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A New Structure of Dynamic Voltage Restorer Based on Asymmetrical Γ-source Inverters to Compensate Voltage Disturbances in Power Distribution Networks

Mahmoud Zadehbagheri[1], Rahim Ildarabadi[2], Majid Baghaei nejad[3], Tole Sutikno[4]
[1,2,3] Faculty of Electrical, Department of Electrical Engineering, Hakim Sabzevari University, Sabzevar, Iran
[4] Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

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ABSTRACT

As a consequence of sensitive, diverse and complex loads in today's distribution networks, improving power quality in distribution systems has attracted great attention. Power quality issues involve voltage sags, transient interrupts and other distortions in sinusoidal waveforms. Enormous methods have been proposed for power quality modification. One of the methods by which power quality problems might be addressed is to apply power electronic devices in the form of custom power devices. One of such devices is Dynamic Voltage Restorer (DVR) which is connected in series to distribution networks. At the same time, through injection of voltage to the network it is able to control voltage amplitude and phase. It is adopted lend to compensate for voltage sags through injecting series and synchronous three phase voltage. Consisted of three single phase inverters and a DC bus, it can protect susceptible loads against various types of voltage sags as well as other disturbances in the power supply. Moreover, it is capable of generating and absorbing active and reactive power. Therefore, in this paper, different structures of DVR have been investigated and eventually proposed a new structure for DVR based on Γ-Source asymmetric inverter. With the proposed structure, severe voltage sags can be retrieved 80- 90 percent. The simulation results that obtained by using MATLAB/Simulink indicate the properly functioning of proposed structure.

Corresponding Author:

Rahim Ildarabadi,
Faculty of Electrical, Department of Electrical Engineering
Hakim Sabzevari University,
Sabzevar, Iran.
Email: r.ildar@hsu.ac.ir

1. INTRODUCTION

Distribution section is the found to be major link between power industry and consumers; for this, it is frequently evaluated and appraised by people. Hence, essential to deal with power quality on distribution section is essential. On the other hand, distribution networks are exposed to traditional disturbances for sinusoid waveforms such as dynamic voltage sag and swell, harmonics and capacitive switching in turn damage power quality and network reliability to large extent. Such foregoing disturbances are incurred by some consumers and affect other consumers and network equipment. Additionally, given some accidents network might impose disturbances on susceptible consumers. Hence, distribution companies are responsible for offering reliable and high quality power for their consumers. This necessitates application of power quality controller devices in the networks. This might be done using power electronic devices called custom power devices, improving disturbances. An example of such devices is found to be Dynamic Voltage Restorer which is modelled and simulated here. At the same time, its impacts on disturbances in distribution networks is investigated. Having been necessity of using DVRs dealt, with, its structure, operation principles and control method are explicated.

To the best of our knowledge, there are several control strategies for DVRs such as “sinusoid current control”, line current in terms of instantaneous power theory and synchronous reference frame. Of these, instantaneous power theory with new modifications was selected as it properly offset all harmonic components, negative and zero sequences of line current and other disturbances of load current among others. To shed lights on performance of DVR a sample network consisting of unbalanced linear and nonlinear loads (e.g. induction motor and electric arc furnace) is simulated in presence of DVR and various types of disturbances are tested. According to the simulation results, DVR serves as a powerful compensator for three phase current unbalance, reactive power compensation, voltage sag and voltage oscillations [1]-[4]. Then we introduce the DVR and the different structures of it and then proposed structure will be discussed. Finally we will pay the simulation results and conclusions discussed in this article.

2. OPERATION PRINCIPLES OF DVR SYSTEM

The major fundamental of DVR operation is to detect voltage sag and to inject lost voltage to the network. A divider model can be utilized to specify voltage sag quantity in radial distribution systems. It is illustrated in Figure 1. This approach assumes that fault current is more greater than loads current along the fault location. Point of Common Coupling (PCC) is the point by which both fault and load are supplied. Voltage sag is basically unbalanced and is characterized with phase angle jump [5]-[8].

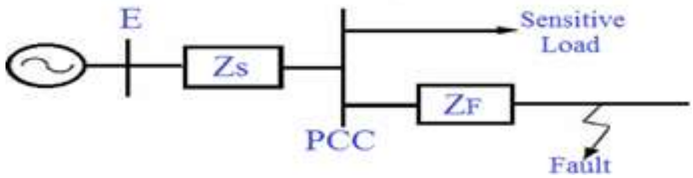


Figure 1. Voltage divider model for voltage sag

As per Figure 1, to calculate voltage in PCC and phase angle following equations are considered:

$$Vsag = \frac{Zf}{Zs+Zf} E = \frac{Zf}{Zs+Zf} \quad (1)$$

$$\Delta\Phi = \arg(Vsag) = \arctan\left(\frac{Xf}{Rf}\right) - \arctan\left(\frac{Xs+Xf}{Rs+Rf}\right) \quad (2)$$

Figure 2 shows DVR power circuit. It is consisted of four parts: inverter (VSI), injection transformer, passive filter and energy storage [7],[9].

