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Dual Functional Z-Source Based Dynamic Voltage Restorer to Voltage Quality Improvement and Fault Current Limiting

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Abstract: Dynamic Voltage Restorer (DVR) is a powerful custom power device for short duration voltage compensation, which is connected in series with the load. Due to the fact that it is connected in series with the distribution line, DVR would suffer from downstream faults. To limit the flow of large fault currents and protect DVR itself as well, a fault current limiting function is proposed in the DVR control strategy. Fault current limiting function of DVR will be activated by the protection system and then DVR will start injecting a series voltage to the line in such a way as to limit fault current to an appropriate level. Recently, the application of Z-source inverter is proposed in order to optimize DVR operation. This inverter makes DVR to operate appropriately when the energy storage device's voltage level severely falls. In this paper, the Z-source inverter based DVR is proposed to compensate voltage disturbance at the PCC and to reduce the fault current in downstream of DVR. The proposed system is simulated under voltage sag and swell and short circuit conditions. The simulation results show that the system operates correctly under voltage sag and short circuit conditions.

Key word: Dynamic voltage Restorer, Z-Source Inverter, Voltage disturbance, fault Current

INTRODUCTION

Dynamic voltage restorer (DVR) is one of the power electronics devices which are connected to distribution system in series to protect sensitive loads against the voltage changes. Fig. 1 shows a kind of DVR circuit. As shown in fig. 1, DVR is composed of an inverter, an energy storage element, LC filter, and a transformer.

In many references, Voltage source inverter (VSI) is used due to the appropriate output voltage with low harmonics level. The main defect of VSI is its reducing characteristics whose maximum output voltage is limited by DC link voltage. This means that the compensation ability of DVR decreases when the DC link voltage falls due to energy reduction in energy storage element (Sing *et al*, 2004),(Vilathgamuwa *et al*, 2006). A dc-dc boost converter application between inverter and the energy storage element is proposed (Sing *et al*, 2004). Using boost converter leads to an increase in size, price and integration of system. In (Sing *et al*, 2004) it is proposed to apply a Z-source inverter (ZSI) instead of VSI. Z-source inverter is a new converter with some special advantages, presented recently as a substitution to conventional converters (Peng, 2003). In (Sing *et al*, 2004) in-phase compensation of voltage sag is studied and executed using Z-source inverter based DVR.

During fault occurrence in downstream of DVR, the voltage falls at the point of common connection (PCC). DVR might try to compensate the voltage fall which enlarges the short circuit current, while this current flow through the DVR causes damage in DVR. In conventional DVRs, passive methods are used to bypass the DVR by applying parallel switches to avoid mentioned damages during the short circuit (Woodley *et al*, 1999; Woodley *et al*, 2000).

Applying active methods is proposed to reduce the fault current in series grid connected devices (Lee *et al*, 2004),(choi *et al*, 2005). In (Li *et al*, 2006),(Axente *et al*, 2006) DVR is applied to reduce the short circuit current using such methods.

In this paper, the short circuit current reduction is studied and simulated applying Z-source inverter based DVR. According to the voltage boost ability of Z-source inverter, the DVR can inject the required voltage to reduce the fault current even at severe DC link voltage reduction. In continuous, the Z-source inverter is described and then the DVR operation under two voltage sag and fault occurrence is explained. At the next part, it is expressed how fault is recognized. Finally, the simulation results of system are analyzed and studied.

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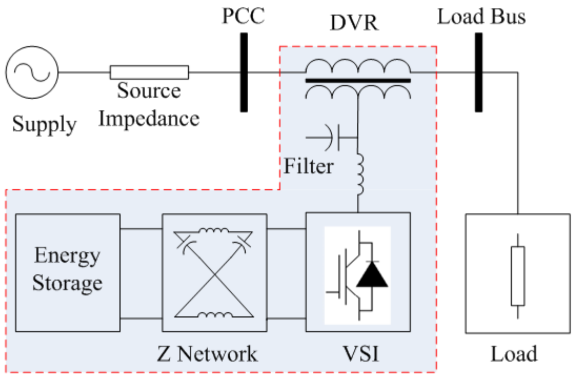


Fig. 1: Z-source based structure of DVR.

