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ANALYSIS OF CURRENT AND VOLTAGE SIGNALS IN MICROPROCESSOR-BASED PROTECTIVE RELAY SYSTEMS USING MATLAB/SIMULINK

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Abstract. The reliability and stability of modern electric power systems largely depend on the effectiveness of protection and control equipment. Microprocessor-Based Protective Relay (MPR) systems have become an essential component of modern power networks due to their high accuracy, flexibility, and capability to process electrical signals in real time. One of the most important tasks of protective relays is the continuous monitoring and analysis of current and voltage signals under both normal and fault operating conditions.

Keywords: Microprocessor-Based Protective Relay, Current Signal Analysis, Voltage Signal Analysis, Power System Protection, MATLAB/Simulink, RMS Measurement, Digital Filtering, Fault Detection, Smart Grid, Signal Processing.

Introduction

Electric power systems represent one of the most important infrastructures of modern society. The reliable operation of industrial facilities, communication systems, transportation networks, and residential consumers depends directly on the continuous supply of electrical energy. As power systems become increasingly complex and interconnected, maintaining operational reliability and system stability has become a major engineering challenge. Protective relay systems play a critical role in ensuring the secure operation of electrical networks.

Microprocessor-Based Protective Relay (MPR) systems continuously monitor electrical quantities such as current, voltage, frequency, phase angle, and power. These parameters provide valuable information about the operating condition of the power system. Any abnormal variation in these quantities may indicate the presence of faults, overloads, equipment failures, or network disturbances.

Among all monitored parameters, current and voltage signals are the most fundamental sources of information used by relay protection algorithms. During normal operating conditions, these signals follow predictable sinusoidal patterns. However, during faults or disturbances, significant deviations occur in amplitude, phase angle, frequency, and waveform shape. Therefore, accurate analysis of current and voltage signals is essential for reliable fault detection and system protection. Modern relay protection devices employ advanced digital signal processing techniques to analyze measured electrical quantities. Analog signals obtained from current transformers (CTs) and voltage transformers (VTs) are converted into digital form using Analog-to-Digital Converters (ADCs). The digitized signals are then processed using mathematical algorithms to extract important characteristics such as RMS values, frequency, phase angles, harmonic content, and symmetrical components.

The increasing penetration of renewable energy sources has introduced additional challenges for relay protection systems. Renewable generation units, such as photovoltaic systems and wind

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turbines, often introduce dynamic operating conditions and power electronic interfaces that affect traditional protection principles. Consequently, advanced signal analysis techniques have become increasingly important for maintaining reliable protection performance.

Methodology

Current and voltage signal acquisition

In microprocessor-based protective relay systems, current and voltage signals are continuously measured through Current Transformers (CTs) and Voltage Transformers (VTs). These analog signals contain valuable information regarding the operating condition of the power system. Under normal operating conditions, the measured waveforms are nearly sinusoidal, while fault conditions introduce distortions, asymmetry, and transient components.

The measured current signal can be represented as:

$$I(t) = I_\alpha(t) + I_\beta(t) + I_0(t) \tag{1}$$

where:

$I(t)$ is the total current signal;

$I_\alpha(t)$ is the active-phase component;

$I_\beta(t)$ is the quadrature component;

$I_0(t)$ is the zero-sequence current component.

The zero-sequence component is particularly important for detecting ground faults and asymmetrical operating conditions.

Similarly, the voltage signal is expressed as:

$$U(t) = U_\alpha(t) + U_\beta(t) + U_0(t) \tag{2}$$

where:

$U_\alpha(t)$ is the active-phase voltage component;

$U_\beta(t)$ is the quadrature voltage component;

$U_0(t)$ is the zero-sequence voltage component.

These signal components are used to identify voltage imbalance, phase-angle variations, and abnormal operating conditions within the electrical network.

Signal digitization and digital processing

The analog current and voltage signals are converted into digital form using an Analog-to-Digital Converter (ADC). The sampling frequency must satisfy the Nyquist criterion to accurately reconstruct the original waveform.

The digitized signal can be represented as:

$$x[n] = x(nT_s) \tag{3}$$

where:

$x[n]$ is the sampled signal;

T_s is the sampling period.

After digitization, digital filtering techniques are applied to eliminate noise and unwanted harmonic components. A discrete low-pass filter is commonly used:

$$y[n] = a\,x[n] + (1 - a)y[n - 1] \tag{4}$$

where:

$x[n]$ is the input signal;

$y[n]$ is the filtered output signal;

a is the filter coefficient.

The filtering process improves measurement accuracy and increases relay sensitivity.

RMS value calculation

Protective relay algorithms frequently utilize Root Mean Square (RMS) values because RMS quantities accurately represent the effective magnitude of alternating current and voltage.

The RMS value of a signal is calculated as:

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} x_k^2} \quad (5)$$

where: X_{RMS} is the effective value; N is the number of samples; x_k represents individual samples.

For sinusoidal waveforms:

$$I_{RMS} = \frac{I_{max}}{\sqrt{2}} \quad (6)$$

$$U_{RMS} = \frac{U_{max}}{\sqrt{2}} \quad (7)$$

RMS values are continuously calculated and compared with predefined protection thresholds.

Current and voltage imbalance analysis

Three-phase systems often experience unequal loading conditions. To quantify asymmetry, imbalance coefficients are calculated.

Current imbalance coefficient:

$$K_I = \frac{I_{max} - I_{min}}{I_{avg}} \times 100\% \quad (10)$$

Voltage imbalance coefficient:

$$K_U = \frac{U_{max} - U_{min}}{U_{avg}} \times 100\% \quad (11)$$

These coefficients provide valuable information regarding phase asymmetry and system operating conditions.

