

Design and Simulation of a Multifunction Protection Relay for Generator–Transformer Units



Shaker M. Khudher^{*ID}, Omar Muwafaq Al-Yousif^{ID}, Saad E. Mohammed^{ID}, Omar Sh. AL-Yozbaky^{ID}

Department of Electrical Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq

Corresponding Author Email: shakeralhyane@uomosul.edu.iq

Copyright: ©2026 The authors. This article is published by IETA and is licensed under the CC BY 4.0 license (<http://creativecommons.org/licenses/by/4.0/>).

<https://doi.org/10.18280/jesa.590214>

ABSTRACT

Received: 18 November 2025

Revised: 11 February 2026

Accepted: 21 February 2026

Available online: 28 February 2026

Keywords:

Universal Protection Relay, generator–transformer unit, multifunction protection, fault detection, MATLAB/Simulink, relay coordination

The generator-transformer (G-T) system plays an important role as an interface system connecting the generation and distribution networks, and reliable protection of these units is necessary for maintaining the stability and continuity of the power supply. In the existing schemes, multiple independent relays are generally used with fixed settings, and these schemes find it difficult to distinguish transients from steady-state faults. This article describes the development of a multifaceted Universal Protection Relay (UPR) for G-T systems, designed using the MATLAB/Simulink platform, along with simulation results for evaluation of the designed relay. The designed relay combines overcurrent, over/under voltage, and frequency protection functions under a single, synchronized, and deterministic logic scheme. A systematic approach for fault categorization, along with a two-mode timing scheme, has been employed to distinguish between transient occurrences and actual faults, based on definite-time delay for voltage & frequency-related disturbances, as well as instantaneous operation for extreme overcurrent situations. The performance of the proposed UPR is verified for a wide range of operating conditions, such as normal operation, voltage, frequency deviation, symmetrical faults, unsymmetrical faults, and load changes. The simulation results verify that the relay offers fast isolation for severe short-circuit faults in 20 ms by instantaneous tripping. Furthermore, the scheme offers selective protection for voltage and frequency disturbances with a definite time delay of 200 ms. This reduces unnecessary tripping. The findings verify that the proposed scheme offers better selectivity, coordination, and reliability in comparison to the conventional method, thus making it suitable for modern medium-voltage systems.

1. INTRODUCTION

Medium voltage power systems are a vital part of the electrical network and play a critical role in connecting the generator units with the transmission and distribution systems. In medium voltage power systems, the generator-transformer unit is one of the critical components, and the reliability of the generator-transformer unit is vital in maintaining the stability of the power system, protection of the equipment, and continuity of power supply [1-4]. Unusual operating conditions in the generator-transformer unit may cause severe damage to the equipment, leading to power system instability and substantial financial losses.

The generator-transformer unit is exposed to a number of abnormal operating conditions, and the abnormal operating conditions include short circuits, overloads, voltage fluctuations, frequency fluctuations, insulation failures, and unbalanced operating conditions. If these abnormal operating conditions are not properly addressed, they may cause catastrophic failures in the generator or the transformer unit [5, 6]. Traditionally, the protection of the generator and the transformer unit is achieved using separate protection schemes, and the protection schemes include overcurrent protection, differential protection, voltage protection, and frequency

protection [1, 6-8], which are achieved using separate protection relays with pre-specified parameters.

Due to the increasing complexity of the power system and the integration of distributed generators and renewable energy sources, the traditional protection schemes are facing a number of challenges in the protection of the generator and the transformer unit [9-11]. In most power systems, a number of protection relays are used separately to protect the generator and the transformer unit. Even though the protection relays are performing their individual tasks satisfactorily, the lack of coordination between the protection relays may reduce the overall protection system's ability to distinguish between transient conditions and faults [12-14].

Recently, a number of studies have been conducted on the protection of the generator and the transformer unit using advanced protection schemes, and the advanced protection schemes include adaptive protection, model-based protection, and machine learning-based protection [6, 14-19]. Even though the advanced protection schemes may provide enhanced protection, the complexity in tuning the parameters is high, and the overall complexity in the protection system is also high, leading to a lack of transparency in the protection system.

To address these challenges, this work proposes a

deterministic Universal Protection Relay (UPR) architecture designed for generator–transformer protection. The proposed relay integrates overcurrent, over/under-voltage, and frequency protection functions within a unified decision-making framework. A coordinated fault classification mechanism and dual-mode timing strategy are implemented to enhance the relay’s ability to discriminate between transient disturbances and permanent faults. The proposed relay is implemented and evaluated using the MATLAB/Simulink platform under various operating scenarios, including voltage disturbances, frequency deviations, symmetrical faults, and unsymmetrical faults.

2. CONTRIBUTIONS OF THIS WORK

However, the current trend of studies related to generator-transformer protection has mainly focused on enhancing the functionality of protection, such as adaptive differential protection, impedance or capability curve supported schemes, transformer-specific numerical protection devices, and machine learning-based support for fault classification algorithms. One of the notable aspects of the aforementioned studies is the fact that generator and transformer protection has been considered as separate systems or has been based on complicated parameter tuning, extensive training data, or additional measurement devices. The technical contributions of this study can be summarized as follows:

1. Integrated protection framework going beyond the function-focused paradigm:

While most existing solutions tackle the problem of protection functions one at a time, like overcurrent, differential, or frequency protection, the proposed work aims to design an integrated multifunction protection relay that includes overcurrent (ANSI 50), over-undervoltage (ANSI 59/27), and frequency (ANSI 81) protection for generator-transformer sets under one common logic system. This would minimize the need to use multiple independently programmed relays and would also provide better coordination as opposed to existing solutions.

2. Deterministic fault discrimination without using data-driven techniques:

As opposed to the more recent literature, which has focused on the use of machine learning or sophisticated pattern recognition techniques for fault detection and classification, the proposed relay utilizes deterministic and standards-compliant logic as guided by the IEEE device function definitions, which ensures transparency and simplicity of operation for the power system protection application.

