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Using Digital Signal Processing in Power System Overcurrent Relay Protection

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Abstract: The reliability and security are very important issues in Power System. However, the fast development in electrical systems makes the protection more complicated and difficult to achieve the desired objective. Digital Signal Processing used in electrical systems to enhance the operation of digital relays. Digital relays has many advantages such as fast operation and involved many characteristic in one relay. This will significantly improve the reliability and security of the electrical systems. In this paper, the overcurrent relay is designed and modeled in MATLAB/SIMULINK. The performance of the modeled relay is investigated and compared with IEC standard equation as well as ETAP simulation results. The overcurrent relay chosen because it is widely used in electrical systems

Keywords: Digital Signal Processing (DSP), Overcurrent Relay, Instantaneous Relay.

1. Introduction

The Institute of Electrical and Electronic Engineers (IEEE) defines protective relays ‘‘a relay whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control circuit action’’. Thus, protective relays are a set of devices contains analog subsystem, sampling and algorithm technique used to detect faults and abnormal conditions and to disconnect the faulted element (or elements) or take other corrective actions in order to prevent further equipment damage or to avoid a system disturbance.

Another important function of protection systems is to facilitate restoration by providing an indication of the fault. Modern digital relays can transmit the information over a communications channel.

External or internal influences are the reasons for electrical faults. The external influence is such as falling tree of human error, while the external influence is like the equipment ageing. The fault could lead to a total blackout, equipment damage and loss system stability. However, the paper will only consider the short circuit effect.

Generally, short circuits cause very high magnitude system current (larger than the normal load currents). The severity of the fault decided based on the operating conditions during the fault. The operating conditions are such as voltage level, load current, fault type and resistance. The fault (see Fig. 1) is known as an insulation breakdown between conductors. Which will have low resistance path for the current due to bypassing the remaining of the circuit. This is a simple explanation for the short circuit or the representation for the meaning of fault.

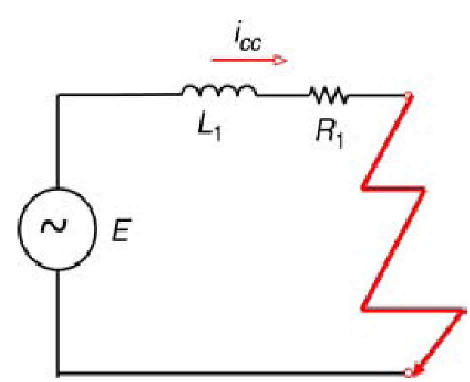

Figure 1. Short Circuit Representation

There are four main types of faults: Line-Line-Line (Three Phase fault), Line-Line, Line-Line-Ground and Line-Ground which is the most famous fault and the occurrence possibility is 85% compared with others. Fig. 2 shows the waveform for the current during the fault. The first cycle looks different due to DC component existence in electrical systems.

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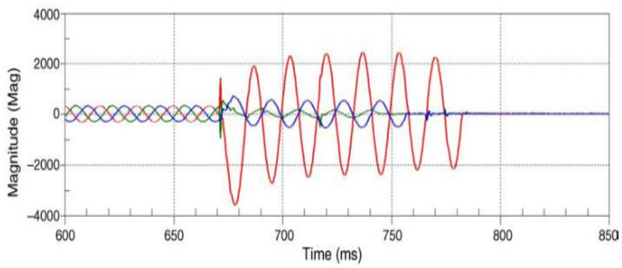

Figure 2. Waveform of Single Phase Fault with DC offset

2. Power System Protections

Electrical system components (overhead lines, cables, transformers, etc.) have metallic conductors (wires) that experience this high current. To explain the importance of speed in protection equipment, Fig. 3 represents a brief overview of thermal damage.

Fig. 3 shows how an insulated conductor is damaged if a large enough current is applied. The damage time is the time required for a cable with a given current to reach a temperature at which damage occurs. We can show (experimentally and analytically) that: The damage time is shorter as the applied current is larger.