Fault detection algorithm

The proposed relay protection algorithm continuously monitors RMS values, frequency deviations, and imbalance coefficients.

A fault condition is identified when:

$$I_{RMS} > I_{set} \text{ or } U\_RMS < U\_set \quad (12)$$

$$K_I > K_{crit} \text{ or } K\_U > K\_crit \quad (13)$$

When any protection criterion is satisfied, the relay generates a trip signal and isolates the faulted section of the network.

Practical calculations and simulation results

Simulation model description

To evaluate the effectiveness of the proposed signal analysis methodology, a simulation model was developed in the MATLAB/Simulink environment. The model represents a three-phase electric power system consisting of a voltage source, transmission line, load, fault module, measurement units, and a microprocessor-based relay protection subsystem. The simulation framework incorporates a three-phase voltage source, three-phase load, current and voltage measurement

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blocks, RMS measurement units, digital filtering modules, a Phase Locked Loop (PLL), a three-phase fault module, relay protection logic, and data visualization tools. These components operate together to simulate both normal and abnormal operating conditions of the electrical network.

The developed model provides a comprehensive platform for analyzing current and voltage signals, evaluating protection performance, and investigating system behavior during disturbances. It allows real-time monitoring of electrical quantities and enables detailed assessment of relay protection algorithms under various operating scenarios, including overloads, voltage disturbances, asymmetrical operating conditions, and short-circuit faults.

Current signal analysis

Table 1. Measured phase currents

Phase	Current (A)
A	102
B	98
C	100

The average phase current is calculated as:

$$I_{avg} = \frac{102 + 98 + 100}{3} \quad ; I_{avg} = 100A$$

The current imbalance coefficient is determined using Equation (10):

$$K_I = \frac{I_{max} - I_{min}}{I_{avg}} \times 100\% \; ; \quad K_I = \frac{102 - 98}{100} \times 100 \;\; ; \; K_I = 4\%$$

The obtained value indicates that the system operates within acceptable limits and no significant current asymmetry is present.

Voltage signal analysis

Table 2. Measured phase voltages

Phase	Voltage (V)
A	399
B	402
C	400

The average voltage is calculated as:

$$U_{avg} = \frac{399 + 402 + 400}{3} \quad ; U_{avg} = 400.33V$$

The voltage imbalance coefficient is:

$$K_U = \frac{U_{max} - U_{min}}{U_{avg}} \times 100\%; \;\; K_U = \frac{402-399}{400.33} \times 100; \;\; K_U = 0.75\%$$

The obtained result confirms that voltage asymmetry is negligible and the network operates under balanced conditions.

RMS calculation results

Table 3. RMS measurement results

Parameter	Peak Value	RMS Value

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Current	141.4 A	100 A
Voltage	565.7 V	400 V

The RMS values were obtained using Equations (6) and (7):

$$I_{RMS} = \frac{141.4}{\sqrt{2}} \quad ; I_{RMS} = 100A \;\; ; U_{RMS} = \frac{565.7}{\sqrt{2}} \quad ; U_{RMS} = 400V$$

The results demonstrate that the implemented RMS measurement algorithm accurately estimates effective electrical quantities.

Fault condition analysis

To evaluate relay performance, a single-phase-to-ground fault was introduced at $t = 0.5$ s.

Table 4. Fault current measurements

Phase	Current before fault (A)	Current during fault (A)
A	102	485
B	98	101
C	100	103

The RMS current of phase A exceeded the protection threshold: $I_{fault} = 485A$

$I_{set} = 250A$ Since: $I_{fault} > I_{set}$ the relay protection algorithm generated a trip command.

The relay operating time obtained from simulation was:

$$t_{trip} = 0.045s$$

which satisfies the requirements for fast fault isolation.

Conclusion

This study investigated the analysis of current and voltage signals in microprocessor-based protective relay systems and evaluated their application in modern electric power networks. The results demonstrated that current and voltage signals contain essential information regarding the operating condition of electrical power systems. Through continuous monitoring and analysis of these signals, abnormal operating conditions such as overloads, short circuits, voltage disturbances, and asymmetrical faults can be detected rapidly and accurately. Future research may focus on integrating artificial intelligence and machine learning algorithms into relay protection systems for adaptive fault detection, predictive maintenance, and real-time decision-making in complex power networks.

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Nomenclature

$I(t)$ - total current signal (A); $I_\alpha(t)$ - active-phase current component (A); $I_\beta(t)$ - quadrature current component (A); $I_0(t)$ - zero-sequence current component (A); $U(t)$ - total voltage signal (V); $U_\alpha(t)$ - active-phase voltage component (V); $U_\beta(t)$ - quadrature voltage component (V); $U_0(t)$ - zero-sequence voltage component (V); I_{RMS} - root mean square current (A); U_{RMS} - root mean square voltage (V); K_I - current imbalance coefficient (%); K_U - voltage imbalance coefficient (%); I_{max} -

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maximum phase current (A); I_{min} - minimum phase current (A); I_{avg} - average phase current (A); U_{max} - maximum phase voltage (V); U_{min} - minimum phase voltage (V); U_{avg} - average phase voltage (V); f - system frequency (Hz); f_0 - nominal frequency (Hz); Δf - frequency deviation (Hz); φ - phase angle difference (rad); T - signal period (s); T_s - sampling period (s); x[n] - sampled signal; y[n] - filtered signal; N - number of samples; I_{set} - overcurrent protection threshold (A); U_{set} - undervoltage protection threshold (V); K_{crit} - critical imbalance threshold (%); ADC - Analog-to-Digital Converter; CT - Current Transformer; VT - Voltage Transformer; PLL - Phase Locked Loop; RMS - Root Mean Square; MPR - Microprocessor-Based Protective Relay.

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