# COORDINATION OF DIRECTIONAL OVER-CURRENT RELAYS (DOCR) IN POWER SYSTEM PROTECTION

**A DISSERTATION**

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**By**

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "**COORDINATION OF DIRECTIONAL OVER-CURRENT RELAYS (DOCR) IN POWER SYSTEM PROTECTION**", in partial fulfilment of the requirements for the award of degree of Master of Technology in Water Resource Development in Water Resources and Management Department of Indian Institute of Technology, Roorkee is an authentic record of my own work carried out under the supervision of Dr. C.Thanga Raj, Assist. Professor, WRD&M. The matter in this report has not been submitted for award of any other degree of this or any other institution.

13/06/13

Srikanth Allamsetty

Enrollment No.-11548023

This is to certify that the statement made by the candidate is correct and true to the best of my knowledge.

13/6/13

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This Dissertation report entitled as, "**COORDINATION OF DIRECTIONAL OVER-CURRENT RELAYS (DOCR) IN POWER SYSTEM PROTECTION**" concludes my work carried out at the Department of Water Resources Development and Management, Indian Institute of Technology Roorkee.

The result of work carried out during the fourth semester of my curriculum whereby I have been accompanied and supported by many people. It is pleasant aspect that I have now the opportunity to express my gratitude for all of them.

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# ABSTRACT

The role of protective relays in a power system is to detect system abnormalities and to execute appropriate commands to isolate swiftly only the faulty component from the healthy system. A reliable protective system is vital to the stable operation of the system and the assurance of the customers' supply security. To safeguard against possible failures of protective devices, back-up protection is required to prevent the system from suffering catastrophic consequences.

In the present study describes MATLAB/Simulink implementation of Coordination of Directional Over-Current Relays (DOCR) using 3 bus and 4 bus test models. These simulation models are developed to support and enhance Power System protection courses at the undergraduate level. This study helps students to acquire a clear understanding of this topic. This study provides the step by step procedure to develop MATLAB/Simulink models for 3 bus and 4 bus test models to test the coordination of DOCRs, for which decision variables TDS & PS are manually calculated. These two models have been tested for different fault occurring chances. This study also explains a model to realize DOCR application, which is described as a 'Model Relay' (MR) in the following sections and shown in Fig. 1. DOCRs in these models are well coordinated such that they operate for the faults occurred in their own zone except to backup a failed relay, thus achieved selective tripping. This study helps in understanding the concept with less complexity compared to the other models available in the literature. Understanding the operation of these test models leads to understanding the principle of DOCRs.

The Model Relay with the same logic has been used to achieve coordination of DOCR's of an existing power system. The data of a 132KV Power network has been collected from APTRANSCO and constructed the same in MATLAB using simulink. Then MRs have been incorporated in the system and tested for various fault conditions and accordingly redesigned those MRs to operate for the fault currents.

A relay should trip for a fault in its own zone of operation only. It should not trip for a fault outside its zone, except to back up a failed relay or circuit breaker Coordination of DOCRs is nothing but obtaining selective tripping.

## TABLE OF CONTENTS

## LIST OF FIGURES

CHAPTER- 1

# INTRODUCTION

## *1.1 Introduction for Relays*

Most of the power systems are interconnected in nature and were introduced to improve the system performance, reliability and economics of power delivery. As peak loads may not occur at the same time in all the areas, exchanging of peak loads is possible with these inter connected systems i.e. local load can be mitigated. Thus reliability of the supply increases. Present day power systems consist of several generating stations, running in parallel and feeding a high voltage network which further supplies consuming centres at different voltage levels. Several such systems belonging to different licenses are again interconnected to form a multi area system or a power pool which serves as an economic and reliable reservoir of power [1]. However this process of development has added complexity in power protection schemes, presenting a new set of conditions on the coordination of protective devices, since the fault current may flow to the fault point from both ends of any meshed line element [2].

An over current relay has a single input in the form of ac current. While a relay starting up, it sends a message to order a corresponding breaker cleaning out the fault. The output of the relay is a normally open contact, which changes over to closed state when the relay trips under fault current. The relays, which control the act of isolation of faulty lines from the system without disturbing the healthy lines, are placed at both ends of each line. Thus, the number of DOCRs in an electrical power system is twice the number of the lines.

There are three types of over current protection systems depending upon its grading. Those are time graded, current graded and time & current graded systems. In time graded systems the relay which is set for lowest time operates first irrespective of fault current at that location. This is sometimes disadvantageous. In current graded systems, the relay which senses highest magnitude of fault current operates first. The most efficient system is the third one, i.e. time & current graded systems. In these systems, the relay has two settings, i.e. time dial setting (TDS) and plug setting (PS). These are called as decision variables as the TDS decides the operating time of the relay and PS decides the current required for the relay to pick up [3].

Normally in optimization problem, both the decision variables (TDS & PS) are unknowns while computing the operating time of the relay. The problem considered in this paper includes computing the value of one of the two decision variables (TDS) when the other (PS) is a known value. As a simple 4-bus test system has been considered as a case study, it has been done by hand calculations only. When the total number of directional overcurrent relays to be coordinated is increased according to a complex transmission network, relay coordination setting is more difficult and cannot be performed by a simple hand calculation.

There are basically three types of over current (OC) relays, i.e. Instantaneous OC relay, Definite time OC relay and Inverse time OC relay. Instantaneous OC relay do not have any intentional time delay. That means these relays have only PS and do not have TDS. Definite time OC relay trips at an adjustable amount of time, after it picks up. Inverse time OC relay achieves the requirement that the more severe a fault is, the faster it should be cleared to avoid damage to the apparatus.

### *1.2 Inverse definite minimum time (IDMT) over current relay:*

The characteristic of this relay is inverse in the initial part and tends to a definite minimum operating time as the current becomes very high. The reason for this is that in the electromechanical relays the flux saturates at high values of current and the relay operating torque, which is proportional to the square of the flux, does not increase substantially after the saturation sets in. it is because of the limitation of the electromechanical technology.

Whatever may be the magnitude of fault current, this relays do not operate until certain time delay. This minimum time delay is necessary to decide whether the disturbance is a momentary disturbance or sustains for longer time.

The mathematical relation between the current and the operating time of IDMT characteristic can be written as

$$T = \frac{k_1 . TDS}{\left(\frac{I_f}{PS . CT_{pr\_rating}}\right)^{k_2} - k_3} \quad (1.1)$$

where '.' represents scalar multiplication.

k1, k2 and k3 are the constants representing the characteristics of the relay in a mathematical way which vary according to the type of DOCR used. If It is assumed that inverse-definite minimum time (IDMT) OCRs are being used, then the constants are given as 0.14, 0.02 and 1.0 respectively as per IEEE std. (1997).

$I_f$ is the fault current at CT primary terminals when fault occurs. CTpr_rating is the primary rating of a particular CT. When the secondary rating of CT is taken as 1 the ratio of I f and CTpr_rating gives us the current seen by the relay i.e. Irelay.

$$I_{relay} = \frac{I_f}{CT_{pr\_rating}} \quad (1.2)$$

Then the ratio of Irelay and TS is the factor which indicates the level of nonlinearity in the equation.

### *1.3 Upstream and downstream for a fault:*

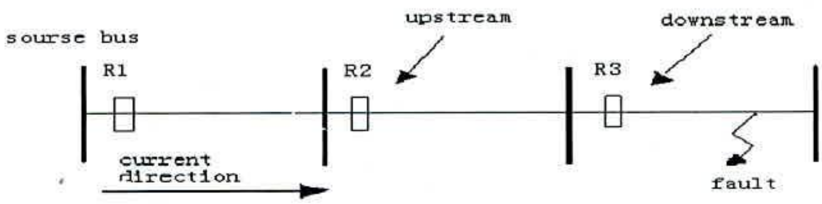


Fig. 1.1: Diagram showing upsream and downstreams for a fault occurred.

All protection relays in a power system can makeup to pairs, one as main protection relay and the other as a backup protection relay. When a fault occurred at the location shown in Fig. 1, the nearer relay R3 is main relay and the further relay R2 is the backup relay of R3. R1 and R2 also makeup a pair in which R2 is main protection and R1 is the back up one.

When comes to the direction of fault current, the main relay is downstream and the backup relay is upstream. Generally, we only consider 3 pairs from faulty point toward upstream. Setting process has to be started from the relay which is at the tail end of the system as this relay is not at all constrained by selectivity problems. All other upstream relay settings are tied up with their downstream neighbours.

So in order to coordinate two over current relays, the difference between the operation time of backup relay and main relay should more than the time interval for coordination (CTI). Otherwise we call a constraint violation happened. CTI is often set between 0.2 to 0.6 seconds.

### *1.4 Setting of the operating time of the relay:*

- Start the setting from the relay at the tail end of the system, i.e. R3 in the above case.
- PS should be such that $I_{L,max} < PS < I_{f,min\ \text{at the end of next section.}}$ i.e. for PS consider minimum fault current at the end of the next section.
- TMS should be decided such that the selectivity with the next relay downstream is maintained for maximum fault current at the beginning of the next section.

TMS of R2 should be such that,

$T_{R2} = T_{R3} + T_{CB\text{-}3} + T_{overshoot,\ R2}$

$T_{R2}$ : operating time of R2 for $I_{f,max,B}$

$T_{R3}$ : operating time of R3 for $I_{f,max,B}$

$T_{CB\text{-}3}$ : operating time of circuit breaker B

$T_{overshoot,\ R2}$ : overshoot time of R2

### 1.5 *Close-end (Near-end) and far-end faults:*

Near-end and far-end faults are the simplest ways to find the critical coordination cases, especially when lines-out and CB failures are included. A fault near the relay on the line is a near-end fault for the relay under consideration. The same fault is a far-end fault for the relay present at the other end of the line [4].

A fault simulated near the relay on the line is near-end fault for the relay (R p_nr) under consideration. The other fault shown at the other end of the line is a far-end fault for the same relay. In Fig. 2, the near-end fault and far-end fault for relay R p_nr are shown.

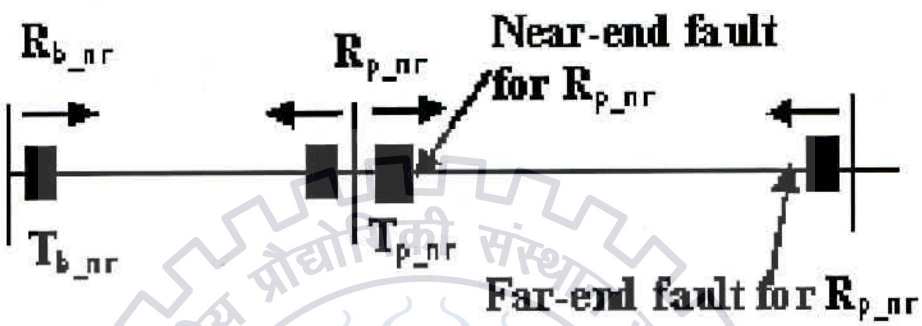


Fig. 1.2. Diagram showing near-end and far-end faults for relay R Pri Near.

Where

R p_nr : Primary relay responding to the near-end fault.

R b_nr : Backup relay responding to the near-end fault.

T p_nr : Operating time of the Primary relay responding to the near-end fault.

T b_nr : Operating time of the Backup relay responding to the near-end fault.

The quality of coordination can be described by DOCR coordination performance based on faults simulated at near ends only as compared to the faults on both ends, i.e., near-ends as well as far-ends.

The near-end fault level is used to coordinate relay operations for high fault currents very close to relay (i.e., at the beginning of line). The far-end fault level coordinates for the minimum fault current at the end of the line.

### 1.6 *Sympathy trips:*

Directional overcurrent relaying, which is simple and economic, is commonly used for providing primary protection in distribution and sub transmission systems and as backup protection in transmission systems. When two or more protective apparatus installed in series have characteristics, which provide a specified operating sequence, they are said to be coordinated or selective.

Historically, the task of computing the directional overcurrent relay (DOCR) settings to achieve satisfactory coordination for the large interconnected networks has been recognized as a difficult problem. In a properly coordinated system, only primary relays corresponding to a given location of fault should trip first to isolate the faulted section of the system. Corresponding backup relays to the fault should trip only when the primary relay fails to trip. In any case, no relay other than the primary or backup relays corresponding to the fault should trip. But in actuality, sometimes depending upon the location and level of fault, some of the other relays that are neither primary nor backup relay for that fault do operate. These unwanted trips are known as sympathy trips.

This is the situation, in which other relay or relays in the system will operate earlier for the fault in the zone of designated relay.

Sympathy trips may be classified in the following categories.

- Before the operation of any backup relay, some other relays operate.
- Before the operation of a primary relay, either its backup or any other relay operates.

These sympathy trips evaluated in terms of loss of load may be one of the criteria for deciding the critical point for initiating the re-coordination of the system.

Sympathy trips can be take place because of following reasons.

- The inherent nature of directional overcurrent relays to trip in one direction and not to trip in the other direction,
- Nature of the interconnected power systems,
- Inappropriate settings of the relays, and
- Changes in the system conditions.

In general, auto reclosing of the circuit breakers (CBs), single-phase tripping of the faulted phase and the adaptive measures are some of the possible ways to tackle the threat of sympathy trips.

Sympathetic trips of breakers occur on un-faulted feeders. A variety of causes can be given. In some cases, transformer connections, large motors, or large feeder capacitor banks were suspected of causing increased currents in the un-faulted feeder. The remedy for this is to alter relaying on the feeder by changing settings or removing an instantaneous trip.

Capacitor bank switching can be said as one of the cause of undesirable feeder tripping. It can be cured by moving or reducing the size of the capacitor banks, removing fast trips from feeder overcurrent relays, and installing series inductance.

# CHAPTER- 2

# PROBLEM DESCRIPTION

Over current (OC) relays which were quite adequate protective devices for radial circuits, are not generally capable of being properly coordinated for meshed transmission systems. It has been improved by the addition of a directional element. This relay is called directional over current relay (DOCR), which is the simplest and least expensive, but the most difficult to apply. They also have the disadvantage in changing their coordination characteristics as the network and generation sources change. Thus these relays may require periodic readjustment.

The probability of faults occurring on the lines is much more due to their greater length and exposure to atmospheric conditions. In the event of a short circuit, the circuit breaker closest to the fault should open, while all other circuit breakers remaining in a closed position. In case the nearest breaker to the fault fails to open, back up protection should be provided.

- A relay should not trip for a fault outside its zone, except to back up a failed relay or circuit breaker.
- To obtain reliable protection, suitable setting of relays should have been selected. Coordination of relays is nothing but obtaining selective tripping.
- While coordinating the backup protection with the primary relay characteristic, we have to ensure that the backup relay has sufficient time delay to allow the primary relay and its breaker to clear the fault.

Coordination of protective relays is nothing but obtaining selective tripping. The determination of the time delays of all backup relays is known as coordination of the protection system. While coordinating the backup protection with the primary relay characteristic, we have to ensure that the backup relay has sufficient time delay to allow the primary relay and its breaker to clear the fault. Main objective is to achieve the minimum possible summation of operating times of all primary relays while maintaining coordination among all relays. The relay operating time should be just as short as possible in order to preserve system stability without unnecessary tripping of circuits.

This study also provides the step by step procedure to develop MATLAB/Simulink models for 3 bus and 4 bus test models to test the coordination of DOCRs, for which decision variables TDS & PS are manually calculated. These two models have been tested for different fault occurring chances. This study explains a model to realize DOCR application, which is described as a 'Model Relay' (MR) in chapter 6 and shown in Fig. 6.1. DOCRs in these models are well-coordinated such that they operate for the faults occurred in their own zone except to backup a failed relay, thus achieved selective tripping. This study helps in understanding the concept with less complexity compared to the other models available in the literature. Understanding the operation of these test models leads to understanding the principle of DOCRs. Later using the same MRs, DOCRs in an existing power network are coordinated using MATLAB which has been explained in chapter 8.

# CHAPTER- 3

# LITERATURE REVIEW

Optimization theory was applied for dealing with coordination of DOCR for the first time in 1988 [5]. Optimal DOCR Coordination has been obtained in [6]-[7] Genetic Algorithms (GA). Here the objective was to minimize the operating times of the relays. Sparse dual revised simplex method of linear programming has been used in [8] which is a parallel processing algorithm to optimize the TDS settings for assumed non-linear TS settings. Linear programming techniques are also applied in [9]. In [10] the non-linear Random Search Technique (RST) has been used to solve the coordination problem and achieved acceptable speed of primary protection while attempting to coordinate the maximum relay pairs. Hybrid GA method has been introduced in [11] to improve the convergence of the GA. This problem has been solved in [12] using the Hybrid GA-NLP (non linear programming) Approach, a hybrid method to overcome the drawbacks of GA and NLP methods and made use of the advantages of both the methods. A new approach based on the interval analysis has been introduced in [13] to solve this problem by considering uncertainty in the network topology. Here, the problem is formulated as an interval linear programming (ILP) problem and has been converted to standard linear programming (LP). As a result, the number of coordination constraints is significantly reduced in the proposed methods. Besides, GA, the other metaheuristics used for coordination of DOCR are as follows: use of Honey Bee algorithm in [14], use of Self organizing migrating algorithm (SOMA) and its hybridization with GA in [15]; an approach based on particle swarm algorithm has proposed in [16] and the act of quantizing the answers is taken into account as a part of optimization procedure, so the outputs are optimized discrete TSM's and PSM's. Optimization methodology named Laplace Crossover Particle Swarm Optimization (LXPSO), which uses a new information sharing strategy amongst the particles of the swarm using a new crossover, called Laplace Crossover (LX) based on Laplace distribution has been introduced in [17]. This problem has been solved using modified differential evolution algorithms in [18] where five new versions of differential evolution (DE) called modified DE versions, i.e. MDE1-MDE5, have been applied and got better results when compared with the classical DE algorithm. The practical significance of the problem prompted the researchers to apply efficient techniques for solving such problems. Optimum TMS and TS of Overcurrent Relays have been determined Using Linear Programming (LP) Technique in [19]. Four LP techniques, namely, revised simplex, dual simplex, two phase simplex and Big-M methods have been used to solve the nonlinear programming problem (NLP). Coordination problem has also been solved considering the priority of constraints by assigning them weightings in

[20]. A selection criterion has been adopted in [21] to get discrete pickup currents, which mitigate the selectivity constraints effect on the minimization of time multiplier settings. Then selectivity constraint equations are classified into individual groups with respect to backup relays. When solving these systems of equations, the initial time multiplier settings are obtained then increased gradually to find the final solution for all of the constraint equations. This problem is formulated as a mixed-integer nonlinear programming problem in [22] and is then solved by seeker optimization technique. Harmony search algorithm (HSA) is proposed for optimal coordination of DOCR in a looped distribution system in [23]. Then this algorithm is developed to Improvised harmony search algorithm (IHSA) to solve the same problem. IHSA employs a method that enhance fine tuning and convergence rate of HAS. A new efficient and reliable approach based on a constrained harmony search algorithm (HSA) has been proposed in [24] to solve the problem by including a technique called Box-Muller harmony search (BMHS) algorithm got good results.

