Over-Current Protection in Transmission Systems using Analog and Digital Relays - Case Study and Comparison

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***Abstract*: This paper focuses on studying a complete comparison between analog and digital overcurrent relays. Analog term is given to the first generation of the electro-mechanical relays whereas digital term is associated with the up-to-dated relays. Digital relays are presently used for secured, dependable and efficient operation of power systems. In power systems, overcurrent protection is essentially required against short circuit faults. The parameters of overcurrent relays are critical and sensitive as incorrect settings of them can cause improper tripping leading to a big problem. Accordingly, these parameters must be tested in order to validate the relay performance subjected to different fault cases. Thus, a radial power system with different fault conditions is taken as a case study using both analog and digital relays individually. The whole proposed system is designed, implemented and simulated using MATLAB program software. The most suitable overcurrent relay adequate with radial power systems is based on time definite characteristics. The overall model is then simulated twice to analyze, study and differentiate the performance of both digital and analog relays when subjected to short circuit faults. Finally, A complete summarized comparison is executed between the analog and digital overcurrent relays showing the features and benefits of digital overcurrent relays over the analog relays.**

Keywords: Digital relays , Radial Network Protection , Over current protective relays, short circuit faults

Acronyms:

CT Current transformer

VT Voltage transformer

OR Overcurrent relay

OCR Over current relay

CB Circuit breaker

TL Transmission line

F-# Fault number

I. INTRODUCTION

A power system faults may cause everlasting damage to power system components resulting in financial burdens for their replacement or maintenance and in long interruption periods of power supply to consumers, which is highly un-recommended. The power systems should be supplied with strong protective elements to make it able to withstand the faults and minimize the hazards on its components also provide satisfied service to customers[1][2].

Thus, a protection relay is essentially used to disconnect a faulty part from the electrical power system after the fault occurring. This protection action guarantees that the healthy section of the electrical power system can continue in operation and secures system from further hazards.

A successful protective relay must characterize by selectivity, high speed, sensitivity, and accuracy [2].

Overcurrent relay is considered one of the most important type of protective devices as it protects against overcurrent dynamic and thermal effects. It is triggered when the sensed current overtakes a pre-setting magnitude. In response, trip signal must be sent to clear the fault very fastly. It is qualified with high speed in clearing high faults because it is inversely proportional to the faulty current value. It means that it needs shorter time to clear higher faulty currents[2][4].

Digital relays have smart algorithms in monitoring the current and voltage of the power system via using CTs and VTs respectively. Protection relays should be tested to confirm their reliability before commissioning them in a substation[2]. In this paper, digital and analog overcurrent relays are provided to be used in protection of a radial power system taken as a testing circuit. This testing model is used to evaluate the performance of both overcurrent relays in clearing faults. The whole system is designed and simulated by using Matlab software. The results obtained by analog and digital relays for the same test system are then compared as it is the main objective of this paper.

The paper is organized as follows. Section I includes the introduction about protective relays and its importance. Section II illustrates the basic concept of overcurrent relays. Section III discusses the standards of selecting and setting the overcurrent relay in brief. Section IV presents the assumed radial network used for testing both analog and digital over current relays . Section V introduces the details of the analog overcurrent relay modelled by Matlab/Simulink Sim-Power Systems in order to validate the operation of the analog overcurrent relay. Results are discussed proving the correct behavior of the proposed relay. A detailed digital overcurrent relay is also modelled by Matlab/Simulink Sim-Power Systems and Then using a radial network testing model in order to validate the operation of the analog overcurrent relay. Also its results are discussed and validation is explained in section VI. Section VII summarizes a complete comparison between the two relays handling various sides and features. Finally in Section VIII, conclusions are drawn and outlined.

II. OVERCURRENT PROTECTION RELAY

As expected from its name, this protective relay is utilized to secure the power system from over currents. The principal methodology of overcurrent protection is to sense the current by CT then compares it with the threshold values[5]. The protection algorithm decides that the overcurrent has occurred when the sensed current surpasses the preset value then sends trip signal to the circuit breaker. Circuit breaker opens its contacts to cut off the protected device and damage is averted[3][5]. Fault pick up state is reached when the relay detects a fault. At the instant of picking up the fault, the relay can send a trip signal immediately in the case of instantaneous overcurrent relays or after a specific delay time in the case of time overcurrent relays. This time delay is calculated according to the used algorithm and it is also called operation time. Fig. 1 presents the simplified protection function block diagram of overcurrent relays[6]. Overcurrent relays classified as instantaneous, inverse time, inverse definite time, very inverse and extremely inverse overcurrent relays.

$$T = \frac{C}{\left(\frac{I}{I_s}\right)^{\alpha} - 1} \times TMS \qquad (1)$$

Where T is the operating time of the relay, C and α are the IDMT relay characteristic constants, I_s is the threshold setting of current, I is the measured current and finally TMS is the abbreviation for time multiplier setting which controls the relay tripping time accommodate to the protection network grade[7][8].

The inverse characteristic curves of different types are obtained depending on α and C constants, listed in Table I [5], which selected also based upon the position of the relays and coordination strategy for the relays[9].

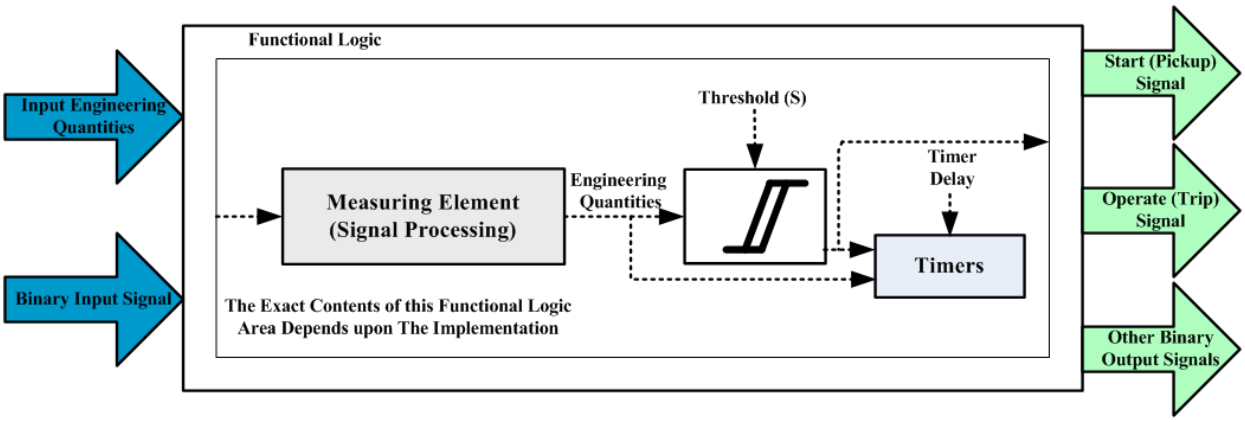

Fig. 1. Simplified function block diagram of protective overcurrent relay.