3. Discrimination between explicit transients and faults by coordinated timing logic:

In numerical relays, usually time delay characteristics are used, which often lead to nuisance tripping for transients like voltage dips, frequency changes, and overcurrent conditions. In this study, it is suggested that coordination be made between definitive time verification of voltage and frequency errors, and immediate operation under severe overcurrent conditions.

4. Integration of diagnostic functions for improved coordination:

In contrast to other protection systems, which provide limited information regarding trip or no trip, this study has included fault codes, which correspond to various types of electrical faults. This will improve coordination, analysis, and situational awareness of operators for systems functioning

abnormally.

5. Overall validation under changing conditions:

Unlike other studies, which have been validated under limited fault conditions, this study validates the designed relay under voltage and frequency changes, symmetrical and unsymmetrical faults, and load changes by developing a comprehensive model through MATLAB/Simulink software. The simulation results show that improved coordination and reliability can be achieved by integrating the protection scheme.

These contributions, in total, form a practical deterministic protection scheme that is applicable to the improvement of coordination and fault discrimination in the protection of generator-transformer units without the need to employ complex methodologies that are often based on data considerations.

3. SIGNIFICANCE OF THE STUDY

The protection of generator-transformer units is a significant aspect in the development of stable power systems. This is attributed to the fact that faults in the units often result in considerable damage to the equipment, long outages, and considerable economic implications. In this regard, the improvement of the coordination and reliability of the protection systems in the units is a primary concern in the development of modern power systems.

The proposed UPR is a practical solution that can be used to enhance the coordination of the protection systems in the units. This is attributed to the fact that the proposed relay is able to integrate the different protection functions in the units in a single deterministic structure. This is achieved by the integration of overcurrent, voltage, and frequency protection functions in a unified structure that is deterministic in nature.

In addition to the enhancement of the fault detection capability of the proposed protection scheme, the proposed structure is able to differentiate between transient faults and permanent faults with the help of the fault classification scheme that is used in the proposed structure. This is a significant aspect in the development of reliable protection systems in the units. In this regard, the proposed structure is a practical solution that can be used in the development of reliable protection systems in the units in the near future. The relay architecture can be extended to incorporate additional protection functions such as differential protection, harmonic restraint, or adaptive protection strategies, making it a promising platform for modern generator–transformer protection applications.

4. PROPOSED PROTECTION MODEL

4.1 Implementation environment and protection architecture

This protection scheme has been developed using the MATLAB/Simulink platform, which finds extensive application in the analysis and validation of protection schemes in power systems because it can simulate the dynamics of the power system. The major part of the developed protection scheme is the UPR which incorporates a variety of functions aimed at protecting the generator-transformer units.

Conventionally, protection schemes use discrete relays for protecting generators and transformers. The protection functions, namely overcurrent, voltage, frequency, and differential protection, involve adjustment in traditional protection schemes [5, 14]. In the proposed UPR scheme, different protection functions are combined under a common platform. The relay system continuously measures the three-phase voltage, current, and frequency in the system and uses decision-making algorithms to produce a single common trip signal for the concerned circuit breakers. As explained in Table 1.

Table 1. Key features of universal relay

Functionality	ANSI Code	Input Signal	Programmed Response Logic
Current Protection	50	I_{abc}	Instantaneous Peak Detection
Voltage Protection	59/27	V_{abc}	Fundamental root mean square (RMS) Comparison
Frequency Protection	81	V_{abc}	PLL-based Frequency Tracking
Decision Logic	-	All Above	Boolean OR-Gate Integration

In contrast to the conventional protection schemes that employ multiple independently programmed relays or data-driven classifiers in the generator-transformer protection scheme [14, 15], the proposed Unified Protective Relaying (UPR) provides fault discrimination in a unified deterministic logic structure in a simpler and transparent manner. In terms of performance, the UPR provides fault isolation in severe short-circuit faults in an instant of around 20 ms, as opposed to the conventional definite time protection scheme with an operating time of 200–300 ms. Furthermore, the verification logic programmed in the relay prevents the relay action during transient faults below 200 ms to prevent unwanted tripping.

4.2 Signal acquisition and sensing logic

The UPR repeatedly measures the voltage and current values of the generator-transformer units in the three-phase system. The fundamental root mean square (RMS) value of the voltage and current are calculated and compared with the predefined protection threshold levels. In digital protection systems, the effective magnitude of electrical quantities is evaluated using the RMS value. For a periodic signal $x(t)$, the RMS value over one fundamental cycle T is defined as:

$$X_{RMS} = \sqrt{\frac{1}{T} \int_0^T X^2(t) dt} \quad (1)$$

where, $x(t)$ represents the instantaneous electrical signal (voltage or current), and T denotes the fundamental cycle period of the waveform.

The RMS value represents the effective magnitude of the electrical signal and is widely used in digital protection algorithms and numerical relays [16, 18].

In the implemented relay model, the three-phase RMS voltages V_{RMS} and currents I_{RMS} are continuously calculated using this formulation and compared with the predefined protection thresholds as shown in Eq. (2) and Eq.(3)

$$V_{RMS} = \sqrt{\frac{1}{T} \int_0^T v^2(t) dt} \quad (2)$$

where, $v(t)$ is the instantaneous voltage waveform measured at the relay input and T represents the fundamental cycle period of the voltage signal.

$$I_{RMS} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} \quad (3)$$

where, $i(t)$ denotes the instantaneous current signal measured in the system and T is the fundamental period of the current waveform.

This approach follows standard numerical relay practices. The system frequency is determined by the phase-locked loop (PLL) algorithm in the voltage signal, In the PLL-based estimation method, the instantaneous phase angle of the fundamental voltage component is tracked. The system frequency is obtained from the time derivative of the phase angle as:

$$f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} \quad (4)$$

where, $f(t)$ is the estimated system frequency, $\theta(t)$ represents the instantaneous phase angle of the fundamental voltage component obtained from the PLL, and $\frac{d\theta(t)}{dt}$ denotes the rate of change of the phase angle with respect to time.

