Digital Directional and Non-Directional Over Current Relays: Modelling and Performance Analysis

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3 authors:

Muhammad Mohsin Aman
NED University of Engineering and Technology,…

Muhammad Qadeer Ahmed Khan

Saad Ahmed Qazi
NED University of Engineering and Technology,…

Digital Directional and Non-Directional Over-Current Relays (Modeling and Performance Analysis)

Muhammad Mohsin Aman[a], Muhammad Qadeer A. Khan[b], Saad A. Qazi[c]

[a]Ph.D. Scholar University of Malaya, Malaysia and working as a lecturer in the Department of Electrical Engineering, NED University of Engineering & Technology. Karachi- Pakistan. Ph. +6014-2274960 Email mohsinaman@siswa.um.edu.my.
[b]Electrical Engineer, working in Siemens Pakistan Ph. +92 (0)343-3382510, Email qadeer88@hotmail.com
[c]Professor & Chairman, Department of Electrical Engineering, NED University of Engineering & Technology, Karachi-Pakistan. Ph. +92 (0)21-99261261-8, Email saadqazi@neduet.edu.pk

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Abstract—**This paper describes the design of a digital over current relay (directional and non directional) and its performance on MATLAB/SIMULINK®. Digital over current relays have advantages over electromechanical relays. Their fast, compact and reliable operation results in minimum outage of power system in case of fault. The paper also describes various data conversion steps involved in a digitization process. The logic based algorithm and developed relay model have been tested under various system dynamics and fault conditions. A 400V industrial distribution power system is used as a tutorial to simulate and test over-current relay's performance results, with motor start up inrush current consideration and backup relay coordination for safe and reliable operation. Similarly, a 132kV loop network is used as another tutorial example to simulate and test the directional over-current relay's performance.**

Key Words: **Digital relay, over current relay, inverse and instantaneous characteristics, slope detection, relay coordination, directional over-current relay.**

1. INTRODUCTION

SIMULATION tools are becoming more and more useful in initial designing of power system as a tool for researcher and in the educational field to give real time feelings to fresh engineers. Currently, varieties of software tools are available to power engineers such as ETAP, DigSilent and Power World Simulator (PWS). These tools are useful but need substantial training to use. MATLAB also offers an open-source Power System Analysis Toolbox for electric power system and control. This toolbox covers many aspects of power system although it currently does not possess many protection system components modules [1]. This paper covers the design of a digital over-current relay (OCR) model and directional OCR on MATLAB/Simulink®. Modelling in MATLAB offers design flexibility and room for exploration which assists in developing better understanding of the physical phenomenon happening behind any module.

Any protection scheme is a combination of various types of relays such as Over-current, over and under-voltage, over and under-frequency relays etc. All of these were traditionally constructed electromechanically and later in solid-state. Currently, digital relays have replaced both types; being faster, compact and reliable in operation ensuring minimum power outage in case of fault [2-5].

OCRs are employed to protect distribution and sub-transmission system from the effects of excessive currents occurring either due to short circuits or overload conditions. It is also used for the protection of generators, power transformers and electric motors. To limit the extent of damage caused by such faults to a minimum level; fast, reliable and selective operation of relay are basic demands of any power system. To meet these expectations, advantages of digital logic, communication, information storage and processing capabilities of modern microprocessors are employed in digital design [2-5]. OCR has its limitation in sensing the direction of fault, which is mitigated by adding a directional element along with it [4]. Directional OCRs are most commonly employed for protecting ring or loop networks [5-7].

2. THEORETICAL BACKGROUND

2.1 Over Current Relay (50/51):

The current–time characteristic of a typical over-current relay is shown in Fig. 1 [2, 4, 6-7].

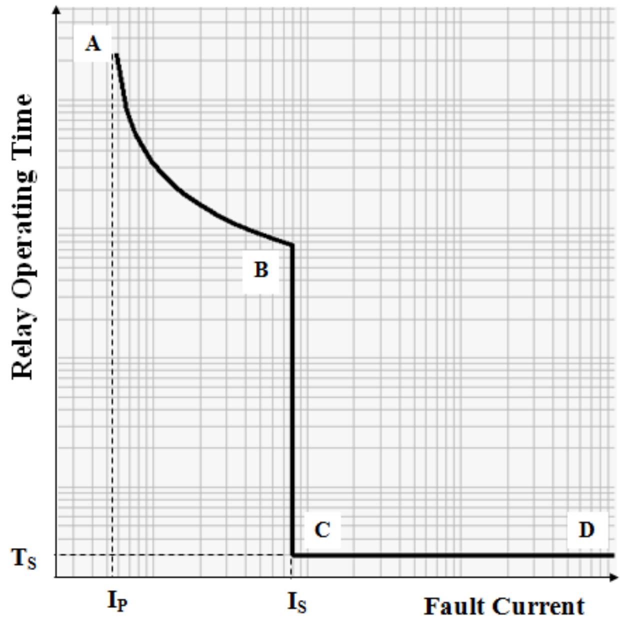


Figure 1. Current Time Characteristics of an Over-Current Relay

In Fig. 1, Curve A-B is the inverse characteristic of the relay and is used to protect apparatus from excessive currents less than severe short circuit fault levels but large enough, that if allowed to sustain for a certain period would damage the apparatus it is meant to protect. Moreover, Curve B-C-D is meant for instantaneous, high speed clearing of severe short circuits ($>I_S$) by reducing the clearing time to only Ts. This paper presents the design of inverse as well as instantaneous portion of over-current relay on MATLAB/SIMULINK.

The general form of the inverse time current characteristic of an over-current relay can be given as [3, 5].

$$T = \frac{K}{I_a^n - 1} \qquad 1 < I_a < \frac{I_S}{I_P} \tag{1}$$

Where T is the operating time of the relay ; Ia is the fault current normalized by the pickup current i.e. $I_a = \frac{I_C}{I_P}$; I_C is the actual current; I_P is the pickup current and I_S is the short circuit current. 'n' and 'K' are constants. 'n' determines the inverse characteristic of the relay and K determines the relative operating time of the relay by shifting the inverse characteristics curve on vertical axis of Fig. 1.

Equation (1) can be modified in terms of actual faults as:

$$T = \frac{K}{I_C^n} \qquad I_P < I_C < I_S \tag{2}$$

Any desired relay curve can be obtained by selecting suitable values of n and K [3]. For instantaneous portion of curve (BCD) of over current relay the relay operation time is given as (3) [6-7]:

$$T = T_S \qquad I_C > I_S \tag{3}$$

Where, Ts is the instantaneous time of operation.

Over-current relays employed in a system should be coordinated with other relays in such a manner that if the primary protection fails to operate, then back- up protection should accomplish the task [6-8].

This is better showcased in a radial feeder system as shown in Fig. 2.

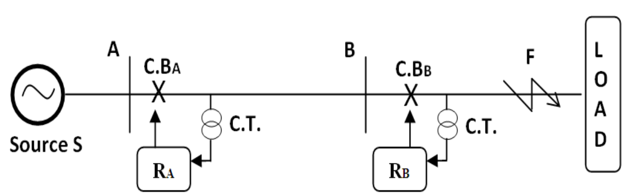


Figure 2. Radial Feeder Network with Relay Coordination

For a fault F, beyond bus bar B, relay R_B should cause its associated circuit breaker $C.B_B$ to clear the fault. If it fails to do so then relay R_A, acting as back-up, should actuate its circuit breaker $C.B_A$, to ensure fault isolation. For correct grading, the time setting of relay R_A should always be greater than that of R_B by an amount in which R_B was supposed to have cleared the fault and this time is usually the sum of operating time of R_B and breaker operating time ($TC.B._B$) i.e.

$$TR_A > \left(TR_B + TCB_A\right) \tag{4}$$

Failure to satisfy (4), irrespective of correct primary protection operation, will result in back-up protection to always operate and thus lead to a greater disruption of service [6-7].

Fig. 3 shows the general block diagram for implementing a microprocessor based O.C. relay [9].

