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Comparative Analysis between Dynamic Voltage Restorer and PWM-Switched Autotransformer in Voltage Sag Mitigation

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Abstract: This research aims to address the problem of voltage sag, which is a significant power quality issue in power systems. Voltage sag can cause power transmission and distribution lines to trip, causing electrical equipment to fail. To mitigate the effects of voltage sag, many voltage sag mitigation devices have been created. The effectiveness of three types of voltage sag mitigation devices under diverse voltage sag scenarios is investigated in this study: three-phase fault, multi-phase fault, and energizing transformer inrush current. Dynamic Voltage Restorer (DVR) with Park's transformation, DVR with Artificial Neural Network (ANN) controller, and PWM-switched autotransformer with Proportional-Integral (PI) controller are the three mitigations investigated. The MATLAB simulation results show that all voltage sag circumstances have been avoided except for PWM-switched autotransformer during voltage sag induced by energizing transformer inrush current due to PI controller scheme restrictions. Based on the analysis of input and output voltage waveforms, three-phase voltage magnitude before and after mitigation, and Total Harmonic Distortion (THD) value after mitigation, DVR with ANN controller is found to be the most effective voltage sag mitigation device, followed by DVR with Park's transformation and PWM-switched autotransformer.

Keywords: Power quality, voltage sag, DVR Park's transformation, DVR ANN controller, PWM-switched

1. Introduction

One of the most problematic power quality problems in power networks, voltage sag can trip power transmission and distribution lines and damage electrical equipment. The mitigation of voltage sag has become a crucial concern in the power system industry to ensure reliable power supply and enhance power quality. Various voltage sag mitigation devices, including Dynamic Voltage Restorer (DVR), Uninterruptible Power Supply (UPS), Pulse Width Modulation (PWM)-switched autotransformers, have been proposed to reduce voltage sag [1-3]. However, selecting the most effective device under different voltage sag conditions remains a challenge. Therefore, a lot of research is doing a comparative study among these mitigation strategies. The importance of comparative study is to help power system engineers make informed decisions about the selection of appropriate voltage sag mitigation devices to ensure a reliable and efficient power system. Therefore, the comparative analysis of these three devices is crucial for identifying the most effective voltage sag mitigation device for a given fault condition.

Another significant power quality issue is that it can cause equipment failure, production downtime, and financial losses for industrial and commercial customers [4]. One example of voltage sag occurred in the US in 2003, where a

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Corresponding author: yusrin262@uitm.edu.my voltage sag led to a massive power outage that affected approximately 55 million people across eight US states and Ontario, Canada. The voltage sag was caused by a software bug that caused a power plant to shut down, leading to a chain reaction of power failures across the region [5]. The consequences of voltage sag vary based on the degree and duration of the sag, as well as the type of equipment impacted. Some of the common effects of voltage sag include equipment malfunction, data loss, production downtime, and financial losses due to downtime and equipment replacement costs.

Voltage sag disturbances are a prevalent issue in Malaysia, impacting all customer segments, with a particularly pronounced impact on industrial customers, particularly those in the semiconductor, electrical and electronics, metal, and aluminium sectors. This problem first came to the attention of Tenaga Nasional Berhad (TNB) in 1990, during the production of electronic wafers [6]. An investigation revealed that the electric oven's control system was overly sensitive to voltage fluctuations. By adjusting the tripping signal for the oven, they were able to effectively address the issue during voltage sags. Following that, the Electric Power Research Institute (EPRI) launched a 24-month power quality monitoring experiment, with about 300 sites monitored to obtain data on power quality at the distribution system level [7].

Furthermore, there have been instances of major financial losses in Malaysia as a result of voltage sags. Within TNB Malaysia's system, one petrochemical-based industrial customer claimed losses of up to RM 164,000 (USD $43,000) per occurrence. Similarly, in the year 2000, a semiconductor-based industry in Klang Valley predicted losses of RM 5 million [7]. It's worth noting that voltage sag disturbances have been an ongoing concern in Malaysia, with various industries facing significant financial losses due to these disruptions.

In semiconductor manufacturing, a stable and reliable power supply is critical to maintain the process conditions and ensure the quality of the final product. Voltage sag can cause fluctuations in the process parameters, such as temperature and pressure, leading to product defects and decreased yield. For instance, a study conducted by Singh and colleagues (2017) found that voltage sag caused by disturbances in the power supply of a semiconductor manufacturing plant resulted in significant yield loss and increased costs [8]. The study demonstrated that the use of a DVR as a voltage sag mitigation device improved the power quality and reduced the yield loss and costs associated with voltage sag. Therefore, mitigating voltage sag is crucial for ensuring the reliability and efficiency of power systems and minimizing the impact of power quality issues on critical infrastructure and operations. In addition, the selection of appropriate voltage sag mitigation devices is critical for ensuring a reliable and efficient power system [9].

Dynamic voltage restorers (DVR), distribution static synchronized compensation, uninterruptible power supplies, flexible AC technology devices, and PWM-switched autotransformers are just a few of the mitigation tools currently being employed to lower voltage sag [10–11]. There are three devices, namely DVR with Park's transformation, DVR with artificial neural network (ANN) controller, and PWM-switched autotransformer with PI controller, are important for comparative research because they are some of the most commonly used voltage sag mitigation devices in power systems [12]. They all aim to mitigate voltage sag, which is a significant power quality issue that can cause power transmission and distribution line tripping and damage to electrical equipment. However, these devices differ in their control strategies, circuit configurations, and capabilities to mitigate voltage sag for different fault conditions.

