

APPLICATION OF SECOND HARMONIC RESTRAINT TO IMPROVE THE RELIABILITY OF P3U30 RELAY PROTECTION DURING ENERGIZATION OF 22KV MEDIUM-VOLTAGE DISTRIBUTION LINES

Ninh Van Nam¹, Nguyen Luong Thanh¹,
Nguyen Thi Tho^{2,*}

DOI: <https://doi.org/10.57001/huih5804.2026.104>

ABSTRACT

In medium-voltage distribution systems, inrush currents during feeder energization may cause undesired relay operations due to their high magnitude and transient characteristics. This paper proposes a reliable protection solution based on the second harmonic restraint method implemented in the P3U30 relay for 22kV feeders. A simulation model is developed in MATLAB/Simulink to analyze three typical operating conditions: inrush current (Case 1), short-circuit fault (Case 2), and switch-on-to-fault (SOTF) condition (Case 3). The results show that during energization, the inrush current contains a significant second harmonic component, with the ratio I_2/I_1 ranging from 0.2 to 0.3, exceeding the restraint threshold and correctly blocking relay operation. In contrast, under fault and SOTF conditions, although the current magnitude is very high, the second harmonic content remains negligible ($I_2/I_1 < 0.05$), allowing the relay to operate accurately and issue a trip signal. The findings confirm that the second harmonic restraint method effectively distinguishes between inrush and fault conditions, preventing false tripping while maintaining fast and reliable fault detection. This approach enhances the reliability, selectivity, and operational security of protection systems in medium-voltage networks and can be readily applied to modern digital relays.

Keywords: P3U30 relay, Second harmonic restraint, Protection reliability, 22kV distribution lines.

¹School of Electrical and Electronic Engineering, Hanoi University of Industry, Vietnam

²Master's Student, 14th Cohort - School of Electrical and Electronic Engineering, Hanoi University of Industry, Vietnam

*Email: thonguyenepu@gmail.com

Received: 05/3/2026

Revised: 15/5/2026

Accepted: 29/5/2026

1. INTRODUCTION

In recent years, the reliability of protective relays in medium-voltage distribution networks has become an important research topic, particularly under transient operating conditions such as feeder energization and synchronization. The increasing penetration of nonlinear loads and distributed energy resources has resulted in significant waveform distortion, introducing harmonic and interharmonic components into power system signals. These distortions directly affect the performance of protection systems, potentially leading to incorrect relay operation [1-3]. Numerous studies have investigated the impact of harmonic distortion on relay performance. It has been shown that harmonic and interharmonic components can significantly alter relay response characteristics, including operating time and sensitivity, potentially leading to coordination issues and maloperation [4-6]. Similarly, both experimental and simulation-based studies on numerical relays indicate that high harmonic content may cause incorrect tripping or failure to operate under abnormal conditions [5]. These findings highlight the necessity of developing advanced techniques to enhance relay reliability in distorted waveform environments.

One of the most commonly adopted techniques is second harmonic restraint, which is widely applied in transformer differential protection and medium-voltage feeder energization schemes to distinguish magnetizing inrush currents from fault currents. This method is founded on the characteristic harmonic behavior of these phenomena: magnetizing inrush currents typically contain a substantial second harmonic component,

whereas fault currents are predominantly composed of the fundamental frequency component with negligible second harmonic content [7]. However, several studies have pointed out that under certain conditions, such as faults involving nonlinear characteristics or the presence of residual flux, the effectiveness of this method may be reduced, requiring further improvement [8]. In addition, various harmonic blocking methods have been proposed to prevent relay maloperation. For instance, harmonic blocking schemes based on IEC 61850 communication standards have been developed to coordinate primary and backup protection, effectively preventing overcurrent relays from operating during transformer energization [6]. These approaches demonstrate the potential of harmonic-based signals not only for fault discrimination but also for adaptive coordination among protection functions. Despite the extensive research on harmonic restraint mechanisms in transformer and distribution line protection, there is still a lack of studies focusing on their application to overcurrent protection and Switch-On-To-Fault (SOTF) functions in distribution networks, particularly under conditions such as load energization and feeder synchronization [9-12]. In these cases, transient currents with high second harmonic content may be misinterpreted as fault currents, leading to undesired relay operation. Existing solutions are mainly based on adjusting pickup thresholds or introducing time delays, which may compromise protection sensitivity and speed.