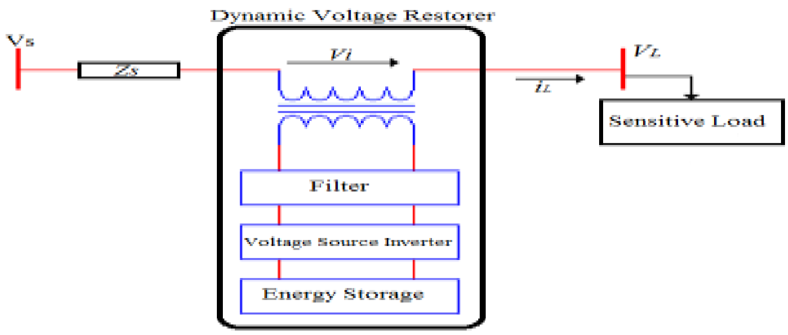


Figure 2. Actual schemes of a DVR

DVR may need to increase active power in order to correct larger faults to satisfy this end, an energy storage system should be utilized. Recently, capacitive banks have been applied in DVR system design. Once fault is corrected and system turns back to normal circumstance, DVR receives the consumed energy from the network and stores it. Given energy storage capabilities capacitive banks classification relies on system factors including load and predicted voltage sag. The DVR is connected in series within distribution lines by an injection transformer. Indeed, three phase transformer in primary side should be designed so that it could bear all line currents. Initial voltage rate is defined as maximum voltage which through DVR might be injected to circuit. Pulse Width Modulation switching will generate output voltage waveforms. In case voltage sag reaches to its lowest voltage level, energy storage system embedded in DVR is used to voltage modification. By ideal restoration it means that load voltage does not subject to any change. In fact, once DVR compensates for large voltage disturbances, from DVR to distribution system active power should be transferred. In case there is an infinite energy storage capacity DVR, line voltage tends to be unchanged while throughout all types of faults. However, presumably, when DC link capacity is limited, energy stored n DVR will be constrained. For instance DVR cannot keep load voltage constant when DC link voltage decreases and the stored energy is lost in severe voltage sags. Therefore, losses of injected energy is essential for DVR. To inject DVR reduced voltage to distribution system some methods can be found in literature [10]-[13]. Inverter system used, converts stored energy DC to AC.

Voltage source inverter used in the DVR has many different structures. Various structures provided for DVR. A bunch of the structure use of a parallel converter to supply the required voltage dc link. That this parallel converter can be placed on the load or source. Other categories use of energy storage elements that can constant dc link voltage by using of dc to dc converter. Batch simultaneous use of a shunt converter and a dc-dc converter. VSI converter is the main structural element of DVR. This converter despite the advantages such output voltage with waveform appropriate, have number of disadvantages. Output ac voltage limited in input dc voltage. Can't go beyond it. and in other words input dc voltage must be greater than the input ac voltage, thus voltage source converter in turn dc to ac is reducing converter. And is one increasing converter in turn ac to dc. Up and down keys on the legs what have target and what are caused by electromagnetic interference can't simultaneously be turned on. In the case of this phenomenon, Short circuit occurred (shoot- through) and keys damaged Source impedance converter use of unique impedance network that can be connected the main circuit power to power supply, load or any other converter, and thus to create unique features that can't be expected in traditional voltage source or current that use of an inductor or a capacitor. The impedance source converter overcome on mentioned problems for current source converters and offers a new concept of power conversion [9],[10],[14],[15].

3. DIFFERENT TYPES OF DVR

DVR structure can be considered from two different aspects. There is a general division, where the focus is how to connect the DVR and other is DVR structures of point of view the inverter which can be used in the DVR structure. Conceptually DVR acts so; that the voltage load remains at its nominal value. During sag / swell voltage, DVR injects a voltage to the grid voltage for restorer voltage load. In this case DVR exchange of active and reactive power with Systems that are connected. If the active power injected into the network by DVR , DVR required source for this power. Here there are two possibilities. One is that provide this energy from an energy storage element and other is that this get the energy required from the main network. The stored energy can be provided from different energy storage systems such as battery, capacitor, fly wheel or SMES. Without energy storage element for topology, DVR hasn't energy storage element, and instead required energy is received from the network. In general, DVR can generally be divided into the following topologies [11].

3.1. Topologies without energy storage element

Structure 1: Energy from the main grid provided by a shunt passive converter that connected towards the source (Figure 3). In this structure the dc-link voltage cannot control. And shunt converter will be charged dc link to the actual voltage source. Dc-link voltage is approximately equal to the phase-phase peak voltage source dc-link voltage. During voltage sags, dc link voltage will reduce the amount of voltage sags.

