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Voltage Sag and Swell Mitigation Using Dynamic Voltage Restorer in Grid Connected PV System

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Abstract

Three transformers and twelve feeders make up the Mandalay Zone (2) substation in Pyigyitagon Township. The industrial load feeder is load feeder B, which has a 45 MVA and 132/11 KV capacity. Other feeders include A, B, C, D, E, F and the Awarat/55 feeders. A number of faults in the industrial load feeder B may result in different voltage sags. The load feeder B can meet voltage swell when the sudden load decrease, fault clearance, capacitor starting, unbalanced loads, lightning strikes, grid overvoltage, etc., appear. A dynamic voltage restorer (DVR) is connected in series between the source and protected load feeder B in order to compensate for voltage sag and swell in the suggested system. The DVR's design is taken into account for a 0.5 sag in voltage. The compensation voltage is produced by the DVR's voltage source inverter and sent into the grid via the injection transformer after the DVR first detects voltage sag and swell. To return it to normal, the DVR absorbs excess voltage during a swell or injects the missing voltage during a sag. The synchronous reference frame theory is used for the control of DVR. The load voltage is approximately 9.02 kV after all feeders and faults have been compensated for, and the rated values have been restored. For every feeder and all faults, the THD% on the voltage of the faulted phase A is less than 5%. After compensation, the THD% for the remaining phases is approximately 5%. Likewise, the THD% on current is less than 5% for every phase and all faults. The DVR can only make up for for grid side voltage sag brought on by different faults. During faults, the solar plant's AC power output dropped.

A. Introduction

Photovoltaic (PV) systems' growing integration into contemporary power networks has completely changed the energy landscape by encouraging sustainable energy production and lowering dependency on fossil fuels. But there are drawbacks to PV system integration as well, especially when it comes to protecting grid stability and electricity quality. One of the most common power quality problems is voltage sags and swells, which are frequently caused by grid faults. These disruptions have the potential to damage delicate equipment, lower electrical system efficiency, and risk power delivery reliability.

Because of the integration of sensitive loads and the manufacturing industry's rapid advancements, power quality has become more and more important. The safety and reliability of voltage and current in relation to frequency fluctuations is referred to as power quality. Power quality problems can affect the distribution network and cause sensitive equipment to malfunction or fail. These problems can be divided into waveform distortions, voltage imbalances, crossover disturbances, flickers, short-term voltage variations, and long-distance voltage fluctuations [2].

Dynamic Voltage Restorers (DVRs) have emerged as a reliable and efficient solution for mitigating voltage sags and swells in grid-connected systems. A DVR is a custom power device that operates by injecting a compensating voltage in series with the grid during disturbances, restoring voltage levels to their nominal values. Its fast response time and ability to adapt to varying fault conditions make it particularly well-suited for addressing voltage issues in grids with high PV penetration[5].

This study focuses on the design and simulation of a DVR for mitigating voltage sags and swells caused by faults in grid connected PV systems[6]. Using MATLAB/Simulink, the performance of the DVR is evaluated under various fault scenarios and operating conditions to assess its effectiveness in improving power quality. The study aims to demonstrate the DVR's capability to maintain stable voltage levels, reduce harmonic distortions, and ensure the reliable operation of PV integrated distribution networks.

B. Research Method

Case Study

The Pyigyitagon Township substation in Mandalay's Industrial Zone (2) consists of twelve feeders and three transformers. It receives power from the 33 kV Shwesaryan transmission line and the 132 kV transmission line connecting Belin and Aungpinlae.

The installed transformer capacities are as follows: 132 kV/11 kV, 45 MVA; 132 kV/11 kV, 18 MVA; and 33 kV/11 kV, 20 MVA.The 20 MVA transformer supplies power to three feeders: Yawmingyi, Macra, and Kanaung. The 18 MVA, 132/11 kV transformer serves Feeder G and Feeder H. The 45 MVA, 132/11 kV transformer is connected to seven feeders. Feeder A, B, C, and D are supplied from main 1, while Feeder E, F, and 55/Awarat are connected to main 2. Additionally, a solar power plant is connected to Feeder B, which supplies industrial factories. 5MW PV system is integrated to grid from Puigyitagon Township substation. So the data of feeders from 132/11 kV, 45 MVA are shown in Table 1.

Table 1. Data of Substation

No	Feeder	P (M)	S(MVA)	Power factor	Voltage,p.u	Current (p.u)	Q,MVAR
1	Feeder A	6.3	7.411	0.85	0.958	0.07	3.904
2	Feeder B	5	5.88	0.85	0.945	0.055	3.1
3	Feeder C	5.5	6.47	0.85	0.949	0.056	3.41
4	Feeder D	4.8	5.647	0.85	0.943	0.053	2.974
5	Feeder E	5.6	6.588	0.85	0.941	0.06	3.5
6	Feeder F	2.5	2.941	0.85	0.976	0.028	1.5
7	Feeder55/Awarat	3.3	3.882	0.85	0.977	0.0348	2.041

Solar Module Specification and Characteristic Curves

Table 2. PV Module Datasheet

No	Specification	*Parameters*
1	Module	1Soltech 1STH 215-P
2	Maximum Power	213.15 V
3	Open Circuit Voltage	36.3 V
4	Voltage at maximun power point(Vmp)	29 V
5	Temperature coefficient of VOC (%/deg.C)	-0.36099
6	Cell per module (Ncell)	60
7	Short circuit current Isc(A)	7.84 A
8	Current at Maximun Power point Imp(A)	7.35 A
9	Temperature coefficient of Isc (%/deg.C)	0.102
10	Parallel String	235
11	Series connected module per string	100
12	Grid connected PV system	5 MW