To achieve the main protection goal, when a fault occurs, the circuit breaker must completely clear the fault before the protected equipment is damaged. In other words, the operating time of the relay, plus the operation time of the circuit breaker, including the arc extinction time, must be shorter than the damage time of the protected equipment. Notice that all of this happens without the intervention of a human being. This is a fast, automatic action.

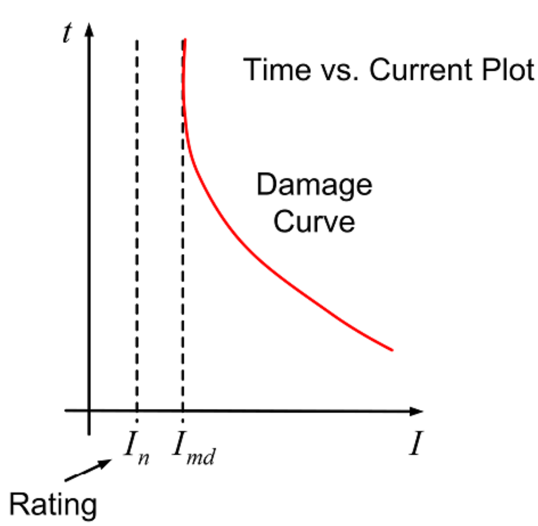

Figure 3. Thermal Damage Curve

Besides the thermal damage, equipment can also suffer mechanical damage during short circuits. Large short-circuit currents produce large mechanical forces. Large mechanical forces can cause permanent deformation in the equipment. The effect could be very destructive in transformers, motors, and generators. Damage occurs instantaneously (in a very short time).

Finally, all relays have a zone of protection controlled by the CT location. The zone of protection shows the area that relay can cover. So, when any fault happen within the zone, the fault will be cleared by the relay responsible on that zone after it get sensed by the CT (See Fig. 4).

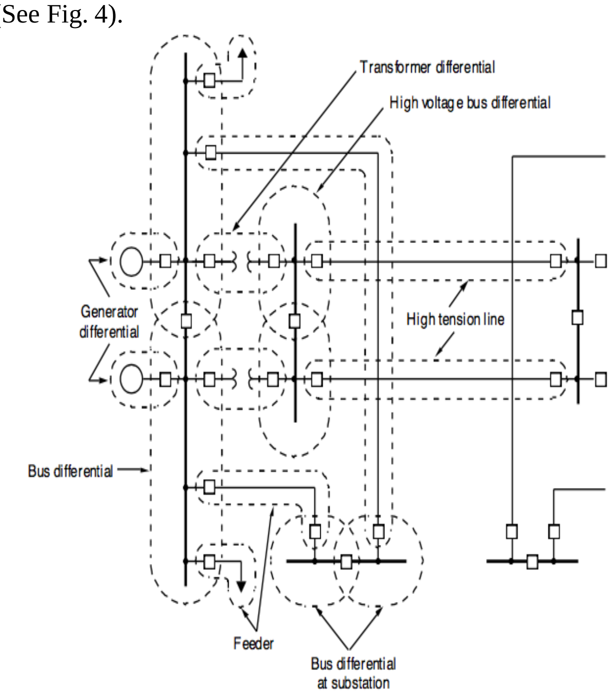

Figure 4. Zones of Protection

3. Protection System Components

Protective relays detect faults and abnormal conditions in the protected element and close an output contact to initiate circuit breaker tripping. Because the relay is a low-voltage device, it must be isolated from the high-voltage system. This is accomplished through the use of current and voltage transformers (CTs and VTs). The one-line diagram shown here depicts a relay that receives current only from the system. Breakers receive the tripping signal from the relays and open the primary circuit to interrupt the fault current. The DC supply system provides the breaker tripping current when protective relay output contacts close. In transmission lines, a communications channel could be necessary for the relays at both line ends to exchange info.

