

Mitigation of Voltage Sag and Swell under Fault Conditions in Power System using a Dynamic Voltage Restorer

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Abstract - The modern power systems are becoming more sensitive to the quality of the power supplied by the utility company. Sag and swell in voltage, harmonics, flicker, interruptions, and disruption of the sinusoidal waveform are the examples of the power quality problems. Industrial users with various sensitive devices are mainly affected due to these problems. They may suffer a huge loss due to these problems. The equipment will be broken or damage if voltage sag exceed the sensitive threshold of the equipment. Thus, device such as Uninterruptable Supply (UPS), Static Synchronous Compensator (STATCOM), Active Voltage Restorer (AVR) and Dynamic Voltage Restorer (DVR) has been created to solve this problem among users. DVR is a custom power devices that most effective and efficient. Therefore, the purpose of this paper is to study how the DVR operates during compensation of voltage sag and swell. The distribution network has been selected as a sample to examine the DVR system. This network consists of two feeders and each feeder connected to the balanced load. Various faults such as LG, LLG and LLLG have been applied to the one of the feeder resulting in voltage sag and swell. MATLAB/ Simulink is chosen as the software to simulate the system. To control the circuit with more accurate and improve the response of the DVR, SVPWM based technique is able to generate an output voltage with minimum of harmonic and distortion. The effect of power devices, different circuit topologies and parameters of components are discussed. The result of the simulation was recorded and discussed.

Key Words: Dynamic Voltage Restorer (DVR), Power Quality (PQ), Voltage Sag and Swell, Space Vector Pulse Width Modulation (SVPWM), MATLAB/Simulink.

1. INTRODUCTION

Electrical power quality is very important in today's competitive and deregulated power sector. It's like service quality in power system. Major concern for electrical power utilities is power quality issues and their mitigation. Majority of the PQ problems are because of faults occurring in power systems. PQ issues encompass a wide range of disturbances such as voltage sags/swells, flicker, harmonics distortion, impulse transient, and interruptions. Voltage sags can easily disrupt the operation of sensitive loads. Nowadays, various types of

electronic equipment are sensitive to voltage sags. For example, variable speed drives controls, motor starter contactor, robotics, programmable logic controller (PLC), controlled power supplies, control relays and many more.

Dynamic Voltage Restorer (DVR) is a custom power device that used to eliminate supply side voltage disturbances. Another name of DVR is Static Series Compensator. The basic operation of DVR is to inject the appropriate voltage in series with the supply through injection transformer when voltage sags or swell is detected. DVR is able to mitigate voltage at both distribution and transmission level. Normally, it was installed at critical load feeder. During standby operation, DVR performs no switching. Voltage variations caused by unsymmetrical line-to-line (LL), line to ground (LG), double-line-to-ground (LLG) and symmetrical three phase faults (LLL) affects the sensitive loads. Power electronic device which is Dynamic voltage controller is used to mitigate this problem. The DVR inject the voltages which are independent to compensate and maintain its nominal value. The power injection by the DVR with null or minimal power for mitigation purposes can be achieved by controlling an appropriate phasor amplitude and angle. However, when voltage sags or swell occurs in the system, DVR starts to inject the missing voltage to the system. Since the events occur very fast, DVR should be able to react as fast as possible to inject the missing voltage to the systems in order to prevent the damage to the sensitive load. DVR can be applied for low to medium voltage applications. Since DVR system is a custom power devices, it combined of power circuit and control unit.

The study will be focusing on DC link or Storage unit for the power circuit unit and SVPWM controlled from the control unit. MATLAB/Simulink is the software that will be used to simulate the operation of DVR in order to mitigate the voltage sag and swell. The simulations are performed on the distribution system which consists of two feeder and balance loads. In order to investigate the sags event, faults such as LG, LLG and LLLG have been applied at feeder A. Then, automatically voltage sag or swell will occur in feeder B. Thus, investigated the application of DVR for voltage sag and swell mitigation and control using SVPWM under different fault conditions.

