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Design to optimize the location, number, and performance of dynamic voltage restorers using artificial neural networks

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ABSTRACT

The need for electrical energy always increases from year to year. This means that the distribution system in the electric power system needs to pay attention to its level of stability and reliability. A low level of stability can cause disruption and result in losses. The system's stability and reliability can be increased by installing custom power devices (CPD) equipment such as a dynamic voltage restorer (DVR). In this research, the location, number, and performance of DVRs are optimized using an artificial neural network based on the voltage stability of the distribution network in the *Sibolga Penyulang* SB02 area. Based on the research results, buses 2, 12, 24, 27, and 35 are the best places to install DVRs, and the system will have five DVRs installed. A three-phase short circuit simulation was used to determine how feeder stability was impacted by DVR performance. Then, the voltage falls to 0.1770 p.u. during a disturbance and then rises to 0.8073 p.u., which is within the typical voltage limit of > 0.9 p.u. It means that DVRs restored the voltage fully to the acceptable threshold.

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1. INTRODUCTION

The demand for electrical energy rises every year, and this trend will continue as the electrification ratio rises; sales of electrical energy are expected to rise by 6.42% between 2019 and 2028 [1], [2]. The evolution of electrical systems has become more sophisticated due to this growing need for electrical energy, pushing the electrical power system to its limitations. The stability and dependability of the system must be taken into account because the distribution system is one component of the electric power system that is impacted by this growth. Voltage stability and power losses are two aspects of the distribution system's dependability that must be considered. About 80% to 90% of users are impacted by voltage disruptions and the following losses; in many instances of electrical power stability, voltage quality is the most commonly treated issue. Installing series capacitors, parallel reactors, and parallel capacitors can lower power losses and preserve voltage stability by absorbing and injecting reactive power into the system [3]-[6]. However, in these three pieces of equipment, the response to changes could be faster, and the control system is still manual, making it less profitable for the system. Custom power devices (CPD) equipment can be used in the system for better results. CPD is equipment composed of power electronic components and other control components to improve electric power systems' control and transfer capabilities [7], [8]. Since 1995, many types of CPD devices have been developed, such as solid state current limiter (SCL) [9]-[11], uninterruptible power supply (UPS) [12], distribution STATCOM (dSTATCOM) [13], [14], unified power quality conditioner (UPQC) [15], [16], dynamic voltage restorer (DVR) [17], [18], and others.

Several studies have been carried out to overcome problems in electrical systems, incorporating studies on DVR-based voltage sag/swell optimization [19]-[21]. The research shows that the performance of the DVR is acceptable in correcting voltage drops/rises. Moreover, the DVR compensates quickly for voltage drops/rises and provides excellent voltage regulation. Furthermore, research on power-quality improvement using DVRs, including interline DVRs and control system updates [22]. In DVR implementations, there is still massive room for improvement in performance and controller response time. Besides that, DVR development can be carried out by integrating renewable energy sources. To improve power quality, previous research on DVR placement optimization has used an IEEE 16-bus test system to determine the best location and capacity of DVRs in a radial distribution system. The firefly algorithm (FA) method was compared using the particle swarm optimization (PSO) and genetic algorithm (GA) methods, demonstrating FA's superior performance in solving the problem of optimal DVR location and size [23]. Based on voltage stability analysis using the cable stability index on the IEEE 14-bus and IEEE 30-bus test systems, the artificial neural network (ANN) method was then used to optimize DVR placement. In this research, ANN succeeded in identifying the weakest cables in the test system, where the optimal placement of the FACTS device was carried out based on the test results [23]-[25]. Furthermore, previous research regarding DVR quality improvement using PSO and ANNN for voltage sag mitigation. The research shows that the DVR-ANN is better at injecting voltage than a DVR with a PI-PSO control system when a voltage sag occurs, with a voltage injection result of 0.0059 p.u. greater than the PI-PSO controller [26]. This research discusses optimizing the dynamic voltage restorers' location, number, and performance using an artificial neural network according to the stability of the voltage of the distribution network in the Sibolga feeder SB02 area. This study proposes the ideal placement and quantity of DVRs. It used a neural network to estimate the number and placement of DVRs.

2. METHOD

2.1. Dynamic voltage restorer

A DVR injects voltage according to injection requirements produced by a DC to AC inverter in series on a distribution network experiencing interference using three single-phase transformers (booster transformer). A DVR often includes an energy supply battery, a DC to AC inverter, a harmonic reduction filter, an injection transformer, and a control circuit. The control circuit regulates the control signal parameters injected by the DVR, including phase shift, frequency, and magnitude. The DVR's injection transformer comprises a load put before the distribution transformer with the sensitive load and a main side linked in series with the distribution line. In the meantime, the DVR circuit is connected in series with the secondary side. Figures 1 and 2 show the location of the DVR placement and the components contained in the DVR.

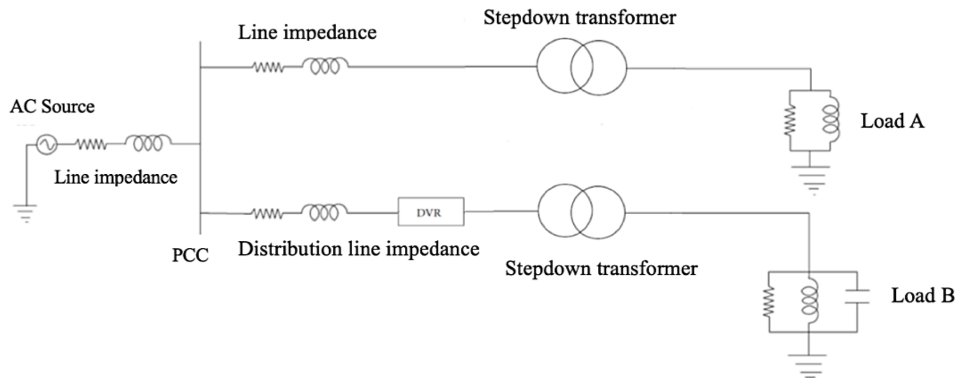

Figure 1. DVR placement location

A DVR's primary job is to identify voltage sags by comparing the supply voltage with a reference value and injecting the proper voltage to correct the disturbance. When a disturbance occurs, the DVR's control unit recognizes a change in the voltage recorded on the load. It compares the voltage recorded at the load with the reference voltage. The control unit produces a pulse output, which is forwarded to pulse width modulation (PWM) and continues to the voltage source inverter (VSI); then, the VSI, supplied with DC power, will respond to the pulse by producing AC voltage. VSI works according to the magnitude, frequency, and phase angle required for the DVR to be injected into the network experiencing interference. VSI does not provide a sinusoidal AC voltage because changes in voltage form can contain harmonics. Then, the AC voltage is passed to the low-pass filter to get a better sinusoidal shape. After a low-pass filter filters the resulting AC voltage, the voltage is then increased by a transformer to a voltage suitable for injection into the network. The working principle of a DVR is shown below based on Figure 3 [27].