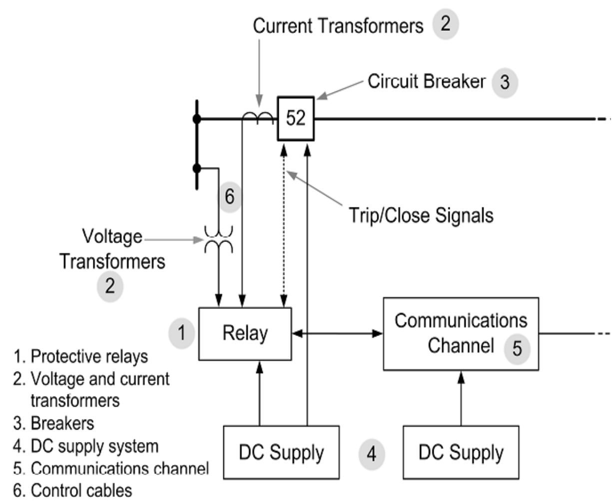

Figure 5. Protective Relays Scheme Elements

Protective relays system reliability depends on all electrical system elements. Electromechanical relays are simple relays but it cause a lot of system faults due to the low reliability and frequent failures. Digital relays are highly reliable devices. These relays, besides providing protection, can also monitor the status of protection system elements, further enhancing protection reliability.

In a classification according to design, we can break protective relays into analog and digital relays. Analog relays include electromechanical and static relays. In digital relays (also called numeric or microprocessor-based relays) the input voltages and currents are converted into digital quantities. Microprocessor platforms digitally process these quantities to execute protection functions. Modern digital relays also provide control and monitoring functions and have communications capabilities.

4. Digital Overcurrent Relay

Overcurrent protection, the simplest and most economical protection, is generally limited to radial lines and widely used in industrial and utility distribution systems. It uses only current information to detect faults in the protected element. The basic idea is that short-circuit currents are larger than normal load currents. In most cases, there is a separation between the load current region and the fault current region. It is therefore possible to set the overcurrent relay pickup current between these two regions.

According to their operating time characteristics, overcurrent relays can be classified into:

- Instantaneous overcurrent relays (50, 50N)
- Time-delayed overcurrent relays (51, 51N): Definite-time overcurrent relays and Inverse-time overcurrent relays, which will be discussed in this paper.

5. Overcurrent Relay Design

In 1985, digital relays dominated electrometrical relays. The circuit of digital relays shown in Fig. 6, a digital relay has an analog input subsystem, an analog-to-digital (A/D) converter, a microprocessor system, a discrete output subsystem, operation signaling elements, and communications ports. The analog and discrete input subsystems prepare the signals before they are converted to digital signals for processing in the relay microprocessor system.

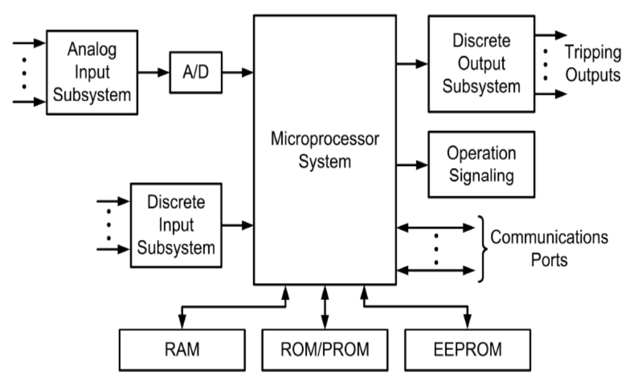

Figure 3. Functional block diagram of a digital relay

A. Analog Antialiasing Filtering

Low pass filters are used to remove the noise and disturbance in the system in order to have a clean wave form for sampling purposes as shown in Fig. 7. The main objective of the low pass filter is to pass the components below f_k and to eliminate the very high frequency components. So, the targeted cut-off frequency of the filter f_c is as follow:

$$f_k < f_c \leq (f_s - f_k)/3 \quad (1)$$

Where f_k is the fundamental frequency, which is 60 Hz in many countries for electrical systems. f_s is the sampling frequency and f_c is the desired cutoff frequency for the filter.