2. DYNAMIC VOLTAGE RESTORER

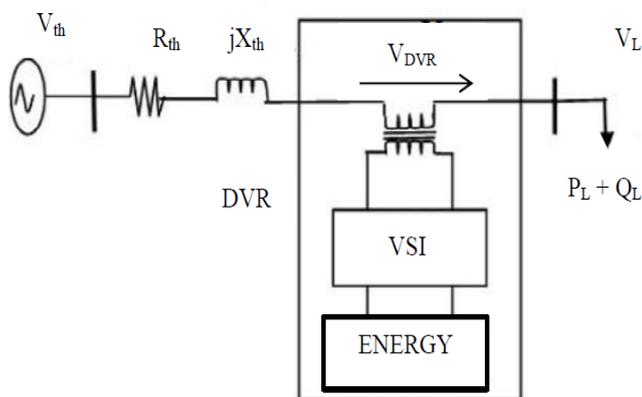


Fig - 1: Schematic of DVR

DVR is a series connected custom power device. Its main function is the protection of sensitive loads from any voltage disturbances except voltage outage. It basically consists of power circuit and control circuit. Four main components of the DVR circuit are: voltage injection/booster transformer, harmonic filter, voltage source inverter (VSI), and storage device or a DC source.

- Voltage injection/booster transformer: The basic function of injection transformer is to increase the voltage supplied by the filtered voltage source inverter (VSI) output to the desired level while isolating the DVR circuit from the distribution networks.
- Harmonic filter: Basically filter unit consists of inductor (L) and capacitor (C). In DVR, filters are helpful to get a sinusoidal wave out of the inverted wave by SVPWM. This can be achieved by eliminating the unwanted harmonic components generated by the VSI actions.
- Storage devices: The DVR needs real power for compensation purposes during voltage disturbance in the distribution system. In this case the real power of the DVR must be supplied by energy storage when the voltage disturbance exits. The energy storage such as battery is responsible to supply an energy source in DC form.
- DC charging circuit: The DC charging circuit has two main tasks; first task is to charge the energy source after a sag compensation event. And the second task is to maintain dc link voltage at the nominal dc link voltage.

2.1 Voltage injection by DVR

Fig. 1 shows the schematic diagram of DVR systems. The circuit located at the left of DVR represents the Thevenin's equivalent circuit of the system. The system impedance ($Z_{th} = R_{th} + j X_{th}$) depends on the fault level of the load bus. When the system voltage (V_{th}) drops, DVR system will inject a series voltage V_{DVR} using injection

transformer. Thus the desired voltage value at the load can be maintained.

By using KVL,

$$V_{th} - Z_{th}I_L + V_{DVR} = V_L$$

$$V_{DVR} + V_{th} = V_L + Z_{th}I_L$$

Hence, the series injection voltage of DVR is,

$$V_{DVR} = V_L + Z_{th}I_L - V_{th}$$

Where,

$$I_L = \left[\frac{P_L + jQ_L}{V_L} \right]^*$$

When V_L is considered as a reference,

$$V_{DVR} \angle \alpha = V_L \angle 0 + Z_L I_L \angle \beta - \phi - V_{th} \angle \delta$$

Here, α, β and δ are the angle of V_{DVR}, Z_{th} and V_{th} respectively and ϕ is the load power factor angle with

$$\phi = \tan^{-1} \left(\frac{Q_L}{P_L} \right)$$

The complex power injection by DVR is

$$S_{DVR} = V_{DVR} I_L^*$$

2.2. Advantages of using DVR

Dynamic Voltage Restorer is the most efficient and effective modern custom power device used in power distribution network. Besides that, DVR also is lower cost, small size and its fast dynamic response to the disturbance.

2.3. Technical issue of using DVR

To improve PQ conventional compensation methods such as passive filters, synchronous capacitors and phase advancers were used. However the conventional methods have many drawbacks such as resonance, fixed level of compensation, bulky and electro-magnetic interference. These disadvantages forced researchers to undertake adjustable and dynamic methods using custom power devices.

It is observed that the cell voltage and efficiency present higher values for low current densities and power densities. On the other side, for higher power values, the voltage and efficiency have lower values. Therefore, when the designer of the control system wants to find the best operation point for the cell, he/she must take into account efficiency and voltage levels suitable for the application. Operating the system with current at constant current resulting in constant potential and power can be a good start.

3. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

SVPWM helps to produce a vector of voltage that is similar to the reference signal with the help of different inverter switching modes. Fig. 2 is the general view of a three-phase VSI model. Each phase is represented as switch S for three-phase inverter circuit ON-OFF. Here,

$S_A(t)$; $S_B(t)$ and $S_C(t)$ are used as the switching functions for the three phases, respectively.