A model of a circuit breaker controlled by OC relay has been built and illustrated its use in [25]. Electrical network protection selectivity has also been checked using Simulink. In [26] a modeling and simulation software has been described which was developed specifically for teaching protective relaying application and design concepts by introducing new libraries of signal sources and relay elements developed for the SIMULINK environment of MATLAB. In [27] the development of a novel digital relay model has been presented, as a SIMULINK Sfunction block, and its validation by a digital relay data analysis application. Also the advantages to use SIMULINK Sfunctions in modelling a digital protective relay have been discussed. In [28] interactive software for evaluating algorithms for digital relay designs has been presented which includes signal processing and protection modules that are used in digital relays and facilities for generating data for testing the performance of digital relay designs. The work presented in [29] explored the application of two software tools, i.e. MATLAB/Simulink and Virtual Test Bed in protective relay modeling, simulation and testing. An instantaneous overcurrent relay model has been developed and tested for fault conditions using both software tools. The modelling of over current relay of Inverse Definite Minimum Time (IDMT) type using DSP board TMS320F2812 has been discussed in [30]. A set of modeling, simulation and testing tools has been presented aiming at better understanding of the design concept and related applications for protective relaying and substation automation solutions for the smart grid in [31], in which advanced teaching approaches have also been presented with examples showing their use.

# CHAPTER- 4

# PROBLEM FORMULATION

## 4.1 *Objective function:*

Objective function in coordination studies is constituted as the summation of operating times of all primary relays, responding to clear all close-in and far-bus faults.

The optimization problem is to minimize this objective function (F).

$$OBJ = \sum_{i=1}^{N_{cl}} T^{i}_{pri\_cl\_in} + \sum_{j=1}^{N_{far}} T^{j}_{pri\_far\_bus} \qquad (4.1)$$

where

$$T^{i}_{pri\_cl\_in} = \frac{0.14.TDS^{i}}{\left(\dfrac{I_f^{\,i}}{PS^{i}.CT^{i}_{pr\_rating}}\right)^{0.02} - 1}$$

$$T^{j}_{pri\_far\_bus} = \frac{0.14.TDS^{j}}{\left(\dfrac{I_f^{\,j}}{PS^{j}.CT^{j}_{pr\_rating}}\right)^{0.02} - 1}$$

## 4.2 *Constraints:*

***a)* Bounds on variables TDSs:**

$TDS^{i}_{min} \leq TDS^{i} \leq TDS^{i}_{max}$ ; Where i varies from 1 to Ncl.

TDS imin is lower limit and TDS imax is upper limit of TDSi.

These limits are 0.05 and 1.1, respectively.

***b)* Bounds on variables TSs:**

$PS^{i}_{min} \leq PS^{i} \leq PS^{i}_{max}$ ; Where i varies from 1 to Nfar.

TS jmin is lower limit and TS jmax is upper limit of TS j.

These are 1.25 and 1.50, respectively.

*c)* **Limits on primary operation times:**

This constraint imposes constraint on each term of objective function to lie between 0.05 and 1.0.

*d)* **Selectivity constraints for all relay pairs:**

The backup relay should operate only after primary relay fails to operate to avoid mal-operation. It is necessary for maintaining the selectivity of primary and backup relays. The sum of operating time of CB associated with primary relay, and the overshoot time is called the coordination time interval (CTI).

In order to coordinate two over current relays, the difference between the operation time of backup relay and main relay should more than the coordination time interval (CTI).

$$T_{backup} - T_{primary} - CTI \geq 0 \; ;$$

Or

$$T_{backup} - T_{primary} \geq CTI \; ; \qquad (4.2)$$

where

$$T^{i}_{backup} = \frac{0.14..TDS^{x}}{\left(\dfrac{I_f^{\,i}}{PS^{x}.CT^{i}_{pr\_rating}}\right)^{0.02} - 1}$$

$$T^{i}_{primary} = \frac{0.14..TDS^{y}}{\left(\dfrac{I_f^{\,i}}{PS^{y}.CT^{i}_{pr\_rating}}\right)^{0.02} - 1}$$



and value of CTI is known and is often set between 0.2 to 0.6 seconds. It varies for different bus models.

The objective function and constraints for every model will be of same form as described above, except the change in no. of relays. The values of Ncl and Nfar are equal to the number of relays or twice the number of lines.

CHAPTER- 5

# COORDINATION OF DOCRs BY OPTIMIZING DECISION VARIABLES

### *5.1 Introduction:*

Mathematical equation for calculating time of operation for each relay has been given in the previous chapter. Also the optimization problem has been described as to minimize the objective function F. In this chapter, IEEE 4-bus model has been taken into consideration and explained the procedure to calculate operation times for each relay and the objective function value. These calculations have been done using Microsoft excel where as to get optimized values we should use optimization algorithms. Using of those algorithms avail us the possibility to solve the non linear equation of operating time with two decision variables TDS, PS. But while calculating manually it is mandatory to assume PS as a constant for each relay in a range of 1.25 to 1.5.

### *5.2 IEEE 4-bus model Data:*

It consists of two synchronous generator buses and two load buses with 4 lines. Each line consists of two relays and thus the model has 8 relays in total, i.e. 1 to 8. The Values of I f and CTpr_rating for these relays have been given in the following tables 5.1 and 5.2.

These values are to be used to calculate the mathematical equations given in the previous chapter for $T^i_{pri\_cl\_in}$, $T^j_{pri\_far\_bus}$, $T^i_{backup}$ and $T^i_{primary}$ .

TABLE 5.1

VALUES OF $I_f$ AND $CT_{pr\_rating}$ FOR MODEL-II WITH $T^i_{pri\_cl\_in}$ AND $T^j_{pri\_far\_bus}$

| $T^i_{pri\_cl\_in}$ | | | $T^j_{pri\_far\_bus}$ | | |
|---|---|---|---|---|---|
| $TDS^i$ | $I_f^i$ | $CT^i_{pr\_rating}$ | $TDS^j$ | $I_f^j$ | $CT^j_{pr\_rating}$ |
| $TDS^1$ | 20.32 | 0.4800 | $TDS^2$ | 23.75 | 0.4800 |
| $TDS^2$ | 88.85 | 0.4800 | $TDS^1$ | 12.48 | 0.4800 |
| $TDS^3$ | 13.6 | 1.1789 | $TDS^4$ | 31.92 | 1.1789 |
| $TDS^4$ | 116.81 | 1.1789 | $TDS^3$ | 10.38 | 1.1789 |
| $TDS^5$ | 116.70 | 1.5259 | $TDS^6$ | 12.07 | 1.5259 |
| $TDS^6$ | 16.67 | 1.5259 | $TDS^5$ | 31.92 | 1.5259 |
| $TDS^7$ | 71.70 | 1.2018 | $TDS^8$ | 11.00 | 1.2018 |
| $TDS^8$ | 19.27 | 1.2018 | $TDS^7$ | 18.91 | 1.2018 |

TABLE 5.2

VALUES OF $I_F$ AND $CT_{PR\_RATING}$ FOR MODEL-II WITH $T^X_{BACKUP}$ AND $T^Y_{PRIMARY}$

| $T^i_{backup}$ | | | $T^i_{primary}$ | | |
|---|---|---|---|---|---|
| Relay | $I_f^i$ | $CT^i_{pr\_rating}$ | Relay | $I_f^j$ | $CT^j_{pr\_rating}$ |
| 5 | 20.32 | 1.5259 | 1 | 20.32 | 0.4800 |
| 5 | 12.48 | 1.5259 | 1 | 12.48 | 0.4800 |
| 7 | 13.61 | 1.2018 | 3 | 13.61 | 1.1789 |
| 7 | 10.38 | 1.2018 | 3 | 10.38 | 1.1789 |
| 1 | 116.81 | 0.4800 | 4 | 116.81 | 1.1789 |
| 2 | 12.07 | 0.4800 | 6 | 12.07 | 1.5259 |
| 2 | 16.67 | 0.4800 | 6 | 16.67 | 1.5259 |
| 4 | 11.00 | 1.1789 | 8 | 11.00 | 1.2018 |
| 4 | 19.27 | 1.1789 | 8 | 19.27 | 1.2018 |

Values of PS for 1 to 8 relays have been assumed as shown in following table.

TABLE 5.3

Assumed Values OF PS

| ps1 | ps2 | ps3 | ps4 | ps5 | ps6 | ps7 | ps8 |
|---|---|---|---|---|---|---|---|
| 1.25 | 1.25 | 1.25 | 1.5 | 1.5 | 1.25 | 1.5 | 1.25 |

## *5.3 Operating times calculated:*

- For close-in faults

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| tds1 | 0.05 | tds3 | 0.05 | tds6 | 0.05 | tds8 | 0.05 |
| tp1 | 0.09590428 | tp3 | 0.153965 | tp6 | 0.157973 | tp8 | 0.133699 |
| tb5 | 0.39590428 | tb7 | 0.453965 | tb2 | 0.457973 | tb4 | 0.433699 |
| tds5 | 0.126233344 | tds7 | 0.133786 | tds2 | 0.224894 | tds4 | 0.151576 |
| tp5 | 0.216033517 | tp7 | 0.245013 | tp2 | 0.299511 | tp4 | 0.242737 |
| tb8 | 0.516033517 | tb6 | 0.545013 | tb3 | 0.599511 | tb1 | 0.542737 |

- For far-end faults

| | |
|---|---|
| tp1 | 0.111858444 |
| tp2 | 0.412423008 |
| tp3 | 0.175811768 |
| tp4 | 0.3562272 |
| tp5 | 0.326562707 |
| tp6 | 0.186223927 |
| tp7 | 0.38915171 |
| tp8 | 0.172320354 |

These values have been calculated in MS Excel using the formula syntax as follows 0.14*tds/(POWER((i/(ps*ct)),0.02)-1)

### *5.4 Objective function:*

$$\sum_{i=1}^{N_{cl}} T^{i}_{pri\_cl\_in} = 1.544$$

$$\sum_{j=1}^{N_{far}} T^{j}_{pri\_far\_bus} = 2.13$$

Then the value of objective function F = 3.674

This value can be further minimized if we use optimization algorithms as discussed earlier by considering both TDS and PS as unknowns.

CHAPTER- 6

# COORDINATION OF DOCRs USING MATLAB/SIMULINK

### *6.1 Nomenclature:*

Ri : Relay number i, i.e. ith relay

TDSi: Time Dial Setting of relay i

PSi: Plug Setting of relay i, taken as a constant for all calculations in this paper, i.e. 1.25

Ifi: fault current corresponding to relay i

Irelay: Current seen by the relay

Tbackupi: operating time of backup relay i.

Tprimaryi: operating time of primary relay i.

### *6.2 Introduction:*

This chapter describes MATLAB/Simulink implementation of Coordination of Directional Over-Current Relays (DOCR) using 3 bus and 4 bus test models. These simulation models are developed to support and enhance Power System protection courses at the undergraduate level. This study helps students to acquire a clear understanding of this topic.

MATLAB with its toolboxes such as Simulink [32] and SimPowerSystems [33] is one of the most popular software packages to solve various problems involved in power system applications. It can also be used to enhance teaching the Coordination of Directional Over-Current Relays (DOCR). This chapter explains the coordination of DOCRs using MATLAB/ Simulink by considering 3 bus and 4 bus test models. This study helps to enhance the power system protection education in undergraduate level.

The relays, which control the act of isolation of faulty lines from the system without disturbing the healthy lines, are placed at both ends of each line. Thus, the number of DOCRs in an electrical power system is twice the number of the lines. A DOCR has a single input in the form of ac current. While a relay starting up, it sends a message to order a corresponding Circuit Breaker (CB) cleaning out the fault. The output of the relay is normally an open contact, which changes over to closed state when the relay trips under fault current.

#### 6.2.1 Problem Description

The probability of faults occurring on the lines is much more due to their greater length and exposure to atmospheric conditions. In the event of a short circuit, the circuit breaker closest to the fault should open, while all other circuit breakers remaining in a closed position. In case the nearest breaker to the fault fails to open, back up protection should be provided. The relay operating time should be just as short as possible in order to preserve system stability without unnecessary tripping of circuits.

### 6.2.2 Contribution

This chapter provides the step by step procedure to develop MATLAB/Simulink models for 3 bus and 4 bus test models to test the coordination of DOCRs, for which decision variables TDS & PS are manually calculated. These two models have been tested for different fault occurring chances. This chapter also explains a model to realize DOCR application, which is described as a 'Model Relay' (MR) in the following sections and shown in Fig. 6.1. DOCRs in these models are well coordinated such that they operate for the faults occurred in their own zone except to backup a failed relay, thus achieved selective tripping. This study helps in understanding the concept with less complexity compared to the other models available in the literature. Understanding the operation of these test models leads to understanding the principle of DOCRs.

### 6.2.3 Chapter Organization

The organization of the remaining chapter is as follows. Section 6.3 gives the detailed discussion of Model Relay, 3 bus and 4 bus test models. Section 6.4 describes the procedure to design the model and presents simulation results for various conditions. The chapter concludes with Section 6.5, in which future scope of work is also mentioned.

## *6.3 MATLAB/Simulink Models:*

This section has been divided into three subsections. Before discussing about the test models a clear explanation has been given on MR in the first subsection. Then 3 bus and 4 bus test models have been discussed in second and third subsections respectively.

### 6.3.1 Model Relay

Fig. 6.1 shows Model Relay (MR), which has been designed in MATLAB such that it operates as per the principles of a DOCR.

The main objectives of MR are:

- To send '1' signal to the corresponding CB when $I_{relay}$ is less than the normal over-load current of that particular branch, which makes the CB remained in closed state.

- To send '0' signal when $I_{relay}$ exceeds the normal over-load current, which turns the CB into open state and thus isolates the faulty branch.

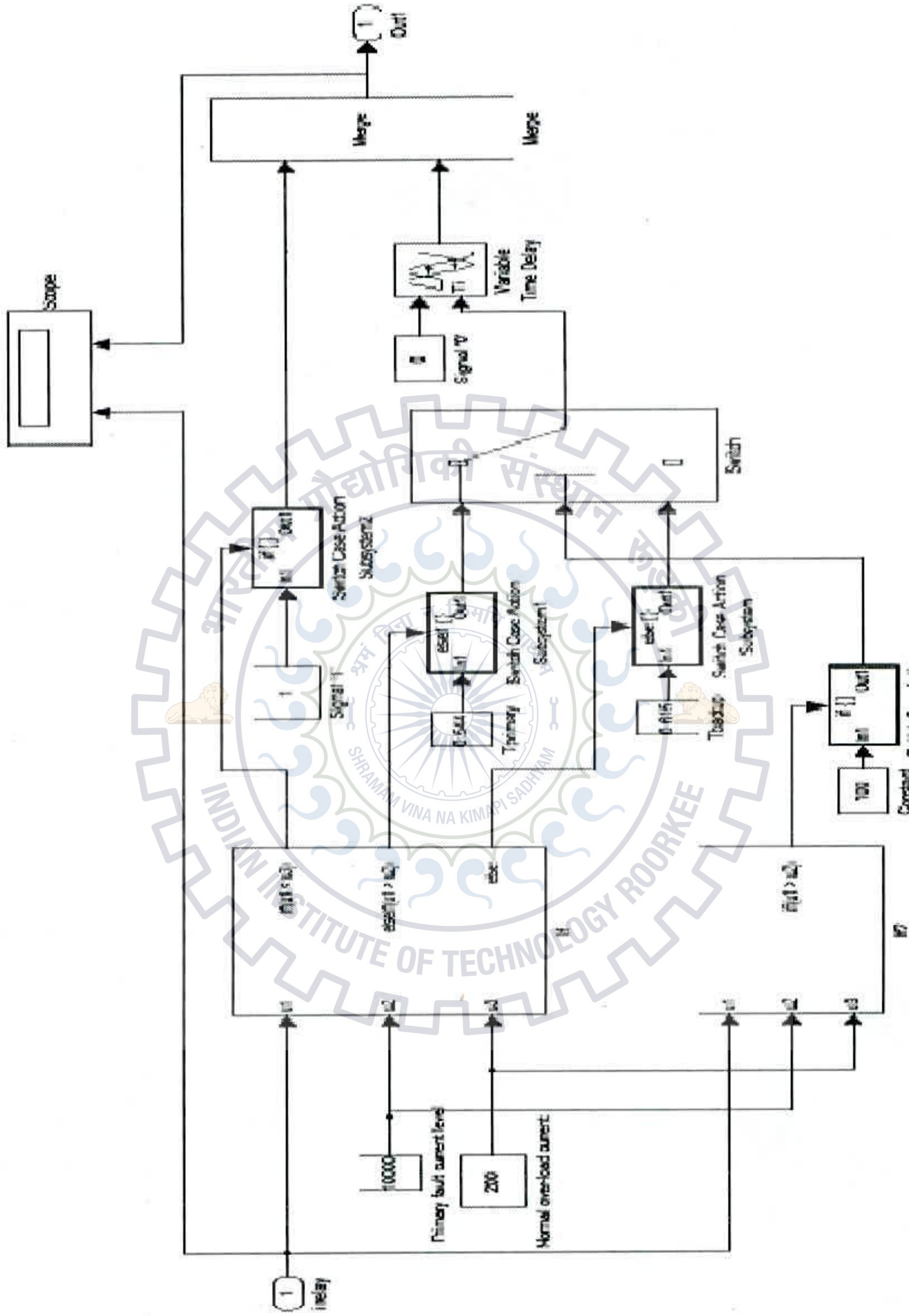

Fig. 6.1 Model Relay

But another thing to check is whether it is primary fault or secondary fault, depending on which MR operates with either $T_{primary}$ or $T_{backup}$. So $I_{relay}$ has been compared with two levels of fault currents. If $I_{relay}$ is greater than the primary fault current range, MR operates with a time delay of $T_{primary}$. If $I_{relay}$ is in between normal over-load current and primary fault current, MR operates with a time delay of $T_{backup}$. 'If' and 'Switch' blocks are used for this logic as shown in Fig. 1. 'Variable Time Delay' block generates a '0' signal with the obtained time delay. The block 'Merge' has been used to send the latest signal generated to the corresponding CB, i.e. either '1' or '0'. 'Scope' block is provided to show the $I_{relay}$ and relay output signal. Calculations of normal over-load current and primary fault currents are explained in detail in the design procedure subsection in Section V.

#### 6.3.2 Primary and backup relay operations in 3 Bus Test Model

Fig. 6.2 shows 3 bus test model when a fault occurred on one of its lines. It consists of one synchronous generator bus and two load buses with 3 lines. Each line consists of two relays and thus the model has 6 relays in total, i.e. 1 to 6.

