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VOLTAGE SAG MITIGATION USING DVR AND DSTATCOM IN POWER SYSTEM NETWORK

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Abstract

A good power quality is crucial to avoid any disruptions or damages to equipment, especially sensitive equipment as most consumers in the industrial sector, utilities, residential, and commercial use a lot of modern technology and devices. The power quality issues that the consumer faced are voltage sag, voltage swell, flickering, fluctuations, and more. This project will focus on voltage sag as it is the most common issue in modern distribution systems. Some causes of these issues are unavoidable, as weather conditions are also one of the factors that contribute to voltage sags. For instance, lightning, storms, heavy rain, and more. Besides equipment failure, consumers could also face an increase in electricity bills, wasted energy, communications interference, and disruption of the whole system. Thus, an effective device or method is needed to mitigate voltage sag. A modelling of Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (DSTATCOM) is done in MATLAB/Simulink to simulate the comparison of effectiveness between two devices. The three-phase test model represents the typical distribution system, incorporating three phase source, step-down transformers, transmission line, and two types of loads, which are inductive load and capacitive load. The simulation is done under three-phase fault, double line-to-ground fault, and single line-to-ground fault. From the analysis of voltage recovery, THD improvement, and power injection, it is proven that DVR is much superior in mitigating voltage sag than DSTATCOM.

Keywords: THD, DVR, DSTATCOM, power injection, voltage sag.

1 INTRODUCTION

In this modern technological era, electrical power has become the main source of electricity for everyday life. However, a few problems arose faced by electrical utilities and consumers. The issues are the presence of voltage harmonic, surge, harmonic wave distortion[1]. These are poor power quality. From the example of problems stated, power quality measures basic electrical parameters like voltage, current and frequency within its specified range.

As technology becomes more advanced daily, most companies or organizations worldwide are facing declining profits. They continue to invest a substantial amount to maintain their electricity systems, especially in technology information services and the process industry. When there is a disturbance occurs, these organizations will face a huge financial loss and sometimes the causes are uncontrollable [2] such as voltage sag or swell that is caused by lightning, storms and heavy rain. This financial loss is not only from maintaining the electricity system but also due to production loss, faulty equipment, loss of important data and more.

The reasons for the existence of problems in power quality are due to the presence of non-linear loads such as furnaces, uninterruptible power supplies (UPSs) , and adjustable speed drives (ASDs). It causes electrical equipment to overheat, which causes the system's voltage to fluctuate [3]. Therefore, electrical isolation is needed to overcome this problem. Among all the issues above, this thesis will be focussing on voltage sag. Voltage sag is a condition where the magnitude of bus voltage reduce to below 0.9 pu of nominal voltage. It can be seen during the half cycle of a power frequency. This can be due to faults like a three-phase fault, double line to ground fault, and single line to ground fault.

It is proposed that the DVR, specifically when implemented with a PI controller, emerges as the most effective method for mitigating voltage sags. This recommendation is substantiated by the DVR's cost-effectiveness, small size, superior performance over STATCOM and SVC, and its ability to handle both balanced and unbalanced faults. The low THD generated by the DVR further reinforces its suitability for enhancing power quality in electrical networks. Further research and experimentation are encouraged to validate and optimize the proposed DVR-PI controller method for widespread application in practical power system scenarios.

2 LITERATURE REVIEW

2.1 Voltage Sag

Voltage sag is a sudden reduction in voltage magnitude (rms value) below 90% of its nominal voltage, and the duration is set 0.5 cycles to 1 min. Sensitive loads frequently trip or shut down when voltage sags occur because of a remote fault in transmission or distribution networks. According to statistics, about 80% of consumers complain as they face losses caused directly by voltage sags [4]. Therefore, it is an urgent matter to control this voltage sag issue.

There are a few causes that lead to voltage sag and the major causes are from the faults in the system, and the starting of large loads. All the other causes include climate conditions, equipment failure of utility companies, bird nesting, and various short-circuit failures, resulting in equipment burnout, which has a negative impact on industrial manufacturing processes and causes sensitive customers to suffer significant financial loss.

2.2 Dynamic Voltage Restorer (DVR)

DVR is one of the most economical solutions to tackle any voltage-related power issue. From Figure 1, it is shown that DVR is mounted in series with the load and an inverter will be connected to the DVR as well. There will be also a battery storage system that is connected to a transformer. This will draw DVR's active energy from a direct current (DC), power sources and introduce its reactive energy into the rest of the system [5]. For voltage stability, DVR injects voltage into the distribution system through the transformer. Additionally, until unexpected network conditions occur, DVR operates in a standby state under typical conditions. The DVR provides the voltage variance across the path while maintaining the original voltage level at the consumer side. To conclude, it will be used to safeguard essential loads by preventing abrupt voltage changes.