In discrete digital implementation, the frequency can be approximated using the phase difference between successive sampling instants:

$$f(k) = \frac{\theta(k) - \theta(k-1)}{2\pi\Delta t} \quad (5)$$

where, $f(k)$ is the estimated system frequency at the discrete sampling instant k , $\theta(k)$ and $\theta(k-1)$ represent the phase angles at the current and previous sampling instants respectively, and Δt denotes the sampling interval.

This equation demonstrates mathematically how the PLL block in the Simulink model tracks system frequency, which is widely used in numerical relays and digital signal processing methods for power system frequency tracking [10, 16].

The relay operates in the abnormal region when the following conditions are met:

- **Overvoltage (OV):** $V_{RMS} \geq V_{OV}$
- **Undervoltage (UV):** $V_{RMS} \leq V_{UV}$
- **Over frequency (OF):** $f \geq f_{OF}$
- **Underfrequency (UF):** $f \leq f_{UF}$
- **Overcurrent (OC):** $I_{RMS} > I_{pickup}$

where, V_{OV} , V_{UV} , f_{OF} , f_{UF} , and I_{pickup} are predefined protection levels selected based on IEEE protection standards.

When any of the above threshold conditions is satisfied, the corresponding protection element is activated and forwarded to the relay decision logic.

The selected protection thresholds follow common practices recommended in power system protection standards. The overvoltage threshold was set to 1.1 pu and the undervoltage threshold to 0.9 pu, which correspond to typical operational

limits used for medium-voltage equipment protection. Likewise, the 200 ms time period used in the verification delay of the voltage and frequency protection functions is in agreement with the recommendations on the coordination of disturbance ride-through and transient immunity. This is done in order to reduce the risk of unnecessary disconnections due to system disturbances.

The system frequency is determined using a PLL method, which is based on the measurement of the voltage signal. In this method, the phase angle of the fundamental voltage component is determined, and the frequency is the time derivative of the phase angle. This approach is widely used in digital relays due to its high accuracy and robustness under dynamic system conditions [16, 18].

4.3 Fault classification and decision logic

To improve the transparency of the protection scheme and aid in coordination, the UPR scheme adopts a systematic fault-coding scheme. Each fault detected is provided with a distinct fault code depending on the protection function that caused the relay to operate, as shown in Table 2.

Table 2. Fault code keys

Fault Type	Programmed Code	Logic Condition
Healthy System	0	No Fault
Overvoltage	1	$V_{RMS} \geq OV$
Undervoltage	2	$V_{RMS} \leq UV$
Over-frequency	3	$f \geq OF$
Under-frequency	4	$f \leq UF$
Overcurrent	5	$I_{RMS} > I_{pickup}$

The fault classification scheme used follows the concepts of device function as proposed by ANSI, which helps to achieve improved diagnostic capability, as suggested by modern numerical relay schemes [5].

A central decision logic based on Boolean logic combines the results of individual protection functions through an OR logic structure. The final trip decision of the proposed relay is implemented using a Boolean OR logic that combines the outputs of all protection elements. The overall trip condition can therefore be expressed as:

$$Trip = OC \vee OV \vee UV \vee OF \vee UF \quad (6)$$

where, OC represents the overcurrent condition, OV denotes the overvoltage condition, UV represents the undervoltage condition, OF denotes the overfrequency condition, and UF represents the underfrequency condition. The logical OR operator (\vee) indicates that the relay issues a trip command when any of the protection conditions is satisfied according to the defined protection thresholds.

This logical formulation ensures coordinated operation of all protection elements within a unified decision framework.

The relay issues a trip command when any of these protection conditions remains active according to the defined timing coordination strategy.

After the completion of every protection operation, the relevant fault code will be generated and sent to the timing logic. The method used here differs from the conventional multi-relay protection scheme, where independent decision-making leads to complexities in fault determination [12-14].

4.4 Timing characteristics and coordination strategy

The proposed relay uses dual-mode timing schemes that offer an optimal trade-off between fast fault selection and selectivity:

(1) Definite-Time Delay Mode:

The definite-time delay applied to voltage and frequency disturbances can be expressed as:

$$t_{trip} = \begin{cases} t + T_d & \text{if Fault code} \in \{1,2,3,4\} \\ t + T_i & \text{if Fault code} = 5 \end{cases} \quad (7)$$

where, t_{trip} represents the relay tripping time, t is the instant at which the fault condition is detected, T_d denotes the definite-time delay applied to voltage and frequency disturbances, and T_i represents the instantaneous tripping delay associated with severe overcurrent faults $T_d = 200 \text{ ms}$ (definite-time verification delay) $T_i \approx 20 \text{ ms}$ (instantaneous trip delay).

In cases of voltage and frequency-related faults (Fault Codes 1 to 4), the definite time delay function is employed. When the fault occurs, the timing counter starts, and the tripping signal is sent only if the fault is sustained for an elapsed time of 200 ms. In the case where the fault is removed within the time delay, the relay undergoes self-resetting. This method satisfies standard protection coordination principles used in power system relaying [5, 7, 9].

(2) Instantaneous Tripping Mode:

Significant overcurrent values (Fault Code 5), normally related to short-circuit faults, cause immediate trip actions without any intentional delay. This helps in fault isolation within a cycle of simulation (around 20 ms), hence reducing heat and torque stress on the generator and transformer, as recommended [5, 7] for high-level faults.

The coordination of timings allows the relay to distinguish between transient and permanent faults while still acting quickly on faults of significance

4.5 Practical significance of the proposed model

The proposed protection model provides a practical method for the comprehensive protection of generators and transformers in medium-voltage power systems. The proposed UPR improves selectivity, coordination, and diagnostics in comparison with traditional protection methods [13, 14] by incorporating different protection methods in one deterministic model. In addition, the proposed model has the flexibility to be developed in the future by including differential protection methods, harmonic restraint, and adaptive setting methods, which are highly emphasized in modern protection research [1, 6].

