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# Dynamic voltage restorer quality improvement analysis using particle swarm optimization and artificial neural networks for voltage sag mitigation

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**ABSTRACT**

Power quality is one of the problems in power systems, caused by increased nonlinear loads and short circuit faults. Short circuits often occur in power systems and generally cause voltage sags that can damage sensitive loads. Dynamic voltage restorer (DVR) is an efficient and flexible solution for overcoming voltage sag problems. The control system on the DVR plays an important role in improving the quality of voltage injection applied to the network. DVR control systems based on particle swarm optimization (PSO) and artificial neural networks (ANN) were proposed in this study to assess better controllers applied to DVRs. In this study, a simulation of voltage sag due to a 3-phase short-circuit fault was carried out based on a load of 70% of the total load and a fault location point of 75% of the feeder's length. The simulation was carried out on the SB 02 Sibolga feeder. Modeling and simulation results are carried out with MATLAB-Simulink. The simulation results show that DVR-PSO and DVR-ANN successfully recover voltage sag by supplying voltage at each phase. Based on the results of the analysis shows that DVR-ANN outperforms DVR-PSO in quality and voltage injection into the network.



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## 1. INTRODUCTION

Power quality is one of the main issues in the electric power system. It is because, along with the increasing need for loads on the consumer side, electricity producers are required to have continuity and reliable power availability. On the other hand, electrical loads are intolerant to voltage changes. In many cases of electrical power quality, voltage quality is the most widely handled because 80%-90% of consumers are affected by voltage disturbances and resulting losses [1], one of which is voltage sags. Voltage sags, a major disturbance in the power system, greatly affect sensitive loads that are intolerant to voltage changes. This voltage sag occurs when the voltage changes with a range of 10%-90% at the rms value of the voltage for a duration of 0.5 cycles (0.01 seconds) to 1 minute. This is due to several factors, namely the use of nonlinear loads, supply to large loads, variations in loading, short circuit faults, and poor system design [2]–[5]. Various techniques, including power electronic devices, solve electrical power quality problems. This device concentrates on the reliability and quality of the power flow of the system applied to the distribution system [6]–[8]. Various types of power electronics devices are active power filters (APF) [9], Battery energy storage systems (BESS) [10], distribution static synchronous compensators (DSTATCOM) [11], dynamic voltage restorer (DVR) [12]–[14]. DVR, one of the power electronics devices, is effective in distribution systems because it requires lower power than other devices, lower maintenance costs, good efficiency, simpler control, and easy implementation [15]. DVRs are connected in series on the distribution network, used to regulate voltage on the network if needed, and used to protect against short-term voltage disturbances between supply and sensitive load [16]. In research [17], the effect of DVR installation on voltage sag on various types of short circuit faults was analyzed. Based on simulations, the largest disturbance was caused by a 3-phase to ground short-circuit fault. The amount of load supplied and the distance of the fault location also affects how much the voltage drops. Moreover, to improve the quality of the DVR is to improve the quality of its control system. The quality of the control system is influenced by the type of control strategy used [18]. This component plays an important role in detecting faults from the voltage supplied and comparing it with the reference voltage. Proportional integral (PI) controller is a controller commonly used in DVRs, but the response is not good to nonlinear loads, as well as long time delays and settling times [19].

Jeyaraj *et al.* [16] introduced particle swarm optimization (PSO) to improve the quality of DVRs by setting on the PI controller. The study used a simple distribution system and was tested on different short-circuit faults. The results showed that PSO successfully improved the response and quality of voltage injection on the DVR. In a related study, Salman *et al.* [18] proposed the adaptive neuro-fuzzy interference system (ANFIS) method to improve the response of the DVR by adjusting the response through the PI-PSO controller. PI-PSO successfully regulates the response for the proposed method, and the PI-PSO response setting is better than the PI controller in the study results. In contrast, comparing and improving the types of reliable control strategies on DVRs is one method of finding the most efficient controller to use [19]. Research by Arpitha *et al.* [20] used a similar method, comparing types of strategy control, namely artificial neural network (ANN) and hysteresis voltage control. This study used photovoltaic as a direct current (DC) source on the DVR, then simulated the sag and swell due to a 3-phase short-circuit fault. The results show that the ANN controller is a more reliable method used in DVRs, with advantages including the ability of the network to learn from experience, self-organize, parallel processing, and the twofold function of the neuron [21]. Research by Ibrahim [22] uses ANN as a control system on DVRs to compensate for voltage sag. ANN input and output data are trained using different types of training algorithms. The most suitable algorithm used according to the simulation results is Lavenberg-Marquardt, and the ANN controller is able to recover voltage with a total harmonic distortion (THD) of 3.50%.

Based on the problem described above. PSO and ANN were introduced as a solution to this problem. PSO is a reliable metaheuristic method that can optimize the controller's performance with few parameters, but the results are optimal. Convergence and optimum values are obtained faster than other methods and do not depend on parameters [20]–[22]. This study proposed to test DVR based on PSO and ANN to find a more suitable controller. Modeling and simulation were carried out using MATLAB Simulink. The simulation was performed based on a 3-phase short-circuit fault based on 70% load and 75% fault location. Simulations were conducted on the distribution network at the SB02 feeder of the Sibolga substation, and the performance of the DVR was analyzed.

