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Multifunctional Digital Protection Relay for Voltage and Current Disturbances in Power Networks

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Abstract – *The protection system is an essential part of the electrical power system, designed to minimize disturbances quickly, accurately, and precisely. Excessive electricity use can lead to frequent voltage and current fluctuations, resulting in short circuits, significant current spikes, and equipment damage. In addition to voltage variations, some electrical equipment is highly sensitive to current changes. Therefore, a device is needed to provide protection, prevent damage to electrical equipment, and ensure reliability. This research focuses on developing a protection relay using digital technology to continuously monitor and analyze voltage and current parameters. When a fault or an out-of-range parameter is detected, the relay activates to protect the electrical system. During the current protection test, a standard inverse test was undertaken with four distinct setpoints. The standard inverse exhibited an error value averaging 9.2%. Voltage testing involved evaluating the overvoltage setting in accordance with the 231-volt overvoltage standard and 198-volt standard for undervoltage, employing various types of time delays. Voltage protection demonstrated an average error value of 6% for overvoltage testing and 7.3% error for undervoltage testing. This device is expected to protect electrical equipment that is highly sensitive to current, frequency, and voltage fluctuations.*

Keywords – *Digital Protection Relay; Voltage Disturbances; Current Monitoring; Electrical System Reliability; Frequency Sensitivity.*

I. Introduction

THE protection system is an essential part of the electrical power system, designed to quickly, accurately, and precisely minimize disturbances [1, 2]. Excessive electricity use can cause voltage and current fluctuations, leading to short circuits, significant current spikes, and ultimately, damage [3]. Some electrical equipment is also highly sensitive to changes in the electrical frequency used [4].

Excessive current in the electrical system is often caused by installing electrical loads beyond the system's capacity [5, 6]. If the current exceeds the capacity of the cables or conductors, it can result in electrical short circuits and even fires, particularly if the circuit breaker installed is not up to specification [7]. Voltage fluctuations can stem from various factors, including an insufficient power supply due to load changes in the network, impacting electrical voltage stability [8, 9]. Frequency variations, whether too high or too low, can result from power supply shortages, excess power generation, or excessive loads, leading to frequency drops [10–12]. Therefore, a device is needed to provide protection, prevent damage to electrical equipment, and ensure equipment reliability. Surge protective devices (SPDs) are crucial for safeguarding electrical equipment against overvoltages caused by lightning and switching events [13, 14]. These devices improve power system reliability by mitigating equipment failure risks [14]. With the integration of renewable energy sources and smart grids, protection challenges have increased, necessitating advanced protection schemes [15, 16]. Various approaches have been developed, including resetting and coordinating protection devices, optimizing SPD settings, and implementing intelligent algorithms [15, 17]. Specific solutions like DC reactor-based protection devices have been proposed to prevent ferroresonance in voltage transformers [18]. Additionally, high-frequency transformer winding models and R-L protection devices have been studied to enhance protection against transient phenomena [19]. Tools and approaches for evaluating SPD system performance and selecting appropriate devices

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have also been developed to ensure optimal protection [20].

In prior studies, various designs for digital protection relay models were developed, each concentrating on a single parameter [21,22]. Examples include digital protection relays for voltage disturbances and those for overcurrent disturbances [23]. This study introduces a digital protection relay capable of simultaneously detecting and protecting both voltage and current parameters in one device [24]. The inverse definite minimum time (IDMT) characteristic curve is widely used in overcurrent relay protection for power systems. It establishes protection parameters by setting time delays based on current levels [25,26]. The curve type significantly impacts relay coordination and trip times, with extremely inverse curves generally providing faster protection [27]. Optimal coordination of IDMT relays involves adjusting time multiplier settings (TMS) and plug setting multipliers (PSM) to achieve proper grading margins [28]. Recent research has explored adaptive relaying techniques [25], multiple characteristic curve selection [29], and optimization methods to overcome coordination challenges in modern power systems [30]. Some studies have proposed alternative approaches, such as using PID controllers [31] or developing precise algorithms based on thermal models [32] to determine time delays for overcurrent protection. The greater the fault current detected in a system, the quicker the relay time delay [33,34].