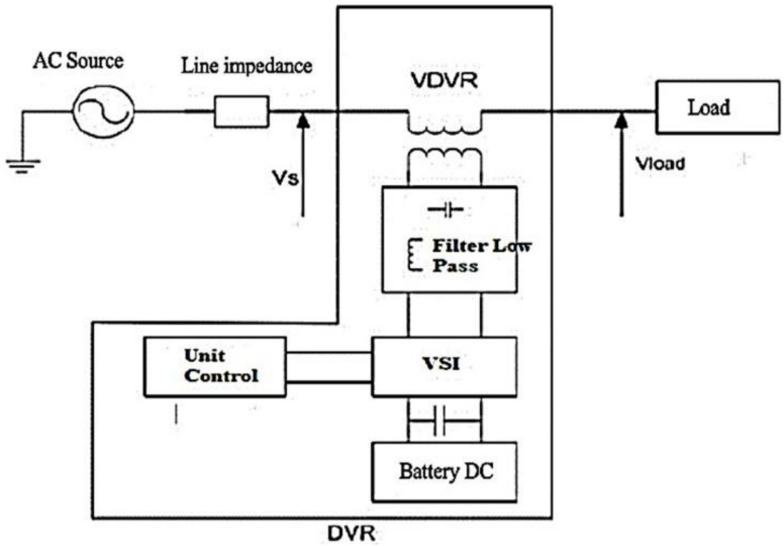

Figure 2. DVR components

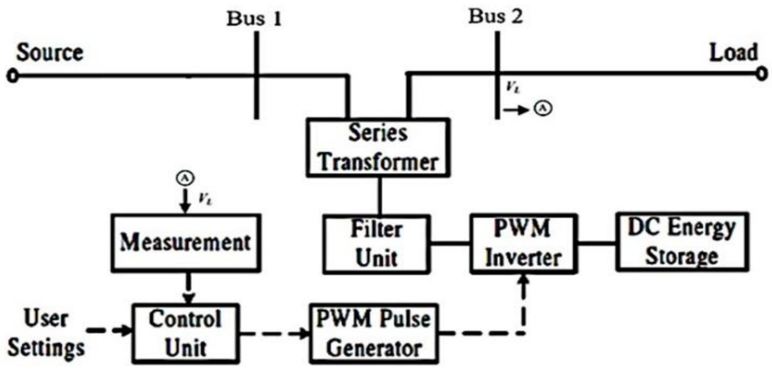

Figure 3. DVR working principle

2.2. DVR-ANN

Change the control system on the DVR to be ANN-based to improve DVR performance using ANN [26], [28]. The design of the ANN control system on the DVR works by using data resulting from the comparison of source voltage and load voltage, consisting of 12,000 data from previous PI controller training. This data is used as system input and target output for ANN control training. The dynamic voltage restorer parameters with the ANN control system used are in Table 1. Meanwhile, the shape of the DVR circuit with the ANN controller has been modeled in Figure 4.

This research was carried out on the 20 kV distribution network system in the Sibolga Region SB 02 feeder with data obtained from PT. PLN (Persero) UP3 Sibolga, North Sumatra Province, Indonesia. The SB02 feeder is depicted on a single-line diagram using MATLAB R2020a software with a load of 36 points, 44 buses, and 43 cables, as seen in Figures 5 and 6. Figure 5 shows the Sibolga SB02 feeder single-line diagram before adding the DVR, and Figure 6 shows the DVR after installing it. Then, Figure 7 shows the implementation steps in the location optimization process and the number of DVRs in the SB02 feeder 20 kV distribution system using an ANN.

Table 1. Specifications of DVR-ANN

Specifications	Value
Injection transformer	70 kVA, 0.40/20 kV
Resistance	1 Ω
Inductance filter	5 µH
Capacitance filter	10 μF
DC source	2 x 2500 V