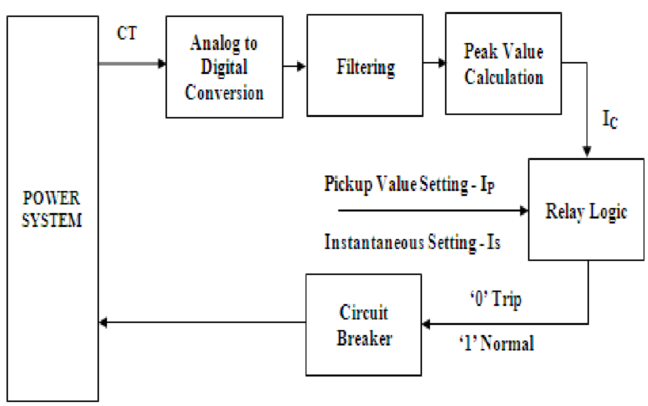


Figure 3. Block Diagram for Implementing a Microprocessor Based OCR

The Current transformer's (C.T) purpose is to produce a scaled down accurate reproduction of the power system fault current. Protection class C.T. is employed with good accuracy class for reproduction of fault current for a wide range to avoid core's saturation [6, 9].

The digital signal in the microprocessor is first conditioned from any decaying DC component and harmonics present in the signal. DC component may cause relay disoperation even when the steady state AC component of fault is less than the pickup current setting of the relay [10]. Harmonics induced into the current signal due to non-linear loads in the power system are filtered out to prevent reduced relay operating time that causes coordination problems [11-12].

In this paper, the MATLAB environment serves the purpose of a microprocessor and the algorithm for implementing the current-time characteristic of an O.C. relay is done on SIMULINK®.

2.2 Directional Over-Current Relay (67).

To protect ring or loop networks directional over current relays are commonly employed. The directional element is added with the over-current relay in order to minimize the outage area [13, 14]. If non-directional relays are applied to parallel feeders, any fault occurring on any one of the feeders will result in complete loss of supply to the other end. With this type of system configuration, it is necessary to apply directional relays at the receiving end and to grade them with the non-directional relays at the sending end, to ensure correct discriminative operation of the relays during line faults. This is done by providing directional relays Q1 and Q2 at the other end looking non directional relays P1 and P2, at the source shown in Fig. 4 [7].

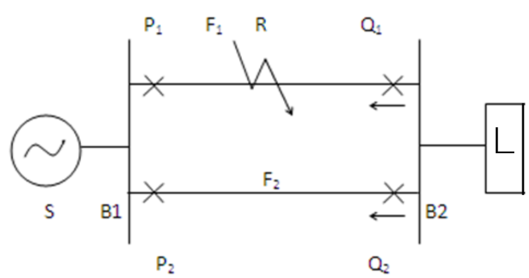


Figure 4. Directional Relay Employed to Parallel Feeders

3. RELAY MODELLING

3.1 Over-Current Relay Modelling (50/51):

This section gives the basic logic for implementing the inverse current-time characteristic of an O.C. relay represented in Fig. 5.

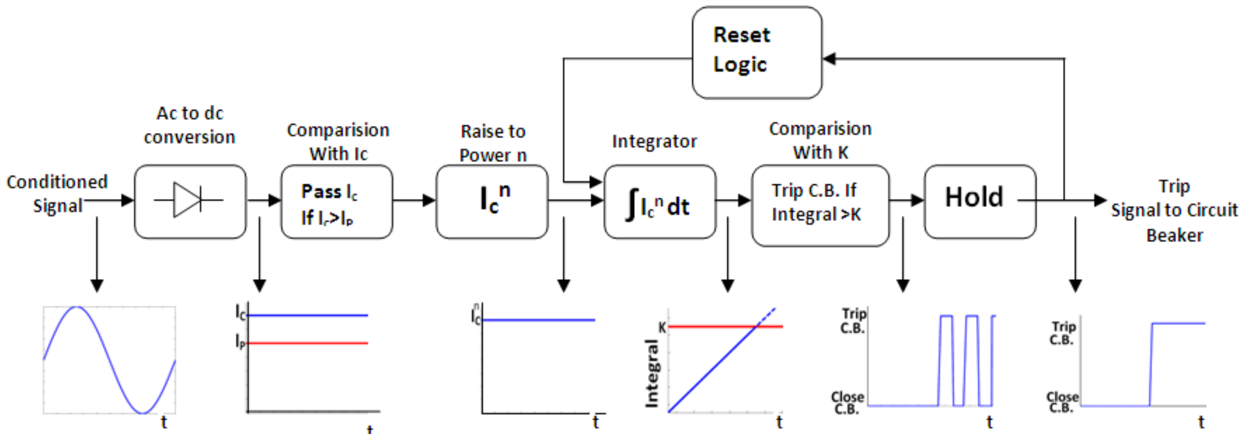


Figure 5. Logic Diagram for implementing the Inverse Current Time characteristics of OCR

3.1.1 Measuring Peak Value Ic:

After filtering the fundamental component, ac current signal(I) of frequency '*f*' entering the relay must first converted to a representative dc value(peak/r.m.s.) for comparison with the pre-set pick-up current of relay. By measuring the slope at the zero crossing of the current signal, we get its peak value (Ic) as mathematically given in (5).

$$I(t) = I_C Sin(2\pi ft) \tag{5}$$

$$\frac{dI(t)}{dt} = I_C 2\pi f Cos(2\pi ft) \tag{6}$$

The slope 'm' at the zero crossing is:

$$m = \frac{dI(t)}{dt} = I_C 2\pi f \tag{7}$$

$$I_C = \frac{m}{2\pi f} \tag{8}$$

The implementation of measuring Ic given by (8) on SIMULINK® is shown in Fig. 6, in which the peak obtained at each zero crossing is held constant by the sample and hold block until the next zero crossing. The detail of zero crossing and its detection can be seen in [15].

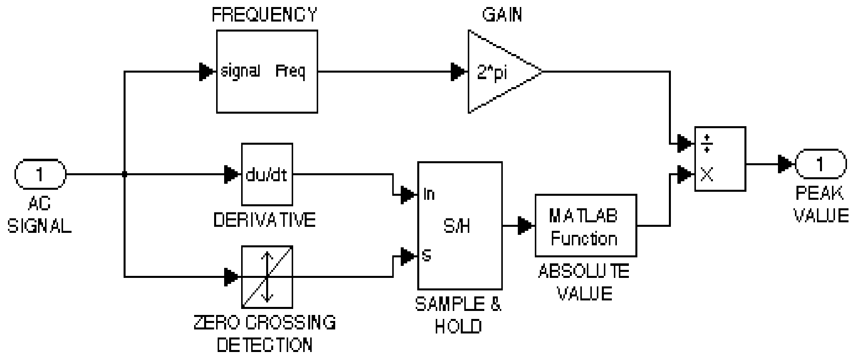


Figure 6. Measuring Peak Value of Current Ic

It may be noted that peak detection in time domain is computationally more expensive and time taken, frequency based methods such as FFT exist [16-18], which could be used for measuring peak detection. However, for the sake of simplicity of demonstration, elementary methods have been used here. The zero-crossing technique can be replaced by more sophisticated phasor estimation methods.

3.1.2 Measuring frequency f:

The frequency is determined by measuring the time between two consecutive zero crossings (T_1 & T_2). This will give half the time period (T) from which frequency is determined as follows:

$$\frac{T}{2} = T_2 - T_1 \tag{9}$$

$$Frequency = \frac{1}{TimePeriod\,(T)} = \frac{1}{2(T_2 - T_1)} \tag{10}$$

3.1.3 Design of frequency Block:

The frequency measuring block implemented on SIMULINK is shown in Fig. 7. '*Hit Crossing'* block is used, which passes the input signal only at its zero crossings to the '*if'* block which in turn sends the value of the ramp signal at that instant to the output. The time duration of generated ramp can be computed and can be saved to a variable 'A'. This value of A must be subtracted from the time of the next zero crossing to determine half the time period. This is done by temporarily storing A into another variable 'B' using the '*Transport Delay*' block. Now subtracting B from A at any instant will give half the time period whose value is held by the 'Sample and Hold' block, till the next zero crossing. After performing the necessary computations, given by (10), on the held value we get the instantaneous frequency.