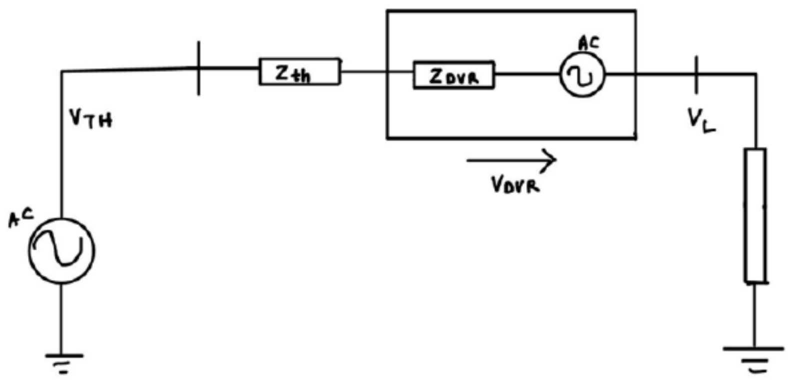

Figure 1 Single Line Diagram of DVR

2.2 Distribution Static Compensator (DSTATCOM)

Distribution Static Compensator (DSTATCOM) is also another custom power device that could be used to mitigate voltage sag. Not only that, it is also used for voltage swell, fluctuation mitigation, reactive power management and elimination of harmonic in the distribution system [6]. As shown in Figure 2, DSTATCOM includes a three-phase inverter module, ac filter, injection transformer and energy storage. DSTATCOM can also be considered as synchronous condenser (compensator) which can regulate the voltage of the bus to which DSTATCOM is connected and supply variable reactive power.

The flow of reactive power is governed by the difference in the magnitude of VSC voltage and AC system voltages, whereas the flow of active power is regulated by the angle between these two voltages. The coupling transformer includes leakage reactance. Through this reactance, phase voltages are aligned with the ac systems [7].

The components description and control unit of DSTATCOM is similar to DVR. The only difference is the connection of the injection transformer. The transformer does not connect in series with the distribution network. Besides, DVR produce voltage injection while DSTATCOM produced injection of shunt current into the system [8]

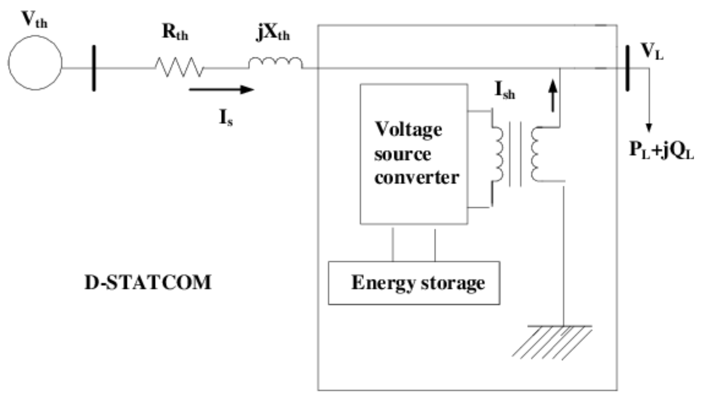

Figure 2 Single Line Diagram of DSTATCOM

Park's Transformation

The dq0 transformation, or Park's transformation, is one of the control techniques used. It stands for direct-quadrature-zero transformation. This method gives the sag depth and phase shift information with start and end times.This method also can reduce the three AC quantities to two DC quantities. The quantities are expressed as the instantaneous space vectors.

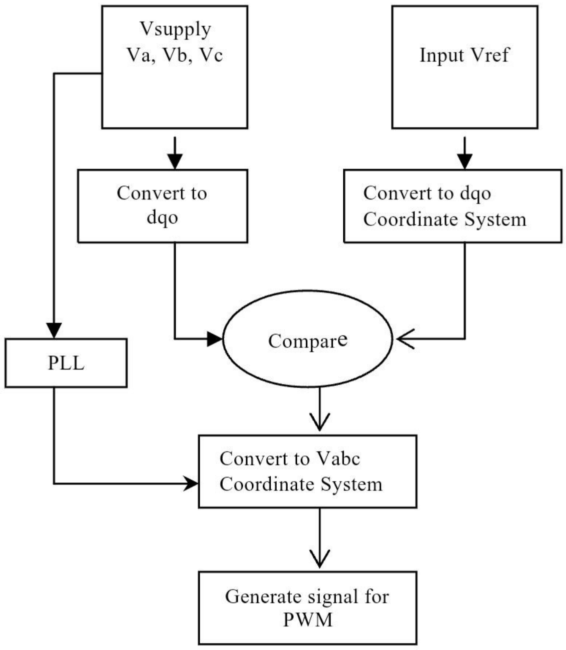

Figure 3: Flow chart of Park's Transformation technique

Figure 3 shows the flow chart of the Park's transformation. The block diagram of the Phase Locked Loop (PLL) is used to generate a unit sinusoidal wave in phase with mains voltage.

PI controller

The Proportional Integral controller has two gain constant, Kp and Ki. Kp is the proportional gain while Ki is the integral gain. From Figure 4, the error signal is obtained by comparing both desired voltage and rms voltage value at the load point. This PI controller is used to process this error signal and then generate the phase angle, δ as the output which then will be sent to the PWM generator.

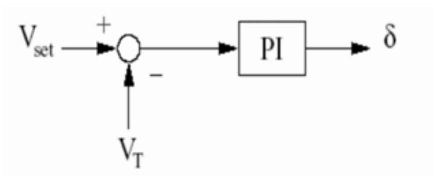

Figure 4 PI controller

2.3 Fuzzy Logic Controller

There are two stages in Fuzzy operation, Fuzzification and Defuzzification [9]. The fundamental operation of FLC is built upon fuzzy control rules that employ the values of fuzzy sets typically for the error, change in error, and control action. Figure 5 shows the operation of fuzzy logic controller.