For the voltage parameter, a time delay is also included to allow a pause and determine if the device should confirm a disturbance [35]. This time delay can be adjusted based on user requirements. Much like commercial digital protection relays that enable users to set the time delay, this device incorporates the same feature. Consequently, this device aims to combine the functions of two separate tools into one [36].

II. Research Methods

i. Inverse Curve

The Inverse Curve in overcurrent relays serves as the foundational algorithm in programming critical responses to current disturbances. This algorithm leverages the concept that the higher the fault current value, the faster the relay must respond to minimize the impact of disturbances on the electrical system. By adjusting the values of TMS (time multiplier setting) and Is (current setting) on the Inverse Curve, programmers can fine-tune the sensitivity and response time of the relay to align with the specific characteristics and requirements of the protected electrical network. Consequently, the Inverse Curve in overcurrent relays becomes a crucial foundation in optimizing the performance and reliability of electrical protection systems.

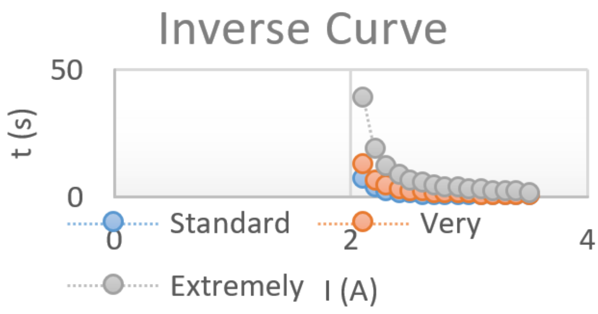

Figure 1: List of selectable time delays for over/under voltage protection

ii. Standard Inverse

$$t = TMS \times \frac{0.14}{[(Ir)^{0.02} - 1]} \tag{1}$$

with $Ir = \frac{I}{Is}$, I = Measured Current, Is = Setting Relay Current, and TMS = Time Multiplier Setting.

When the current sensor measures 2.5 Amperes, with a Time Multiplier Setting (TMS) of 0.05 and a relay current setting of 2 Amperes, the relay will trip in the time calculated using Equation (2).

$$t = 0.05 \times \frac{0.14}{\left(\frac{2.5}{2}\right)^{0.02} - 1} = 1.565s \tag{2}$$

Then, the time required by the relay to trip when the measured current is 2.5 A, with a current setting value of 2 A, is 1.565 seconds.

iii. Very Inverse

$$t = TMS \times \frac{13.5}{Ir - 1} \tag{3}$$

with $Ir = \frac{I}{Is}$, I = Measured Current, Is = Setting Relay Current, and TMS = Time Multiplier Setting.

When the current sensor detects 2.5 Amperes, with a Time Multiplier Setting (TMS) of 0.05 and the relay current set to 2 Amperes, the time required for the relay to trip can be found in Equation (4).

$$t = 0.05 \times \frac{13.5}{\left(\frac{2.5}{2}\right) - 1} = 2.7s \tag{4}$$

Then, the time required by the relay to trip when the measured current is 2.5 A, with a current setting value of 2 A, is 2.7 seconds.

iv. Extremely Inverse

$$t = TMS \times \frac{80}{[(Ir)^2 - 1]} \quad (5)$$

with $Ir = \frac{I}{Is}$, I = Measured Current, Is = Setting Relay Current, and TMS = Time Multiplier Setting.

When the current sensor measures 2.5 Amperes, with a Time Multiplier Setting (TMS) of 0.05 and a relay current setting of 2 Amperes, the time required for the relay to trip is given in Equation (6).

$$t = 0.05 \times \frac{80}{\left(\frac{2.5}{2}\right)^2 - 1} = 7.1s \quad (6)$$

Then, the time required by the relay to trip when the measured current is 2.5 A, with a current setting value of 2 A, is 7.1 seconds.

v. Over/Under Voltage

The under/over voltage relay operates on the principle that if the voltage exceeds or falls below the allowable standard, the relay will disconnect the load to protect the electrical equipment. A time delay in Table 1 is provided to allow users to select the delay duration, ensuring that the relay does not activate immediately if the voltage fluctuation is brief.