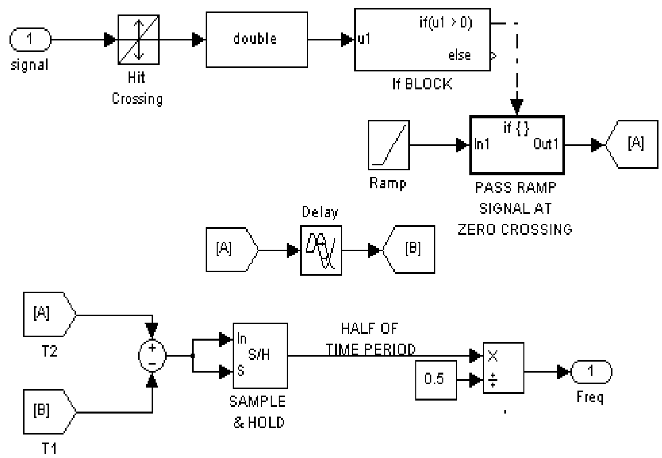


Figure 7. Modelling of frequency on Simulink®

3.1.4 Comparison of Ic with Ip and Inverse Characteristic of Over-current Relay:

The peak value of current (I_C) obtained in section 3.1.1 is then compared with the pre-set constant value of pickup current (I_P) setting of the relay using the comparator block which allows I_C when $I_C > I_P$. The value of I_C is then raised to a suitable power of n to achieve desired relay curve and then integrated as shown below:

$$\text{Constant} = \int I_C^n dt \qquad (11)$$

As long as the current is in excess of I_P (pickup current), the integrator output keeps rising until it becomes equal to the pre-set value of constant K, causing the relay to send a trip signal ('0').

If the excess current is temporary; either due to motor starting or any switching action; the rising integral output is reset to zero when the excess current dies out to below I_P, before reaching K by the feedback reset logic to avoid any mal operation of relay.

If the fault current level is constant during permanent fault, the value of I_c^n will also remain constant and causing the integrator output given by (12) & (13).

$$\text{Constant} = I_C^n \int dt \tag{12}$$

$$\text{Constant} = I_C^n t \tag{13}$$

(13) is the equation of a straight line with slope I_c^n .So a large magnitude of fault current will result in a higher rate of rise of the integrator output and thus a smaller time to reach the value of constant K. This is shown in Fig. 8 for two current levels I_C1 and I_C2, providing inverse current time characteristic of relay curve (portion AB) of Fig. 1.

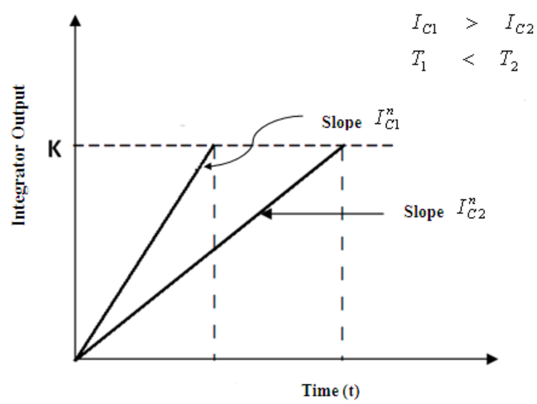


Figure 8. Integrator out for achieving Inverse time characteristics

3.1.5 Instantaneous Characteristic of OC Relay:

If the value of I_C as determined from slope detection is greater than the pre-set value of severe short circuit current level I_S (I_C>I_S), the relay sends a '0' (trip command signal) to its associated C.B. after a fixed delay of T_S seconds. Fig. 9 shows the logic for implementing the instantaneous characteristic; shown previously in curve BCD of Fig. 1.

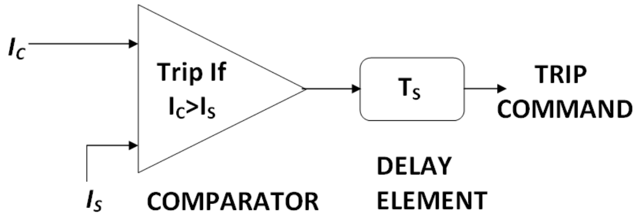


Figure 9. Block Diagram for Implementing Instantaneous Characteristics of a Digital OCR

3.1.6 Digital Over-current Relay:

The overall digital relay output is the logical multiplication (AND) of instantaneous element and inverse characteristic element outputs, as shown in block diagram Fig. 10.

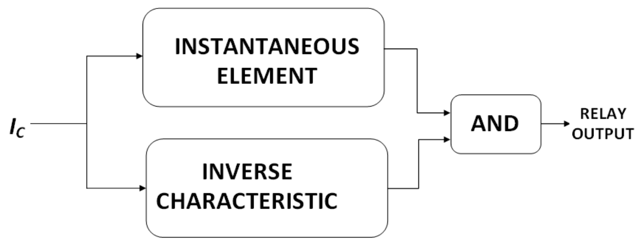


Figure 10. Block Diagram for Implementing a Digital Over-Current Relay

3.2 Directional Overcurrent Relay Modelling:

The OCR relay designed above can be modified to behave also as a directional O.C. relay simply by incorporating a directional feature with the relay. The directional feature acts as a switch to allow current to pass to the O.C. relay to take decision only when power flows in a particular direction [19, 20] as shown in Fig. 11.

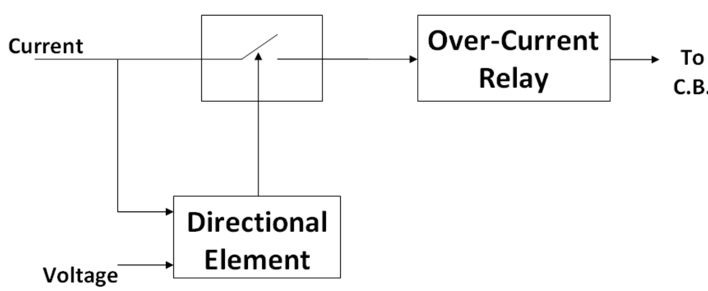


Figure 11. Directional Relay Principle

These directional relays may use the phase angle between the fault current and some reference quantity (the corresponding voltage, for example) to determine the direction (forward or reverse) of the fault [14].

If 'Ψ' (let) is the angle between current in a phase and voltage on that phase then

$-90^o < \Psi < 90^o$ shows Normal direction of load flow

$90^o > \Psi > 270^o$ shows Reversed power flow

Fig. 12a shows that during normal conditions ($-90^o < \Psi < 90^o$) the overlapping interval between voltage and current is longer than their non-overlapping interval whereas under reversed power flow conditions ($90^o > \Psi > 270^o$) the opposite is true as shown in Fig. 12b.

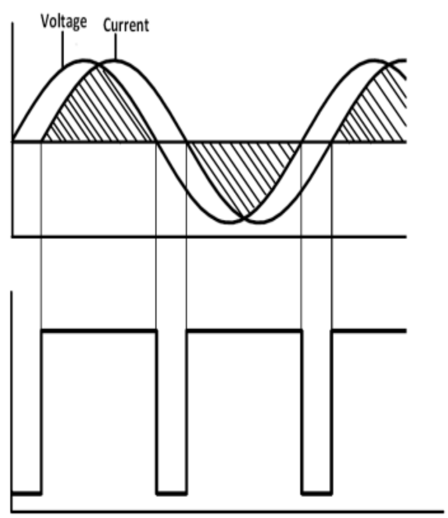


Figure 12(a) Angle between Voltage and Current Phasors under normal conditions

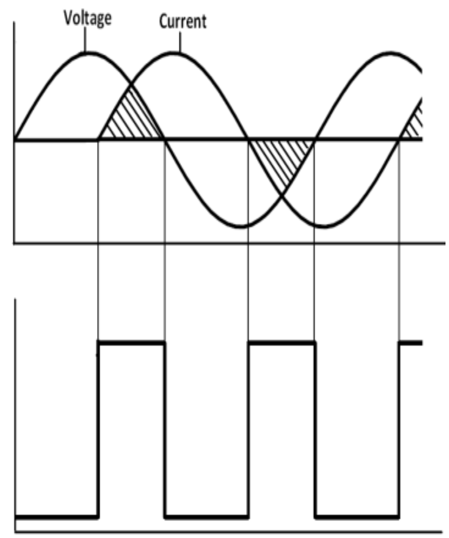


Figure 12(b) Angle between Voltage and Current Phasors under fault conditions

This difference in the overlapping interval under normal and reversed power flow conditions can be used to implement the directional element of a relay.