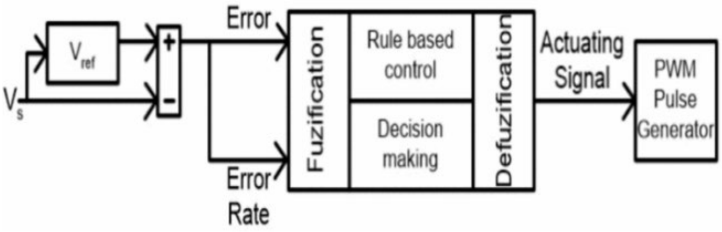

Figure 5: Operation of Fuzzy Controller

Converting the crisp input to a fuzzy value is called Fuzzificaton. Defuzzification is when the result is combined to provide a clear output regulating the output variable. The output results of the FLC is generated using the rules. Table 1 shows 49 rules of FLC [9]. The output is produced by the fuzzy sets and fuzzy-logic operations, evaluated for all the rules. A simple 'if-then' rule is defined as follows: If error is Z and error rate is Z then output is Z.

$$\text{Error} = \text{Vref} - \text{Vs} \quad (1)$$

$$\text{Error rate} = \text{error}(n) - \text{error}(n-1) \quad (2)$$

Table 1 FLC Rules

		ERROR						
CHANGE IN ERROR	**Ce/e**	NB	NM	NS	Z	PS	PM	PB
	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

The efficiency of DVR and DSTATCOM depends on the performance of the control techniques, which involved on switching and inverters. The control strategy is mainly implemented in the following steps:

- Computation of the correcting voltage
- Generation of trigger pulses to the sinusoidal PWM based DC-AC inverter
- Correction of any anomalies in the series voltage injection and termination of the trigger pulses when the event has passed

3 METHODOLOGY

3.1 Simulink Model and Simulations

Figure 6 shows the flow chart of the simulations.

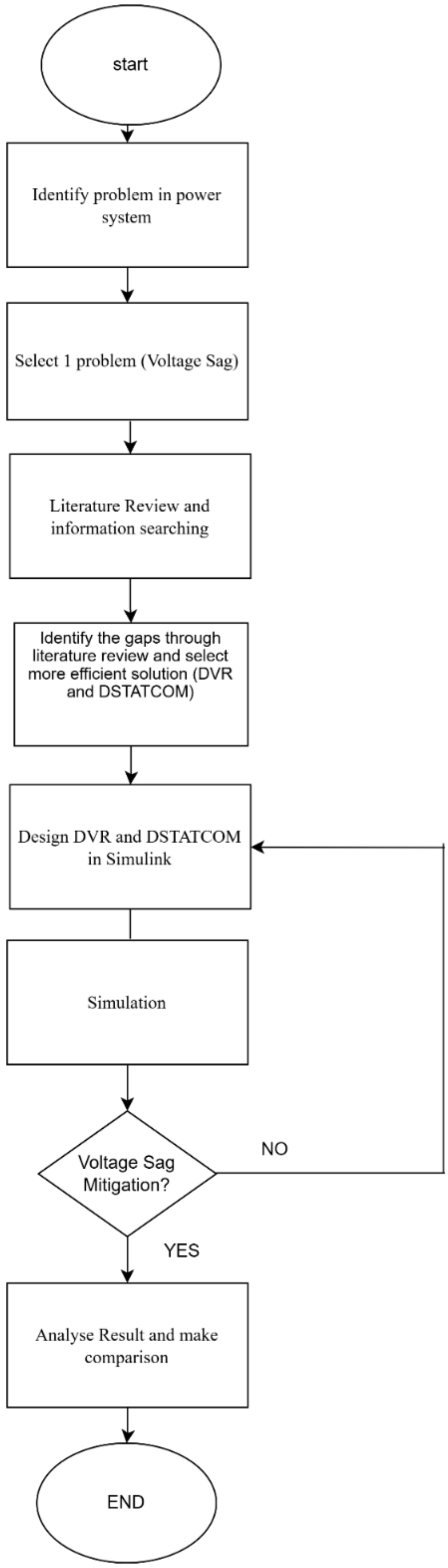

Figure 6: Flow chart of the project

3.1.1 Simulink Model of DVR

The detailed model of DVR is shown in Figure 7 where there is a three-phase transformer connected to the distribution line. The primary part of the transformer is connected to the converter while the secondary part is connected to the supply side. The transformer will inject the missing voltage provided by the DC energy storage. This DVR will be placed at the 400 V side of the distribution transformer to protect the load.