Structure 2: Energy provide of main grid by a shunt passive converter that connected towards the load (Figure 4). Shunt converter input voltage control with this structure and dc voltage link can be kept almost constant. This structure has this disadvantage that the series converters have pass more flow through it which leads to an increase nominal values of this converters. For example, if the source voltage is reduced to 0.3 pu. the current through the series and parallel converters is 2.33 and 3.33 respectively. In addition, the load voltage can be disturbed by a nonlinear flow which drawn by the shunt converter. However, with this structure dc-link voltage can be maintained constant.

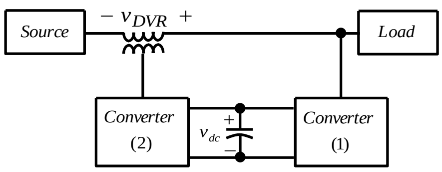


Figure 3. source side connected

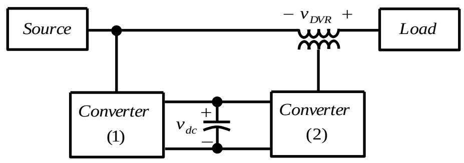


Figure 4. load side connected

3.2. Topologies with energy storage element

Structure 3: Energy stored in the dc link and dc-link voltage is variable. The energy stored in the capacitor dc and dc-link voltage is variable, in this structure, the energy stored in a capacitor dc voltage is used to compensate for the voltage dip. Since this capacitor is not connected to any other external source. Voltage decreases with energy consumption during voltage sags. In This structure, the converter is relatively simple and dc link can be charged with using of converter series at normal network operation mode which hasn't required to additional elements charge.

Structure 4: energy transformed from an energy storage by a dc-dc converter to the dc link. In this case structure can be maintained constant dc-link voltage (Figure 6). These typologies are different in terms of performance, complexity, cost and control. Various dc energy storage elements can be used in the DVR. In this structure, a high power converter required to transfer energy from energy storage to dc link with a nominal value of less. As the dc-link voltage can be maintained in this structure. Performance of this structure improved rather than structure 3. But this structure has high cost due to the use of auxiliary energy storage elements and additional power converter.

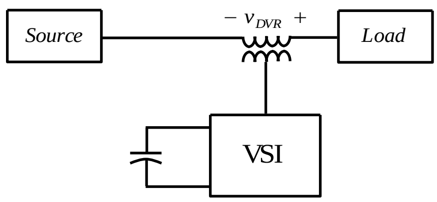


Figure 5. DVR based on self-charging capacitor of grid (structure 3)

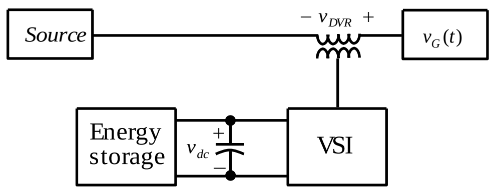


Figure 6. DVR with foreign energy storage connected to the link dc (structure 4)

3.3. Types of DVRs in term of converters used in their structure

Since the terms of converters used in the DVRs structure, they can be divided in two general categories (Figure 7). The first category are DVRs based on two-level converters and two categories are based on multilevel converters. Each of these structures has advantages and disadvantages, and on which depends heavily on the type of inverter used in the DVR, DVR's operating voltage. Usually In low voltage applications use of the DVR-based on two-level converters. Two-level inverter work with the lowest number of key business and therefore are suitable for low voltage levels. For high power applications that medium-voltage power electronic devices connected to the network, using two-level converters seem to be a problem because power electronic keys must work at much higher voltages. In addition, produce a lot of harmonic content that need a filter to remove theme and Electromagnetic Interference (EMI) occur. To solve these problems, interesting solution is the use of multilevel voltage source converters [12].