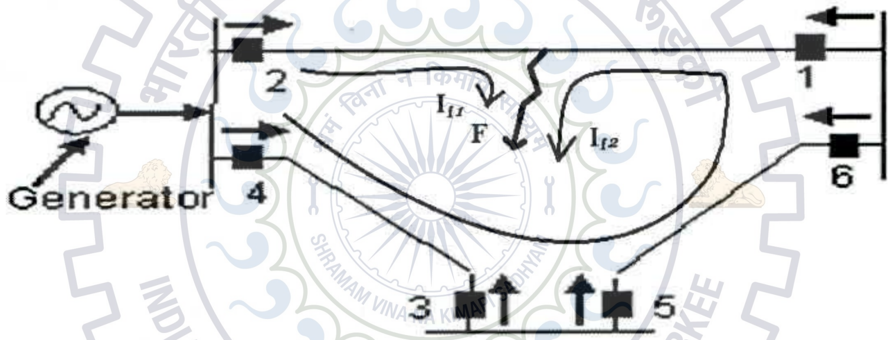


Fig. 6.2. Illustration of primary and backup relays in 3-Bus Test Model.

This Figure shows the direction of fault currents if a fault occurs in a particular line. As per the principles of DOCR, when fault occurs the relay which senses a fault current leaving the bus operates for that fault. For better explanation each relay has assigned with an arrow symbol on its top. If the fault current direction matches with the arrow direction, then that particular relay operates either as a primary relay or backup relay depending upon the fault current level. For the fault shown in Figure, the relays 2 & 1 operate as primary relays. As per the direction of If2 Relay 5 acts as a backup relay for relay 1 and relay 4 acts as a backup relay for relay 5. There is no backup relay for relay 2 as the fault current If1 is not flowing in any other line.

In reality, generated voltage will be raised to a high voltage level by using a step up transformer at the beginning of transmission line for transmitting the power with fewer losses. Current Transformers shall have to be provided to measure the currents as well as to reduce the current levels for the relay circuits. This arrangement shall be done to increase the sensitivity of the protection system and to reduce the cost of relay circuits.

But here in MATLAB, these issues are need not to be considered thus not provided to reduce complexity. MATLAB model for the 3-bus test model is similar in all means to that of 4 bus test model, which is shown in Fig. 4, except the number of lines and relays.

#### 6.3.3 4-Bus Test Model

Fig. 6.3 shows single line diagram for 4-bus test model which consists of two synchronous generator buses and two load buses with 4 lines. Each line consists of two relays and thus the model has 8 relays in total, i.e. 1 to 8.

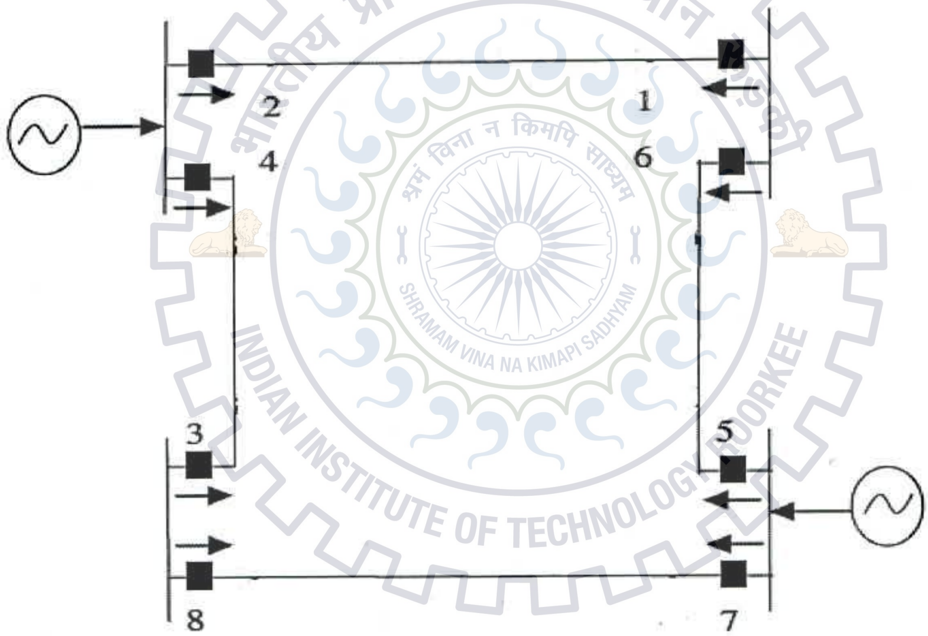


Fig. 6.3. Single line diagram of 4-Bus Test Model.

Simulink model of this 4-bus test system is presented in Fig. 6.4. Various blocks used from MATLAB library have been described as follows. Relay 1 to relay 8 are sub blocks which are having MRs inside them. CB1 to CB 8 are 'Breaker' blocks and CM1 to CM8 are 'Current Measurement' blocks. After running this model under normal conditions, normal branch currents for each branch can be seen in the scope 3 and scope 4 blocks connected in the test model. Then overloaded current can be calculated by multiplying these values with a fixed/assumed PS, i.e. 1.25. Now connect a 'Three phase fault' block in any particular line by modifying its properties as a single phase to ground fault and note down the values of current magnitudes from the scope 3 and scope 4 blocks. These values are nothing but the primary fault current levels for the relays connected at the both sides of that particular line and backup current levels for their backup relays. This has been explained in Section 6.4.2 in detail by considering fault locations on each and every line.

### *6.4 Design Procedure and Fault Analysis:*

This section has been divided into 2 subsections. Procedure for designing 4-bus test model has been given along with testing for various cases respectively. Table 6.1 describes the primary relays and their corresponding backup relays for faults occurred on each line as shown in Fig. 6.4.

TABLE 6.1
PRIMARY AND BACKUP RELAYS FOR VARIOUS FAULT LOCATIONS

| **Fault Location** | **Primary relays** | **Corresponding Backup relays** |
|---|---|---|
| Fault 1 | 2<br>1 | -<br>5 |
| Fault 2 | 4<br>3 | -<br>7 |
| Fault 3 | 5<br>6 | -<br>2 |
| Fault 4 | 7<br>8 | -<br>4 |

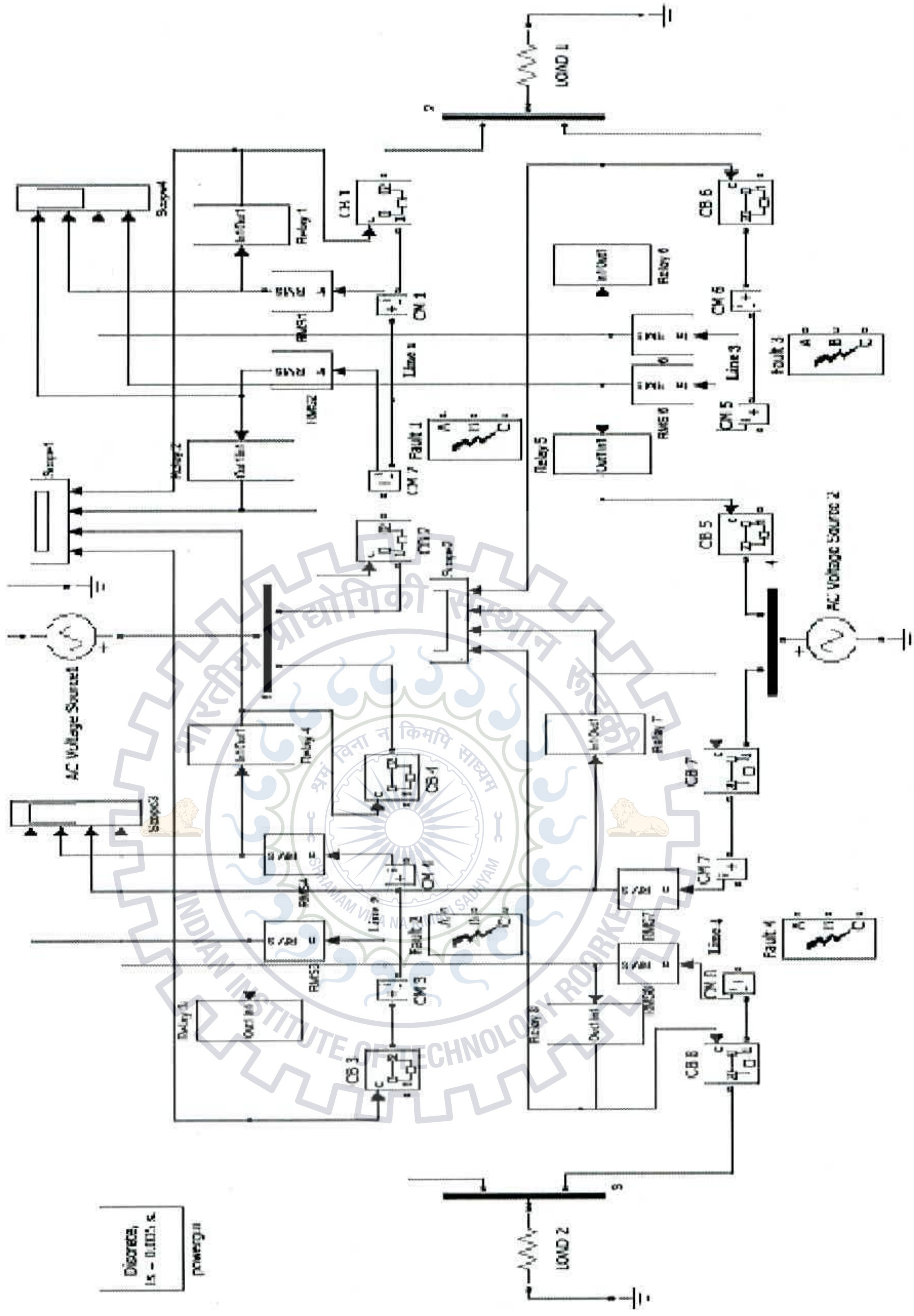


Fig. 6.4. MATLAB model for 4-Bus Test Model

### 6.4.1 Design procedure

Before analyzing the faults, design procedure for MRs has been explained in this subsection by calculating Tprimary & Tbackup for all the relays in a step by step procedure as follows.

Operating times of primary and backup relays can be calculated using the following formula [3].

$$T^{i} = \frac{0.14 * TDS^{i}}{\left(\frac{I_f^{i}}{PS^{i}}\right)^{0.02} - 1} \tag{6.1}$$

Step1: Run the model with an additional connection between 'Fault 1' block and 'line 1'. When Fault 1 occurs in the model, as shown in the Table I, relays 2 & 1 act as primary relays. There is no backup relay for 2 as the fault current flowing through this relay is not flowing through any other relay. However, as this relay is at the generating station itself, it can be observed if fails to operate for the fault. Relay 5 acts as a backup relay for relay 1.

Step2: Fault current $I_f$ values are found and tabulated in Table 6.2 under the 'Fault 1' column.

Step3: Calculate $T_{primary}^{1}$ by assuming a lowest possible value for TDS1, i.e. 0.05 and substituting all the values in (6.1) which gives T= 0.036 Sec.

Step4: Calculate $T_{backup}^{5}$ as follows.

It is necessary for maintaining the selectivity of primary and backup relays. The sum of operating time of CB associated with primary relay and the overshoot time is called the coordination time interval (CTI). In order to coordinate two over current relays, the difference between the operation time of backup relay and main relay should more than the CTI.

$$T_{backup} - T_{primary} \geq CTI$$

Value of CTI is known and is often set between 0.2 to 0.6 seconds. It varies for different bus models and taken as 0.3 for the test model.

So $T_{backup}^{5} = T_{primary}^{1} + 0.3 = 0.336$ sec.

Step5: Construct MRs of relays 1 & 5 using the values of $T_{primary}^{1}$ & $T_{backup}^{5}$ respectively for which the values of $T_{primary}^{5}$ & $T_{backup}^{1}$ are calculated in other cases.

Step6: Substitute $T_{backup}^{5}$ and $I_f^5$ in (1) and calculate TDS5 as 0.456, which is useful to calculate $T_{primary}^{5}$ when fault 3 occurs.

Step7: Repeat the steps 1 to 6 by creating remaining faults too with additional connections between 'Fault' blocks and their respective lines, only one connection at a time.

Step8: Tabulate the values after completing the calculations of $T_{primary}$ & $T_{backup}$ for all the relays with all possible faults.

TABLE 6.2

FAULT CURRENTS SEEN BY PRIMARY AND BACKUP RELAYS FOR EACH FAULT

| **Fault 1** | | **Fault 2** | | **Fault 3** | | **Fault 4** | |
|---|---|---|---|---|---|---|---|
| $R_i$ | $I_f^i$ (KA) | $R_i$ | $I_f^i$ (KA) | $R_i$ | $I_f^i$ (KA) | $R_i$ | $I_f^i$ (KA) |
| Primary relays | | Primary relays | | Primary relays | | Primary relays | |
| 1 | 7.435 | 3 | 7.438 | 6 | 7.435 | 8 | 7.438 |
| 2 | 23.55 | 4 | 23.57 | 5 | 23.55 | 7 | 23.57 |
| Backup relay | | Backup relay | | Backup relay | | Backup relay | |
| 5 | 7.448 | 7 | 7.446 | 2 | 7.448 | 4 | 7.446 |

TABLE 6.3

VALUES OF $T_{PRIMARY}$ & $T_{BACKUP}$ FOR ALL THE RELAYS

| ***Relay i*** | $T_{primary}^{i}$ | $T_{backup}^{i}$ |
|---|---|---|
| 1 | 0.036 | - |
| 2 | 0.293 | 0.336 |
| 3 | 0.036 | - |
| 4 | 0.293 | 0.336 |
| 5 | 0.293 | 0.336 |
| 6 | 0.036 | - |
| 7 | 0.293 | 0.336 |
| 8 | 0.036 | - |

The primary and backup operating times of all the relays are tabulated in Table 6.3. These values are used to construct MRs for all the relays. '$T_{primary}$' & '$T_{backup}$' blocks in MR are filled with these constant values to get required time delays while operating as DOCRs for the faults occurred in the system. Table 6.3 also shows that the relays 1, 3, 6 and 8 do not act as backup relays for any of the possible faults.

### 6.4.2 Testing for the faults

4-bus test model has been tested for various conditions in this subsection as follows.

- Case-I (Without any fault, Normal conditions)

In this case the model runs under normal conditions without connecting any fault, for which simulation results have been shown in following Figures, i.e. Fig. 6.5 to Fig. 6.8. Continuous signal '1' is maintained by all the relays to keep the CBs in closed state, which can be seen in scopes 1 & 2 in Fig. 6.5 and Fig. 6.6 respectively. Normal branch currents of each branch can be observed in scopes 3 & 4 shown in Fig. 6.7 and Fig. 6.8 respectively.

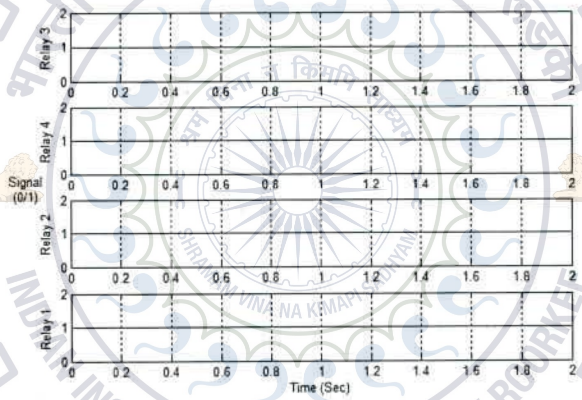


Fig. 6.5 Simulation results for Case-I: output of relay blocks connected to scope 1.

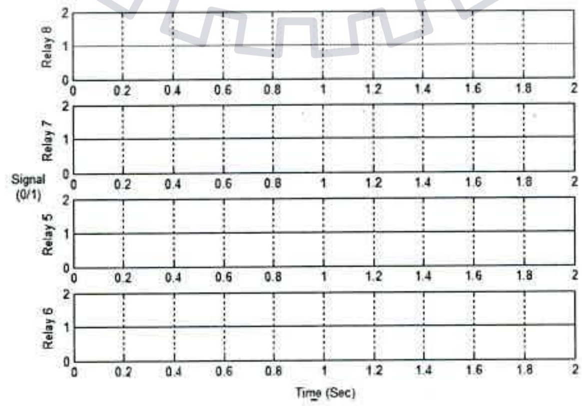


Fig. 6.6 Simulation results for Case-I: output of relay blocks connected to scope 2.

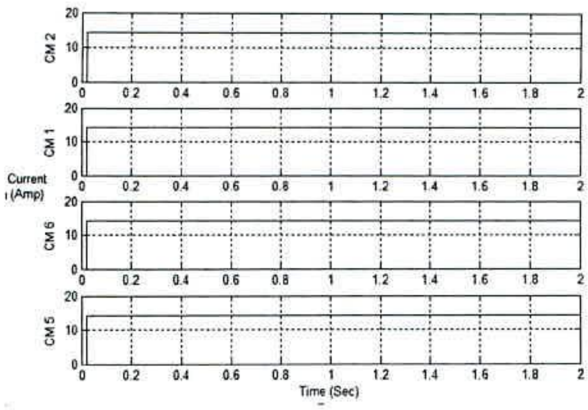


Fig. 6.7 Simulation results for Case-I: branch currents connected to scope 3.

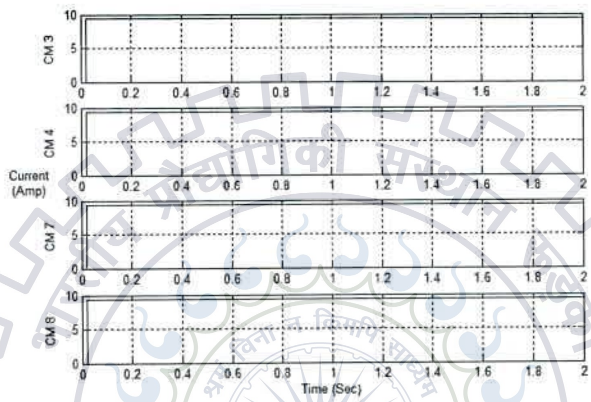


Fig. 6.8 Simulation results for Case-I: branch currents connected to scope 4.

- Case-II (Occurrence of fault 1)

Fault 1 is connected to line 1 in this case. Transition time in its properties is adjusted such that it occurs at 1 sec. The relays which have to be tripped for this fault will send a '0' signal to its corresponding CB, i.e. all the relays send signal '1' initially and the signal changes to '0' if they trip for the particular fault. The CB which receives signal '1' will get opened and fault current reduces to zero at the same instant. For this case the simulation results from scopes 1 to 4 have been given in following Figures, i.e. Fig. 6.9 to Fig. 6.12 respectively. It can be observed in Fig. 6.9 that the primary relays 1 & 2 are only tripping but not 3 & 4. No other relays are tripping as per the Fig. 6.10. Normal branch currents flow in healthy lines of the system as per Fig. 6.11. Fault current falls to zero as and when the corresponding relay sends signal '1' which can be observed in Fig. 6.12.