## 2. PROPOSED METHOD

### 2.1. Dynamic voltage restorer

Dynamic voltage restorers (DVRs) are installed in the distribution system to protect sensitive loads from voltage sag. DVR is considered a variable that can be controlled and linked in series between point of common coupling (PCC) and load [13], [23]. DVR injects the voltage the inverter generates when a disturbance occurs using a 3-phase transformer in series. DVR consists of several components, a battery as an energy source, DC to AC inverter, a filter to reduce harmonics, an injection transformer, and a control circuit. When a fault occurs, the control unit on the DVR detects a measured voltage change in the load. Then the control unit will generate pulses on the voltage source inverter (VSI), and VSI responds by generating AC voltage. The resulting AC voltage contains harmonics, so the low-pass filter works to get a better waveform. Then the voltage is stepped up to nominal voltage and then injected through an injection transformer [13], [24].

DVR works with three operating modes, namely standby mode, when the system is in a normal state [18], [25]. When voltage sag occurs, the DVR goes into injection mode, where the DVR supplies the required voltage, phase, and frequency. When a fault occurs, a large current flow into the network, and the DVR goes into protection mode by activating a bypass switch to protect the DVR circuit from disturbances. Figure 1 shows the components contained in a DVR.

Voltage compensation by the DVR is carried out with the required magnitude and phase angle. The power injected by the DVR is in the form of active and reactive power. The amount of power injected can be calculated by (1). Where $S_{DVR}$ is the apparent power produced by the DVR, $I_L$ is the current in the network and $V_{DVR}$ is the voltage injected by the DVR. The amount of active power that the DVR injects is known as in (2). Then $P_{DVR}$ is the active power produced by the DVR, $V_L$ is the measured voltage on the network and $V_S$ is the source voltage. $\theta_L$ is the phase angle on the network while $\theta_S$ is the phase angle at the source. The amount of voltage produced by (3).

$$S_{DVR} = I_L.V_{DVR} \tag{1}$$

$$P_{DVR} = I_L(V_L \cos\theta_L - \cos\theta_S) \tag{2}$$

$$V_{DVR} = [{V_L}^2 + {V_S}^2 - 2V_LV_S\cos(\theta_L - \theta_S)]^{1/2} \tag{3}$$

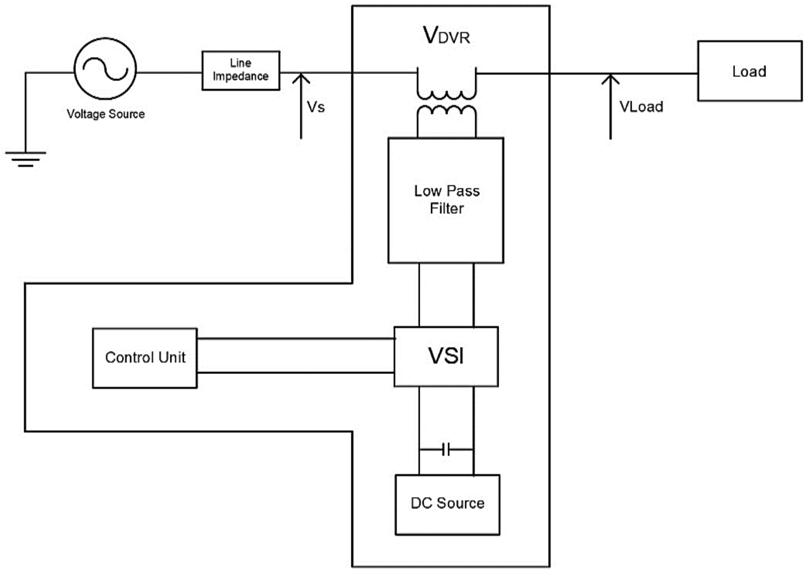



Figure 1. DVR components

### 2.2. DVR control strategies

The voltage compensation method by DVR is done by maintaining a constant load voltage based on voltage magnitude, phase angle, or both. In this case, pre-sag compensation is used [25] to maintain the voltage and phase angle in the network simultaneously and then measured by the controller. The controller then sends pulse width modulation (PWM) pulses to be converted into the required voltage. This work proposes two types of control strategy techniques, which are shown below.

#### 2.2.1. Particle swarm optimization

Particle swarm optimization (PSO) is a population-based stochastic search algorithm used as an alternative solution to complex nonlinear optimization problems. This algorithm belongs to the metaheuristic method, inspired by the social behavior of animals such as flocks of birds and fish. Each particle moves freely through the search space to find solutions by updating the position and speed of each iteration. Each iteration will keep the particles' best and the swarm's best positions [26], [27]. The global best value in the last iteration is the DVR controller optimization solution. To reach a solution, equations (4) and (5) are used to update the velocity and position of the particles per iteration:

$$v_{ij}^{t+1} = v_{ij}^t + c_1r_{1j}^t\left[P_{best,i}^t - x_{ij}^t\right] + c_2r_{2j}^t\left[G_{best} - x_{ij}^t\right] \tag{4}$$

$$x_i^{t+1} = x_i^t + v_1^{t+1} \tag{5}$$

where $r_1$ and $r_2$ are random numbers with a range of [0,1], $c_1$ and $c_2$ is the acceleration coefficient, the value is static which is 2. $v_{ij}^t$ is the velocity vector of particle i in dimension *j* at time *t*, while $x_{ij}^t$ is the position vector of particle *i* in dimension *j* at time *t*. $P_{Best}$ and $G_{Best}$ are the best positions of particles and swarms respectively.