DVR with Park's transformation is a voltage sag mitigation device that uses a mathematical transformation called Park's transformation to convert the three-phase voltage sag into a positive and negative sequence component. The positive sequence component is then amplified and added back to the power system to mitigate the voltage sag. The advantage of this method is that it can mitigate voltage sag for all fault conditions, including multi-phase and unbalanced faults. Meanwhile, the DVR with ANN controller is a voltage sag mitigation device that uses an ANN controller to control the output voltage of the DVR.

The ANN controller is trained to predict the optimal output voltage of the DVR for a given input voltage to mitigate the voltage sag. This method has the advantage of providing fast and accurate voltage sag mitigation, even for complex and nonlinear fault conditions. Finally, the PWM-switched autotransformer with PI controller is a voltage sag mitigation device that uses a PWM technique to control the output voltage of the autotransformer. The PI controller is used to regulate the output voltage of the autotransformer by adjusting the duty cycle of the PWM waveform. However, the limitation of this method is that it cannot mitigate voltage sag for all fault conditions, such as voltage sag caused by energizing transformer inrush current, due to the limitations of the PI controller scheme [13-14].

The study conducted by A. B. A. Mohamed et al. (2020) focused on analyzing and simulating voltage sag. It specifically examined three different voltage sag scenarios: three-phase fault, multi-phase fault, and energizing transformer inrush current [15]. The study evaluated the efficacy of three voltage sag mitigation devices, namely DVR with Park's transformation, DVR with ANN controller, and PWM-switched autotransformer with PI controller, through MATLAB simulation. The simulation results validated the effectiveness of these devices in various voltage sag scenarios, except for the limitations of the PI controller scheme when dealing with PWM-switched autotransformers during voltage sag caused by energizing transformer inrush current. The study determined that the DVR with ANN controller was the most effective device for mitigating voltage sag, followed by the DVR with Park's transformation and PWM-switched autotransformer. The analysis in Mohamed et al.'s (2020) research involved studying the input and output voltage waveforms, the magnitude of three-phase voltage before and after mitigation, and the total harmonic distortion (THD) value after mitigation. The research also compared two voltage sag mitigation devices (DVR and

DSTATCOM) under various fault conditions, using the D-Q reference frame theory and fuzzy logic controller [12, 15].

The simulation findings demonstrate the efficacy of both devices in minimizing voltage sag. However, the fuzzy logic controller exhibits superior performance compared to the standard PI controller for both devices. Thus, this study aims to analyze and simulate the efficacy of three voltage sag mitigation devices: DVR with Park's transformation, DVR with ANN controller, and PWM-switched autotransformer with PI controller. These devices will be tested under three distinct voltage sag conditions: three-phase fault, multi-phase fault, and energizing transformer inrush current. Therefore, the process of comparing and analyzing is carried out via MATLAB Simulink. The disparity is in the examination and comparison of voltage sag mitigation devices, along with the utilization of control strategies and simulation approaches, between our research and the work conducted by Mohamed et al. (2020).

2. Methodologies

2.1 Power System Circuit Model

Fig. 1 illustrates the power system circuit model utilized in this investigation. Voltage buses, a 30MVA, 11kV voltage source, a 1MVA, 11kV/400V three-phase transformer, a three-phase circuit breaker, a DVR circuit block, and a 1.5kW and 100Var inductive load comprise the circuit model. Utilizing a three-phase circuit breaker, power is bypassed from the transformer's secondary winding to the DVR when the system voltage decreases. Bus 1 and Bus 2 voltages are monitored in order to compare voltage sag prior to and following mitigation. In this circuit model, the distribution portion of the electric power system is represented.

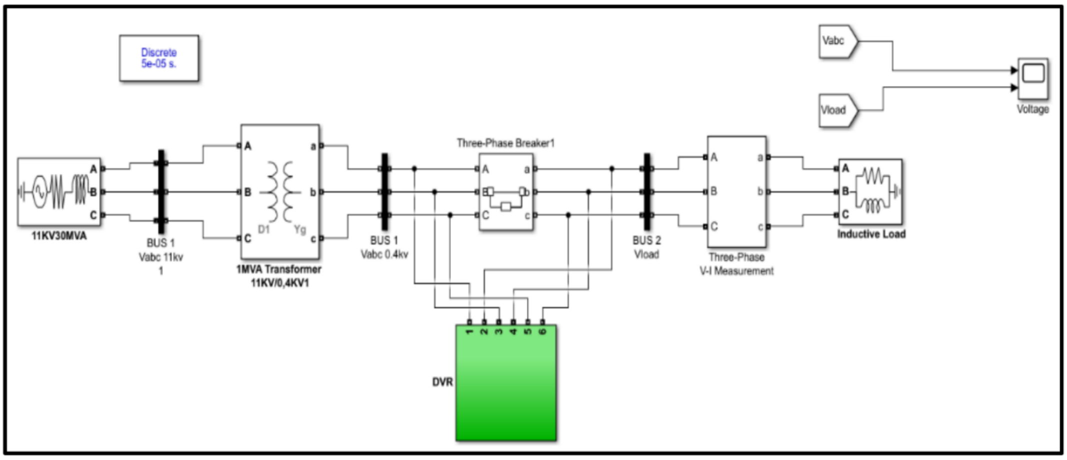


Fig. 1 - Circuit model of power system

A model of the three-phase fault circuit is illustrated in Figure 2. A three-phase fault block is connected to Bus 1, which is powered by 400V, and the 1MVA, 11kV/400V three-phase transformer in order to induce a three-phase malfunction in the system. The concept of a multi-stage failure circuit is illustrated in Figure 3. A multi-stage fault block and a three-phase fault block are connected in series between the 1MVA, 11kV/400V three-phase transformer, and Bus 1 of 400V; this configuration generates a multi-stage issue within the system. The voltage sag for the initial stage of a three-phase fault typically occurs within 0.1 to 0.2 seconds. Conversely, in the case of a multi-stage fault, the voltage sag for the second stage occurs between 0.2 and 0.3 seconds. The circuit illustrates the progression of two sequential faults within the system, which can be attributed to the protective mechanism failing after the initial fault.