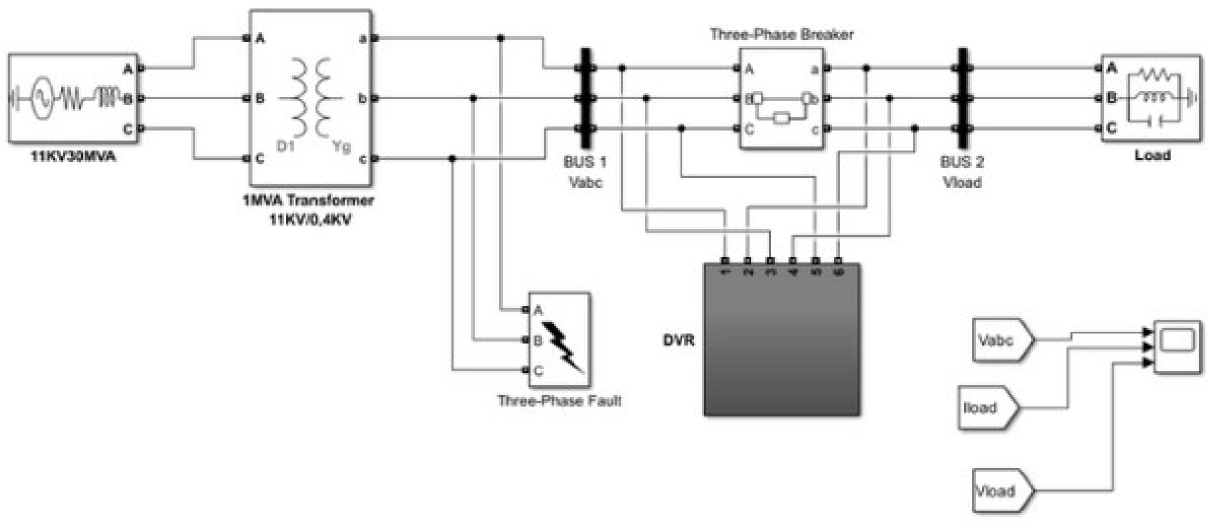

Figure 7 MATLAB Simulink model of a three-phase supply system with proposed DVR design

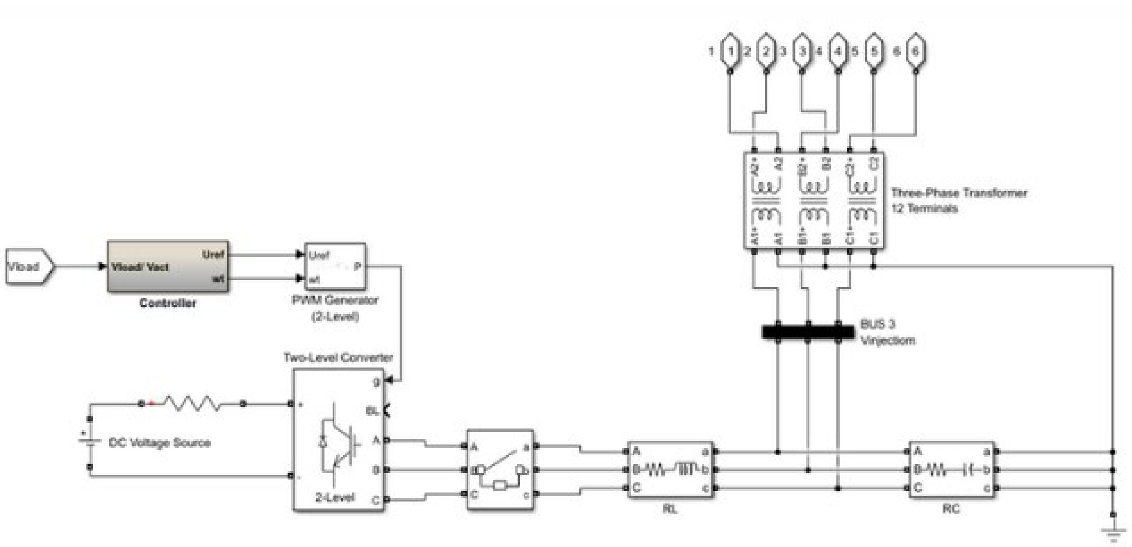

Figure 8 Simulink Model of DVR

The ability of the DVR to compensate for voltage sag depends on the capacity of energy storage or the DC voltage source [10]. Therefore, there are a few values of DC voltage that were tested before finalising it into the power device. This was tested with a single line-to-ground fault for load power rating P=2.5kW and QL=500Var. From the table, it can be concluded that 300V is the best value, which is proven by the PU increment percentage of voltage. Values below 300V are not suitable to choose as they are less capable of mitigating voltage sags, besides the voltage waveforms are not as smooth as those in 300V. This value also applies to DSTATCOM.

Besides energy storage capacity, the filters also play an important role in mitigating the harmonics in the injection current and voltage value. If the harmonic is too high, it will reduce the efficiency of the power device. In this project, an LC filter is used to mitigate harmonics. Theoretically, increasing the L (inductor filter) will increase the ability to eliminate high-frequency harmonics, but there will be a high amplification at the resonant frequency. This high amplification at the resonant frequency can be solved by increasing the C value (capacitive filter) [10].

Table 2 Energy Storage Capability

Vdc	VL before mitigation (pu)	VL after mitigation (pu)	Pu increment (%)
300	0.5727	0.9883	41.56
200	0.5727	0.9736	40.09
180	0.5727	0.9347	36.20
150	0.5727	0.8311	25.84
110	0.5727	0.6668	9.41

Table 3 LC Filter Parameters for DVR

Inductor Filter (mH)	Capacitor Filter (uF)	THD (%)
1	5	12.64
2	10	6.18
3	15	5.04
3	30	4.91
5	20	5.46
7	50	2.13

3.1.2 Simulink Model of DSTATCOM

A DSTATCOM model is added to the three-phase supply system as shown in Figure 9 and the 10detailed model of DSTATCOM is shown in Figure 8. The connection for DSTATCOM is almost similar to DVR. The only difference is DVR is connected in series while DSTATCOM is connected in shunt. The injection transformer and LC filter parameters were changed for the optimization of this power device.