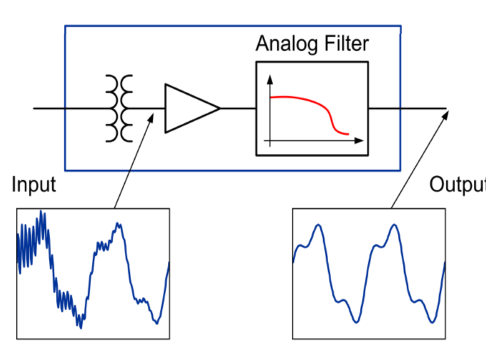

Figure 4. Low Pass Analog Flirting of The Input signal

The number of samples that the relay is taken is controlling the sampling frequency. The relays are available in the market nowadays are capable to take 24 sample per cycle. Thus, the sampling frequency is 1440 Hz with 60 Hz as fundamental frequency. The designed low pass filter frequency response shown in Fig. 8.

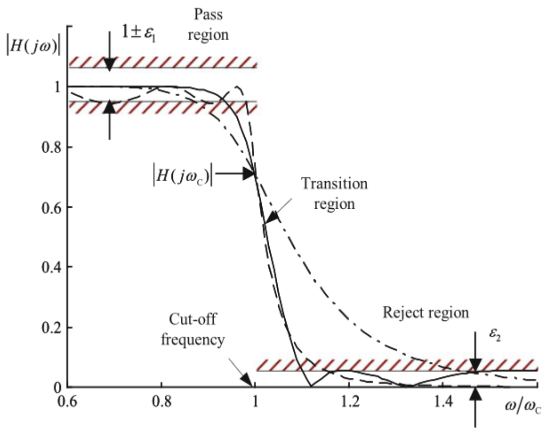

Figure 8. Low Pass Filter Frequency Response [1]

B. Sampling and A/D Conversion

The A/D converter samples the incoming analog signals and converts the sampled values to a digital format as required for further processing in the relay microprocessor system as Seen in Fig. 9. As a rule of thumps "Shannon Theorem", the minimum sampling frequency is twice the fundamental frequency [1].

$$f_s \geq 2f_k \tag{2}$$

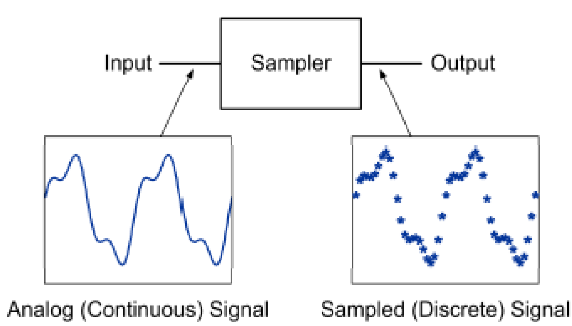

Figure 9. Sampling of Analog Signals

Sampling frequency is decided based on the number of samples will be taken in a cycle. For example, 16 samples and 60 Hz fundamental frequency is resulted in 960 Hz sampling frequency. The A/D converter parameters are the number of bits and converter range. Where the gain conversion is

$$d = M/(2^m - 1) \tag{3}$$

Where M is the converter range (usually 3 [2]) and m is the number of bits. So, higher bits means higher resolution. Overcurrent relay must have higher number of bits, in order to get the high current level during short circuit (usually 12 to 16 bits [1]). The minimum number of bits can be calculated using [1]

$$m \geq \log_2[0.5M/(\varepsilon X_{min})] + 1 \tag{4}$$

Where X_{min} is the smallest expected signal value and ε is the minimum error maintained by the designer.