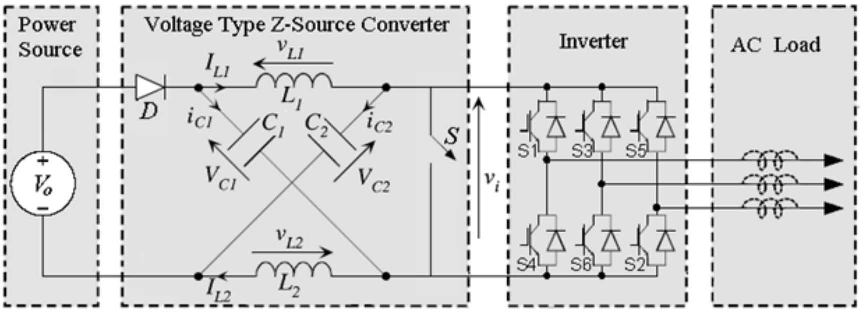


Fig. 2: Voltage Type Z-Source Inverter.

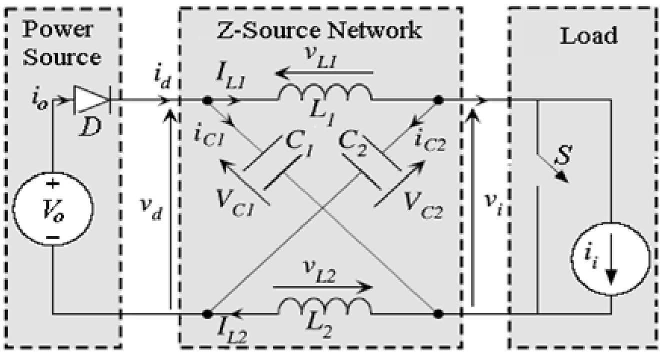


Fig. 3: Equivalent circuit of ZSI.

MATERIALS AND METHODS

The proposed system is consisted of four main parts: Z-source inverter, DVR operation to compensate the voltage disturbance, DVR operation to reduce the fault current, detection and recovery from downstream fault. Theses parts have discussed and finally the simulation results have been introduced.

A. Z-source Inverter:

Fig. 2 shows the structure of Z-source inverter (ZSI). ZSI uses an LC impedance grid to couple power source to inverter circuit and prepares the possibility of voltage boost by short circuiting the inverter legs. As shown in Fig (2), Z-source inverter's impedance grid is composed of two parted L_1 and L_2 inductors and C_1 and C_2 capacitors arranged in *X* shaped configuration. Usual inverters have six active switching vectors and two zero switching ones where, ZSI has another zero vector called short circuit vector used to boost the input voltage. Fig. 3 shows the equivalent ZSI circuit where the inverter and load are modeled as switches and current source respectively. The operation of voltage type ZSI can be analyzed in two modes. First is the time during which the *S* switch is on (T_0) and the second is the time during which it is off (T_1). During T_0 the inductors are being charged by capacitors and consequently the capacitors are being discharged.

The currents of inductors are increasing linearly due to their voltages which are equal with the constant voltages of capacitors. The voltage and current equations are as follow:

KVL equations:

$$v_{L1} = V_{C1}$$
$$v_{L2} = V_{C2} \qquad (1)$$
$$v_i = 0$$

KCL equations:

$$i_{C1} = -I_{L1}$$
$$i_{C2} = -I_{L2} \qquad (2)$$

Switch S is off during T_1. Now, inductors are being discharged and capacitors are being charged. The currents of inductors decrease linearly according to negative and almost constant voltages of capacitors. The voltage and current equations of circuit are as follow:

KVL equations:

$$v_{L1} = V_o - V_{C2}$$
$$v_{L2} = V_o - V_{C1} \qquad (3)$$
$$v_i = V_{C1} + V_{C2} - V_o$$

KCL equations:

$$i_{C1} = I_{L2} - i_i$$
$$i_{C2} = I_{L1} - i_i \qquad (4)$$

The average value of inductors voltages should be zero in each cycle:

$$T_o\, v_{L1}(T_o) + T_1\, v_{L1}(T_1) = 0$$
$$T_o\, V_{C1} + T_1 (V_o - V_{C2}) = 0 \qquad (5)$$

$$T_o\, v_{L2}(T_o) + T_1\, v_{L2}(T_1) = 0$$
$$T_o\, V_{C2} + T_1 (V_o - V_{C1}) = 0 \qquad (6)$$

And so the capacitors voltages would be as follow:

$$V_C = V_{C1} = V_{C2} = \frac{T_1}{T_1 - T_o} V_o \qquad (7)$$

v_i during T_1 is:

$$v_i \big|_{t=T_1} = V_i = \frac{T_1 + T_o}{T_1 - T_o} V_o \qquad (8)$$

Considering $T = T_1 + T_o$ leads to:

$$V_i = \frac{1}{1-2\frac{T_o}{T}} V_o = BV_o \tag{9}$$

In the above relation, B is called boost coefficient which is:

$$B = \frac{1}{1-2\frac{T_o}{T}} \tag{10}$$

According to the above relation, the short circuit time ratio D_s is defined as follow:

$$D_S = \frac{T_o}{T} \tag{11}$$

The output phase voltage peak is as follow:

$$V_{ac} = MB\frac{V_o}{2} \tag{12}$$

where the M is the modulation coefficient of inverter.
V_i can be expressed in terms of V_c:

$$V_i = \frac{1}{1-D_S} V_C \tag{13}$$

B. DVR Operation To Compensate The Voltage Disturbance:

Voltage sag is the most common problem in power quality field which is mainly created by fault occurrence in grid. Fig. 4 shows two samples of fault locations which cause voltage sag in PCC (DVR connection point).

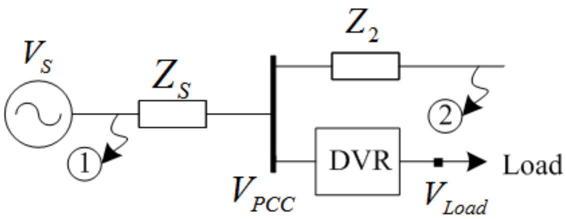


Fig. 4: Voltage sag or swell in PCC.

Here, DVR has to inject proper series voltage to grid in order to restore the load voltage level to its desired level. The compensation should be executed in Pre-sag mode (optimum power quality), in-phase (minimum voltage amplitude) and with minimum energy consumption, due to the load sensitivity and system limitations (Meyer *et al*, 2006). Fig. 5 shows the proposed control circuit of DVR under voltage disturbance compensation conditions. The voltage injected by DVR is determined by feed backing the source voltage and load. Capacitor voltage (V_c) is feed backed to control V_i. V_i is calculated using relation (13) and D_s is determined by comparing V_i with $V_{i\text{-}ref}$ and applying the inductor current feed back (I_L).

