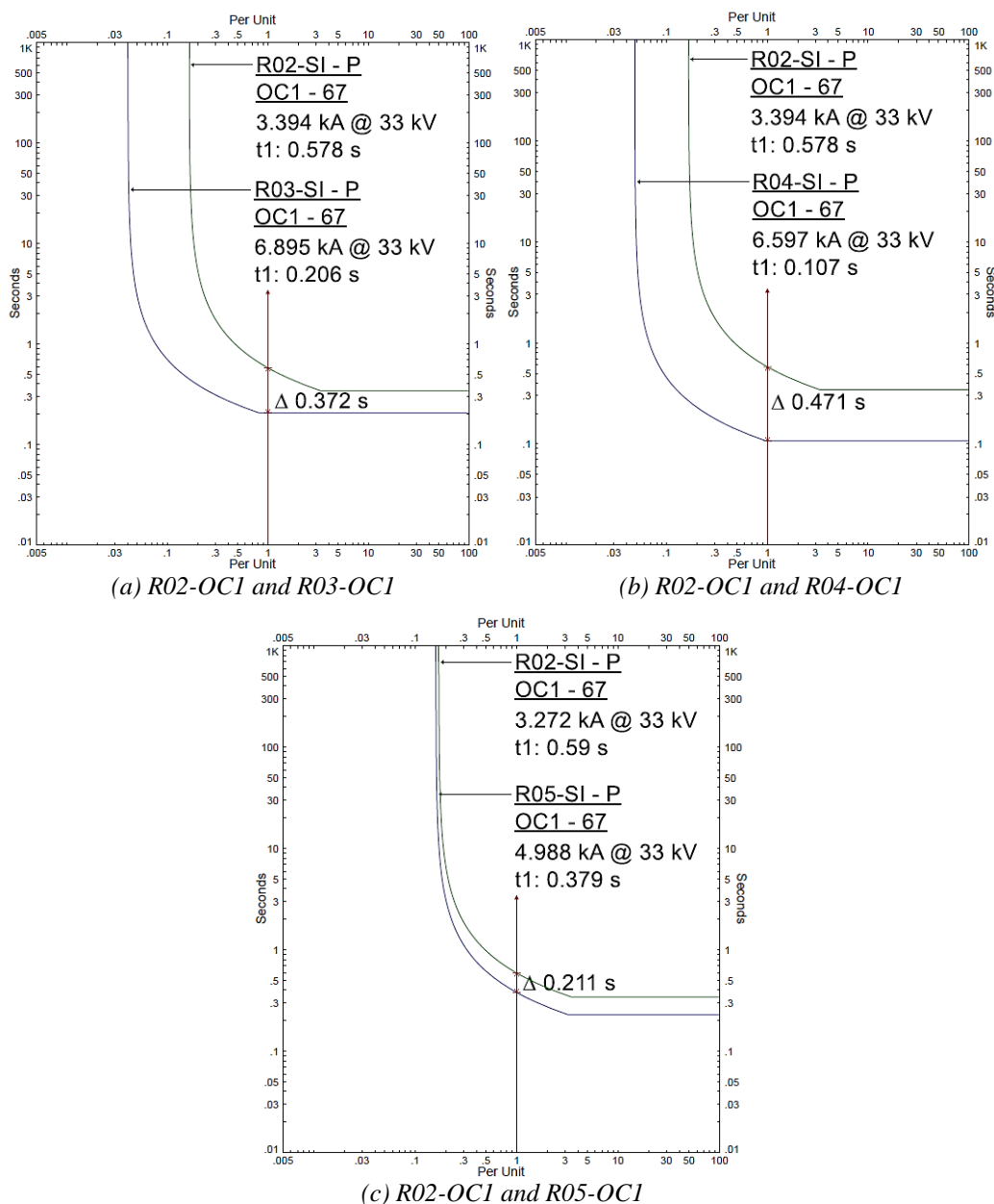


Figure 4.16 Time-Current Curves of Backup Relay Named R02-OC1 for Different Primary Relays for Case 2-Scenario 2

Figure 4.16 shows the IEC-SI time-current curves of relay pairs when *R02-OC1* works as a backup relay. The *CTI* values of relay pairs *R02-OC1/R03-OC1*, *R02-OC1/R03-OC1*, and *R02-OC1/R03-OC1* are 0.372 s, 0.471 s, and 0.211 s, respectively. It can be seen that the *CTI* values of relay pairs and *TOP* value of each OCR shown in Figure 4.16 are very close to the *CTI* and *TOP* values shown in Table 4.15 and Table 4.14. Time-current curve of more relay pairs are shown in APPENDIX C.

4.2.3 Scenario 3: Using IEC-VI

In this optimization, the number of initial populations of *TDS* is 30 and the population values are carried out in Table 4.16.

Table 4.16 Initial *TDS* Population of Relay R02-OC1 for Case 2-Scenario 3

Population	TDS	Population	TDS	Population	TDS
1	8.09	11	11.20	21	2.34
2	3.42	12	8.08	22	2.85
3	9.86	13	1.80	23	1.58
4	7.31	14	0.97	24	4.84
5	1.76	15	10.69	25	11.26
6	10.61	16	11.69	26	12.50
7	0.72	17	5.23	27	5.87
8	0.20	18	2.54	28	11.02
9	0.26	19	7.73	29	5.38
10	3.96	20	11.50	30	5.05

Figure 4.17 shows the dot plot of FA initial population (blue dot plot) and the best optimized solution of *TDS* (red dot plot) for relay R02-OC1. The red dot plots represent the values of *TDS* for the last iteration of FA when the best cost is reached.

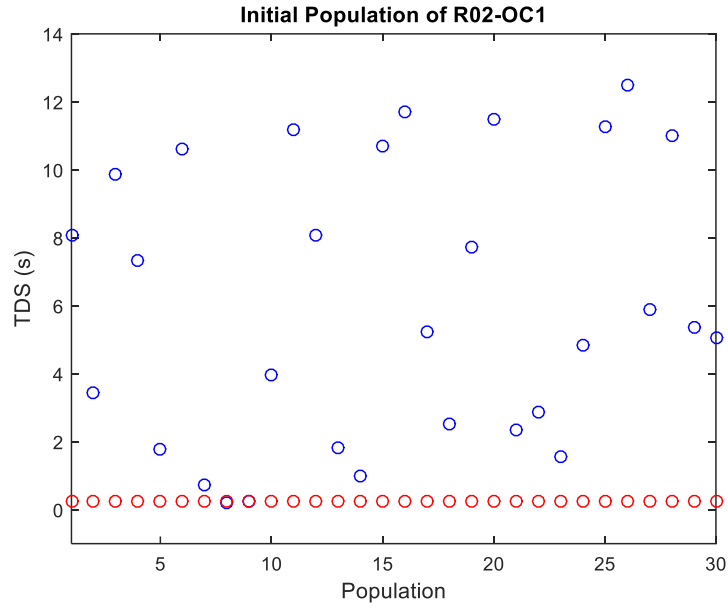


Figure 4.17 TDS Population of Relay R02-OC1 for Case 2-Scenario 3

Figure 4.18 shows the convergence of FA in optimization of operating time of relay R02-OC1 when it works as a backup relay of R05-OC1. The convergence is reached unless all *TDS* populations of FA (red dot plot) are equal as shown in Figure 4.17.

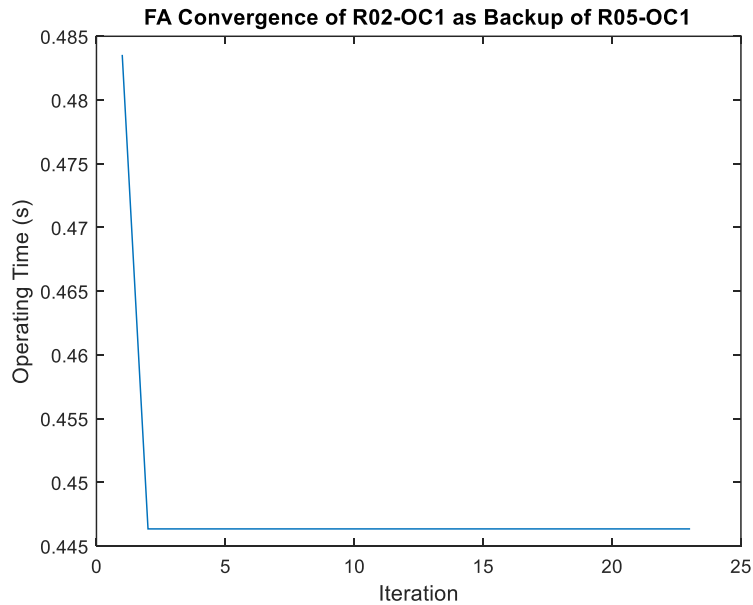


Figure 4.18 FA Convergence of Relay R02-OC1 for Case 2-Scenario 3

In scenario 3, IEC-VI curves are used for all OCRs excepts protection relay of motor named *R14-OC1* which uses IEC-EI curve. By applying the proposed method FA, the optimized values of *PS*, *TDS*, *TOP* for each primary and backup OCR, and the objective function (*OF*) are listed in Table 4.17. The *CTI* values of relay pairs are presented in Table 4.18.

Table 4.17 Optimal Coordination of OCRs for Case 2-Scenario 3

Primary				Backup			
Relay ID	PS	TDS	TOP	Relay ID	PS	TDS	TOP
R01-OC1	0.70	0.24	0.1137	-	-	-	-
R01-OC2	0.70	0.10	0.3210	R02-OC2	0.70	0.10	0.3210
R02-OC1	0.70	0.24	0.4259	R01-OC1	0.70	0.24	0.4259
R02-OC2	0.70	0.10	0.1366	R05-OC2	1.00	0.10	0.4337
R03-OC1	0.70	0.22	0.1042	R02-OC1	0.70	0.24	0.4274
				R05-OC2	1.00	0.10	0.4337
R04-OC1	0.80	0.22	0.1042	R02-OC1	0.70	0.24	0.4274
				R05-OC2	1.00	0.10	0.4337
R05-OC1	1.00	0.14	0.2406	R02-OC1	0.70	0.24	0.4463
R05-OC2	1.00	0.10	0.4337	R08-OC2	1.20	0.11	0.4762
R06-OC1	0.50	0.17	0.3122	R03-OC1	0.70	0.22	0.3131
R07-OC1	0.80	0.10	0.1778	R04-OC1	0.80	0.22	0.1853
R08-OC1	1.20	0.13	0.5506	R05-OC1	1.00	0.14	0.5929
R08-OC2	1.20	0.11	0.1886	R13-OC1	0.90	0.25	0.5956
R09-OC1	0.20	0.22	0.1042	R06-OC1	0.50	0.17	0.3669
R10-OC1	0.20	0.22	0.1042	R06-OC1	0.50	0.17	0.3660
R11-OC1	0.50	0.19	0.1007	R06-OC1	0.50	0.17	0.3122
R12-OC1	0.40	0.22	0.1042	R06-OC1	0.50	0.17	0.3643
R13-OC1	0.90	0.25	0.5907	-	-	-	-
R14-OC1	1.00	2.08	0.5161	R08-OC1	1.20	0.13	0.7200
				R13-OC1	0.90	0.25	0.7401
R15-OC1	0.30	0.22	0.1042	R08-OC1	1.20	0.13	0.5605
				R13-OC1	0.90	0.25	0.5998
R16-OC1	0.60	0.22	0.1042	R08-OC1	1.20	0.13	0.7844
				R13-OC1	0.90	0.25	0.7935
OF				15.9579 s			

Table 4.18 Coordination Time Interval of Relay Pair for Case 2-Scenario 3

Scenario 3: Using IEC-VI		
<i>Backup Relay</i>	<i>Primary Relay</i>	<i>CTI</i>
R02-OC1	R03-OC1	0.3232
	R04-OC1	0.3232
	R05-OC1	0.2058
R05-OC2	R02-OC2	0.2971
	R03-OC1	0.3295
	R04-OC1	0.3295
R06-OC1	R09-OC1	0.2627
	R10-OC1	0.2618
	R11-OC1	0.2115
	R12-OC1	0.2601
R08-OC1	R14-OC1	0.2039
	R15-OC1	0.4563
	R16-OC1	0.6801
R13-OC1	R08-OC2	0.4070
	R14-OC1	0.2240
	R15-OC1	0.4956
	R16-OC1	0.6893

Figure 4.19 shows the IEC-VI time-current curves of relay pairs when *R02-OC1* works as a backup relay. The *CTI* values of relay pairs *R02-OC1* and *R03-OC1*, *R02-OC1* and *R04-OC1*, *R02-OC1* and *R05-OC1* are 0.322 s, 0.322 s, and 0.205 s, respectively. It can be seen that the *CTI* values of relay pairs and *TOP* value of each OCR shown in Figure 4.19 are very close to the *CTI* and *TOP* values shown in Table 4.18 and Table 4.17. Time-current curve of more relay pairs are shown in APPENDIX C.