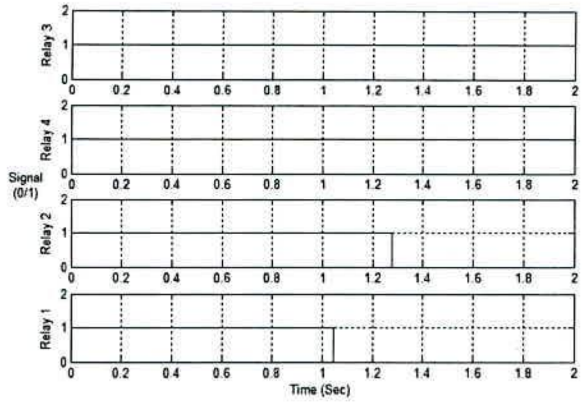


Fig. 6.9 Simulation results for Case-II: output of relay blocks connected to scope 1.

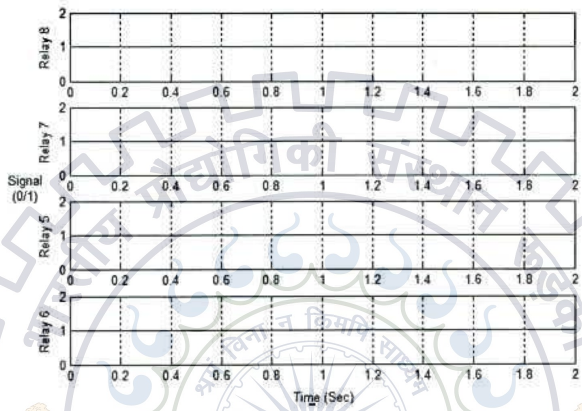


Fig. 6.10 Simulation results for Case-II: output of relay blocks connected to scope 2.

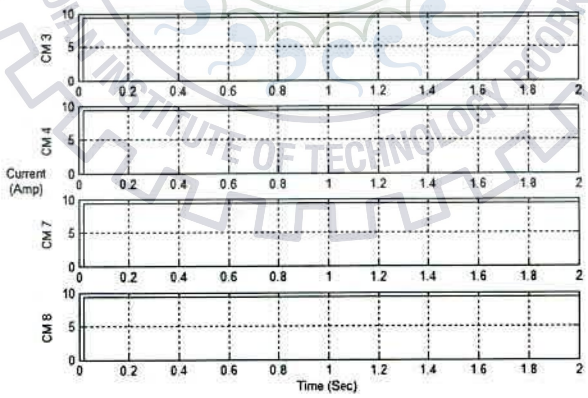


Fig. 6.11 Simulation results for Case-II: branch currents connected to scope 3.

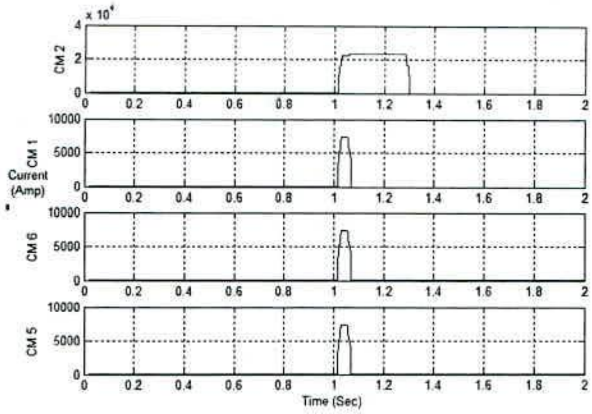


Fig. 6.12 Simulation results for Case-II: branch currents connected to scope 4.

Lines 2 & 4 have not been disturbed with this fault. Scope 3 shows unchanged normal branch current levels in lines 2 & 4 even after the fault 1 occurs at 1 sec. The current levels in lines 1 & 3 are rising at 1 sec, when the fault is occurred and coming to zero when trip signal '0' is sent to CB1 & CB2. This can be observed in scope 4. Scope 1also shows the instant of time when the relays 1 & 2 send the trip signals to the CB1 & CB2 respectively. These instants are nothing but the values we provided as $T_{primary}^{1}$ ,$T_{primary}^{2}$ in their respective MR blocks.

➤ Case-III (fault 1 occurs and Relay 1 fails)

In this case after connecting the fault1 block to the line 1, a continuous signal '1' is given to CB1 instead of output of relay 1 to make the CB remains closed even after fault occurs at 1 sec. The results from scope 1 to 4 have been shown in Fig. 6.13 to Fig. 6.16. This is achieved by removing connection from 'relay' block and connecting 'constant 1' block, from MATLAB library, as a control signal to CB 1 block.

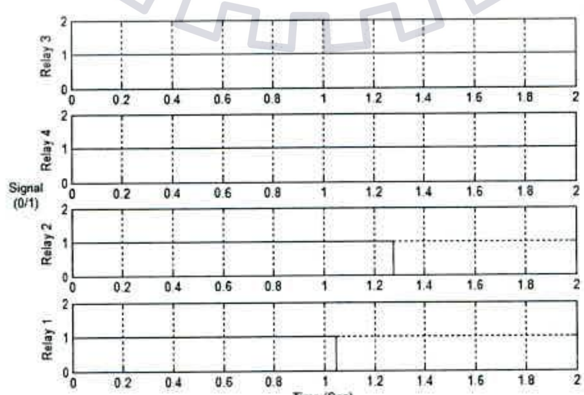


Fig. 6.13 Simulation results for Case-III: output of relay blocks connected to scope 1.

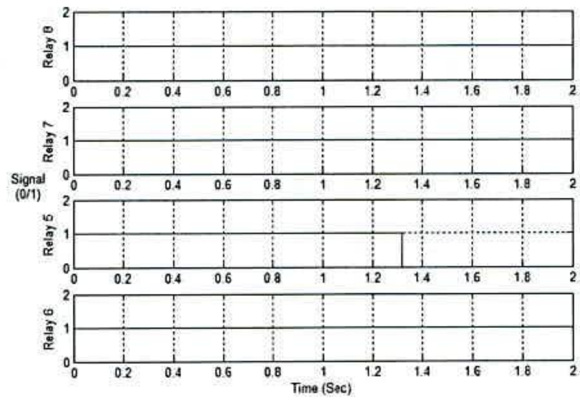


Fig. 6.14 Simulation results for Case-III: output of relay blocks connected to scope 2.

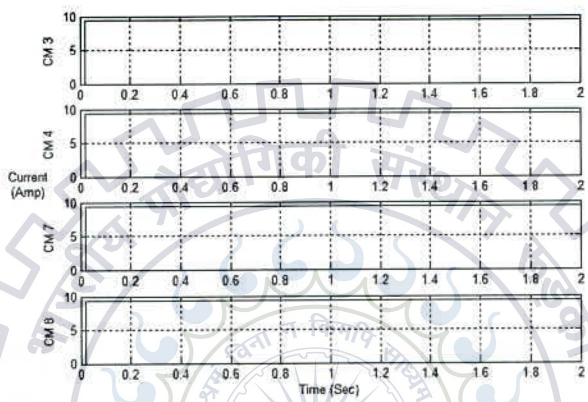


Fig. 6.15 Simulation results for Case-III: branch currents connected to scope 3.

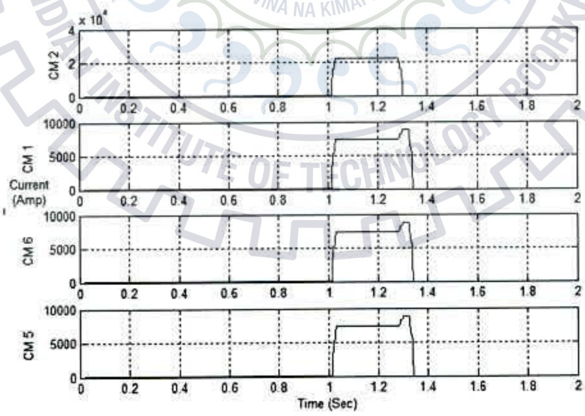


Fig. 6.16 Simulation results for Case-III: branch currents connected to scope 4.

As shown in Fig. 6.13, even though the relay 1 is sending the trip signal, CB1 remains in closed state because of the constant 1 signal given to it. So relay 5 works as a backup relay and gives a trip signal '0' to CB5 as shown in Fig. 6.14. It can be observed that no other relay is tripping. So lines 2 & 4 still works and serves normal loads as shown in Fig. 6.15. Fault currents come to zero as and when CB 5 receives trip signal as shown in Fig. 6.16. This model can be tested for remaining three fault conditions also in the same way.

### *6.5 Conclusion for the chapter:*

The procedure for designing test models using MATLAB/Simulink and testing them for various conditions have been discussed in this chapter. However there are some adjustments made while simulating the models to reduce the complexity. This chapter explains how to achieve coordination of DOCRs using MATLAB.

CHAPTER- 7

# MODIFIED MODEL RELAY AND TEST MODELS

### *7.1 Modified Model Relay:*

Model Relay which has been shown in Fig. 6.1 was later modified as shown in Fig. 7.1 for the sake of development. The mathematical expression for calculating operation time has been incorporated in the relay model itself and hence called modified model relay.

With this modified MR it is possible to calculate operating times within the MATLAB model itself. In this way it reduces the complexity in calculating those operating times for each relays manually. However constructing this type of model itself involves lot of complexity and sometimes leads to confusion.

In this model, 'Go to' and 'From' blocks from MATLAB library have been used to bring the value of current seen by some other relay to the present relay. This is to calculate the backup operation time of the present relay and also to coordinate with its primary relay for a particular fault.

All the mathematical operations like summation, product, division and power have been done using corresponding MATLAB blocks from library. Once after calculating the operation time, it has been sent to 'variable time delay' block to operate when the current exceeds normal over load current (200 Amp in this particular example Figure).

Now this modified MR is able to calculate operation time of its own when a fault occurs and sends signal '0' to its corresponding CB with that time delay.

### *7.2 Modified 4-bus test model:*

4-bus test model that has been shown in Fig. 6.4 has been modified as shown in Fig. 7.2. The block 'Π section model' has been inserted between each line to get the effect of long line. So now the test model turned into a long line model hence named modified test model.

This avails us the possibility to check for two fault conditions on each line, i.e. close-in fault and far-end fault. This can be achieved by connecting the 'fault' block at the both ends of 'Π section model' respectively. This model has also been well coordinated using MRs and checked for the all possible fault conditions.

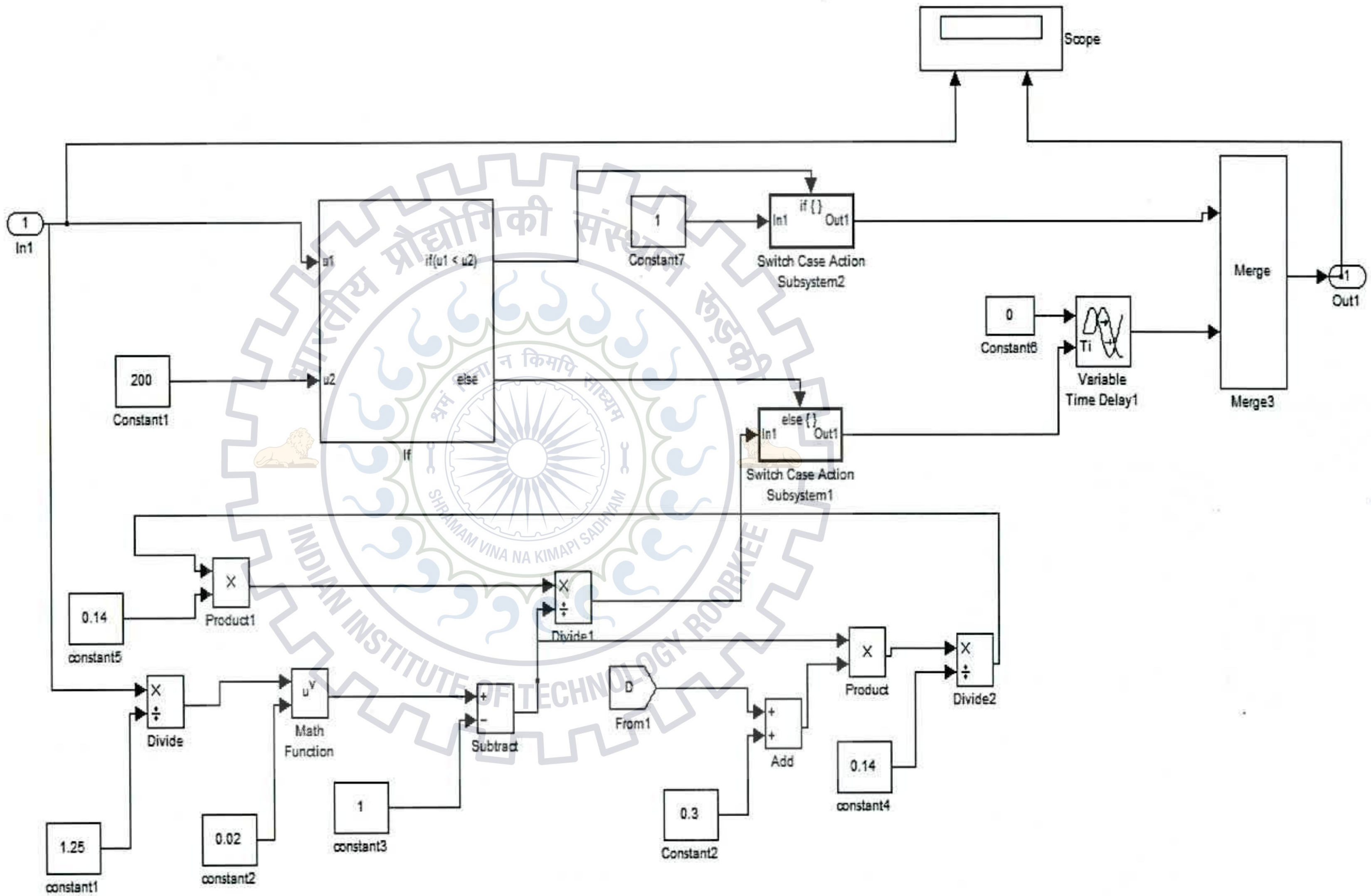


Fig. 7.1 Modified MR

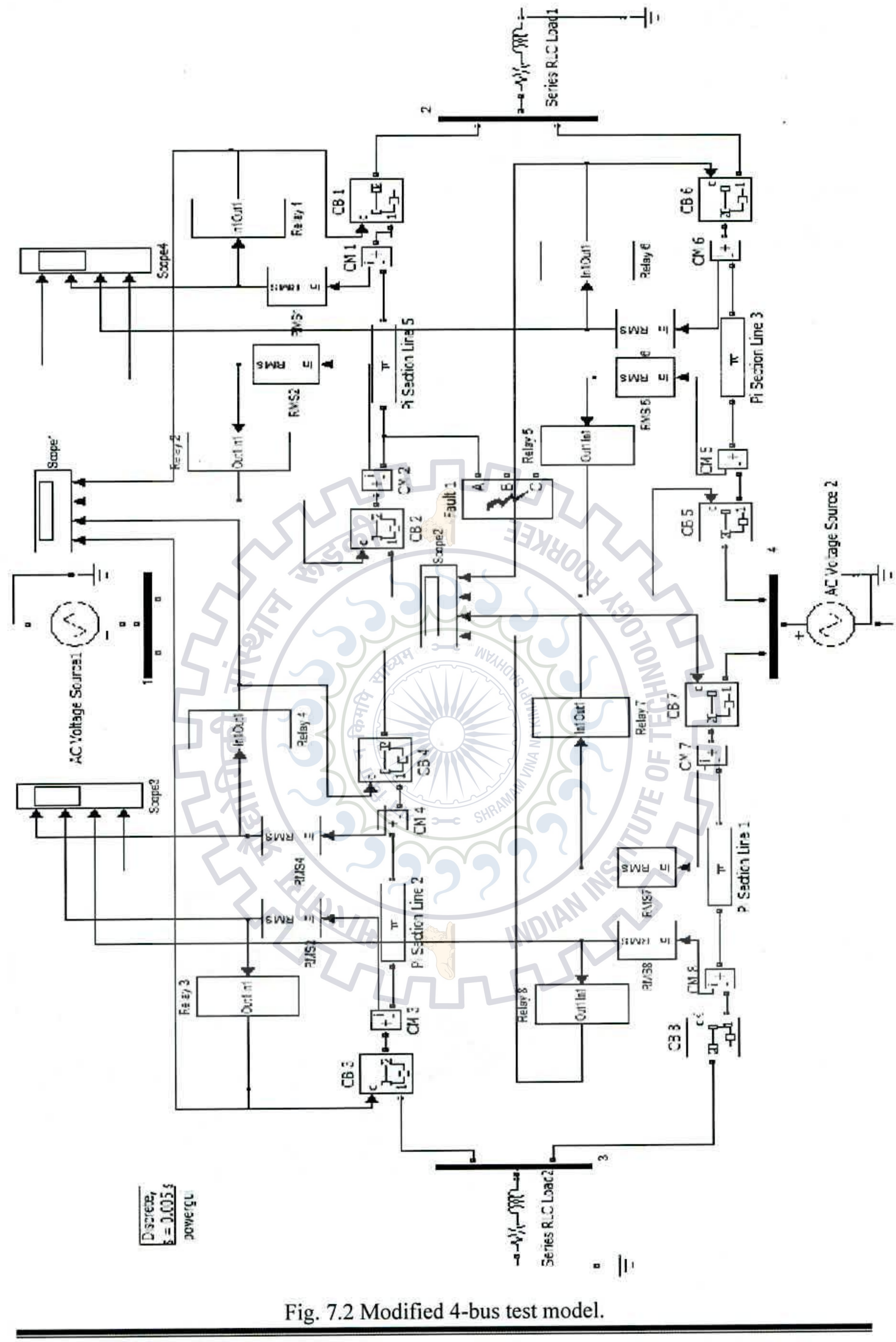


Fig. 7.2 Modified 4-bus test model.

CHAPTER-8

# COORDINATION OF DOCRs FOR AN EXISTING POWER NETWORK

### *8.1 Introduction:*

The data of an existing power network has been collected from APTRANSCO. Using that data a model has been made in MATLAB and used as a test model for present study. MRs have been incorporated at both ends of each line. Operating times for various fault occurring chances have been calculated using MS Excel. Then those values have been inserted in their particular MR and run the model to check whether those are coordinated well or not. No sympathy trips have been occurred. This chapter explains the procedure to construct a model in MATLAB for any existing power network and also explains the step by step procedure to coordinate all the DOCRs of that network without giving scope for sympathy trips.

### *8.2 Collected data of the existing power network:*

The test model for the present study is that of an existing 132kv power network located in Andhra Pradesh which is shown in Fig. 8.1. It consists of 6 substations in a ring and 4 other substations connected to a particular substation, thus 10 in total, which are considered as 10 buses in the MATLAB model constructed. Length of lines and individual load values has been collected and made the test model accordingly.