Therefore, this paper aims to address the aforementioned gap by proposing a second harmonic-based restraint method for blocking the SOTF function in P3U30 relays during synchronization of 22kV distribution feeders. The proposed method exploits the differences in harmonic characteristics between transient and fault conditions to improve relay selectivity and reliability without degrading fault detection capability.

2. SECOND HARMONIC BLOCKING PRINCIPLE IN PROTECTIVE RELAYS

Second harmonic restraint is a widely used blocking technique in protective relaying, which utilizes current or magnetic signals at twice the fundamental system frequency (typically $2f_0 = 1002f_0 = 1002f_0 = 100\text{Hz}$ for a 50Hz system). In power system protection and substation automation, the second harmonic component is employed to distinguish transformer magnetizing inrush current from internal fault currents within the protected zone.

This principle is based on the following characteristics:

- **Inrush current** contains a significant second harmonic component, typically exceeding 15 - 20% of the fundamental component.
- **Fault current** exhibits a very low second harmonic content, usually below 5 - 7%.

The measured current signal is obtained from current transformers (CTs), processed through filtering stages, and then decomposed into its fundamental component I_1 and second harmonic component I_2 using digital filters or Fast Fourier Transform (FFT) techniques.

The total current signal can be expressed using a Fourier series as follows [13]:

$$i(t) = I_1 \sin(\omega t + \varphi_1) + I_2 \sin(2\omega t + \varphi_2) + \sum_{n=3}^{\infty} I_n \sin(n\omega t + \varphi_n) \tag{1}$$

where I_1 and I_2 represent the fundamental and second harmonic components, respectively.

The second harmonic ratio is defined as:

$$K_2 = \frac{I_2}{I_1} \cdot 100\% \tag{2}$$

During energization conditions, the value of K_2 can increase abnormally (typically from 15% to 40%), whereas under actual short-circuit fault conditions, this component is very small.

The SOTF (Switch-On-To-Fault) function is designed to rapidly detect faults when energizing a line with an existing fault. However, it cannot distinguish between fault current and transient current if only the current magnitude is considered. The proposed solution is to use the second harmonic ratio to identify the energization condition:

- If: $K_2 \geq K_{set} \rightarrow$ relay operation is blocked (BLOCK = 1)
- If: $K_2 < K_{set} \rightarrow$ relay operation is allowed (BLOCK = 0)

Where K_{set} is the setting threshold, typically selected in the range: $K_{set} = 15 \div 20\%$ [14]

However, under certain conditions such as CT saturation, residual flux, or fault currents with nonlinear characteristics, the second harmonic content in inrush currents may decrease significantly, potentially reducing the effectiveness of conventional second harmonic restraint methods.

In digital relays, the signal is sampled, and I_1, I_2 are calculated using the transformation:

$$I_k = \sqrt{A_k^2 + A_k'^2}; A_k = \frac{2}{N} \sum_{n=0}^{N-1} i[n] \cos\left(\frac{2\pi kn}{N}\right);$$

$$B_k = \frac{2}{N} \sum_{n=0}^{N-1} i[n] \sin\left(\frac{2\pi kn}{N}\right)$$
(3)

Proposed Method: Therefore, to overcome the limitations of conventional second harmonic restraint methods, this paper proposes an enhanced harmonic-based blocking algorithm for Switch-On-To-Fault (SOTF) protection in medium-voltage distribution networks. The proposed method exploits the dynamic behavior of the second harmonic component during transient conditions, particularly during line energization and synchronization processes, where conventional techniques may fail to provide reliable discrimination between inrush and fault currents. Instead of relying solely on a fixed second harmonic threshold, the proposed approach incorporates adaptive criteria based on the temporal variation of harmonic content, enabling more accurate identification of transient phenomena. In addition, the algorithm is designed to coordinate with overcurrent protection functions, ensuring secure blocking during non-fault conditions while maintaining fast and reliable fault detection. The effectiveness of the proposed method is validated through detailed simulations in MATLAB/Simulink under various operating scenarios, including transformer energization, fault conditions, and SOTF events in 22kV distribution feeders.