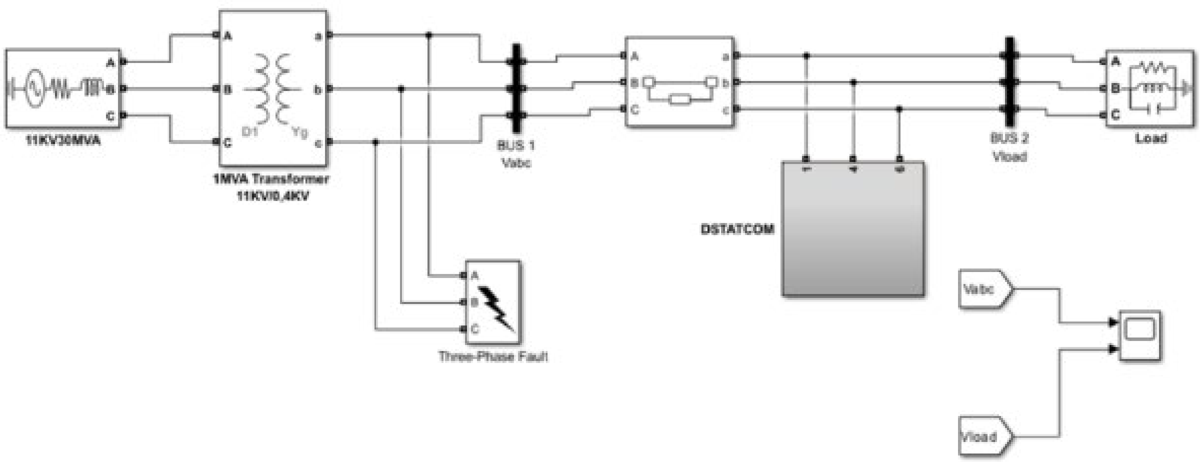

Figure 9 MATLAB Simulink model of three-phase supply system with proposed DSTATCOM design

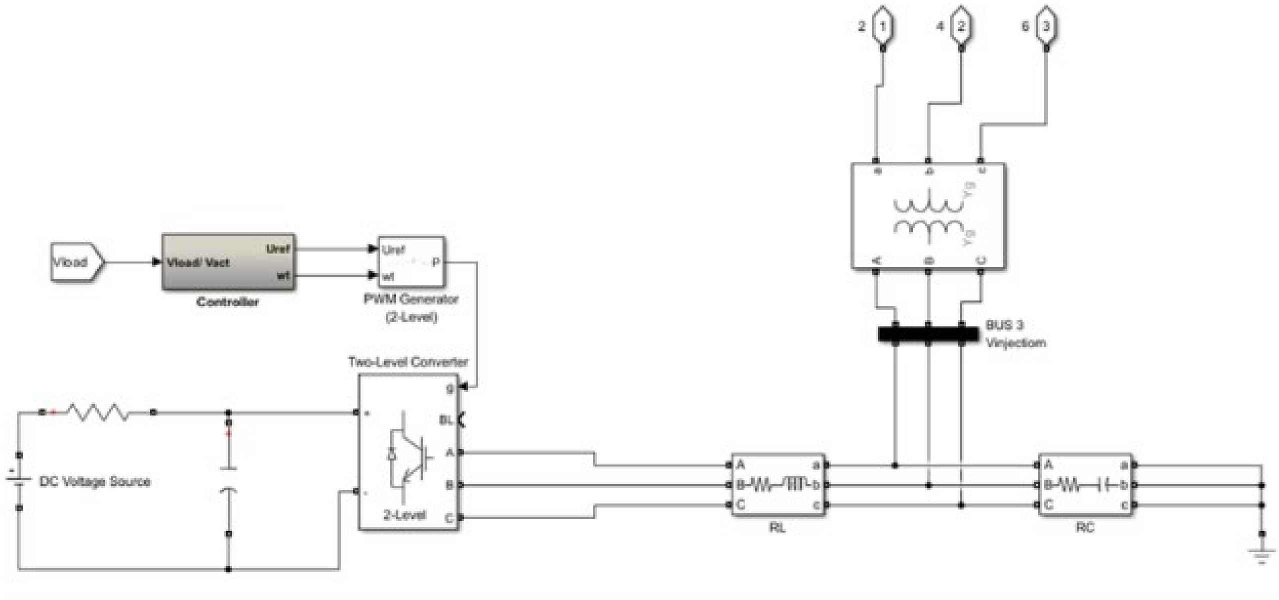

Figure 10 Simulink Model of DSTATOM

A change in the filter parameter is needed to optimize the efficiency of DSTATCOM. From Table 4, it can be seen that using the same filter parameter as DVR is not the best option for the current THD value. Therefore, L = 9mH and C = 50μF is chosen as it proofs the best THD value for this power device.

