International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 2, April 2024, pp. 1215~1227
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i2.pp1215-1227

Dynamic voltage restorer performance analysis using fuzzy logic controller and battery energy storage system for voltage sagging

Yulianta Siregar[1], Azrial Aziz Azhari Nasution[1], Mai Kai Suan Tial[2], Naemah Mubarakah[1], Soeharwinto[1]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara, Medan, Indonesia
[2]Department of Electrical Power Engineering, Faculty of Engineering, Yangon Technological University, Yangon, Myanmar

Article Info

Article history:

Received Jul 25, 2023
Revised Oct 23, 2023
Accepted Nov 12, 2023

Keywords:

Battery energy storage system
Dynamic voltage restorer
Fuzzy logic controller
Power quality
Voltage sags

ABSTRACT

Power quality is a major issue in the power transfer process. This is caused by disturbances such as voltage sags, voltage spikes, and harmonics. Voltage sag is the most common disturbance in the electric power system. However, the dynamic voltage restorer (DVR) is the most effective device for voltage sags. This research uses the DVR to overcome voltage sags using fuzzy logic controller (FLC) and battery energy storage system (BESS) to improve the performance of the DVR. The results showed that DVR using FLC improved the quality of voltage recovery compared to BESS because FLC injected a greater voltage of 0.0991 pu than BESS.

Corresponding Author:

Yulianta Siregar
Department of Electrical Engineering, Faculty of Engineering, Universitas Sumatera Utara
Medan, North Sumatera, Indonesia
Email: julianta_srg@usu.ac.id

1. INTRODUCTION

Voltage sag is a decreasing voltage of 10% to 90%, which occurs for 0.5 cycles (0.01 seconds to 1 minute). Voltage sags will affect the power quality in the power grid system and the safe operation of electrical components. The voltage sag occurs due to a short circuit disturbance which is then followed by a shift in the phase angle [1]–[3]. A short circuit fault is an intentional or unintentional conduction connection through resistance or impedance between two or more points under normal circumstances with a potential difference. Therefore, additional power electronics devices are needed to perform voltage compensation, namely dynamic voltage restorer (DVR) [4]–[6], unified power quality control (UPQC) [7], and distributed static compensator (DSTATCOM) [8]. DVR is the most effective device in dealing with voltage sags. DVR is a connected device in series on a distribution network location between the supply and load. DVR protects the load from short circuit disturbances caused by voltage sags [9].

The control system on the DVR device plays an important role in assisting the DVR in detecting voltage sag disturbances in the distribution network system from the supplied supply voltage and then comparing it with the reference voltage. Many types of control methods are used to control DVRs, but proportional integral (PI) controllers are the most commonly used control system. In research conducted by Sarwade *et al.* [10] entitled power quality problems mitigation using dynamic voltage restorer with PI controller and fuzzy logic controller, in the study it was found that the use of fuzzy logic controller affects the optimal set of PI control parameters and can improve the control system.

In another study by Rajasekaran *et al.* [11] titled dynamic voltage restorer based on fuzzy logic controller for voltage sag restoration. In this study, fuzzy logic controller (FLC) was implemented to improve the voltage compensation performance of the DVR, and FLC was also tested against resistive and inductive loads. The results of this research, the implementation of FLC on the DVR as a control system is very effective in reducing the impact of voltage sags and increasing system stability compared to PI controller. From the results obtained, it can be concluded that the fuzzy logic controller is an ideal control system for DVR.

The other previous study, performance improvement of DVR by control of reduced-rating with a battery energy storage system, was conducted by Rakesh and Kumar [12]. This study used the battery energy storage system (BESS) to improve DVR performance. The use of BESS aims to reduce the effects of voltage sags that occur in network systems. The results obtained show that BESS can work to reduce the effect of voltage sags and inject the required voltage.

Based on the background of the problem and previous research, this research will be carried out by simulating and analyzing a comparison of the dynamic voltage restorer control method for voltage sags due to 3-phase short circuit faults. The method to be tested in this study is the fuzzy logic controller and the battery energy storage system. The simulation is carried out based on short circuit faults with a load of 70% of the total load and based on fault points at 75% of the line length.

2. PROPOSED METHOD

2.1. Power quality

The quality of electric power is the problem of electric power which has deviations from voltage, current, and frequency which impact the work system's failure on electrical equipment that occurs to consumers. Electric power is the amount of electrical energy sent from the generator to the load, where the amount of electric power is proportional to the multiplication of the voltage and current [5], [13]. Attention to electric power quality is increasing along with the increasing use of electrical energy and electricity utilities. Electric power quality is a concept that can provide an overview of the good or bad quality of electric power due to disturbances in the electric power system.

2.2. Short circuit

A short circuit is a disturbance caused by failure or damage to insulation in the circuit. This is caused by excess heat created along the conducting wire, causing overvoltage, which endangers the insulation that wraps the conducting wire. The short circuit current that occurs produces heat which is proportional to I^2R. This equation is the heat that arises because of a short circuit, and from this heat, it can damage the insulation of machines, conductor wires, circuit breakers, transformers, and so on [14], [15]. In the process in the field, a short circuit can occur not only due to the heat that arises on the conductor wire but also from external consequences such as a lightning strike, a fallen tree, and so on. Therefore, to minimize the impact caused by short circuit disturbances, it is necessary to provide protective devices in the electric power system. Electrical energy is transferred from the generator to the consumer through the electric power system, where the electric power system consists of several subsystems, namely generation, transmission, and distribution. The distribution network subsystem is a network that distributes electrical energy directly to consumers. The distribution network is divided into two network systems, namely the primary and secondary distribution networks. The short circuit disturbances often occur in the energy transfer process are phase-to-phase short circuits and phase-to-ground short circuits [3], [16], [17].

2.3. Voltage sag

Voltage sag is the phenomenon of a sudden decrease in the rms value of the voltage for a duration of 0.5 cycles to 1 minute and the value of the voltage drop is in the range of 0.1–0.9 pu at rms values. This voltage drop in the electric power system occurs due to the operation of electrical equipment that has a large load or can also occur due to disturbances in the transmission network and distribution network [4], [18]–[20].