Modern protection research emphasizes the need for integrated and coordinated relay architectures capable of operating reliably under increasingly complex power system conditions [18, 20].

It is important to note that, normally, differential protection is used as the main protection for generator transformer units. This study aims to prove the feasibility of an integrated deterministic protection scheme, which incorporates various auxiliary protection functions. In the future, this study will be extended to incorporate various components of differential protection and harmonic restraint to achieve a fully integrated protection scheme.

4.6 Consideration of transformer inrush conditions

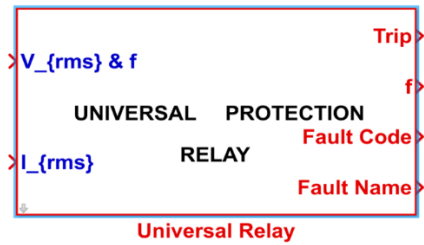


Figure 1. Universal Protection Relay (UPR) block

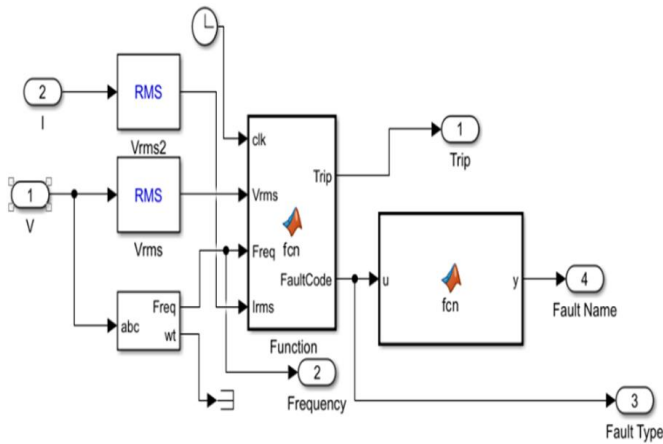


Figure 2. Subsystem of the Universal Protection Relay (UPR) block

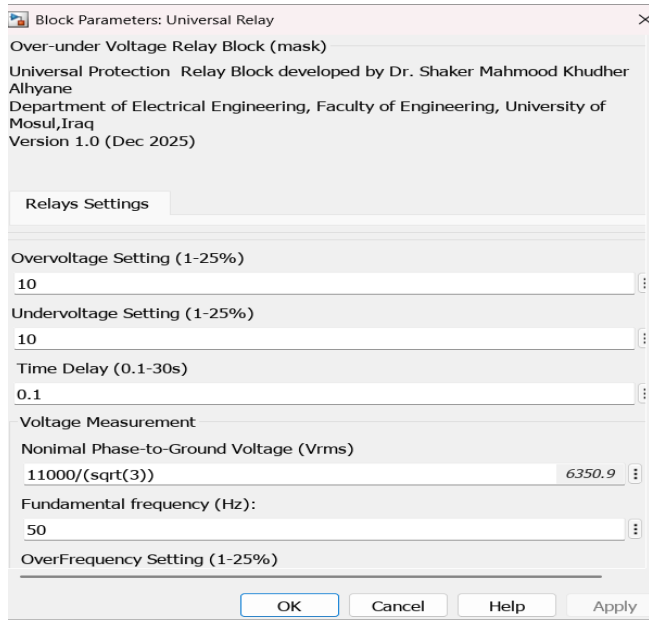


Figure 3. Properties of the Universal Protection Relay (UPR) block

In fact, transformer energization can produce magnetizing inrush currents, which can be several times higher than the rated current and can even initiate instantaneous overcurrent protection. However, these types of inrush currents have high levels of harmonic content and usually have a short duration. In fact, numerical relays usually incorporate features such as harmonic restraint or blocking functions. Although the simulation model does not have an explicit feature for

harmonic restraint, it is possible to easily incorporate this feature by means of the UPR architecture. Future work will incorporate harmonic-based blocking methods to further improve relay security during transformer energization.

The overall UPR architecture and its internal subsystems are illustrated in Figures 1-3.

5. RESULTS AND CONCLUSION

The three-phase programmable voltage source with a rating of 11 kV, together with the 11/0.4 kV three-phase transformer with a rating of 250 kVA, feeding a load of 100 kW and 1 kVAr, is used for the testing and simulation of the universal relay. The system is designed to provide accurate detection and protection processes by allowing a practical evaluation of the relay operation for different faults. For the improvement of the relay setting for proper operation, the simulation studies the operation of the relay, as shown in Figure 4.

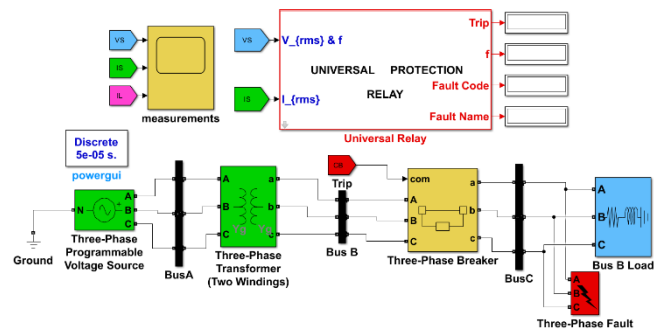


Figure 4. Overall diagram of Simulink model

The overall MATLAB/Simulink model used for evaluating the proposed UPR is shown in Figure 4. The relay setting of the proposed system has a definite time delay of 0.2 s for voltage and frequency faults (Fault Codes 1 to 4), and an instantaneous trip of one simulation cycle, which is approximately 20 ms, for an overcurrent fault (Fault Code 5).

The relays are tested under different scenarios. The test conditions, results, and discussions are given below.