The circuit model of the inrush current of the initiating transformer is illustrated in Figure 4. In order to simulate the activation of the transformer, the 1 MVA, 11kV/400V three-phase transformer is set up to attain flux saturation, which generates an inrush current in the system. After 0.06 seconds, a three-phase circuit breaker is activated to arrest the inrush current. This indicates that between 0 and 0.06 seconds will elapse before the voltage drops due to the inrush current of the activating transformer.

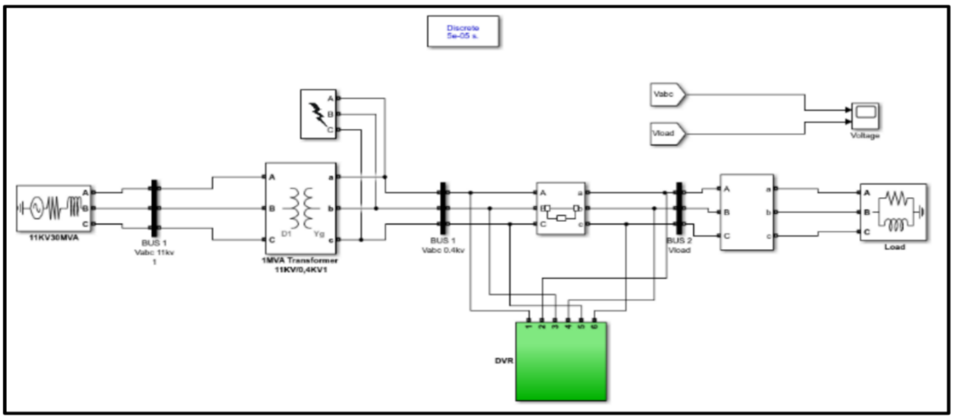


Fig. 2 - Three-phase fault circuit model

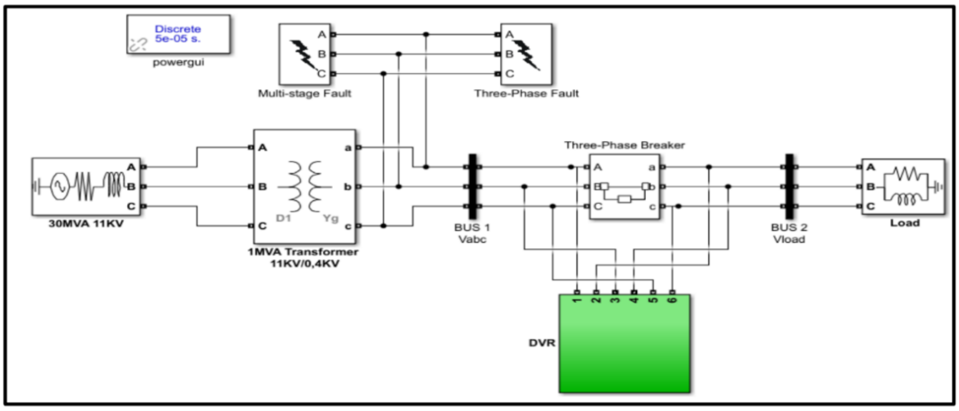


Fig. 3 - Multi-stage fault circuit model

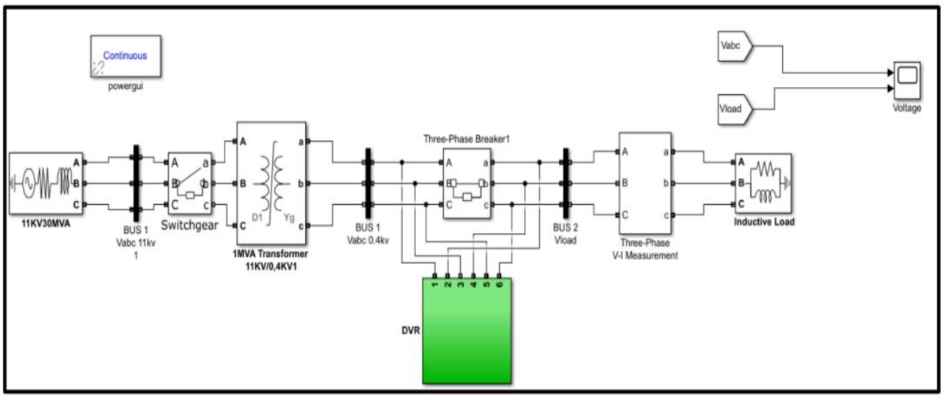


Fig. 4 - Energizing transformer inrush current circuit model

2.2 Control Unit-Based on Park's Transformation

The control technique has an impact on the effectiveness and efficiency of the DVR in mitigating voltage sag. It is the responsibility of the control mechanism to identify and mitigate voltage sags. In this investigation, Park's transformation and an ANN controller are utilized as alternative control strategies. The modified DVR control unit is illustrated in Figure 5. Using Park's transformation, also referred to as the dq0 transformation, the three AC quantities are converted into two DC quantities so that the mitigation voltage can be calculated. The transformation-based controller proposed by Park will ascertain the optimal input voltage for the system in the event of a voltage drop [15].