2.3.1. Characteristics of a voltage sag

Two parameters that must be considered in this voltage flicker are voltage and duration. Disturbances in the electric power system will also cause changes in the phase angle. The parameters that characterize voltage sags are voltage, duration, and phase angle shift. Voltage sag is characterized in terms of the following parameters:

a. Large of voltage sag: One of the general characteristics indicates the magnitude of the voltage sag, namely, the remaining voltage during the voltage sag. The magnitude of the voltage sag at different points has a varying magnitude of voltage sag, which is contingent upon the problem's kind and resistance, proximity to the fault, and system setup [21]. As for calculating the magnitude of the voltage sag in a radial network, Figure 1 depicts the voltage divider model.

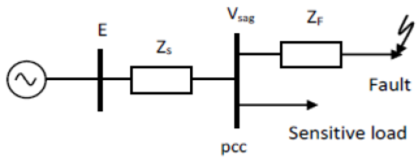


Figure 1. Models of voltage dividers

$$V_{sag} = \frac{Z_f}{Z_f + Z_s} V_s \quad (1)$$

In these equations, the following variables were used: V_{sag} is voltage sag (Volt), V_s is voltage source (Volt), Z_f is impedance between point of common coupling (PCC) and noise (Ohm), Z_s is impedance source (Ohms).

b. Duration of voltage sag: The duration of the voltage sag is the time needed to normalize the network system after the voltage sag occurs.
c. Shift in phase angle: The difference in the X/R ratio between the source and the fault point causes the phase angle shift during a fault. Comparing the phase angles during the observed voltage sag with the phase angles before the voltage sag allows one to determine the magnitude of the phase angle shift.

2.3.2. Causes of voltage sagging

Voltage sags can occur in the network system or the load. The things that cause voltage sags include starting induction motors, large loads, and short circuit disturbances in the distribution network. Voltage sag is a phenomenon of voltage drop between 10% to 90% of the nominal voltage value with the shortest duration of 1 minute. The voltage sag will affect the load's working system before the circuit breaker (CB) works to extinguish the disturbance [22], [23].

2.4. Dynamic voltage restorer

A voltage-compensating device that is connected in series with the distribution system is called a DVR. DVR is a very useful tool for regulating the voltage on the load side by injecting voltage to overcome voltage sags [24]. The injection voltage magnitude provided by the DVR is calculated (2).

$$V_{inj} = V_{load} + V_s \quad (2)$$

In these equations, the following variables were used: V_{inj} is injection voltage by DVR (Volt), V_{load} is voltage load (Volt). The following is a DVR circuit that compensates for voltage in the event of a disturbance, as shown in Figure 2. The main function of the DVR is to compensate for the electrical voltage on the load side when interference occurs. DVR can also be used for other needs, namely limiting fault currents, compensating for transient voltages, and reducing transient voltages. There is a voltage injection transformer on the DVR consisting of primary and secondary sides. The transformer's secondary side is connected in series with the DVR, and the primary side is connected in series with the distribution line and load. So, the position of the DVR is between the transmission and distribution channels.

2.4.1. Working principle of dynamic voltage restorer

DVR is a device that can inject voltage when there is a disturbance in the network system. The regulator will read the measured voltage at the load to provide a signal to the voltage source inverter (VSI). The signal sent is pulse width modulation (PWM) [25]. This PWM signal will be responded to by the inverter, which is supplied by the battery to produce alternating current (AC) voltage. Because the inverter is supplied by direct current (DC) voltage, the AC voltage signal produced by the inverter is not perfectly sinusoidal, so it contains harmonics. Therefore, a filter is needed to correct the shape of the AC voltage generated by the inverter.

Dynamic voltage restorer (DVR) consists of several components: DC batteries, VSI, filters, and voltage injection transformers. The arrangement of these components can be seen in Figure 2. The DC battery is a component that supplies the DVR and is an input voltage source to inject voltage. Then a VSI is a power electronics device supporting the voltage compensation process by converting the voltage from the battery to AC voltage. The filter used on the DVR is the LC filter. The filter is placed after the VSI, so before the voltage is sent to the transformer, the harmonics contained in the voltage can be prevented before being injected into the network. The injection transformer functions to inject voltage into the missing parts of the system using the voltage from the VSI. DVR has several compensation methods to overcome voltage sags [26], namely:

a. Compensation of pre-sag voltage: This compensation strategy aims to maintain the same voltage, amplitude, and phase angle on the load. This technique can be applied to non-linear loads susceptible to voltage fluctuations. The amount of injection voltage from the DVR can be calculated using (3).

$$V_{DVR} = \sqrt{V_S^2 + V_L^2 - 2V_S V_L cos\delta} \quad (3)$$

b. Compensation in-phase: The goal of this compensation strategy is to keep the load amplitude constant. This method suits linear loads because it does not require phase angle compensation. The amount of injection voltage carried out by the DVR can use (4) and (5).

$$V_{DVR} = V_L - V_S \quad (4)$$

$$\theta_{DVR} = \theta_S \quad (5)$$

c. Energy optimization compensation: In this compensation mode, the load is actively powered by the pre-sag and in-phase compensation techniques. However, in order to reduce the amount of active power injected, the necessary voltage is set at a 90° phase angle to the load current, resulting in nearly zero active power. This method's benefit is that it does not require active power and reduces the energy consumption of the DC source by injecting reactive power. However, the disadvantage is that the smaller the DC energy consumption required, the ability to inject voltage will increase, so in this technique, the injected voltage is greater than in the in-phase technique.