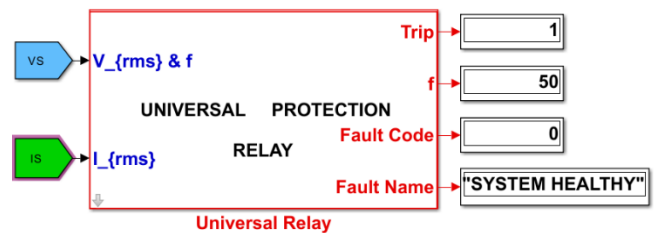


Figure 5. Universal Protection Relay (UPR) stats at normal operation

A. Case 1:

In this case, the system voltage and frequency are equal to the rated values, and there is no fault, which is considered a normal operation condition. The three-phase voltage, three-phase current, system frequency, and relay status observed are shown in Figures 5 and 6.

Figure 5 illustrates the UPR internal status during normal operation. No protection thresholds are violated, and the relay maintains Fault Code 0 (Healthy System) throughout the entire simulation interval ($t = 0-0.5$ s), confirming stable operation

with zero false trips. While Figure 6 shows balanced three-phase voltage and current waveforms with nominal frequency. Since no fault condition persists beyond pickup thresholds, the relay correctly remains inactive with no timing initiation or trip command issued.

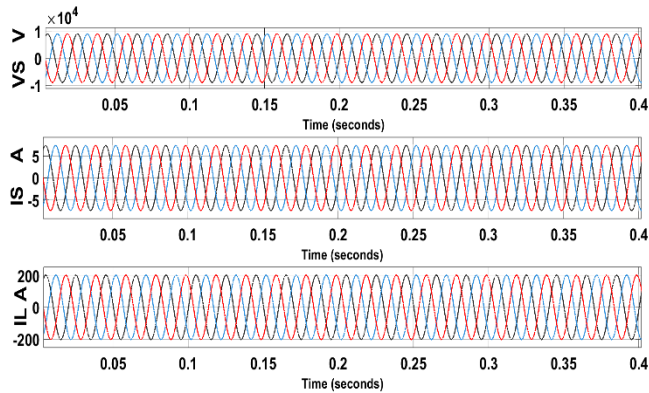


Figure 6. Source voltage, current, and load current at normal operation

B. Case 2:

In the second case, the generator voltage is changed in two forms:

1- at 0.1 sec when a sudden rise in generator voltage from (1 pu to 1.1 pu), the three-phase voltage, three-phase current, system frequency, and relay status observed are as illustrated in Figures 7 and 8.

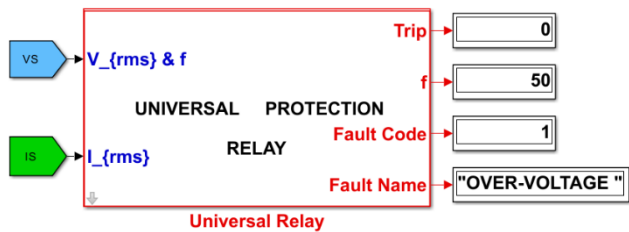


Figure 7. Universal Protection Relay (UPR) stats at over voltage

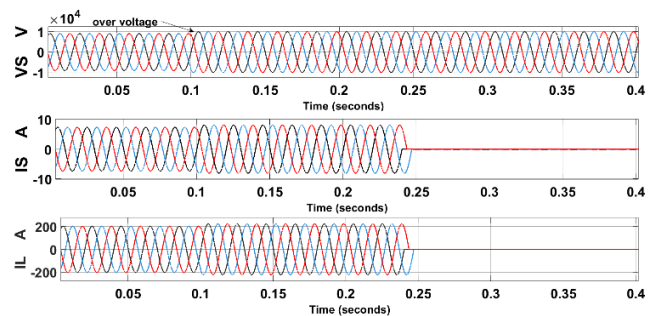


Figure 8. Source voltage, current, and load current at over voltage

The upstream protection relay response to the overvoltage disturbance is shown in Figure 7. After the RMS voltage exceeds the threshold value of 1.1 per unit (pu), the relay sends out the Fault Code 1 - Overvoltage signal and enters its definite time delay. The trip signal is then sent out after approximately 0.3 seconds, indicating that the relay is functioning correctly. It is immune to transients. Figure 8 shows the sustained overvoltage condition following the overvoltage disturbance.

The current is within acceptable limits. The relay will now trip after the 200 ms verification time.

2- If there is a sudden reduction in the generator voltage from 1 pu to 0.9 pu at time 0.1 s, the three-phase voltage, three-phase current, system frequency, and the state of the relay will be as given in Figures 9 and 10.

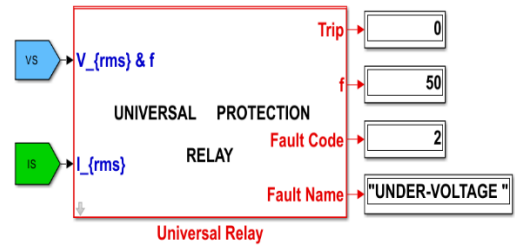


Figure 9. Universal Protection Relay (UPR) stats at under voltage

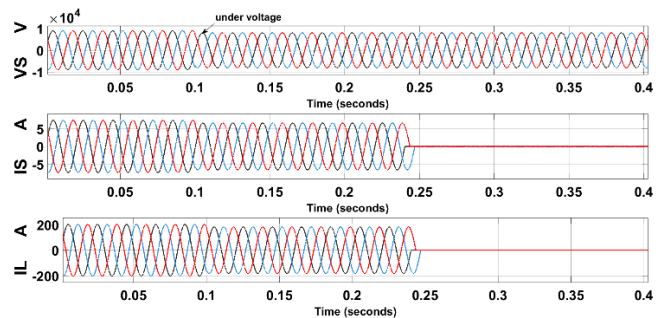


Figure 10. Source voltage, current, and load current at under voltage

Figure 9 shows the UPR response to the undervoltage event initiated at time $t = 0.1$ s. The relay detects a voltage level beneath the defined threshold, sending out a Fault Code 2 message, Undervoltage. The trip command is sent at time $t \approx 0.3$ s, in accordance with the programmed delay of 200 ms, thus avoiding nuisance tripping. Figure 10 also shows the reduction in voltage level while the current level remains stable, thus confirming the relay operation strictly on the basis of voltage persistence.