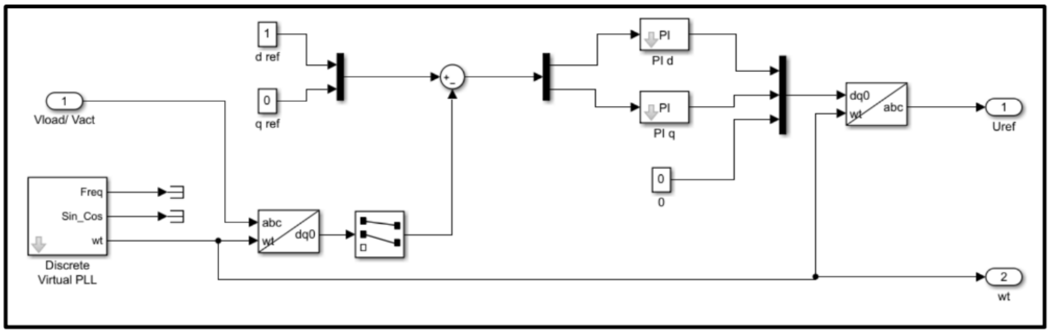


Fig. 5 - Park's transformation-based PI control unit

2.3 Control Unit-Based on ANN Controller

Figure 6 depicts the DVR control unit equipped with an ANN controller. When optimizing backpropagation, the ANN controller employs the Levenberg Marquardt algorithm. This technique is often referred to as the damped least-squares method. To manage loss functions that are denoted by the sum of mean squared errors (MSE), the algorithm was developed. This training method may rapidly reduce voltage sag and is the quickest currently available.

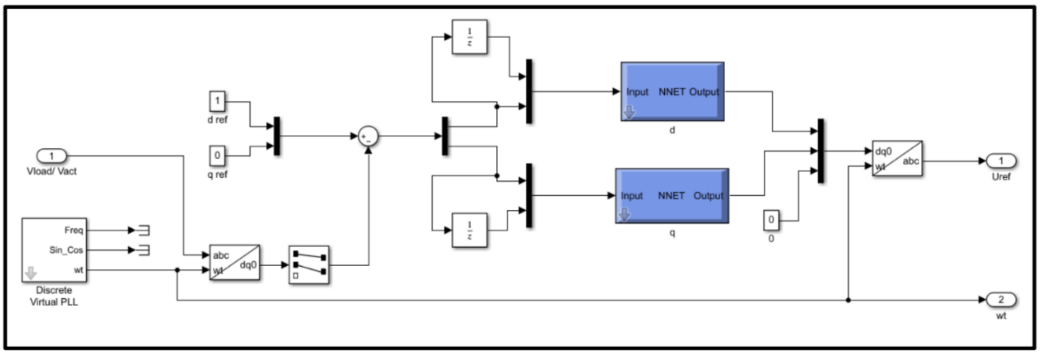
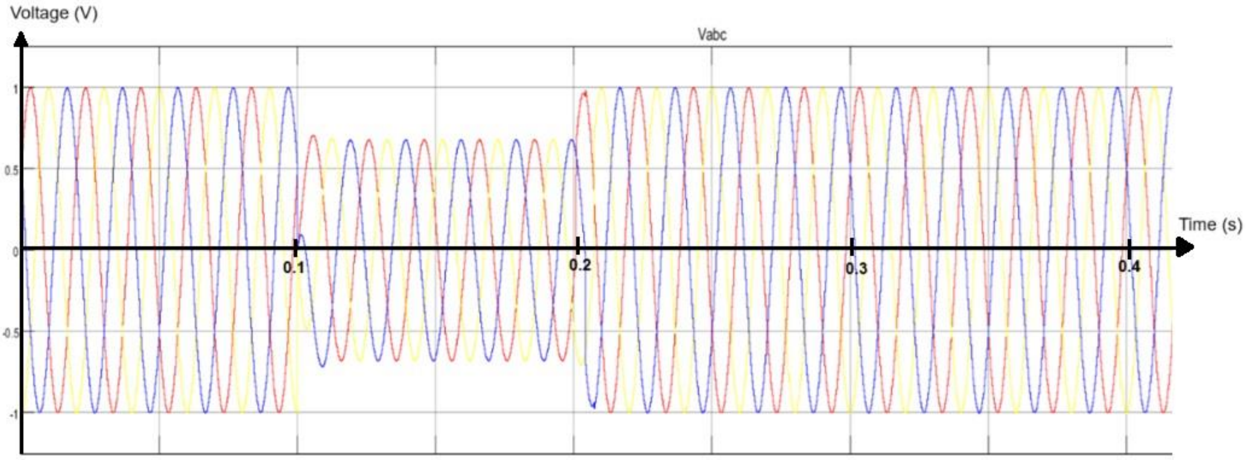