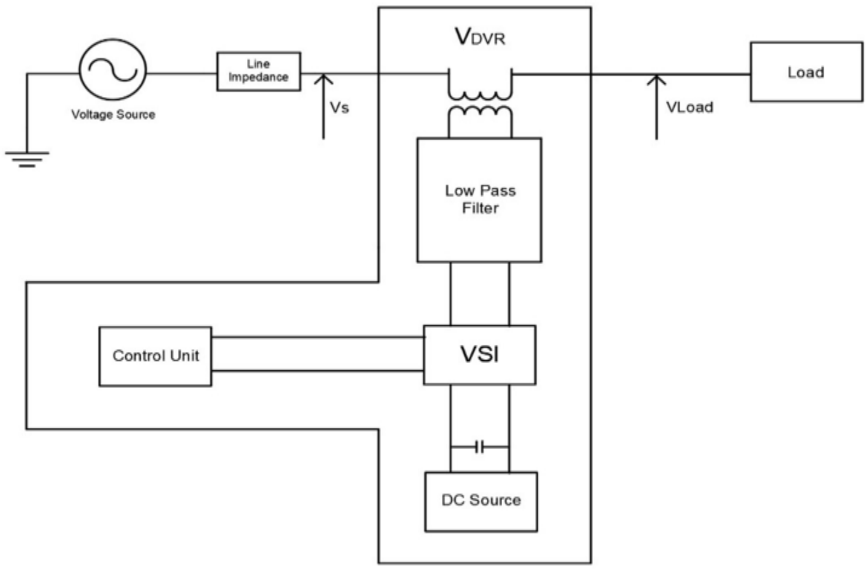


Figure 2. Circuit of the dynamic voltage restorer

2.4.2. Operation mode of dynamic voltage restorer

The DVR compensation device is designed to perform voltage adjustment. DVR has several operating modes in the distribution system: protection, standby, and injection [27]. In protection mode, the DVR is protected against overcurrent on the load side where the current exceeds the minimum acceptable limit. The DVR may sustain damage from overcurrent resulting from load-side defects. Therefore, the DVR must be covered from overcurrent disturbances. A bypass switch protects the DVR by providing an alternative path in this protection mode. Meanwhile, due to the lack of interference, the DVR does not inject voltage when in standby mode. Therefore, in order to avoid any potential voltage injection, a bypass switch avoids the DVR. If a fault is detected, the voltage injection from the transformer winding on the lower voltage side will be short-circuited through the VSI. Further, injection mode transitions from standby mode to mode if interference is detected. Once the disrupted voltage returns to normal, the DVR injects the necessary voltage through the transformer.

2.5. Fuzzy logic controller

Fuzzy logic controller (FLC) is a practical control system. FLC is a control system that uses fuzzy set theory. Fuzzy controllers provide a simple work system based on the input information, and fuzzy controllers are based on system understanding and depend on controller rules [10], [28], [29]. This study uses fuzzy logic to control voltage injection on the DVR. FLC is determined by linguistic variables, through which linguistic variables are transformed from numerical ones. Two real-time inputs are measured for each real-time sample in fuzzy logic [11], [30]. Therefore, it is necessary to define the basic rules of fuzzy logic as depict in Table 1.

Table 1. Basic rules of fuzzy logic

(ce)\(e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

2.6. Battery energy storage system

DVR voltage compensation to overcome voltage sags by injecting voltage. A DC energy storage device supports the voltage injection process by the DVR. The compensation voltage from the DVR is injected into the system via an injection transformer, and the DVR is also arranged on VSI as a DC voltage rectifier originating from a DC energy storage device. The operation of the VSI depends on the signals the control system receives. The operation of the BESS uses the self-resonant frequency (SRF) method [12], [31], [32]. Where the injection voltage that the DVR will inject will be controlled via SRF, the following is an SRF equivalent circuit shown in Figure 3 [33].

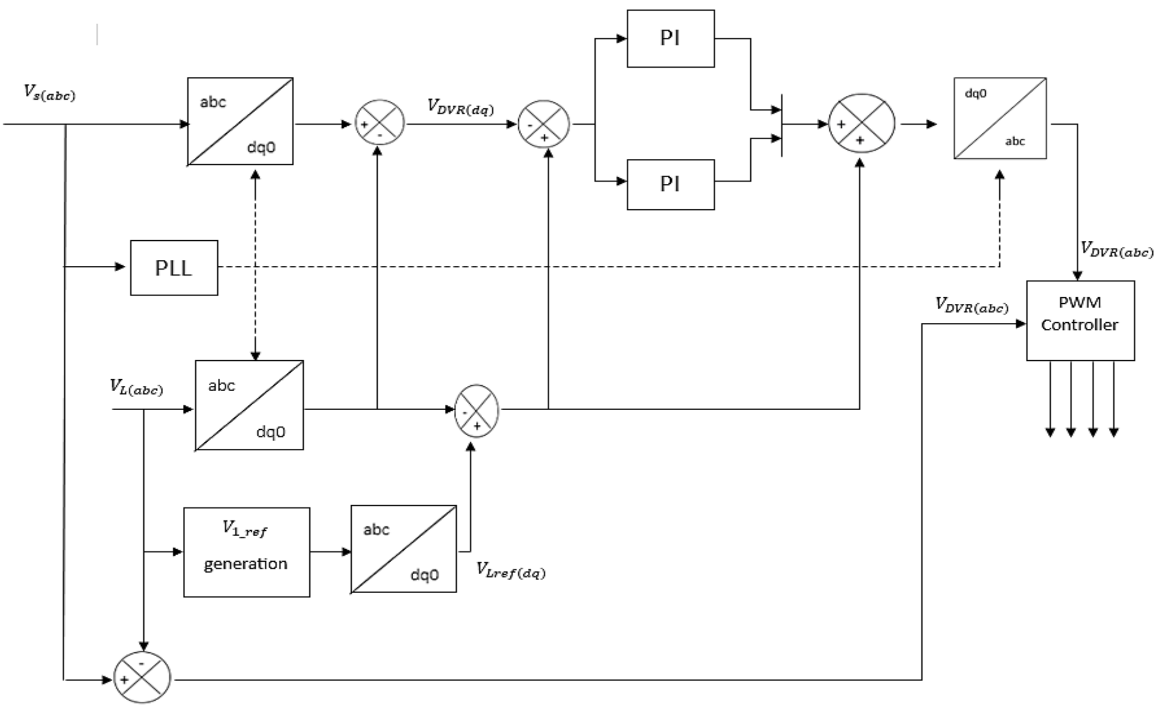


Figure 3. SRF control system on BESS

3. METHOD

System modeling uses a radar distribution system based on the Sibolga SB02 feeder network. The length of this network is 33.12 km with a load of 636.65 kVA. The DVR as a voltage compensation device is installed using the rating in Table 2. After the DVR parameters are designed, the next step is to model the dynamic voltage restorer, as seen in Figure 4. DVR modeling uses MATLAB Simulink to see the effect of installing a DVR due to short circuit disturbances. Meanwhile, the dynamic voltage restorer circuit modeled in MATLAB Simulink can be seen in Figure 5.