To model the directional element, the current and voltage signals are first converted to a two level square wave, whose value is '1' for positive values and '-1' for negative values of the signals. The 2 level voltage and currents signals are then multiplied, giving an output '1' during the overlapping and '-1' for the non-overlapping interval. The product is then integrated. The upper limit of the integrator is set to saturate at a value of 0 so that under normal load flow conditions the integral always remains less than 0.However,under reversed power flow conditions the integral output tends to fall until it reaches the level below 'L', in which case the directional element's output switches from '0' to '1'. Fig. 13 shows the concept diagram for implementing the directional element.

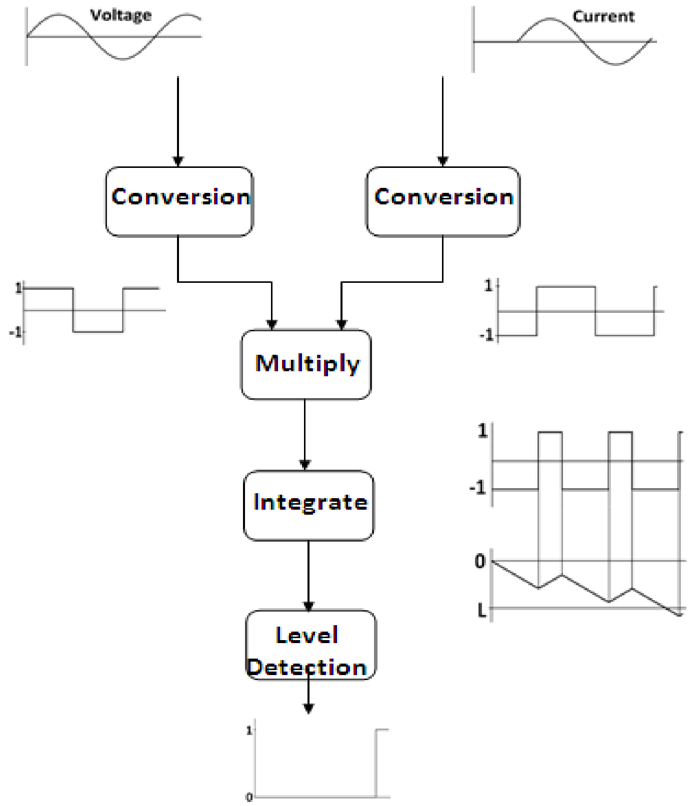


Figure 13. Concept Diagram for Implementing Directional Element

The directional element with an output '1' under abnormal conditions and '0' otherwise, serves as a switch by multiplying its output with the samples of current, to be sent to the O.C. relay as illustrated in Fig. 14.

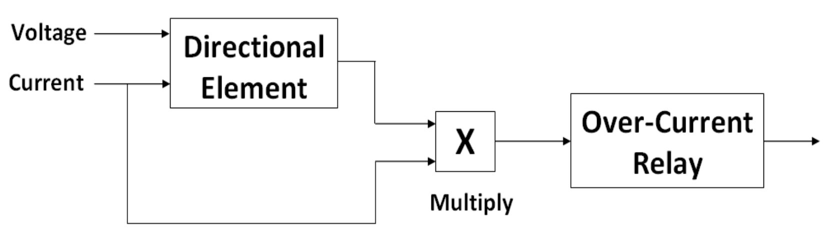


Figure 14. Block Diagram for Implementing Directional Relay

These models of relays (OCR and Directional OCR) have also been contributed to MATLAB's resources to strengthen their Power System Tools [21].

4. CASE STUDIES AND PERFORMANCE ANALYSIS

4.1 Overcurrent Relay Performance:

To demonstrate performance of the current time characteristics of the relay designed, we consider a radial network shown in Fig. 2. The load is considered to be a motor, rated 110kW, 400V, 0.885 power factors whose initial starting current is 4 times the nominal current. The accelerating period of the motor is 3 seconds.

The relay settings (shown in table 1) are such that.

1. The pickup current setting I_P allows the motor to carry continuous full load current (i.e. 179A r.m.s. or 253 A peak).
2. Severe fault current setting (I_S) is more than the initial starting current of the motor (1000A peak). The relay R_A has higher Is setting than that of relay R_B.
3. Constant K is such selected that it does not cause false tripping during motor starting and transient conditions.

The K and Ts setting of R_A is kept greater than that of R_B for proper relay coordination. The circuit breaker contacts operating time is assumed zero here.

Table 1- Relay Settings for R_A and R_B for n=0.9

Relay	Pickup Current Setting IP	Constant K	Severe fault current setting, IS	Instantaneous Time Setting, TS
RA	260A	1400	1500 A	0.2 sec
RB	260A	1100	1200 A	0.1 sec

Motor Starting Analysis:

During the accelerating period the motor current is above the pickup setting of R_B causing its integrator output to rise. At t=3 seconds, when the motor current falls below I_P ,the integrator output being below the K setting of R_B is reset. The K value of R_B is purposely set above its maximum integrator output during the accelerating period to prevent any false tripping of motor.

We will now consider cases for different fault current levels occurring at t=6 seconds at position F of Fig. 2.

Case 1: For fault current Ic=560 A.

In this case the integrator output of R_B rises until it reaches the value of K (1100) causing the relay R_B to trip the circuit breaker after 3.7 seconds of fault (neglecting CB operating time). This is shown in Fig. 15a, indicating the fault current and relay performance during the fault. It can be noticed that the relay R_A will take more time (4.7s) due to greater value of K settings.

The operating time of relay R_B can be determined as follows:

$$T = \frac{K}{I_C^n} = \frac{1100}{560^n} = 3.7\sec$$

Case 2: For fault current Ic =770 A.

In this case, the relay R_B will operate much quicker than the previous case because the current is more and the relay follows inverse current-time characteristics. The operating time of the relay can also be found by:

$$T = \frac{K}{I_C^n} = \frac{1100}{770^n} = 2.7\sec$$

Fig. 15b indicating the relay performance during the fault current of 770A, which clearly shows inverse characteristic as compared to previous case.

Case 3: For fault current Ic=770A with $C.B_B$ failing to 'open'.

In this case $C.B_B$ fails to open at 8.7 sec as directed by R_B. In that case R_A acting as backup operates $C.B_A$ to interrupt the fault current at t=9.5 in 3.5seconds after the fault as verified below.

$$T = \frac{K}{I_C^n} = \frac{1400}{770^n} = 3.5\sec$$

Fig. 15c indicating the relays performance during the fault current of 770A, the backup protection operated due to mal operation of $C.B_B$ failing to operate.

<u>Case 4</u>: For fault current Ic=1350A (> Is).

In this case the relay R_B will operate instantaneously (0.1 sec) in order to minimize extent of damage to the power equipments involved, while status of R_A will not be changed.

Fig. 15d is indicating the relay's instantaneous characteristic performance during the severe fault current of 1350A.