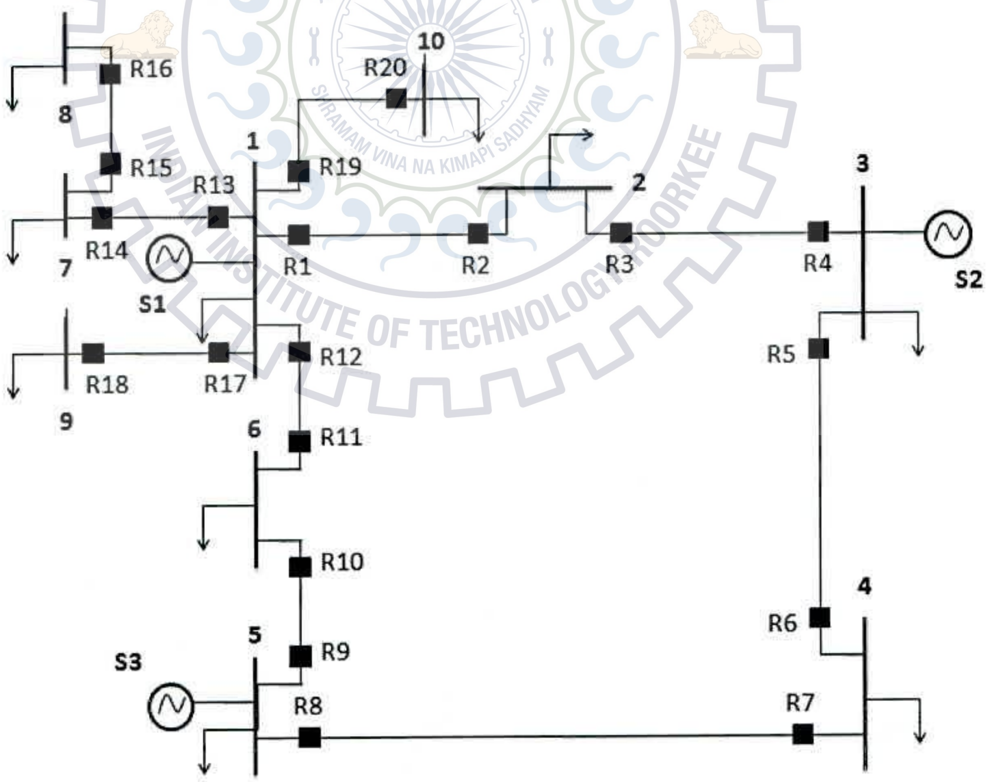


Fig. 8.1 Existing power network i.e. test model.

The data has been tabulated as given below. Table 8.1 consists of local load details in MWs and MVARs, i.e. Real and Reactive powers separately for each and every bus. Table 8.2 consists of the details of length of lines between the pairs of buses which are connected.

TABLE 8.1

LOCAL LOAD VALUES FOR ALL BUSES

| Bus No. | Local load | |
|---|---|---|
| | MW | MVAR |
| 1 | 168.58 | 61.18 |
| 2 | 10 | 3.62 |
| 3 | 71 | 32.34 |
| 4 | 54.5 | 21.5 |
| 5 | 150 | 60 |
| 6 | 41 | 14.88 |
| 7 | 28.8 | 10.45 |
| 8 | 24 | 8.71 |
| 9 | 23 | 8.5 |
| 10 | 14.4 | 5.23 |

TABLE 8.2

LENGTH OF LINES BETWEEN THE BUSES WHICH ARE CONNECTED

| Bus No. | | Length of line (Kms) |
|---|---|---|
| from | to | |
| 1 | 2 | 65.77 |
| 2 | 3 | 15.41 |
| 3 | 4 | 48 |
| 4 | 5 | 27 |
| 5 | 6 | 58.1 |
| 6 | 1 | 61.02 |
| 1 | 7 | 29.3 |
| 7 | 8 | 54 |
| 1 | 9 | 34.5 |
| 1 | 10 | 27.8 |

Per kilo meter values of line parameters have been calculated for 132 Kv line from skin effect, GMR and GMD calculations which are given below.

Resistance R = 0.2224 ohms/Km

Inductive Reactance L = 0.476 mH/Km

Capacitive Reactance C = 0.024 μF/Km

### *8.3 MATLAB model for the test model:*

The test model i.e. existing power network has been constructed in MATLAB using simlink. The data given above has been inserted in each block of the model. Relay and its corresponding Circuit Breaker (CB) and Current Measurement (CM) blocks, which are at one side of the pi section block, have been made as a subsystem to make it look simple. Therefore, there are two such subsystems for each line having pi section block in the middle for each transmission line. These subsystems are named as 'CB & Relay system' and numbered from 1 to 20. i.e. total 20 such sub systems. This relay is again a subsystem and is said to be MR, which has been explained in chapter 6. The test model has been shown in Fig. 8.1 and its MATLAB model has been shown in Fig. 8.3. Per Km values of R, L and C have been given as perameters for the pi section block shown in Fig. 8.2.

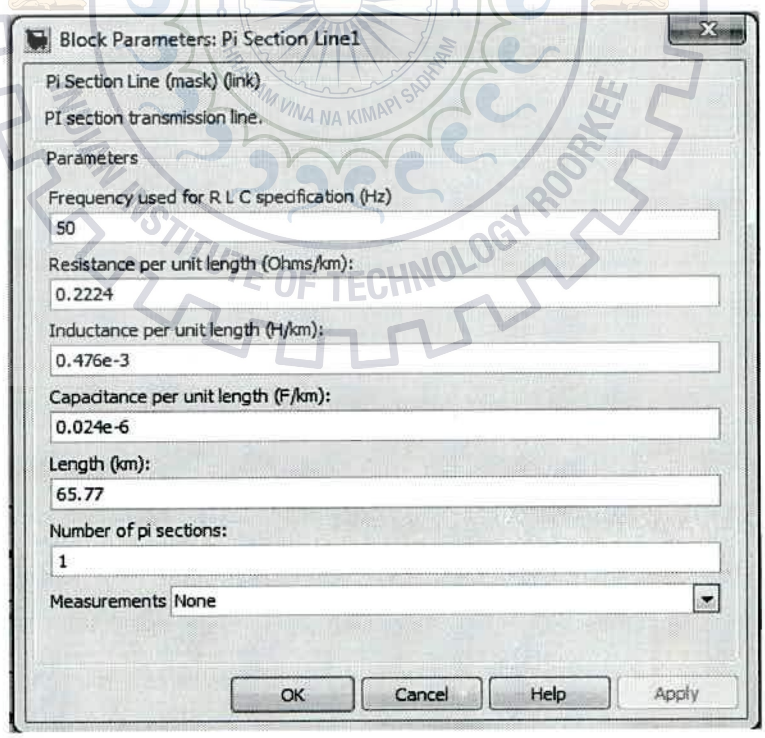


Fig. 8.2 Pi Section line parameters

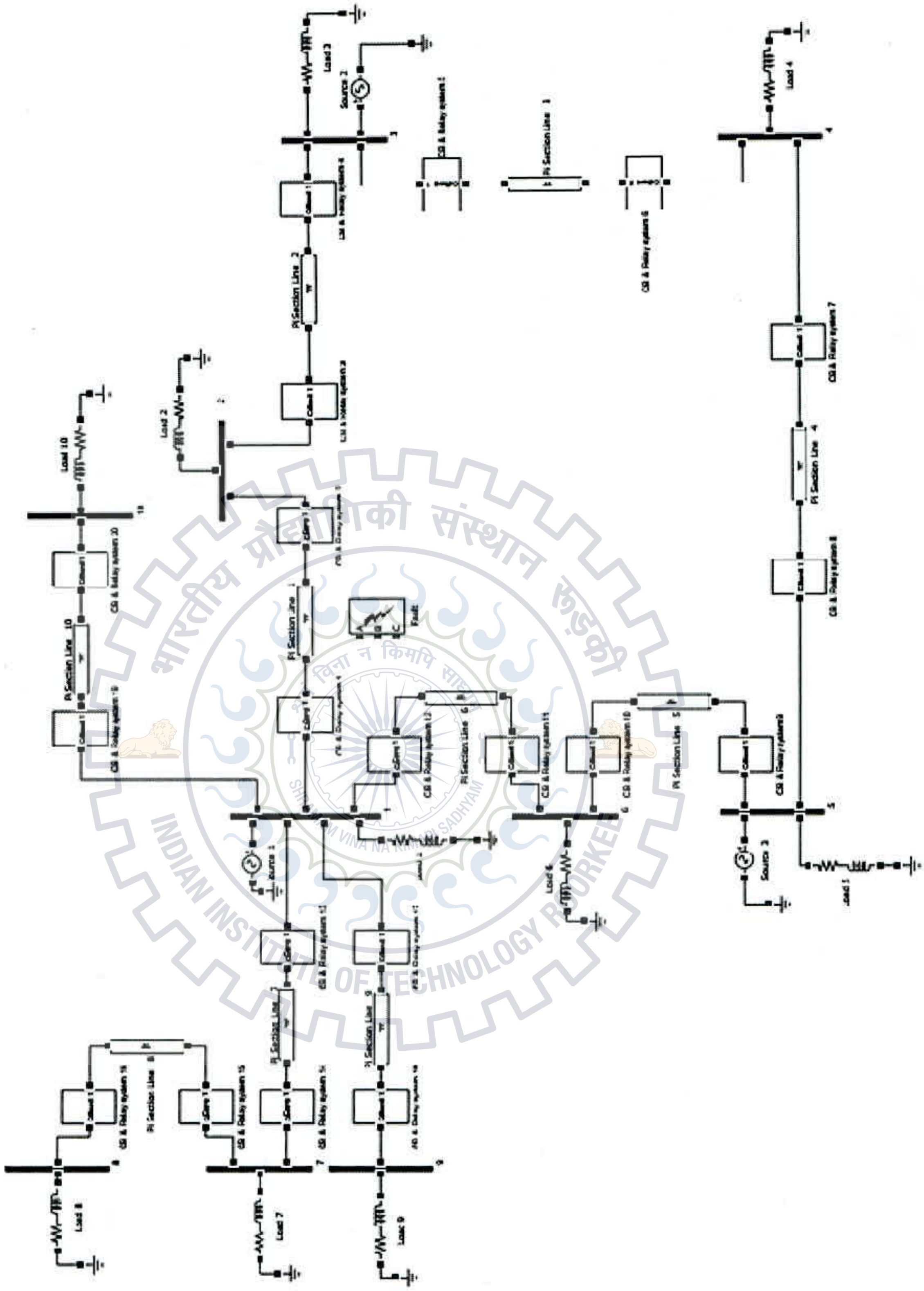

Fig. 8.3 MATLAB model for test model

### *8.4 Fault current values:*

Before designing the MRs, the fault current levels in all transmission lines should be known for each and every fault occurring possibility. This can be done by connecting 'fault' block on both the ends of lines, i.e. on both sides of the 'pi section model' block. This will avail us the facility to check for the close in and far end fault conditions. As discussed earlier, if the fault is connected at one end of the pi section model, it will be close in fault for the relay nearer to that location and far end fault for the relay on the other side. Current levels sensed by relays 1 to 20 have been tabulated in Table. 8.3 by connecting the faults on both ends. There is a ring main system of 6 buses in the test model in which 6 transmission lines are there. So, for those 6 lines, 12 no. of conditions can be created for fault occurrences.

TABLE 8.3

CURRENT LEVELS WHEN CONNECTED FAULTS ON BOTH ENDS OF EACH LINE

| Lines -> | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Relay | Current (Amp) | | Current (Amp) | | Current (Amp) | | Current (Amp) | | Current (Amp) | | Current (Amp) | |
| | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| 1 | 8E+06 | 4827 | 4823 | 3253 | 42 | 42 | 42 | 42 | 42 | 42 | 42 | 42 |
| 2 | 3250 | 20575 | 4842 | 3279 | 33 | 33 | 33 | 33 | 33 | 33 | 33 | 33 |
| 3 | 3295 | 20577 | 4842 | 3261 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 |
| 4 | 3285 | 20572 | 20642 | 8E+06 | 47 | 47 | 47 | 47 | 47 | 47 | 47 | 47 |
| 5 | 101 | 101 | 101 | 101 | 8E+06 | 6625 | 6617 | 3570 | 101 | 101 | 101 | 101 |
| 6 | 112 | 112 | 112 | 112 | 3462 | 11770 | 6631 | 3590 | 112 | 112 | 112 | 112 |
| 7 | 186 | 186 | 186 | 186 | 3664 | 11772 | 6631 | 3456 | 186 | 186 | 186 | 186 |
| 8 | 191 | 191 | 191 | 191 | 3652 | 11765 | 11780 | 8E+06 | 191 | 191 | 191 | 191 |
| 9 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 8E+06 | 5464 | 5460 | 4193 |
| 10 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 4176 | 62700 | 5476 | 4215 |
| 11 | 199 | 199 | 199 | 199 | 199 | 199 | 199 | 199 | 4379 | 62710 | 5476 | 4164 |
| 12 | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 210 | 4376 | 62706 | 63360 | 8E+06 |
| 13 | 268 | 268 | 268 | 268 | 268 | 268 | 268 | 268 | 268 | 268 | 268 | 268 |
| 14 | 271 | 271 | 271 | 271 | 271 | 271 | 271 | 271 | 271 | 271 | 271 | 271 |
| 15 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 | 127 |
| 16 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 |
| 17 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 | 126 |
| 18 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 | 130 |
| 19 | 74 | 74 | 74 | 74 | 74 | 74 | 74 | 74 | 74 | 74 | 74 | 74 |
| 20 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 | 79 |

The fault current levels have been tabulated again in Table. 8.4 and Table. 8.5 for increasing clarity in understanding them according to the problem formulation of DOCRs as discussed in chapter 4. These two tables are prepared as per the concepts of close in & far end fault currents and primary and back up fault current levels respectively.

TABLE 8.4

VALUES OF $I_f$ WITH $T^i_{pri\_cl\_in}$ AND $T^j_{pri\_far\_bus}$

| TDS (for the Relay) | $T^i_{pri\_cl\_in}$ | $T^j_{pri\_far\_bus}$ |
|---|---|---|
| | $I_f$ | $I_f$ |
| TDS1 | 7750000 | 4827 |
| TDS2 | 20575 | 3250 |
| TDS3 | 4842 | 3261 |
| TDS4 | 7778000 | 20642 |
| TDS5 | 7778000 | 6625 |
| TDS6 | 11770 | 3462 |
| TDS7 | 6631 | 3456 |
| TDS8 | 7777700 | 11780 |
| TDS9 | 7777600 | 5464 |
| TDS10 | 62700 | 4176 |
| TDS11 | 5476 | 4164 |
| TDS12 | 7777700 | 63360 |

TABLE 8.5

VALUES OF I F WITH $T^x_{BACKUP}$ AND $T^Y_{PRIMARY}$

| | $T^x_{backup}$ | | $T^y_{primary}$ |
|---|---|---|---|
| Relay | I f | Relay | I f |
| 4 | 3285 | 2 | 3250 |
| 1 | 4823 | 3 | 4842 |
| 8 | 3652 | 6 | 3462 |
| 5 | 6617 | 7 | 6631 |
| 12 | 4376 | 10 | 4176 |
| 9 | 5460 | 11 | 5476 |
| 4 | 20572 | 2 | 20575 |
| 1 | 3253 | 3 | 3261 |
| 8 | 11765 | 6 | 11770 |
| 5 | 3570 | 7 | 3456 |
| 12 | 62706 | 10 | 62700 |
| 9 | 4193 | 11 | 4164 |

## *8.5 Designing of MRs:*

As said before each subsystem i.e. CB & Relay system is having one relay and one CB which is shown in Fig. 8.4. Again the relay itself is a subsystem which is described as Model Relay (MR) in chapter 6. It has also been shown in Fig. 6.1. Here in this chapter this MR has been slightly modified according to the requirements of present test model.

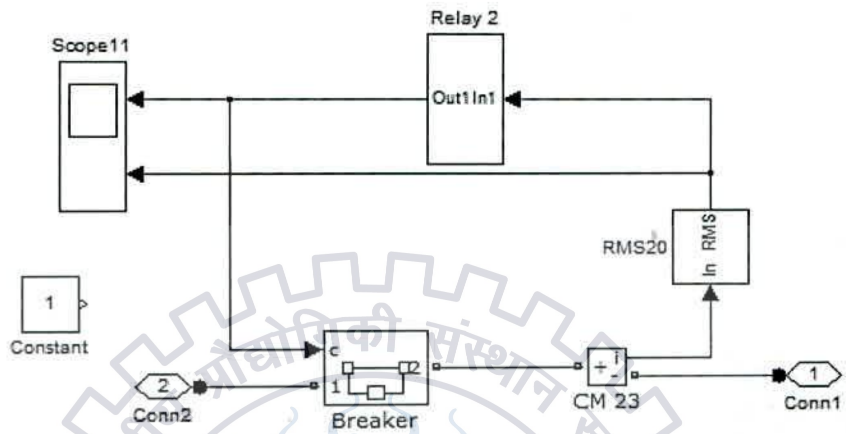


Fig. 8.4 CB & Relay system

The procedure for constructing MRs of CB & Relay system 1 to CB & Relay system 4 has been explained as follows.

### 8.5.1 MR of CB & Relay system 1 (MR1):

Any relay should operate for the fault on its own line and should not be tripped for the faults on the other lines unless it is the backup relay for that particular fault. As per the fault current values given in Table 8.3, MR1 should operate as a primary relay for the fault current values of 8 MA and 4827 A and it should operate as a backup relay for MR3 when a fault occurs on line 2 i.e. it should be tripped for the fault current values of 4823 A and 3253 A with a CTI of 0.3 sec with MR3. To implement all these logics, the condition that should be given in the 'If' block has to be given as shown in Fig. 8.5. When $u1 < u3$, i.e. current seen by the relay (i) is less than normal over load current, MR1 will send signal '1' to its corresponding CB. When $u1 > u2$, i.e. i is greater than minimum fault current level for primary operation, MR1 will send signal '0' with a lesser time of operation, i.e. 0.165 sec in this case. Otherwise it will operate as a backup relay for MR3 and sends signal '0' with a time delay of 0.338 sec.