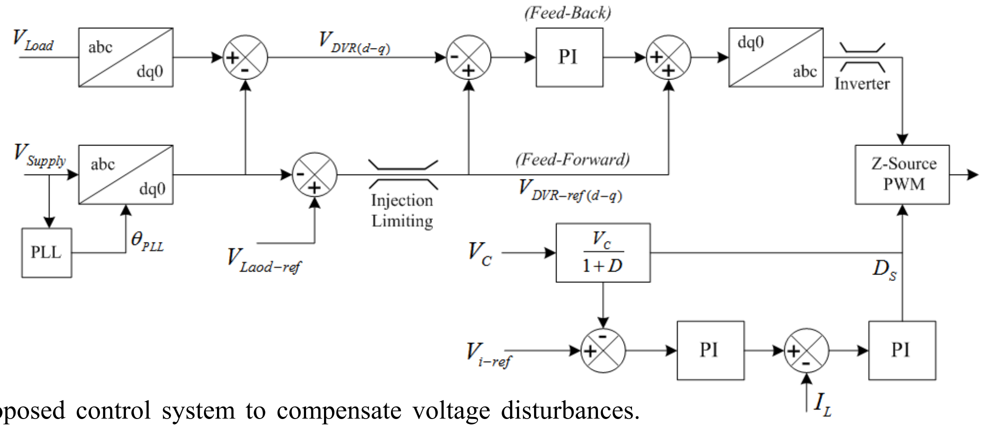


Fig. 5: Proposed control system to compensate voltage disturbances.

C. DVR Operation To Reduce The Fault Current:

Fig. 6 shows the fault occurrence in downstream of DVR. This fault causes severe current flow through DVR which might damage DVR. This current also causes voltage fall at PCC and it would be worst if DVR tries to compensate.

In order to solve the problem, DVR should be controlled in a way that it reduces the fault current by injecting appropriate voltage to grid. Here, DVR is operated as virtual impedance (Li *et al*, 2006). Fig. 7 shows the phasor diagram of voltages. V_{Line} is the voltage fall at the length of upstream and downstream feeders impedances and fault impedances (Z_S+Z_{Line}) and V_{Inj} and V_S are the voltage injected by DVR and the voltage of main feeder respectively:

$$V_S = V_{Inj} + V_{Line} \tag{14}$$

The fault currents with and without limitation are as follow:

$$I_{Fault} = \frac{V_S}{Z_S + Z_{Line}} \tag{15}$$

$$I_{Fault-Limited} = \frac{V_S}{Z_S + Z_{Line} + Z_o} \tag{16}$$

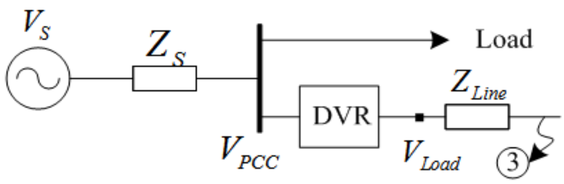


Fig. 6: Downstream fault in presence of DVR.

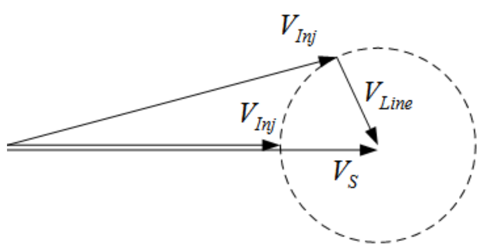


Fig. 7: DVR injected voltages phasor diagram during downstream fault

If the fault current is reduced to a constant value, V_{Line} will fall in the dotted circle depend on the voltage injected by DVR.

Fig. 7 obviously shows that the minimum injecting voltage would be required if the injected voltage (V_{Inj}) and V_{Line} are in phase. In order to achieve this, the R/X ratio of virtual impedance (Z_0) should be in proportion with the feeder impedance (Z_S+Z_{Line}). The existence of virtual ohmic component causes active power consumption and limits in voltage reduction of energy storage element. So, DVR should operate as a pure virtual inductance to minimize the energy consumption, where the V_{Inj} should have 90 degrees phase difference with fault current.

D. Detection And Recovery From Downstream Fault:

For fast downstream fault detection and therefore fast DVR reaction to the fault current, instantaneous current magnitude is calculated in synchronous frame. Once the current magnitude exceeds a preset threshold, the DVR would inject a series voltage so that it would act as a virtual inductor to limit the fault current and to restore the PCC voltage. Recovery from a downstream fault can be done by sensing the load voltage (voltage at downstream side of the DVR injection transformer) as in Fig. 6. When the fault is cleared, the load voltage will increase. Once is restored to a preset level, the fault current limiting function of DVR can be terminated. Furthermore, to ensure DVR compensation is not turned off by any spurious transient distortion or measurement noises, low pass filter like characteristic is added to this recovery detection.