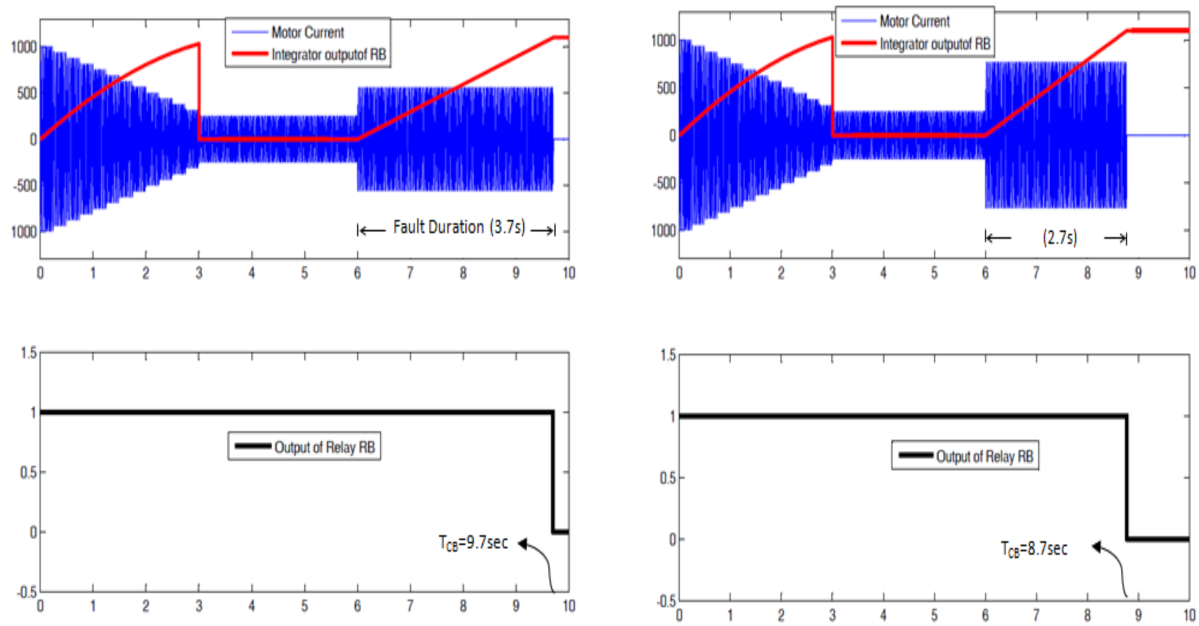
<u>Case 5</u>: For fault current Ic=1350A ($I_{S(RB)} < I_C < I_{S(RA)}$) with CB_B failing to 'open'.

In this case, relay R_A will provide the backup protection. However since the level of fault current falls in the inverse characteristic region of R_A, therefore the time taken by it to operate will be given by (rather than instantaneous)

$$T = \frac{K}{I_C^n} = \frac{1400}{1350^n} = 2.13\,\text{sec}$$

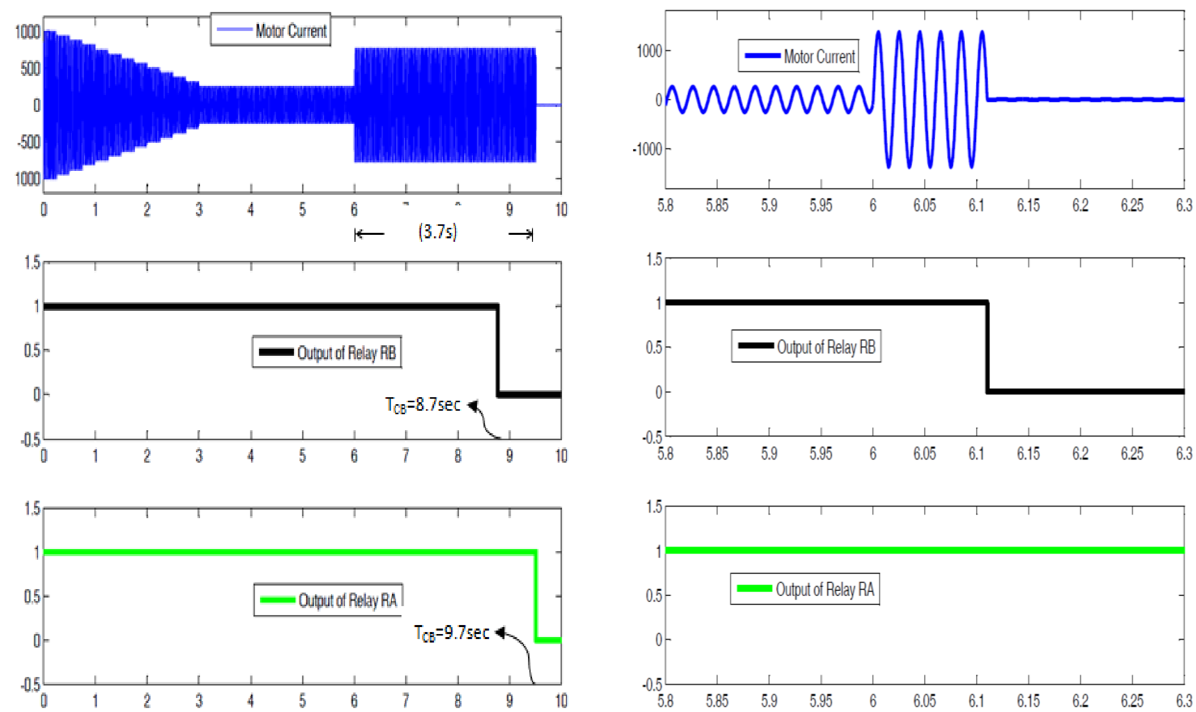
This is illustrated in Fig. 15e.

However for fault current Ic=2000A (>I_S) with CB_B failing to 'open'. The relay R_A will provide the backup protection and operate after 0.2 sec of fault, maintaining coordination with relay R_B. Fig. 15f indicating the relay's instantaneous characteristic performance during the severe fault current of 2000A.



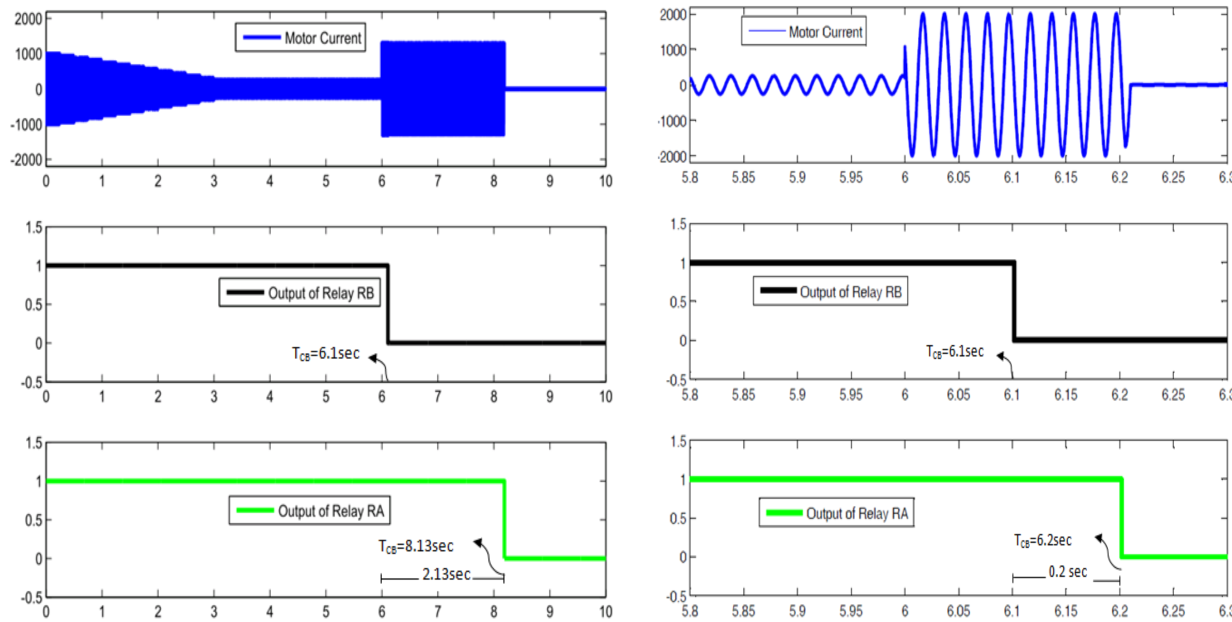
(a) (b)

Figure 15. Relay Performance for for fault current (a) Ic=560A (b) 770 A



(c) (d)

Figure 15. Relay Performance for fault current (c) Ic=770A & CB_B failure (d) Ic=1350A



(e) (f)

Figure 15. Relay Performance with CB_B failure for fault current (e) Ic=1350 and (f) Is=2000A

Table 2 summarizes the operating times of R_A and R_B for peak levels of fault current as simulated above.