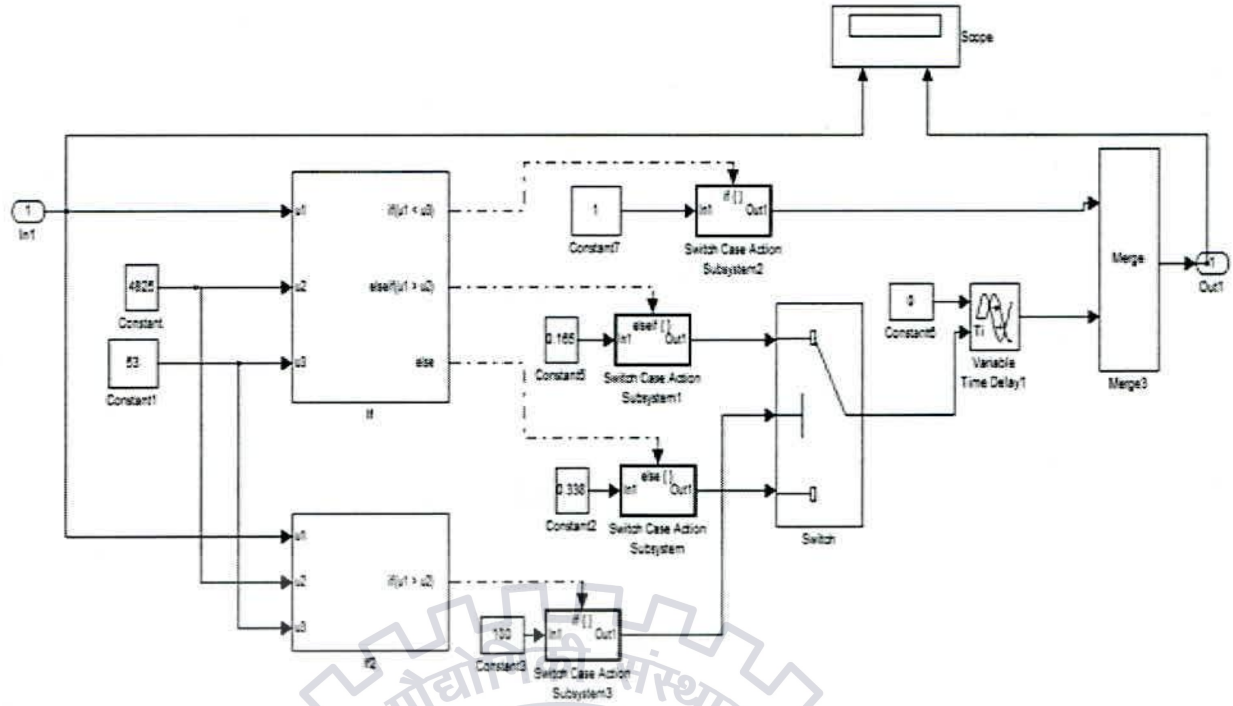


Fig. 8.5 MR1

### 8.5.2 MR of CB & Relay system 2 (MR2):

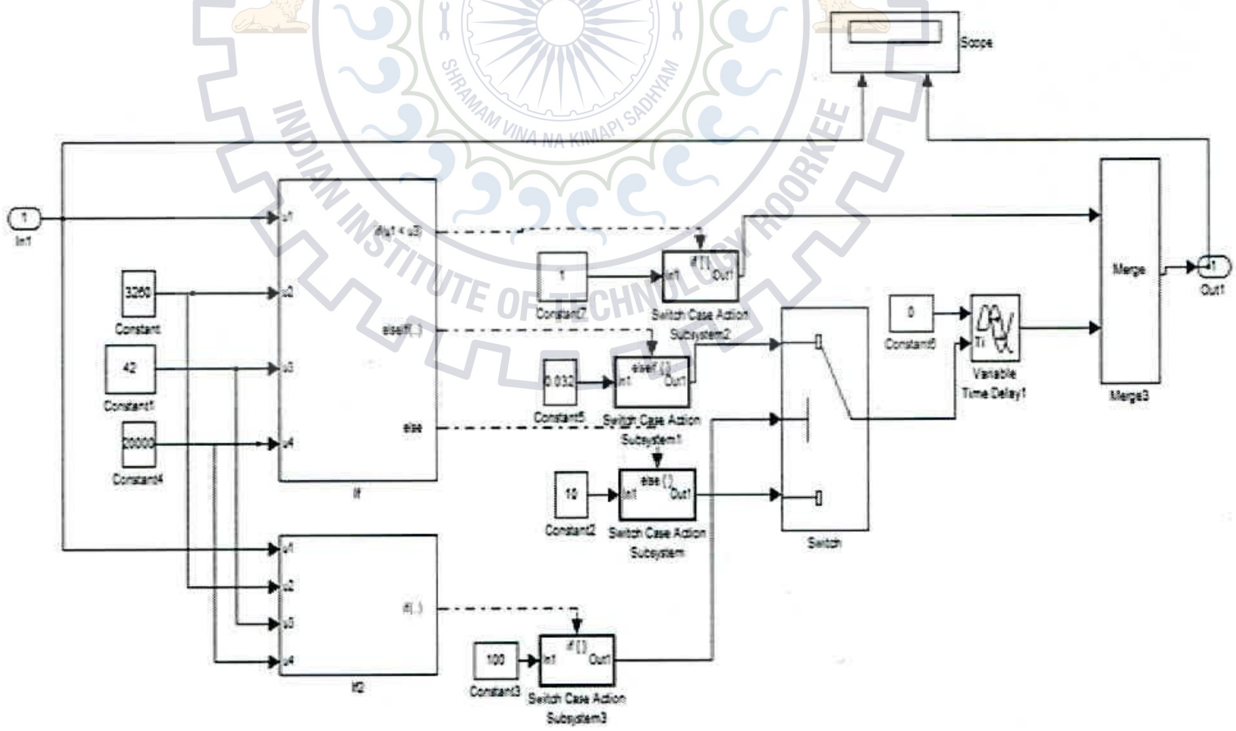


Fig. 8.6 MR2

As per the fault current values given in Table 8.3, MR2 should operate as a primary relay for the fault current values of 3250 A and 20575 A and it should not operate as a backup relay when a fault occurs on line 2 i.e. it should not be tripped for the fault current values of 4842 A and 3279 A. to implement this logic 'If' block of the MR2 should be designed as shown in Fig. 8.6.

The else-if condition for this MR2 is 'u3 < u1 < u2 | u1 > u4' and this logic can be inserted in the 'if' block as shown in Fig. 8.7. the symbol '|' is used to obtain the logic operation 'OR'.

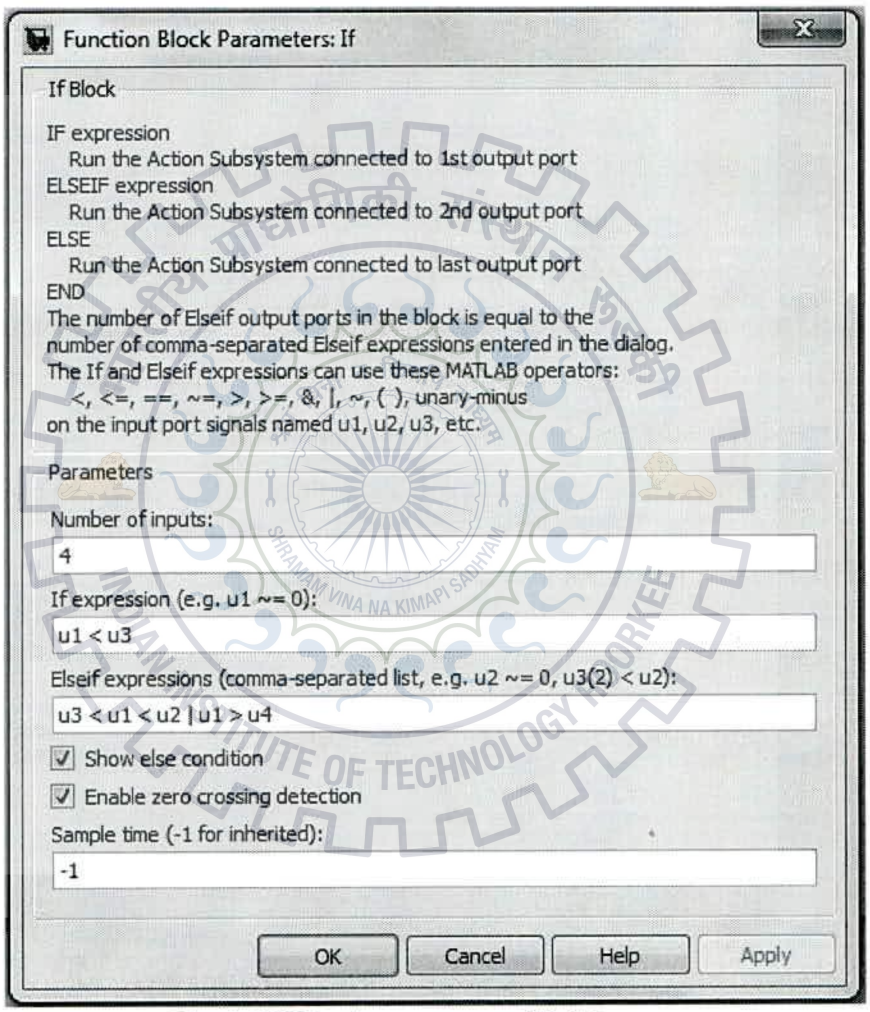

Fig. 8.7 If block parameters of MR2

### 8.5.3 MR of CB & Relay system 3 (MR3):

As per the fault current values given in Table 8.3, MR3 should operate as a primary relay for the fault current values of 4842 A and 3261 A and it should not operate as a backup relay when a fault occurs on line 1 i.e. it should not be tripped for the fault current values of 3295 A and 20577 A. To implement this logic of MR3 should be designed as shown in Fig. 8.8.

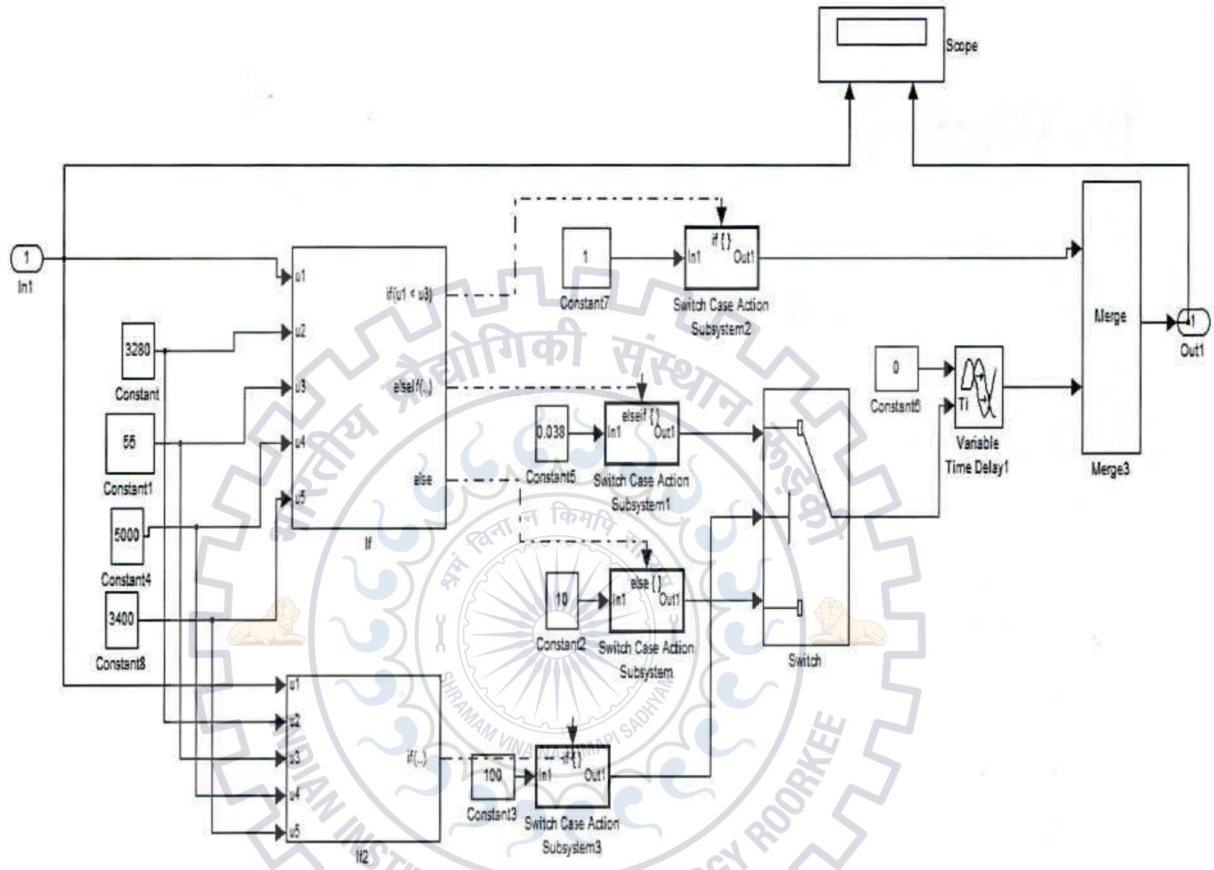


Fig. 8.8 MR3

The logic given to 'If' block is somewhat complicated when compared to other MRs because of the closeness between the values of fault current levels. It should operate for 3261A but should not operate for 3295 A and again it should operate for 4842. So there have been given five no. of current levels as inputs for the 'If' block. So the else-if condition for this MR3 is 'u3 < u1 < u2 | u4 > u1 > u5' and this logic can be inserted in the 'if' block as shown in Fig. 8.9.

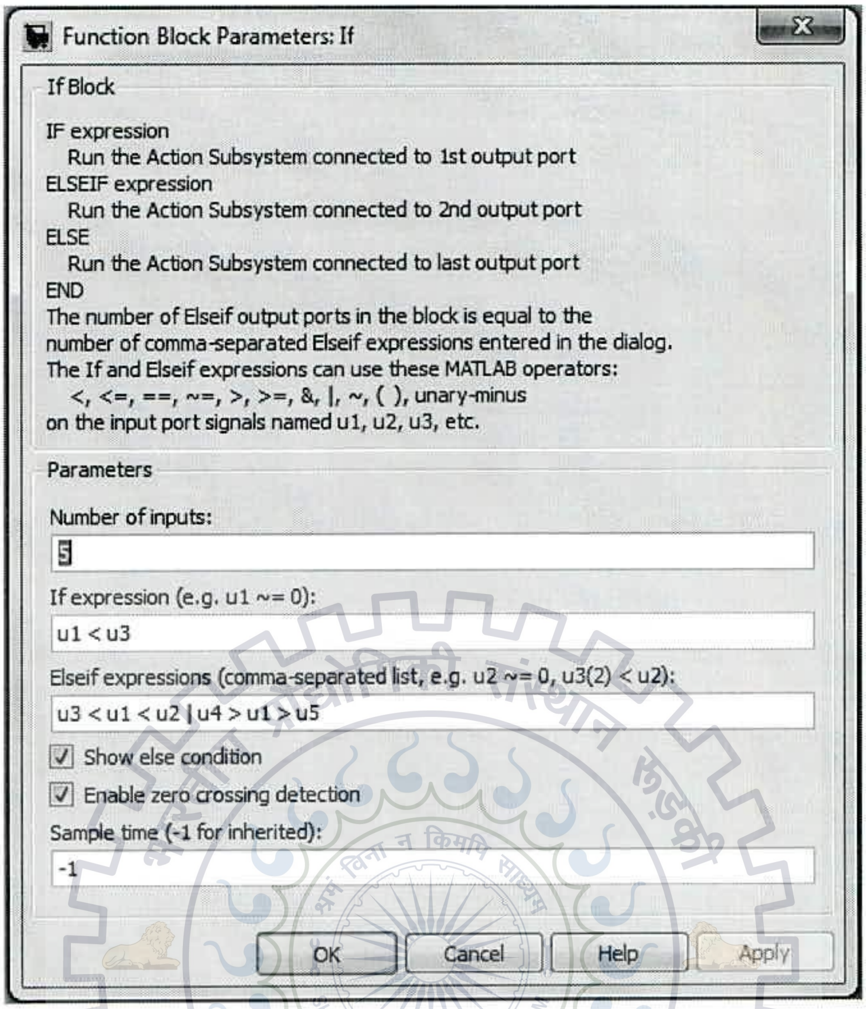


Fig. 8.9 If block parameters of MR3

### 8.5.4 MR of CB & Relay system 4 (MR4):

As per the fault current values given in Table 8.3, MR4 should operate as a primary relay for the fault current values of 20642 A and 8 MA and it should operate as a backup relay for MR2 when a fault occurs on line 1 i.e. it should be tripped for the fault current values of 3285 A and 20572 A with a CTI of 0.3 sec with MR2. To implement all these logics, the condition that should be given in the 'If' block of MR4, has to be given same as that of MR1. Even thought the logic is same as that of MR1 the operating times are different for this MR4.

Calculation procedure for the operating times for the relays in the ring main system i.e. from 1 to 12 has been explained in subsection 8.6.

### *8.6 Operating times and Objective function:*

As explained in Chapter 4, the optimization problem for coordination of DOCRs is to minimize the objective function F. F is nothing but the summation of all primary operating times of all the relays of a particular system. Calculating these values has already been explained in Chapter 5. Here in Table 8.6 and Table 8.7, primary and backup operating time calculations, which are done in MS Excel, have been given for close in and far end faults respectively. PS has been assumed as constant i.e. 1.25 for all the relays.

TABLE 8.6

VALUES OF PRIMARY AND BACKUP OPERATING TIMES FOR CLOSE IN FAULTS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| tds2 | 0.05 | tds3 | 0.05 | tds6 | 0.05 | tds7 | 0.05 | tds10 | 0.05 | tds11 | 0.05 |
| **tp2** | **0.033** | **tp3** | **0.039** | **tp6** | **0.035** | **tp7** | **0.037** | **tp10** | **0.029** | **tp11** | **0.038** |
| tb4 | 0.333 | tb1 | 0.339 | tb8 | 0.335 | tb5 | 0.337 | tb12 | 0.329 | tb9 | 0.338 |
| tds4 | 0.509 | tds1 | 0.435 | tds8 | 0.480 | tds5 | 0.451 | tds12 | 0.568 | tds9 | 0.441 |
| **tp4** | **0.194** | **tp1** | **0.166** | **tp8** | **0.183** | **tp5** | **0.172** | **tp12** | **0.216** | **tp9** | **0.168** |

TABLE 8.7

VALUES OF PRIMARY AND BACKUP OPERATING TIMES FOR FAR END FAULTS

| | |
|---|---|
| **tp1** | 0.339 |
| **tp2** | 0.041 |
| **tp3** | 0.041 |
| **tp4** | 0.333 |
| **tp5** | 0.337 |
| **tp6** | 0.041 |
| **tp7** | 0.041 |
| **tp8** | 0.335 |
| **tp9** | 0.01 |
| **tp10** | 0.01 |
| **tp11** | 0.040 |
| **tp12** | 0.329 |

$$\sum_{i=1}^{N_{cl}} T^{i}_{pri\_cl\_in} = 1.31$$

$$\sum_{j=1}^{N_{far}} T^{j}_{pri\_far\_bus} = 1.895,$$ Then the value of objective function F = 3.2

This value can be further minimized if we use optimization algorithms as discussed earlier by considering both TDS and PS as unknowns.