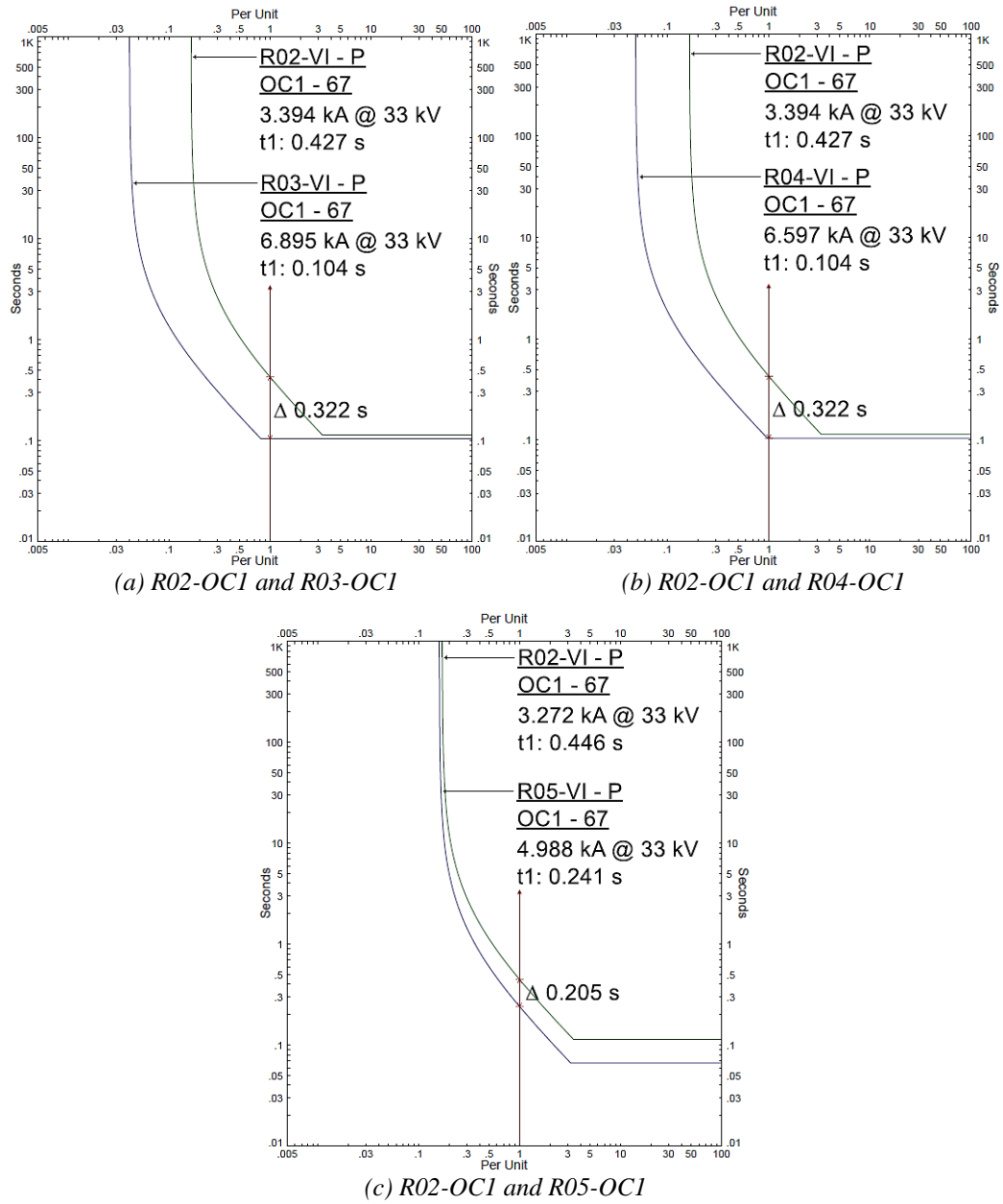


Figure 4.19 Time-Current Curves of Backup Relay Named R02-OC1 for Different Primary Relays for Case 2-Scenario 3

4.2.4 Discussion

Similar to study case 1, the objective function, which is the overall opting of all primary and backup OCRs, will be compared to select the best curve with the smallest value. In study case 2, the objective functions of each scenario with different curves are 25.1864 s for scenario 1 which used IEC-EI curve, 16.9322 s for scenario 2 which used IEC-SI curve, and 15.9579 s for scenario 3 which used

IEC-VI curve. As shown in Figure 4.20, the objective function of scenario 3, which used IEC-VI curve, is the smallest value with 36.64% smaller than scenario 1 and 5.75% smaller than scenario 2. Therefore, scenario 3 using IEC-VI curve should be selected to use in protection coordination of OCRs for radial-industrial system, in case there is a DG connected to the electrical system of Tanjung Harapan.

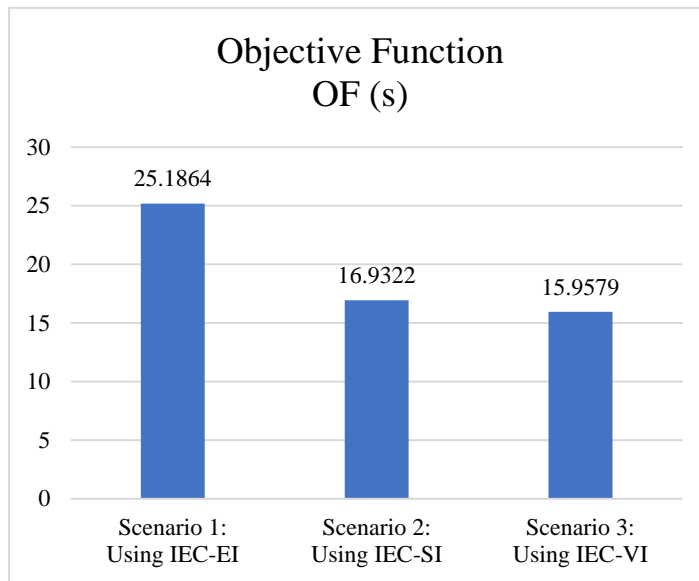


Figure 4.20 Objective Function Values for Study Case 2

CHAPTER 5

CONCLUSION

A proposed method based on FA optimization is proposed to obtain the optimal protection coordination of OCR in Tanjung Harapan, a radial distribution of an industrial plant called Pupuk Kalimantan Timur. The program works by minimizing the total operating time of primary and backup OCRs with the consideration of CTIs between relay pairs. The optimization was done with two study cases: 1) the system of Tanjung Harapan without DG, and 2) the system of Tanjung Harapan with DG. According to the results obtained and discussed in previous chapter, the conclusion of study cases can be drawn as following:

1. For study case 1, optimal protection coordination of OCRs has been approached with appropriate CTI and time-current curve selection. The best curve to be used in protection coordination of OCRs in Tanjung Harapan electrical system is IEC-VI curve (scenario 3 of study case 1) since this type of curve provides the smallest overall operating time (objective function) with 25.66% smaller than scenario 1 (using IEC-EI) and 9.90% smaller than scenario 2 (using IEC-SI).

2. For study case 2, optimal protection coordination of OCRs has also been approached with appropriate CTI and time-current curve selection. Similar to study case 1, the best curve to be used in study case 2 is IEC-VI curve (scenario 3 of study case 2) since it offers the smallest overall operating time with 36.64% smaller than scenario 1 (using IEC-EI) and 5.75% smaller than scenario 2 (using IEC-SI).

To sum up, IEC-VI curve is the best curve to be used in protecting electrical equipment in Tanjung Harapan electrical system for both study cases (Case 1: without DG, and Case 2: with DG) because it gives the smallest overall operating time compared to other curves.

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APPENDIX A

Basic Manual Calculation for Study Case 1-Scenario 3

➤ **R09-OC1, R10-OC1, R11-OC1 and R12-OC1 as Primary Relays**

- Full load amps: $FLA = 157.5A$
- Pick up current: $I_p = FLA \times 1.05 = 165.375A$
- Maximum short circuit current: $I_{sc,p} = 7340A$
- Rated primary current of CT: $I_{CT,p} = 1200A$
- Rated secondary current of CT: $I_{CT,s} = 5A$
- Step of pick up setting: $PS_{step} = 0.1$
- Step of TDS: $TDS_{step} = 0.01$
- Coefficient values of very inverse curve: $k = 13.5, \alpha = 1, \beta = 1.5$
- Target operating time of primary OCR: $t = 0.1s$

where $PS = \frac{I_p}{I_{CT,prim}} = \frac{165.375}{1200} = 0.1378$

Since $PS_{step} = 0.1 \Rightarrow PS_{set} = 0.2$

Then $I_{P,set} = PS_{set} \times I_{CT,prim} = 0.2 \times 1200 = 240A$

$$PSM = \frac{I_{sc,p}}{I_{P,set}} = \frac{7340}{240} = 30.58$$

Since $PSM > 20 \Rightarrow PSM = 20$

By using equation (2.1), the operating time of OCR is: $t = \frac{k \times TDS}{(PSM^\alpha - 1) \times \beta}$

$$\Rightarrow TDS = \frac{t \times (PSM^\alpha - 1) \times \beta}{k} = \frac{0.1 \times (20^1 - 1) \times 1.5}{13.5} = 0.2111s$$

Since $TDS_{step} = 0.01 \Rightarrow TDS = 0.22s$

Then operating time is $t = \frac{k \times TDS}{(PSM^\alpha - 1) \times \beta} = \frac{13.5 \times 0.22}{(20^1 - 1) \times 1.5} = 0.1042s$

Therefore, the setting of relay R09-OC1 is:

$$PS_{set} = 0.2, TDS = 0.22s \text{ with } t_{p1} = 0.1042s$$

By doing the same with above calculation, the setting of relay R10-OC1, R11-OC1 and R12-OC1 are:

$$\text{Relay R10-OC1: } PS_{set} = 0.2, TDS = 0.22s \text{ with } t_{p2} = 0.1042s$$

$$\text{Relay R11-OC1: } PS_{set} = 0.5, TDS = 0.18s \text{ with } t_{p3} = 0.1005s$$

$$\text{Relay R12-OC1: } PS_{set} = 0.4, TDS = 0.22s \text{ with } t_{p4} = 0.1042s$$

Note: - if $PSM < 20 \Rightarrow PSM = \frac{I_{sc,p}}{I_{P,set}}$ - if $PSM > 20 \Rightarrow PSM = 20$

➤ **R06-OC1 as Backup Relay**

- Full load amps: $FLA = 787.3A$
- Pick up current: $I_p = FLA \times 1.05 = 826.665A$
- Maximum short circuit current:
 - As primary relay: $I_{sc,p} = 5510A$
 - As backup of R09-OC1: $I_{sc,b1} = 4860A$
 - As backup of R10-OC1: $I_{sc,b2} = 4860A$
 - As backup of R11-OC1: $I_{sc,b3} = 5510A$
 - As backup of R12-OC1: $I_{sc,b4} = 4880A$
- Rated primary current of CT: $I_{CT,p} = 2000A$
- Rated secondary current of CT: $I_{CT,s} = 5A$
- Step of pick up setting: $PS_{step} = 0.1$
- Step of TDS: $TDS_{step} = 0.01$
- Coefficient values of very inverse curve: $k = 13.5, \alpha = 1, \beta = 1.5$
- Target operating time with $CTI = 0.2s$:
 - As backup of R09-OC1: $t_{b1} = CTI + t_{p1} = 0.2 + 0.1042 = 0.3042s$
 - As backup of R10-OC1: $t_{b2} = CTI + t_{p2} = 0.2 + 0.1042 = 0.3042s$

- As backup of R11-OC1: $t_{b3} = CTI + t_{p3} = 0.2 + 0.1005 = 0.3005s$
- As backup of R12-OC1: $t_{b4} = CTI + t_{p4} = 0.2 + 0.1042 = 0.3042s$

We have $PS = \frac{I_P}{I_{CT,prim}} = \frac{826.665}{2000} = 0.4133$

Since $PS_{step} = 0.1 \Rightarrow PS_{set} = 0.5$

Then $I_{P,set} = PS_{set} \times I_{CT,prim} = 0.5 \times 2000 = 1000A$

$$PSM_{b1} = \frac{I_{sc,b1}}{I_{P,set}} = \frac{4860}{1000} = 4.86, \quad PSM_{b2} = \frac{I_{sc,b2}}{I_{P,set}} = \frac{4860}{1000} = 4.86$$

$$PSM_{b3} = \frac{I_{sc,b3}}{I_{P,set}} = \frac{5510}{1000} = 5.51, \quad PSM_{b4} = \frac{I_{sc,b4}}{I_{P,set}} = \frac{4880}{1000} = 4.88$$

Since $PSM_{b1} < 20 \Rightarrow PSM_{b1} = 4.86$, $PSM_{b2} < 20 \Rightarrow PSM_{b2} = 4.86$

$PSM_{b3} < 20 \Rightarrow PSM_{b3} = 5.51$, $PSM_{b4} < 20 \Rightarrow PSM_{b4} = 4.88$

Scenario 1: R06-OC1 Coordinating with R09-OC1

By using equation (2.1), the operating time of OCR is: $t_{b1} = \frac{k \times TDS}{(PSM_{b1}^\alpha - 1) \times \beta}$

$$\Rightarrow TDS_1 = \frac{t_{b1} \times (PSM_{b1}^\alpha - 1) \times \beta}{k} = \frac{0.3042 \times (4.86^1 - 1) \times 1.5}{13.5} = 0.1305s$$

Since $TDS_{step} = 0.01 \Rightarrow TDS_1 = 0.14s$

Then operating time is:

$$t_{b1,1} = \frac{k \times TDS_1}{(PSM_{b1}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(4.86^1 - 1) \times 1.5} = 0.3264s$$

$$\Rightarrow CTI_{b1,1} = 0.3264 - 0.1042 = 0.2222s$$

$$t_{b2,1} = \frac{k \times TDS_1}{(PSM_{b2}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(4.86^1 - 1) \times 1.5} = 0.3264s$$

$$\Rightarrow CTI_{b2,1} = 0.3264 - 0.1042 = 0.2222s$$

$$t_{b3,1} = \frac{k \times TDS_1}{(PSM_{b3}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(5.51^1 - 1) \times 1.5} = 0.2794s$$

$$\Rightarrow CTI_{b3,1} = 0.2794 - 0.1005 = 0.1789s$$

$$t_{b4,1} = \frac{k \times TDS_1}{(PSM_{b4}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(4.88^1 - 1) \times 1.5} = 0.3247s$$

$$\Rightarrow CTI_{b4,1} = 0.3247 - 0.1042 = 0.2205s$$

Since $CTI_{b3,1} < 0.2s \Rightarrow$ Scenario 1 is rejected.