A. Instantaneous overcurrent relay

These relays are used nearby the system power supply where the value of fault current is very high and any delay time in clearing fault will cause a great damage. Instantaneous overcurrent relay offers zero time delay and sends trip signal to the circuit breaker immediately at the instant of fault occurrence.

B. Definite time overcurrent relay

Definite time overcurrent relays is mostly suitable for backup protection in which if the assigned relay fail to operate then buck up relay should operate and send a trip signal to the breaker. Its time delay is greater than the principal relay time added to the breaker operating time. Definite time overcurrent relay algorithm is used for delayed tripping of over currents.

C. Inverse Definite Minimum Time (IDMT) Overcurrent Relay

The operating time of this relay is inversely proportional to the level of short circuit fault current. It responds faster for higher fault currents[5]. The operating time of specific overcurrent relay given in (1) is calculated corresponding to a particular characteristic curve. This relation is expressed as follows;

TABLE 1. CONSTANTS OF INVERSE TIME CHARACTERISTIC CURVES OF DIFFERENT TYPES

Relay Characteristic Curve	***α***	***C***
Standard Inverse	0.02	0.14
Very Inverse	1	13.5
Extremely Inverse	2	80
Long Inverse	1	120

III. OVERCURRENT RELAY SPECIFICATIONS

The input current of the selected relay should be accommodated with the output of the used current transformer CT. Also the pick-up current and time delay settings must meet the requirements of the location of a given relay. In case of definite time relay, the coordination setting begins at the farthest relay from the supply moving relay by relay towards the source.

A. Pick-up curren

The pick-up current is commonly at 120–150 % of the maximum load current after applying the CT ratio[9].

B. Time delay

The time delay setting is computed by equation (2)[9] :

Time delay = maximum time delay of the relay downstream + maximum CB operating time + security margin (2)

The security margin ranges from 0.3 to 0.5 s as it relies on the installed relays accuracy of and the operating time of the CB.

IV. The Proposed Radial Network Used for Testing Analog and Digital Overcurrent Relays

The circuit used for testing the analog and digital relays is a radial network contains system source, two transmission lines and three bus bars feeding several loads as shown in Fig. 2. The radial networks to be protected from faults, coordination and selectivity require certain time delays which are satisfied by using definite time overcurrent relay type. The time delays of overcurrent relays in protection system of the proposed network are developed based on the definite-time overcurrent relaying principle which clarified in Fig. 3.

V. Modelling and Testing of Analog Overcurrent Relay

Analog concept is assigned to the first generation of electro-mechanical commercial relays.

A. *Analog Overcurrent relaying principle*

Applying overcurrent relaying principle on the testing circuit shown in Fig.2, it is found that;

Case 1: When the fault is detected at load 3 (F-3) by CT 3, OR 3 operates and trips CB 3 removing load3 and the rest of the network continue in operating.

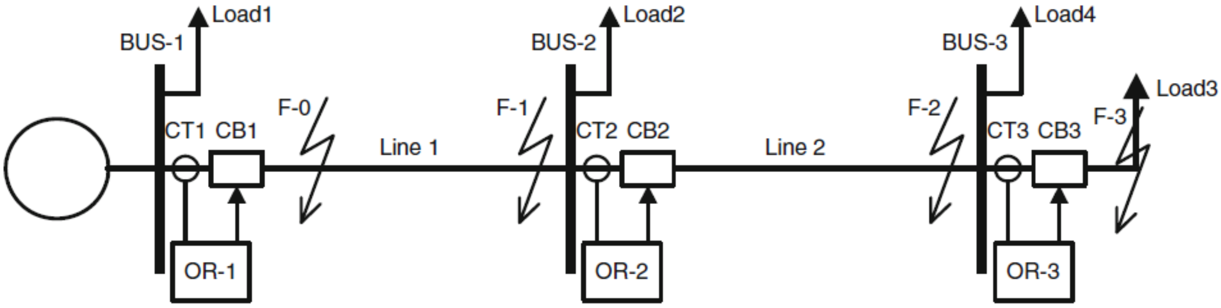

Fig. 2. The proposed radial network used for testing overcurrent relays

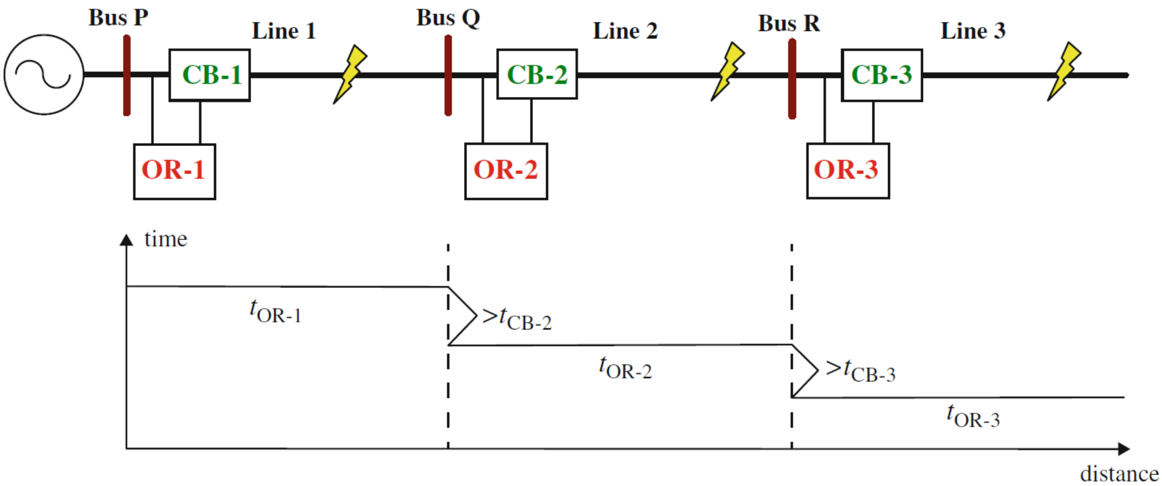

Fig. 3. Time delay of definite-time overcurrent protection principle used in radial networks

A. *The performance sequence of definite time OCRs is summarized in the following;*

- The current transformer and circuit breaker, used to protect certain element, are connected to that element from the source side terminal to be capable of cutting it off at fault case.
- The current magnitude is sensed by CT and compared to the threshold setting by the overcurrent relay.
- The fault is cleared in a protected element after both periods of relay and CB operating times.
- Moving from the farthest relay of the source towards the nearest one, a delay time must be added so that the nearest relay to the fault operates first.