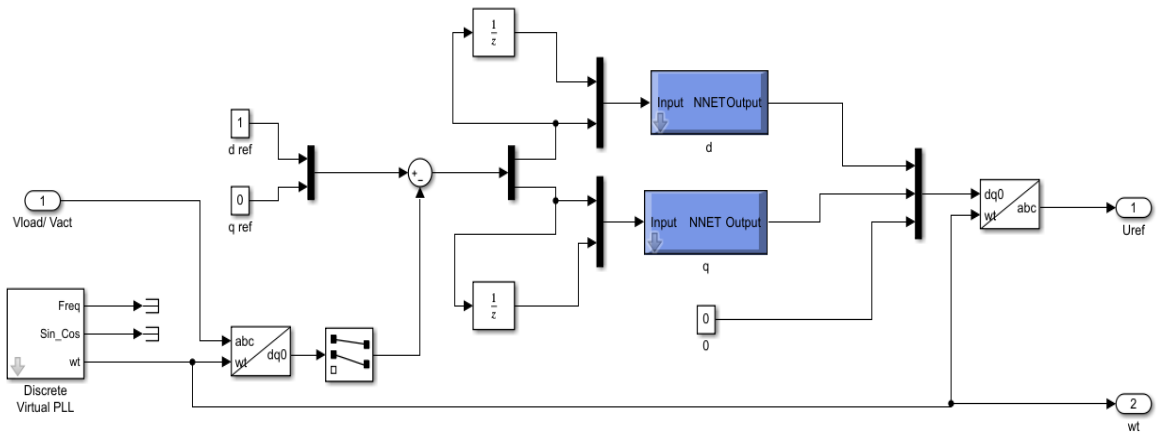

Figure 4. ANN controller model on DVR

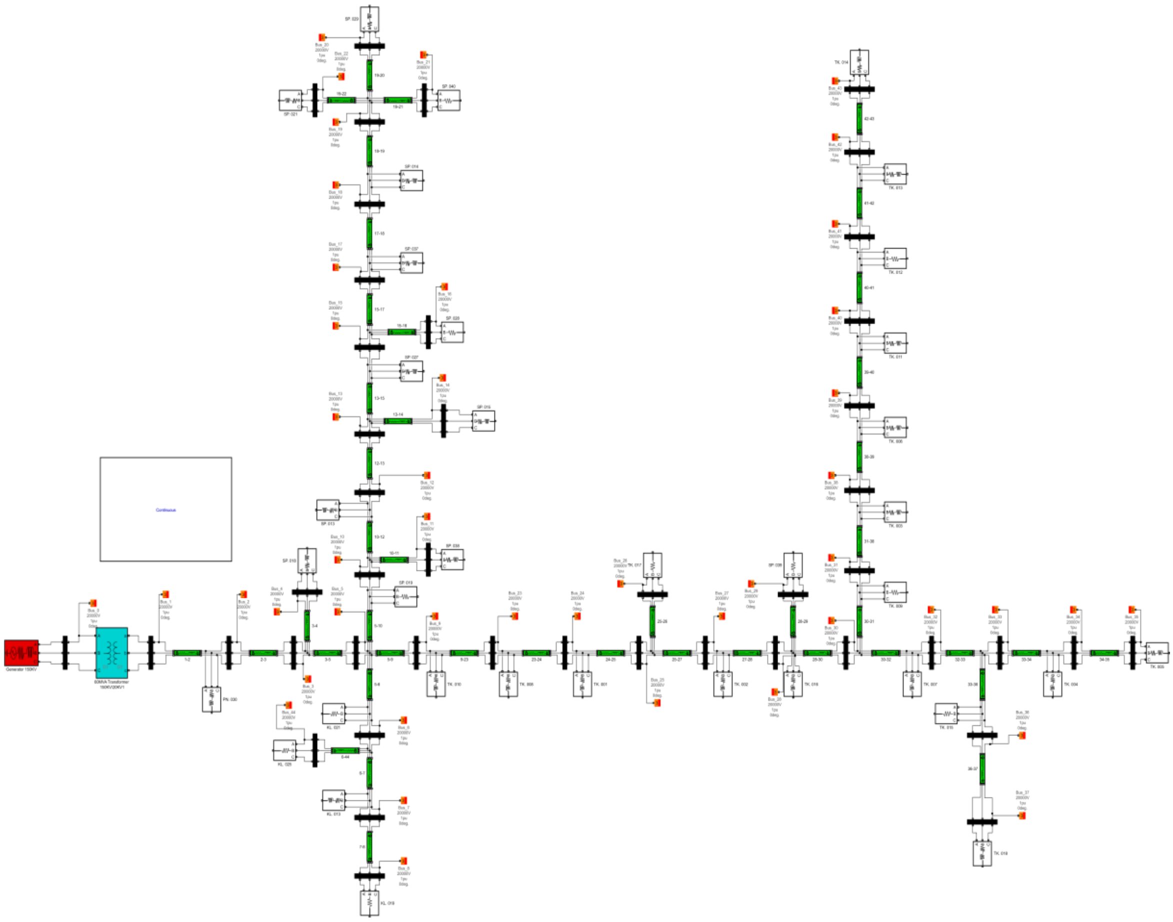

Figure 5. Single line diagram of SB02 Sibolga feeder before DVR placement

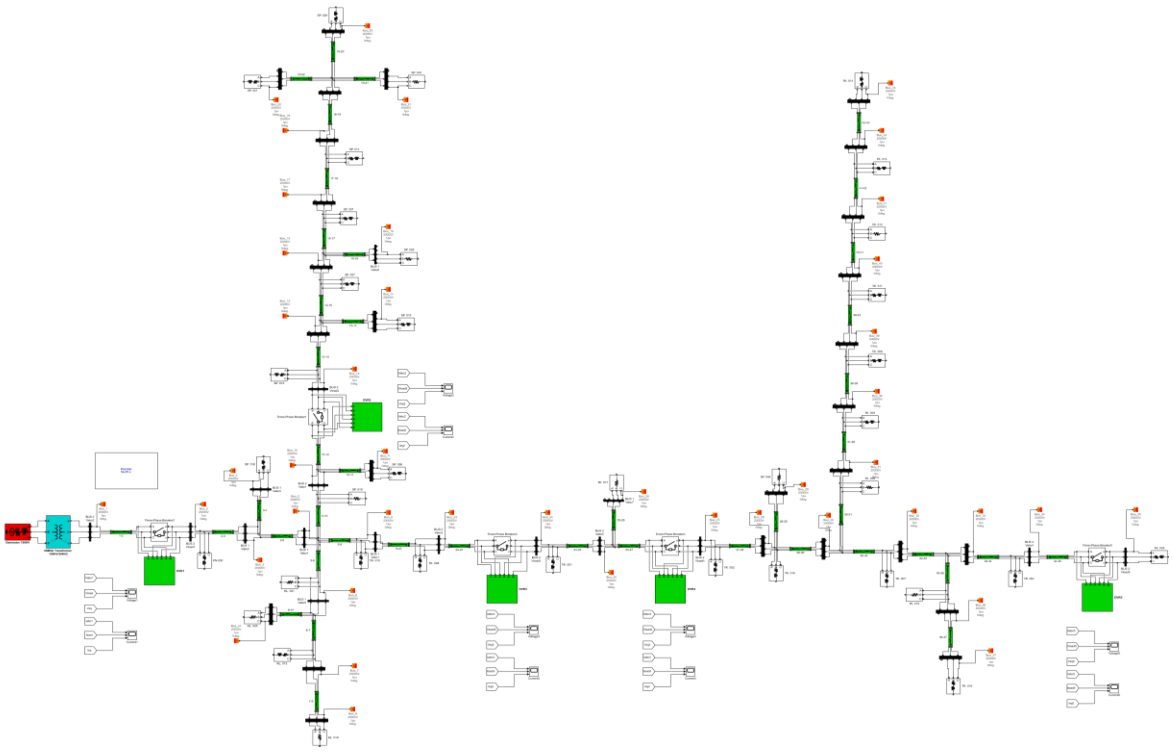

Figure 6. Single line diagram of SB02 Sibolga feeder after DVR placement

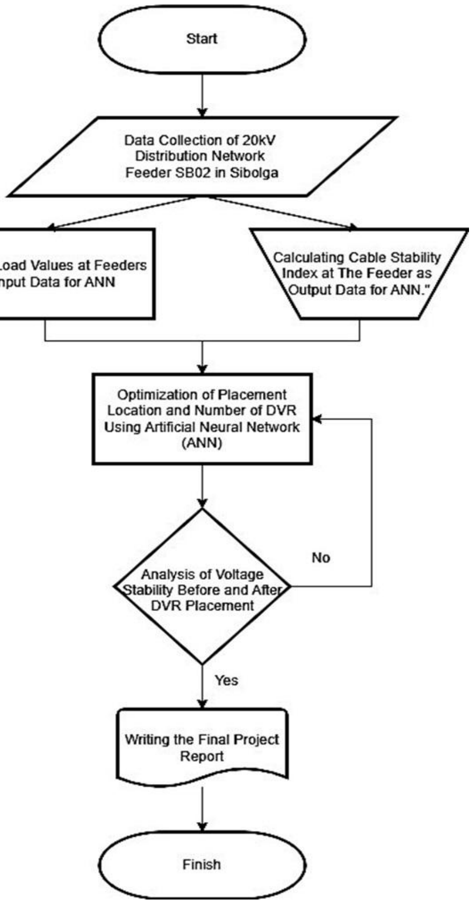

Figure 7. Research flow diagram

3. RESULTS AND DISCUSSION
3.1. Load flow analysis before DVR placement
Load flow analysis is performed using MATLAB R2020a by first constructing the single-line diagram of the SB02 feeder and setting the required parameters. Figure 8 presents the load flow results prior to the installation of the DVR. These results represent the system condition before the DVR is applied.

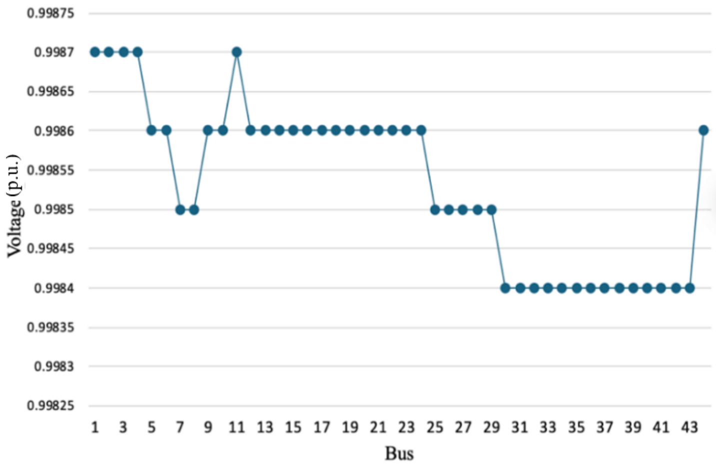

Figure 8. Load flow result before the installation of the DVR

3.2. Results from artificial neural network
ANN is used to find the optimal location and number of DVRs placed on the 20 kV SB02 feeder distribution network where the ANN works by conducting training data before it can carry out optimization. In optimization, data variations were carried out by 0% to 200% with a variation level of 50% for each data to improve ANN training performance. The data that is varied is the reactive power of the load, where this data is the training input, and the L_{mn} value based on the load variation is the training output. After training, the data is carried out, with the training and validation result values approaching 1, as in Figure 9. Table 2 shows the optimization simulation results sorted by the largest L_{mn} value, which shows the bus locations that are most vulnerable to interference. Table 2 describes the optimization simulation's results sorted the ten largest L_{mn} values on the system's buses. The optimal location for DVR placement was found, namely on bus 2, bus 12, bus 24, bus 27, and bus 35, with a total of 5 DVRs.

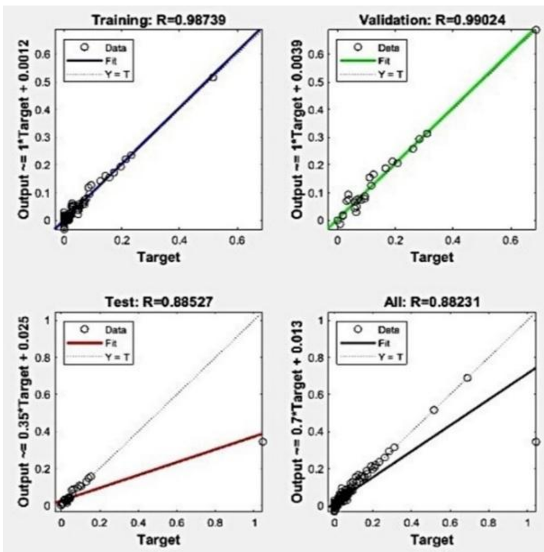

Figure 9. ANN training and validation results

Table 2. Optimization results with the largest L_{mn} value

No.	No bus	Outputsim1	No bus	Outputsim2	No bus	L_{mn} begin