Table 2 - R_A and R_B Operating Times for Various Fault Levels

Fault current (A)	Operating time of R_A (seconds)	Operating time of R_B (seconds)
560	4.7	3.7
770	3.5	2.7
1350	2.13	0.1
2000	0.2	0.1

4.2 Directional Overcurrent Relay Performance:

To demonstrate performance of the D-OCR relay on MATLAB/SIMULINK®, consider a 132kV network shown in Fig. 4, which shows two parallel 220 kV transmission lines feeding a load(L) such that each carries 900A (peak) under normal conditions.

We will now consider cases for different positions of fault occurring in transmission line i.e.

- Case 1: For Fault occurring at point F1
- Case 2: For Fault occurring at point F2

- Case 3: For Fault occurring at point B1
- Case 4: For Fault occurring at point B2

Case 1: For Fault occurring at point 'R' on Feeder F1.

To ensure removal of only line F_1 for minimum outage; relays Q1 and Q_2 are directional O.C. relays, functioning only when power flows in the direction [22] as indicated in Fig. 4. Relays P1 and P2 are non-directional O.C. relays .The fault at R which is fed by the supply through paths S.-P_1.-R and S-P_2-Q2-Q_1-R causes current levels on both feeders to rise. The direction of power flow remains the same as prior to the fault in relay Q_2 and reverse in Q_1, therefore relay Q_2 remains idle no matter how high the current flowing through the respective C.T. is, whereas relay Q1 functions to send a trip command to the its associated C.B. at t=5.35s resulting in the fault current to no longer be fed from path S-P_2-Q2-Q_1-R. Non directional O.C. relay P_1 will trip its associated C.B. at t=5.8sec., thereby ultimately removing the faulty feeder from the network resulting in the entire load current to be fed by healthy feeder F2.

Fig. 16a shows the status of relays at P_1, P_2, Q_1, Q_2 and the currents at the positions of these relays for fault occurring on feeder F1.

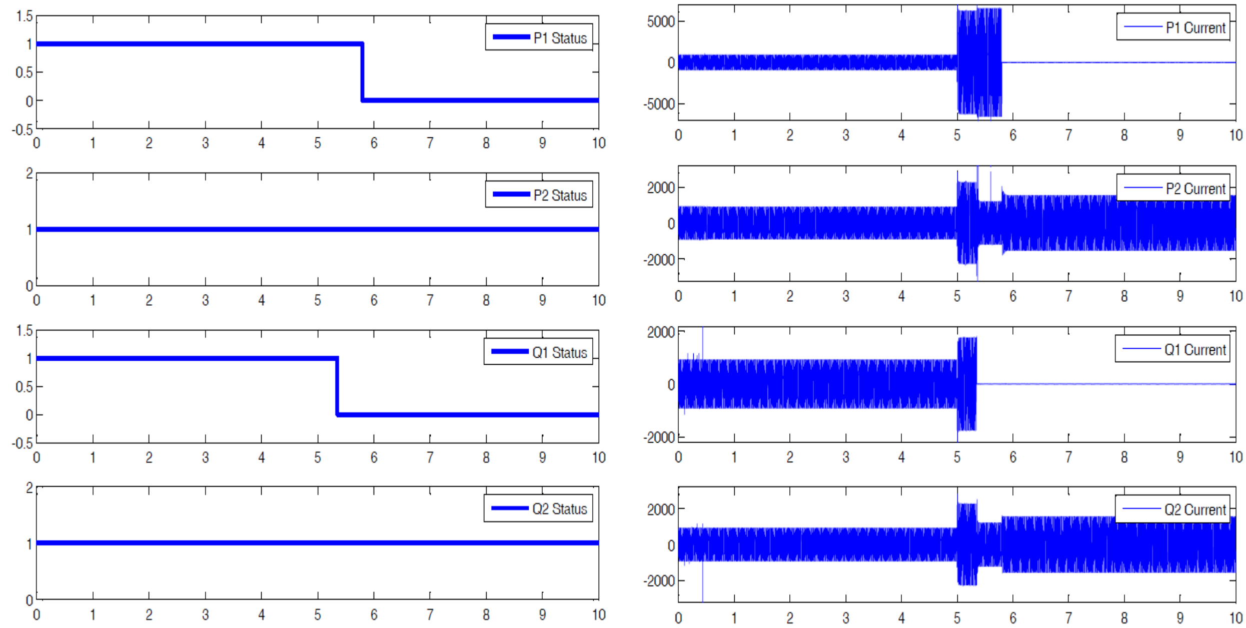


Figure 16 (a) Relay status and fault current in case 1

<u>Case 2</u>: For Fault occurring at point 'F2'.

In this case, only P2 and Q_2 will open for minimum outage, load will be transferred to the healthy line F1. Fig. 16b shows the status of relays at P_1,P_2,Q_1,Q_2 and the currents at the positions of these relays for fault occurring on feeder F2.

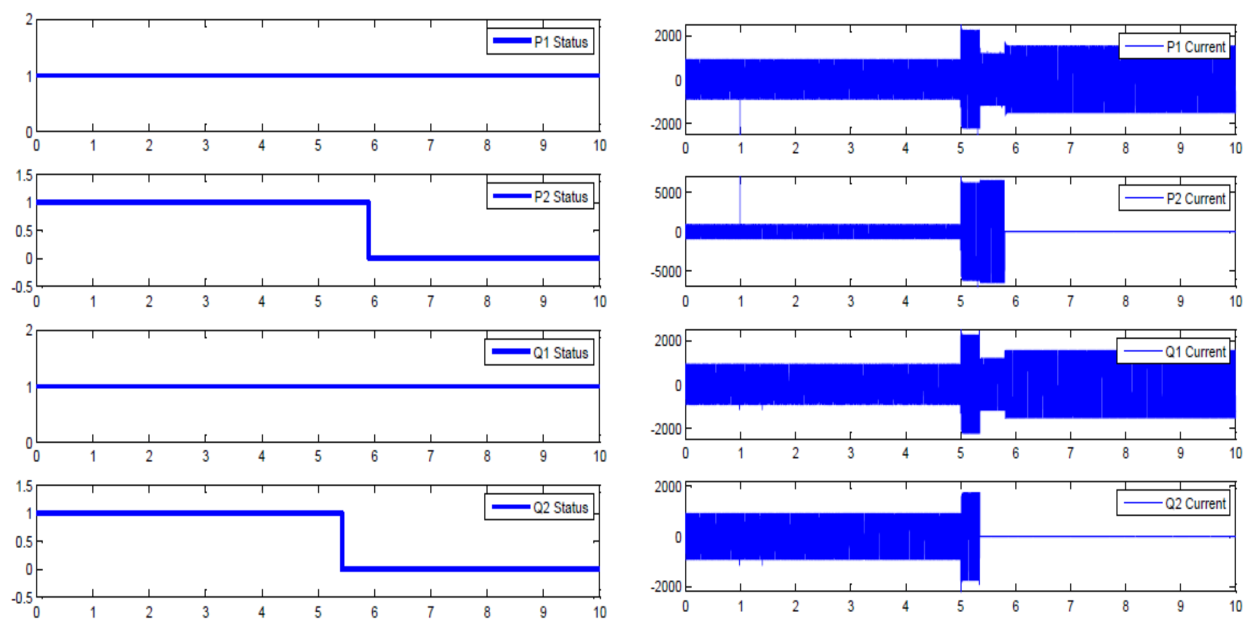


Figure 16 (b) Relay status and fault current in case 2

Case 3: For Fault occurring at Bus ‘1’.