### *8.7 Normal load currents:*

When system is operating without any fault, every branch will serve normal load currents to the loads connected on the bus at the end of the line. From the scopes connected in every 'CB relay system' these values can be observed in Figures from Fig. 8.10. to Fig. 8.21.

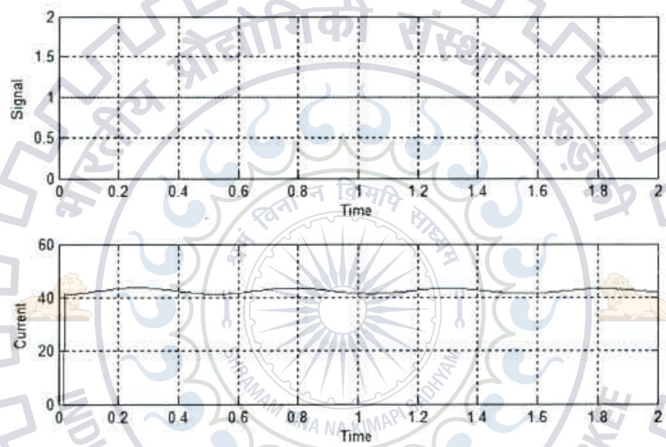


Fig. 8.10 Normal load current seen by MR1

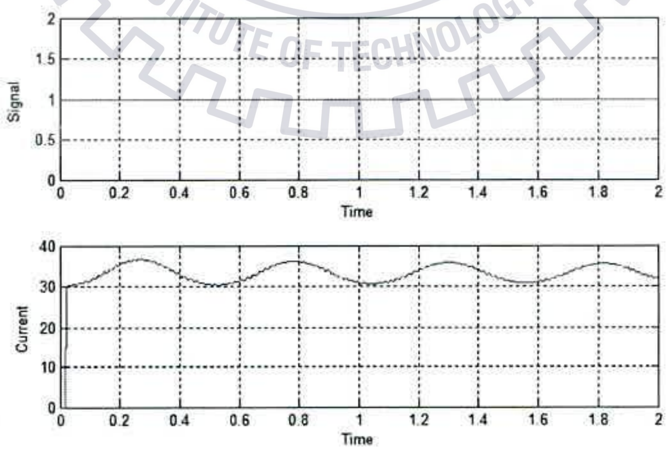


Fig. 8.11 Normal load current seen by MR2

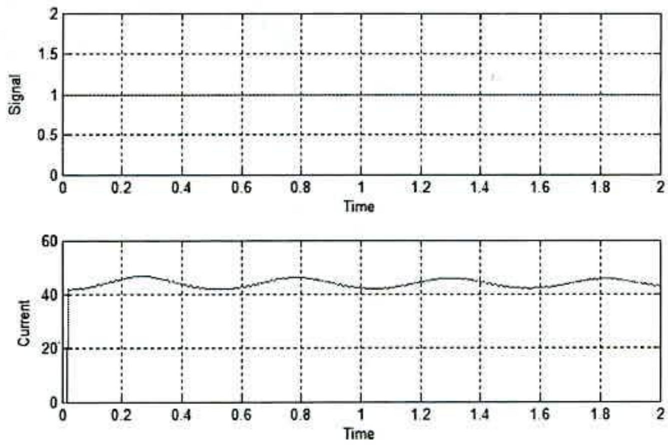


Fig. 8.12 Normal load current seen by MR3

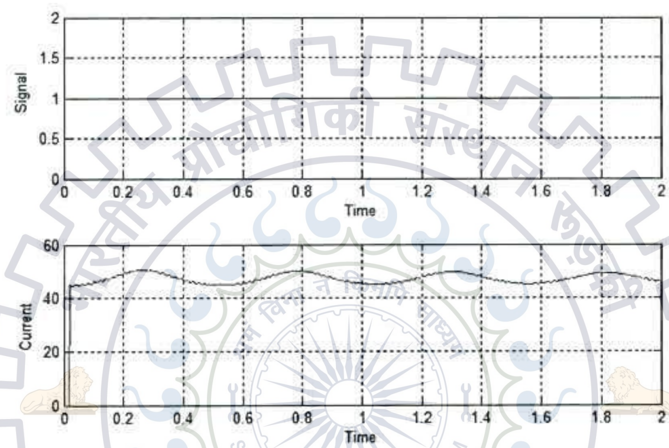


Fig. 8.13 Normal load current seen by MR4

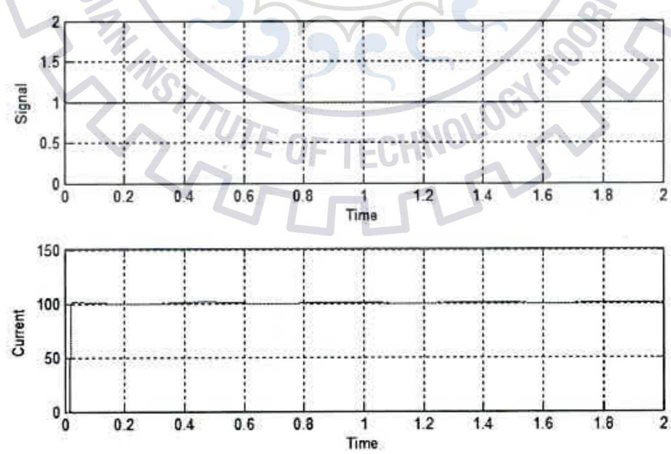


Fig. 8.14 Normal load current seen by MR5

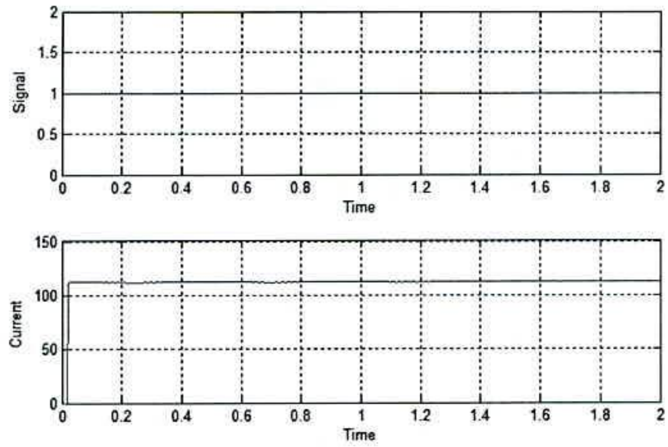


Fig. 8.15 Normal load current seen by MR6

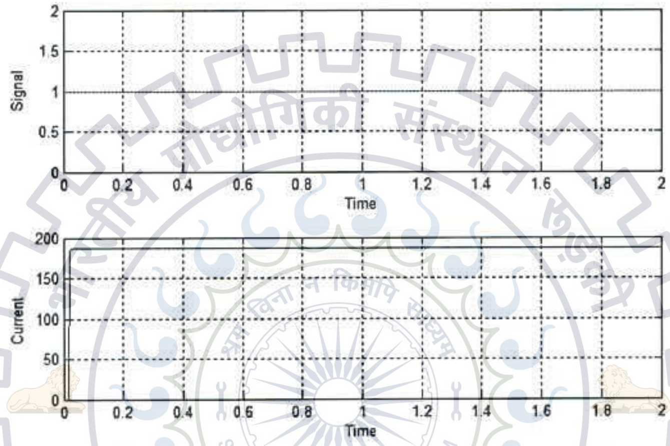


Fig. 8.16 Normal load current seen by MR7

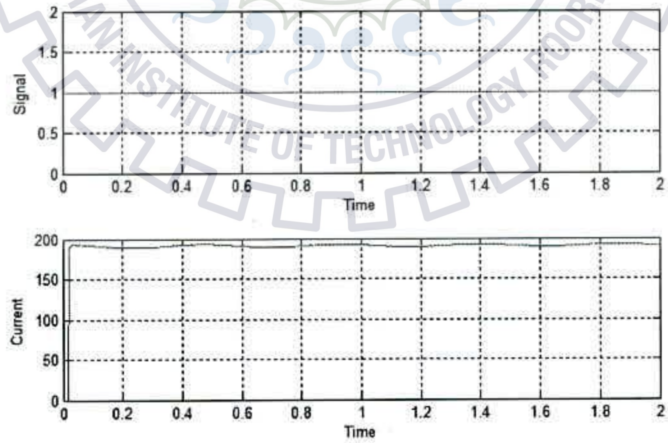


Fig. 8.17 Normal load current seen by MR8

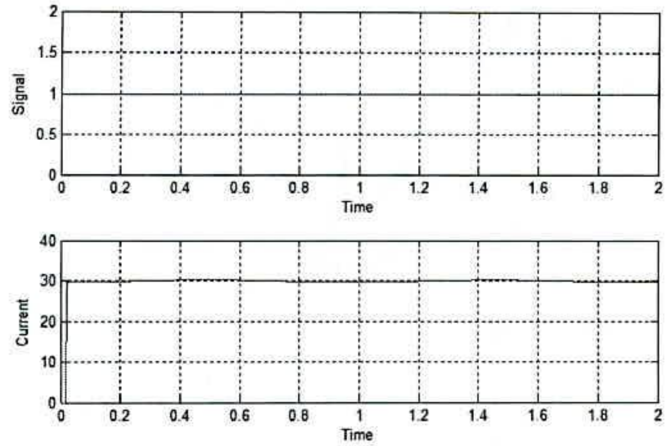


Fig. 8.18 Normal load current seen by MR9

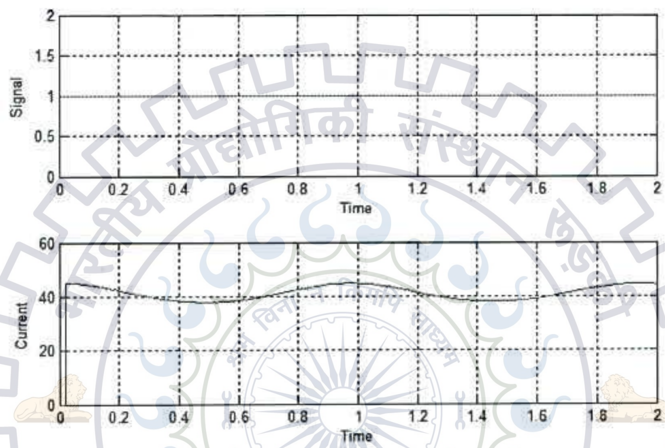


Fig. 8.19 Normal load current seen by MR10

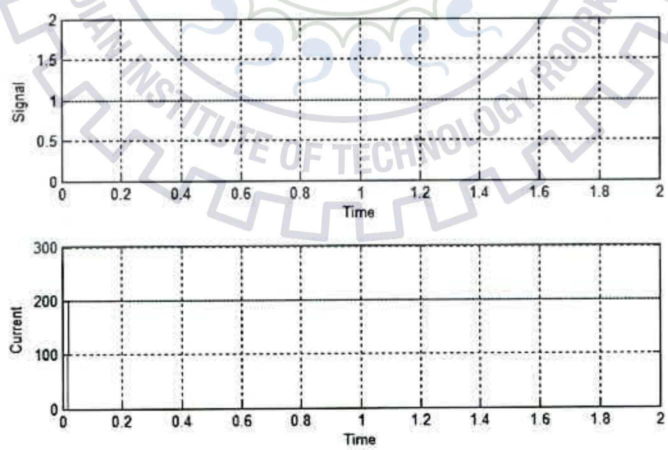


Fig. 8.20 Normal load current seen by MR11

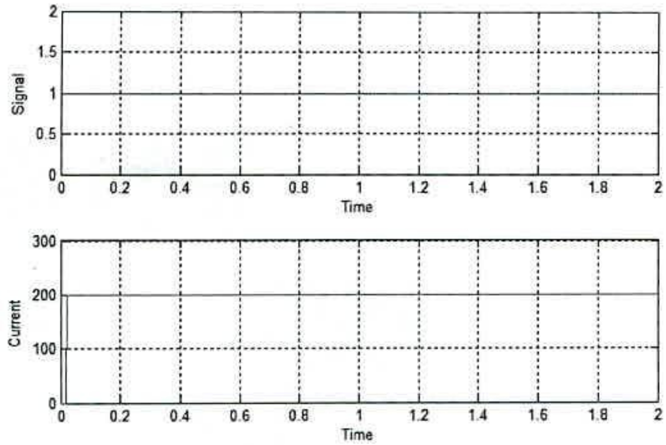


Fig. 8.21 Normal load current seen by MR12

As per these normal load currents, normal over load currents should be calculated (1.25 times the normal load current) and should be given as u3 in the 'if' block of each MR. It can also be observed from all the above Figures that the signal sent by all MRs under no fault condition is '1' only.

## *8.8 Fault analysis:*

Some of the fault occurring chances have been discussed in this subsection. There could be a total of 12 locations in the ring main system in which if fault occurs it could be a close in fault for some relay and causes high fault current. Here in this subsection, 4 such locations have been discussed in 6 different cases.

### 8.8.1 Case I (Close in fault for MR1)

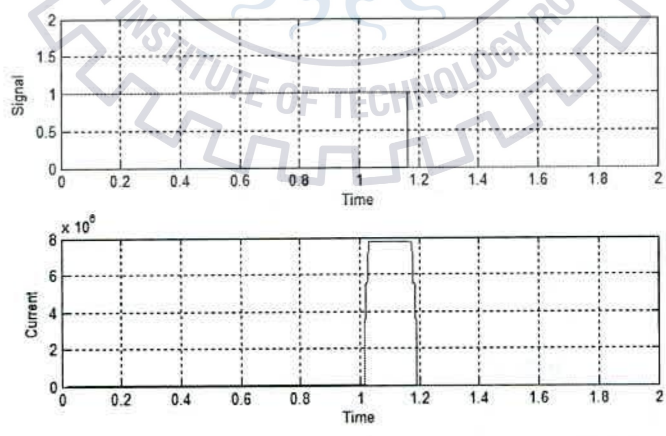


Fig. 8.22 Scope connected in MR1 in case I

When a close in fault occurs for MR1, it operates as a primary relay along with MR2. It can be observed from Fig. 22 and Fig. 23 that MR1 and MR2 are giving trip signals as per their primary operating times.

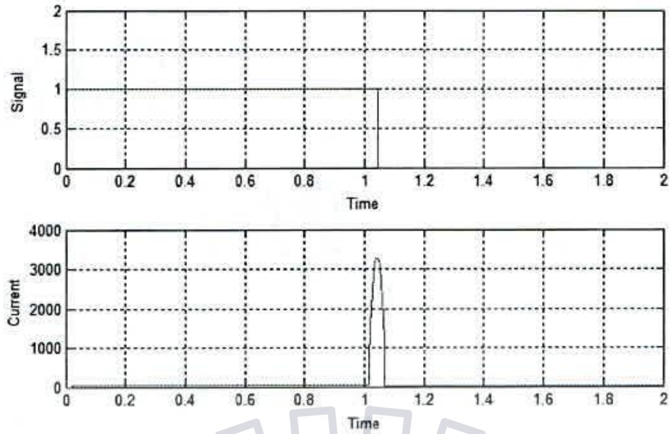


Fig. 8.23 Scope connected in MR2 in case I

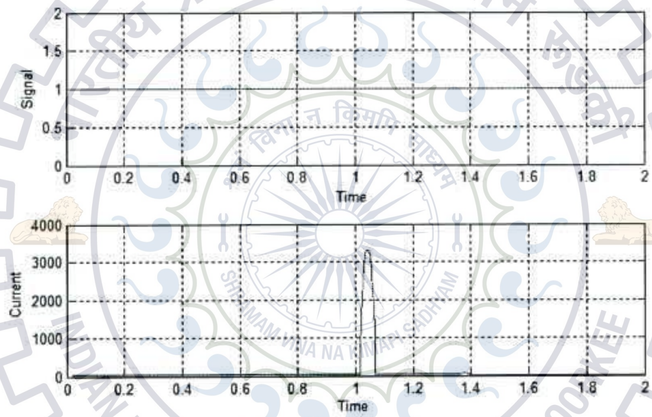


Fig. 8.24 Scope connected in MR3 in case I

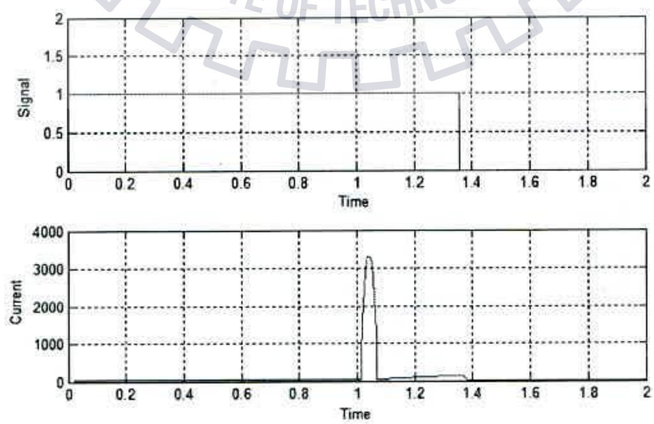


Fig. 8.25 Scope connected in MR4 in case I

As per the Table 8.3, in this case, fault currents will also been seen by MR3 and MR4. Remaining MRs will see normal load current only. But MR3 and MR4 should not be tripped for this fault instantaneously and MR3 should operate as a backup relay such that it would operate only when MR1 failed to operate. But as shown in Fig. 8.26, MR4 sends trip signal because the fault current is reduced but still above MR4's normal overload current, which can be observed in that Figure.

### 8.8.2 Case II (Close in fault for MR2)

When a close in fault occurs for MR2, it operates as a primary relay along with MR1. It will be a far end fault for MR1. It can be observed from Fig. 26 and Fig. 27 that MR1 and MR2 are giving trip signals as per their primary operating times.