1	12	0.228915	27	0.860449	27	0.17212
2	27	0.153677	35	0.391532	35	0.12889
3	32	0.134926	24	0.365622	12	0.07724
4	37	0.090731	12	0.323549	38	0.06921
5	2	0.081611	20	0.264304	34	0.04447
6	35	0.062808	4	0.25817	24	0.04398
7	7	0.046895	38	0.234013	2	0.0299
8	40	0.034573	2	0.205097	4	0.02709
9	24	0.03101	34	0.190053	43	0.02683
10	22	0.03041	32	0.156396	9	0.02515

3.3. Simulation results of DVR placement

After obtaining the optimization of the location and number of DVRs, a simulation is carried out to optimize the performance of the DVRs using ANN. Simulations were also carried out to see the effect of voltage stability after DVR placement. Improving DVR performance was carried out using data from a source and load voltage comparison of 12,000 data from previous PI controller training. The changes to the DVR parameters on the DC source (Table 2) after optimization are 2×6000 V at point 1 (bus 2), 2×4000 V at point 3 (bus 24), and 2×1800 V at point 5 (bus 35). The simulation results for DVR placement were carried out using a 3-phase short circuit at each placement point to see the effect of voltage stability after installing the DVR.

3.3.1. Simulation results of DVR placement at point 1

Figure 10 shows the simulation results at point 1 (bus 2). The simulation was performed with the DVR placed on bus 2 as a voltage recovery device. The simulation results are shown in Figure 10, with the voltage values for phases A, B, and C remaining within the permitted standards. Then, the voltage value when a disturbance occurs, and the voltage value after it is restored using a DVR can be seen using the FFT tools from MATLAB\Simulink, as in Figures 11 and 12.

3.3.2. Simulation results of DVR placement at point 2

Figure 13 shows the simulation results at point 2 (bus 12). The simulation results are shown in Figure 13 with the voltage values for phases A, B, and C remaining within the permitted standards. Then, the voltage value when a disturbance occurs, and the voltage value after it is restored using a DVR can be seen using the FFT tools from MATLAB\Simulink, as in Figures 14 and 15.