The block diagram of the second harmonic blocking function is presented in Figure 1.

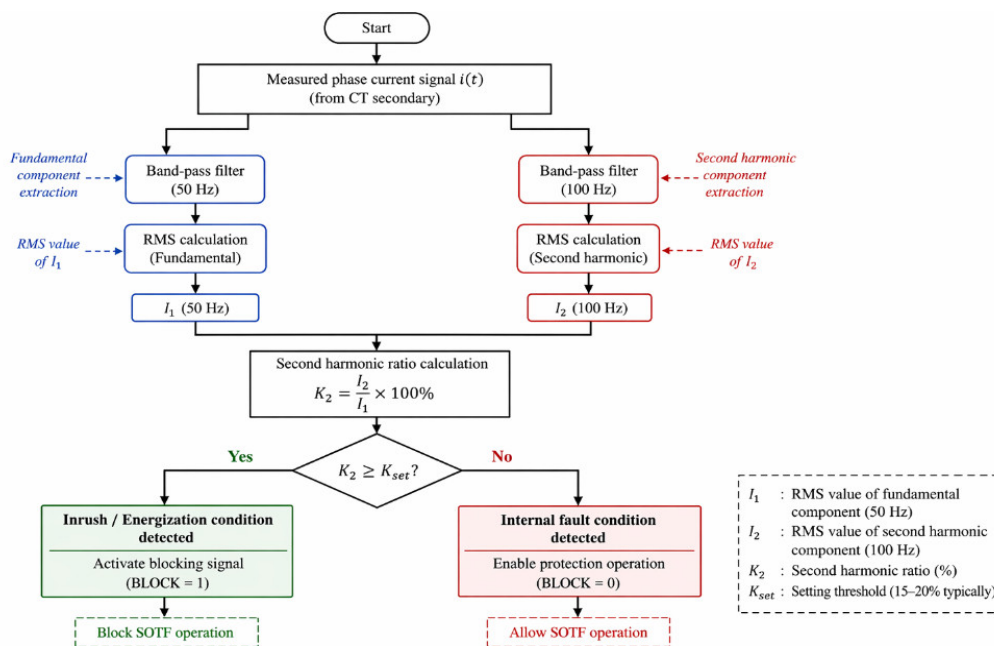


Figure 1. Functional block diagram of second harmonic blocking

The proposed algorithm extracts the fundamental and second harmonic components of the current signal using band-pass filters at 50Hz and 100Hz, respectively. The Root Mean Square (RMS) values of these components are computed to determine the second harmonic ratio K_2 . This ratio is then compared with a predefined threshold K_{set} to distinguish between inrush conditions and fault events. If K_2 exceeds the threshold, the protection function is blocked; otherwise, normal protection operation is allowed.

3. PROBLEM DESCRIPTION

During the operation of medium-voltage distribution networks configured in a ring topology with two power sources, the reclosing or synchronization of line sections after fault isolation often introduces significant electromagnetic transients (Figure 2). Under normal operating conditions, the load is supplied from two sources, denoted as NG1 and NG2, while the tie switch T remains open (the feeder is energized under load). Assume a fault occurs at location SC1. When a fault happens near source NG1, the circuit breaker (CB) at NG1 trips to isolate the fault. After fault clearance, the operator opens the disconnecter at location F1 to isolate the faulty section between F1 and M1.

At this stage, although the fault has been isolated, the load between M1 and T, as well as the section between NG1 and F1, is de-energized. To restore supply, the operator closes the tie switch T to energize the section from T to M1. Similarly, the load between NG1 and F1 is restored by reclosing the circuit breaker at NG1. Thus, the faulted section remains isolated while service continuity is partially restored.

After the fault has been fully cleared and the section between F1 and M1 is confirmed to be healthy, the operator recloses the disconnectors at F1 and M1 (while the tie switch T remains closed). To restore the original network configuration (ensuring redundancy and optimal operation), the tie switch T is then opened.

However, during the synchronization process when reconnecting source NG1, significant transient currents containing high second harmonic components may arise. These transient inrush currents can exceed the pickup threshold of the Switch-On-To-Fault (SOTF) function, causing the relay at NG1 or NG2 to misinterpret the condition as a fault and trip the corresponding circuit breaker.