Scenario 2: R06-OC1 Coordinating with R10-OC1

Since $PSM_{b2} = PSM_{b1} = 4.86$ and $t_{b2} = t_{b1} = 0.3042s$, then the results must be the same with Scenario 1.

$$CTI_{b1,2} = CTI_{b1,1} = 0.2222s, CTI_{b2,2} = CTI_{b2,1} = 0.2222s,$$

$$CTI_{b3,2} = CTI_{b3,1} = 0.1789s, CTI_{b4,2} = CTI_{b4,1} = 0.2205s$$

Since $CTI_{b3,2} < 0.2s \Rightarrow$ Scenario 2 is rejected.

Scenario 3: R06-OC1 Coordinating with R11-OC1

By using equation (2.1), the operating time of OCR is: $t_{b3} = \frac{k \times TDS_3}{(PSM_{b3}^\alpha - 1) \times \beta}$

$$\Rightarrow TDS_3 = \frac{t_{b3} \times (PSM_{b3}^\alpha - 1) \times \beta}{k} = \frac{0.3005 \times (5.51^1 - 1) \times 1.5}{13.5} = 0.1506s$$

Since $TDS_{step} = 0.01 \Rightarrow TDS_3 = 0.16s$

Then operating time is:

$$t_{b1,3} = \frac{k \times TDS_3}{(PSM_{b1}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.16}{(4.86^1 - 1) \times 1.5} = 0.3731s$$

$$\Rightarrow CTI_{b1,3} = 0.3731 - 0.1042 = 0.2689s$$

$$t_{b2,3} = \frac{k \times TDS_3}{(PSM_{b2}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.16}{(4.86^1 - 1) \times 1.5} = 0.3731s$$

$$\Rightarrow CTI_{b2,3} = 0.3731 - 0.1042 = 0.2689s$$

$$t_{b3,3} = \frac{k \times TDS_3}{(PSM_{b3}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.16}{(5.51^1 - 1) \times 1.5} = 0.3193s$$

$$\Rightarrow CTI_{b3,3} = 0.3193 - 0.1005 = 0.2188s$$

$$t_{b4,3} = \frac{k \times TDS_3}{(PSM_{b4}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.16}{(4.88^1 - 1) \times 1.5} = 0.3711s$$

$$\Rightarrow CTI_{b4,3} = 0.3711 - 0.1042 = 0.2669s$$

Since $CTI_{b1,3}$, $CTI_{b2,3}$, $CTI_{b3,3}$, and $CTI_{b4,3} > 0.2s \Rightarrow$ Scenario 3 is accepted.

Scenario 4: R06-OC1 Coordinating with R12-OC1

By using equation (2.1), the operating time of OCR is: $t_{b4} = \frac{k \times TDS_4}{(PSM_{b4}^\alpha - 1) \times \beta}$

$$\Rightarrow TDS_4 = \frac{t_{b4} \times (PSM_{b4}^\alpha - 1) \times \beta}{k} = \frac{0.3042 \times (4.88^1 - 1) \times 1.5}{13.5} = 0.1311s$$

Since $TDS_{step} = 0.01 \Rightarrow TDS_4 = 0.14s$

Then operating time is:

$$t_{b1,4} = \frac{k \times TDS_4}{(PSM_{b1}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(4.86^1 - 1) \times 1.5} = 0.3264s$$

$$\Rightarrow CTI_{b1,4} = 0.3264 - 0.1042 = 0.2222s$$

$$t_{b2,4} = \frac{k \times TDS_4}{(PSM_{b2}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(4.86^1 - 1) \times 1.5} = 0.3264s$$

$$\Rightarrow CTI_{b2,4} = 0.3264 - 0.1042 = 0.2222s$$

$$t_{b3,4} = \frac{k \times TDS_4}{(PSM_{b3}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(5.51^1 - 1) \times 1.5} = 0.2794s$$

$$\Rightarrow CTI_{b3,4} = 0.2794 - 0.1005 = 0.1789s$$

$$t_{b4,4} = \frac{k \times TDS_4}{(PSM_{b4}^\alpha - 1) \times \beta} = \frac{13.5 \times 0.14}{(4.88^1 - 1) \times 1.5} = 0.3247s$$

$$\Rightarrow CTI_{b4,4} = 0.3247 - 0.1042 = 0.2205s$$

Since $CTI_{b3,4} < 0.2s \Rightarrow$ Scenario 4 is rejected.

Since the scenario 3 is accepted. Therefore, R06-OC1 must be coordinated with R11-OC1. The operating time of R06-OC1 works as primary relay is:

$$t_p = \frac{k \times TDS_3}{\left(\left(\frac{I_{sc,p}}{I_{P,set}} \right)^\alpha - 1 \right) \times \beta} = \frac{13.5 \times 0.16}{\left(\left(\frac{5510}{1000} \right)^1 - 1 \right) \times 1.5} = 0.3193s$$

Then, the setting of relay R06-OC1 is:

$$PS_{set} = 0.5, TDS = 0.16s \text{ with } t_p = 0.3193s$$

APPENDIX B

Case 1: The System without DG

Scenario 1: Using IEC-EI

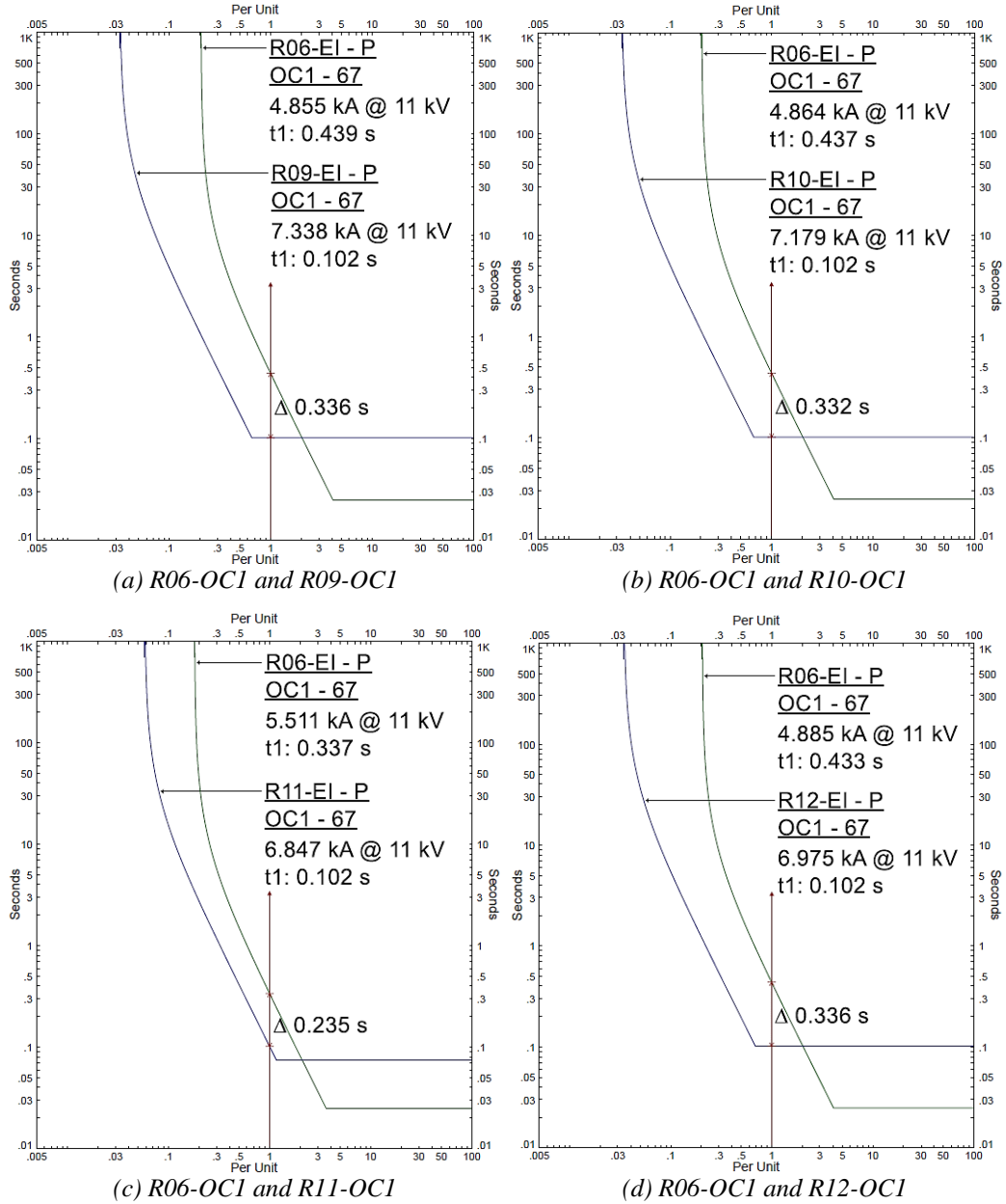


Figure 5.1 Time-Current Curves of Backup Relay Named R06-OC1 for Different Primary Relays for Case 1-Scenario 1

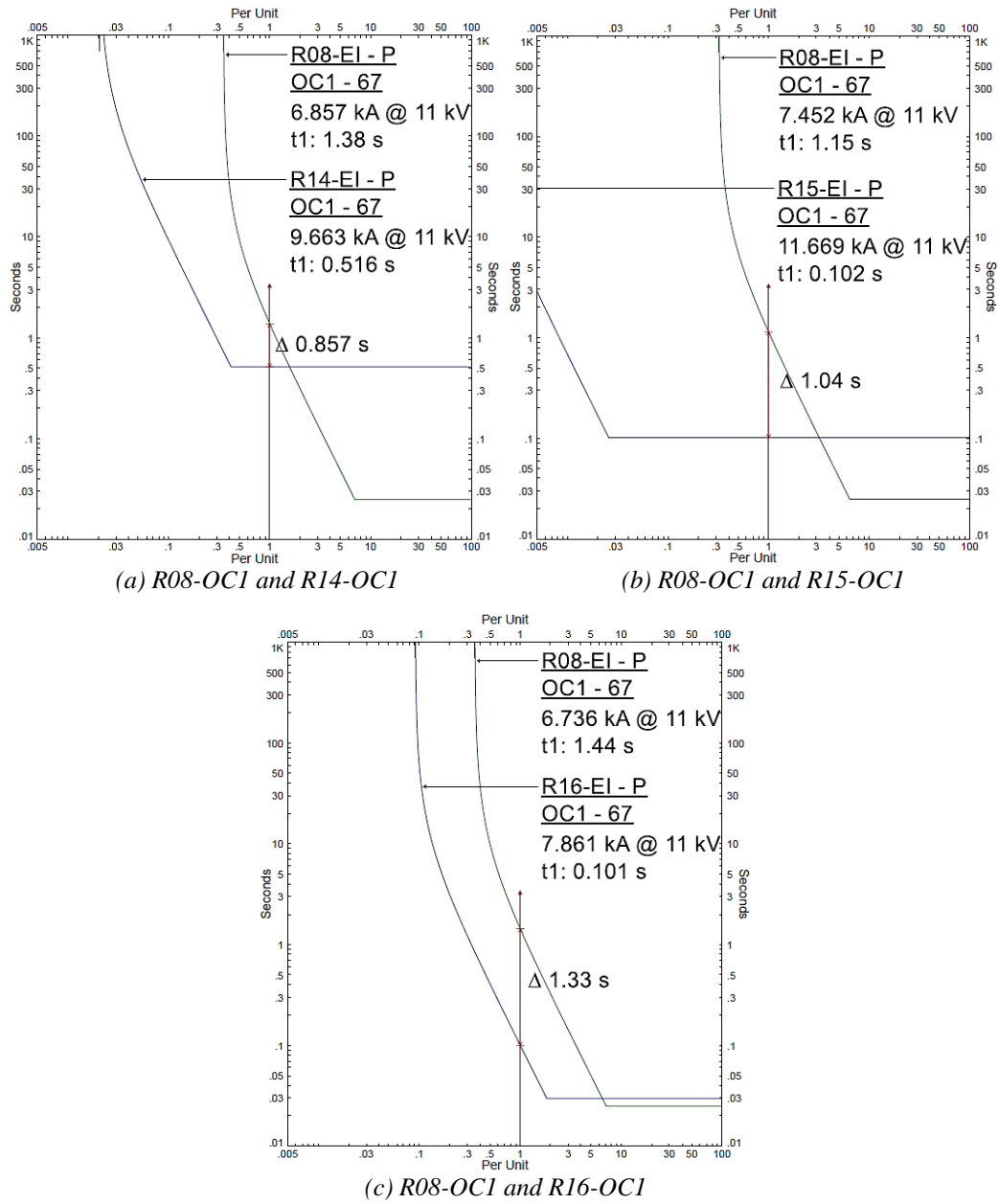


Figure 5.2 Time-Current Curves of Backup Relay Named R08-OC1 for Different Primary Relays for Case 1-Scenario 1