C. Digital Signal Processing (DSP)

The digital relay algorithm is a set of mathematical operations implemented in a program. These operations are performed over the last N samples of the input signal. The relay makes the decision of tripping or not tripping the breaker based on the result of the algorithm.
The relay algorithm is programmed and stored in the ROM memory. The algorithm is divided in several routines, or functions. A protection algorithm includes the following routines:

1) Reading (read last sample): Digital relay algorithms process a given number of the most recent digitized samples. So they read the last sample of the input signals. The typical data window length in relays is one cycle, so N is generally the number of samples that fit in cycle.
2) Protection functions: Implements the relay protection function(s), such as overcurrent, directional, distance, differential, and other functions.
3) Relay logic: With the results of the protection function routine, the relay logic makes the final decisions for tripping and other functions. In some modern relays, the user can program the logic.

The Inverse Definite Minimum Time (IDMT) equation that is used for the overcurrent relay algorithm

$$t = \frac{C}{\left(\frac{I}{Is}\right)^{\alpha} - 1} \times TMS \tag{5}$$

Where t is the operation time, C is the constant for relay characteristics, α is constant representing the inverse time type, I is the current detected by the relay, I_s is the current set point and TMS is the time multiplier setting.
The relay characteristics constants as shown in TABLE I and Fig. 10.

TABLE I
RELAY CHARACTERISTICS TYPES DATA

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

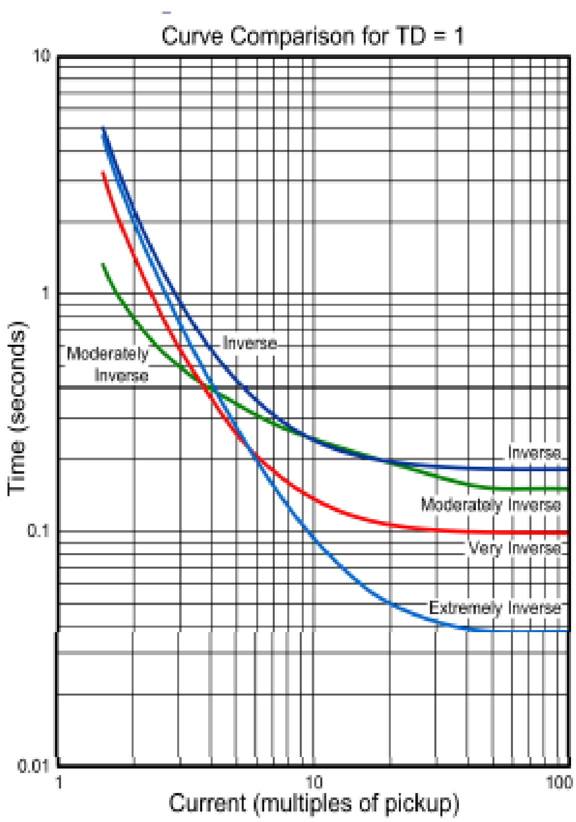

Figure 10. Different Inverse Characteristics Curves

6. CASE STUDY AND RESULT DISCUSSION

In this paper, the design of a digital overcurrent (O/C) protection function simulated on MATLAB/Simulink. The relay will be designed to protect a 5000 kVA transformer with 13.8 kV high voltage and 480 V in the secondary voltage from overloading or short circuit.

$$FLA = \frac{VA}{\sqrt{3} \times V} \quad (6)$$

The current on the primary will be 209A and as per IEEE protection standards, the current pickup of OC shall be (110%-125%) of the full load current, which is around 230A. The current transformer (CT) ratio will be 300/5. So the secondary pickup current will be 3.833A.

The protection scheme time-current curve is drawn by the ETAP as shown in Fig. 11. It can be seen that the transformer is fully protected against the thermal damage by this OC relay. The relay will send the signal to the breaker to trip if the overload is detected.