Such unintended operation of the SOTF function contradicts its intended purpose and introduces operational challenges in modern smart grid systems. It also reduces the reliability of relay protection. Therefore, it is necessary to develop an optimal and reliable solution to ensure correct relay operation.

Through analysis of disturbance records under these conditions, it is observed that second harmonic components are present during the synchronization of 22kV feeders when circuit breakers at both ends are closed. Hence, analyzing the system behavior after feeder synchronization to identify the origin of second harmonic components, and applying second harmonic detection to block the SOTF function during synchronization, is essential. This approach can reduce operational complexity for system operators, improve protection reliability, and enhance the stability and dependability of medium-voltage distribution networks.

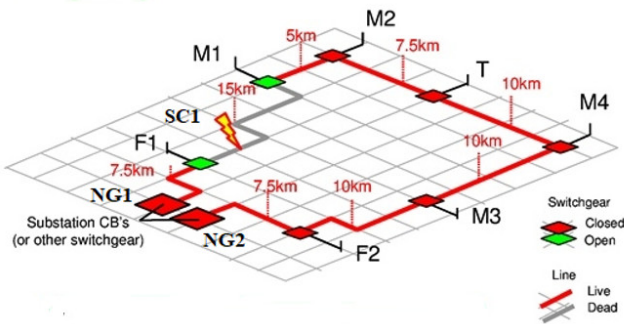


Figure 2. Configuration of a 22kV medium-voltage ring network supplied by two sources with a normally open tie switch

4. SIMULATION RESULTS AND ALGORITHM ANALYSIS

4.1. Simulation Setup and Parameter Calculation

To verify the effectiveness of the second harmonic blocking function for SOTF protection, the authors developed a power system model in MATLAB/Simulink. The study focuses on a 22kV distribution feeder energized under two conditions: no-load energization (resulting in inrush current) and energization onto a short-circuit fault (SOTF condition). The initial data and simulation parameters are as follow:

Table 1. Source Parameters

Parameter	Symbol	Value
Rated voltage	U_n	22kV
Frequency	f	50Hz
Short-circuit capacity	S_{sc}	100MVA
Source reactance	X_s	0.2pu
Source resistance	R_s	0.02pu
Phase angle difference	$\Delta\varphi$	0 - 10°

Table 2. Line Parameters

Section	Length (km)	Resistance (Ω /km)	Inductance (mH/km)	Capacitance (μ F/km)
NG1 - F1	7.5	0.4	1.2	0.01
F1 - M1	15	0.4	1.2	0.01
M1 - M2	5	0.4	1.2	0.01
M2 - T	7.5	0.4	1.2	0.01
T - M4	10	0.4	1.2	0.01
M4 - M3	10	0.4	1.2	0.01
M3 - F2	10	0.4	1.2	0.01
F2-NG2	7.5	0.4	1.2	0.01

Table 3. Load Parameters

Parameter	Symbol	Value
Total load	P_{load}	6 - 8MW
Power factor	$\cos\varphi$	0.85
Load locations	—	M1, M2, M3

Table 4. Fault Parameters

Parameter	Symbol	Value
Fault location	—	SC1 (F1-M1)
Fault type	—	3-phase / SLG
Fault resistance	R_f	0.01 - 10 Ω
Fault inception time	t_f	0.1s
Clearing time	t_c	0.2s

Table 5. Switching and SOTF Conditions

Parameter	Symbol	Value
Tie switch closing time	t_T	0.3s
Circuit breaker reclosing	t_{CB}	0.35s
Switching angle	θ	0° - 90°
Residual flux	ϕ_r	0.2 - 0.8pu
Inrush current	I_{inrush}	5pu

Table 6. Current Transformer Parameters

Parameter	Symbol	Value
CT ratio	—	600/1A
Accuracy class	—	5P20
Measurement error	—	< 5%
CT saturation	—	Considered

Table 7. Relay Parameters (P3U30)

Parameter	Symbol	Value
Protection function	—	Overcurrent + SOTF
Pickup current	I_{set}	1.2 - 1.5pu
Operating time	t_{op}	0.1 - 0.3s
Sampling frequency	f_s	1 - 5kHz