Scenario 2: Using IEC-SI

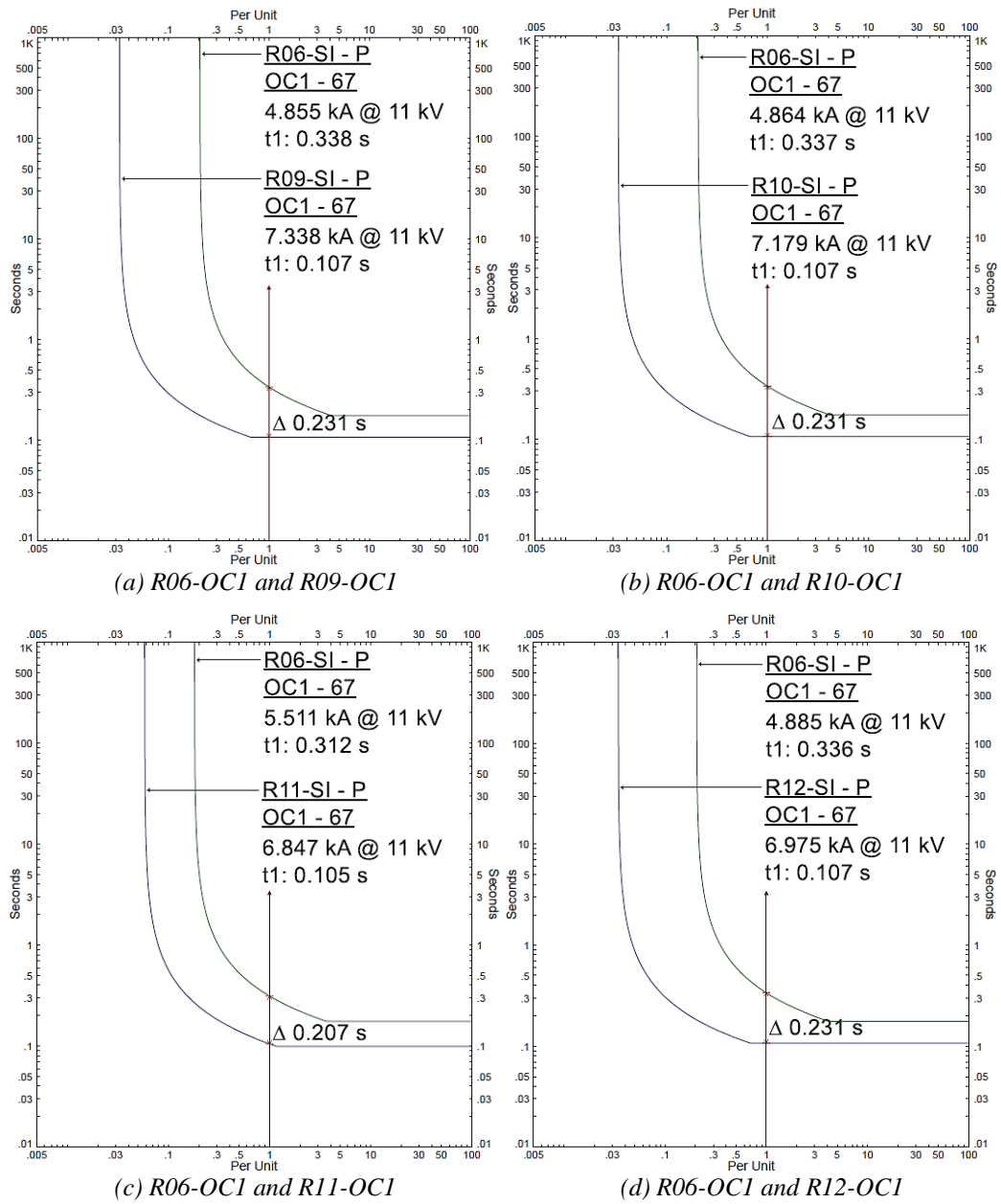


Figure 5.3 Time-Current Curves of Backup Relay Named R06-OC1 for Different Primary Relays for Case 1-Scenario 2

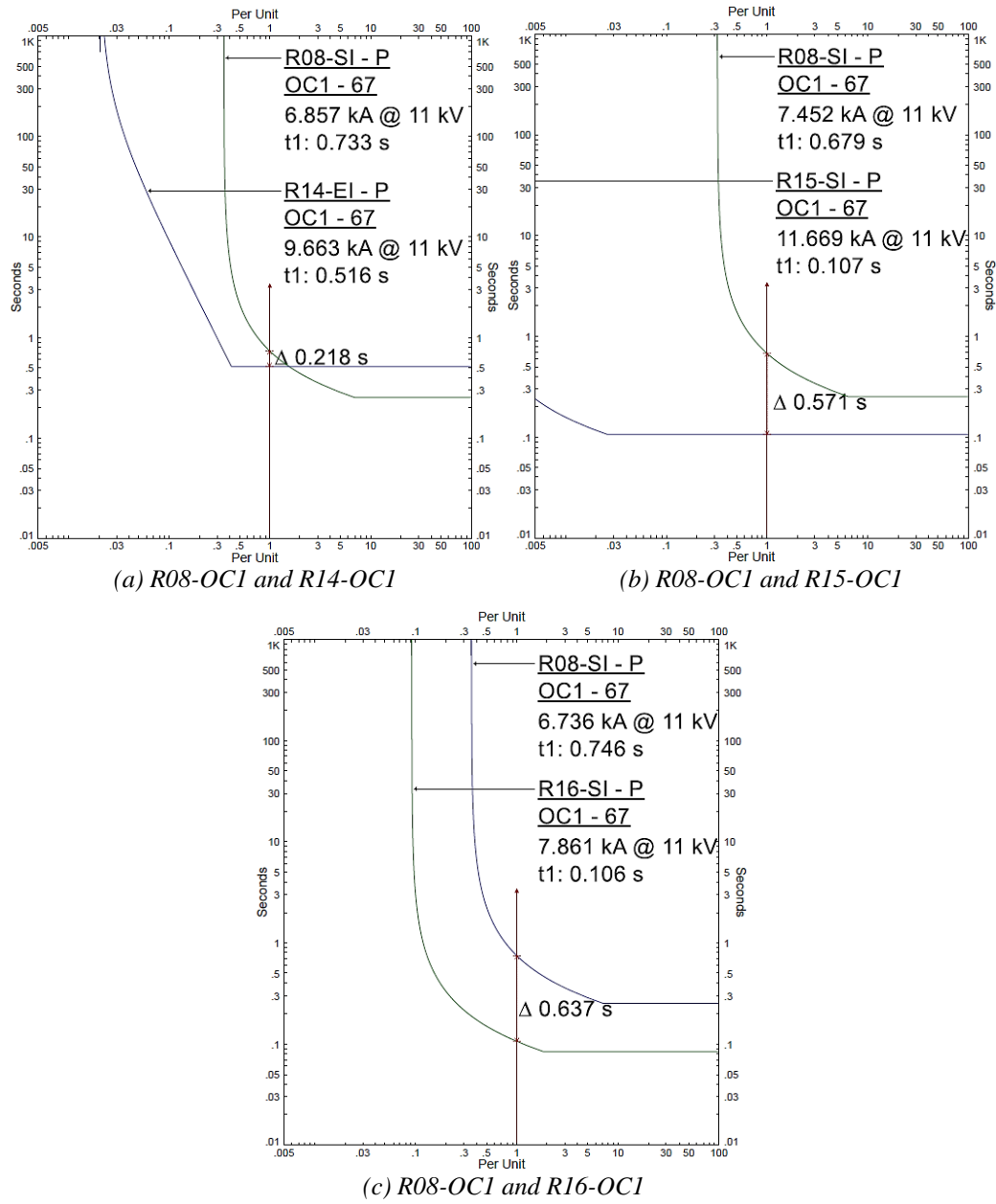


Figure 5.4 Time-Current Curves of Backup Relay Named R08-OC1 for Different Primary Relays for Case 1-Scenario 2

Scenario 3: Using IEC-VI

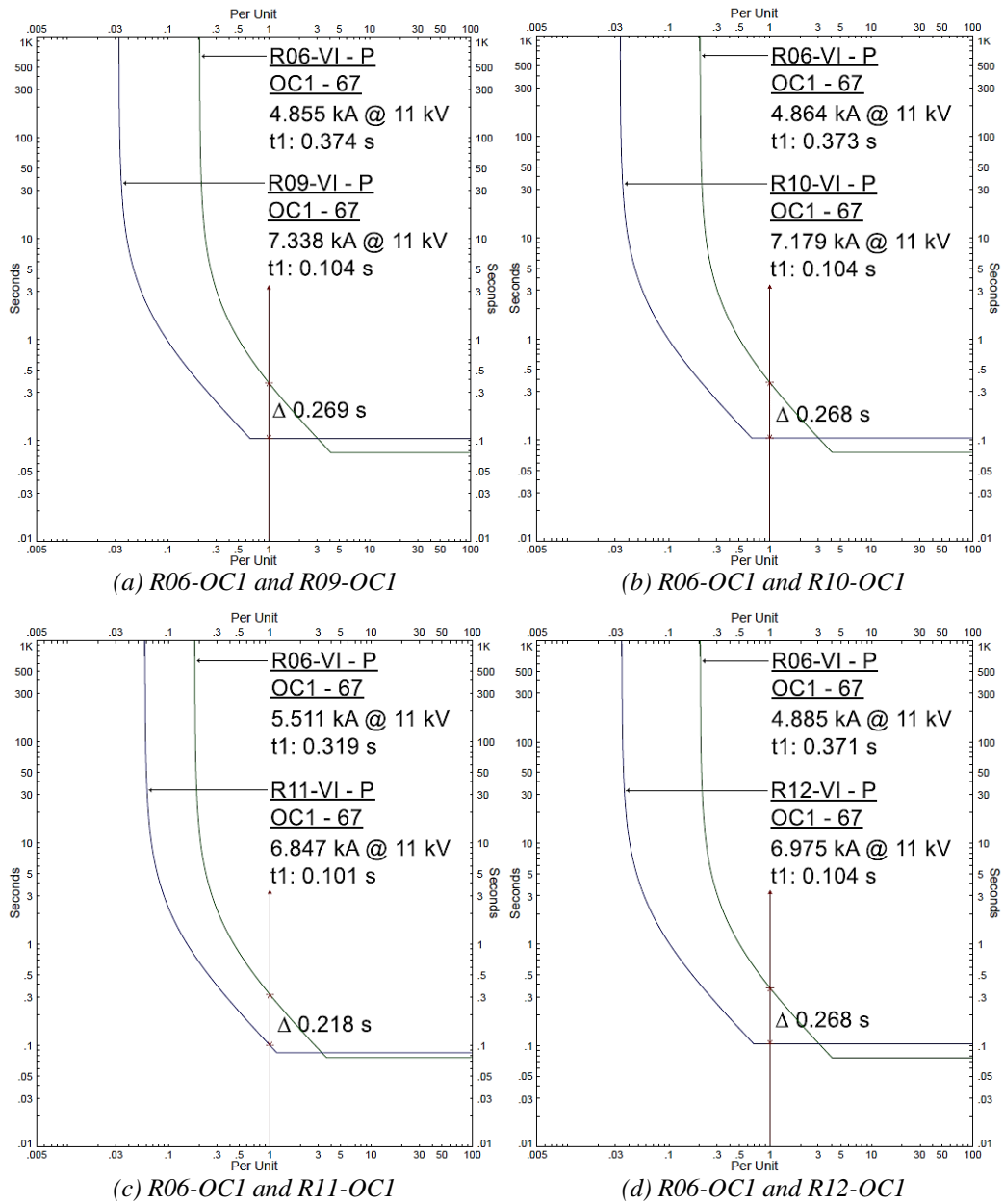


Figure 5.5 Time-Current Curves of Backup Relay Named R06-OC1 for Different Primary Relays for Case 1-Scenario 3