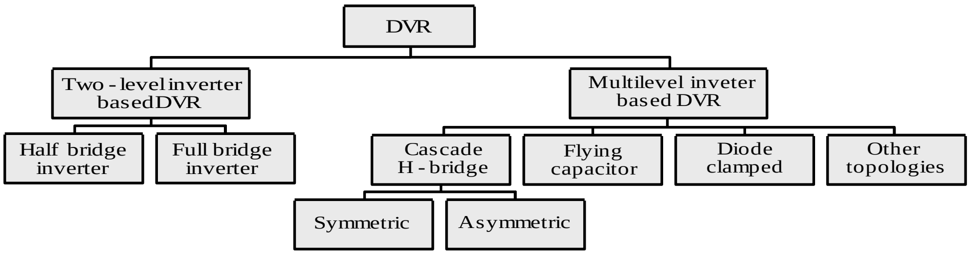


Figure 7. DVR category in terms of inverter which used in their structure

3.4. Dynamic Voltage Restorer structure based on impedance sources converters

More of DVR structures are based on VSI converters. That fed of one dc link and without middle stage between the inverter and dc link. One of the main disadvantages of these structures is low interest inverter and thus reduce its ability to compensate low the DVR. This problem is especially effective when the dc-link voltage is less than a limiting value, and causes the DVR fails to complete compensation. To deal with this problem, a method is to use a dc-dc boost converter and inverter [16]. This added an additional converter class and increases losses and complexity of control. Suitable method is the use of impedance source inverter [17]. So far have been proposed Impedance source inverter based on a variety of structures. By changing the right time to short bonding mode and short non bonding mode optimum performance DVR can save energy when the DC voltage is low, be maintained; therefore, this method can be used with arrows, with a duration longer than methods conventional offset. Previous structure was investigated is based on energy storage. In reference [18] DVR is based on impedance source inverter that fed by the rectifier circuit is provided. This structure is shown in the Figure 8. In this structure DVR feeds from the network and therefore not requires external energy storage. This system helps to reduce costs, but with this action DVR in the range of voltage sag compensation greater flow of liner. As the depth of voltage sag more and network impedance be more voltage drops, there will be a greater voltage in line impedance. Additional structures are provided structures that are based on impedance source AC-AC converters. The structure proposed in reference [19] which is shown in the Figure 9. A DVR based on single-phase AC-AC converter .This converter actually is two bilateral keys that network impedance is located between the two keys. As mentioned in the relevant reference, this structure has the ability to compensate for voltage sag more than 50 percent. Provided structure in reference [20] is based on quasi Z-source AC-AC converter that shown in Figure 10.

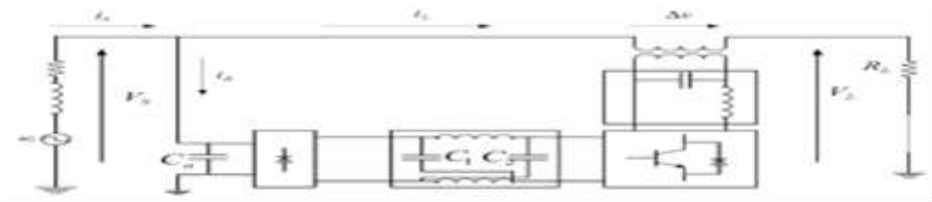


Figure 8. DVR based on impedance source inverter that feeds from the network

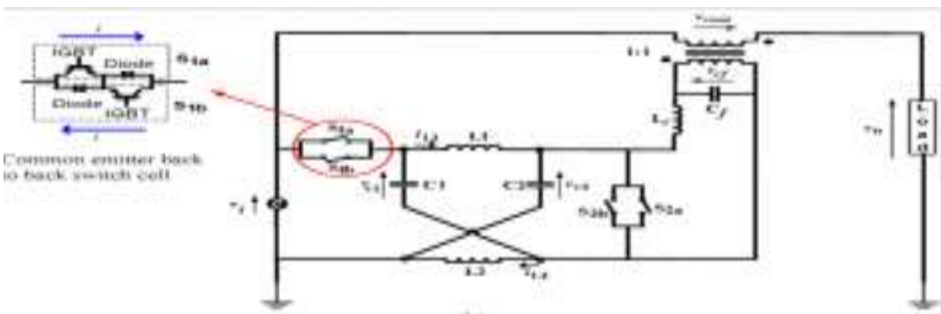


Figure 9. DVR based on single-phase AC-AC impedance source converter

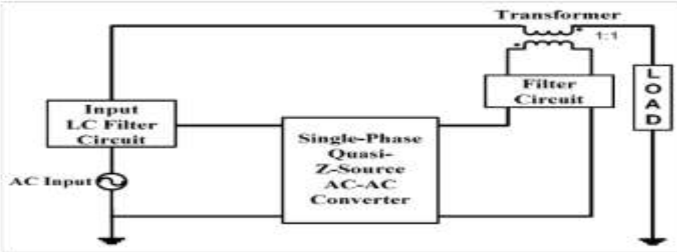


Figure 10. DVR based on single-phase quasi Z-source AC-AC impedance source converter

After introducing the different structures of impedance source converters we will pay to the different control methods that used in dynamic voltage restorer. Γ-Source Inverters also is a member of the family of impedance source converters that benefited from high gain. After a brief introduction of different structures of DVR and according to the above we will pay to introduce a new structure for DVR by using of Γ-Source asymmetric converter.

4. ASYMMETRICAL Γ-SOURCE CONVERTERS [13]

Inverter with an asymmetric Γ-Source is shown in the Figure 11.This structure has been determined something different states in Figure 12. This type of inverter, contains: transformer coupled, two capacitors, and inductor. Performance of This structure is similar to traditional Z-Source converters and Trans-Z- Source converters.