Case 2: CT 2, OR 2, CB 2 are assigned to protect transmission line 2 but it cannot differentiate between F-2 and F-3. Thus OR-2 should have a specified time delay longer than the clearing time associated with elements fed by bus bar 3. Accordingly, the relay OR 2 will operate when the fault downstream from transmission line 2 or when OR 3 failed to operate as buck up protection.

Case 3: similarly, CT 1, OR 1, CB 1 are assigned to protect transmission line 1. OR 1 should be coordinated with downstream relays OR 2 and OR 3 in order to guarantee selectivity of operation.

B. *Analog overcurrent relay testing MATLAB/SIMULINK model*

In this section, analog OCR testing model for three-phase power system designed by MATLAB/SIMULINK program is shown in Fig. 4. It consists of three bus bars and loads are connected at each one of them. There are two transmission lines connecting between them. Table II introduces the parameters' values used in the simulation of the testing power system using analog ORs. The detailed model of analog overcurrent relay based a definite-time type is shown in Fig. 5. There are three fault locations to be tested, one at the end of the line 3 at load 3, the other fault to be tested is at bus bar 1, short circuit in the middle of transmission line one as shown in Fig.4. basic functions are used to model the analog relay.

C. *Simulation results for the analog overcurrent relay*

The simulation results of the power system performance

validate and observe how the given protection system using definite time overcurrent type displayed in Fig. 4 works in accurate and correct manner. The relays operate as expecting and verified by simulation results.

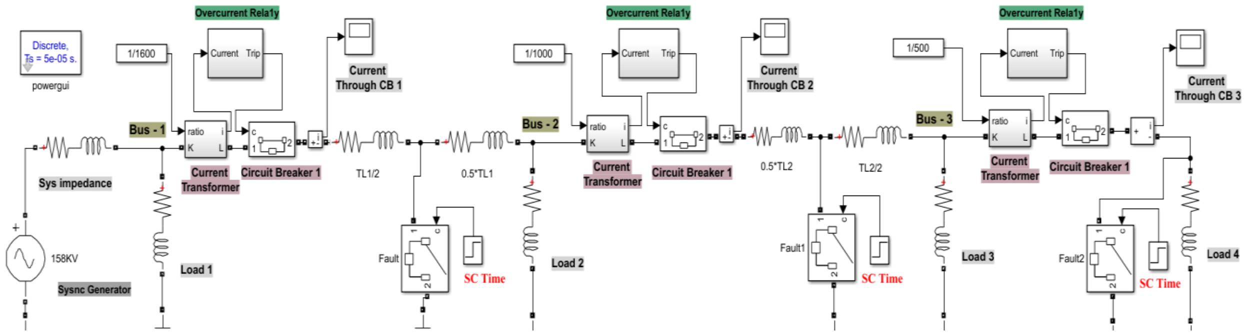

Fig. 4. Analog overcurrent relay MATLAB model

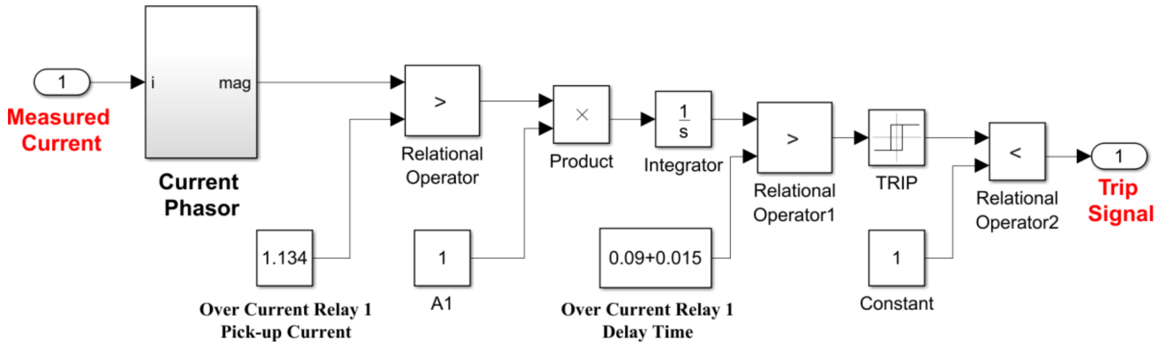

Fig. 5. The functional model of analog overcurrent relay based a definite-time type

TABLE 2. TESTING POWER SYSTEM DATA (ANALOG MODEL)

Testing Power System Data (Analog Model)				
System voltage	158 kV, 114% of 138 kV / 0 phase angle / 50 Hz			
System impedance	1+ *j* 10 Ω			
Transmission Lines	TL 1 impedance		2+ j 20 Ω	Fault location 0.5
	TL 2 impedance		2+ j 20 Ω	Fault location 0.5
Loads	Load-1	138 kV	100MW	30 MVAR
	Load-2	138 kV	100MW	30 MVAR
	Load-3	138 kV	50MW	15 MVAR
	Load-4	138 kV	50MW	15 MVAR
Fault	0 Ω		Fault occurrence 10 ms	
Circuit Breaker	CB-1	operating time 15 ms		
	CB-2	operating time 20 ms		
	CB-3	operating time 25 ms		
Current Transformer	CT-1	1600/1		
	CT-2	1000/1		
	CT-3	500/1		
Over current Relay	OR-1	Pick up 1.134 A	delay 90 ms	
	OR-2	Pick up 0.907 A	delay 50 ms	
	OR-3	Pick up 0.907 A	delay 5 ms	

Back-up protection principles are also checked and verified by the testing cases included by the testing model. It means that the relays' operation and coordination are checked with failure of the prospective protective relay or CB. Thus simulation of the radial network protected with overcurrent relays is carried under the following cases which are a fault occurs at the connected load and the other is the same but with circuit breaker failure.

1. *Single line to ground fault at load 3*

Single line to ground fault occurs at 0.1 second, which is then detected by the overcurrent relay nearest to the fault. The analog relay OR 3 sends trip signal immediately to CB3 once the fault is detected to clear it as shown in Fig.6.

The currents through the CT1 and CT2 are affected at the instant of fault occurrence but they continue in these transmission lines, after clearing the fault by disconnecting CB3, but with smaller values than before because the loads after CB3 are disconnected.