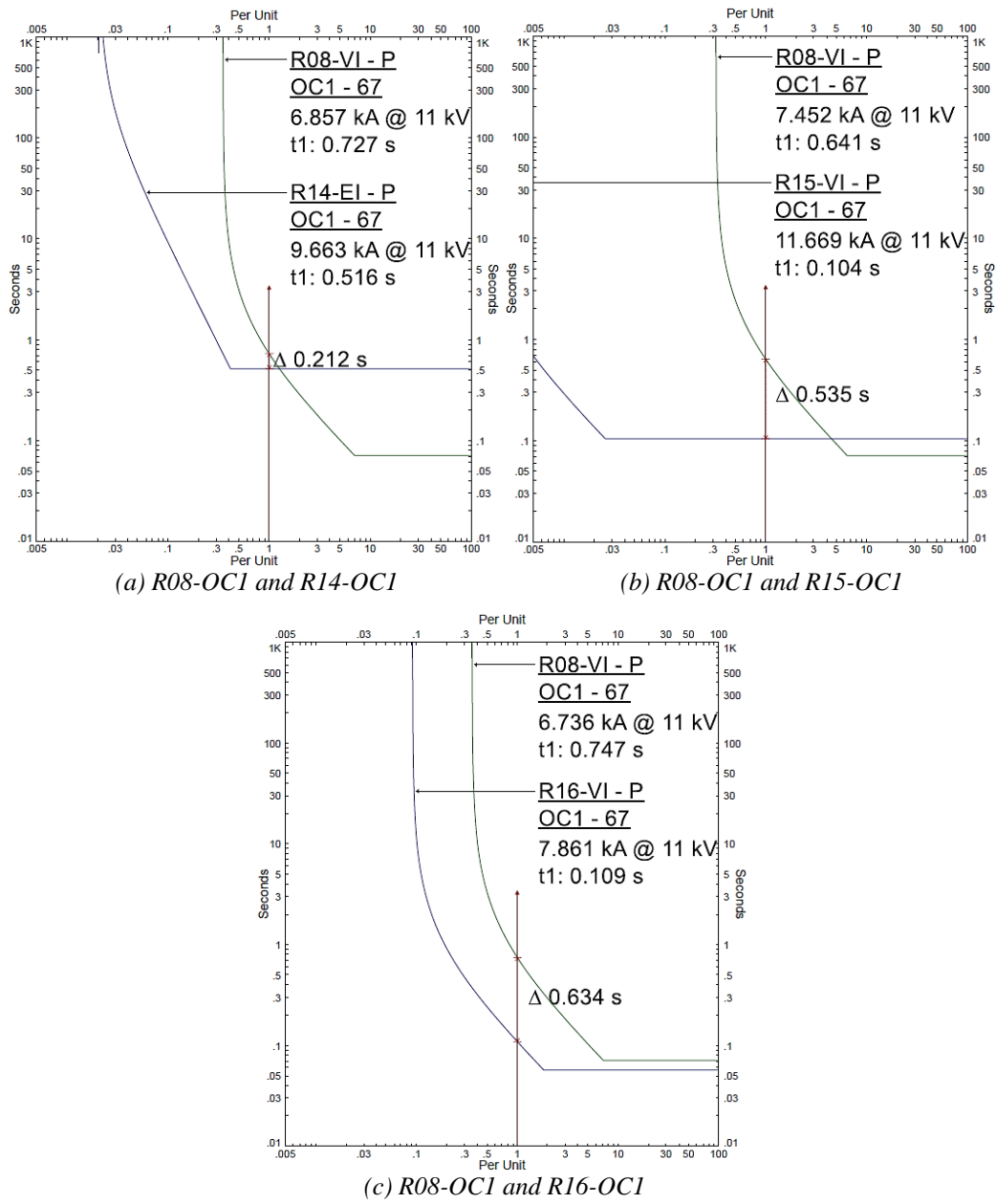


Figure 5.6 Time-Current Curves of Backup Relay Named R08-OC1 for Different Primary Relays for Case 1-Scenario 3

APPENDIX C

Case 2: The System with DG

Scenario 1: Using IEC-EI

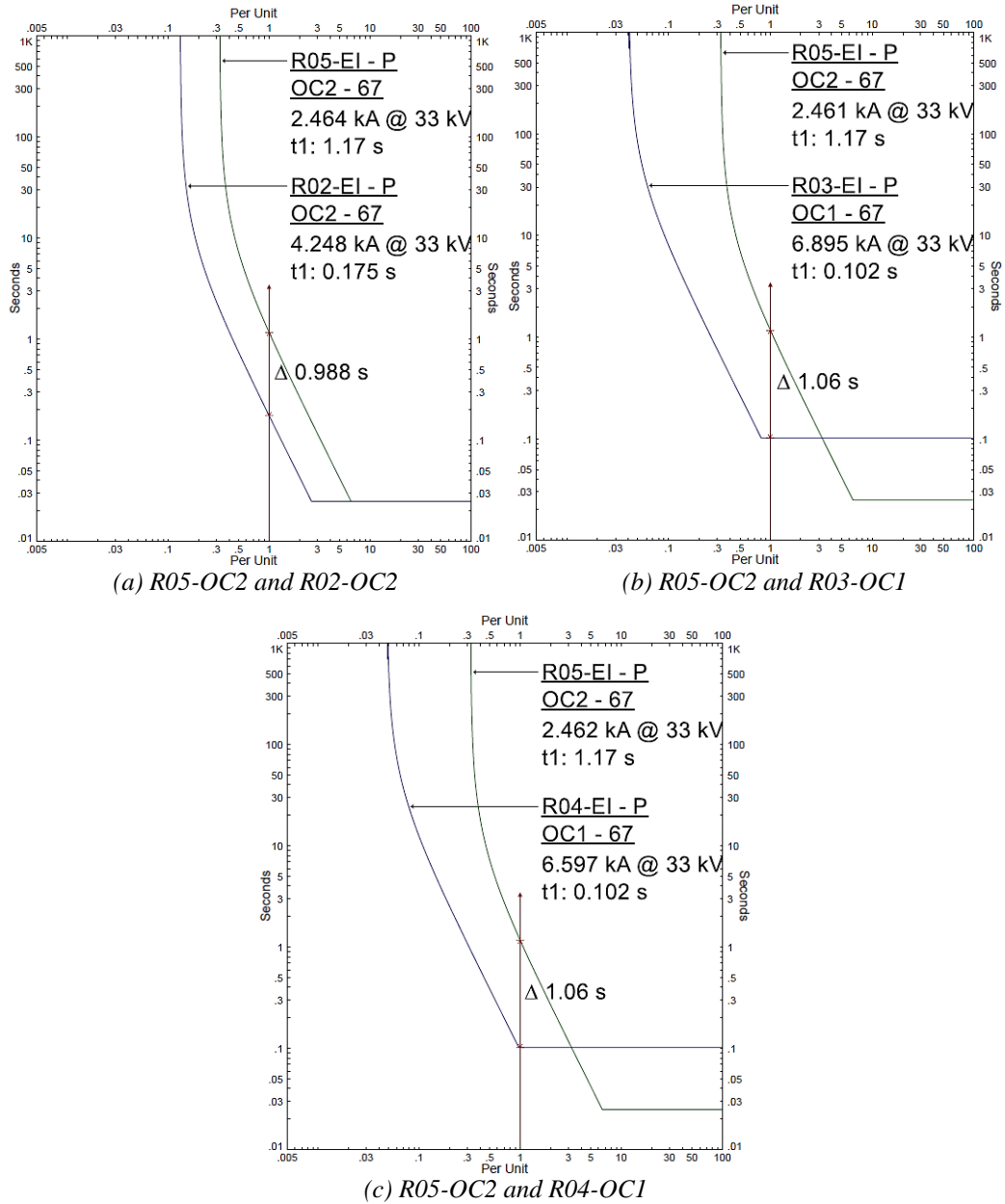


Figure 5.7 Time-Current Curves of Backup Relay Named R05-OC2 for Different Primary Relays for Case 2-Scenario 1

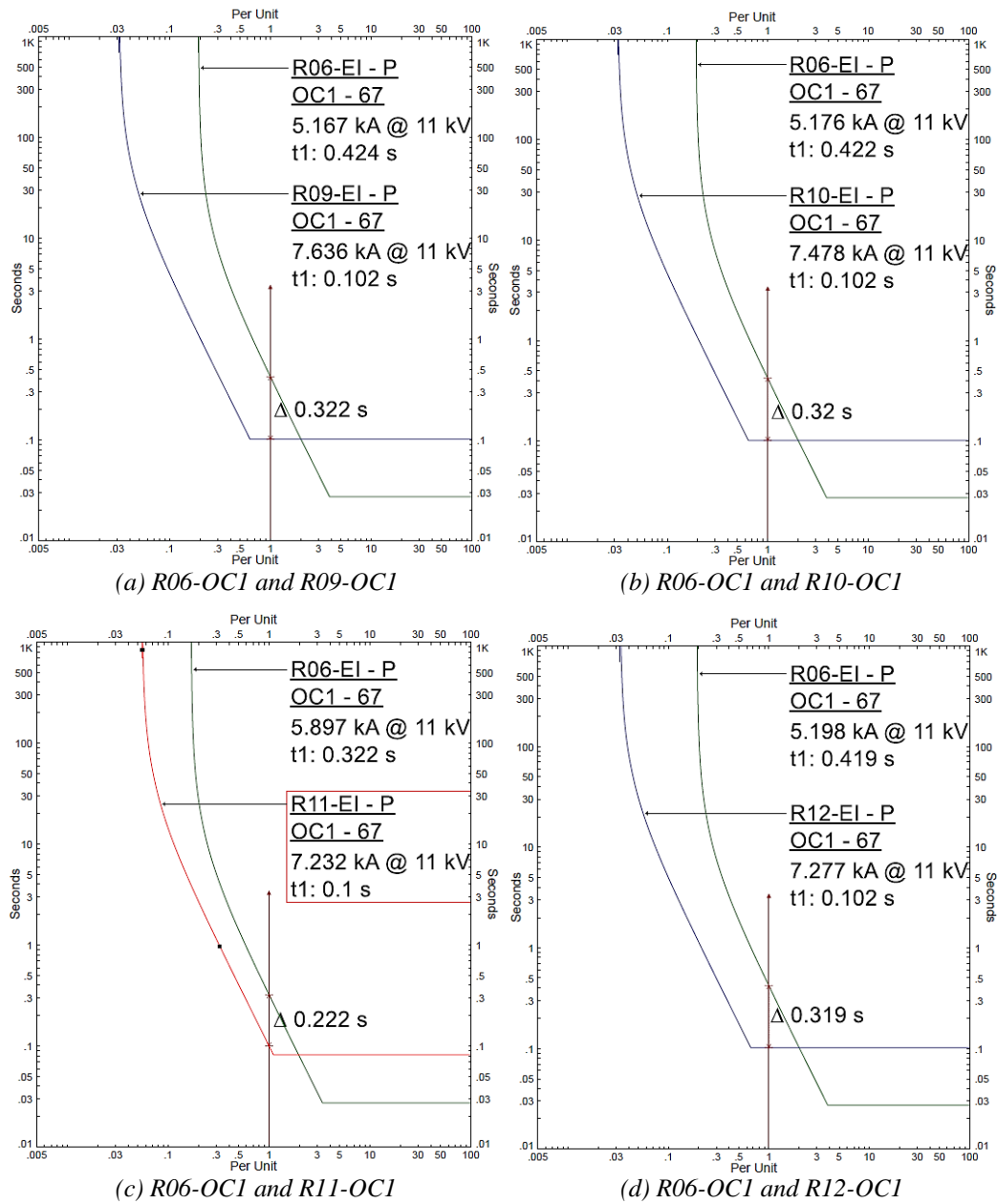


Figure 5.8 Time-Current Curves of Backup Relay Named R06-OC1 for Different Primary Relays for Case 2-Scenario 1