Table 2. Component ratings of the dynamic voltage restorer

Parameters	Specifications
Injection transformer	70 kVA, 0.38/20 kV
Resistance	1Ω
Inductance filter	5 mH
Capacitive filter	10 mF
DC Source	2 x 2500 V

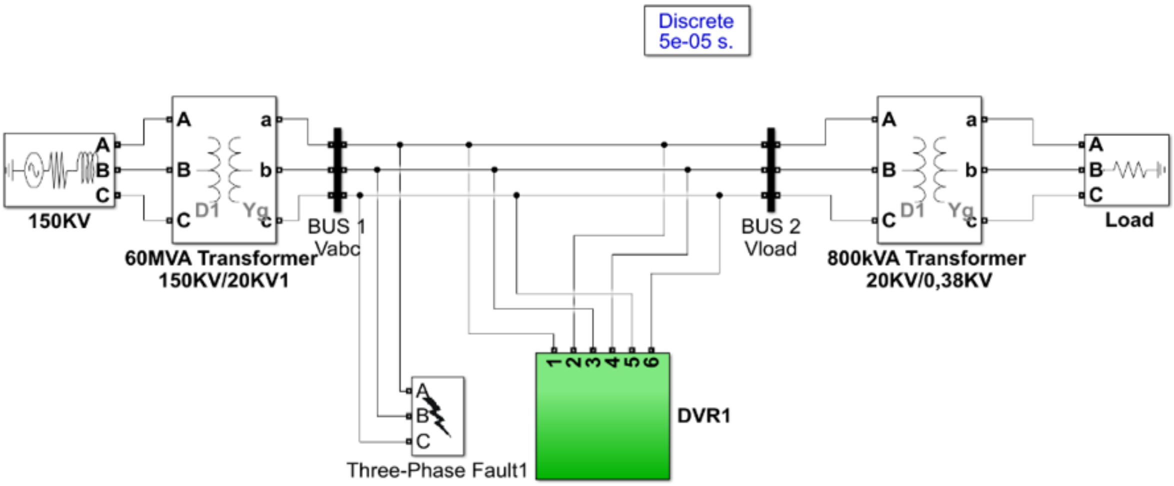


Figure 4. Distribution network modeling

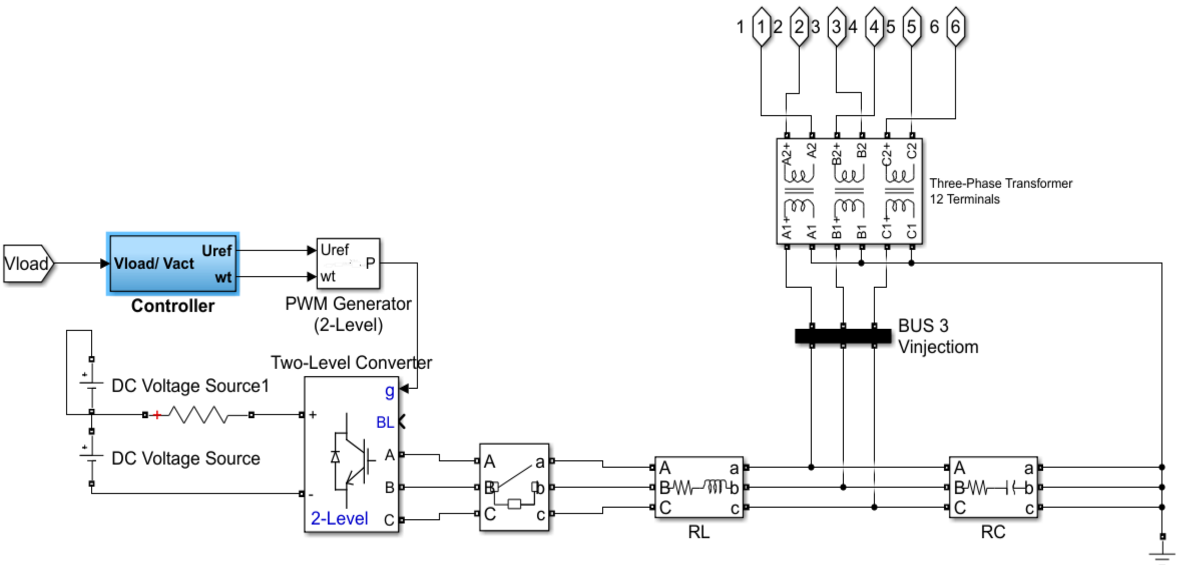


Figure 5. Circuit of the dynamic voltage restorer

3.1. DVR design using a fuzzy logic controller

After the DVR has been designed and connected to the distribution system, the next step is to model the control system on the DVR to have a reliable system. The amount of voltage, phase angle, and frequency injected through the DVR must be correct. Then FLC is used as a DVR control system. Figure 6 shows a DVR circuit with an FLC control system.