### 2.2.2. Artificial neural network

Artificial neural network (ANN) is a type of computational method consisting of different types of simple elements operating in parallel similar to the human nervous system. ANN is an algorithm with great results achieved by accommodating input changes without changing output conditions. This computational method consists of computational units called neurons. These neurons are arranged into layers or have their combinations. The neural network consists of 3 layers i.e., the input, the hidden, and the output [28], [29].

Neural networks are trained through learning algorithms to solve a given problem, otherwise called learning from experience. The Levenberg-Marquardt (LM) algorithm is the fastest learning algorithm in achieving convergence [30], [31]. This work is used to determine network configuration and network capabilities in overcoming voltage sag.

## 3. METHOD

### 3.1. System description

The proposed system is modeled as a radial distribution system based on the SB02 feeder of the Sibolga substation. This system consists of a grid voltage of 150 kV, two step-down transformers rated at 150/20 kV, 60 MVA, and 20/0.38 kV, 750 kVA. The network length is 33.12 km with a load of 636.65 kVA. As a voltage sag compensation device, DVR is installed in the system between the PCC and the load with component ratings according to Table 1. System and DVR modeling are shown in Figures 2 and 3, respectively.

Table 1. DVR component ratings

| Parameters | Specifications |
|---|---|
| Injection transformer | 70 kVA, 0.38/20 kV |
| Resistance | 1 Ω |
| Inductance filter | 5 mH |
| Capacitive filter | 10 mF |
| DC source | 2×2,500 V |

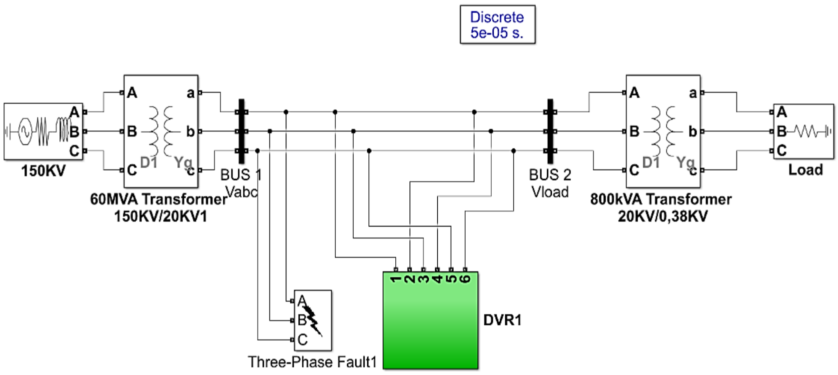



Figure 2. Proposed system modeling

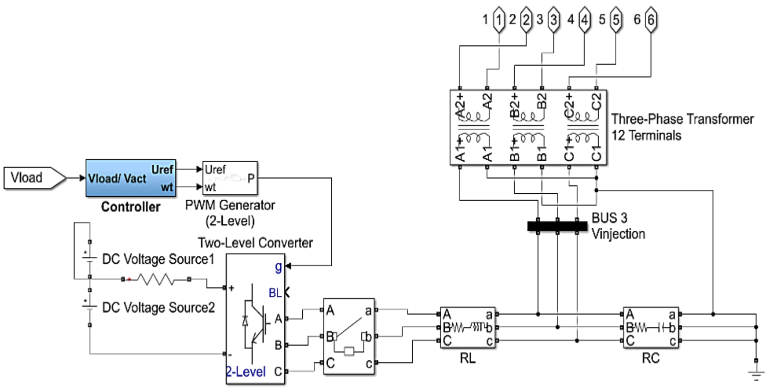



Figure 3. DVR circuit

### 3.2. Controller design

In nonlinear systems, the control system affects how the quality of the DVR. The choice of controller type becomes important to get the appropriate response and results. In this sub-section, two types of controllers will be described as proposed as a solution to find a more suitable controller.

#### 3.2.1. PSO algorithm for PI controller tuning

PSO, as one of the optimization methods, is used in this work to optimize the PI controller parameters, namely $K_p$ and $K_i$. The objective function of PSO is to minimize fitness function by evaluating it with a standard metric called integral square error (ISE). ISE is more error tolerant for long periods, so PI-PSO controllers have a faster response than use (6) [16], [26], [32].

$$ISE = \int (e)^2 \, dt \tag{6}$$

where $e$ is the error between the measured voltage and it is reference voltage, the parameters selected for optimization as shown in Table 2. The PSO flowchart and PI-PSO controller modeling are shown in Figures 4 and 5, respectively.