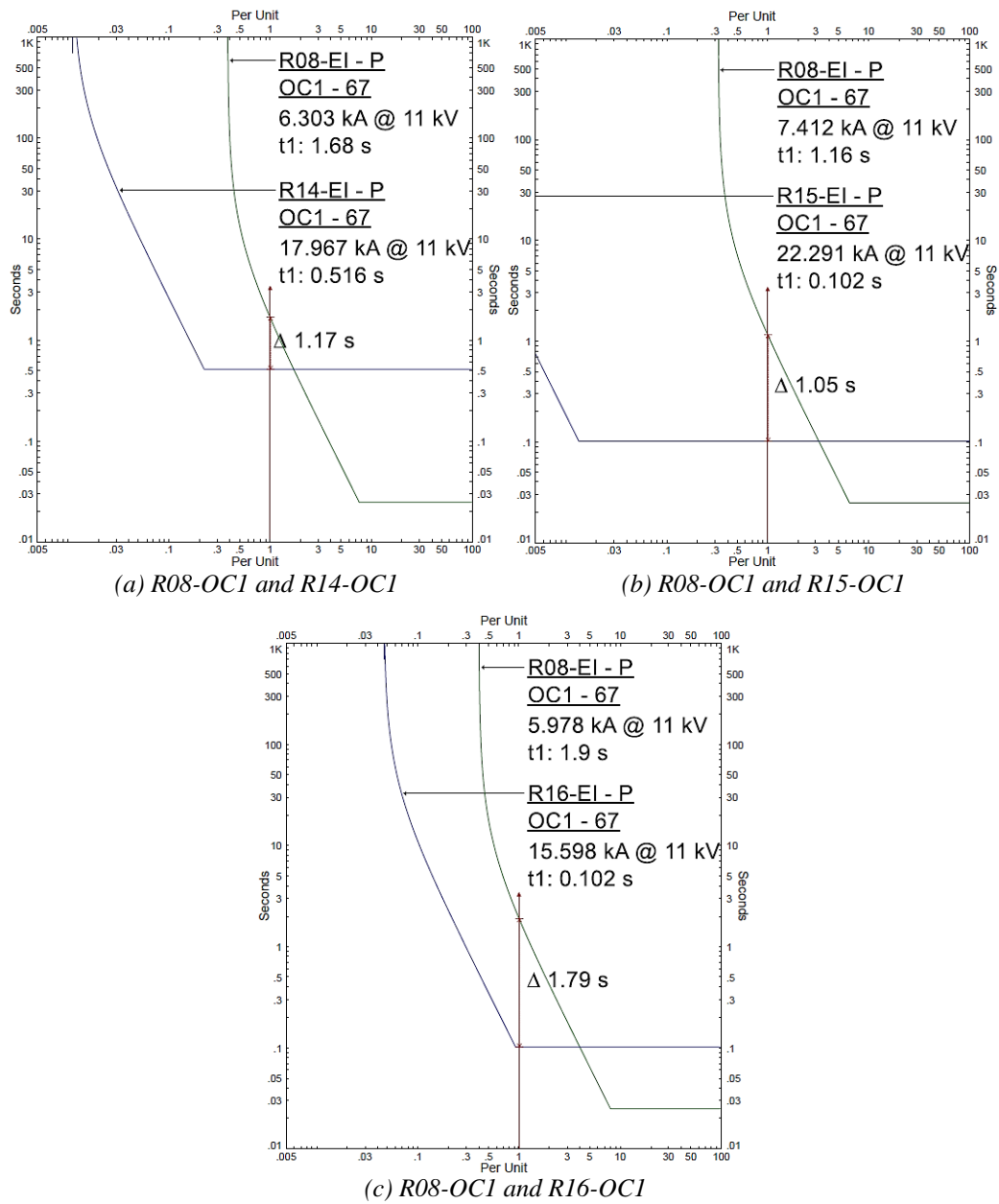


Figure 5.9 Time-Current Curves of Backup Relay Named R08-OC1 for Different Primary Relays for Case 2-Scenario 1

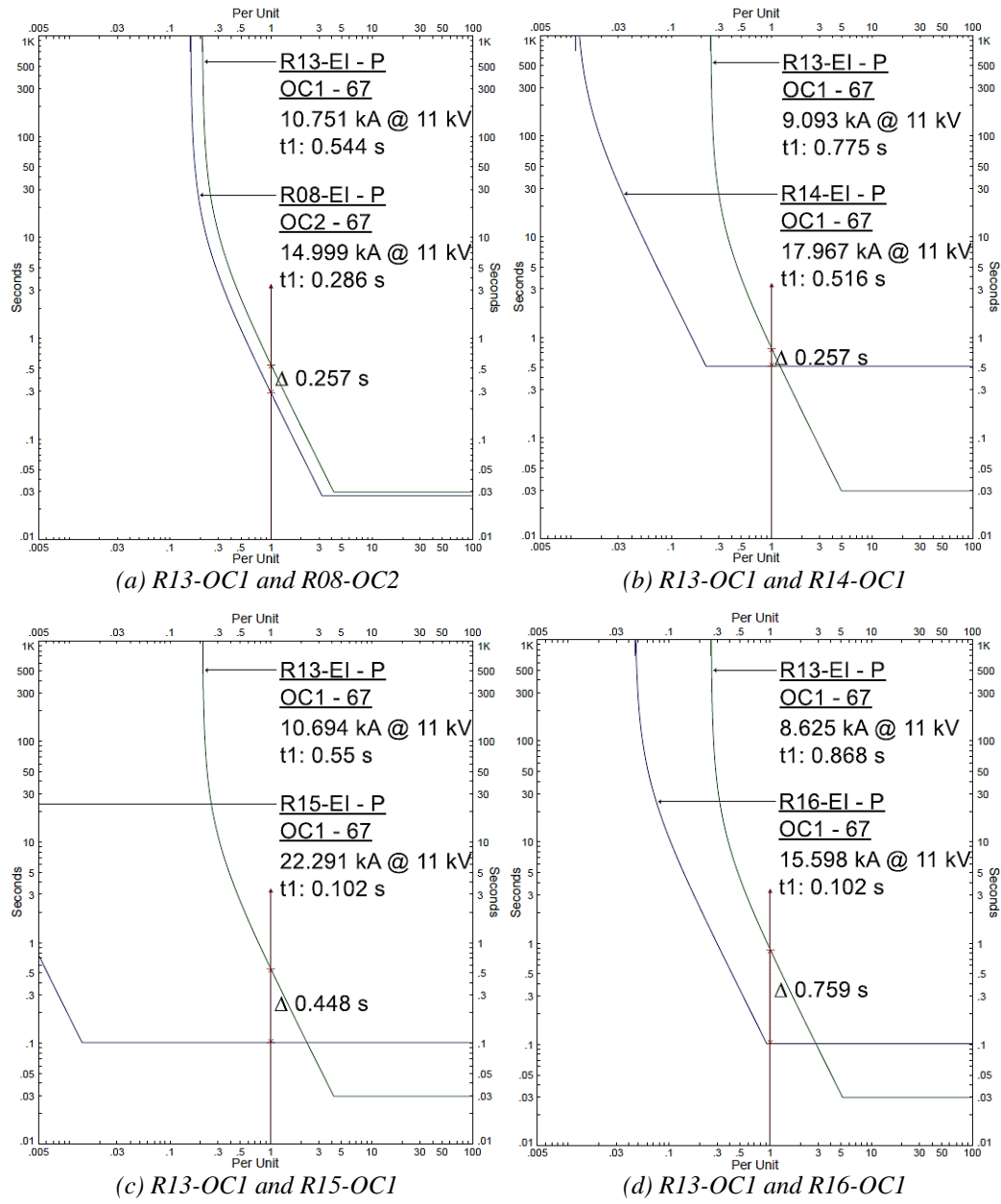


Figure 5.10 Time-Current Curves of Backup Relay Named R13-OC1 for Different Primary Relays for Case 2-Scenario 1

Scenario 2: Using IEC-SI

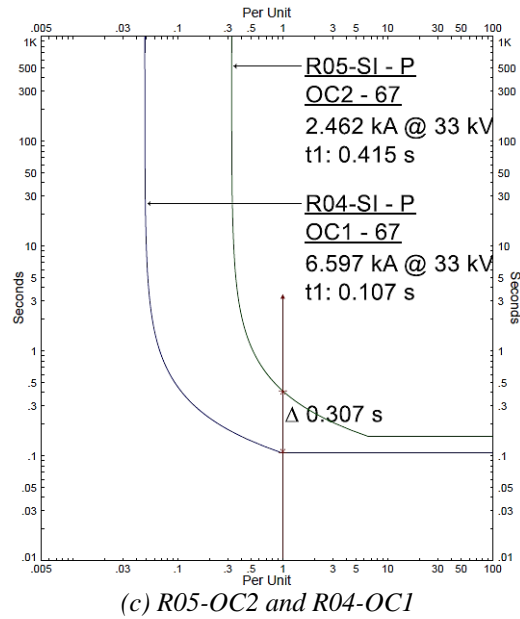
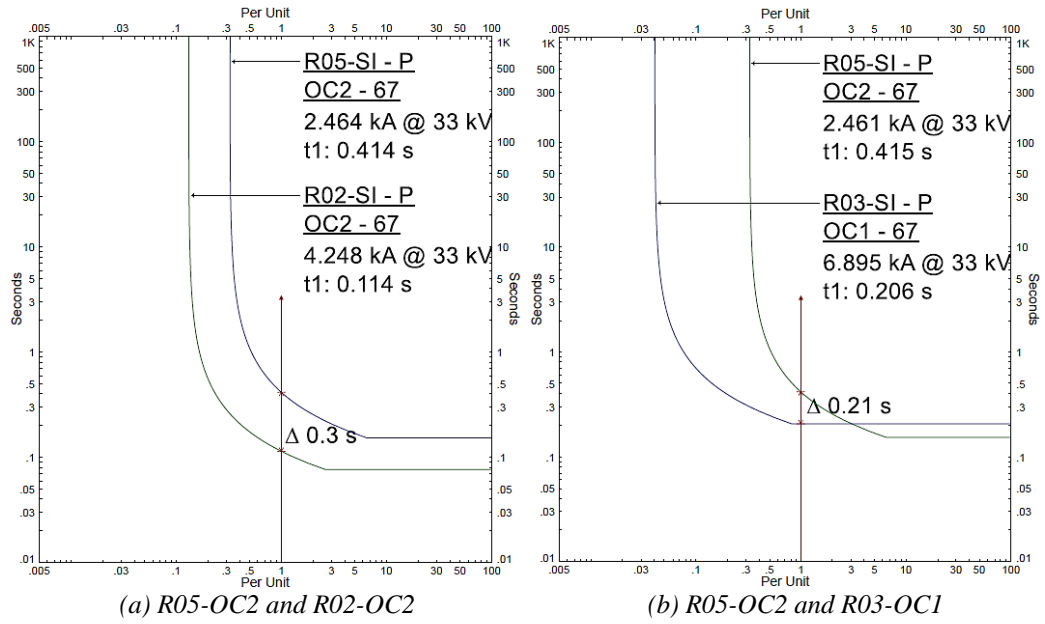


Figure 5.11 Time-Current Curves of Backup Relay Named R05-OC2 for Different Primary Relays for Case 2-Scenario 2

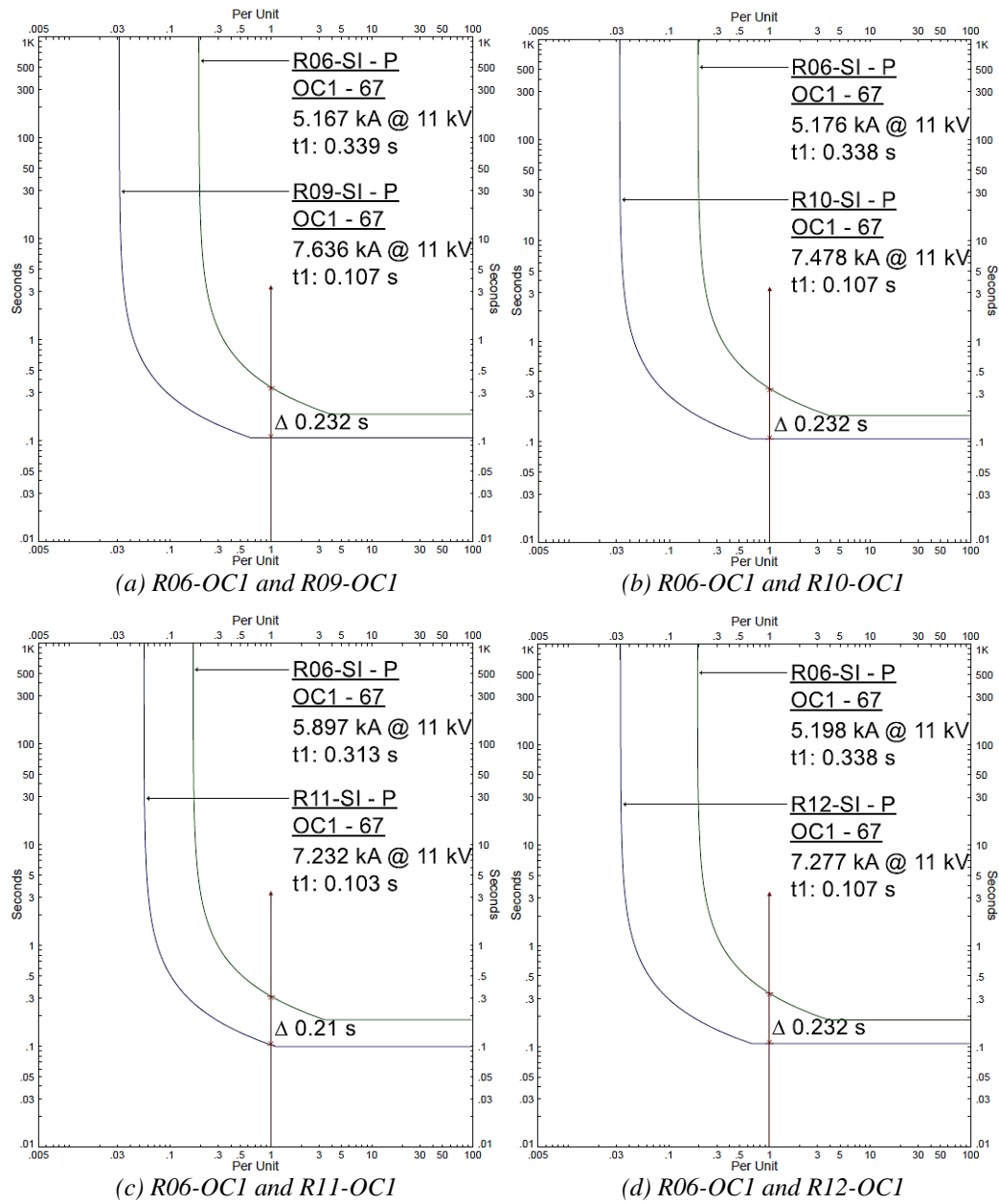


Figure 5.12 Time-Current Curves of Backup Relay Named R06-OC1 for Different Primary Relays for Case 2-Scenario 2