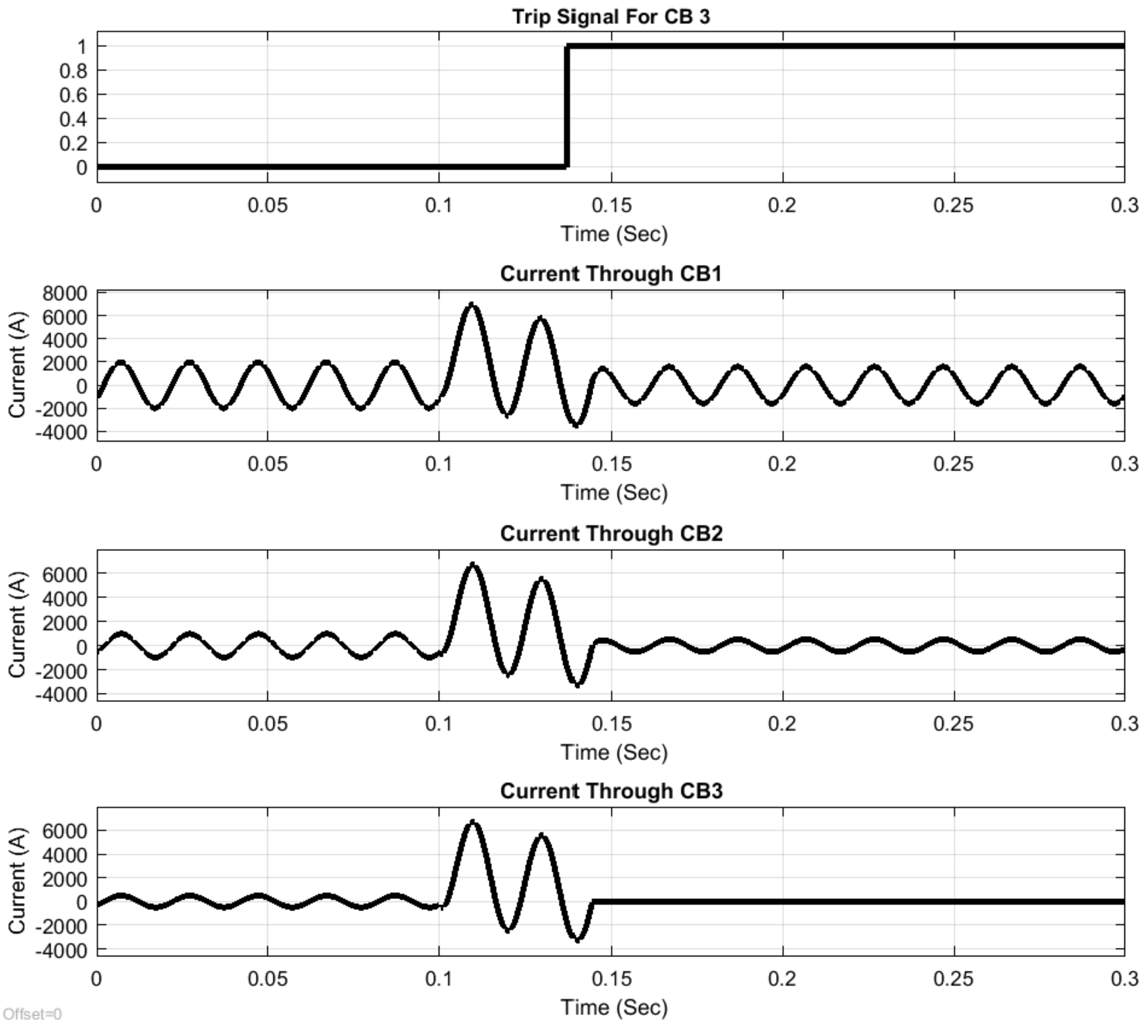

Fig. 6. The analog overcurrent relay's performance when a fault occurs at the connected load.

2. *Single line to ground fault at load 3 with circuit breaker 3 failure*

The fault occurs at 0.1 second, so the current starts to increase. At this instant, the overcurrent relay nearest to the fault detects the fault and starts breaking the circuit by opening the circuit breaker which is connected to it. But due to failure of CB3 associated with this case, the short circuit current lasts longer time until backup relay OR 2 starts working after delay time and clear the fault as shown in Fig.7.

The trip signal of CB2 is introduced after some delay to accomplish coordination between circuit breakers so that circuit breaker 2 is the backup for circuit breaker 3 in case of failure that's why it takes longer to send trip signal to circuit breaker 2, and that is also reflected on the current waveform seen already before.

Due to failure of Circuit breaker 3, circuit breaker is used to clear the fault, that's why the current rests at zero after clearing the fault because circuit breaker 2 is now open and the loads connected after it is isolated from the power source so no current flows.

loads are connected after it so after clearing the fault current continues to flow in the circuit but with smaller value than before because some loads are disconnected.

3. *Single line to ground fault at the middle of the distance of transmission line 1*

The fault occurs at 0.1 second, when it occurs it draws all the current from the power source leaving no current to flow in the rest of the system, that's why current rests at zero at 0.1 second.

Same as before, when fault occurs, it is detected by overcurrent relay and the breaker is opened to clear the fault.

VI. Modelling and Testing of Digital Overcurrent Relay

The digital overcurrent relay is basically similar to the ordinary overcurrent relay as it uses function in detecting the faulty current and as a result it sends the information signal to trip the CB in order to cut off the faulty part. It is also used as principal and back-up protective relay to minimize the damage.

The major difference of digital relay is that it is implemented using microprocessor, DSP or FPGA to make the protection operation faster, more reliable, flexible and controllable[10].