Table 4 Filter Parameters for DSTATCOM

Inductor Filter (mH)	Capacitor Filter (uF)	THD (%)
4	10	5.41
7	10	4.04
7	30	3.68
7	50	3.61
9	40	3.03
9	50	2.92

3.1.3 Fuzzy Logic Controller

For this project, a fuzzy logic controller (FLC) is used for both power devices. This controller is created by an application in MATLAB which is fuzzy logic designer. Figure 11 shows the setup of FLC in the fuzzy logic designer and Figure 10 shows the subsystem if the FLC. There are 2 inputs, 1 output, and 49 rules. This table of rules was mentioned in section 2.3.

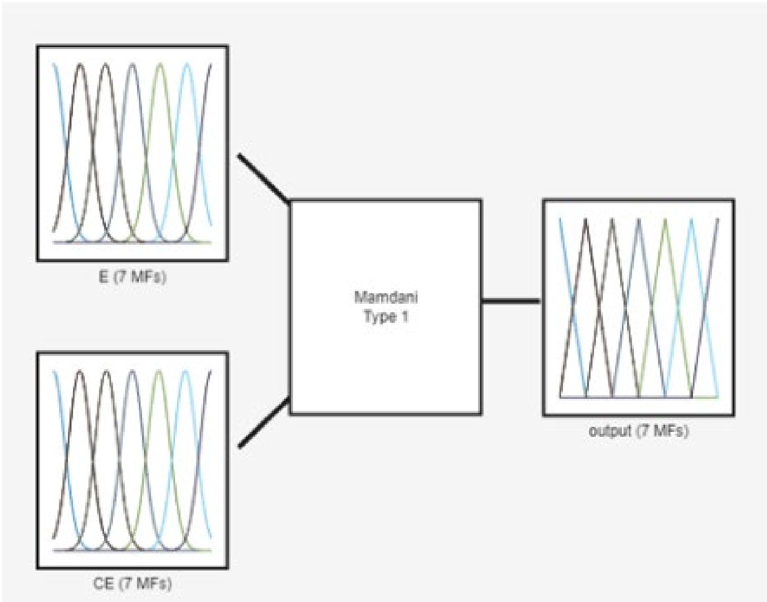

Figure 11 Fuzzy Logic Designer

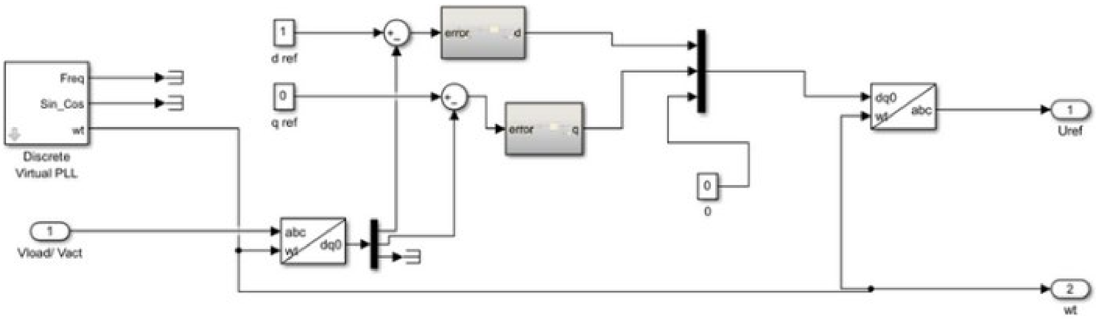

Figure 12 Controller Subsystem of DVR and DSTATCOM

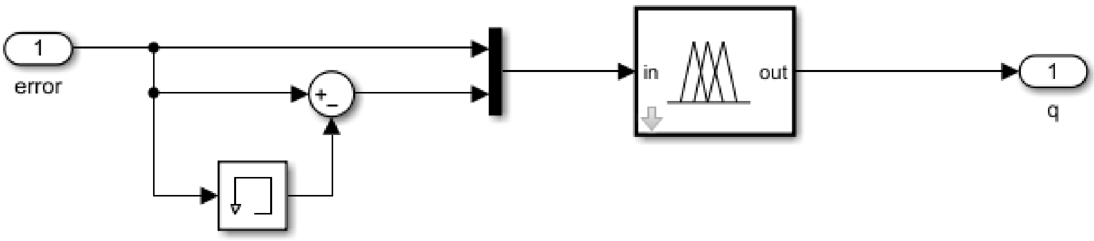

Figure 13 Fuzzy Logic Controller Connection

4 RESULTS AND ANALYSIS

Two cases for each power device are done:

(a) Case 1: RL (inductive load)
(b) Case 2: RC (capacitive load)

For each case, three types of analysis are done. There are load voltage per unit increment analysis, Total Harmonic Distortion (THD) analysis, and injection power analysis.

4.1 Results of DVR

4.1.1 Case 1: RL (inductive load)

Table 5 shows the percentage voltage recovery, which is 46.77%, 30.58%, and 15.01% for its respective faults. According to the table, the results also demonstrate a significant improvement in the load voltage, as it achieves nearly 1 pu in each phase for each fault.