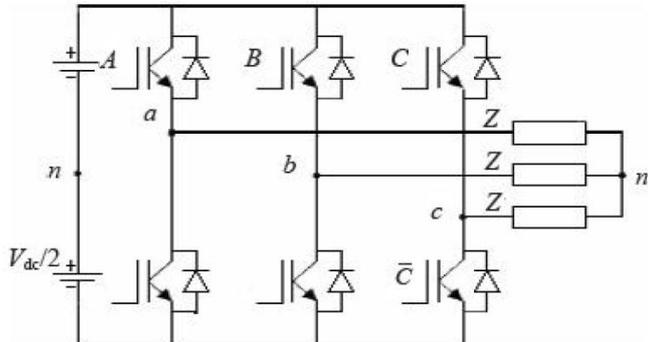


Fig - 2: Three-phase inverter

The space vector of output voltage of inverter can be expressed as $V = V_{dc} (S_A + \alpha S_B + \alpha^2 S_C)$, where, V_{dc} is voltage of the Dc bus and $\alpha = e^{j120}$. If we express the on state of the upper-arm with 1 and the off state with 0, the on-off states of three phases have eight combinations, correspondingly forming eight voltage space vectors, as shown in Fig. 3. T refers to the operation times of two adjacent non-zero voltage space vectors in the same zone. Both $V_0(000)$ and $V_7(111)$ are called the zero voltage space vector, and the other six vectors are called the effective vector with a magnitude of $2V_{dc}/3$. For example, when the output voltage vector V is within zone one, it is composed of V_4, V_6, V_0 and V_7 and can be obtained by $V_{out} = (T_4V_4)/T + (T_6V_6)/T$

ON-OFF states of inverter are as shown in Table 1.

Table - 1: Inverter's ON-OFF states

State	$S_A S_B S_C$	$S_A - S_B - S_C$	V_A/V_{dc}	V_B/V_{dc}	V_C/V_{dc}
0	000	111	0	0	0
1	001	110	-1/3	-1/3	2/3
2	010	101	-1/3	2/3	-1/3
3	011	100	-2/3	1/3	1/3
4	100	011	2/3	-1/3	-1/3
5	101	010	1/3	-2/3	1/3
6	110	001	1/3	1/3	-2/3
7	111	000	0	0	0

Based on the principle of SVPWM, the Embedded MATLAB functions for generating SVPWM waveforms mainly include the sector selection model, switching time calculator, time switching signal generator, and generation model of SVPWM waveforms.

In the application of SVPWM method, first step is to determine the voltage vector sector. For control purpose α - β coordinate system is used to determine the appropriate sector. When $V_\beta > 0$, $A = 1$; when $3V_\alpha + V_\beta < 0$, $B = 1$; when $3V_\alpha + V_\beta < 0$, $C = 1$. Then, the sector containing the voltage vector can be decided according to $N = A + 2B + 4C$, listed in Table 2.

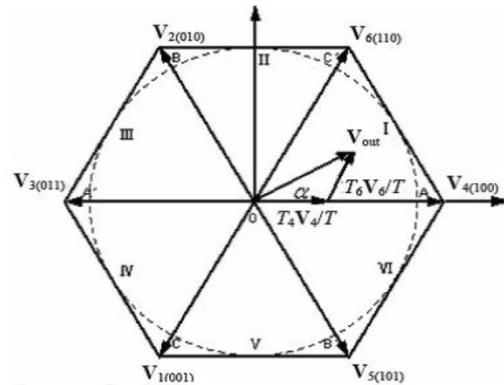


Fig - 3: Voltage space vectors

Table - 2: Sector containing the voltage vector vs N

Sector	I	II	III	IV	V	VI
N	3	1	5	4	6	2

Table 3 lists the operation times of fundamental vectors against N, where T_1 and T_m refer to the operation times of two adjacent non-zero voltage space vectors in the same zone. $Z = T(-3V_\alpha + V_\beta)/(2V_{dc})$, $Y = T(3V_\alpha + V_\beta)/(2V_{dc})$, $X = 2T[V_\beta/2V_{dc}]$. The sum of T_1 and T_m must be smaller than or equal to T (PWM modulation period). The over saturation state must be judged: if $T_1 + T_m > T$; take $T_1 = T_1[T/(T_1 + T_m)]$; $T_m = T_m[T/(T_1 + T_m)]$.

Table - 3: Operating time of fundamental vector

N	1	2	3	4	5	6
T_1	Z	Y	-Z	-X	X	-Y
T_m	Y	-X	X	Z	-Y	-Z

The relation between N and operating time of switches is presented in Table 4. $T_a = (T - T_1 - T_m)/4$, $T_b = T_a + T_1/2$, and $T_c = T_b + T_m/2$, T_{cm1} , T_{cm2} and T_{cm3} are the operation times of the three phases respectively.