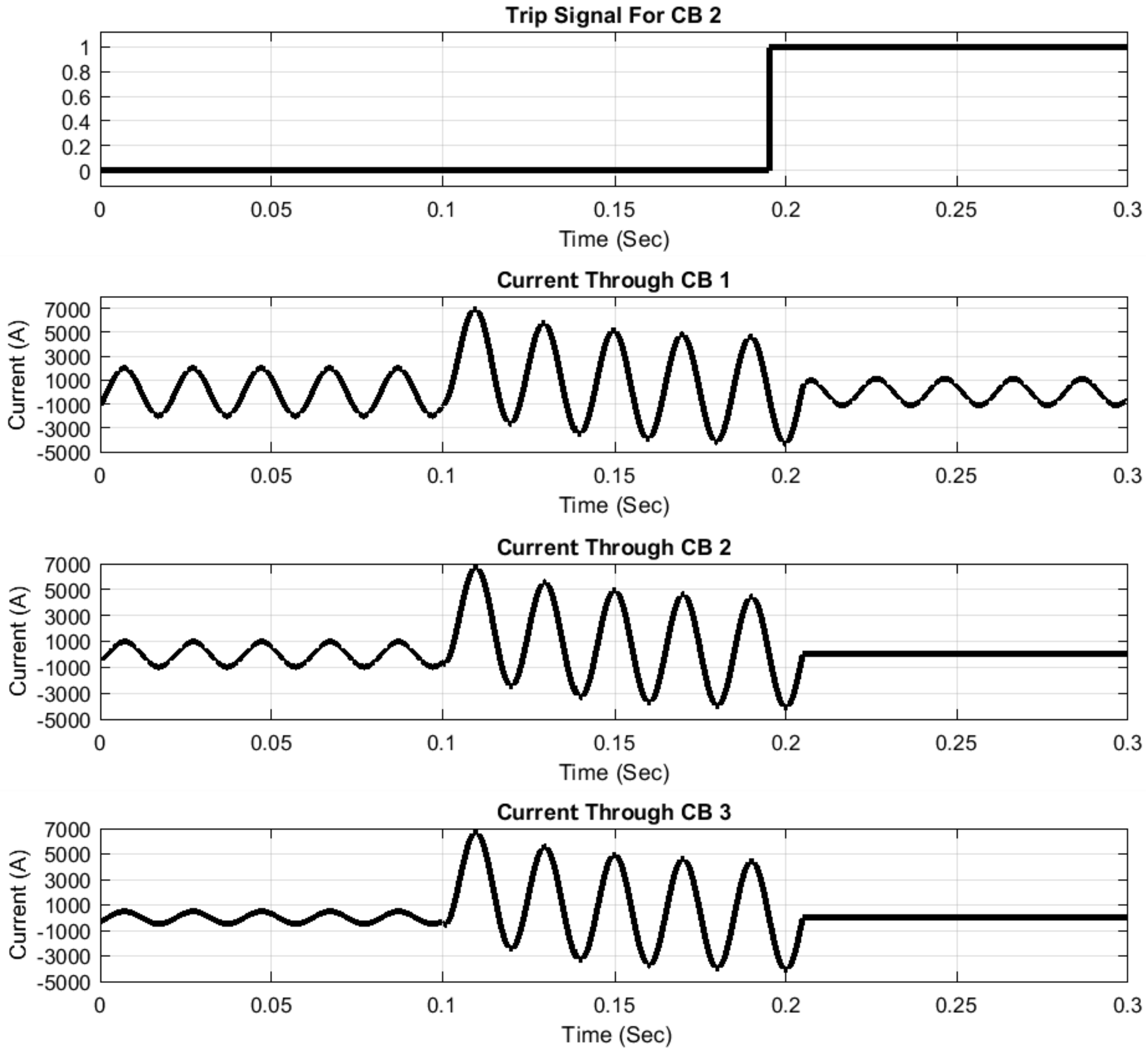

Fig. 7. Analog overcurrent relay's performance when a fault occurs at the connected load with failure of CB3.

A. The components of digital overcurrent relay

Fig.9 presents the basic components of the digital overcurrent relay. It consists of three parts[9];

- The data acquisition part: it interfaces the analog input and connects it to the digital processing bit of the relay.
- The measuring part: it measures specified parameters like magnitude, phase angle, resistance and reactance, active and reactive power considered as input signals in order to make the tripping decision.
- The decision-making part: it compares the signal parameters obtained from the measuring unit with the thresholds settings. Then uses the time delays and logic functions so as to send the trip and alarm signals.

B. Digital overcurrent relaying principle

Applying overcurrent relaying principle on the testing circuit shown in Fig.2, it is found that;

Case 1: When the fault is detected at transmission line 2 (F-2) by CT 2, all upstream relays OR 2 and OR1 will pick up and start timing out. The nearest relay OR 2 operates and trips CB 2 as it has the lowest time delay and the remaining upstream relays OR 1 will stop timing and reset. The downstream part of the network will be disconnected while the upstream will continue normally.

Case 2: When the fault is detected at transmission line 3 (F-3) by CT 3 but OR 3 or CB 3 fails to operate, the next upstream relay OR 2 will clear the fault as a back-up protective relay and the downstream part is disconnected and cutting off healthy part which is undesired.