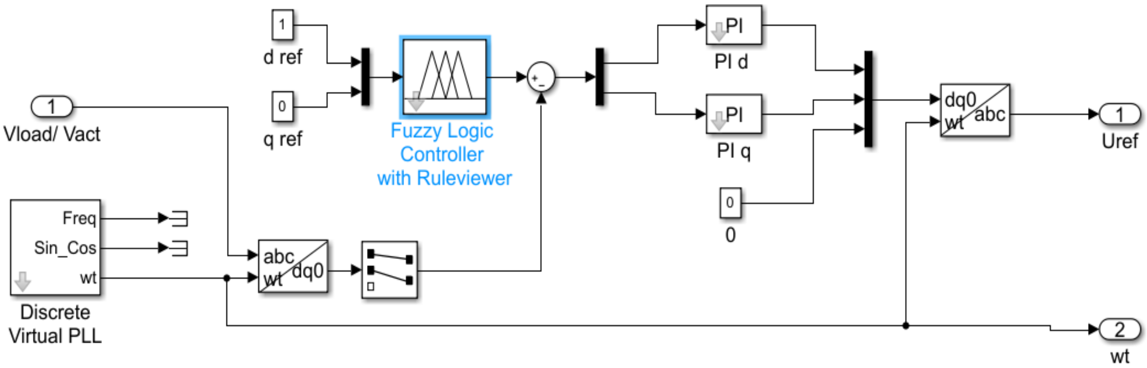


Figure 6. Fuzzy logic controller circuit on DVR

3.2. DVR design uses a battery energy storage system

Another system used in this study is the BESS. In this system, several parameters are used, as seen in Table 3, and the BESS circuit on the DVR can be seen in Figure 7. Meanwhile, the research procedure is seen in Figure 8.

Table 3. Parameter battery energy storage system

Parameters	Specifications
DC source	2×2,500 V
AC inductor	2 mH
PWM switching frequency	10 kHz