C. Case 3:

For the third scenario, the generator frequency is adjusted based on the following formula:

1- At time $t = 0.1$ s, a sudden change in the generator frequency is introduced, increasing it from 50 Hz to 53 Hz. The changes in the three-phase voltage, three-phase current, frequency, and the status of the relay are shown in Figures 11 and 12.

The relay response following the over frequency event at time $t = 0.1$ s is depicted in Figure 11. The relay detects the frequency deviation, which is higher than the allowable limit, and declares Fault Code 3, Over frequency. The trip signal is generated at time $t \approx 0.3$ s, reflecting the coordinated frequency protection with an intentional time delay. Additionally, Figure 12 reveals that the voltage and current magnitude are not affected during the frequency deviation. Therefore, the relay response is based on the sustained frequency deviation, exceeding the time of 200 ms.

2- In the event that there is a sudden drop in frequency, such as from 50 Hz to 47 Hz over 0.1 seconds, it is apparent that the resulting three-phase voltage, three-phase current, frequency, and status will be as illustrated in Figures 13 and 14.

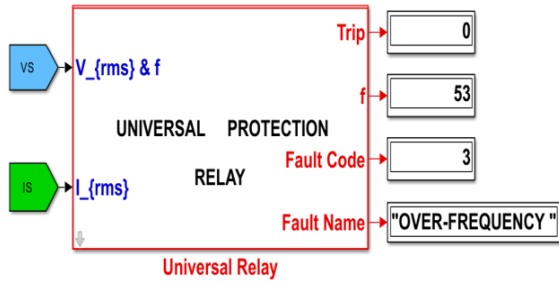


Figure 11. Universal Protection Relay (UPR) Stats at over frequency

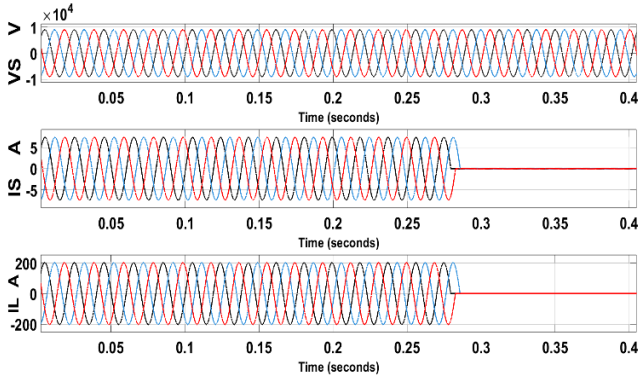


Figure 12. Source voltage, current, and load current at over frequency

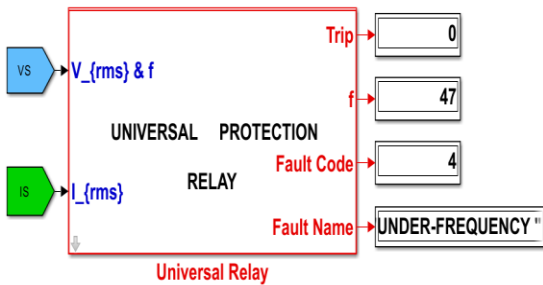


Figure 13. Universal Protection Relay (UPR) stats at under frequency

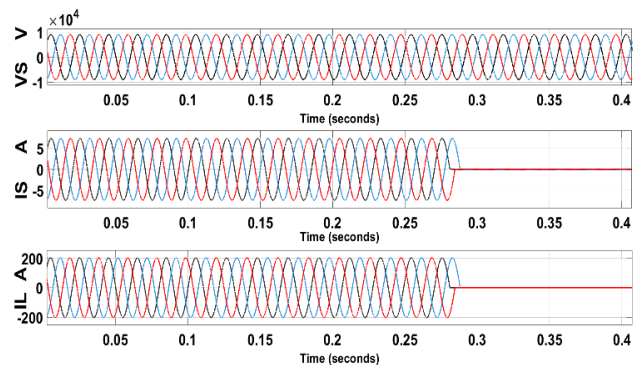


Figure 14. Source voltage, current, and load current at under frequency

In Figure 13, the performance of the UPR relay is shown when an under-frequency condition is created at time $t = 0.1$ seconds. The relay correctly issues the Fault Code 4 - Under Frequency condition and initiates the trip command at approximately time $t = 0.3$ seconds, thus validating the performance of the definite time frequency protection scheme.

Figure 14 further verifies the continuously dropping frequency while the voltage and current remain steady. The intention of the delay in the performance of the relay is to maintain selectivity in the system to avoid unnecessary disconnections.

D. Case 4:

In the fourth case, the generator voltage and frequency are constant while symmetrical and unsymmetrical faults occur at the load side as illustrated below:

1- at 0.1 sec when a three phase to ground fault at load side occurs, the three-phase voltage, three-phase current, system frequency, and relay status observed are as illustrated in Figures 15 and 16.