Table 2. PSO parameters

| Parameters | Value |
|---|---|
| Number of Particles | 30 |
| Number of Iteration | 50 |
| Inertia Weight ($\omega$) | $\omega_{max}$ = 0.9 and $\omega_{min}$ = 0.4 |
| Acceleration Constant (C) | $C_1 = C_2 = 2$ |

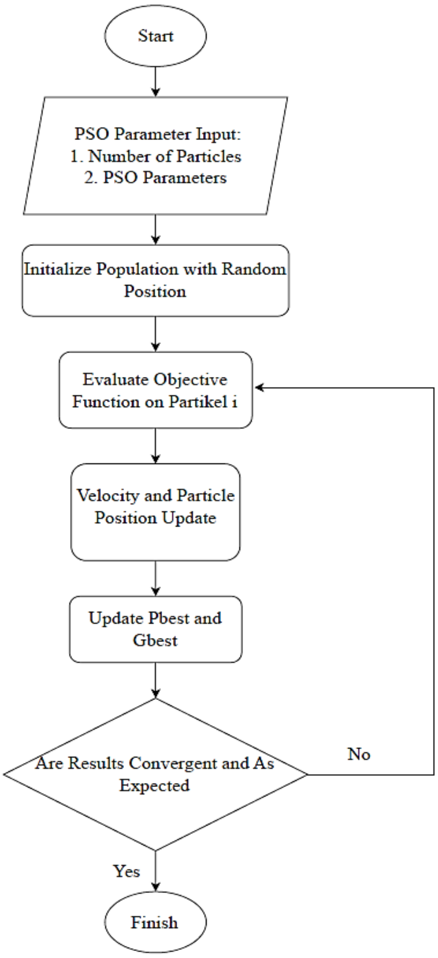



Figure 4. Flowchart of PSO

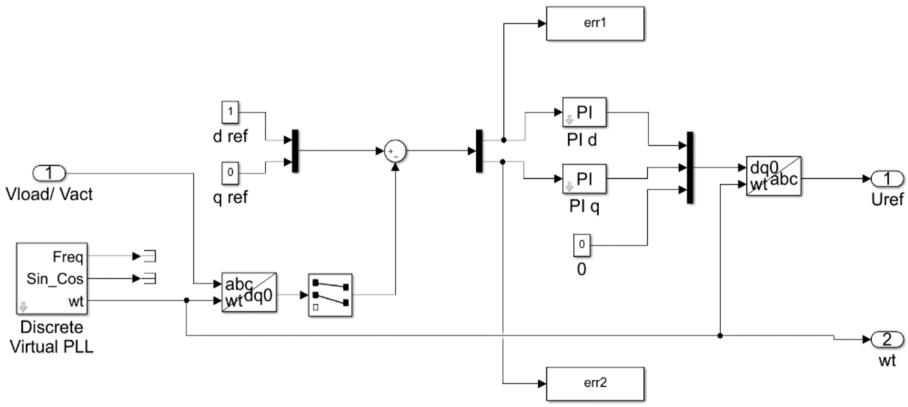



Figure 5. PI-PSO control circuit

#### 3.2.2. ANN training

ANN is an algorithm for real-time voltage compensation, requires a dataset to be trained to the network before it can be used on a DVR. The network consists of 1 input layer, two hidden layers, and one output layer. The ANN flowchart is shown in Figure 6, where the dataset for training (input and output data) is collected based on the conventional PI controller on the DVR. Then, 10,000 datasets were selected for use as ANN controller training. 70% of the data was used to train ANN, 15% to test the training data results, and the rest to validate the system network. Figure 7 shows an ANN controller circuit that has been trained and evaluated for performance based on mean square error (MSE), a standard metric used to calculate the average squared error between the actual value and the reference value [20], [26], [29].

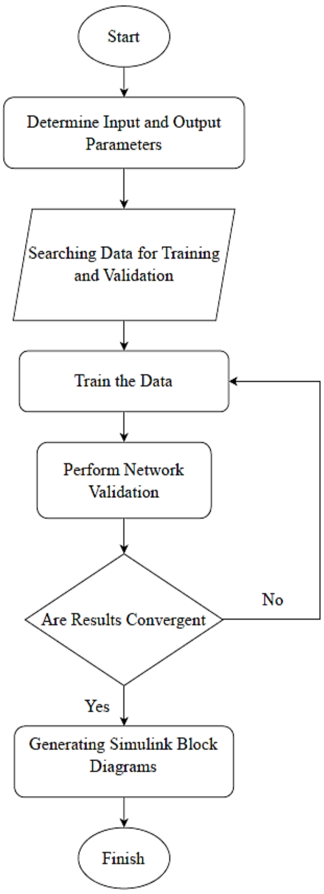



Figure 6. Flowchart of ANN

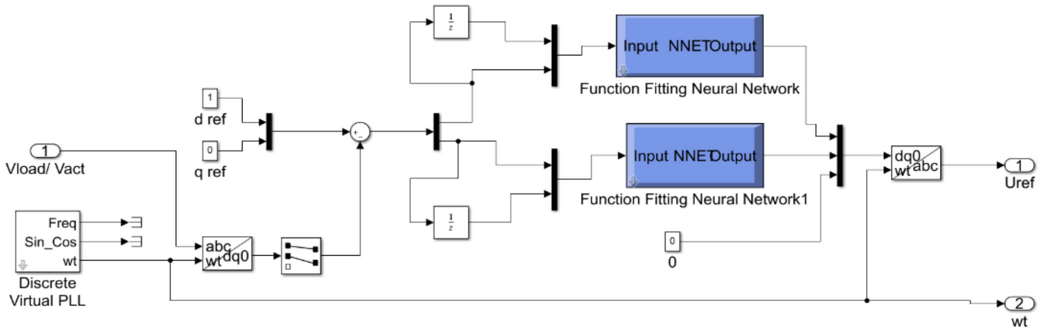



Figure 7. ANN control circuit

## 4. RESULTS AND DISCUSSION

Comparison of 2 types of DVR control systems modeled and simulated with MATLAB-Simulink software. The control system's performance is analyzed for a 3-phase short circuit fault based on 70% load and 75% fault location points. The distribution system in Figure 2 will be implemented to simulate the proposed DVR control system. The simulation was conducted within 0.1 s, and voltage sag was generated in time between 0.03-0.07 s.