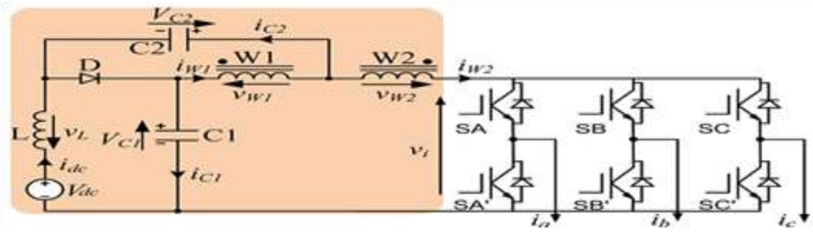
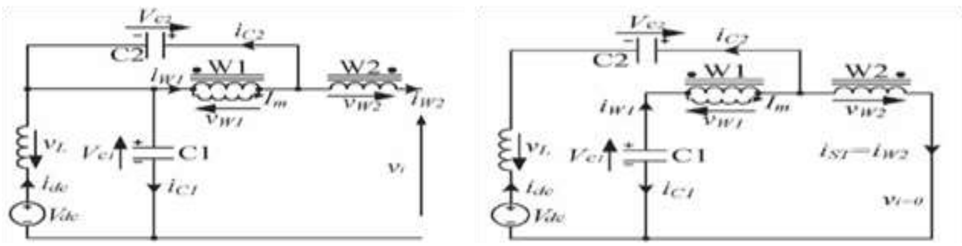


Figure 11. structure of asymmetrical Γ-Source converter



(a) (b)

Figure 12. operating different modes of Γ-Source asymmetrical inverter:
(a) in mode through-Shoot, and (b) in mode Non-Shoot- through

This means that it can be assumed that there is the eight Non-Shoot- through active and neutral state and Shoot-though mode the unit is to increase the voltage. So it can be controlled with same parameters of modulation and the same method with Z-Source [13]. With regard to the high gain of this converters, can be a good candidate for use in DVR, because it can be compensated the severe voltage dip. Short circuit state in the Figure 11 happens by turning on two switches one leg. This work causes diode reverse bias and capacitors discharge into inductor and transformer. Corresponding voltages and currents can be written as:

$$v_{W1} = v_{W2} + V_{C1},\ \ V_{C2} + v_{W2} + V_{dc} = v_L \tag{3}$$

$$v_{W1} = n_\Gamma v_{W2}\ , n_\Gamma = \frac{W_1}{W_2} \tag{4}$$

$$i_{C2} = -I_{dc} = i_{W1} - i_{W2} \tag{5}$$

$$i_{C1} = -i_{W1}, i_{W1} = \frac{i_{W2}}{n_\Gamma} + I_m \tag{6}$$

If one of the non-shorting modes, then diode D conducts and two capacitors will be charged. At this time the energy of the inductor and transformer discharges towards the load.

4.1. Modeling and Simulation of Asymmetrical Γ-Source converters

As it was mentioned, Γ- converters are types of impedance source converters which contain less passive components as well as transformers with the number of less turns ratio. The low cost of these converters and their similar control to that of other impedance converters, make them a suitable selection to apply in industrial applications like drives and so on. Simulation in this section is based on the convertor shown in Figure 13. Of course to amplify the converter's output voltage level, it is recommended to use multi-level converter instead of two-level converter. It should be noted that to increase the voltage output gain, the turns ratio must be increased. This is the biggest and the most important difference with the structure shown in Figure 11.

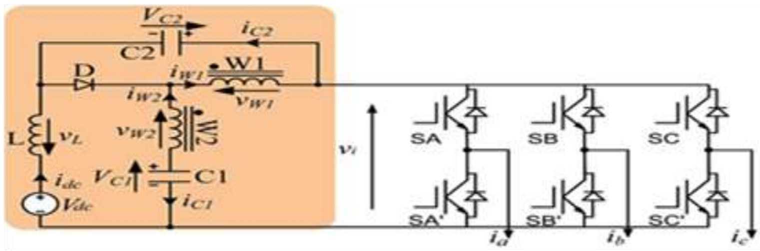


Figure 13. Another structure of asymmetric Γ-Source converter

Modelling of the impedance source converter and its related switching patterns are done by MATLAB/Simulink. PWM modulation technique is considered to switching the converter. To amplify the voltage levels, it is recommended to use Γ- source impedance multilevel converter. Beside amplifying voltage, this causes amount of the output current and voltage harmonics to reduce. In this way, the formation of switching pulses for a Γ- source impedance three-level converter is shown in Figure 14 by software of SIMULINK. As seen, to produce necessary switching pulses, first the reference sinusoidal waveform is formed, then by comparing it to that of a triangular waveform, the switching pulses are generate. In switching strategy, short-circuit times must be determined.