Table - 4: Relation between N, T_{cm} , T_a , T_b and T_c

N	1	2	3	4	5	6
T_{cm1}	T_b	T_a	T_a	T_c	T_c	T_b
T_{cm2}	T_a	T_c	T_b	T_b	T_a	T_c
T_{cm3}	T_c	T_b	T_c	T_a	T_b	T_a

By comparing the computed T_{cm1} , T_{cm2} and T_{cm3} with the equilateral triangle diagram, a symmetrical space vector PWM waveform can be generated. The waveforms of PWM_2 , PWM_4 and PWM_6 are obtained by reversing those of PWM_1 , PWM_3 and PWM_5 , respectively.

The SVPWM waveform in a sampling period is shown in Fig. 4. T_s refers to sampling time, T_0 refers to the time of zero vector operation, T_k and T_{k+1} refer to the operation times of two adjacent non-zero voltage space vectors in the same zone, then the resultant torque increases to 3 times. The phase is switched to the next in every 60 electrical degrees. The duration of operation for each power electronic part is 120 electrical degrees. The exciting duration of each winding is 240 electrical degrees: including 120 degrees for positive direction and 120 degrees for negative direction.

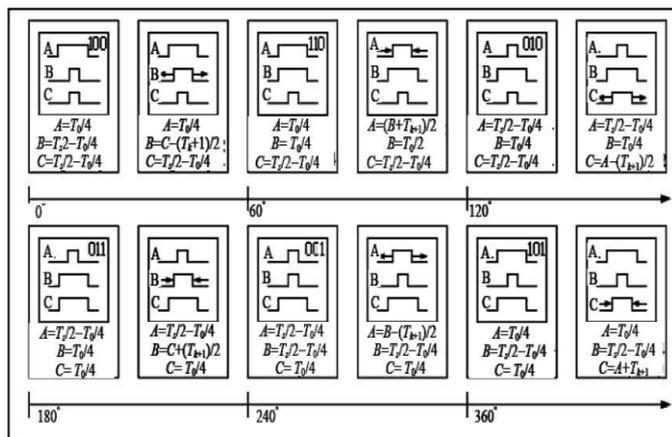


Fig - 4: SVPWM waveform in a single sampling period

4. SIMULATION RESULTS

Fig. 5 shows the main circuit of distribution network with installation of DVR systems. The load connected to the system is balanced loads. The three phase fault generator was placed at feeder A.

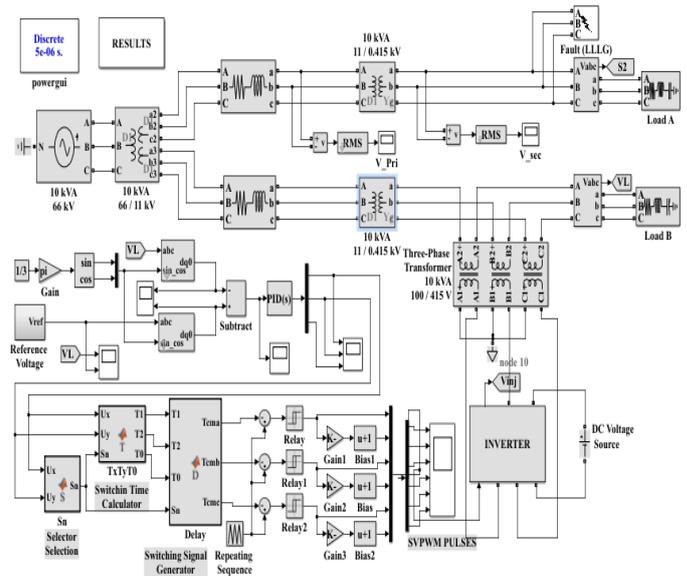


Fig - 5: MATLAB/ Simulink model of distribution network with DVR

Fig. 6 shows the result of the simulation without installation of the DVR system. When, a LLLG fault applied at feeder A, the voltage sags occurred on feeder B between 0.1-0.2 second. The event occurred during the interval of time can be considered as voltage sag because the period of the voltage sag is between 0.5 cycles until 1minute. From this result, it means the next simulation of distribution network installed with DVR system can be proceeds by using the same value and configuration of the fault occurred in the simulation.