Table 8. Harmonic Detection Parameters

Parameter	Symbol	Value
Fundamental frequency	f_1	50Hz
Second harmonic frequency	f_2	100Hz
RMS window	—	1 cycle (20ms)
Second harmonic ratio	K_2	I_2/I_1 times 100%
Threshold	K_{set}	15% - 20%

Table 9. Simulation Scenarios

Parameter	Description
Case 1	Inrush current
Case 2	Short-circuit fault at SC1
Case 3	Switch-on-to-fault (SOTF) condition

Tables 1 ÷ 9 summarize the system parameters and simulation conditions used to evaluate the proposed second harmonic restraint-based SOTF blocking method

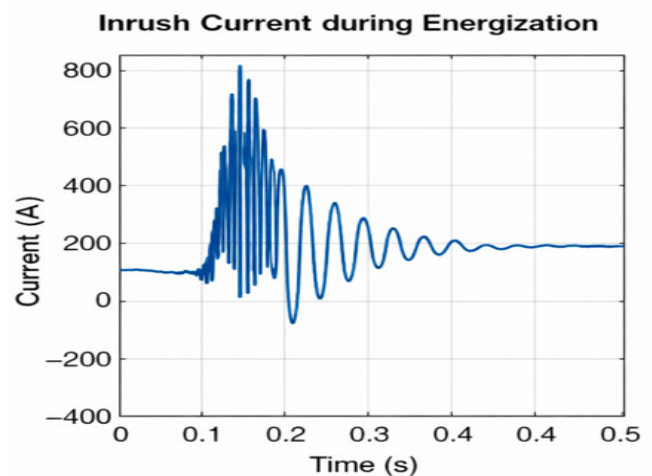
4.2. Inrush current (Case 1)

Figure 3(a) depicts the current waveform observed during the no-load energization of a 22kV distribution feeder. It can be seen that immediately after the circuit breaker is closed ($t \approx 0.1s$), a pronounced inrush current is generated, reaching a peak value of approximately 800A, which is several times greater than the rated current. This transient phenomenon is characterized by a high initial magnitude and a gradual decay toward steady-state conditions. This phenomenon is mainly attributed to non-optimal switching instants (unsynchronized zero-crossing) and the presence of residual flux in the system. Compared to the pickup setting $I_{set} = 1.3I_n$ (at $U_n = 22kV$), the measured current significantly exceeds the relay operating threshold. The waveform exhibits pronounced

asymmetry with a noticeable DC offset, resulting in a bias toward the positive half-cycle. Furthermore, the current magnitude gradually decays over time (from 0.1s to 0.5s), following the transient characteristics of the 22kV distribution system.

Figure 3(b) illustrates the frequency spectrum of the measured current signal, obtained through Fast Fourier Transform (FFT) analysis. The spectrum provides a clear representation of the harmonic content present in the current waveform during the energization process. The harmonic analysis reveals that the fundamental component (50Hz) has the largest magnitude (approximately 1.0pu. in the FFT plot). Notably, the second harmonic component (100Hz) appears prominently, with an amplitude of approximately 0.23pu., resulting in a second harmonic ratio I_2/I_1 of 23%. Compared to the predefined restraint threshold $K = 0.15$ (15%) used in the P3U30 relay, this value is significantly higher.

Discussion and Evaluation: The results clearly indicate that under no-load energization conditions (Case 1), the second harmonic component is dominant, which serves as a key distinguishing feature from short-circuit currents. In terms of relay operation, although the current magnitude reaches approximately 800A (satisfying the condition $I > I_{set}$), the second harmonic ratio (23%) exceeds the restraint threshold $K = 15\%$. Therefore, the harmonic restraint condition $I_2/I_1 > K$ is activated, and the P3U30 relay is effectively blocked from issuing a trip signal. These findings confirm that the second harmonic restraint method successfully prevents unintended relay tripping during line energization, thereby enhancing the reliability and security of the 22kV power distribution system.