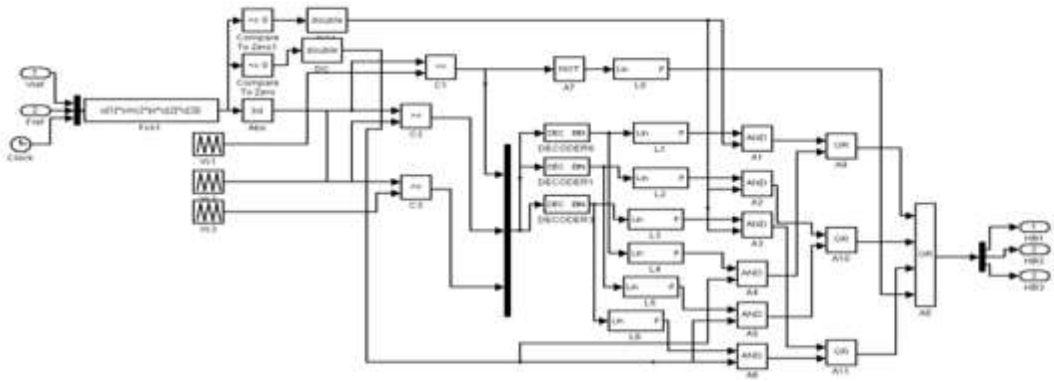


Figure 14. creating modulation pulses for Γ- source impedance multilevel converter

Figure 15 shows the comparison of the forms of the reference sinusoidal waveform (which should be generated at the output of the converter) and the triangular waveform (to generate the applied switching pulses). The frequency of the triangular waveform is 5 kHz and the frequency of the reference wave is 50 Hz. In Figure 16 the load-current waveform (output current of Γ- source impedance converter), and in Figure 17 the load -voltage waveform (output voltage of Γ- source impedance converter) are shown:

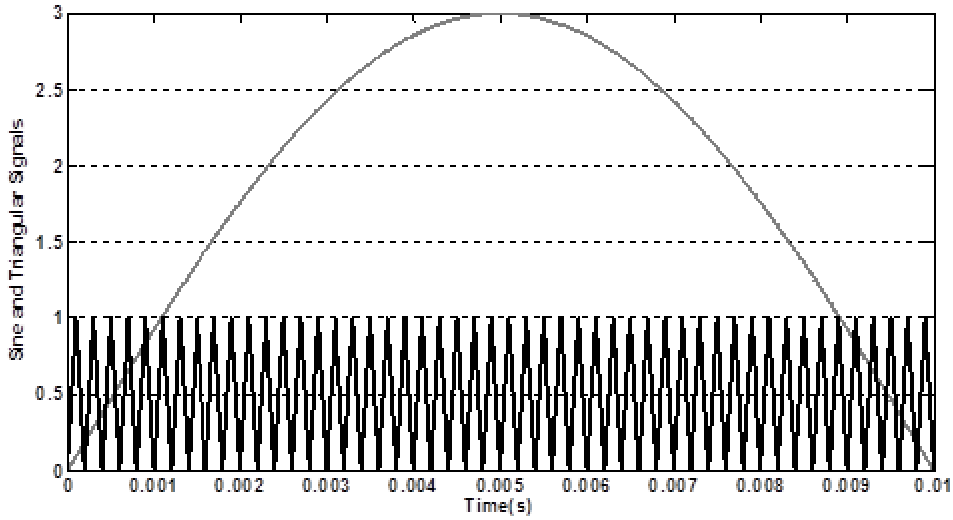


Figure 15. Comparison between reference sinusoidal waveform and triangular waveform to generate switching pulses

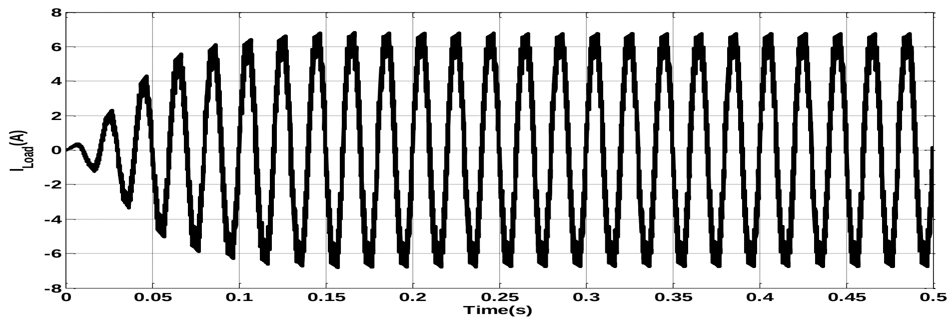


Figure 16. Load current waveform (output current of Γ- impedance source converter)