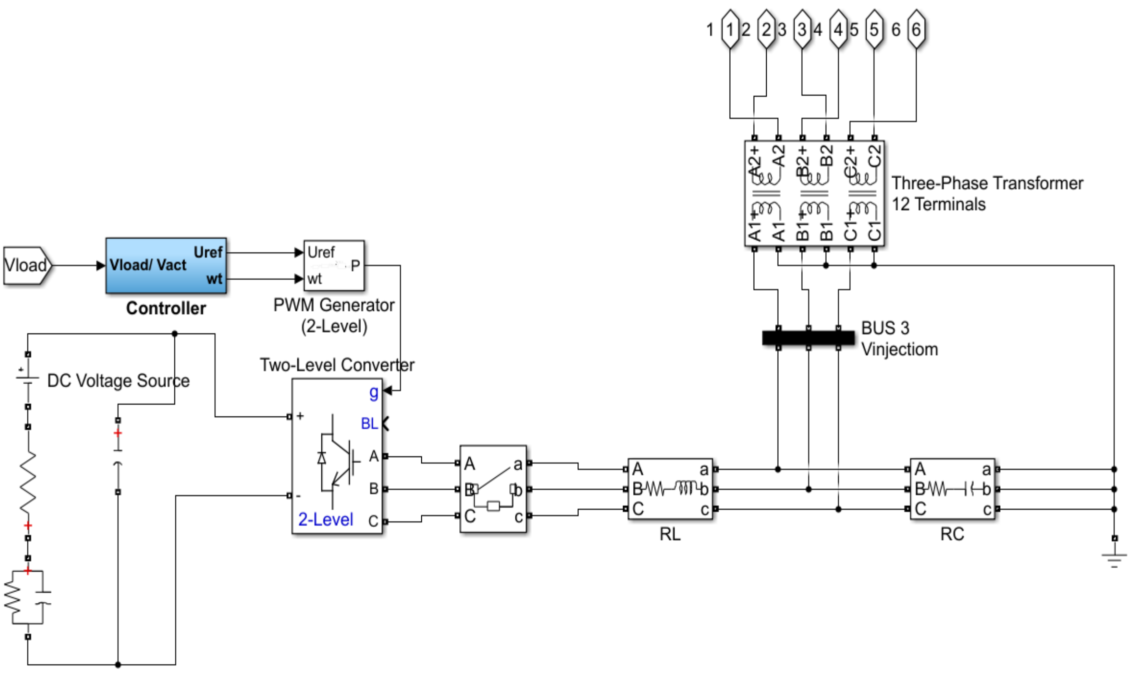


Figure 7. DVR using battery energy storage system

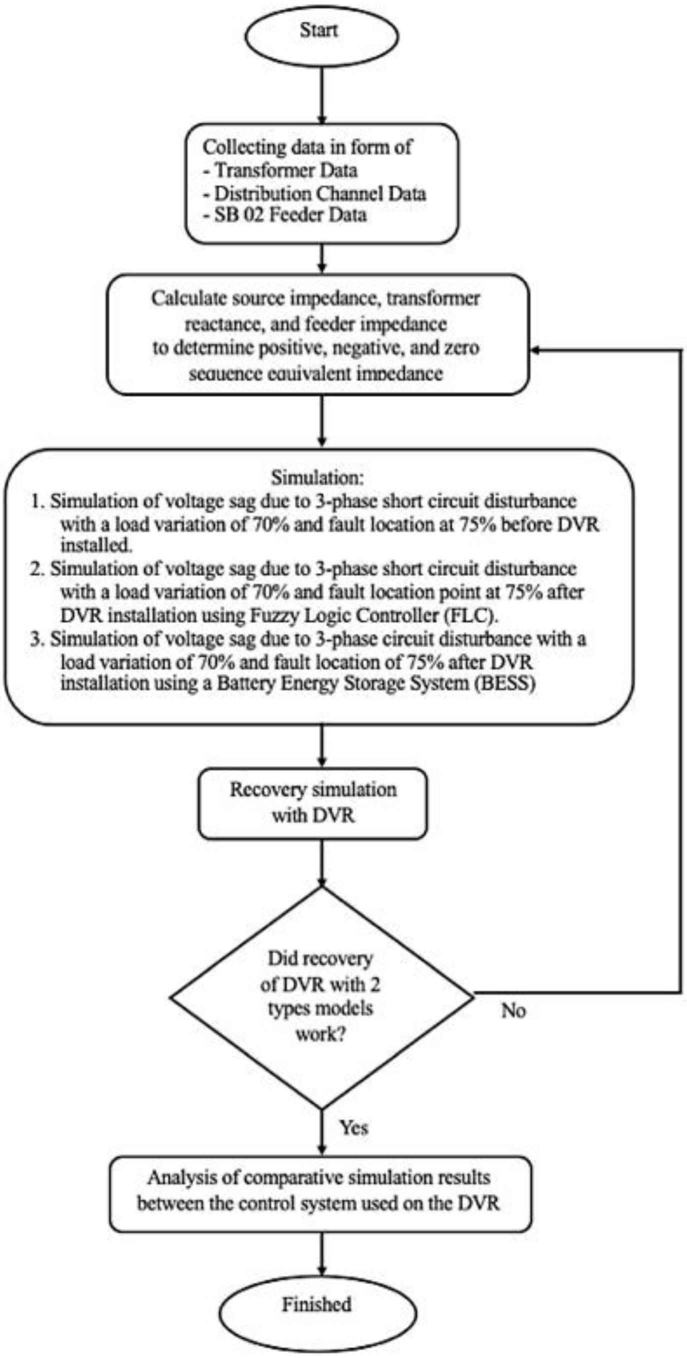


Figure 8. Research flow chart

4. RESULTS AND DISCUSSION

This chapter discusses the effects of a DVR using a FLC and BESS installed on the 20 kV SB02 Feeder distribution network at the Sibolga Main Substation. MATLAB-Simulink software was used to model and simulate comparing two types of DVR devices. Two-phase short circuit testing was conducted with 70% load conditions and 75% fault location to evaluate the two devices' performance.

4.1. DVR results using FLC

When a short circuit occurs, the voltage on each phase will decrease. Voltage sag will affect sensitive loads and devices. Figure 9 shows the voltage surge when a short course occurs before the DVR compensates. Figure 10 shows the voltage surge analysis before DVR compensation on phase A in Figures 10(a), 10(b) in phase B, and Figure 10(c) in phase C has decreased to 0.3019 pu, 0.2644 pu, and 0.247 pu, respectively, for a time duration of 0.03 to 0.07 seconds. Voltage sags cause this. On the other hand, after DVR installation using FLC, the simulation results of a three-phase short circuit fault with a load condition of 70% and a fault location of 75% as a voltage restorer can be seen in Figure 11. Figure 12 shows the voltage surge analysis before DVR compensation on phase A in Figures 12(a), 12(b) in Phase B, and Figure 12(c) in phase C has increased to 0.9053 pu, 0.874 pu, and 0.8678 pu, respectively.

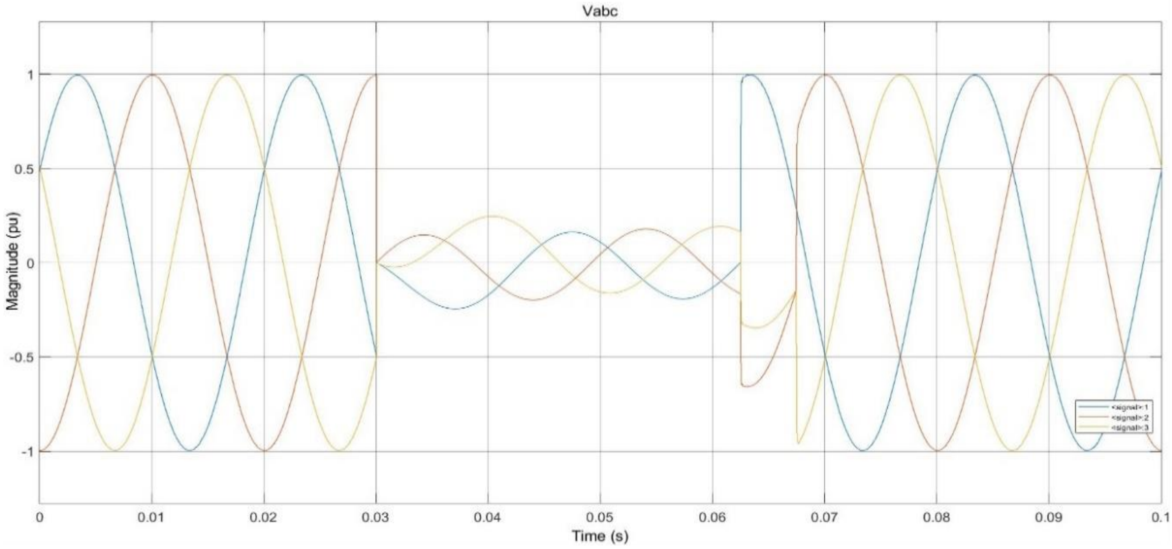
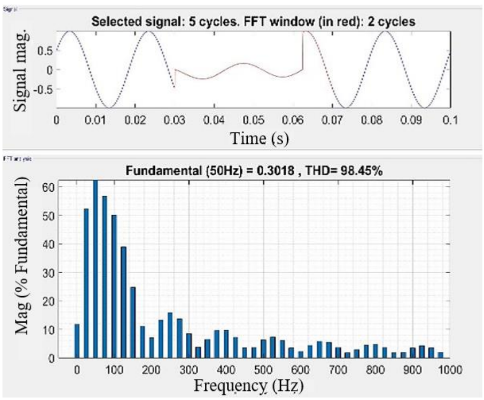
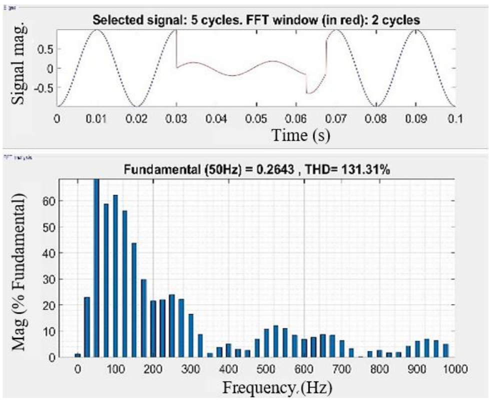