Fig. 6 - ANN controller circuit model

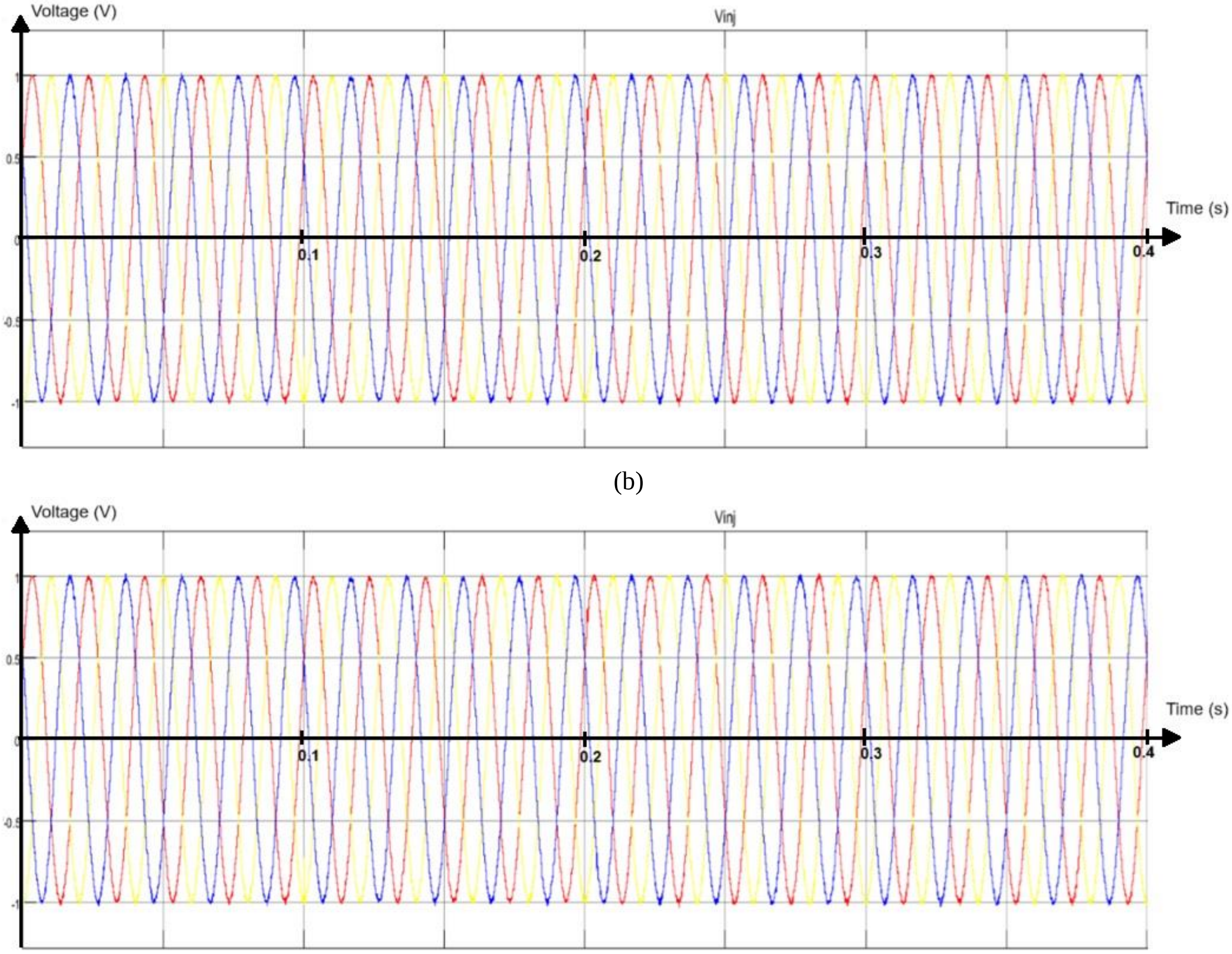
3. Results and Discussion

3.1 Simulation Results Using Three-Phase Fault

An essential aspect of this evaluation is the efficacy of the DVR equipped with Park's transformation-based PI controller and the DVR equipped with ANN controller in mitigating the voltage drop resulting from the three-phase failure. Voltage sag was effectively resolved by both DVR systems, as evidenced by the simulated results for the three-phase fault condition. An initial voltage sag ranging from 0.1 to 0.2 seconds was caused by a three-phase defect; this voltage sag was characterized as balanced across all phases. As shown by the output voltage waveforms in Figures 7 (b) and 7 (c), both DVR configurations effectively mitigated the voltage drop that occurred during the specified time period.



(a)



(b)

(c)

Fig. 7 - (a) Input voltage sag due to a three-phase fault; (b) DVR output voltage waveform using Park's transformation-based PI controller; (c) DVR output voltage waveform with ANN controller

The magnitudes of the three-phase input and output voltages for both mitigation approaches were shown in Table 1. The magnitude of the input voltage revealed that the three-phase failure had caused a 33% voltage sag in the system. However, both DVR systems successfully minimized this sag, in accordance with Malaysia's voltage quality standard, which states that the system voltage magnitude must be within 0.85 p.u. to 1.05 p.u. of the rated voltage magnitude. Notably, when compared to the DVR equipped with Park's transformation-based PI controller, the DVR outfitted with the ANN controller outperformed by bringing the voltage sag magnitude closer to the reference voltage magnitude of 1 p.u. for all three phases. While all three approaches efficiently addressed the voltage sag generated by the three-phase failure, the DVR with the ANN controller outperformed the others, reducing the sag to the nearest reference voltage magnitude value of 1 pu.

Table 1 - Three-phase input and output voltages before and after three-phase fault mitigation

Before injection (pu)			**Mitigation by DVR Park's Transformation (pu)**		
A	B	C	A	B	C
0.6795	0.6793	0.6787	0.9867	0.9887	0.9775
			Mitigation by DVR ANN controller (pu)		
			0.9979	1.002	0.9969

THD before and after mitigation by the three ways generated by a three-phase fault is shown in Table 2. DVR with ANN controller produced the lowest THD (1.61%), followed by DVR with Park's Transformation (1.93%). Both the DVR with Park's transformation-based PI controller and the DVR with ANN controller effectively mitigated the voltage sag caused by the three-phase fault. However, the DVR with the ANN controller demonstrated superior performance by not only effectively correcting the sag but also achieving a lower THD, bringing the voltage magnitude closer to the reference values specified in Malaysia's voltage quality requirements.