Table 1: List of selectable time delays

Disturbance	Time delay (s)					
Overvoltage	1	3	5	10	15	20
Undervoltage	1	3	5	10	15	20

The table 1 shows the list of time delays that users can choose to determine how long the desired time delay should be to protect the voltage. The time delays listed in the table are derived from various sources for over and under voltage protection relays that are commonly found on the market.

vi. Voltage Sensor

The AMC1100 voltage sensor is employed to detect input voltage from the power grid. It is capable of sensing voltages up to 245 VAC, with an overvoltage tolerance of 10% above the nominal value. To function properly, the sensor requires a voltage divider circuit. The value of R_{shunt} is determined by setting the maximum voltage to 250 mV, as specified in the datasheet. The calculation is provided in Equation (7).

$$\begin{aligned} V_{peak} &= \sqrt{2} \times V_{rms} \\ &= \sqrt{2} \times 245 = 346.48V \end{aligned} \quad (7)$$

After determining the V_{peak} value, the next step is to calculate the resistor value for the voltage divider circuit. With R_{shunt} set at 1KΩ, the value of R_1 can be found using Equations (8) and (9).

$$V_{out} = \frac{R_{shunt}}{R_1 + R_{shunt}} \times V_{peak} \quad (8)$$

$$\begin{aligned} R_1 &= \left(\frac{V_{peak}}{V_{out}} \times R_{shunt}\right) - R_{shunt} \\ R_1 &= \left(\frac{346.48}{0.25} \times 620\right) - 620 \\ &= 858640\,\Omega \end{aligned} \quad (9)$$

Based on the calculation above, the value of R_1 is rounded to 863,000 Ω. Consequently, the value of V_{out} is determined as shown in Equation (10).

$$V_{out} = \frac{620}{863000 + 620} \times 346.48 = 248.74mV \quad (10)$$

III. Results and Discussion

After designing and planning various circuits and systems for the tool created in this Project, the next step is to test the system or a circuit to obtain practical results from the previously determined design. The testing method conducted in this Final Project is system integration testing. In this method, testing is carried out in an integrated manner within a system or per system to understand the results and performance of each circuit or system that can be tested.

i. Current Protection Testing

In this test, the protection of a single parameter, specifically the current parameter, is evaluated. The load used to draw current consists of five 200-watt lamps connected in parallel, generating a total current of approximately 4.54 A. The standard inverse characteristic curve is utilized, which provides faster protection speed compared to very inverse or extremely inverse characteristics. The relay's current setting is 0.5 A.

This experiment includes two types of protection tests: overload protection and short-circuit protection, with the short-circuit current assumed to be about four times the measured nominal current. If the nominal current is 0.5 A, the short-circuit current is approximately 2 A. According to the standard inverse curve, the greater the fault current, the quicker the trip time, consistent with the inverse relay characteristic curve described in the previous chapter.

The target delay time for a short circuit is 0.1 seconds. The Time Multiplier Setting (TMS) for both overload and short-circuit conditions can be calculated using the equation for determining the time delay on the standard inverse characteristic. The calculation is as follows:

$$\begin{aligned} t &= TMS \times \frac{0.14}{([Ir]^{0.02} - 1)} \\ &= TMS \times \frac{0.14}{\left(\frac{2}{0.5}\right)^{0.02} - 1} \\ &= 0.02 \end{aligned} \tag{11}$$

Therefore, the Time Multiplier Setting (TMS) to be used is 0.02. To determine the duration of the time delay in the system during an overload current event, an oscilloscope is used to observe the waveform between the GPIO output pin on the microcontroller and the output waveform when the load is disconnected.