Table 5 Load Voltage mitigation before and after DVR operation for RL load

Types of faults	Load Voltage before mitigation (pu)			Load Voltage after mitigation (pu)			DVR Voltage Recovery (%)
	A	B	C	A	B	C	
Three-phase fault	0.5243	0.5287	0.5315	0.9942	0.9967	0.9969	46.77
Double line-to-ground	0.9485	0.5733	0.5301	0.9912	0.9913	0.9868	30.58
Single line-to-ground	0.9564	1.0000	0.5728	0.9947	0.9965	0.9883	15.01

Total Harmonic Distortion (THD) is also to be analysed to test the ability of DVR to reduce harmonic distortion. Table 6 and Table 7 show the current and voltage THD before and after DVR application for RL load. In the FFT analysis of voltage sag, it can be seen that THD is 47.91%, 55.44%, and 45.01%, which does not comply with the IEEE harmonic standard in a system and it is stated that it needs to achieve THD lower than 5%. However, FFT analysis of compensated load voltage shows an improvement after DVR application as it reduced to 1.41%,1.93%, and 1.51%. Besides, the voltage THD also shows an improvement where it achieves 1.43%, 1.98%, and 1.54% for its respective faults.

Table 6 Current THD before and after voltage mitigation by using DVR for RL load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three-phase fault	47.91	1.41
Double line-to-ground	55.44	1.93
Single line-to-ground	45.01	1.51

Table 7 Voltage THD before and after voltage mitigation by using DVR for RL load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	48.61	1.43
Double line-to-ground	56.44	1.98
Single line-to-ground	45.57	1.54

Table 8 shows the analysis of the power injected by DVR. The results demonstrate that different faults yield different values of injected power. It can be seen that the three-phase fault injects the most power, which is 0.6206+j0.584 kVA, and the single line-to-ground fault injects the least power, which is 0.1798+j0.1503 kVA, into the system. This suggests that DVR is significantly affected by the amplitude of voltage sag. As the voltage sag amplitude increases, the power injected by the DVR also increases.

Table 8: Injection power of DVR for RL load

Types of fault	Injection power (kVA)
Three phase fault	0.6206+j0.584
Double line-to-ground	0.4153+j0.3801
Single line-to-ground	0.1798+j0.1503

4.1.2 Case 2: RC (capacitive load)

The table shows the percentage voltage recovery, which is 46.71%, 30.92%, and 15.27% for its respective faults. According to the table, the results also demonstrate a significant improvement in the load voltage, as it achieves nearly 1 pu in each phase for each fault. It can be seen that THD is 199.40%, 67.89%, and 47.10%, which does not comply with the IEEE harmonic standard in a system and it is stated that it needs to achieve THD lower than 5%. However, FFT analysis of compensated load voltage shows an improvement after DVR application, as it reduced to 2.57%, 3.15%, and 2.44%. Besides, the voltage THD also shows an improvement where it achieves 0.71%, 0.79%, and 0.62% for its respective faults.

Table 9 Load Voltage mitigation before and after DVR operation for RC load

Types of faults	Load Voltage before mitigation (pu)			Load Voltage after mitigation (pu)			DVR efficiency (%)
	A	B	C	A	B	C	
Three-phase fault	0.5245	0.5289	0.5318	0.9954	0.9953	0.9959	46.71
Double line-to-ground	0.9573	0.5735	0.5303	1.0000	0.9936	0.9950	30.92
Single line-to-ground	0.9571	1.0000	0.5730	0.9981	1.0000	0.9902	15.27

Table 10 Current THD before and after DVR application for RC Load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	199.40	2.57
Double line-to-ground	67.89	3.15
Single line-to-ground	47.10	2.44

Table 11 Voltage THD before and after DVR application for RC Load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	48.60	0.71
Double line-to-ground	56.40	0.79
Single line-to-ground	45.56	0.62

Table 12 shows the analysis of the power injected by the DVR. The results demonstrate that different faults give different values of power injected. It can be seen that the three-phase fault injects the most power, which is 0.8159+j0.2939 kVA, and the single line-to-ground fault injects the least power, which is 0.2393+j0.5807 kVA, into the system. This suggests that DVR is significantly affected by the amplitude of voltage sag. As the voltage sag amplitude increases, the power injected by the DVR also increases.

Table 12 Injection power of DVR for RC load

Types of fault	Injection power (kVA)
Three phase fault	0.8159+j0.2939
Double line-to-ground	0.5469+j0.1812
Single line-to-ground	0.2393+j0.5807

4.2 Results of DSTATCOM

4.2.1 Case 1: RL (inductive load)

All these waveforms were tested with the same value of load, which is P=2.5kW and Q_L=500Var. The results of pu voltage for each waveform and fault were recorded in Table 13. The table also shows the percentage voltage recovery, which is 45.35%, 29.49%, and 13.85% for its respective faults. According to the table, the results also demonstrate a significant improvement in the load voltage, as it achieves nearly 1 pu in each phase for each fault.

Table 13 Load Voltage mitigation before and after DSTATCOM operation for RL load

Types of faults	Load Voltage before mitigation (pu)			Load Voltage after mitigation (pu)			DSTATCOM efficiency (%)
	A	B	C	A	B	C	
Three-phase fault	0.5244	0.5287	0.5316	0.9810	0.9820	0.9821	45.35
Double line-to-ground	0.9569	0.5734	0.5302	0.9810	0.9820	0.9821	29.49
Single line-to-ground	0.9566	0.9998	0.5731	0.9810	0.9820	0.9821	13.85

Total Harmonic Distortion (THD) is also to be analysed to test the ability of DSTATCOM to reduce harmonic distortion. In the FFT analysis of voltage sag in Table 14 it can be seen that THD is 47.91%, 55.44%, and 45.01%, which does not comply with the IEEE harmonic standard in a system and it is stated that it needs to achieve THD lower than 5%. However, FFT analysis of compensated load voltage shows an improvement after DVR application as it reduced to 2.02%, 1.92%, and 2.08%. Besides, the voltage THD also shows an improvement, where it achieves 2.02%, 1.80%, and 2.11% for its respective fault.