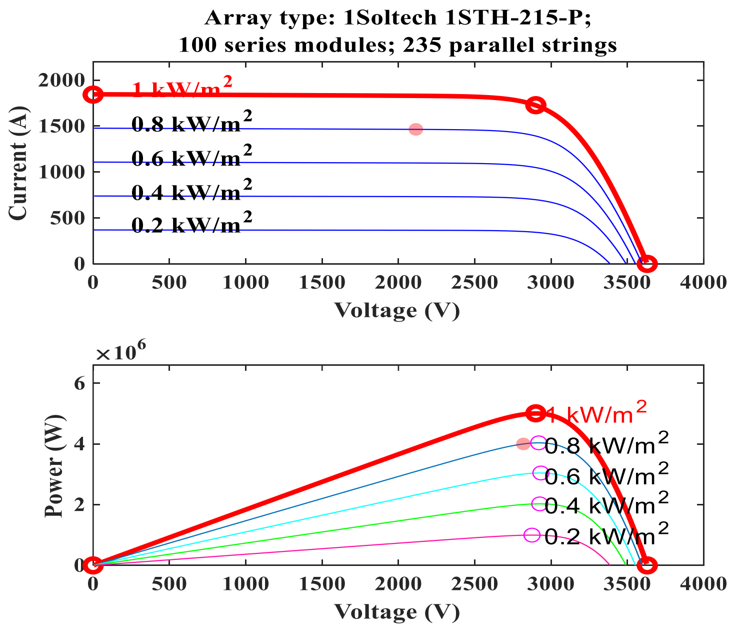


Figure 1. I-V and P-V characteristics at constant temperature 25 °C and Various Irradiance

The solar module specifications shown in Table 2 are used to build the 5 Mw solar power plant. The solar array is contracted with a number of 235 parallel strings and a number of 100 module series for a 5 MW solar plant. The more parallel strings, the more current can be produced. By series connection, the more voltage can get. The output power of the solar power plant depends on the number of series and parallel modules, the amount of irradiance, and the temperature [3].

In solar arrays, several series strings can be connected in parallel to combine both the increased voltage from series and increased current from parallel connections, optimizing the total power output. Figure shows I-V and P-V characteristics at constant temperature 25 °C and various irradiances. The output current is directly proportional to irradiance. The higher the irradiance level, the more current it produces. The large power can be produced at the higher irradiance level [3].

More power is produced at the lowest temperature with constant irradiation than at the highest power with constant irradiance. In array, the lowest cell temperature can result in the highest voltage, while in array, the highest temperature can result in the lowest voltage.