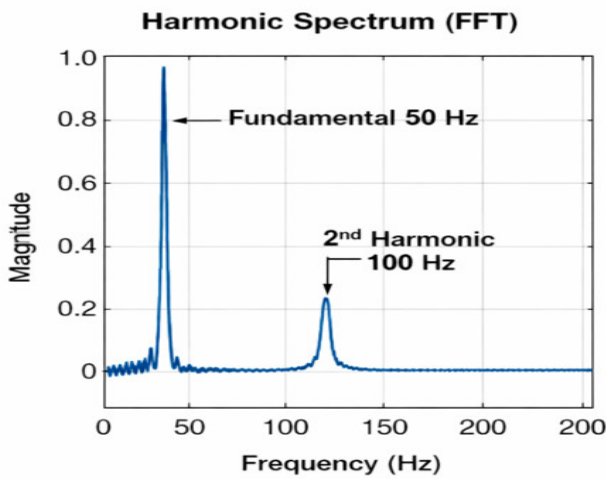


Figure 3. (a) Phase current under inrush condition; (b) harmonic spectrum showing a significant second harmonic component

4.3. Short-circuit fault at SC1 (Case 2)

From the time-domain current waveform (Figure 4a), it can be observed that at the fault inception instant ($t \approx 0.1s$), the current increases abruptly to a very high magnitude, reaching approximately 3000 - 3500A, which is characteristic of a short-circuit condition in the system. In the initial stage, the waveform contains a noticeable DC offset, as evidenced by the asymmetry between successive half-cycles. However, this component decays rapidly, and the current quickly returns to a nearly symmetrical sinusoidal waveform.

In the frequency domain (Figure 4b), the Fast Fourier Transform (FFT) spectrum shows that the fundamental component at 50Hz is dominant, while harmonic components particularly the second harmonic (100Hz)-are negligible. As a result, the second harmonic ratio I_2/I_1 is very small (typically less than 0.05), which is significantly lower than the typical restraint threshold.

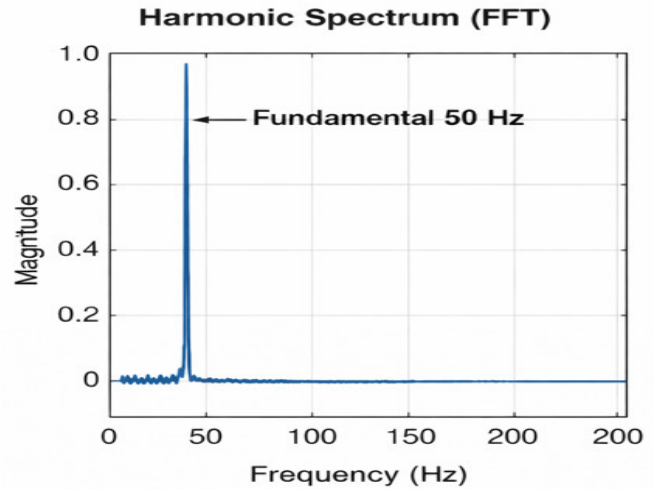
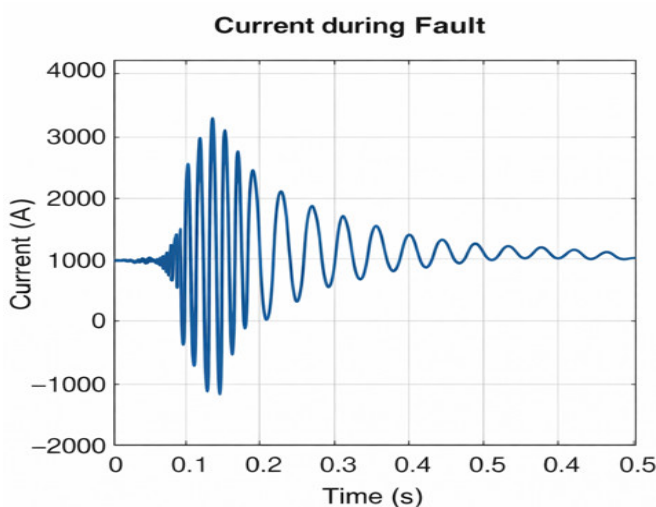


Figure 4. (a) Phase current under internal fault condition at SC1; (b) harmonic spectrum showing a dominant fundamental component and negligible second harmonic content

Since the second harmonic ratio is below the preset threshold ($K \approx 0.15K \approx 0.15$), the harmonic restraint function of the P3U30 relay is not activated. Consequently, the relay correctly identifies this condition as a genuine fault and promptly issues a trip signal to isolate the faulted element.