This is done by turning off the DVR when (where is a threshold voltage) is sustained for a specific period of time and no other downstream fault is detected during this period. (In this paper, 20 ms is used for symmetrical faults, and 50 ms is used for unsymmetrical faults to eliminate the effects of oscillatory load voltage magnitude due to the unbalanced effects).

Table I: Grid Parameters

Source Phase-Phase rms Voltage (V_S)	380v – 50Hz
Source Inductance (L_S)	0.2 mH
Source Resistance (R_S)	0 Ω
Load Inductance (L_{Load})	4 mH
Load Resistance (R_{Load})	8 Ω
Line Inductance (L_{Line})	1 mH
inverter Inductance (L_F)	2 mH
Inverter Capacitance (C_F)	60 μF
Inverter Resistance (R_F)	10 µ
Switching Frequency (f)	1 kHz

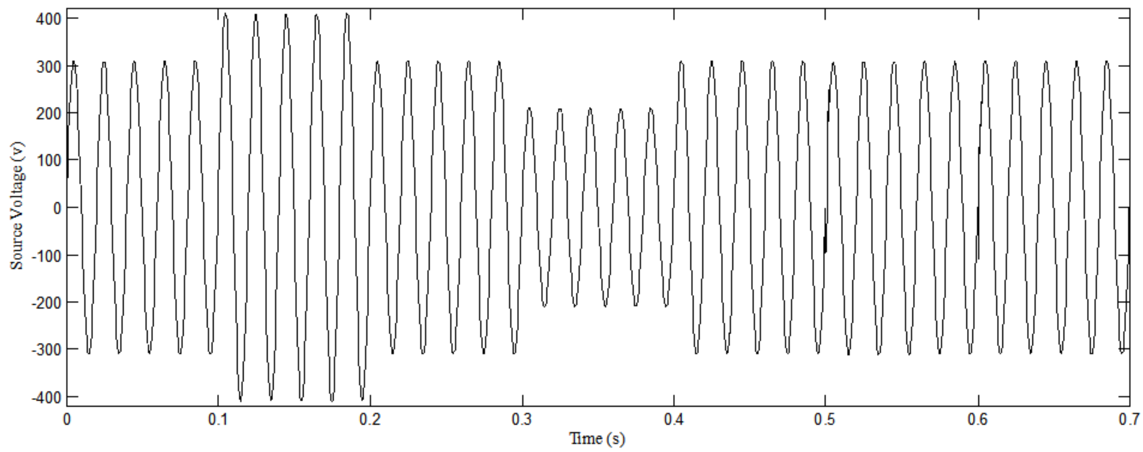
RESULTS AND DISCUSSION

The proposed system is simulated by MATLAB/SIMULINK to study the correctness of its operation. A Z-source inverter based DVR located on a 0.38kv line is simulated to compensate the voltage sag and swell of main feeder to provide nominal voltage of downstream loads and also to reduce short circuit current of downstream fault and compensate voltage of main feeder. The simulation parameters are presented in table (1).the simulation, in the main feeder, a 30% voltage swell has started at t=0.1 sec and lasts for t=0.2 sec, a 45% voltage sag has started at t=0.3 sec and lasts for t=0.4 sec and finally in downstream of DVR, a three phase fault to ground has occurred between t=0.5 sec to t=0.6 sec.