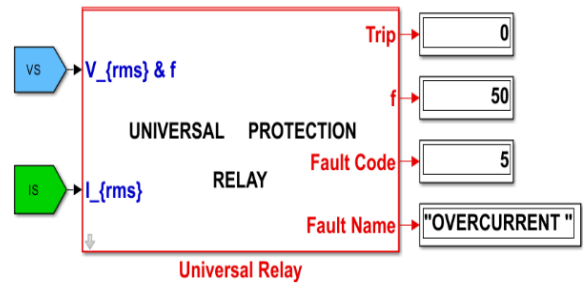


Figure 15. Universal Protection Relay (UPR) stats at three phase to ground fault

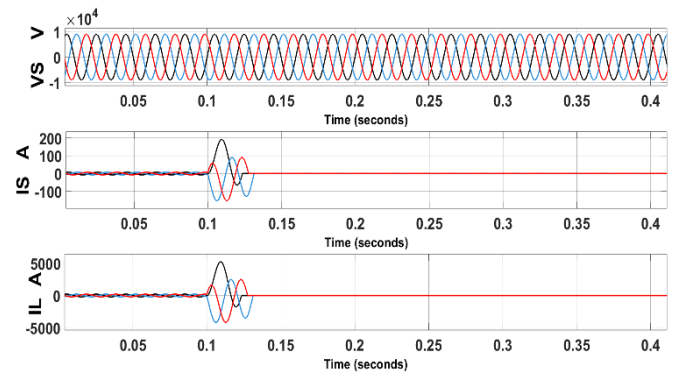


Figure 16. Source voltage, current, and load current at three phase to ground fault

Figure 15 shows the UPR response to a severe three-phase-to-ground fault occurring at $t = 0.1$ s. The resulting high fault current causes the relay to assert Fault Code 5 (Overcurrent) and issue an instantaneous trip within one simulation cycle (≈ 20 ms), bypassing intentional delays with Figure 16 illustrates the sharp current rise and voltage collapse following the fault. The rapid trip time (≈ 20 ms) confirms the effectiveness of the relays fast overcurrent protection in minimizing thermal and mechanical stress.

2- at 0.1 sec when a single line to ground fault at load side happen, the three-phase voltage, three-phase current, system frequency, and relay status observed are as shown in Figures 17 and 18.

Figure 17 demonstrates relay operation during a single line-to-ground fault initiated at $t = 0.1$ s. The unbalanced fault current exceeds the pickup threshold, triggering Fault Code 5 (Overcurrent) and instantaneous tripping within ≈ 20 ms. Figure 18 also shows unbalanced voltages and currents characteristic of unsymmetrical faults. The relay has a fast response time of around 20 ms, which ensures adequate isolation before the onset of the extended unbalance condition, which otherwise may affect the system components.

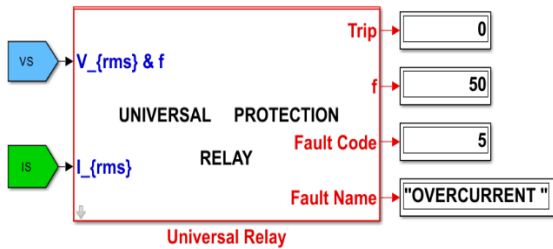


Figure 17. Universal Protection Relay (UPR) stats at single line to ground fault

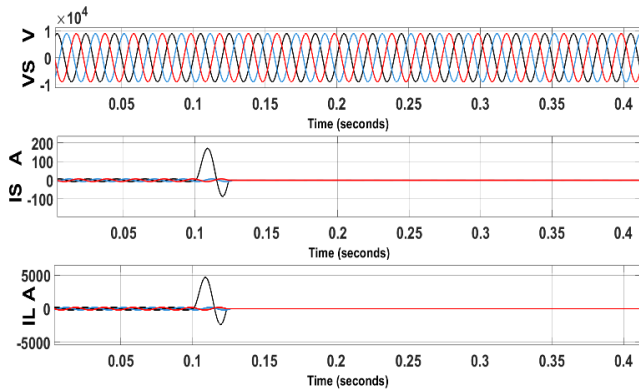


Figure 18. Source voltage, current, and load current at single line to ground fault

The simulation results validate that the proposed UPR provides fast fault isolation in the case of severe short-circuit faults (around 20 ms, Fault Code 5) and ensures selective and coherent protection in the case of voltage and frequency disturbances (200 ms, Fault Codes 1 through 4). The dual-mode timing scheme developed in this research greatly reduces the nuisance tripping problem and, at the same time, ensures the reliable protection of the generator-transformer units in both steady and faulted states.

The presented simulation cases represent representative disturbances commonly encountered in generator-transformer systems. These include voltage and frequency deviations, symmetrical three-phase faults, and unsymmetrical single-line-to-ground faults. These test scenarios represent typical disturbances encountered in generator-transformer systems and provide a practical basis for evaluating the proposed relay performance under both steady-state and fault conditions.

5.1 Comparative analysis with conventional protection

To evaluate the effectiveness of the proposed protection scheme, a comparison was performed with a conventional fixed-setting relay configuration using definite-time overcurrent protection. In the conventional scheme, the issues of voltage and frequency problems are handled by individual protection schemes without verification logic. The simulation results reveal that the conventional relay requires an operating time of 200-300 ms to verify the faults [16, 18], whereas the proposed UPR scheme isolates severe short-circuit faults in 20 ms using instantaneous overcurrent protection. Further, the verification logic in the proposed relay avoids unnecessary tripping during short-duration faults, thereby improving the overall system reliability.

6. CONCLUSIONS

In this paper, the design and simulation validation of a UPR with multi-functionality capabilities for the generator and transformer combination has been proposed to overcome the real-life constraints associated with the use of separate protection relays with fixed and separately designed settings. Unlike the function or data-related designs proposed in the previous research studies, the design of the proposed relay in this paper utilizes a deterministic universal protection scheme that combines overcurrent, over/under voltage, and frequency protection in a single logic platform with coordination capabilities. A fault categorization scheme with a dual timing mode was used to differentiate transient and permanent fault conditions. Simulation results using the MATLAB/Simulink environment reveal that the designed UPR is capable of quickly isolating severe short-circuit faults (Fault Code 5) by instantaneous tripping within 20 ms, and the relay is capable of maintaining selective and coordinated protection for voltage and frequency disturbances by means of 200 ms definite time delay (Fault Codes 1–4). The relay worked properly and remained stable under both normal and fault operating conditions, including symmetrical and unsymmetrical faults, and various voltage and frequency deviations. These results validate the efficiency of the proposed protective scheme to increase the fault discrimination and operating reliability of generator-transformer units. Even though the research is limited to the simulation-based evaluation, the proposed work establishes a rationale for the practical and standards-compliant solution for the integrated generator-transformer protection scheme. The future research will focus on the development of the relay scheme to include the differential and harmonic restraint protection schemes and the implementation of real-time and hardware-in-the-loop tests to evaluate the scheme.