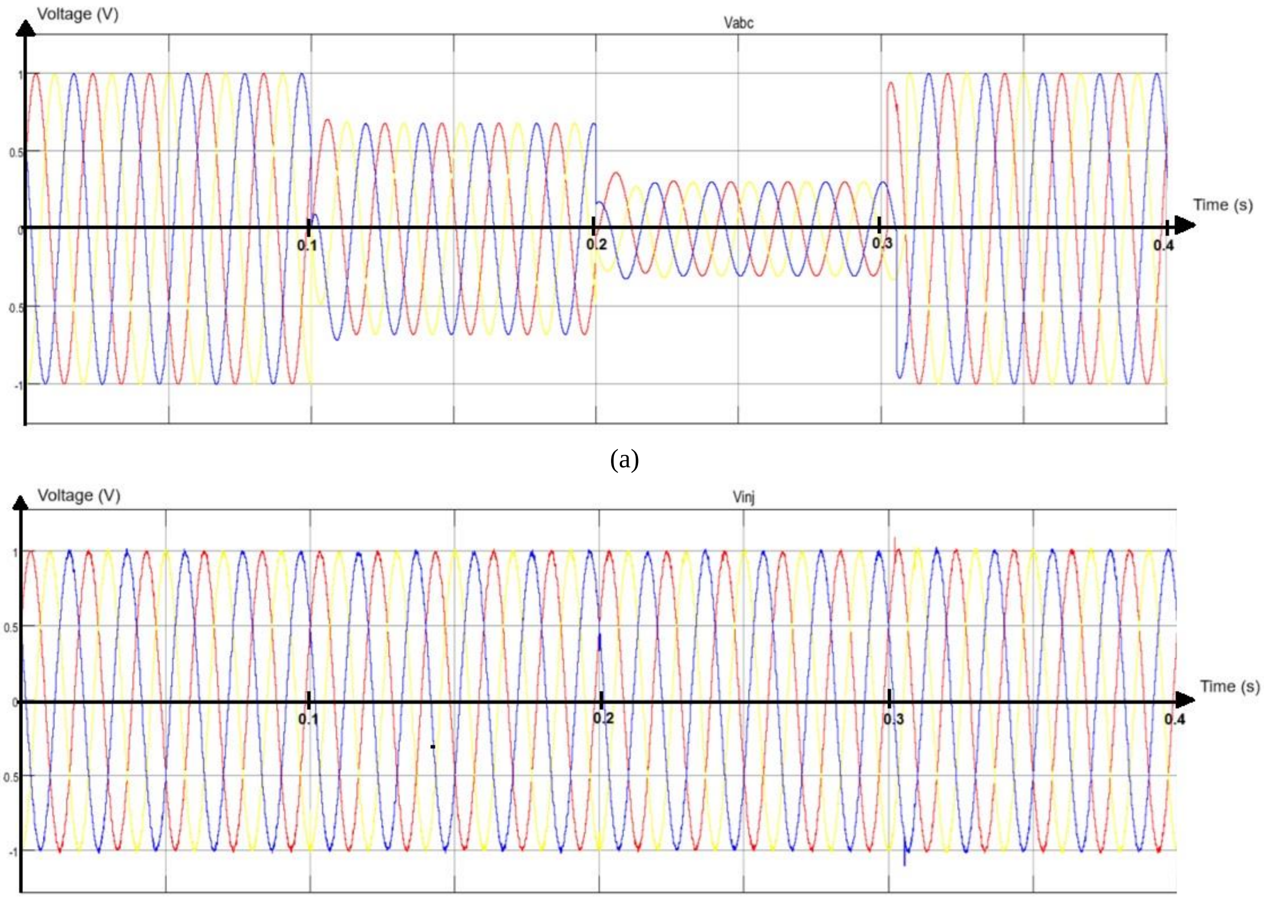
Table 2 - THD before and after voltage sag mitigation for a three-phase fault

Mitigation Technique	THD before mitigation (%)	THD after mitigation (%)
DVR Park's Transformation	23.60	1.93
DVR ANN controller	23.60	1.61

3.2 Simulation Results Using Multi-Phase Fault

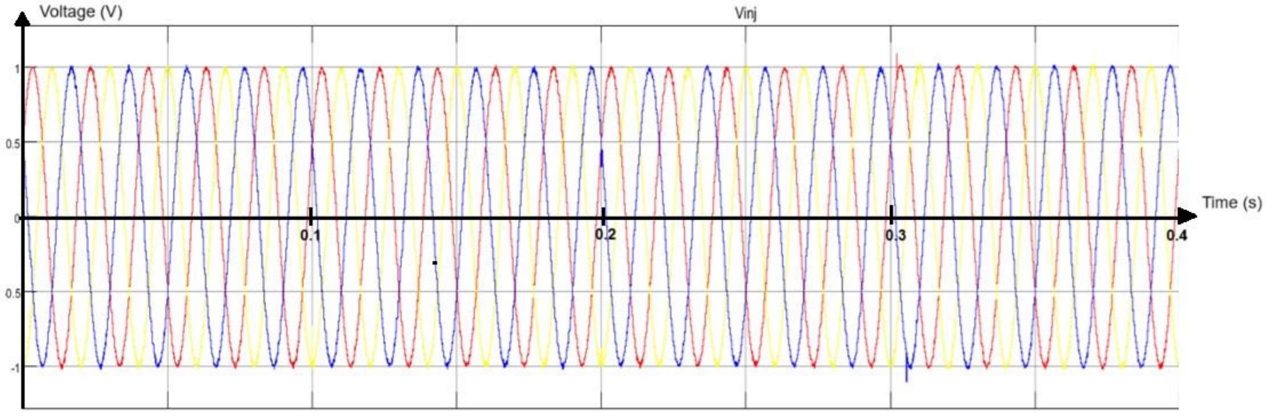
In the analysis of the simulation results for the multi-phase fault scenario, a complex fault pattern involving two consecutive three-phase faults connected in series at the output of the 11kV/400V transformer secondary winding was examined, as depicted in Fig. 8 (a). The first-stage fault occurred from 0.1 seconds to 0.2 seconds, while the second-stage fault followed from 0.2 seconds to 0.3 seconds. Notably, the first-stage fault had a fault resistance of 0.3 ohms, whereas the second-stage fault had a lower resistance of 0.1 ohms. This distinction in fault resistances contributed to differences in the sag waveform shapes for the two fault stages.