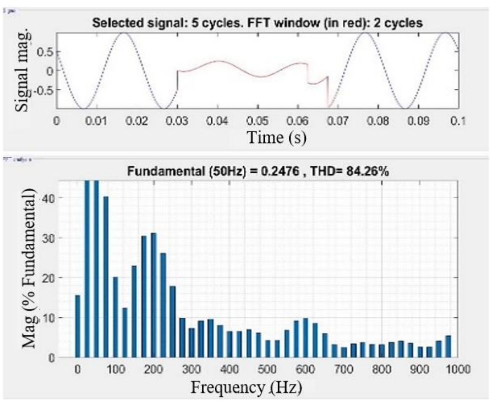
Figure 9. Surge before compensated DVR



(a)



(b)



(c)

Figure 10. Voltage surge analysis before DVR compensation on (a) phase A, (b) phase B, and (c) phase C

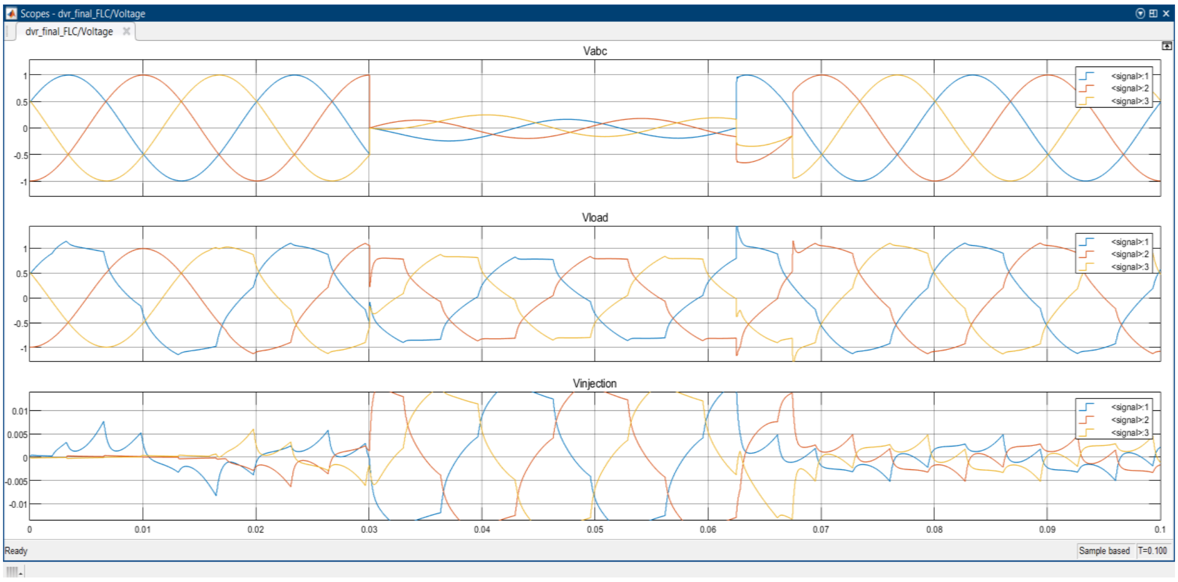
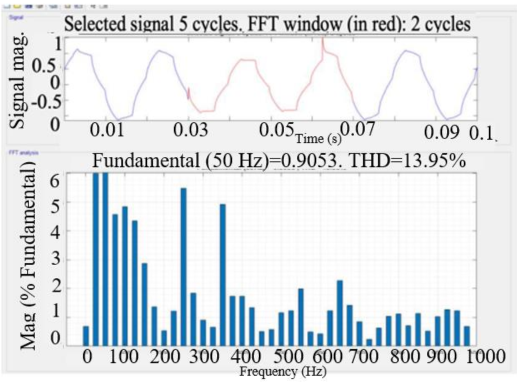
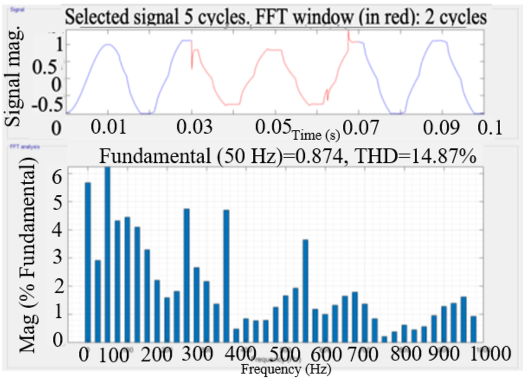


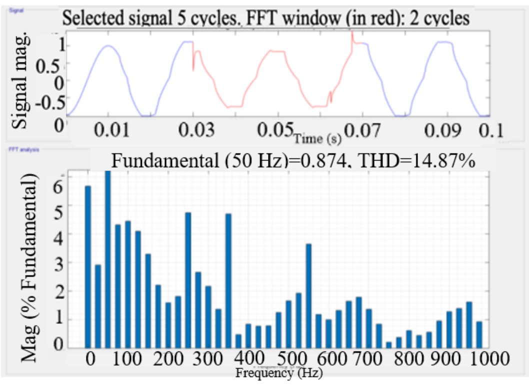
Figure 11. Simulation results of voltage sags after DVR installation using FLC



(a)



(b)