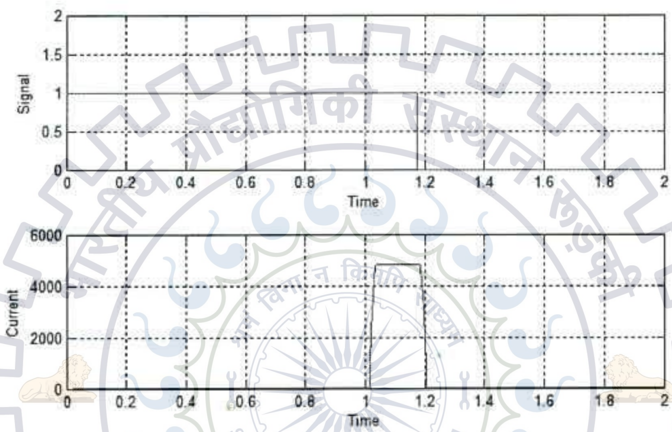


Fig. 8.26 Scope connected in MR1 in case II

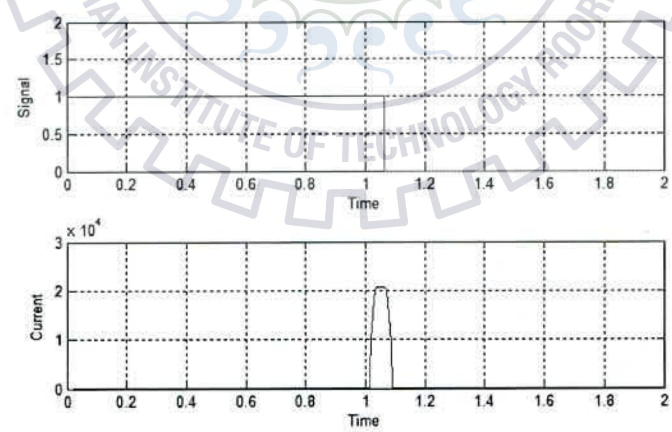


Fig. 8.27 Scope connected in MR2 in case II

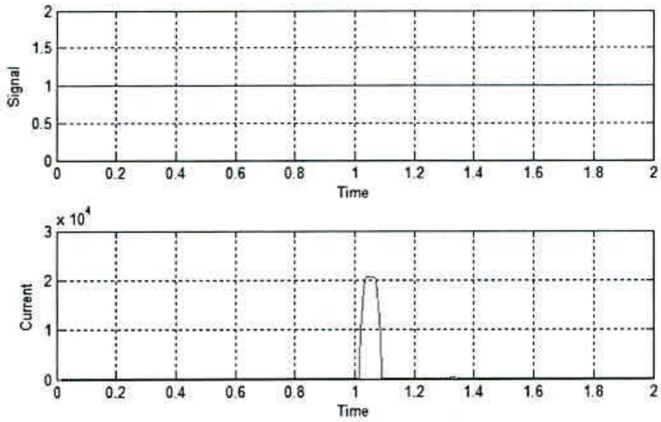


Fig. 8.28 Scope connected in MR3 in case II

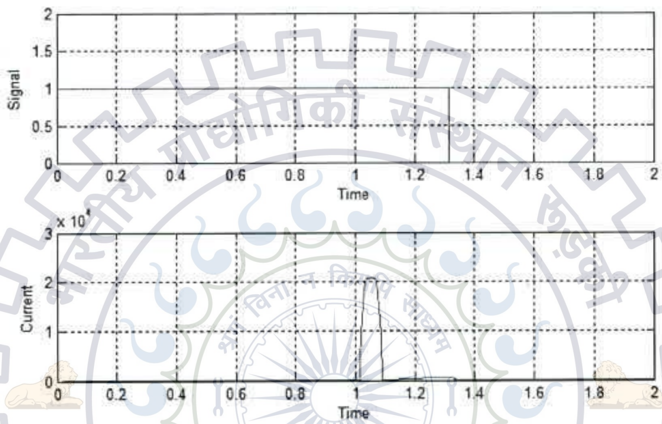


Fig. 8.29 Scope connected in MR4 in case II

From Fig. 28, it can be observed that MR3 has not sent any trip signal in this case. As shown in Fig. 8.29, MR4 sends trip signal because the fault current is reduced but still above MR4's normal overload current, which can be observed in that Figure.

### 8.8.3 Case III (Close in fault for MR3)

When a close in fault occurs for MR3, it operates as a primary relay along with MR4. It will be a far end fault for MR4. It can be observed from Fig. 30 and Fig. 31 that MR1 and MR2 are not any giving trip signals in this case.

From Fig. 32 and Fig. 33, it can be said that MR3 and MR4 are sending trip signals as per their primary operating times.

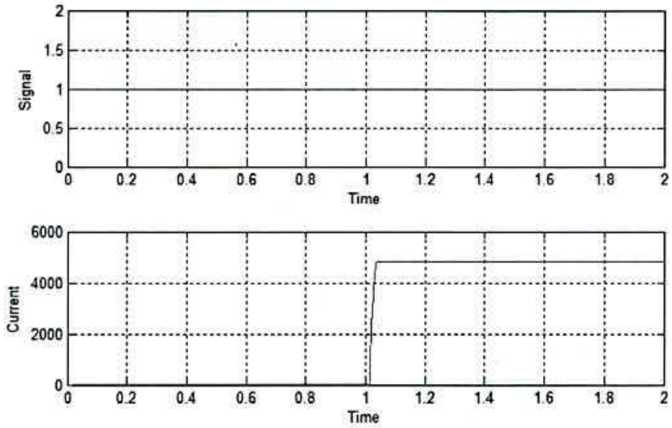


Fig. 8.30 Scope connected in MR1 in case III

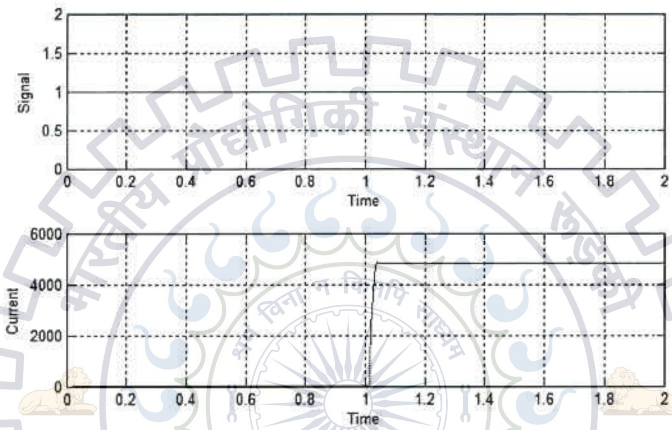


Fig. 8.31 Scope connected in MR2 in case III

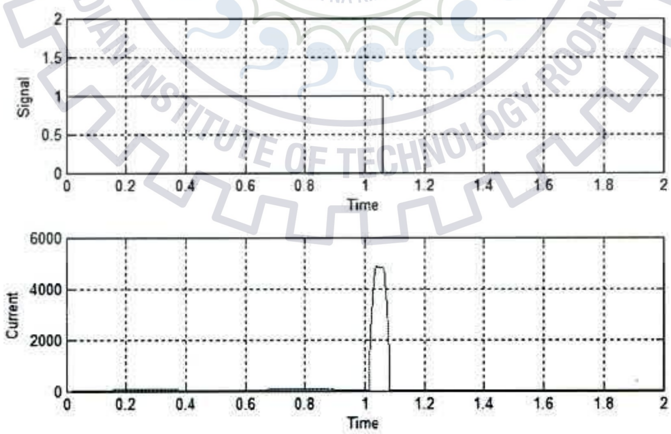


Fig. 8.32 Scope connected in MR3 in case III

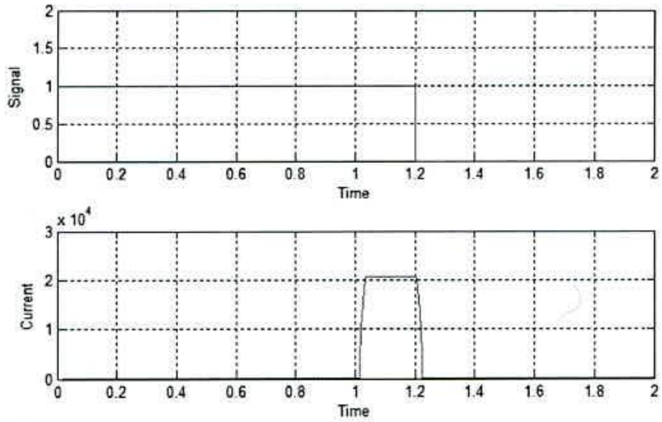


Fig. 8.33 Scope connected in MR4 in case III

### 8.8.4 Case IV (Close in fault for MR1 and MR2 fails to operate)

In this case, 'fault' block is connected nearer to MR1 and a continuous signal '1' has been given to CB2 by connecting constant block with value 1 at its terminal 'm', i.e. as a control signal instead of MR2's output.

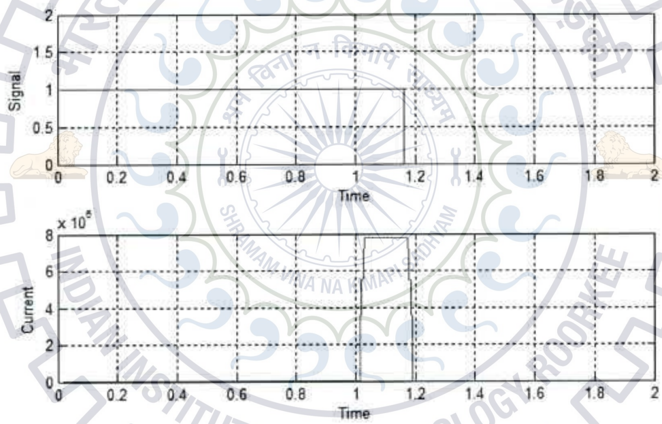


Fig. 8.34 Scope connected in MR1 in case IV

Fig. 8.34 remains as it was in the case I but from the Fig. 8.35 it can be observed that fault current did not come back to normal even after the trip signal from MR2. It happened so because MR2's output is not connected to CB2 in this case instead which a constant '1' signal has been connected. Fig. 8.36 shows that there is no trip signal from MR3. From Fig. 8.37, it can be observed that the fault current came back to normal only after getting a trip signal from MR4. It is happened at its backup operating time.

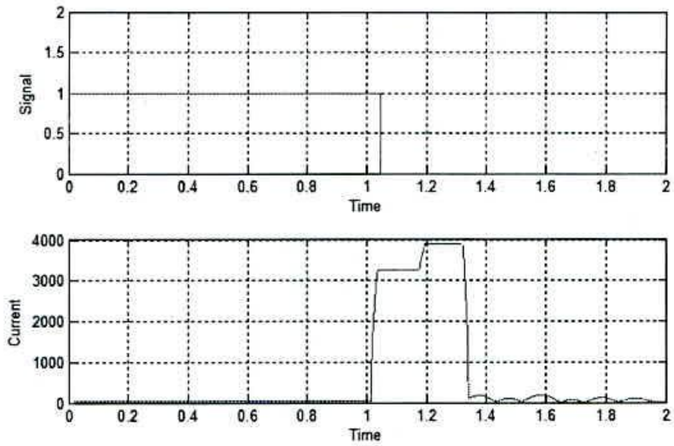


Fig. 8.35 Scope connected in MR2 in case IV

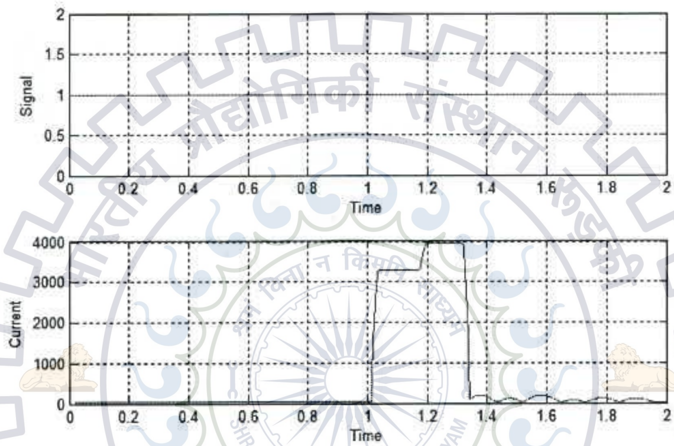


Fig. 8.36 Scope connected in MR3 in case IV

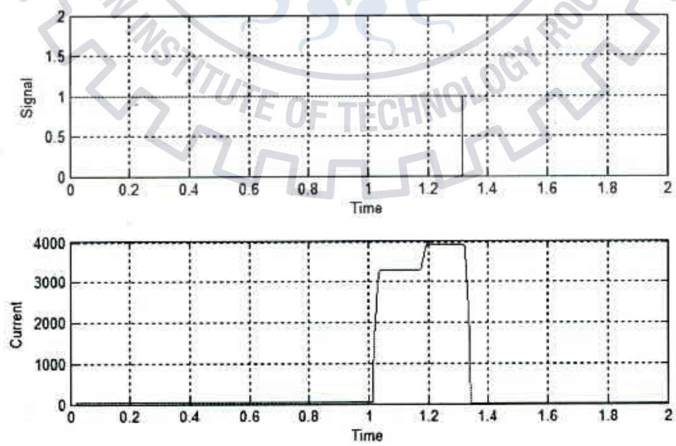


Fig. 8.37 Scope connected in MR4 in case IV

### 8.8.5 Case V (Close in fault for MR2 and MR2 fails to operate)

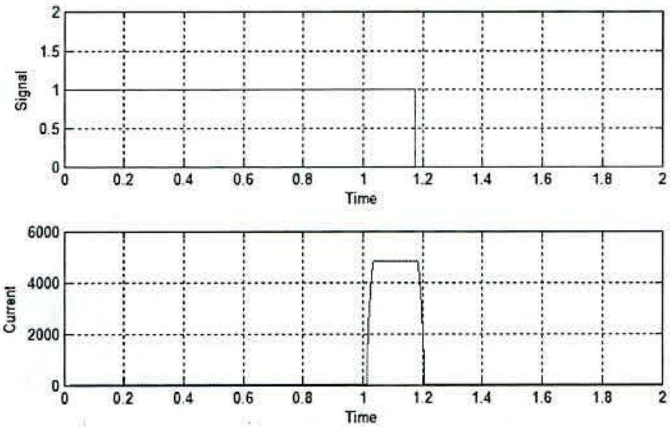


Fig. 8.38 Scope connected in MR1 in case V

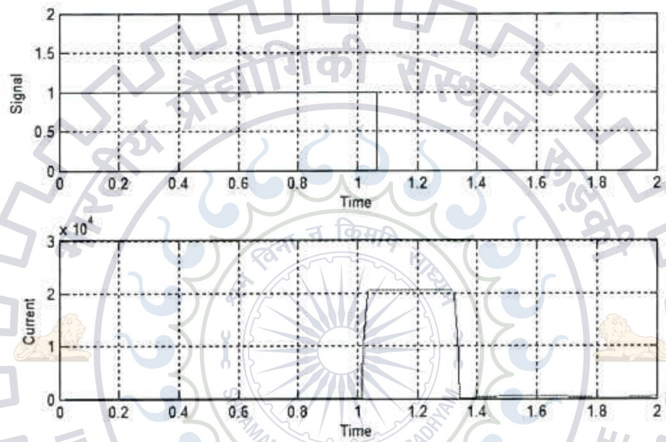


Fig. 8.39 Scope connected in MR2 in case V

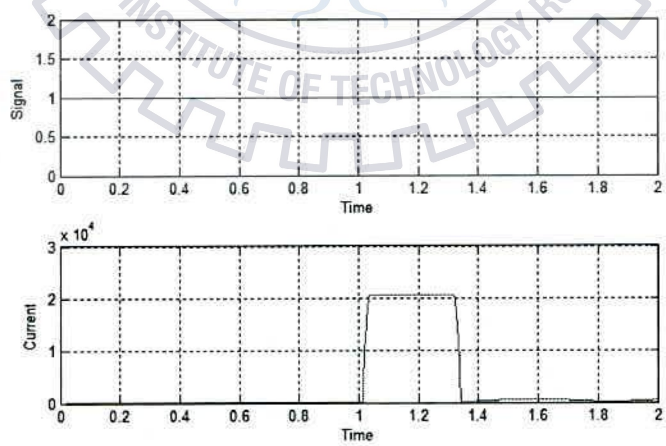


Fig. 8.40 Scope connected in MR3 in case V

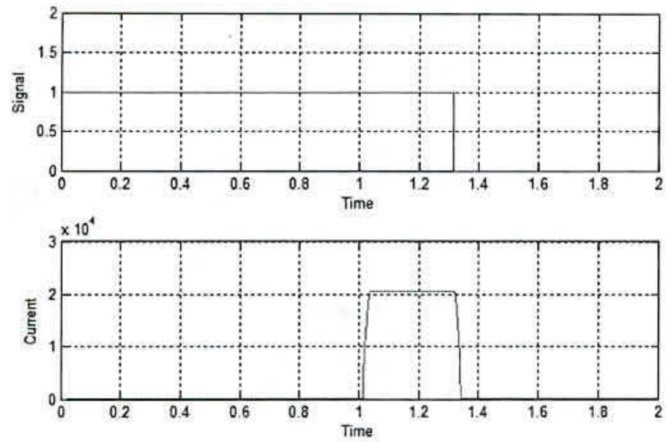


Fig. 8.41 Scope connected in MR4 in case V

In this case, 'fault' block is connected nearer to MR2 and a continuous signal '1' has been given to CB2 by connecting constant block with value 1 at its terminal 'm', i.e. as a control signal instead of MR2's output.

Fig. 8.38 remains as it was in the case II but from the Fig. 8.39 it can be observed that fault current did not come back to normal even after the trip signal from MR2 because MR2's output is not connected to CB2 in this case instead which a constant '1' signal has been connected. Fig. 8.40 shows that there is no trip signal from MR3. From Fig. 8.41, it can be observed that the fault current came back to normal only after getting a trip signal from MR4. It is happened at its backup operating time.

### *8.9 Conclusion:*

Different fault occurring cases have been discussed, from which it can be said that the test model is well designed in MATLAB such that there are no sympathy trips. So it can be said that DOCRs in the test model are well coordinated thus proved MRs have been well designed to achieve the operation of DOCRs.

CHAPTER-9

# CONCLUSION

The process of development in modern power systems has added complexity in power protection schemes, presenting a new set of conditions on the coordination of protective devices, since the fault current may flow to the fault point from both ends of any meshed line element.

Directional overcurrent relaying, which is simple and economic, is commonly used for providing primary protection in distribution and sub transmission systems and as backup protection in transmission systems. When two or more protective apparatus installed in series have characteristics, which provide a specified operating sequence, they are said to be coordinated or selective.

A relay should trip for a fault in its own zone of operation only. It should not trip for a fault outside its zone, except to back up a failed relay or circuit breaker Coordination of DOCRs is nothing but obtaining selective tripping.

MATLAB/Simulink implementation of Coordination of Directional Over-Current Relays (DOCR) using 3 bus, 4 bus test models and an existing power network test model has been explained in the present study. This study helps students to acquire a clear understanding of this topic. This study has provided the step by step procedure to develop MATLAB/Simulink models for the test models to test the coordination of DOCRs, for which decision variables TDS & PS are manually calculated. These test models have been tested for different fault occurring chances.

This study also explained a model to realize DOCR application, which is described as a 'Model Relay' (MR) in Chapter 6 and shown in Fig. 6.1. DOCRs in these models are well coordinated such that they operate for the faults occurred in their own zone except to backup a failed relay, thus achieved selective tripping. This study helps in understanding the concept with less complexity compared to the other models available in the literature.

The procedure for designing test models using MATLAB/Simulink and testing them for various fault conditions have been discussed. However there are some adjustments made while simulating the models to reduce the complexity. This study explains how to achieve coordination of DOCRs using MATLAB.

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