3.3.3. Simulation results of DVR placement at point 3

Figure 16 shows the simulation results at point 3 (bus 24). The simulation results are shown in Figure 16 with the voltage values for phases A, B, and C remaining within the permitted standards. Then, the voltage value when a disturbance occurs, and the voltage value after it is restored using a DVR can be seen using the FFT tools from MATLAB\Simulink, as in Figures 17 and 18.

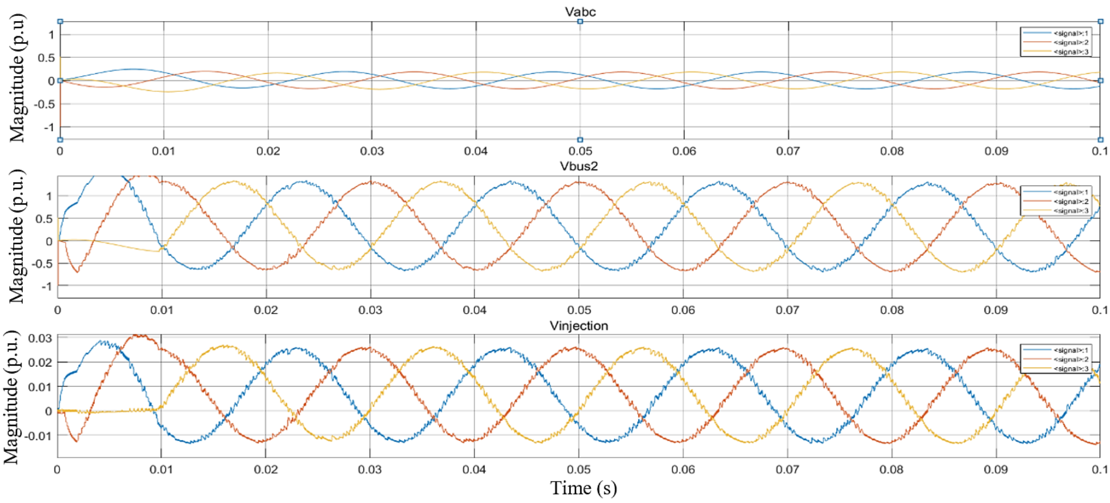

Figure 10. Simulation results of DVR placement at point 1

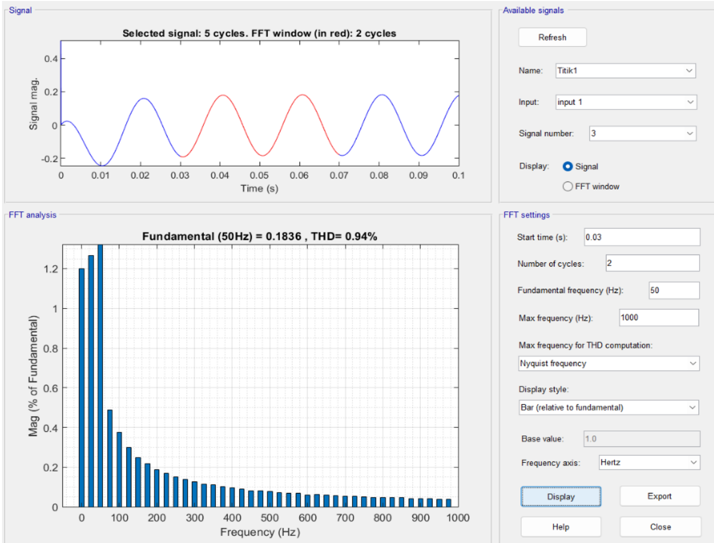

Figure 11. FFT voltage wave analysis before DVR placement

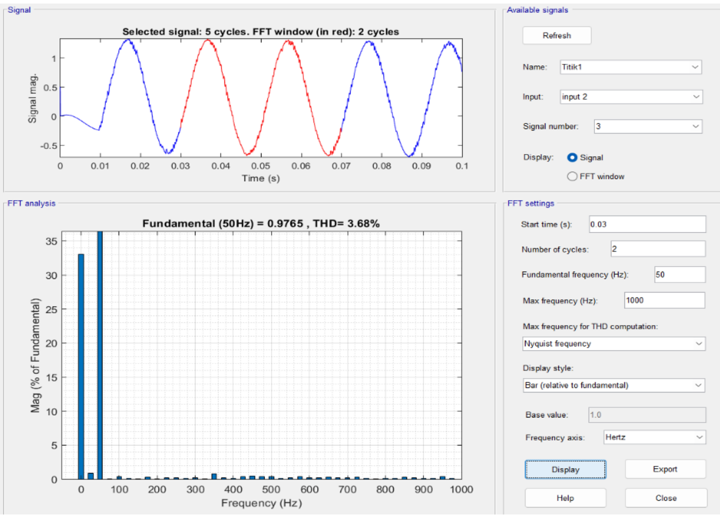

Figure 12. FFT voltage wave analysis after DVR placement

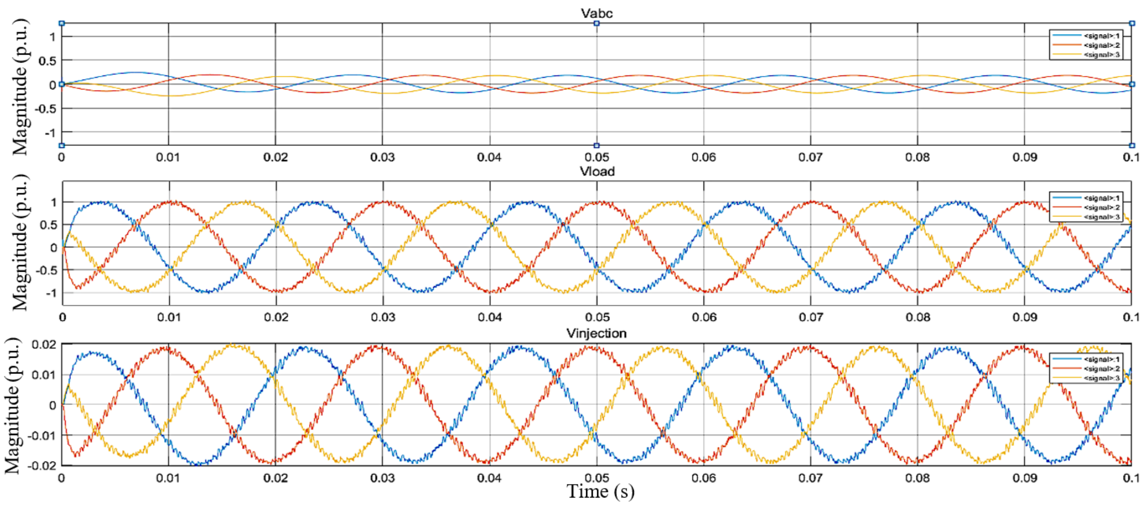

Figure 13. Simulation results of DVR placement at point 2

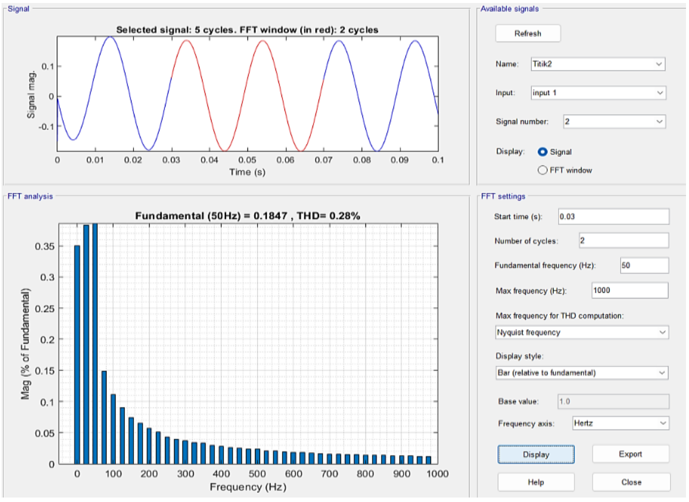

Figure 14. FFT voltage wave analysis before DVR placement at point 2

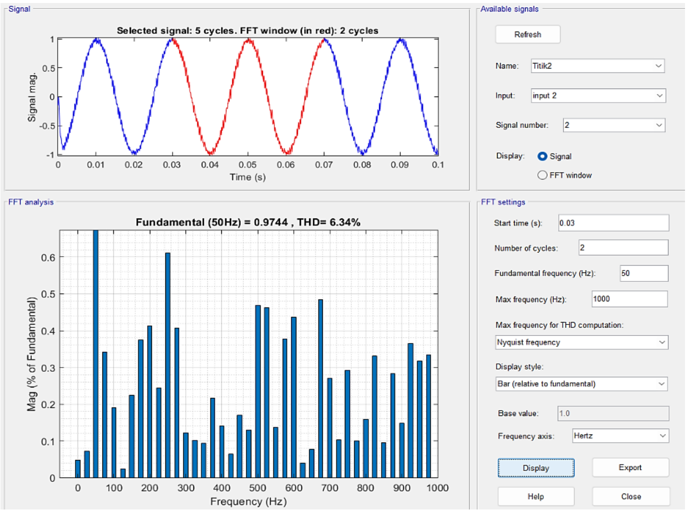

Figure 15. FFT voltage wave analysis after DVR placement at point 2

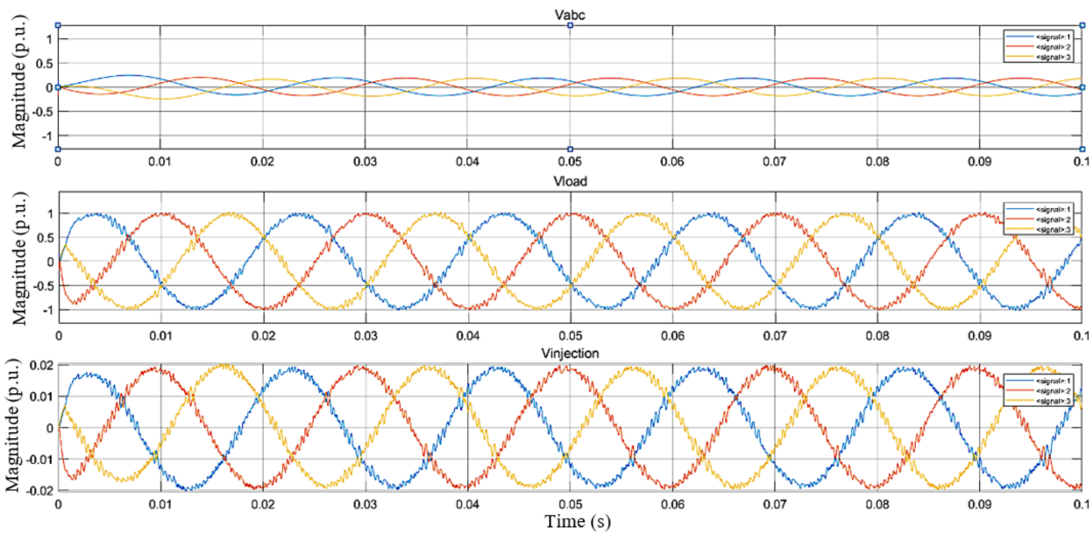