Modelling Grid Connected PV system

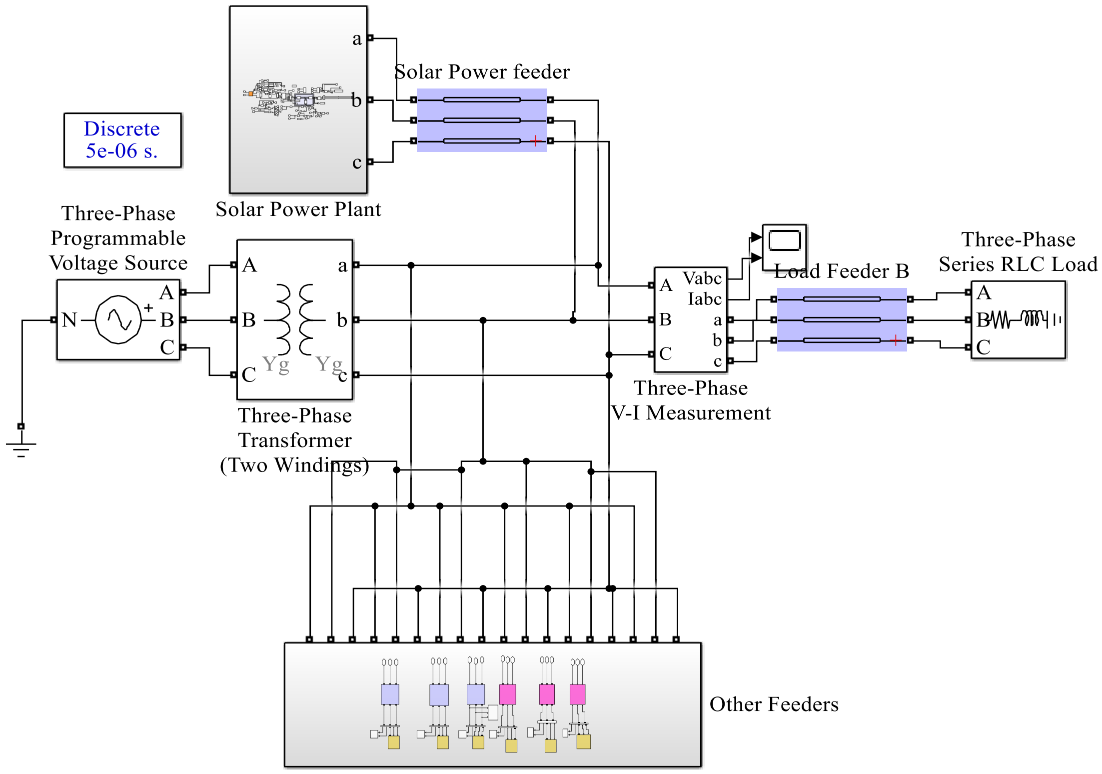


Figure 2. Grid Connected PV System without DVR

In Normal condition of grid connected PV system, the solar power plant generate the power according to the irradiance level. At 1000W/m^2 condition, the generated power from the solar power plant is 5 MW.The irradiance level is directly proportional to the current and also the power.Integration power to the grid with the various irradiance level, the load voltage and current are normal condition in proposed system. There is no voltage sag and voltage swell.The THD% on load voltage and current are less than 5 %.But there are various voltage sag due to faults on the other feeders in grid connected PV system.

Occurrence of Voltage Sag in Proposed Grid Connected PV System

The normal rated load voltage is 11 kV in line to line.The output voltage waveform values are peak values (15.556 kV). The voltage values in Table 4 are peak phase voltage.The peak phase voltage in normal is 8.981 kV.There are seven feeders of substation with grid connected PV system. The faults are single line to ground faults (SLG), double line to ground faults (2LG), line to line faults (LL), three phase line to line fault (LLL), and three phase line to ground (LLLG) faults. LLL and LLLG faults are balanced faults, and the other faults are unbalanced faults.

The voltage sag due to faults on feeder A is 0.8 for SlG faults, 0.74 for 2LG faults, 0.8 for LL faults, and 0.7 for LLL and LLLG faults. The voltage sags due to unbalanced faults on the feeder C are 0.74 for SLG faults, 0.82 for 2LG faults, and 0.86 voltage sags for LL faults. There are 0.84 voltage sags for SLG faults, 0.8 voltage sags for 2LG faults, and 0.83 voltage sags for LL on the feeder D. The voltage sags due to LLL and LLLG faults are equal values on the feeders C, D, and E. This voltage sag value is 0.72. And the voltage sag for feeder F and feeder Awarat/55 due to balanced faults is 0.75 and 0.74 for balanced faults. The voltage sag due to unbalanced faults is 0.85 for SLG, 0.82 for 2LG faults, and 0.84 for LL faults. The voltage sag due to SLG faults on the feeder F and the feeder Awarat/55 is 0.8 and the voltage sag is 0.75 for 2LG faults.The voltage sag due to LL faults for both feeders is 0.79 and 0.82[1].

Mathmatical Model of DVR injected Voltage

The design of dynamic voltage restorer studied for the feeder B with load 5 MW, power factor 0.85 in the substation. The series impedance line is(1.7735+j2.0945). The load current of feeder B in substation is 308.619 A. The injected voltage of dynamic voltage restorer is calculated using the Equation 1[7].

$$V_{DVR} = V_L + Z_S I_L - V_S \quad (1)$$

Where; V_{DVR} =injected voltage

V_L =load voltage

Z_S =line impedance

I_L =load current

V_S =maximun sag value

The rating of dynamic voltage restorer is found in Equation 2

$$S_{DVR} = \sqrt{3} \times V_{DVR} \times I_L \quad (2)$$

The Load current of feeder B in the substation also can calculate

$$I_L = \frac{S}{\sqrt{3} \times V_L} \quad (3)$$

To compensate voltage for sensitive load in feeder B and the DC supply is solved using the Equation 4

$$V_{DC} = \frac{3\times\sqrt{3}}{\pi} \times V_S \quad (4)$$

The load voltage feeder B in the substation regulate to be stable on real time operation .The DVR design with 50 % voltage sag is chosen to compensate any voltage sag and voltage swell occuring in grid connected PV system.The selected design parameters and rating are shown in Table 3.

Table 3. Selected DVR Design Values

No	Parameters	Rating
1	$S_{DVR,}$ (Injection Transformer)	2.134 MVA
2	Turn ratio	2.755
3	Filter capacitor	6 µF
4	Interfacing inductor	3.6 mH
5	DC bus Capacitance	30 µF
6	DC source Voltage	20 kV

Control strategy of DVR

Measure the grid voltage and compare it with the reference voltage to identify disturbances such as sags, swells, or harmonics. Use dq transformation or similar methods to detect and analyze these issues. Based on the identified disturbance, generate the required compensating voltage waveform. Apply PWM techniques to create precise inverter switching signals, ensuring accurate voltage injection. Inject the compensating voltage through the coupling transformer to stabilize the load-side voltage. Continuously monitor the system's performance and make adjustments as needed to maintain stability and improve power quality[6].

C. Result and Discussion

Mitigation of voltage Sag and swell From Power Supply

Transformer tap changes, switching of capacitor bank can cause voltage swell. Various faults, large motor starting and rapid load chanes, and intermittance renewable energy sources can cause voltage sags. 0.7 voltage sag and 1.4 voltage swell are considered from the voltage supply. Various voltage sag from supply and 1.4, 1.6 voltage swell are shown in Table II.