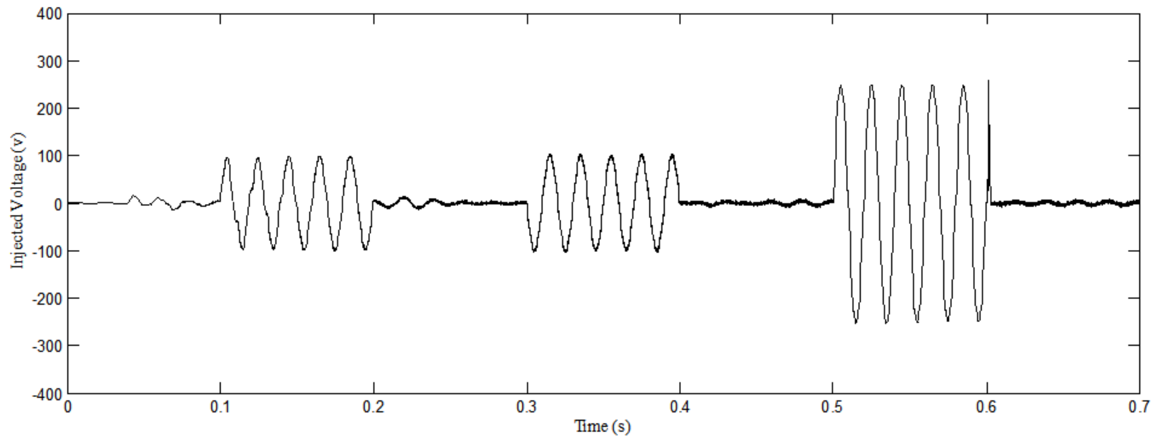
Fig. 8 shows the main feeder voltage, injected voltage by DVR and load side voltage respectively. It is shown in this figure that voltage sag and swell in main feeder have been compensated by DVR and the load side voltage has the nominal value. Furthermore, by occurrence of fault in downstream of DVR, the PCC voltage has been compensated by DVR accurately.

Conclusion:

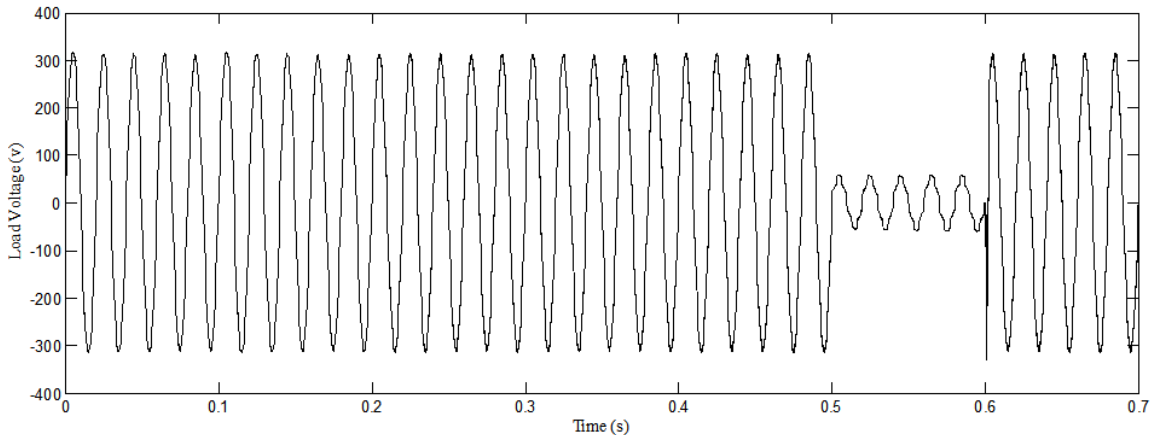
In distribution networks to improve voltage quality, dynamic voltage restorer is one of most usable devices. Correct operation of DVR significantly depends on its DC link voltage. By reducing DC link voltage, DVR faces with defect. Recently, Z-source inverter application is recommended to solve this problem. ZSI with voltage boost ability can solve this problem. In this paper ZSI based DVR is proposed to compensate voltage disturbance in PCC and reduce the short circuit current at the downstream of DVR. By calculating instantaneous current magnitude in synchronous frame, control system recognizes if the fault exists or not, and determines whether DVR should compensate voltage disturbance or try to reduce the fault current. The proposed system is simulated under voltage sag and swell and short circuit conditions. The results show that the proposed system operates correctly.