In this case, no relay will operate since the fault is out of reach. Fig. 16c shows the status of relays at P_1,P_2,Q_1,Q_2 and the currents at the positions of these relays for fault occurring on Bus ‘1’.

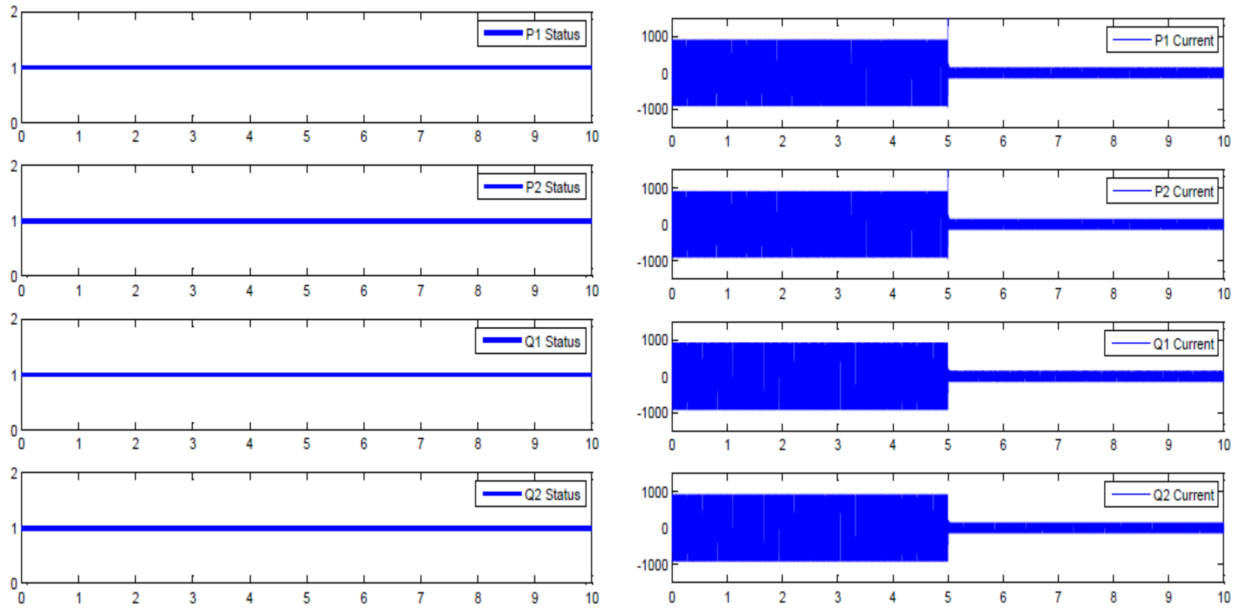


Figure 16 (c) Relay status and fault current for case 4

Case 4: For Fault occurring at Bus ‘2’ (Similar to Case ‘3’).

In this case, only over-current relays P1 and P2 will operate. Fig. 16d shows the status of relays at P_1,P_2,Q_1,Q_2 and the currents at the positions of these relays for fault occurring on Bus ‘2’.

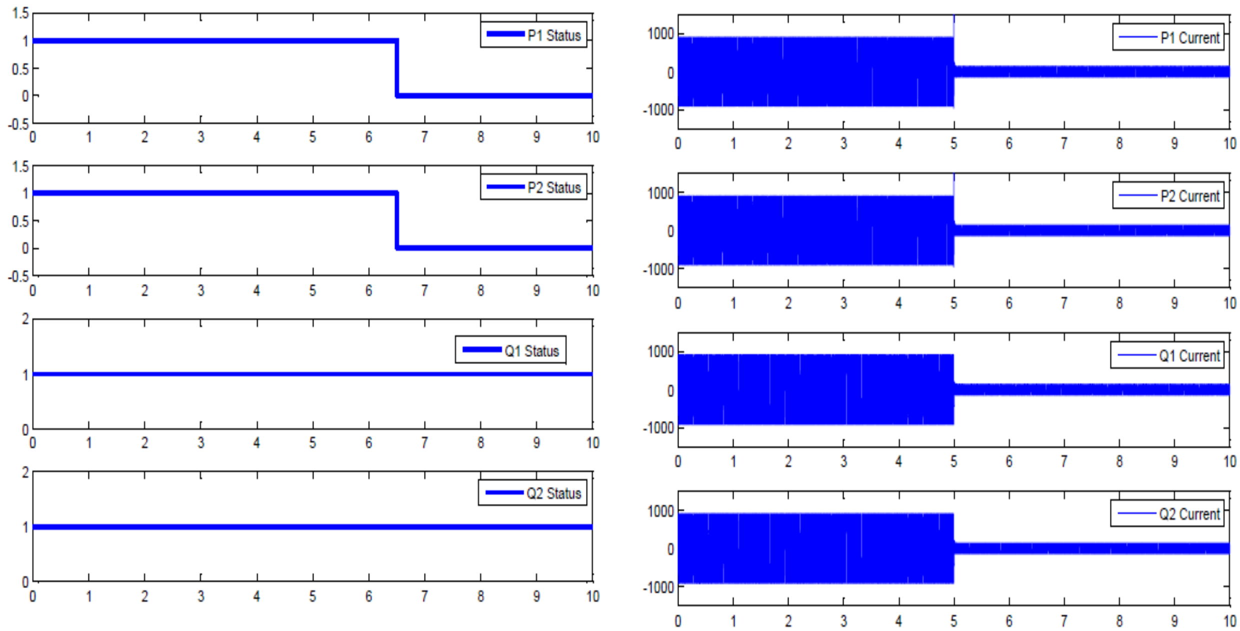


Figure 16 (d) Relay status and fault current for case 5

The relay also tested for unsymmetrical faults i.e.

Case 5: For SLG Fault occurring at point F1

Case 6: For DLG Fault occurring at point F1

Case 7: For DL Fault occurring at point F1

For the above cases the relay also works satisfactorily.

Fig. 16(e-g) shows the status of relays at P_1,P_2,Q_1,Q_2 and the currents at the positions of these relays for above three (SLG, DLG,LL) non symmetrical faults.