### 4.1. Result

When a short circuit occurs, the source voltage decreases in voltage at each phase. Voltage sag will affect the load and damage sensitive equipment. Figure 8 shows the voltage waveform when a short circuit occurs before being compensated by the DVR. The amount of voltage remaining in pu and the total harmonic distortion (THD) produced when the disturbance is shown sequentially in Figure 9. Meanwhile, Figure 9(a) for phase A, Figure 9(b) phase B, and Figure 9(c) phase C under voltage sag, respectively.

Figure 10 shows the maintenance at the voltage range allowed in the Indonesian PLN standard (+5%, -10%). Further, Figures 10(a) and 10(b) show the source voltage and load side, respectively. Meanwhile, DVR with PI-PSO controller works to compensate for voltage and harmonics due to disturbance by injecting voltage for 0.04 s, as shown in Figure 10(c). The amount of voltage maintained in pu and harmonics reduced in each phase, as shown in Figures 11(a) to (c). In contrast, Figure 12 shows the performance of the DVR-ANN in injecting the required voltage. The voltage waveform due to disturbance is introduced in Figure 12(a). Figure 12(b) shows how the ANN controller managed to maintain the voltage at the required level, and Figure 12(c) shows the voltage injected by the DVR-ANN. DVR-ANN also has reduced harmonics in voltage waveforms, as seen in Figures 13(a) to (c) for each phase, respectively.

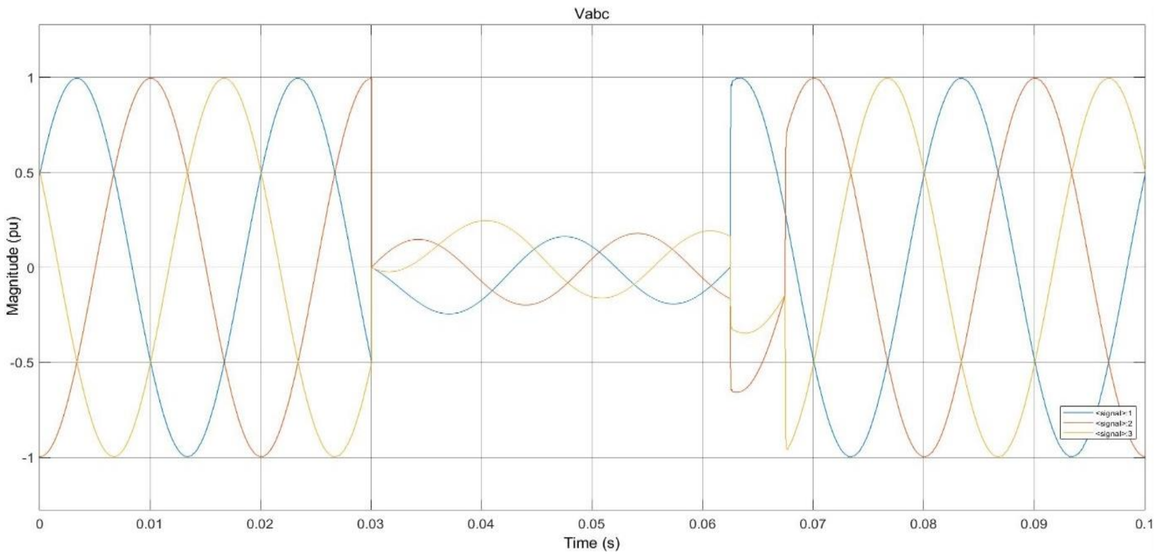
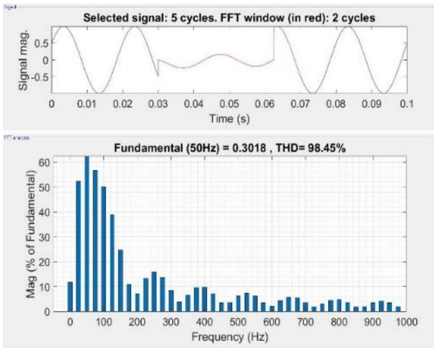
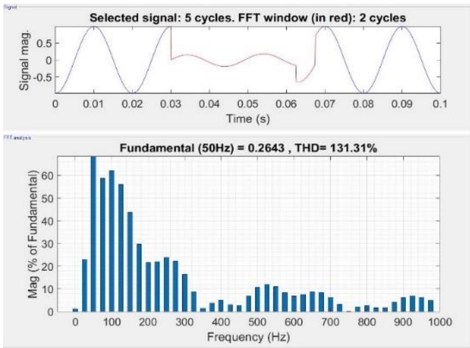