(A)

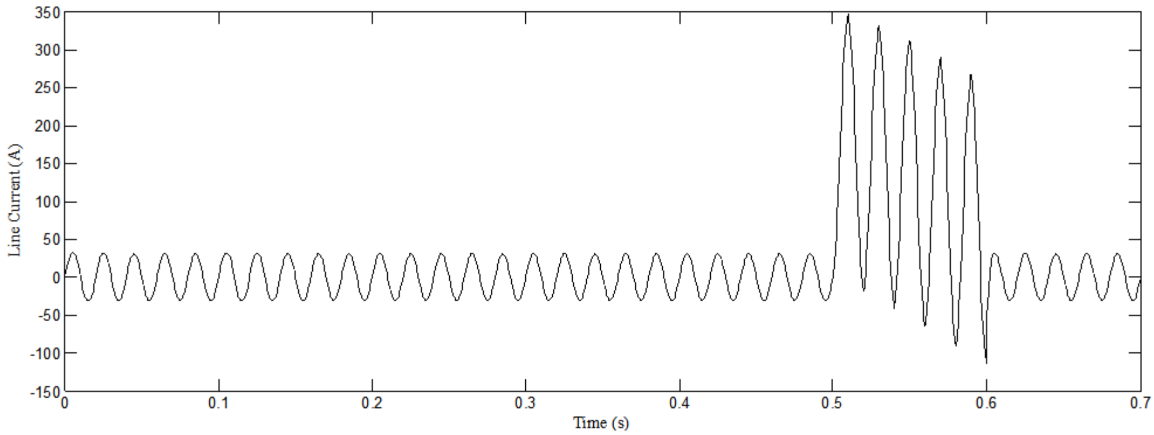


(B)

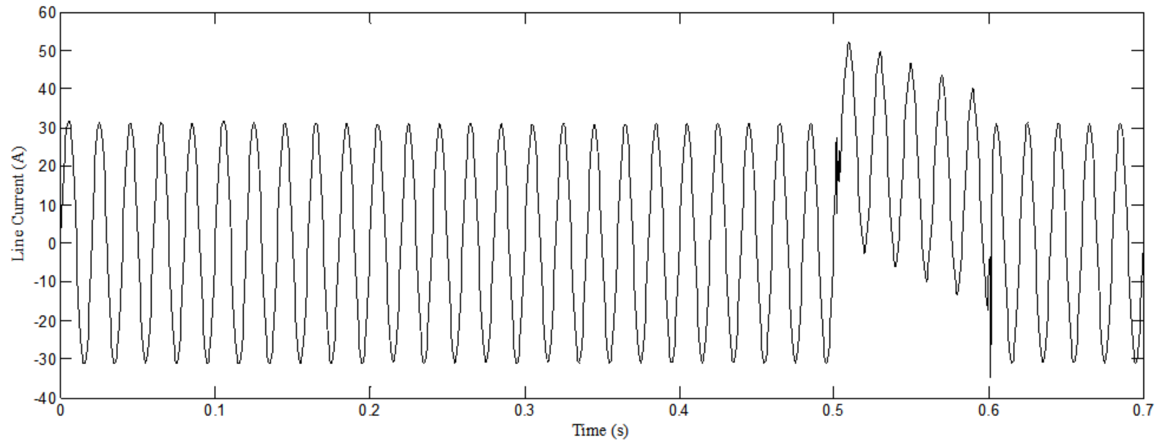


(C)

Fig. 8: (a).Main feeder side voltage, (b). Injected voltage by DVR, (c). Load side Voltage.



(A)



(B)

Fig. 9: (a). Downstream line fault current, (b). Limited downstream current by DVR.

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