The higher the injected voltage, the smaller the voltage sag. Under normal circumstances, the load voltage at the common couple point is 9.01 kV, and the current values are almost equal (432.2 A). With varying voltage sag, the source terminal voltage sag varies in magnitude. The higher the voltage sag, the lower the magnitude sag values. The injected voltage and voltage are the same values for balanced sag. The design of DVR is considered for a 0.5 voltage sag to restore the rated values. It is a convenience other magnitude of voltage sag. This proposed DVR design can be conducted to produce and channel the required voltage to restore the rated load voltage. The output voltage waveform of voltage sag and swell is shown in Figs 3 and 4. The voltage sag duration is 0.1s to 0.15s.

Table 4. Load Voltage before and after compensation and injected voltage with various sag and swell

Voltage sag and swell	Before without DVR			After With DVR			Injected Voltage		
	A(kV)	B(kV)	C(kV)	A(kV)	B(kV)	C(kV)	A(kV)	B(kV)	C(kV)
0.8	6.863	6.863	6.849	9.05	9.08	9.05	2.361	2.378	2.379
0.7	5.97	5.962	5.963	9.09	9.09	9.01	3.212	3.188	3.197
0.6	5.044	5.047	5.099	9.03	9.03	9.05	4.05	4.046	4.027
0.5	4.179	4.217	4.144	8.98	9	8.99	4.912	4.9	4.9
0.4	3.321	3.32	3.242	8.964	8.932	8.924	5.717	5.664	5.71
0.3	2.828	2.406	2.28	8.855	8.859	8.869	6.572	6.61	6.69
0.2	1.985	1.795	1.93	8.897	8.844	8.845	7.433	7.49	7.189
1.4	12.01	12.02	12.02	9.276	9.269	9.29	2.973	2.954	2.983
1.6	13.66	13.68	13.67	9.231	9.248	9.274	4.644	4.645	4.649

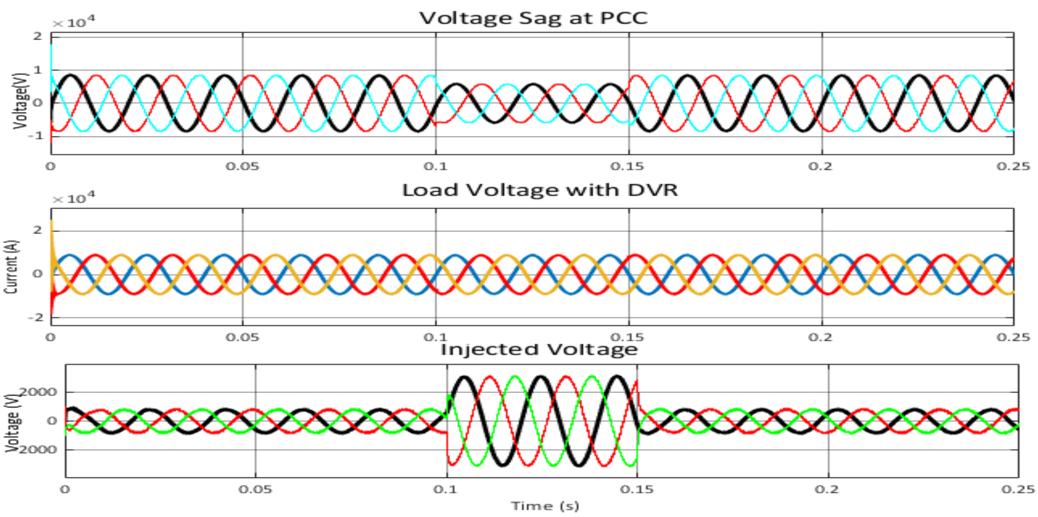


Figure 3. Voltage Sag Mitigation with DVR

The magnitude of voltage sag for 0.7 voltage sag is 5.96 kV for DVR installation. After DVR installation, the load voltage is 9.01 kV, restoring the injected voltage values to almost 3.212 kV for all phases. The magnitude of the injected voltage for 0.7 voltage sag is about 3.2kV.

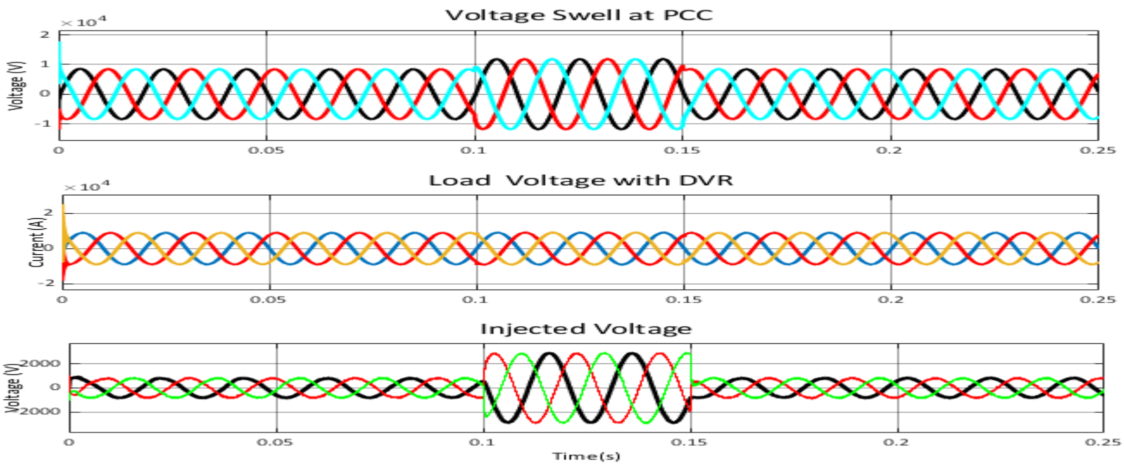


Figure4. Voltage Swell Mitigation with DVR

Similarlly, the voltage swell is 1.4. The magnitude of voltage swell became 12.02 kV overrated voltage. So, the DVR absorbs the injected voltage (around 2.973 kV).