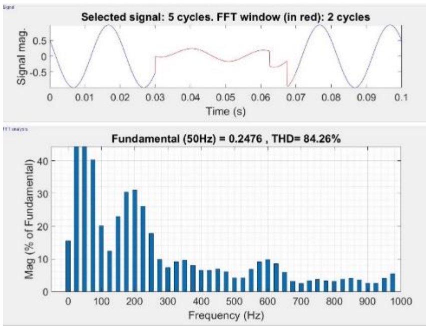

Figure 8. Voltage waveform before being compensated by DVR




(a)

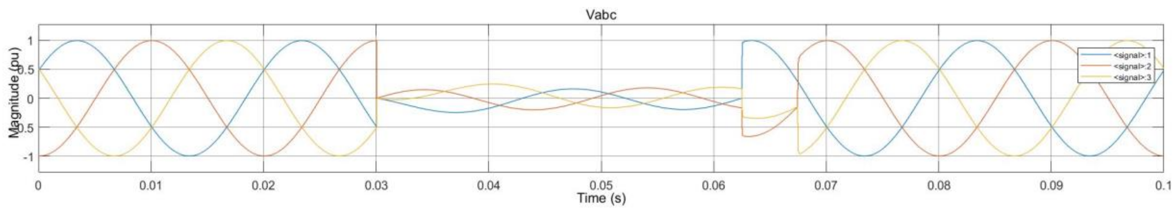



(b)

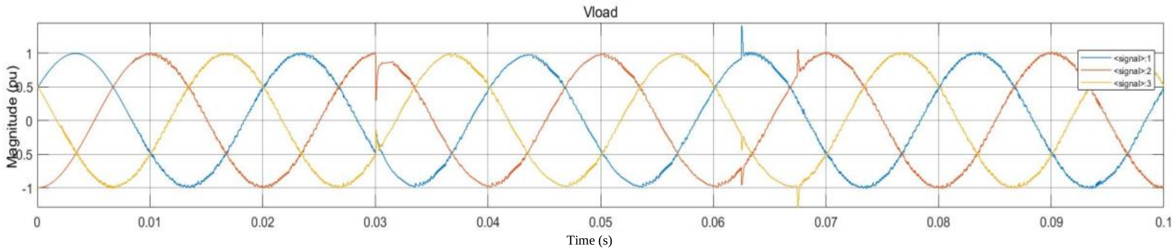



(c)

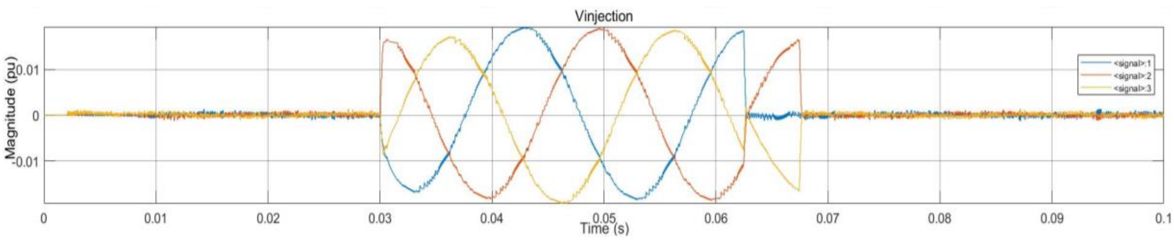
Figure 9. Source voltage in pu and THD generated before being compensated by the DVR for (a) phase A, (b) phase B, and (c) phase C under voltage sag




(a)

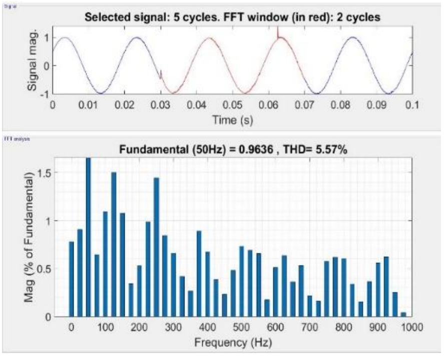



(b)

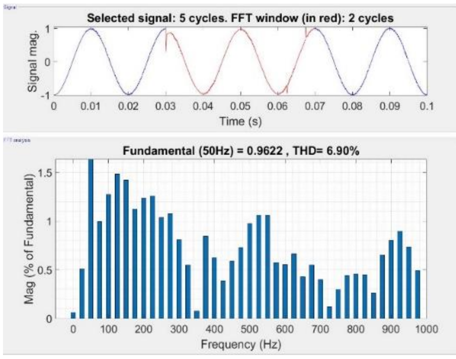



(c)

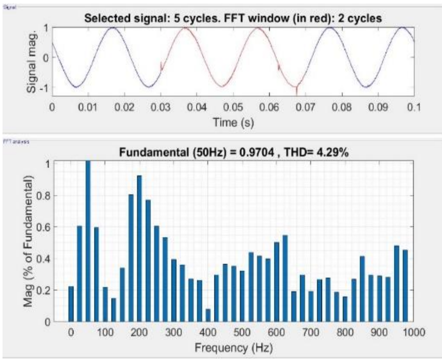
Figure 10. Plot for (a) source voltage, (b) load voltage, and (c) DVR with PI -PSO injected voltage