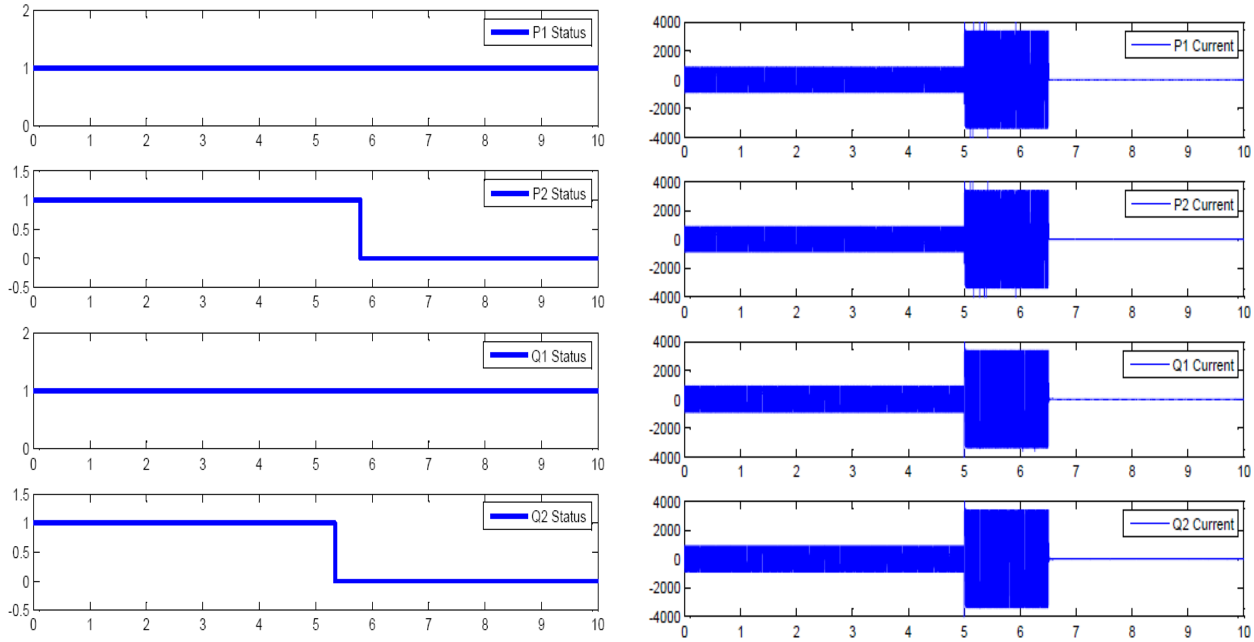


Figure 16 (e) Relay status and fault current in case of SLG fault

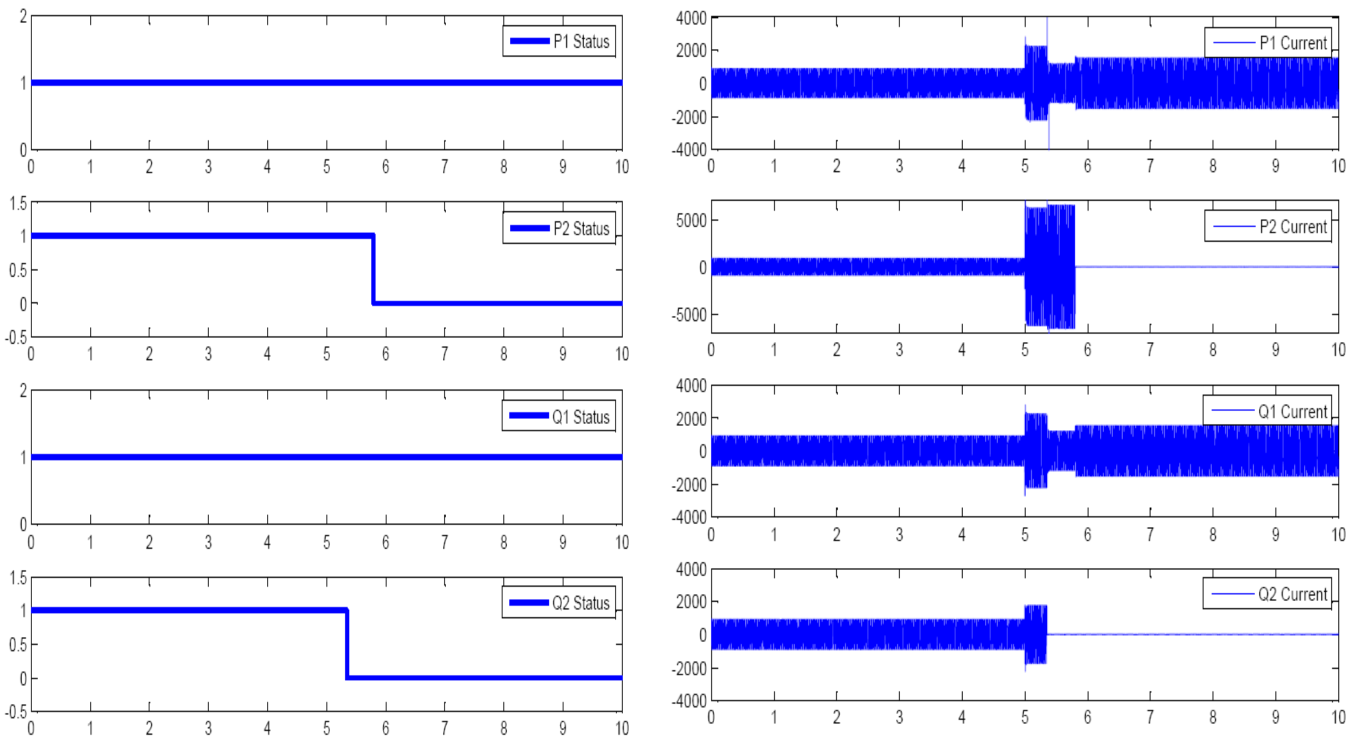


Figure 16 (f) Relay status and fault current in case of DLG fault

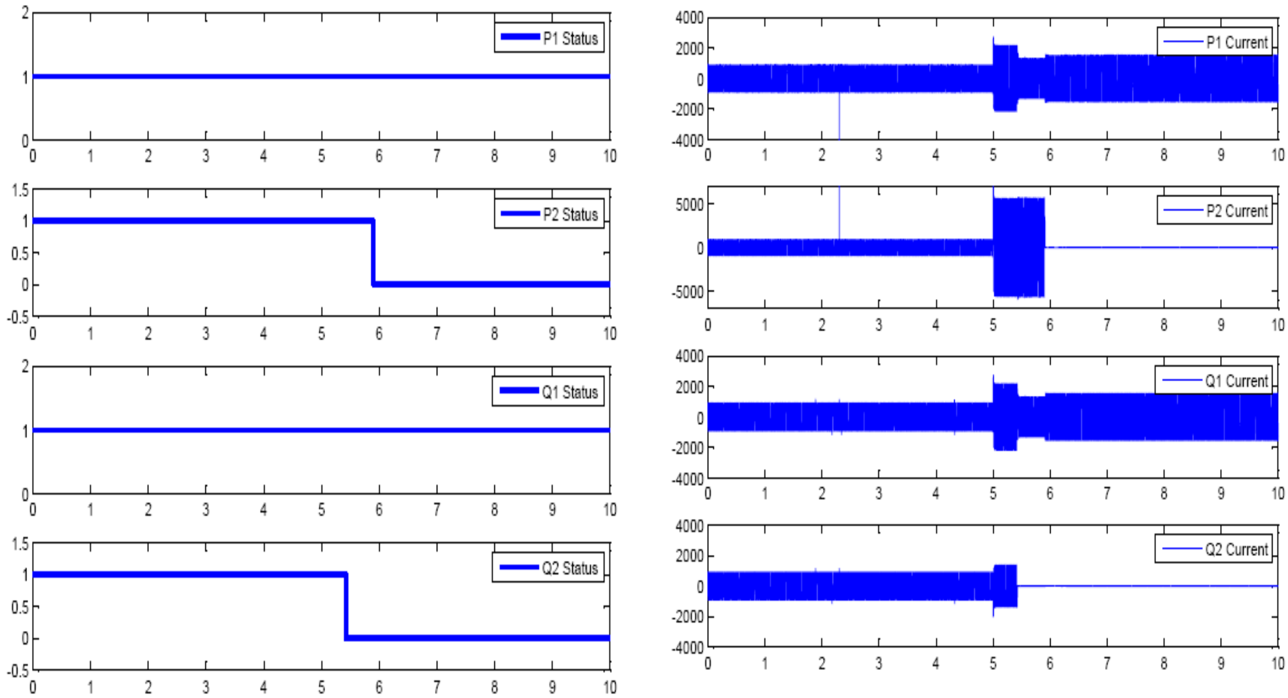


Figure 16 (g) Relay status and fault current in case of DL fault

CONCLUSION

Models of Digital OCR and Digital Directional OCR have been presented in this paper in MATLAB/SIMULINK. These models have also been contributed to MATLAB's resources to strengthen their Power System Tools. The performance of these models was showcased using suitable tutorial examples. It is shown that these models offer effective means for explaining the functionality of OCR and Directional OCR under various operating scenarios. Additionally, the systematic unfolding style of model development and performance analysis means that this paper could also serves as guide to develop similar relay models and benchmark performance.

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