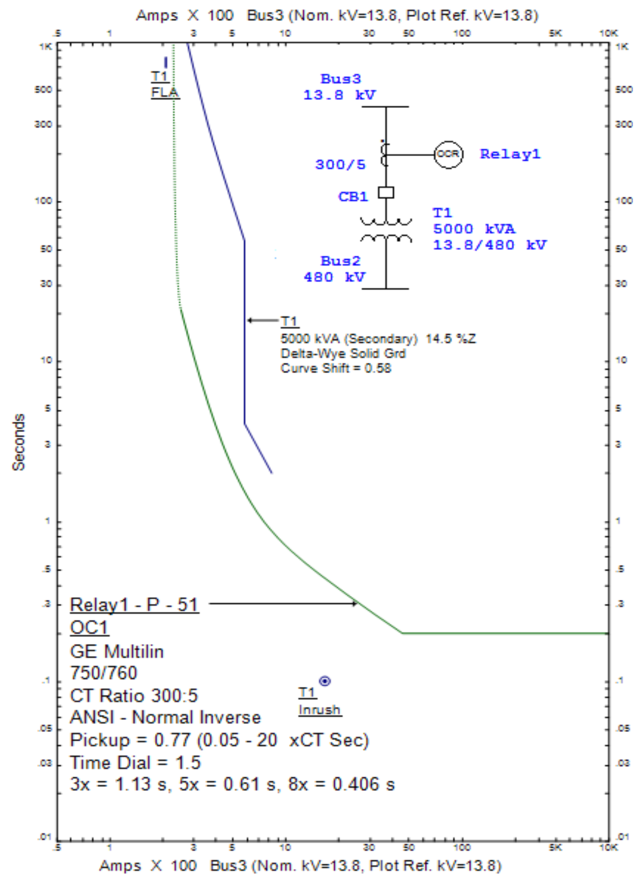

Figure 11. ETAP TCC for protecting transformer

The input for the system in the normal condition (transformer fully loaded) will be a sine wave with magnitude 209 A RMS and 60 Hz frequency which is the fundamental frequency in the power system. This current will be divided by 60 which is the CT ratio. However, another high frequencies signal will be added to the fundamental signal to represent the transient during the fault condition.

For the Low pass filter, as mentioned before it is used to meet the following requirements:

$$fk < fc \leq \frac{fs - fk}{3}$$

Where fs is a sampling frequency. So if our fs is 1200, the cut off frequency shall be between 60 and 380. In this paper, the cut of frequency selected to be 100 Hz.