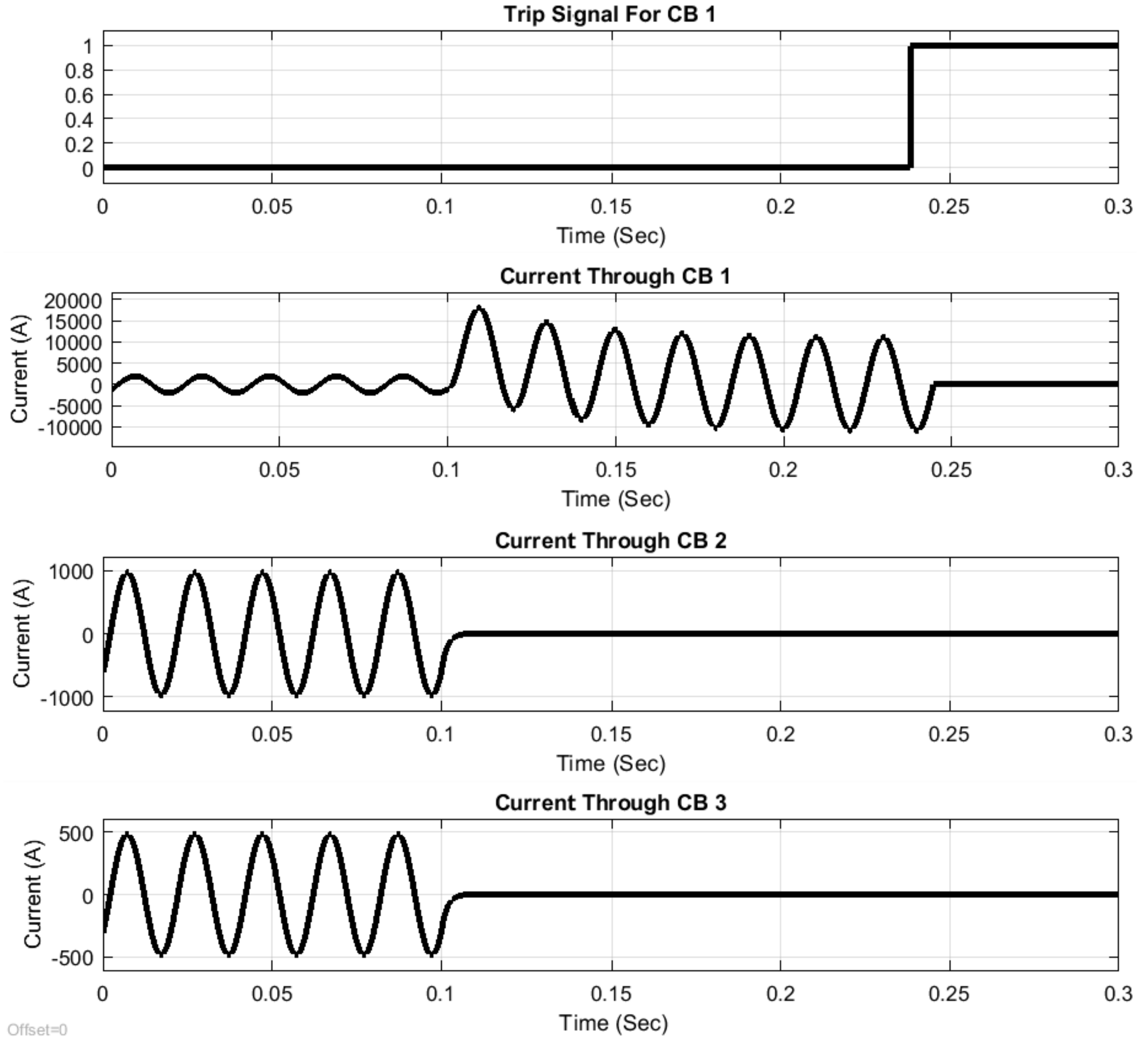

Fig. 8. The analog overcurrent relay's performance when a fault occurs at the middle of transmission line 1.

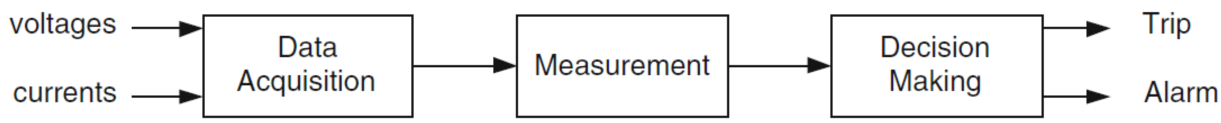

Fig. 9. Basic parts of a digital overcurrent relay

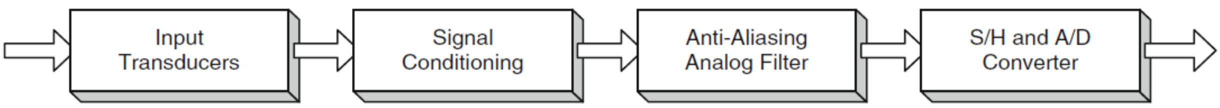

Fig. 10. The detailed input interface part of a digital relay

C. The digital overcurrent relay testing MATLAB/SIMULINK model

In this section, digital OCR testing model for three-phase power system designed by MATLAB/SIMULINK program is presented in Fig.11. It consists of definite-time overcurrent relays used as primary protection for the three transmission lines. The upstream relays are used as back-up relays for the downstream elements.

The input parameters of The relay's block include pickup current, time delay and current threshold and the output parameter is the trip terminal sent to the CB as shown in Fig. 11. Table III presents the parameters' values used in the simulation of the testing power system using digital ORs.

D. Simulation results for the digital overcurrent relay

The simulation results show, study and validate how the protection system using definite time overcurrent relays shown in Fig. 11 operates in accurate and correct manner under the following assumed cases which are a fault occurs at the connected load and the other is the same but with circuit breaker failure.

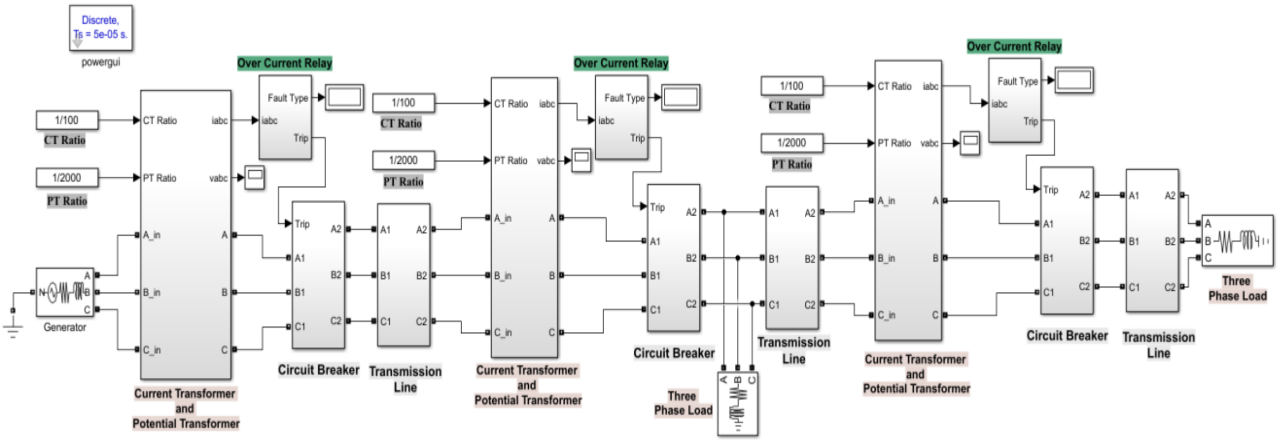

Fig. 11. Digital Overcurrent Relay Matlab Model

TABLE 3. TESTING POWER SYSTEM DATA (DIGITAL MODEL)

Testing Power System Data (Digital Model)				
System voltage	230 kV, 194.367 V / 0 phase angle / 60 Hz			
System impedance	2π × 60×(3.4878 + j 0.1323)Ω			
Transmission Lines	TL resistance	R=0.0815 Ω/mile	R0= 0.3666 Ω/mile	
	TL inductance	L=2.1e-3 H/mile	L0=6.5e-3 H/mile	
	TL capacitance	C=31.6e-9 F/mile	C0=12.7e-9 F/mile	
	Line length = 40 miles			
Load	Load	230 kV	54 kW	26 kVAR
Fault	0.01 Ω	Fault location 0.9 p.u.	Fault time [9 10 11 12 13] s	
Circuit Breaker	CB	Operating time 0.02 ms		
		Breaker resistance Ron =0.01 Ω		
		Snubber resistance RS = 1e6 Ω	Snubber Capacitance CS = inf F	
		Initial state (Closed)		
Current Transformer	CT	100/1		
Voltage Transformer	VT	2000/1		
Over current Relay	OR-1	Pick up 3.8 A	delay 1 ms	Residual threshold 0.1A
	OR-2	Pick up 2.6 A	delay 0.6 ms	Residual threshold 0.1A
	OR-3	Pick up 1.4 A	delay 0 ms	Residual threshold 0.1A

E. *Simulation results for the digital overcurrent relay*

The simulation results show, study and validate how the protection system using definite time overcurrent relays shown in Fig. 11 operates in accurate and correct manner under the following assumed cases which are a fault occurs at the connected load and the other is the same but with circuit breaker failure.