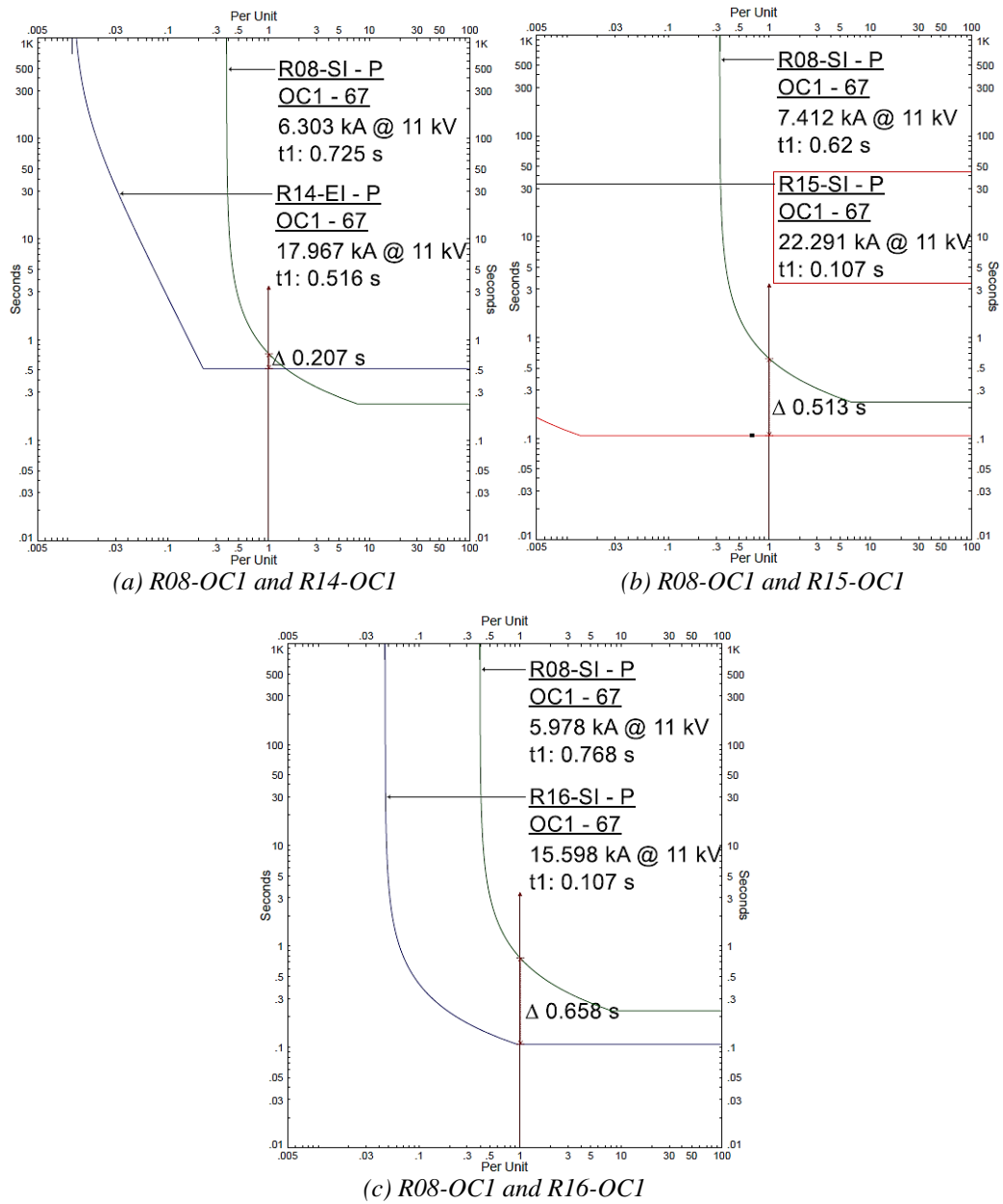


Figure 5.13 Time-Current Curves of Backup Relay Named R08-OC1 for Different Primary Relays for Case 2-Scenario 2

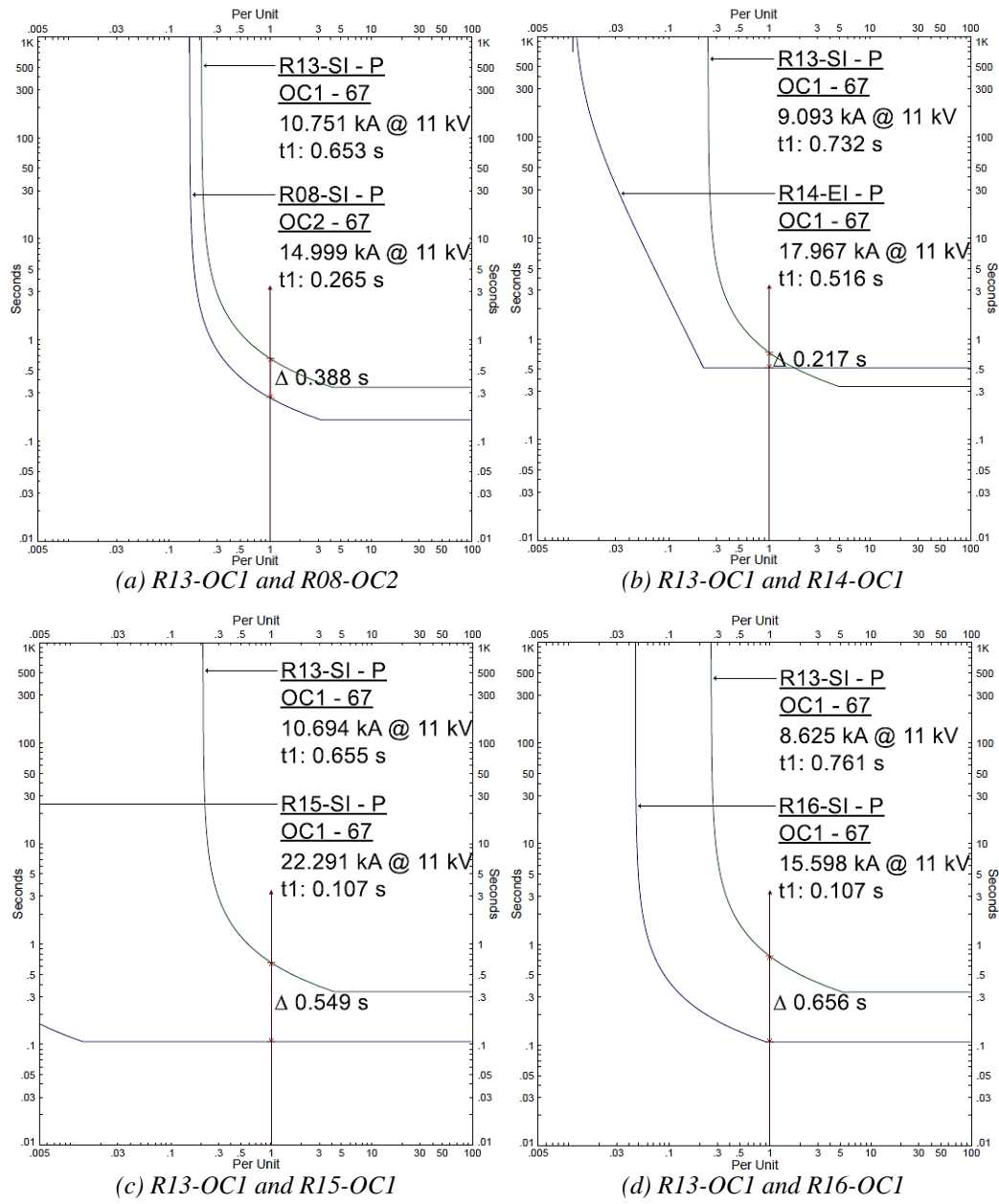


Figure 5.14 Time-Current Curves of Backup Relay Named R13-OC1 for Different Primary Relays for Case 2-Scenario 2

Scenario 3: Using IEC-VI

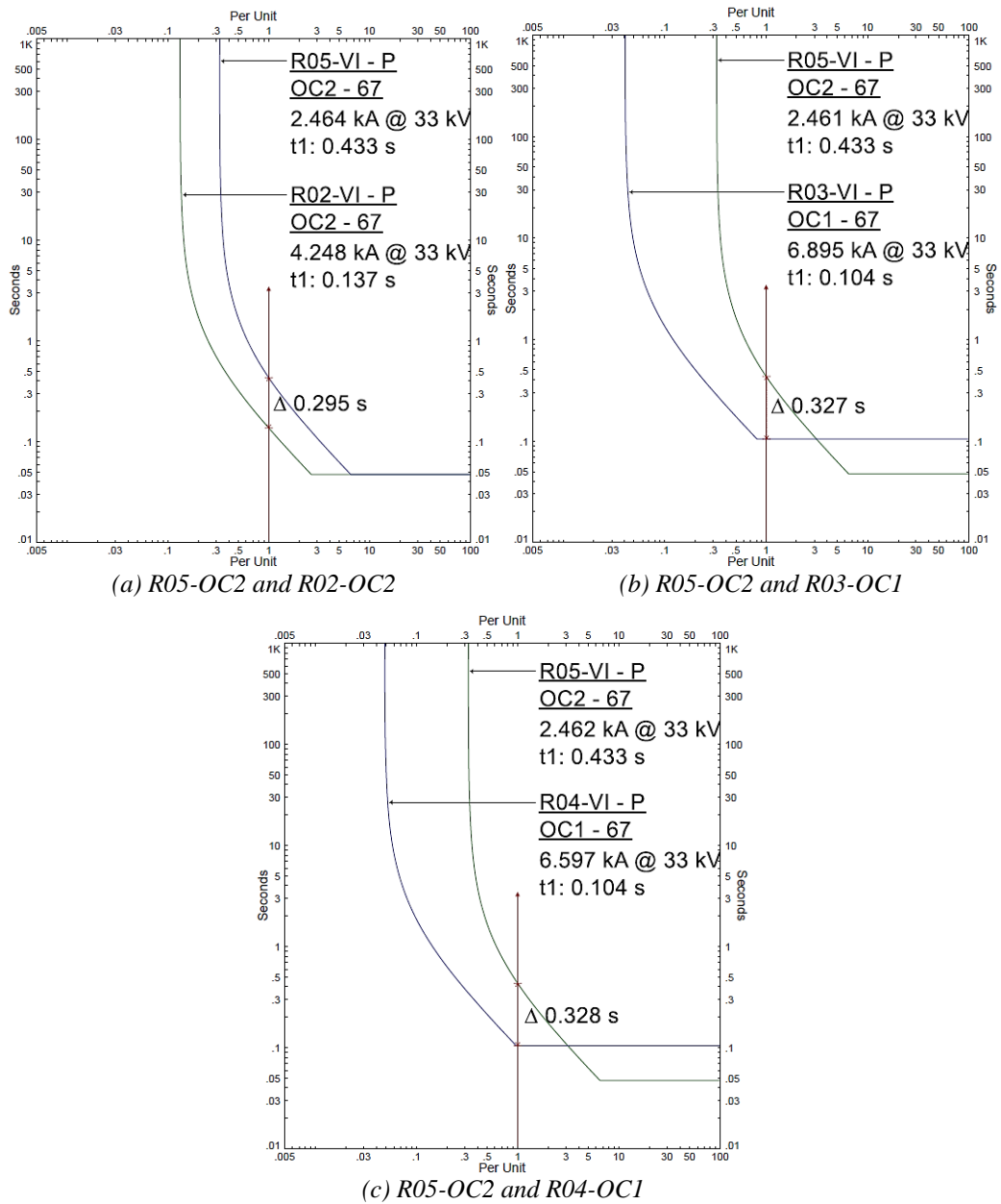


Figure 5.15 Time-Current Curves of Backup Relay Named R05-OC2 for Different Primary Relays for Case 2-Scenario 3