Fig. 8 (b) and Fig. 8 (c) illustrate the mitigated output voltage waveforms achieved by both the DVR with Park's transformation-based PI controller and the DVR with ANN controller. It is evident that these devices effectively mitigated the voltage sags that occurred during the specified time intervals. The first stage input voltage sag waveform is the same as in Fig. 7 (a), but the second stage fault's sag waveform has a deeper shape than the first stage fault's sag waveform. This is brought on by the disparity in fault resistance between the various faults.



(a)

(b)



(c)

Fig. 8 - (a) Multi-stage fault input voltage sag waveform; (b) DVR output voltage waveform with Park's transformation-based PI controller; (c) DVR output voltage waveform with ANN controller

Table 3 - Three phase input and output voltages before and after mitigation for multi-phase fault condition

Before injection (pu)			**Mitigation by DVR Park's Transformation (pu)**		
A	B	C	A	B	C
0.6795	0.6793	0.6787	0.9867	0.9887	0.9775
			Mitigation by DVR ANN controller (pu)		
			0.9979	1.002	0.9969

Furthermore, Table 4 presents the THD values before and after mitigation by the two DVR techniques in response to the multi-phase fault scenario. It is noteworthy that the DVR with Park's transformation-based PI controller achieved a THD reduction from 30.82% before mitigation to 1.95% after mitigation. In contrast, the DVR with the ANN controller demonstrated an even more substantial reduction in THD, decreasing from 30.82% to an impressive 1.64%.

The results from the multi-phase fault simulations underscore the effectiveness of both the DVR with Park's transformation-based PI controller and the DVR with the ANN controller in mitigating voltage sags. These devices successfully addressed the complex multi-stage fault, with the ANN controller exhibiting superior performance in reducing THD, indicative of its enhanced ability to improve power quality in such scenarios. The differing fault resistances in the two stages contributed to variations in sag waveform depths, emphasizing the adaptability of these DVR systems to diverse fault conditions.

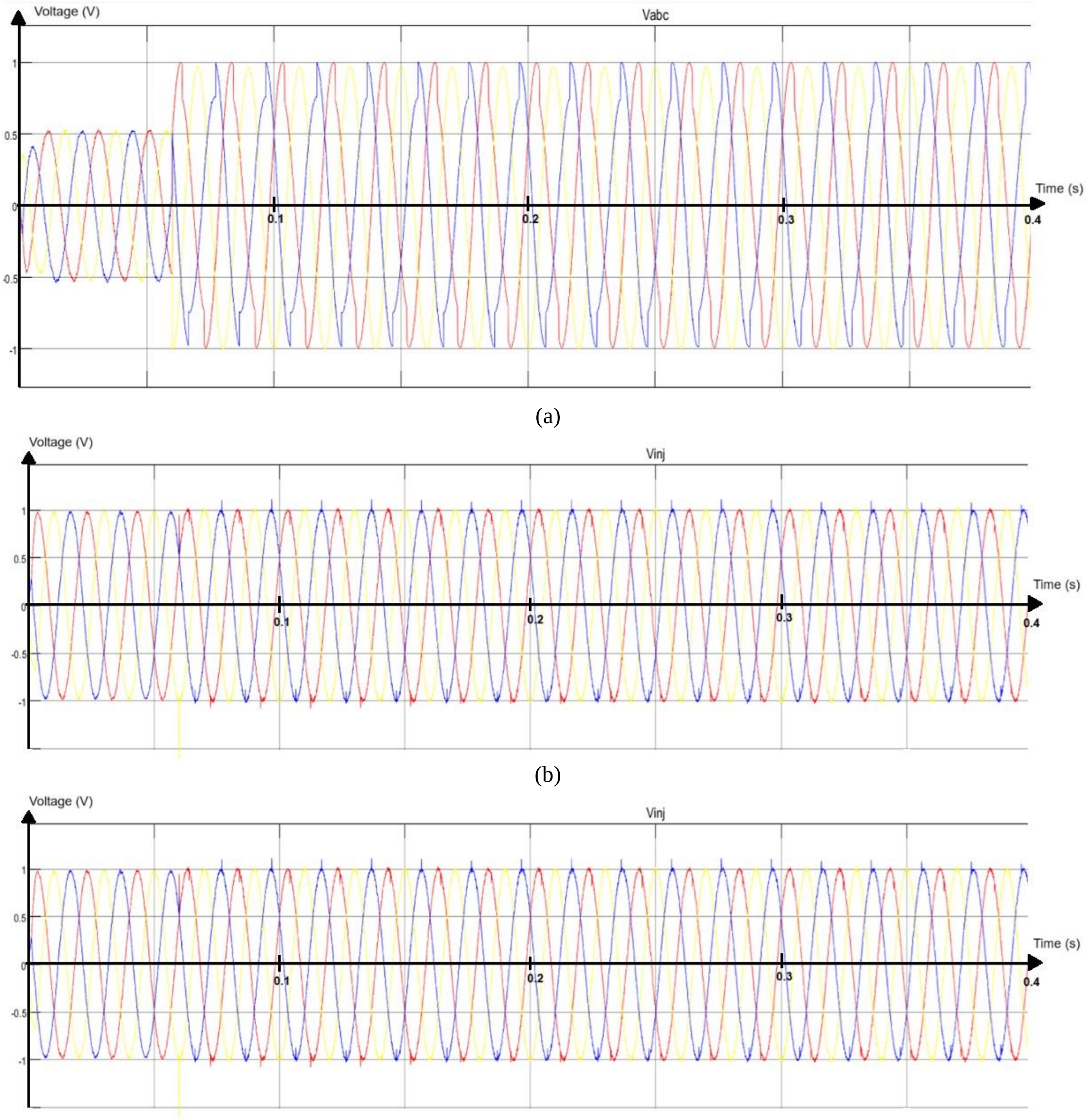
Table 4 - THD before and after mitigation for voltage sag caused by multi-phase fault