Mitigation of Voltage Sag due to Faults on other Feeders

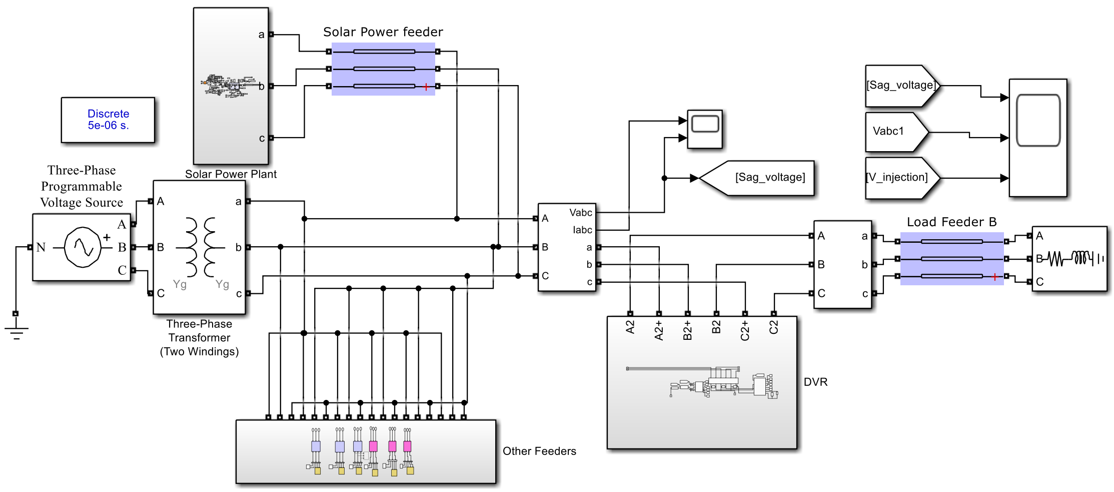


Figure5. Grid Connected PV System with DVR

Mitigation of voltage sag due to various faults on grid connected PV system are shown in Fig.5 by Matlab Simulink Model.It gives voltage sag at PCC, injected voltage and load voltage with DVR.Matlab Simulink Model consist of three phase power supply, solar power plant, DVR, other load feeders and sensitive load feeder B to protect.

The Table 5 shows the voltage sag due to various faults on the other feeders such as A, C, D, E, F and Awarat/55 feeder.These values are the peak phase voltage values.

Table 5. Voltage Sag Magnitude due toVarious Faults on the other Feeders

No	Feeder Name	SLG			2DLG			LL			LLL and LLLG		
		A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)
1	Feeder A	7.07	8.51	8.44	6.61	6.77	8.45	6.94	7.27	8.61	6.43	6.5	6.5
2	Feeder C	6.61	8.29	10.4	7.33	7.37	8.44	7.48	7.75	8.59	7.18	7.2	7.2
3	Feeder D	7.5	8.55	8.47	7.34	7.36	8.44	7.48	7.74	8.59	7.19	7.2	7.2
4	Feeder E	7.17	8.6	8.6	7.36	7.4	8.34	7.52	7.66	8.52	7.22	7.2	7.3
5	Feeder F	7.26	8.57	8.46	6.79	6.95	8.46	7.13	7.42	8.58	6.67	6.2	6.7
6	Feeder Awarat/ 55	7.24	8.56	8.5	6.86	6.93	8.46	7.11	7.4	8.59	6.65	6.6	6.7

The injected voltages from the dynanic voltage restorer are absorbed or generated to restore the rated voltage. These are shown in Table 6. The injected voltages for each phase are different.The higher the voltage sag, the injcted voltage is more. The compensation of output waveforms for voltage sag due to faults on the feeder A and the feeder D are only generated among the feeders in the substation by the Matlab Simulink Model shown in Fig.5.

Table 6. Injected Voltage with Phase from DVR at Various Faults

Feeder name	Fault Type											
	SLG			2LG			LL			LLL and LLLG		
	Injected Voltage			Injected Voltage			Injected Voltage			Injected Voltage		
	A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)
Feeder A	1.36	0.87	1	2.72	2.06	1.03	2.63	2.03	0.87	2.72	2.7	2.68
Feeder C	1.34	0.86	1	2.07	1.50	1.05	1.04	1.49	0.89	2.04	2	2.0
Feeder D	1.35	0.83	1	2.08	1.53	1.04	2.05	1.50	0.88	2.05	2.0	2.01
Feeder E	1.34	0.86	1.	2.05	1.50	1.04	2.02	1.47	0.89	1.99	2	1.99
Feeder F	1.30	0.87	1	2.49	1.91	1.01	2.47	1.88	0.85	2.51	2.5	2.46
Feeder Awarat / 55	1.28	0.87	1	2.51	1.96	1.03	2.48	1.88	0.85	2.53	2.5	2.49

Mitigation of Voltage Sag due to Various Faults on Load Feeder A

When the unbalanced faults and balanced faults on the feeder A occur, the maximum voltage sag is 7.073 kV and the injected voltage is 1.36 kV for SLG faults. In 2LG faults, the maximum sag values are 6.612 kV at phase A and 6.765 at phase B, and the injected voltages are 2.72 kV and 2.06 kV, respectively. And for LL faults, the maximum sag values are 6.972 kV at phase A and 7.27 kV at phase B. The injected voltages to restore the rated voltage are 2.63 kV and 2.03 kV.