Figure 16. Simulation results of DVR placement at point 3

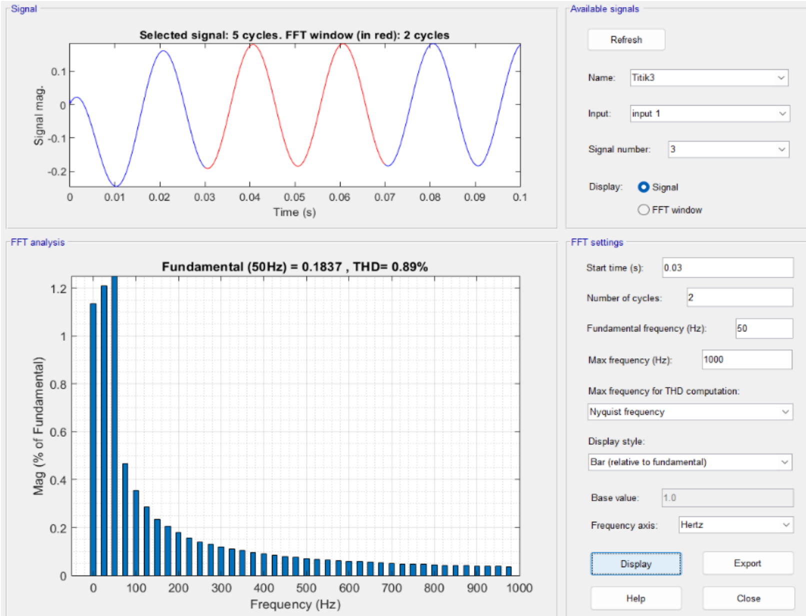

Figure 17. FFT voltage wave analysis before DVR placement at point 3

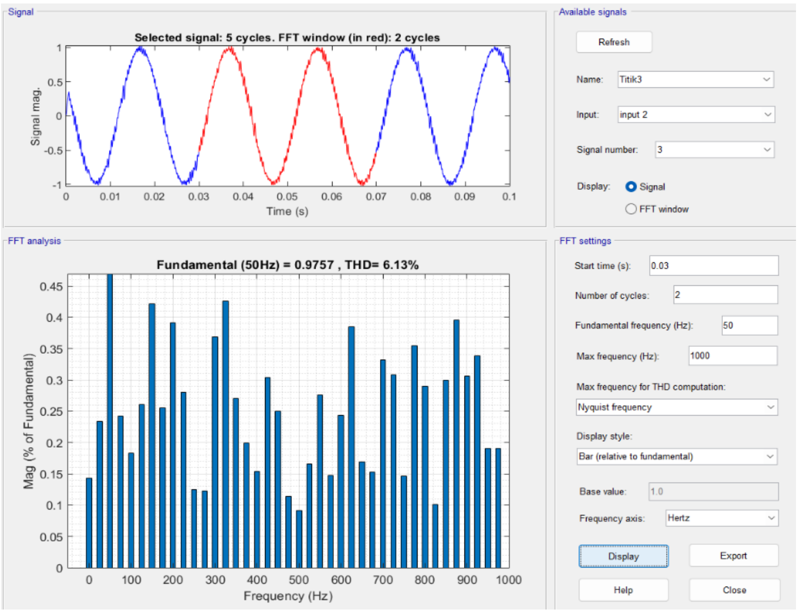

Figure 18. FFT voltage wave analysis after DVR placement at point 3

3.3.4. Simulation results of DVR placement at point 4

Figure 19 shows the simulation results at point 4 (bus 27). The simulation results are shown in Figure 19, with the voltage values for phases A, B, and C remaining within the permitted standards. Then, the voltage value when a disturbance occurs, and the voltage value after it is restored using a DVR can be seen using the FFT tools from MATLAB\Simulink, as in Figures 20 and 21.

3.3.5. Simulation results of DVR placement at point 5

Figure 22 shows the simulation results at point 5 (bus 35). The simulation results are shown in Figure 22, with the voltage values for phases A, B, and C remaining within the permitted standards. Then, the voltage value when a disturbance occurs, and the voltage value after it is restored using a DVR can be seen using the FFT tools from MATLAB\Simulink, as in Figures 23 and 24.