Mitigation Technique	**THD before mitigation (%)**	**THD after mitigation (%)**
DVR Park's Transformation	30.82	1.95
DVR ANN controller		1.64

3.3 Simulation Results Using Multi-Phase Fault

The input voltage sag waveform induced by energizing transformer inrush current is shown in Fig. 9 (a). The voltage waveforms of phases A (red) and C (blue) are unbalanced after the voltage sag, whereas phase B (yellow) is standard. This is due to the voltage sag characteristics induced by energizing transformer inrush current, where the voltage sag occurs quickly and the voltage is imbalanced at least for two phases of three-phase voltage. Unbalanced phase voltage happened in this scenario for two phases, phase A and phase C.

The output waveforms of DVR with Park's transformation-based PI controller and DVR with ANN controller are presented in Figs. 9 (b) and 9 (c), respectively, as the outcome of voltage sag mitigation. The voltage sag induced by the inrush current generated by the transformer has been reduced, and the waveforms of phases A and C have been balanced using both procedures.



(a)

(b)

(C)

Fig. 9 - (a) Input voltage sag waveform induced by inrush current from the energizing transformer; (b) DVR output voltage waveform using Park's transformation-based PI controller; (c) DVR output voltage waveform with ANN controller

The magnitudes of the three-phase input and output voltages for both mitigation strategies are shown in Table 5. The initial input voltage sag revealed that the energizing transformer inrush current had caused a voltage sag of approximately 53% in the system. Both DVR systems, however, efficiently minimized this sag by complying to voltage quality criteria that require voltage magnitudes ranging from 0.85 p.u. to 1.05 p.u. Nonetheless, the DVR with the ANN controller outperformed the DVR with Park's transformation-based PI controller by minimizing voltage sag and getting it closer to the reference voltage magnitude of 1 p.u. for all three phases.

Table 5 - Three phase input and output voltages before and after mitigation for energizing transformer inrush current

Before injection (pu)			Mitigation by DVR Park's Transformation (pu)		
A	B	C	A	B	C
0.4774	0.4710	0.4667	0.9763	0.9720	0.9850
			Mitigation by DVR ANN controller (pu)		
			0.9803	0.9740	0.9923

Table 6 - THD before and after voltage sag mitigation due to energizing transformer inrush current

Mitigation Technique	THD before mitigation (%)	THD after mitigation (%)
DVR Park's Transformation	40.76	4.38
DVR ANN controller		3.82

Table 6 also shows the Total Harmonic Distortion (THD) values before and after mitigation for voltage sag caused by energizing transformer inrush current. The DVR with Park's transformation-based PI controller reduced THD from 40.76% before mitigation to 4.38% after mitigation, according to the results. The DVR with the ANN controller, on the other hand, produced an even greater reduction in THD, dropping it from 40.76% to a remarkable 3.82%.

The findings of the examination of energizing transformer inrush current situations highlight the usefulness of both the DVR with Park's transformation-based PI controller and the DVR with the ANN controller in mitigating voltage sags. These devices successfully balanced voltage waveforms and met voltage quality specifications. Once again, the DVR with the ANN controller outperformed the competition, reducing voltage sag to levels closer to the reference values and attaining lower THD, suggesting its improved capacity to improve power quality in conditions requiring energizing transformer inrush currents.

4. Conclusion

In this study, we conducted a comprehensive assessment of the effectiveness of Dynamic Voltage Restorers (DVRs) equipped with two distinct control strategies, namely Park's transformation-based PI controller and Artificial Neural Network (ANN) controller, in mitigating voltage sags caused by various fault scenarios. The investigation encompassed multi-phase faults and voltage sags resulting from energizing transformer inrush currents, both of which are known to challenge power quality in electrical distribution systems.

Our simulation results revealed that both DVR configurations exhibited remarkable capabilities in mitigating voltage sags across all scenarios considered. In the case of multi-phase faults, these devices effectively corrected voltage sags, adapting to variations in fault resistance and providing voltage waveforms in compliance with voltage quality requirements. Notably, the DVR with the ANN controller consistently outperformed the DVR with Park's transformation-based PI controller, achieving a more precise restoration of voltage magnitude and reducing Total Harmonic Distortion (THD) to a greater extent. Specifically, the THD after mitigation for the DVR with Park's transformation-based PI controller was reduced to 4.38%, while the DVR with the ANN controller achieved a notably lower THD of 3.82%.

For scenarios involving energizing transformer inrush currents, both DVR systems successfully addressed the rapid and unbalanced voltage sags caused by this transient phenomenon. Again, the DVR with the ANN controller demonstrated superior performance, achieving better voltage sag mitigation and significantly lower THD levels, further highlighting its efficacy in enhancing power quality. Specifically, the THD after mitigation for the DVR with Park's transformation-based PI controller was 4.38%, whereas the DVR with the ANN controller achieved a remarkably lower THD of 3.82%.

Our findings emphasize the potential of DVRs as effective solutions for mitigating voltage sags and improving power quality in electrical distribution systems. Furthermore, the ANN-based control strategy exhibited a higher degree of adaptability and precision in mitigating voltage sags, making it a promising choice for future applications. These results, with the notable THD reductions, contribute valuable insights for practitioners and researchers aiming to enhance power quality and reliability in modern electrical grids.

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