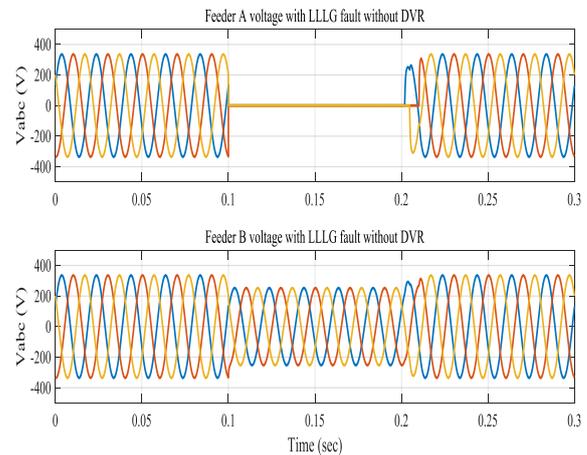


Fig - 6: Load voltage for feeder A and B respectively without DVR (LLLG fault)

Fig. 7 shows that the DVR successfully compensated the voltage sag at feeder B produced due to a LLLG fault on feeder A. Voltage during the 0.1-0.2 second restored back to the nominal value and voltage injected by DVR is also observed.

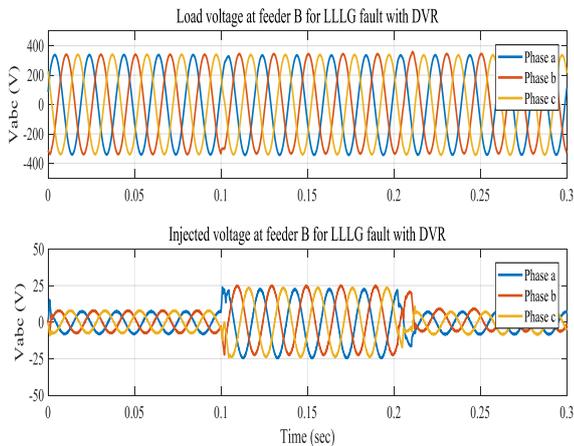


Fig - 7: Load and injected voltage at feeder B with compensation by DVR (LLG fault)

Fig. 8 shows load voltage at feeder A and B when a LLG fault occurred at feeder A, the voltage sag is observed on feeder B.

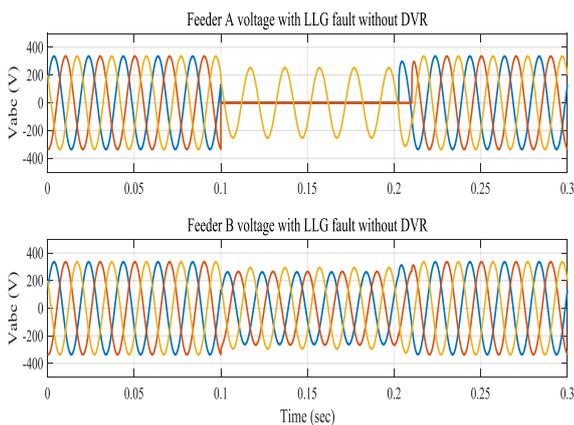


Fig - 8: Load voltage for feeder A and B respectively without DVR (LLG fault)

Fig. 9 shows that the DVR successfully compensated the voltage sag at feeder B produced due to a LLG fault on feeder A.

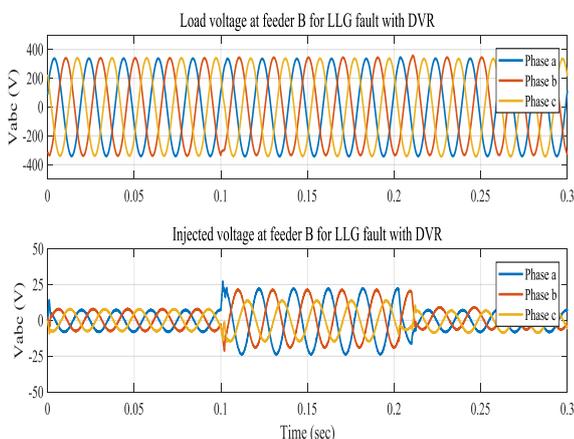


Fig - 9: Load and injected voltage at feeder B after compensation by DVR (LLG)

Fig. 10 shows load voltage at feeder A and B when a LG fault occurred at feeder A, the voltage sag is observed on feeder B.