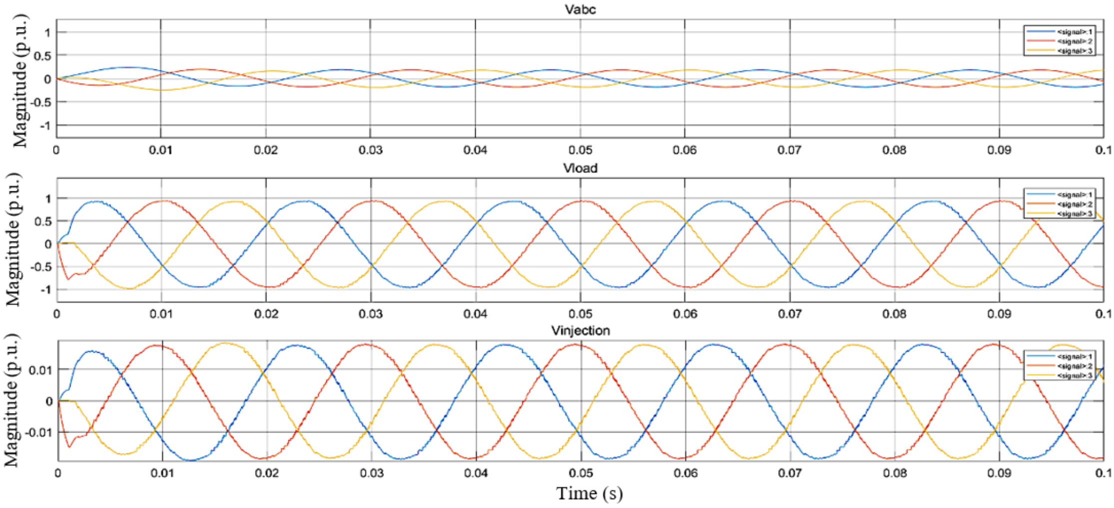

Figure 19. Simulation results of DVR placement at point 4

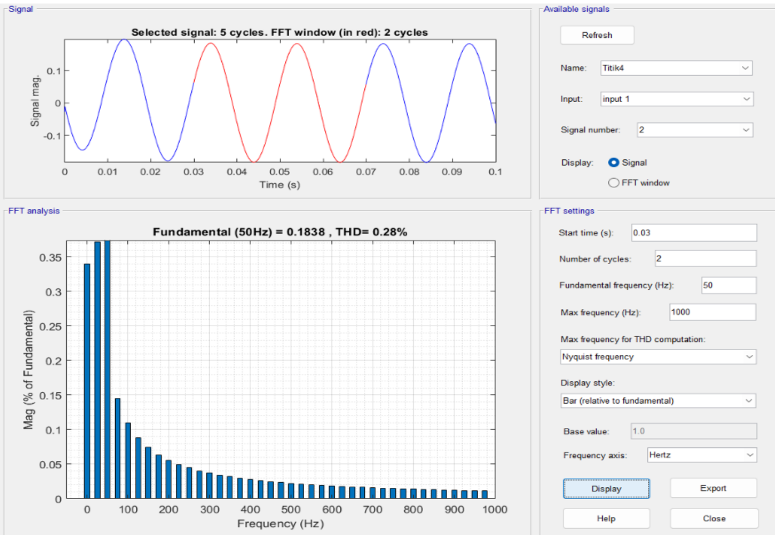

Figure 20. FFT voltage wave analysis before DVR placement at point 4

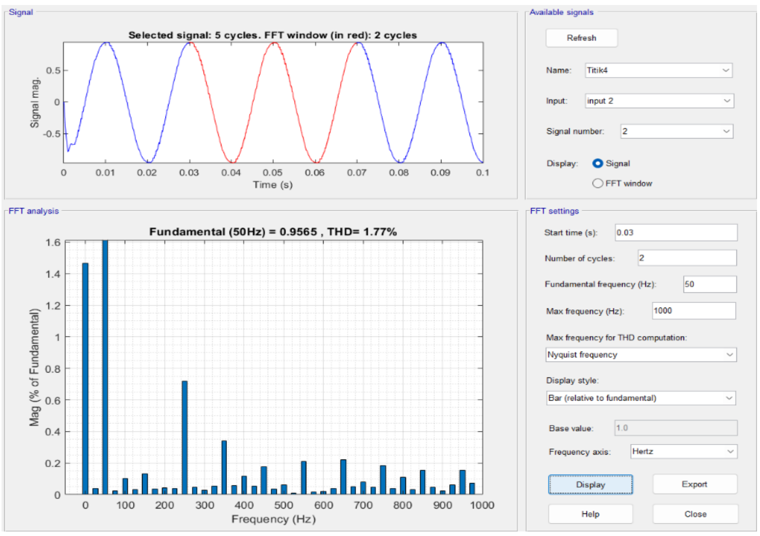

Figure 21. FFT voltage wave analysis after DVR placement at point 4

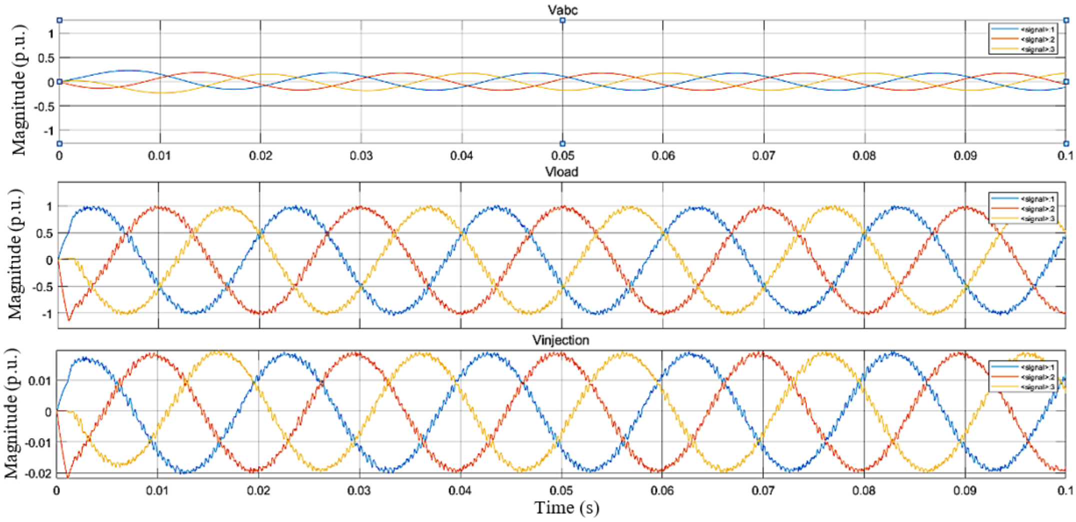

Figure 22. Simulation results of DVR placement at point 5

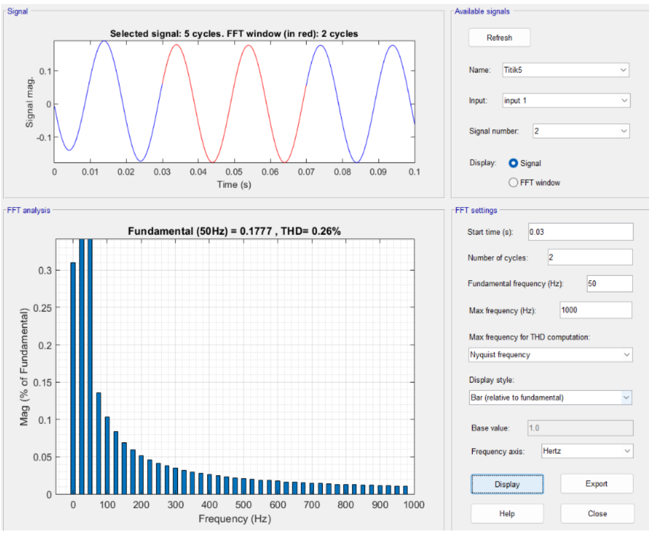

Figure 23. FFT voltage wave analysis before DVR placement at point 5

Figure 24. FFT voltage wave analysis after DVR placement at point 5

3.4. Voltage stability analysis after DVR placement

A three-phase short circuit is a significant disruption since it can result in a drop of up to 0.17 to 0.19 p.u., according to the data gathered during the simulation. At each predefined point, the DVR tested the injected voltage up to 0.8073 p.u., which is the standard voltage limit of > 0.9 p.u. Table 3 displays about three three-phase short circuit faults.

Table 3. Simulation results for three-phase short circuit faults

Placement point	V fundamentals without DVR (p.u.)	V fundamentals with DVR (p.u.)	V injection DVR (p.u.)
Point 1 (bus 2)	0.1836	0.9765	0.7929
Point 2 (bus 12)	0.1847	0.9764	0.7917
Point 3 (bus 24)	0.1837	0.9757	0.7920
Point 4 (bus 27)	0.1838	0.9565	0.7727
Point 5 (bus 35)	0.1777	0.9850	0.8073

4. CONCLUSION