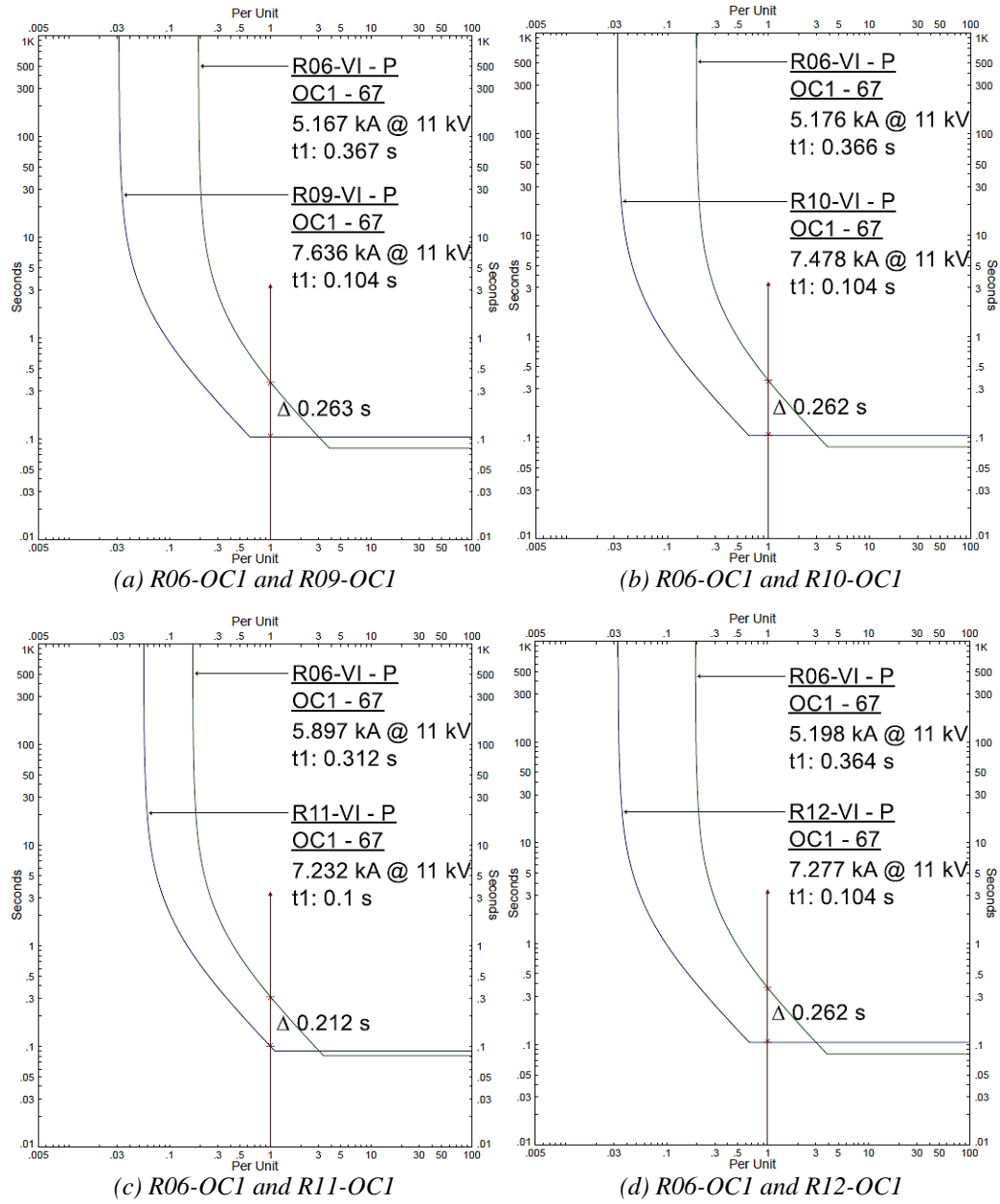


Figure 5.16 Time-Current Curves of Backup Relay Named R06-OC1 for Different Primary Relays for Case 2-Scenario 3

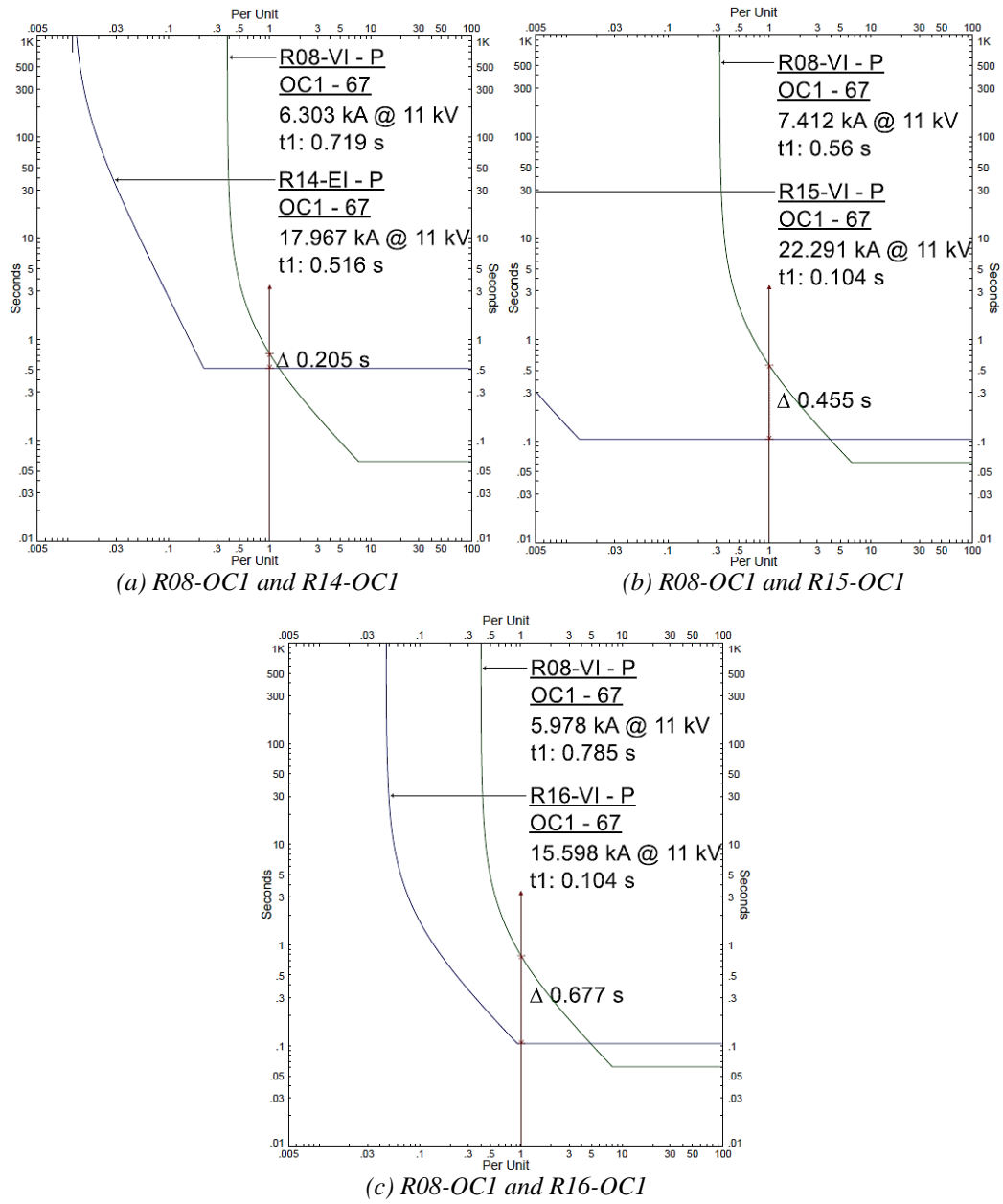


Figure 5.17 Time-Current Curves of Backup Relay Named R08-OC1 for Different Primary Relays for Case 2-Scenario 3

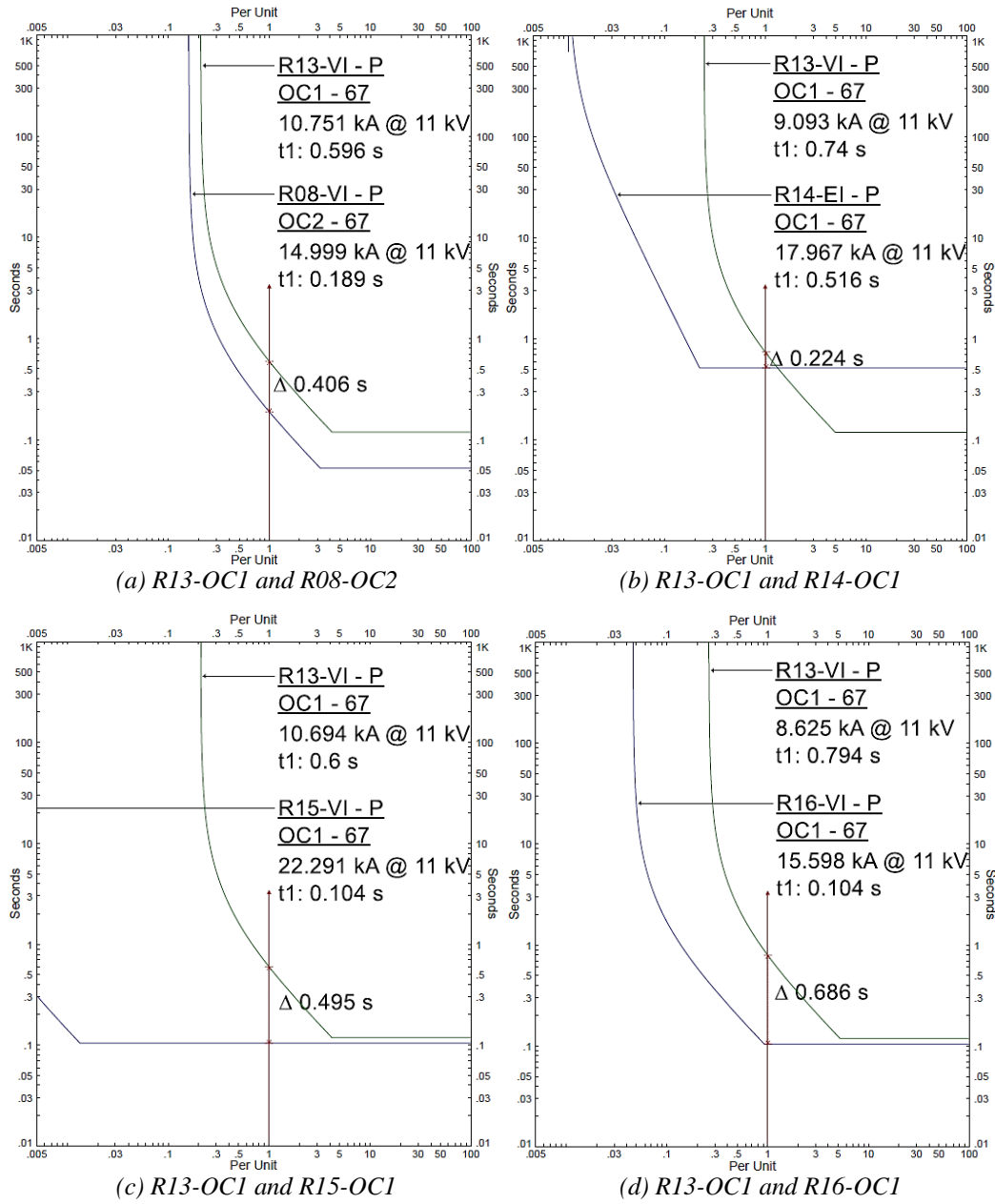


Figure 5.18 Time-Current Curves of Backup Relay Named R13-OC1 for Different Primary Relays for Case 2-Scenario 3

AUTHOR PROFILE



The author, Mr. Punleu Chhun, was born on 12 October 1995 in Kampong Cham province, Cambodia. The author is the youngest child among four children of his parents, Mr. Chhun Pao Leng and Mrs. Ek Chhyn. The author currently completed his bachelor degree in Institute of Technology of Cambodia (ITC) in 2018, majoring in Electrical Engineering with a concentration in Power System Engineering. After finished his bachelor degree, the author continued his master degree in Institut Teknologi Sepuluh Nopember (ITS), Indonesia and took a linear field with the previous level, namely Power System Engineering. The author can be contacted via email address: punleuchhun1995@gmail.com