4.4. Switch-on-to-fault (SOTF) condition (Case 3)

From the time-domain current waveform (Figure 5a), it can be observed that immediately after the switching instant ($t \approx 0.1s$), the current rises abruptly to a very high magnitude, reaching approximately 3000 - 3500A. This behavior is characteristic of a fault condition occurring simultaneously with the energization process. The waveform initially contains a noticeable DC offset, as indicated by the asymmetry in the first few cycles; however, it quickly transitions to a nearly sinusoidal shape and gradually decays toward steady-state conditions. Compared to inrush current, this waveform exhibits less distortion and a higher degree of symmetry.

In the frequency domain (Figure 5b), the FFT spectrum shows that the fundamental component at 50Hz is dominant, while harmonic components particularly the second harmonic (100Hz) are negligible. As a result, the second harmonic ratio I_2/I_1 is very small (typically less than 0.05), which is significantly lower than the predefined restraint threshold.

Therefore, the protection relay is not affected by the second harmonic restraint mechanism and correctly identifies this condition as a genuine fault. Consequently, the relay issues a trip signal promptly to isolate the faulted element. These results confirm that the second

harmonic restraint criterion not only prevents maloperation during inrush conditions but also preserves correct operation under fault conditions occurring during switching (SOTF), thereby enhancing the overall reliability of the protection system.

Under genuine short-circuit fault conditions, although the current magnitude may be comparable to or even exceed that observed during inrush events, the second harmonic content remains negligible. Consequently, the ratio I_2/I_1 stays well below the preset restraint threshold, preventing activation of the harmonic blocking function. As a result, the P3U30 relay correctly identifies the fault condition and operates rapidly to isolate the faulted section. These results demonstrate that the proposed method maintains both the dependability and operating speed of the protection system while effectively avoiding unnecessary restraint during fault conditions.

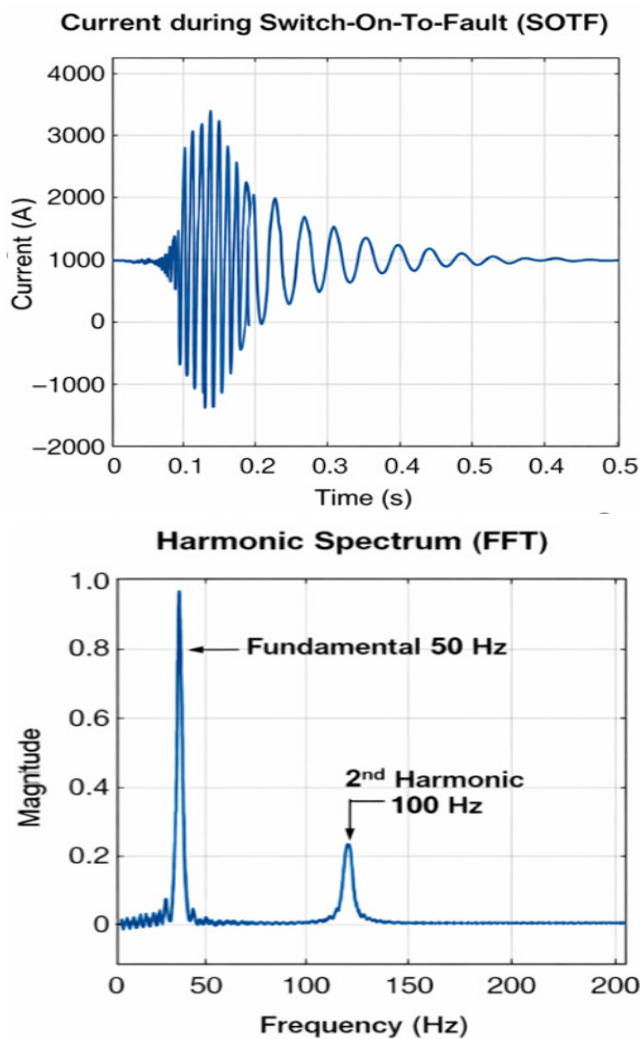


Figure 5. (a) Phase current under SOTF with internal fault condition; (b) harmonic spectrum indicating a diminished second harmonic component due to the presence of fault current

5. CONCLUSION

This paper presented a second harmonic restraint-based method to improve the reliability of protection systems during the energization of 22kV medium-voltage lines using the P3U30 relay. The proposed approach was evaluated under three representative operating conditions, including inrush current, short-circuit fault, and switching onto a fault (SOTF).