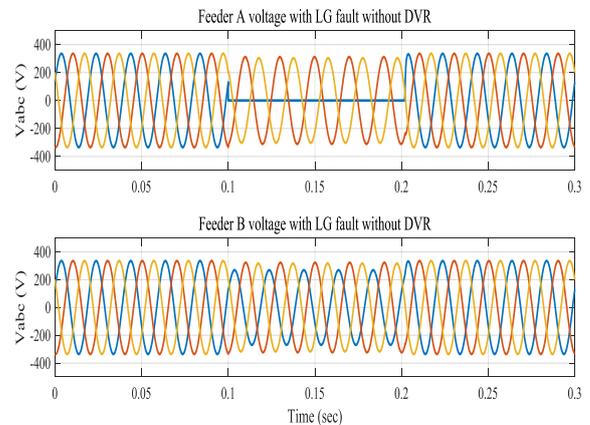


Fig - 10: Load voltage for feeder A and B respectively without DVR (LG fault)

Fig. 11 shows that the DVR successfully compensated the voltage sag at feeder B produced due to a LG fault on feeder A.

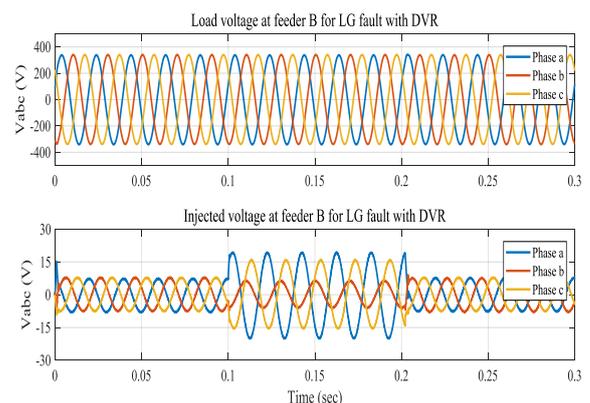


Fig - 11: Load and injected voltage at feeder B after compensation by DVR (LG)

Fig. 12 shows load voltage at feeder A and B when a voltage swell is produced through the source voltage magnitude control.

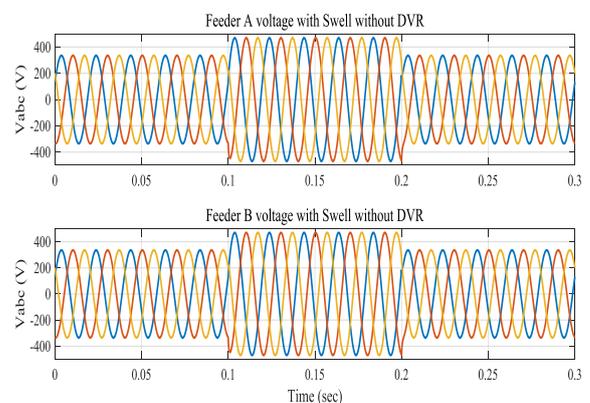


Fig - 12: Load voltage for feeder A and B respectively without DVR (Swell)

Fig. 13 shows that the DVR successfully compensated the voltage swell at feeder B and the voltage injected by DVR is also represented.

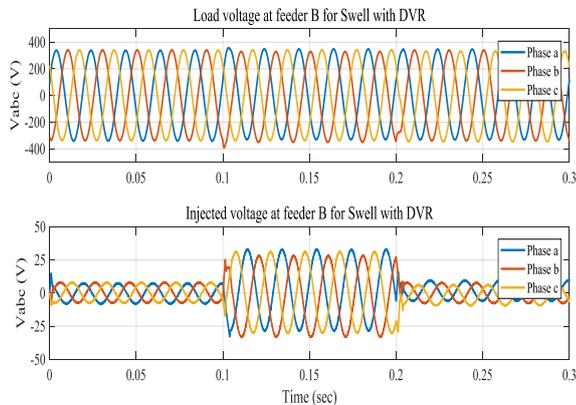


Fig - 13: Load and injected voltage at feeder B after compensation (Swell)

5. CONCLUSION

In this paper, mitigation of voltage sag and swell using DVR is presented under fault conditions. In order to investigate whether the DVR is able to deal with this problem, MATLAB/Simulink is used to simulate the system and mitigate the voltage sag and swell. Based on the simulation that had been done, it can be proved that DVR is the dynamic fast response devices that able to overcome the issues with the use of SVPWM method. DVR is able to mitigate voltage during sag as well as swell and output voltage after compensation is in range of the nominal value. The simulation was implemented by using the distribution network where the effectiveness of the DVR system is better compared to the transmission network.

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