Future work will focus on hardware-in-the-loop implementation and real-time digital simulation to further validate the proposed protection algorithm under practical operating conditions.

ACKNOWLEDGMENT

The authors would like to thank the University of Mosul for their assistance with this work.

REFERENCES

- [1] Blackburn, J.L., Domin, T.J. (2006). Protective Relaying: Principles and Applications. CRC Press. <https://doi.org/10.1201/9781420017847>
- [2] Grigsby, L.L. (2007). Power System Stability and Control. CRC Press.
- [3] Najem, W.M., Khudher, S.M., Alyozbaky, O.S. (2023). Impact of EV charging stations integration on power system performance. *Przeegląd Elektrotechniczny*, 99(3): 227-231. <https://doi.org/10.15199/48.2023.03.40>
- [4] Azizan, N.S., Wooi, C.L., Ismail, B., Arshad, S.N.M., Isa, M., Mustafa, W.A., Rohani, M.N.K. (2020). Simulation of differential relay for transformer protection. *IOP Conference Series: Materials Science and Engineering*, 767(1): 012004. <https://doi.org/10.1088/1757-899X/767/1/012004>

- [5] Elsadd, M.A., Yousef, W., Abdelaziz, A.Y. (2020). New adaptive coordination approach between generator-transformer unit overall differential protection and generator capability curves. *International Journal of Electrical Power & Energy Systems*, 118: 105788. <https://doi.org/10.1016/j.ijepes.2019.105788>
- [6] Andreev, M., Suvorov, A., Askarov, A., Rudnik, V., Bhalja, B.R. (2022). Novel approach for relays tuning using detailed mathematical model of electric power system. *International Journal of Electrical Power & Energy Systems*, 135: 107572. <https://doi.org/10.1016/j.ijepes.2021.107572>
- [7] IEEE Guide for Protective Relay Applications to Power Transformers. (2000). In IEEE Std C37.91-2000, pp.1-85. <https://doi.org/10.1109/IEEESTD.2000.91943>
- [8] Jaiswal, G.C., Ballal, M.S., Tutakne, D.R., Doorwar, A. (2018). A review of diagnostic tests and condition monitoring techniques for improving the reliability of power transformers. In 2018 International Conference on Smart Electric Drives and Power System (ICSEDPS), pp. 209-214. <https://doi.org/10.1109/ICSEDPS.2018.8536067>
- [9] Sahebkar Farkhani, J., Zareein, M., Najafi, A., Melicio, R., Rodrigues, E.M. (2020). The power system and microgrid protection—A review. *Applied Sciences*, 10(22): 8271. <https://doi.org/10.3390/app10228271>
- [10] Bo, Z.Q., Lin, X.N., Wang, Q.P., Yi, Y.H., Zhou, F.Q. (2016). Developments of power system protection and control. *Protection and Control of Modern Power Systems*, 1(1): 1-8. <https://doi.org/10.1186/s41601-016-0012-2>
- [11] Agwa, A.M., El-Fergany, A.A. (2023). Protective relaying coordination in power systems comprising renewable sources: Challenges and future insights. *Sustainability*, 15(9): 7279. <https://doi.org/10.3390/su15097279>
- [12] Alahmed, S.H.A., Alsammak, A.N.B., Mohammed, H.A. (2025). A review of the conventional and intelligent multifunctions electrical generator protection system, challenges and opportunities. *Journal Européen des Systèmes Automatisés*, 58(3): 523-536. <https://doi.org/10.18280/jesa.580310>
- [13] Mohideen, H. (2024). Modern numerical relays in protection of power transformer. *i-Manager's Journal on Power Systems Engineering*, 11(4): 39-46. <https://doi.org/10.26634/jps.11.4.20841>
- [14] Sarajcev, P., Lovric, D. (2024). Machine learning classifier for supporting generator's impedance-based relay protection functions. *Energies*, 17(8): 1820. <https://doi.org/10.3390/en17081820>
- [15] Jain, R., Velaga, Y.N., Prabakar, K., Baggu, M., Schneider, K. (2022). Modern trends in power system protection for distribution grid with high DER penetration. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, 2: 100080. <https://doi.org/10.1016/j.prime.2022.100080>
- [16] Ghezelayagh, M. (2020). *Power Systems Protection, Control & Automation: Numerical Relays: Field Applications*. Maty Ghezelayagh
- [17] Gómez, P., Segundo-Ramírez, J. (2021). Frequency domain approach for statistical switching studies: Computational efficiency and effect of network equivalents. *Electric Power Systems Research*, 196: 107257. <https://doi.org/10.1016/j.epsr.2021.107257>
- [18] Chen, L., Li, X., Cao, Y., Yang, D. (2025). The value and development of relay protection technology in modern power systems. In 4th International Conference on Power Electronics and Electrical Technology (ICPEET 2025), pp. 178-182. <https://doi.org/10.1049/icp.2025.3024>
- [19] Kale, P.R., Dongre, K.A., Ahmad, M. (2021). Machine Learning Approaches in Power System Protection: A Review. In *Proceedings of Integrated Intelligence Enable Networks and Computing: IIENC 2020*, pp. 707-715. https://doi.org/10.1007/978-981-33-6307-6_73
- [20] Tariq, A., Khatri, K.L., Haque, M.I.U., Raza, M.A., Ahmed, S., Muzammil, M. (2021). Investigation of the effects of distributed generation on protection coordination in a power system. *Engineering, Technology & Applied Science Research*, 11(5): 7628-7634. <https://doi.org/10.48084/etasr.4338>