1. *Single Line to Ground Fault at the Connected Load*

Single line to ground fault occurs at 0.1 second, which is then detected by the digital overcurrent relay. The digital relay OR 3 sends trip signal immediately to CB3 once the fault is detected to clear it. Phase A at which fault occurs is shown in red in Fig.12.

The CT1 and CT2 sense the fault and the currents are continued in these transmission lines after clearing the fault but with smaller values than before because some loads are disconnected (the loads in the same side as the fault).

2. *Single Line to Ground Fault at the Connected Load with Failure of CB3*

The fault occurs at 0.1 second, so current of phase A starts to increase as shown in Fig.13 but due to failure of CB3, it lasts longer until backup relay OR 2 starts working after delay time and clear the circuit. The trip signal is delayed to accomplish coordination.

Since there are no loads connected after CB 2 and before CB 3, current rests at zero after CB 2 is opened.

The CT 1 sense the fault and the current is continued in transmission line 1 after clearing the fault but with smaller value than before because some loads are disconnected (the loads in the same side as the fault).

VII. COMPARISON BETWEEN ANALOG AND DIGITAL OVERCURRENT RELAYS

A. *Similarities*

Both require Current transformers to obtain current value of the current, which based on it the decision is made whether to send trip signal or do nothing.

B. *Differences*

The current signal obtained from current transformer is used differently in each type

- Analog overcurrent relay uses the current itself to generate attraction force that changes the state of the switch used to send trip signal
- Numerical overcurrent relay doesn't use the current itself but the value of the current, so it adds additional stage of converting the value of the current to numerical value processed by the processor of the relay.

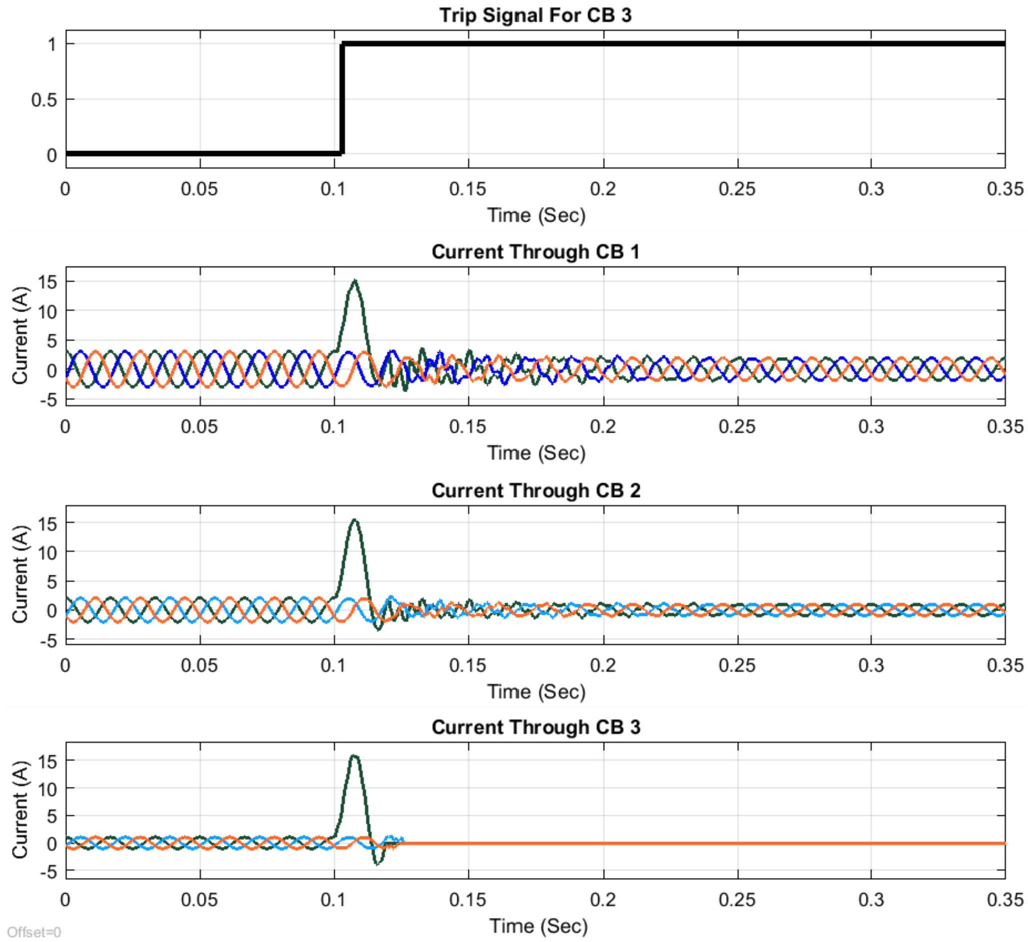

Fig. 12. The digital overcurrent relay's performance when a fault occurs at the connected load.