Based on the results of the research that has been carried out, several conclusions have been obtained, such as the voltage stability value that is most susceptible to interference on the SB02 feeder is on bus 27 with an output L_{mn} value of 0.860449, based on the results of training using an artificial neural network. Second, optimization of the location and number of DVR-ANNs was successfully determined using an artificial neural network, where the optimal location for DVR-ANN placement was on bus 2, bus 12, bus 24, bus 27, and bus 35, with a total of 5 DVR-ANNs placed in the system SB02 feeder distribution. Third, the optimal point for placing the DVR on the SB02 feeder is a 3-phase short circuit fault simulation where the voltage drops to 0.1777 p.u., when the fault occurs. Simulation shows the DVR successfully recovers up to 0.8073 p.u. to the normal voltage limit of ≥ 0.9 p.u. Future research can be developed by using other algorithms to identify the most effective algorithm. Then, efficiency can be increased based on the components in the dynamic voltage restorer.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Faizzufar Taqy		✓				✓		✓	✓	✓	✓	✓		
Mohd Najib Mohd Hussain	✓		✓	✓			✓			✓	✓		✓	
Hafizh Prihtiadi		✓	✓		✓		✓		✓		✓		✓	
Muldi Yuhendri	✓			✓		✓		✓		✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, [YS], on request.

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