(a)

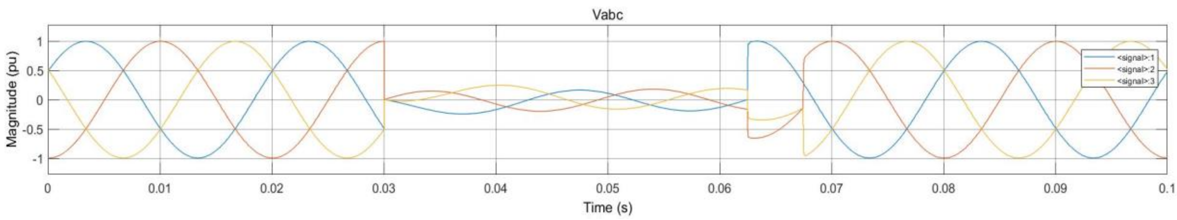



(b)

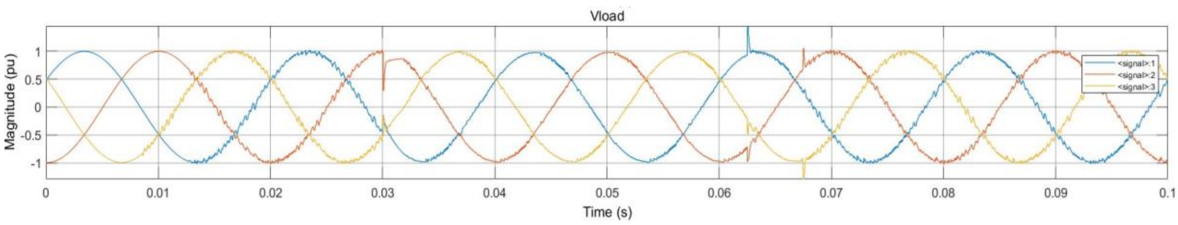



(c)

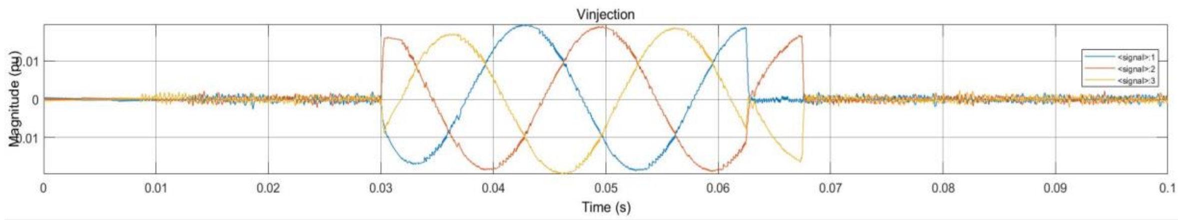
Figure 11. Load voltage in pu and THD for (a) phase A, (b) phase B, and (c) phase C after being compensated by DVR with PI-PSO




(a)