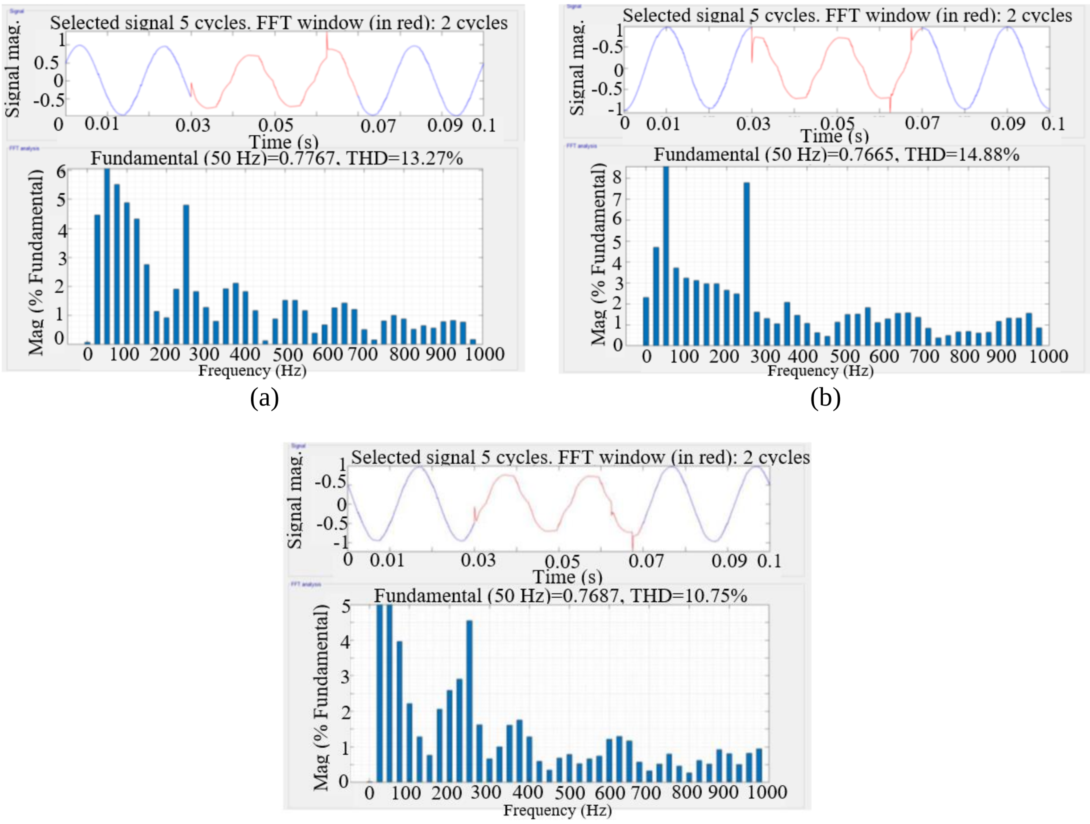


(c)

Figure 12. Voltage surge analysis after DVR compensation using FLC on (a) phase A, (b) phase B, and (c) phase C

4.2. DVR results using BESS

The simulation results of a three-phase short circuit fault with a load condition of 70% and a fault location of 75% as a voltage restorer can be seen in Figure 13. Figure 13 shows the voltage surge analysis before DVR compensation on phase A in Figures 13(a), 13(b) in phase B, and Figure 13(c) in phase C based on the results that have been displayed, the DVR using these two types of devices can compensate for the voltage allowed by the PLN standard. In Table 4, information is shown based on the simulation results.



(a) (b) (c)

Figure 13. Voltage surge analysis after DVR compensation using BESS on (a) phase A, (b) phase B, and (c) phase C

Table 4. DVR results using FLC and BESS

Parameters	Phase	Without DVR	DVR with FLC	DVR with BESS
Voltage (pu)	A	0.3019	0.9053	0.7767
	B	0.2644	0.874	0.7665
	C	0.2477	0.8678	0.7687

5. CONCLUSION

Based on the results and discussion, the following conclusions are obtained: Voltage sags that occur due to a 3-phase short circuit fault based on a load of 70% and a fault location point of 75% cause the smallest voltage drop reaching 0.2477 pu on phase C. Then, the DVR using FLC recovered the voltage due to a 3-phase short circuit at the SB 02 feeder based on a load of 70% and the fault location point being 75%. Based on the simulation results, the greatest FLC voltage sag recovery occurs in phase C, namely 0.6201 pu from 0.2477 pu to 0.8678 pu. Furthermore, the greatest BESS voltage sag recovery occurred in phase C, 0.521 pu from 0.2477 pu to 0.7687 pu. Finally, DVR using FLC improves the quality of voltage recovery compared to BESS because FLC can inject a voltage of 0.0991 pu greater than BESS. This proves that FLC is better than BESS for installation on a DVR.

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BIOGRAPHIES OF AUTHORS

Yulianta Siregar was born July 09, 1978, in Medan, North Sumatera, Indonesia. He did his undergraduate work at University of Sumatera Utara in Medan, North Sumatera, Indonesia. He received a Bachelor of Engineering in 2004. After a while, he worked for a private company. He continued taking a master's program in electrical engineering at the Institut Teknologi Sepuluh Nopember, Surabaya, East Java, Indonesia, from 2007-2009. He was in a Ph.D. program at Kanazawa University, Japan, from 2016-2019. Until now, he lectured at Universitas Sumatera Utara. He can be contacted at email: julianta_srg@usu.ac.id.

Azrial Aziz Azhari Nasution is a fresh graduate of electrical engineering bachelor's degree from Universitas Sumatera Utara in 2023. His research area field study is electrical power system. He can be contacted at email: azrialazhari@gmail.com.

Mai Kai Suan Tial received the B.Sc. degrees in electrical power engineering from Technological University (Keng Tong) Myanmar (2000~2006), M.E degree in electrical power engineering, Technological University (Meikhtila) Myanmar (2007~2009), and the Ph.D. degree in electrical engineering, Kanazawa University, Japan (2014~2017). She has been a professor of electrical power engineering with Ain Shams University, since 2007. Her research interests include high voltage engineering, plasma applications (plasma agriculture, environmental applications), plasma science and engineering. Until now, she lectured at Electrical Power Engineering Department, Yangon Technological University, Yangon, Myanmar. She can be contacted at email: maikaisuantial21@gmail.com.

Naemah Mubarakah received the B.Sc. degrees in electrical power engineering from University of Sumatera Utara, Medan, Indonesia (1998~2004), master's program in electrical engineering at the Institut Teknologi Sepuluh Nopember, Surabaya, East Java, Indonesia, from (2007–2009). She continued taking a PhD Student at Universitas Sumatera Utara, Indonesia (2018–Now). She can be contacted at email: naemah.mubarakah@gmail.com.

Soeharwinto his PhD student in electrical engineering, Universitas Sumatera Utara, Indonesia (Now). Master's in computer networks, Institut Teknologi Bandung (2001). Bachelor's degree in electrical engineering, University of Sumatera Utara, Indonesia (1996). Lecturer in University of Sumatera Utara, Indonesia, since 2000. He can be contacted at email: soeharwinto@usu.ac.id.