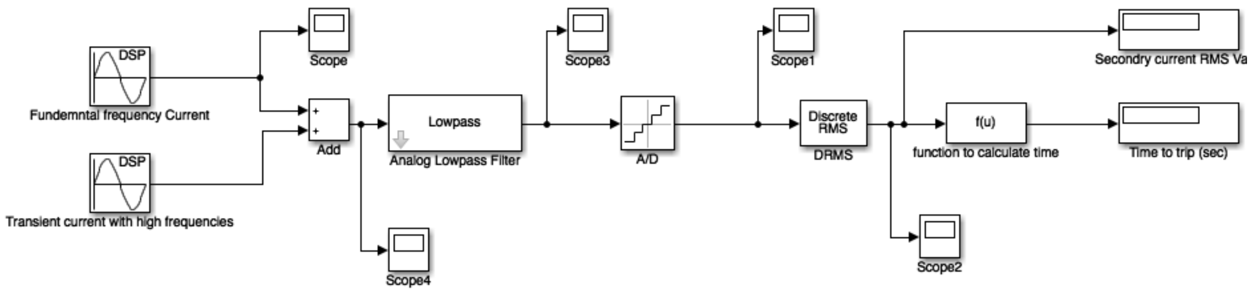

Figure 13. Designed Overcurrent Relay Model in Simulink Environment

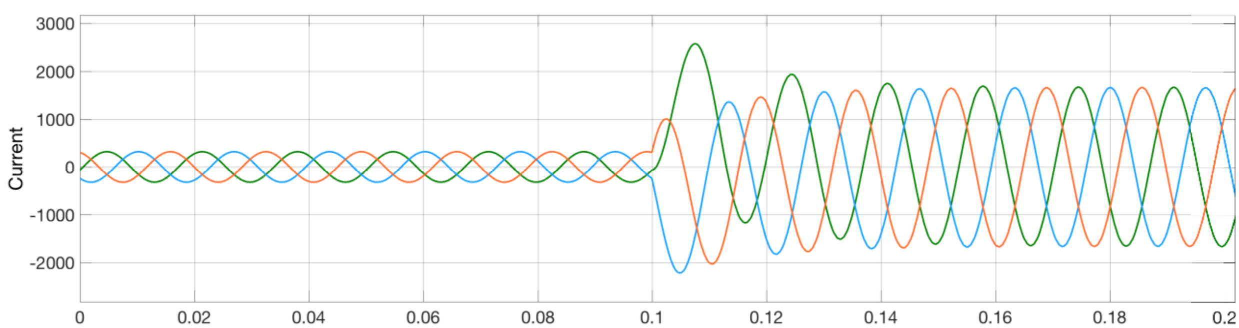

Figure 14. Fault Effect Voltage and Current

Then, the analog input, after the low pass filter cleared the signal, will be sampled at 1.2kHz sampling rate. As stated before, the sampling frequency must meet the Nyquist criteria by taking double of the sampling rate as a sampling frequency. Using this sampling rate, the number of samples will be 20 samples per cycle.

Digital overcurrent relays respond to the RMS current value. For a pure sinusoidal wave current, the true RMS current coincides with the magnitude of the fundamental frequency component. The 20 samples taken from the input current in A/D converter are used for the root mean square (RMS) calculations. The RMS computation is used for fundamental component extraction using the input current samples. This RMS value is compared with the pickup value in the design stage, which is 3.833 Ampere. If the RMS is lower, it will go for the other cycle. Otherwise, the digital relay will see abnormal condition and will calculate the time to trip the breaker.

Finally, the calculated RMS values will be compared with the setpoint for the current. In this case, 230A is the setpoint for the current. If more than 1 is obtained from the currents ratio, this means the input exceeded the setpoint. Thus, a command will enable the relay operation and the operation time will be calculated based on IEC standard equation for the inverse characteristic shown in (5). The selected values are: $C = 13.5$ and $\alpha = 1$ for very inverse, TMS= 1.5, IS= 3.833 current pickup time.

The overcurrent relay design in MATLAB/SIMULINK is shown in Fig. 13 and the summery of its process in Fig. 12. The final results obtained from MATLAB simulation compared with IEC shown in TABLE II.