Table 14 Current THD before and after DSTATCOM application for RL Load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	47.91	2.02
Double line-to-ground	55.44	1.92
Single line-to-ground	45.01	2.08

Table 15 Voltage THD before and after DSTATCOM application for RL Load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	48.60	2.02
Double line-to-ground	56.39	1.80
Single line-to-ground	45.55	2.11

The injected voltage does not really change based on voltage sag amplitude. At Every fault, DSTATCOM injects about 1.491+j1.811 kVA to the load.

Table 16 Injected Power after DSTATCOM application for RL Load

Types of fault	Injection power (kVA)
Three phase fault	1.491+j1.811
Double line-to-ground	1.491+j1.811
Single line-to-ground	1.492+j1.182

4.2.2 Case 2: RC (capacitive load)

The results of pu voltage for each waveform and fault were recorded in Table 17. The table also shows the percentage voltage recovery, which is 48.10%, 32.18%, and 16.57% for its respective faults. According to the table, the results also demonstrate a slight overvoltage due to capacitive VAR surplus.

Table 17 Load Voltage mitigation before and after DSTATCOM operation for RC load

Types of faults	Load Voltage before mitigation (pu)			Load Voltage after mitigation (pu)			DSTATCOM efficiency (%)
	A	B	C	A	B	C	
Three-phase fault	0.5250	0.5293	0.5296	1.008	1.010	1.009	48.10
Double line-to-ground	0.9570	0.5740	0.5306	1.008	1.010	1.009	32.18
Single line-to-ground	0.9566	0.9998	0.5736	1.008	1.010	1.009	16.57

In the FFT analysis of voltage sag in Table 18 it can be seen that THD is 199.40%, 187.91%, and

161.12%, which does not comply with the IEEE harmonic standard in a system and it is stated that it needs to achieve THD lower than 5%. However, FFT analysis of compensated load voltage shows an improvement after DVR application as it reduced to 3.61%, 3.89%, and 3.80%. Besides, the voltage THD also shows an improvement, where it achieves 1.76%, 1.58%, and 1.69% for its respective faults.

Table 18 Current THD before and after DSTATCOM application for RC Load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	199.40	3.61
Double line-to-ground	187.91	3.89
Single line-to-ground	161.12	3.80

Table 20 shows the analysis of the power injected by DSTATCOM. By comparing the results shown below, the injected voltage does not really change based on voltage sag amplitude. At every fault, DSTATCOM injects about 1.548-j0.4596 kVA to the load. The negative sign indicates that DSTATCOM is absorbing reactive power from the bus.

Table 19 Voltage THD before and after DSTATCOM application for RL Load

Types of fault	THD before mitigation (%)	THD after mitigation (%)
Three phase fault	48.55	1.76
Double line-to-ground	56.32	1.58
Single line-to-ground	45.51	1.69

Table 20 Injected Power after DSTATCOM application for RC Load

Types of fault	Injection power (kVA)
Three phase fault	1.548-j0.4596
Double line-to-ground	1.544-j0.4585
Single line-to-ground	1.545-j.04543

5 CONCLUSION

Voltage sags caused by various fault conditions,including three-phase faults, double line-to-ground (DLG) faults, and single line-to-ground (SLG) faults, were successfully mitigated through the application of Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (DSTATCOM). The performance of both devices was evaluated under two different load conditions: a inductive load (RL) and a capacitive load (RC). All simulations were successfully developed and implemented using MATLAB/Simulink.

Based on the results, it can be concluded that the DVR demonstrates superior performance in mitigating voltage sags compared to the DSTATCOM. This is particularly evident in the voltage recovery percentage, where DVR consistently exhibits higher values across all fault scenarios and load types. One key factor influencing the DVR's performance is the amplitude of the voltage sag. As the sag amplitude increases, the DVR injects a correspondingly greater amount of power to restore voltage levels. This behavior indicates a direct relationship between sag depth and DVR power injection.

In contrast, the DSTATCOM's power injection is less sensitive to the fault type or sag amplitude. However, its behavior varies depending on the nature of the connected load. For RL loads, the DSTATCOM typically injects reactive power to support the voltage. For RC loads, the DSTATCOM may operate in inductive mode, absorbing excess reactive power from the system. This is reflected in the simulation results, where negative reactive power (VARs) values are observed, indicating absorption of VARs to prevent overvoltage due to the capacitive nature of the load. Although it is not fully achieved in all cases, the post-mitigation voltages remained within acceptable limits, adhering to the IEEE standard nominal voltage range, which is typically 1.0 ± 0.05 p.u. Furthermore, both DVR and DSTATCOM were effective in reducing harmonic distortion in the system. This is largely attributed to the effectiveness of LC filters in the system. Both voltage and current THD, maintain levels below 5%, in compliance with IEEE 519 standards.

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