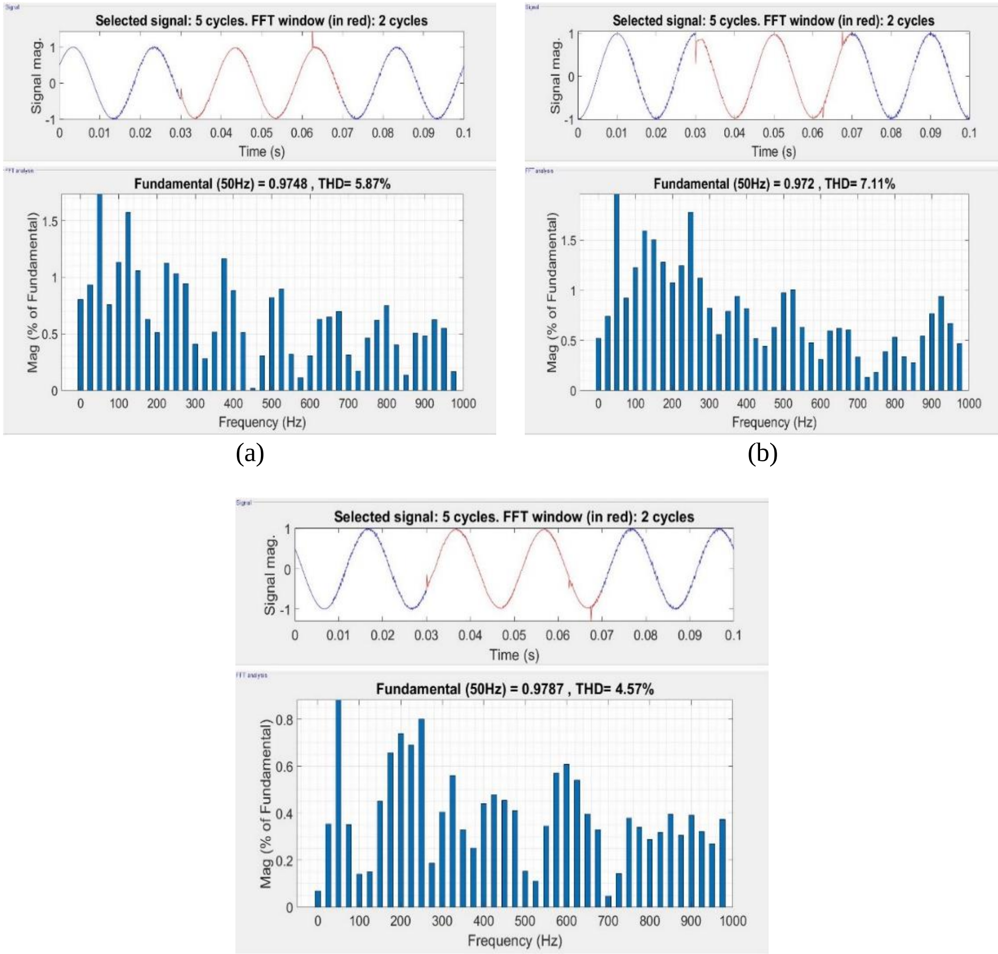



(b)




(c)

Figure 12. Plot for (a) source voltage, (b) load voltage, and (c) DVR-ANN injected voltage




(a) (b)

(c)

Figure 13. Load voltage in pu and THD for (a) phase A, (b) phase B, and (c) phase C after being compensated by DVR-ANN

### 4.2. Discussion

Based on the results, DVRs with two types of controllers restored voltage in the range allowed in the Indonesian PLN standard. Moreover, the DVR reduced the harmonics produced with the PI-PSO and ANN controllers, as shown in Table 3. The information shows the comparison between 2 types of controllers in recovering voltage due to 3-phase short circuit faults for the time range 0.03 to 0.07 s.

Table 3. Load voltage in PU and THD for each phase before and after compensation

| Parameters | Phase | Without DVR | DVR with PI-PSO | DVR-ANN |
|---|---|---|---|---|
| Voltage (pu) | A | 0.3018 | 0.9636 | 0.9748 |
| | B | 0.2643 | 0.9622 | 0.9720 |
| | C | 0.2476 | 0.9704 | 0.9787 |
| THD (%) | A | 98.45 | 5.57 | 5.87 |
| | B | 131.31 | 6.90 | 7.11 |
| | C | 84.26 | 4.29 | 4.57 |

The measured voltage during the fault was between 0.26 to 0.30 pu, and the DVR with PI-PSO managed to recover the voltage at the desired level, as shown in Figure 10. Referring to Figure 12, DVR-ANN also successfully recovered voltage with better voltage values, as Table 3 shows. Table 3 also compares how DVRs successfully reduce THD on the load side using PSO and ANN controllers. The simulation results showed that the greatest THD was reduced to 4.29% in phase C using PI-PSO while using the ANN controller was successfully reduced to 4.59% in phase C.

Table 3 shows how much the DVR injects voltage, which is 0.6618 pu in phase A, 0.6979 pu in phase B, and 0.7228 pu in phase C using PI-PSO. Meanwhile, DVR-ANN injects a voltage of 0.673 pu in phase A, 0.7077 pu in phase B, and 0.7311 pu in phase C. The voltage this DVR injects is influenced by the inverter output rating and DC source rating. Based on the simulations, the results have shown that DVR-ANN has greater voltage injection quality and successfully recovers a voltage close to the nominal voltage of 1 pu. The ANN controller uses a conventional PI controller on the DVR for data training, then validated through a neural network into a new controller resistant to various possible disturbances [22], [29]. In contrast, PI-PSO is only able to find the optimum value in the controller PI parameters based on the disturbance that occurs in the system, then inject the required voltage [32].

Table 4 shows how the DVR controller responds to the resulting voltage sags. Based on these results, DVR-ANN outperforms DVR with PI-PSO, and all DVR-ANN response results are better than DVR response with PI-PSO, meaning that the error produced by DVR-ANN is smaller than DVR with PI-PSO, faster rise time and settling time, as well as less undershoot and overshoot. This is because when datasets are trained on ANN, the network minimizes errors by adjusting the weights on each data's target inputs and outputs, so the ANN controller is more precise [28].

Table 4. DVR controller response analysis

| DVR | Rise time (s) | Settling time (s) | Undershoot (%) | Overshoot (%) | Steady state time(s) |
|---|---|---|---|---|---|
| PI-PSO | 0.0002 | 0.0994 | 2.78 | 6.89 | 1.052 |
| ANN | 0.00004 | 0.0991 | 1.3 | 5.51 | 1.049 |

## 5. CONCLUSION

In this research, DVR modeling was carried out with two different types of controllers, namely DVR with PI-PSO and DVR-ANN. The simulation was carried out on the radial distribution system of the SB02 feeder of the Sibolga substation. Simulations were performed on voltage sag due to a 3-phase short-circuit fault at 70% load conditions and 75% fault locations. Then the quality of both types of controllers was evaluated. Meanwhile, voltage sag is generated, and the DVR installed in the network successfully injects voltage at the required level. DVR-ANN injected 0.0112, 0.0098, and 0.0083 pu greater voltage in each phase, respectively, than DVR with PI-PSO. Both controllers reduced harmonic distortion by 4.57% and 4.29% in phase C interrupted. Finally, our conclusion is DVR-ANN has a better response and smaller errors than DVR with PI-PSO. The quality of DVR-ANN outperforms that of DVR with PI-PSO.

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