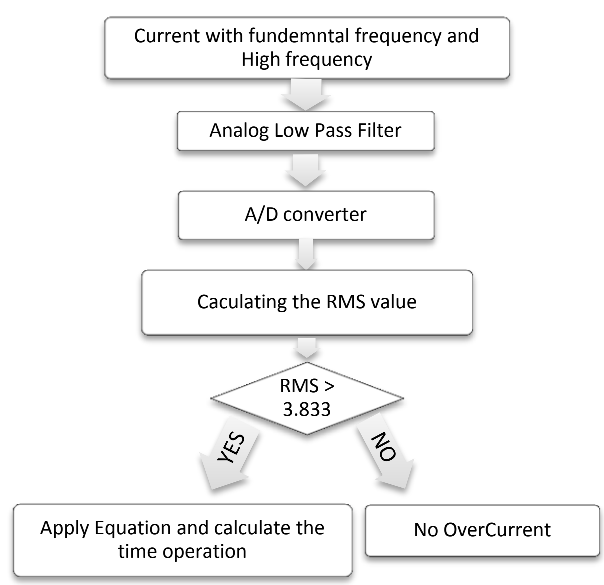

Figure 12. Summarized Flow Chart

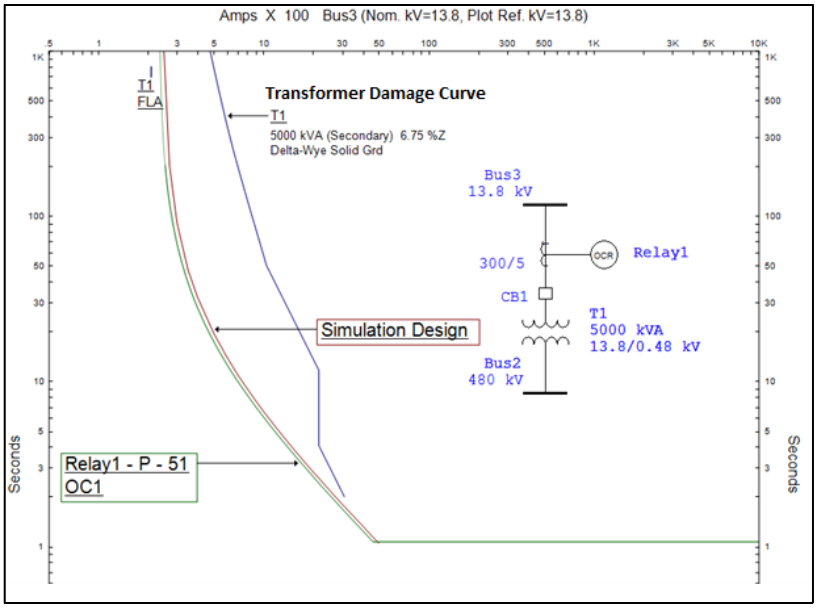

Figure 15. Modeling Simulation Results in the ETAP

TABLE II
RELAY OPERATION TIME FOR (VERY INVERSE, TMS = 1.5)

Amp	IEC	SIMULINK Simulation Results	
		Sec.	Error
231	N/A	N/A	N/A
270	116.44	203	86.56
300	66.54	90.82	24.28
350	38.81	46.99	8.18
400	27.40	32.16	4.76
500	17.25	19.54	2.29
600	12.59	14.05	1.46
700	9.91	10.94	1.03
900	6.95	7.603	0.65
1000	6.05	6.593	0.54
1400	3.98	4.304	0.32
2000	2.63	2.833	0.20
3000	1.68	1.805	0.12
4000	1.24	1.33	0.09
5000	0.98	1.046	0.07

It can be seen from TABLE II that the operation time of the paper design is higher than the ideal formula (IEC) and the difference is decreasing as the input current is increasing from 230 ampere to 5000 ampere. However, to examine the performance of the relay in protecting the 5000kVA transformer, the results from the simulation is modeled in the ETAP. This is to insure that our design will be below the damage curve of the transformer.

It can be seen from Fig.15 that the proposed relay simulation has an excellent result in protecting the transformer since it is below the damage curve of the transformer. Also it has the same characteristics as the ideal relay from the ETAP library.

7. CONCLUSION

Relays are used in electrical system to protect the system and the equipment. One of the most famous relay and used everywhere is the overcurrent relay. It is designed to protect the system and the equipment from internal or external faults. Overcurrent relay is a simple relay with a huge benefit to the electrical system.

Electrometrical relays in the past were not efficient and slow in operation. Nowadays, Digital Signal Processing (DSP) used to enhance the reliability and increase the operation time of relays. The new relays are developed with the help of DSP is Digital Relays.

The paper developed a digital overcurrent relay in MATLAB/SIMULINK environment. The result has been compared with IEC results. In addition to a real case study developed in ETAP to check the operation time. Results clearly indicate that the operation time obtained for simulation method is close to IEC 255-3 standard.

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Omar Bamasq received a BSEE degree in electrical engineering from King Fahad University of Petroleum and Minerals in Dhahran, Saudi Arabia in 2012. He joined Saudi Aramco as an Electrical Power Engineer in the Power System Engineering Department upon graduation and continue to work in the area of Power System Design, Protection and System studies. He handled several projects in the area of Power Systems. He has been successfully completed both FE and PE exams to be licensed as a professional Engineer. He has been accepted to University of Southern California in USA to continue his graduate studies in the area of Electrical Power Engineering commencing from fall 2017.

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