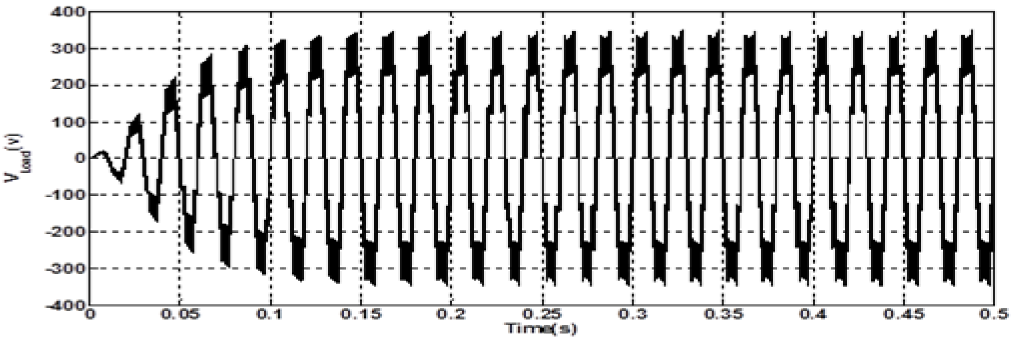


Figure 17. Load voltage waveform (output voltage of Γ- impedance source converter)

Fourier analysis of the output voltage waveform and the calculation of the system's THD are shown in Figure 18. Accordingly, THD for this converter while any filter is not installed at the input or output, is about 22/75 percent which is quite acceptable.

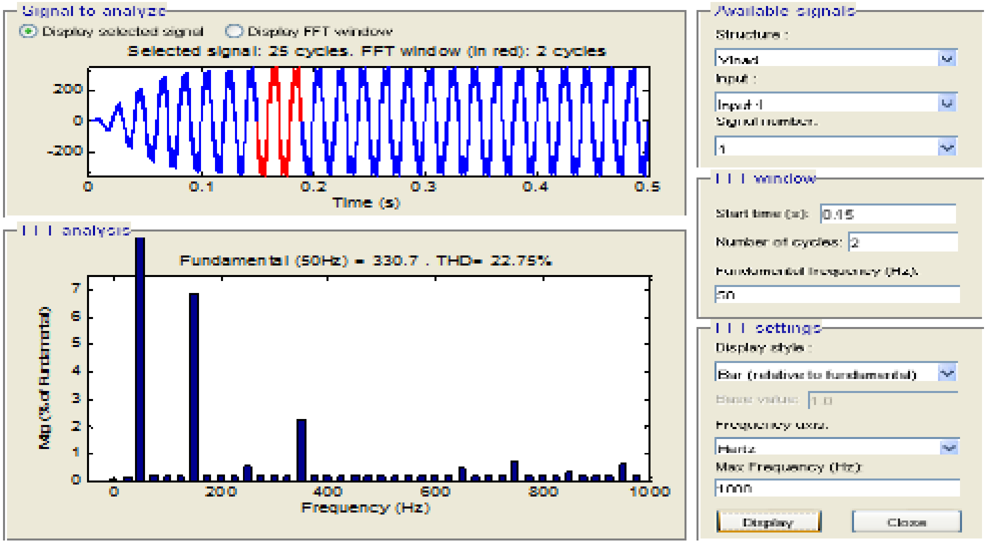


Figure 18. Fourier analysis and calculate THD

5. STRATEGY OF CONTROL

Control system design is of great importance in DVR structure as this section specifies response time and ways of voltage sag compensation. to infer control signal parameters such as amplitude, frequency, phase shift and so control circuits are utilized on which are injected by DVR. The injected voltage is generated by present inverters considering control signals. Control schemes for DVR either closed loop or open loop can be used. Closed loop approach outperforms while is more complicated and non-cost-effective. Here, open loop scheme is explicated.

Three phase voltage of the source similar to SPLL is transformed to two phase; then, values are obtained in synchronous reference frame (Vq, Vd) where values are DC and constant. These values get smaller while voltage sag and the difference between their values before sag and while voltage sag will generate an error signal (Vq error, Vd error). The required pulses for switching of inverter are obtained Using inverse of the mentioned transforms and the same angle estimated by SPLL, obtained. In fact, information about voltage supply phase and amplitude are essential for DVR. SPLL is adopted to evaluate phase of voltage supply.

In case of occurring single phase to ground short circuit fault, positive, negative and zero sequences will be generated in voltage, in turn, results in errors in phase measurement [7]. It should be noted that to eliminate the shifting effect of injection transformer shift block is applied. As simulation results showed, DVR can appropriately compensate for three phase and single phase short circuit faults as well. For DVR control of dq method is used, see (Figure 19). Therefore, the first phase and frequency of the grid voltage (Vabc) calculated by using a phase-locked loop (PLL) circuit. Proportional to the network voltage in output PLL a signal that named (Sin–Cos) that is the in phase or perpendicular to network voltage. That used to apply to the conversion (abc) to the (dq), and as a result, the grid voltage is converted into quadrature component d and q.