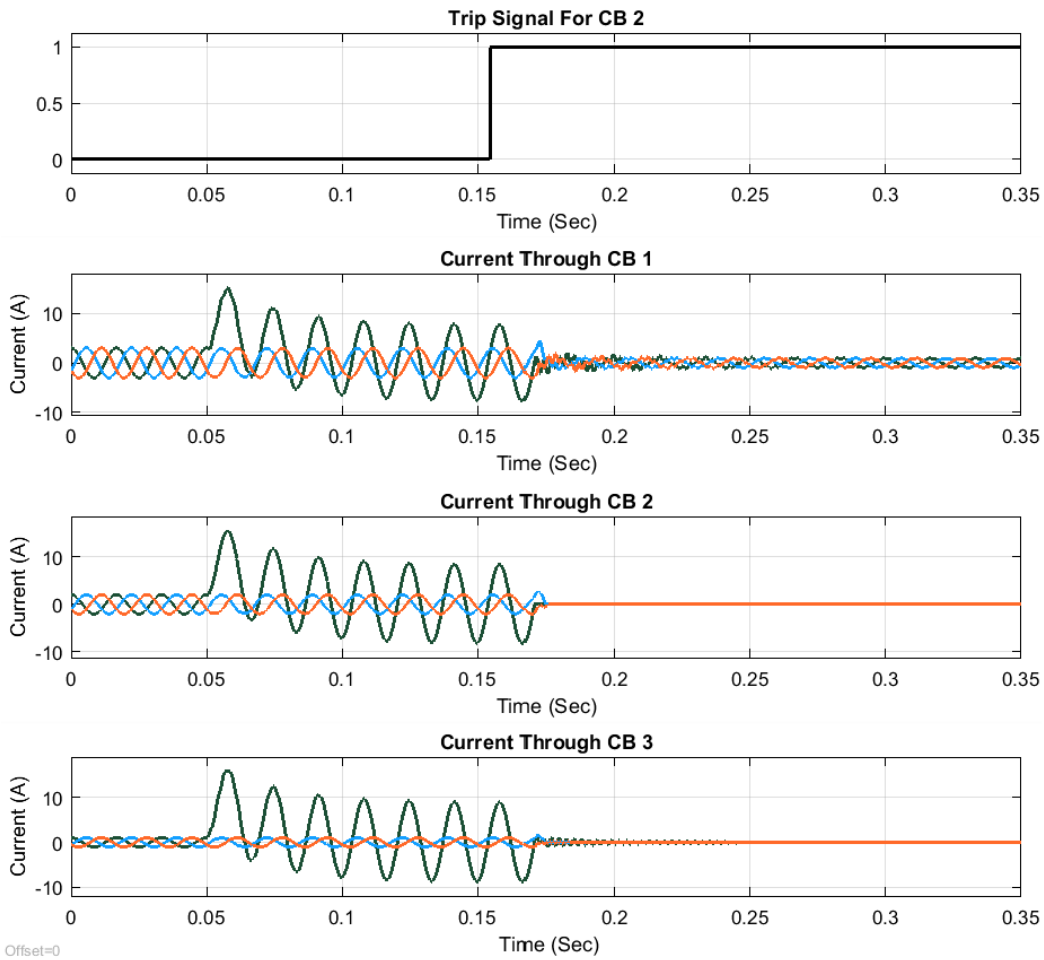

Fig. 13. The digital overcurrent relay's performance when a fault occurs at the connected load with failure of CB3.

C. *Working Principal*

1. Analog Overcurrent Relay

The analog overcurrent relay uses the current itself to generate electromechanical force that change the state of a switch when current exceeds certain value.

This switch is connected in series in the tripping signal circuit, normally it is open and it closes when fault occurs sending trip signal to the breaker.

The current and the time it takes to change the switch can be changed mechanically so to adjust the relay to perform coordination based on pre-calculated curves of pickup current and time.

2. Numerical Overcurrent Relay

A code that evaluates the current value of the current (after using analog to digital converter to obtain the numerical value) and determines whether to trip or just send alarm signal.

The whole process and logic are accomplished in the CPU of the relay and no need for any electromechanical components, only solid-state devices.

D. *Adjustment of critical values*

1. Analog Overcurrent Relay

The values such as pickup current and time settings affect mechanical components that are places inside the relay such as springs and spaces between contacts.

Mechanical components are inaccurate (may cause different trip times for same conditions) and wear out overtime or undergo behaviors that is related to mechanical problems which consequently will affect the breaking process.

2. Numerical Overcurrent Relay

The adjustments required can be made digitally and will be kept the same overtime, no loss or change of information may occur of the power source of the relay is maintained operating all the time.

Same performance is expected every time as the values are logically analyzed.

E. *Tripping Signal and Coordination*

As shown in simulation results above, the tripping signal can be adjusted for both types, each by its own way, however, the accuracy is different.

Digital overcurrent relays tend to have higher accuracy regarding timing, for example once the fault is detected, trip signal can be sent immediately while the same action may take longer time in analog relays for the contacts to move and complete tripping circuit.

Time delays required to achieve coordination can be easily set using digital overcurrent relays because it is numerical values that can be entered meanwhile for analog overcurrent relays it may be more inaccurate and harder because timing curves are required for each relay and more analysis is required based on certain factors and other criteria that may affect the calculations such as current transformer ratio.

The following table summarizes all the features, pros and cons mentioned above in more ordered fusion.

TABLE 4. COMPLETE COMPARISON BETWEEN ANALOG AND DIGITAL RELAYS

Characteristic	El. Mech. Relay	Digital Relay
Technology Standard	1st generation relays.	Present generation relays.
Operating Principle	They use principle of electromagnetic principle.	They use microprocessor. Within built software with predefined values
Measuring elements/ Hardware	Induction disc, electromagnets, induction cup, balance beam	Microprocessors, digital ICs, digital signal processors
Measuring method	Electrical qtys converted into mechanical force, torque	A/D conversion, numerical algorithm techniques
Surrounding Environment	Depend upon gravitation and the value changes to the surrounding magnetic fields also.	
Relay Size	Bulky	Small
Speed of Response	Slow	Fast
Timing function	Mechanical clock works, dashpot	Counter
Time of Accuracy	Temp. dependent	Stable
Reliability	High	High
Vibration Proof	No	Yes
Characteristics	Limited	Wide
Requirement of Draw Out	Required	Not required
CT Burden	High	Low
CT Burden	8 to 10 VA	< 0.5 VA
Reset Time	Very High	Less
Auxiliary supply	Required	Required
Range of settings	Limited	Wide
Isolation Voltage	Low	High
Function	Single function	Multi-function
Maintenance	Frequent	Low
Resistance	100 milli ohms	10 Ohms
Output Capacitance	< 1 Pico Farad	> 20 Pico Farads
Deterioration due to Operation	Yes	No
Relay Programming	No	Programmable
SCADA Compatibility	No	Possible
Operational value indication	Not Possible	Possible
Visual indication	Flags, targets	LEDs, LCD
Self-monitoring	No	Yes
Parameter setting	Plug setting, dial setting	Keypad for numeric values, through computer
Fault Disturbance Recording	Not possible	Possible

VIII. CONCLUSION

The paper introduces the modeling and simulation of digital and analog overcurrent relays based definite time overcurrent principle using MATLAB/SIMULINK software. The testing model is used to differentiate and validate the operation principles of both digital and analog overcurrent relays. Also discusses the behaviors of both over current relays under various scenarios. Proving their effectiveness in fast and correct responding either as primary or back-up relays. Additionally, a complete comparison between digital and analog over current relays are carried showing the benefits of recent digital relays over the analog electromechanical ones.

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