The results show that inrush current is characterized by a high second harmonic content, allowing the restraint function to effectively block undesired relay operation. In contrast, fault conditions exhibit negligible second harmonic components, ensuring that the relay operates correctly without restraint.

These findings confirm that the proposed method can reliably distinguish between inrush and fault currents, thereby preventing maloperation while maintaining fast and dependable fault clearance. The approach is practical, requires no additional hardware, and can be readily implemented in modern digital protection systems.

Case	Operating condition	K	Relay
Case 1	Inrush	0.2 - 0.3	✗ Block
Case 2	Fault	< 0.05	☑ Trip
Case 3	SOTF	< 0.05	☑ Trip

REFERENCES

[1]. Farzin Hossein, et al. "A reliability model for overcurrent relays considering harmonic-related malfunctions," *International Journal of Electrical Power & Energy Systems*, 131: 107093, 2021. <https://doi.org/10.1016/j.ijepes.2021.107093>

[2]. IEEE Std C37. 91-2000, *IEEE guide for protective relay applications to power transformers*. New York, NY, USA: The Institute of Electrical and Electronics Engineers, 2000.

[3]. B. Kasztenny, N. Fischer, M. Mynam, "An improved transformer inrush restraint algorithm increases security while maintaining fault response performance," *IEEE Transactions on Power Delivery*, 33, 1, 256-265, 2018.

[4]. Ferreira Gustavo DM, João Ricardo MS de Souza, Alberto De Conti, "Evaluation of the effect of harmonic and interharmonic distortions on inverse time protective relays," *Electric Power Systems Research* 252: 112389, 2026. <https://doi.org/10.1016/j.epr.2025.112389>

[5]. Wannous Kinan, Petr Toman, "Evaluation of harmonics impact on digital relays," *Energies*, 11.4: 893, 2018.

- [6]. Hodder B. Kasztenny, N. Fischer, "Low second-harmonic content in transformer inrush currents - Analysis and practical solutions for protection security," in *Proc. IEEE Power and Energy Society General Meeting*, 1-5, 2014.
- [7]. Mo C., et al. "Equivalent statisticsbased inrush identification method for differential protection of power transformer," *Electric Power Systems Research*, 203: 107664, 2022. <https://doi.org/10.1016/j.epsr.2021.107664>
- [8]. Nazari Ali Akbar, Seyed Amir Hosseini, Behrooz Taheri, "Improving the performance of differential relays in distinguishing between high second harmonic faults and inrush current," *Electric Power Systems Research*, 223: 109675, 2023. <https://doi.org/10.1016/j.epsr.2023.109675>
- [9]. Krishnamurthy Senthil, Bwandakassy Elenga Banningobera, "IEC61850 standard-based harmonic blocking scheme for power transformers," *Protection and Control of Modern Power Systems*, 4.2: 1-15, 2019
- [10]. J. L. Blackburn, T. J. Domin, *Protective Relaying: Principles and Applications*, 4th ed. Boca Raton, FL, USA: CRC Press, 2014.
- [11]. A. Guzmán, S. Zocholl, "Improvements in line current differential protection for high-resistance faults and line energization," *IEEE Trans. Power Delivery*, 17, 4, 951-957, 2002.
- [12]. H. Khorashadi-Zadeh, M. Sanaye-Pasand, "A novel approach for discrimination between inrush and fault currents," *Electric Power Systems Research*, 78, 7, 1239-1246, 2008.
- [13]. Bollen M. H., Gu I. Y., *Signal processing of power quality disturbances*. John Wiley & Sons, 2006.
- [14]. IEEE Power and Energy Society, *IEEE Std C37.91 - Guide for Protective Relay Applications to Power Transformers*. New York, NY, USA: The Institute of Electrical and Electronics Engineers, 2021.