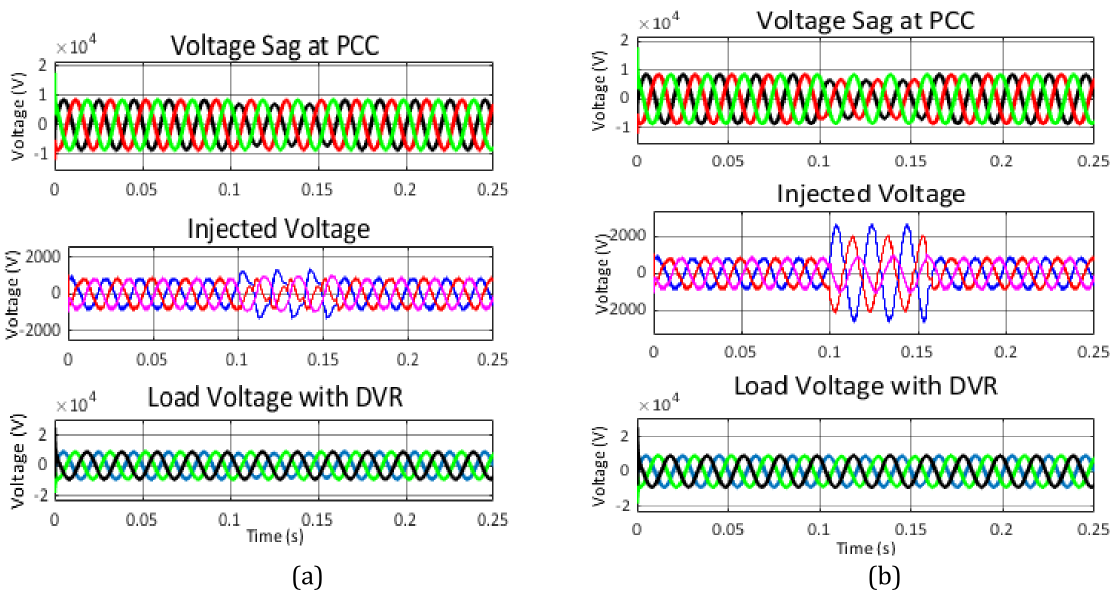


Figure 6. Compensation of Voltage Sag due to (a) SLG Faults and (b) 2LG Faults on the Feeder A

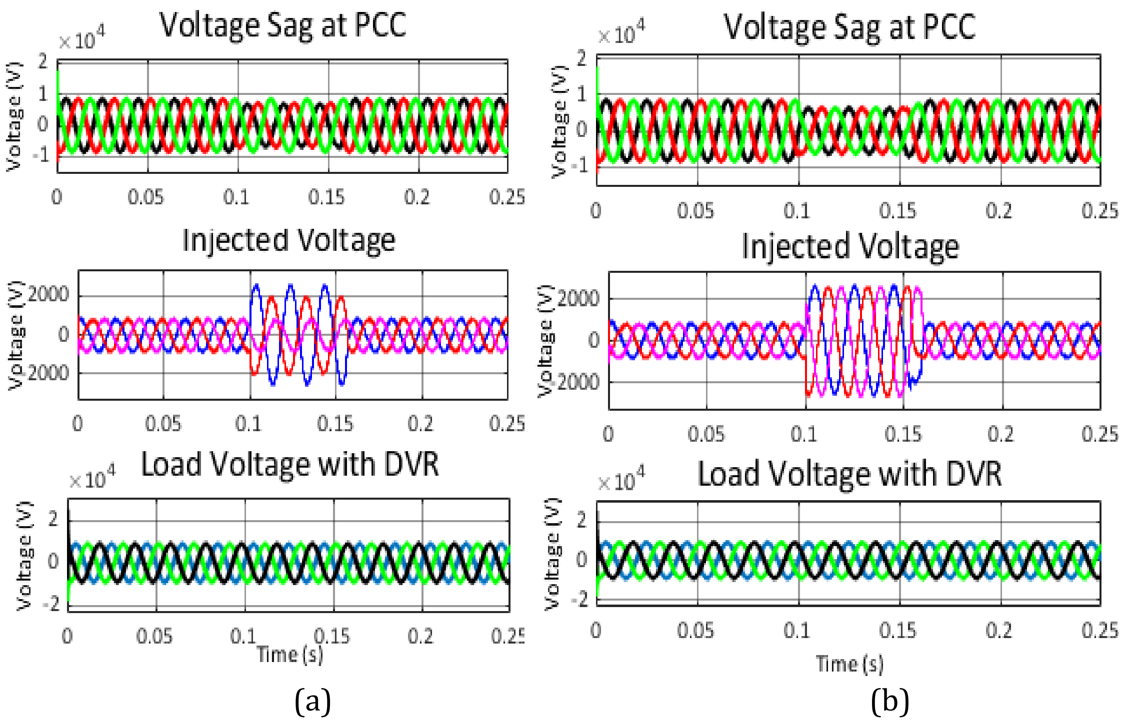
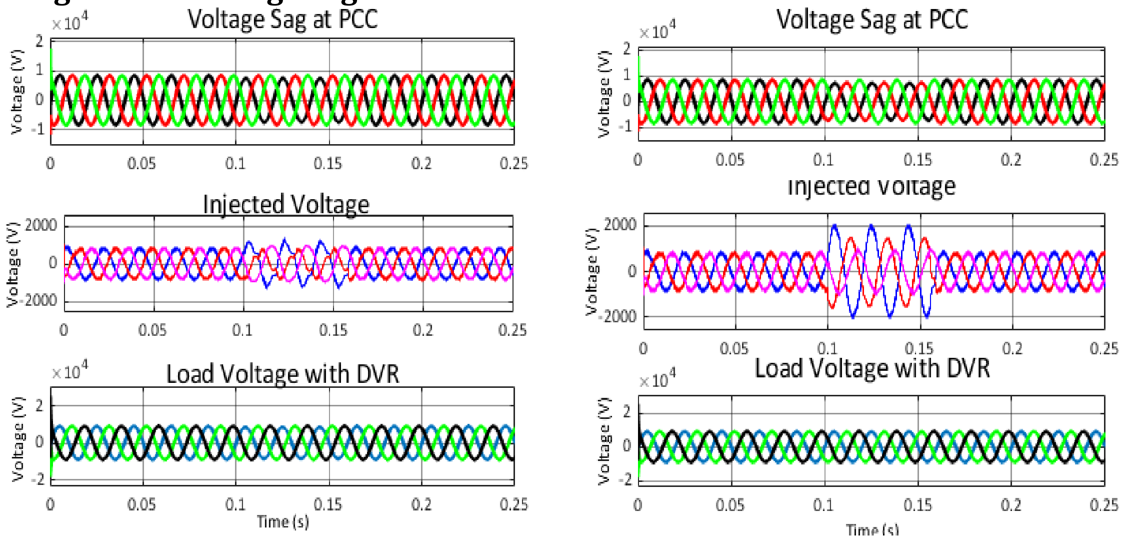