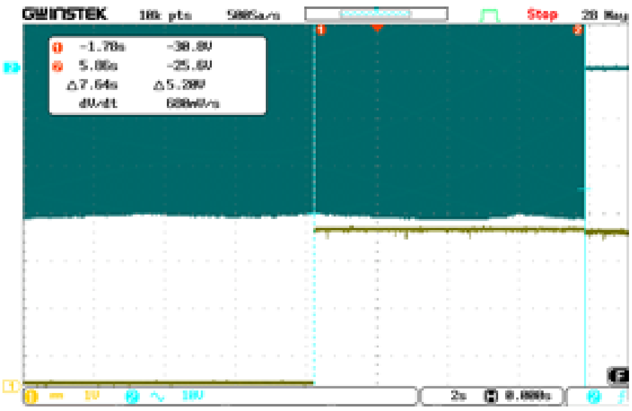

Figure 2: Oscilloscope Display of Current Protection Testing

The figure 2 depicted illustrates the oscilloscope's display indicating an overload current of 0.51 A detected within the system, as indicated on the 20x4 LCD screen. The relay operates only after a delay of 7.64 seconds, disconnecting the load approximately 7.64 seconds following the detection of the fault. A noticeable variance exists between the observed delay time and the calculated delay time. This difference could stem from discrepancies in the display between the LCD and the actual fault value detected by the microcontroller, as well as the inherent lack of precision between what the microcontroller captures and what is displayed on the LCD.

For this test, a current setpoint of 2 A is utilized. This is carried out to analyze several current setpoints that can be safeguarded, encompassing the smallest feasible current to the largest anticipated current to be used by the user. Table 2 presents the data table from the 2 A current test.

The Table 2 displays data from the system integration test concerning the current parameter. The data recorded in the table utilizes the standard inverse curve, recognized for its swiftest trip time among alternative curves. Notably, the table illustrates a discrepancy or

Table 2: Standard Inverse Current Testing Data

No.	Is (A)	I (A)	t Theory (s)	t Practical (A)	Error (%)
1	2	2.01	28.06	30.05	6.6
2	2	2.02	14.06	16.54	14.9
3	2	2.03	9.4	12.32	23
4	2	2.04	7.06	6.54	7.9
5	2	2.05	5.66	6.01	5.8
6	2	2.06	4.73	4.75	0.42
7	2	2.07	4.06	4.56	10.1
8	2	2.08	3.56	4.01	11.2
9	2	2.09	3.17	3.54	10.4
10	2	2.1	2.86	2.91	1.7
			Total		9.2

margin of error of 9.2%. This variance persists between the anticipated output time delay and the actual output time delay due to the inherent limitations in the accuracy of measured values obtained by the microcontroller, which cannot achieve perfect precision as theoretically expected. Subsequently, the subsequent image illustrates a comparison of the inverse curve between the theoretical output outcomes and the practical output outcomes.

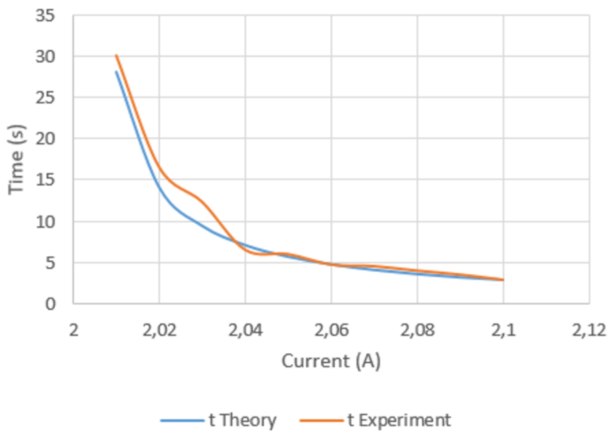

Figure 3: Comparison of Theoretical and Practical Standard Inverse Curves

The figure 3 shows a comparison between the theoretical inverse curve in blue and the practical inverse curve in orange. There are still spikes in the practical results due to errors produced during the data collection process.

ii. Voltage Protection Testing

System integration testing is executed to safeguard the voltage parameter, encompassing both overvoltage and undervoltage scenarios. According to voltage standards observed in Indonesia, the upper voltage threshold for 220 volts electricity stands at 5% above its nominal voltage, amounting to 231 volts. Conversely, the lower voltage threshold, known as undervoltage, is set at 10% below its nominal voltage, totaling 198 volts.

The operation of the under/over voltage relay functions by disconnecting the load if the voltage parameter surpasses or falls below the permissible standard voltage. This protective measure ensures the safety of electrical equipment. Nevertheless, a time delay is incorporated to permit users to freely select the relay's delay duration, ensuring that if the occurrence of under/over voltage is brief, the relay does not trigger instantaneously.