Figure 7. Compensation of Voltage Sag due to (a) LL Faults and (b) LLL Faults on the Feeder A

As balanced faults such as three phase line to line(LLL) and three phase ground(LLLG) faults occur on the feeder A, the voltage sag on the load feeder in all phases is nearly 6.48 kV, but 6.43 kV is for phase A, and the injected voltage of phase A is 2.72 kV, and the other phases have 2.68 kV. The load voltage with DVR for all faults are nearly equal.

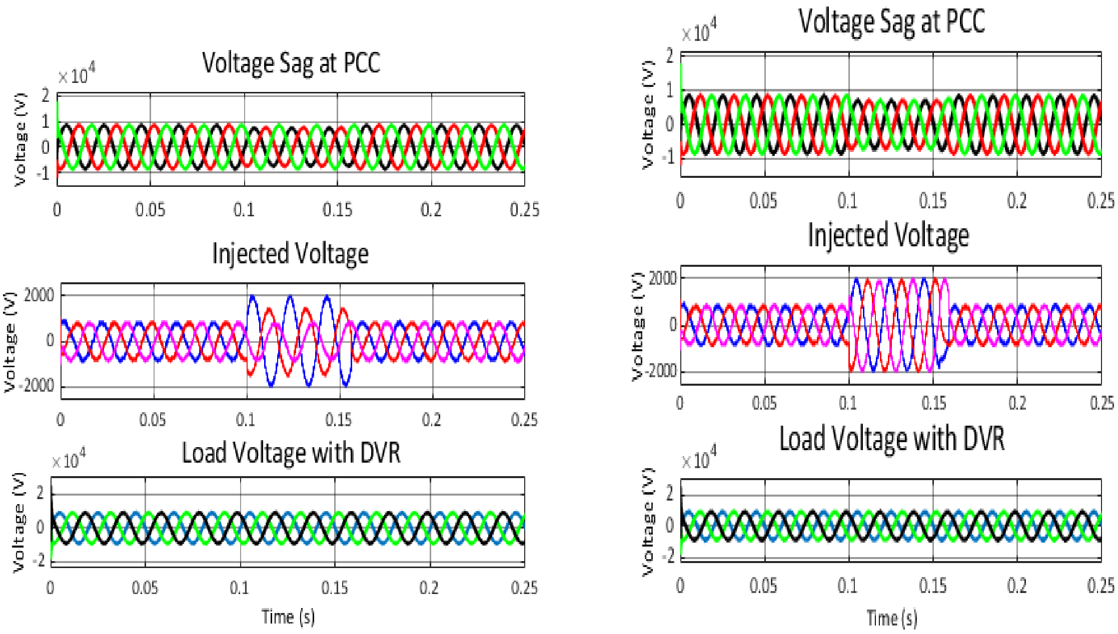
Mitigation of Voltage Sag due to Various faults on Load Feeder D



(a) (b)

Figure 8. Compensation of Voltage Sag due to(a) SLG Faults and (b) 2LG Faults on the Feeder D

The sensitive load feeder B needs to be protected from voltage sag and swell. So, the voltage sag is mainly analyzed in this case. The other feeders can occur randomly with various faults. now The voltage sags due to various faults on feeder D are studied. The output voltage waveforms for SLG, DLG, LL, LLL, and LLG are shown in Figs. 8 and 9. For SLG, the maximum sag value is 7.5 kV for phase A, and the injected voltage is 1.35 kV. In 2LG faults, the voltage sags for phase A and phase B are 7.337 kV and 7.358 kV, and the injected voltages from the DVR are 2.08 kV and 1.53 kV. There are different voltage sags for each phase with different faults. So, the injected voltages are also different values. When the LL faults occur on the feeder D, the maximum sag values are 7.48 kV for phase A and 7.742 kV for phase B. So, the injected voltages from DVR are 2.05 kV and 1.5 kV, respectively. There are equal value voltage sags for LLL and LLLG faults, and the injected voltages are the same values.



(a) (b)

Figure 9. Compensation of voltage sag due to(a) LLL and (b) LLLG faults on the Feeder D

THD% on Load Voltage and Load Current with DVR

Following compensation, the load voltage is nearly equal for all faults and balanced for each phase in different faults. In all faults, the THD% on the load voltage could be become less and over 5% for each phase, while the THD% on the other two phases approximately 5%. For every fault phase, the THD percentage on load current is less than 5%.

The Table 7 states Total Harmonic Distortion (THD) percentages for different feeders under various fault types, phases, and conditions. It evaluates THD in load voltage and load current for single line to ground (SLG), double line to ground (2LG), line to line (LL), and three phase faults (LLL and LLLG). Each feeder (A, C, D, E, F, and Awaeat/55) shows consistent trends across three phases (A, B, and C), highlighting variations in THD levels depending on the fault type and phase. Each phase typically show lower THD in current. This indicates distinct variations in harmonic distortion influenced by both the phase and the specific feeder.

Table 7. THD% in Load Voltage and Load Current for each phase with type of Faults After compensation

Feeder Name	Phase	SLG THD% on Load Voltage	SLG THD% on Load Current	2LG THD% on Load Voltage	2LG THD% on Load Current	LL THD% on Load Voltage	LL THD% on Load Current	LLL and LLLG THD% on Load Voltage	LLL and LLLG THD% on Load Current
Feeder A	A	4.29	2.63	3.45	1.25	3.16	0.63	3.13	0.63
	B	6	1.73	6.25	2.2	5.92	1.5	5.94	1.51
	C	7.58	1.65	7.58	1.68	7.67	1.65	7.68	1.64
Feeder C	A	3.21	1.08	3.14	0.72	3.09	0.63	3.09	0.62
	B	5.88	1.52	5.91	1.54	5.93	1.51	5.95	1.5
	C	7.64	1.67	7.64	1.69	7.66	1.64	7.69	1.65
Feeder D	A	3.42	1.43	3.11	0.78	3.14	0.62	3.14	0.62
	B	5.92	1.62	5.97	1.7	5.93	1.5	5.93	1.5
	C	7.58	1.66	7.59	1.68	7.65	1.64	7.68	1.64
Feeder E	A	4.29	2.63	3.45	1.25	3.12	0.63	3.13	0.63
	B	6	1.73	6.25	2.2	5.94	1.5	5.94	1.51
	C	7.58	1.65	7.58	1.68	7.68	1.64	7.68	1.64
Feeder F	A	4.29	2.63	3.45	1.25	3.32	0.63	3.13	0.63
	B	6	1.73	6.25	2.2	5.94	1.5	5.94	1.51
	C	7.58	1.65	7.58	1.68	7.65	1.64	7.68	1.64
Awaeat /55	A	4.02	2.3	3.34	1.13	3.13	0.63	3.13	0.63
	B	5.97	1.68	6.14	2	5.95	1.51	5.95	1.51
	C	7.58	1.66	7.58	1.68	7.65	1.65	7.65	1.65

The voltage sags are caused by various faults on the other feeder. The load feeder B is an industrial sensitive load. It is protected from power quality problems.The faulted phase reduced to less than 0.9 voltage. In duration fault, the integrated power from the solar power plant became reduced because of voltage sag due to faults. After the faults, the integration condition is normal. The voltage sags have different values with various types of faults, and the injected voltages are different with phase and type of faults. After compensation, the rated load voltage and current became acceptable limits.This value is 9.02 kV.THD% on load voltage and current are also around acceptable limits. The irradiance level is 1000 W/m^2, and all faults have equal grid voltage and current, but the lower irradiance level with all faults has the lower current and the same voltage. So, the integration power also decreased.

D. Conclusion

When the voltage sags due to various faults on the other feeder and voltage sag and swell from the power supply side occur, the industrial load feeder B can cause increased harmonics, loss of production in industries, tripping of equipment, and overheating of equipment.The higher the voltage sag, the higher THD% before compensation. So, the design of the DVR for 0.5 voltage sag is selected to compensate for occurring voltage sags and swells in this system.It cover for all various voltage sag and It gives full compensation. If the DVR's design is less than it, that design of the DVR cannot give full compensation. After DVR installation, the various voltage sags due to faults on the other feeder as well as the various voltage sags and swells from the power supply side are compensated by DVR to restore its rated voltage values to 9.02 kV. When faults occur on each feeder, THD% on voltage in the faulted phase is less than 5% after compensation, and particularly THD% on voltage with DVR is less than the THD% on voltage without DVR in all cases. These values are around 5%.THD % on load current without a DVR and with a DVR in the proposed system is less than 5%.

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