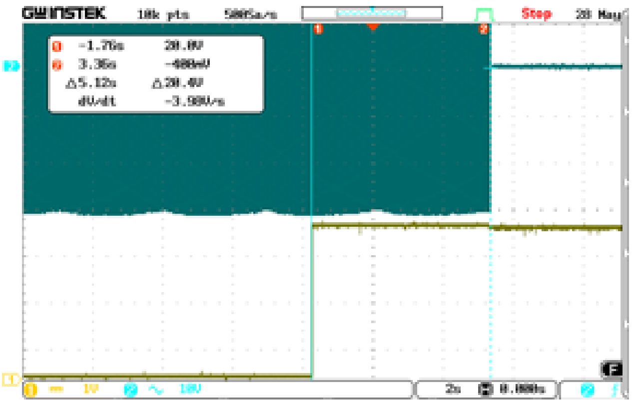

Figure 4: Display of the Oscilloscope for a Time Delay of 3 Seconds

Then, in the figure 4, the display of the oscilloscope shows that the yellow graph represents the 220 Volt AC signal, and the blue graph represents the DC signal output from the GPIO on the microcontroller to indicate the delay time that occurs when the setting is 5 seconds. The actual value for the time delay is found to be 5.12 seconds.

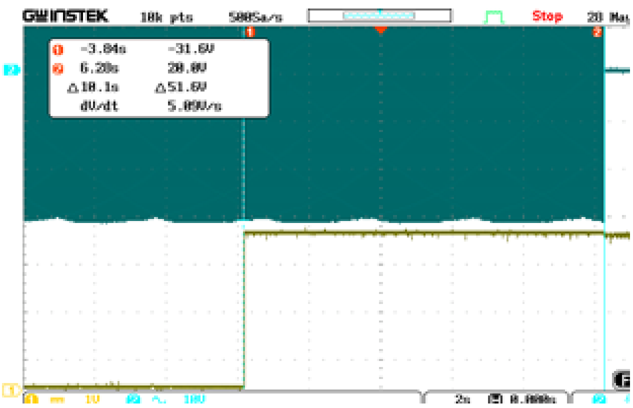

Figure 5: Display of the Oscilloscope for a Time Delay of 5 Seconds

And in the figure 5, the display of the oscilloscope shows that the yellow graph represents the 220 Volt AC signal, and the blue graph represents the DC signal output from the GPIO on the microcontroller to indicate the delay time that occurs when the setting is 10 seconds. The actual value for the time delay is found to be 10.1 seconds.

Table 3: Overvoltage Relay Testing Data

Delay (s)	Setting (V)	Measured (V)	Real Time (s)	Error (%)
1	231	232.4	1.12	10.7
3	231	231.7	3.56	15.7
5	231	233.1	5.45	8.2
10	231	232.7	10.1	0.9
15	231	232.1	15.08	0.5
20	231	233.6	20.1	0.49
		Mean		6

In the provided Table 3, it's noticeable that during the overvoltage relay test, all time delay settings with the consistent overvoltage setting of 231 volts yielded real-time delay values closely aligned with the anticipated ones. An error margin of 6% was recorded, attributed to the microcontroller's reading inaccuracies of the sensor and the operational time needed for the contactor and relay. Below follows the table detailing the undervoltage relay test.

Table 4: Undervoltage Relay Testing Data

Delay (s)	Setting (V)	Measured (V)	Real Time (s)	Error (%)
1	198	197.6	1.16	13.7
3	198	197.4	3.65	17.8
5	198	197.7	5.54	9.7
10	198	197.6	10.2	1.9
15	198	197.9	15.1	0.6
20	198	197.5	20.1	0.49
		Mean		7.3

The provided Table 4 indicates that during the undervoltage relay test, all time delay settings aligned with the consistent undervoltage setting of 198 volts produced real-time delay values closely matching the anticipated ones. An error margin of 7.3% was recorded, attributed to the microcontroller's inaccuracies in sensor readings and the operational time required for the contactor and relay.

IV. Conclusion

During the current protection test, a standard inverse test was undertaken with four distinct setpoints. The standard inverse exhibited an error value averaging 9.2%. Voltage testing involved evaluating the overvoltage setting in accordance with the 231-volt overvoltage standard and 198-volt standard for undervoltage, employing various types of time delays. Voltage protection demonstrated an average error value of 6% for ovevoltage testing and 7.3% error for undervoltage testing. The development of this device aims to safeguard electrical equipment sensitive to current and voltage parameters.

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