In normal mode when there is no any disturbance in the grid voltage, amount of the d-axis component must be equal to the network peak voltage (in this paper voltage peak considered equal to 311 V). So d-axis component compared with the voltage peak and error used to reverse convert of orthogonal component to 3-phase voltage. Q-axis in the presence of harmonics will have a value, the inverter must be injected symmetry of this harmonic. Therefore q-axis component must be transferred directly and without comparison. After converting 2 to 3 generated signals as sinusoidal signals for PWM method because of system has more accurate response, compared with a voltage that inverter injects at any moment. These signals are compared with the carrier wave and compared to the inverter switching.

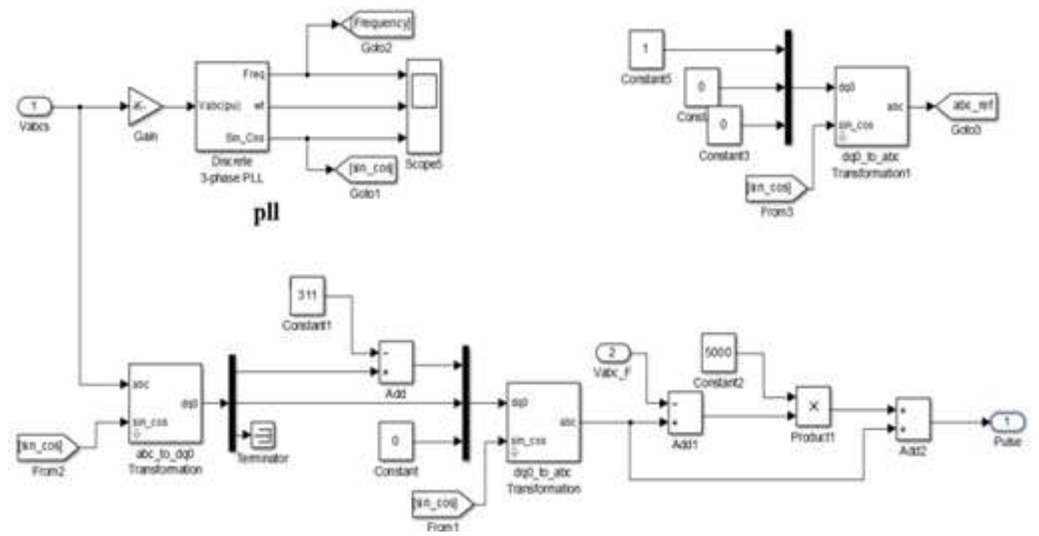


Figure 19. Control of DVR by dq method

For converting a three-phase waveforms to a waveform in the dq reference system, can be easily applied to the following formula:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \times \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{8}$$

Block diagram that did this transformation according to the following figure is shown.

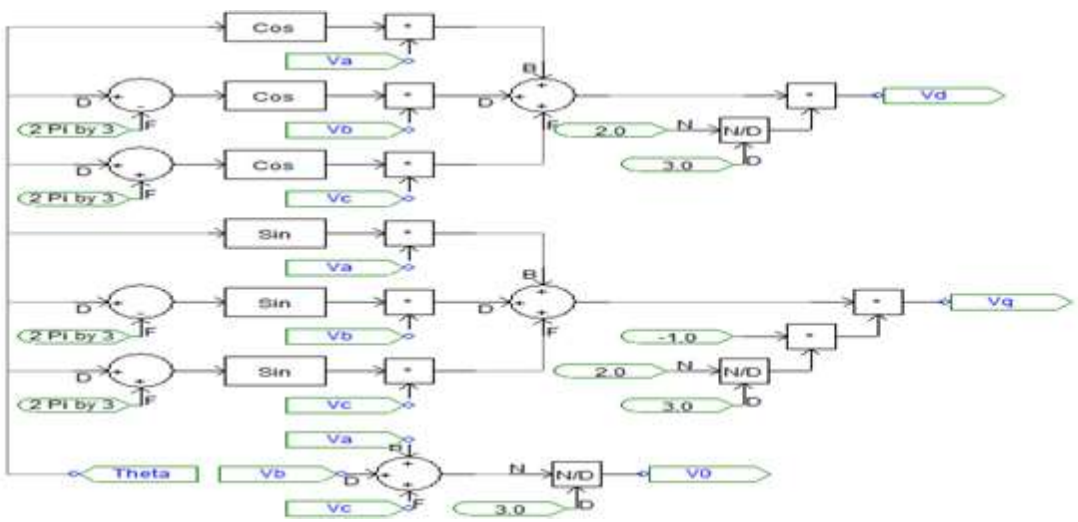


Figure 20. Block Diagram of reference conversion abc to dq

6. SIMULATION

The proposed structure based on asymmetrical Γ-Source inverter of family of impedance source converters has been identified in Figure 21. This structure shows a three-phase network that feeds a three-phase load. The structure of the DVR through a three-phase diode rectifier, Provides required dc voltage for Γ-Source inverter. As well as an injection transformer of voltage to network is also used.

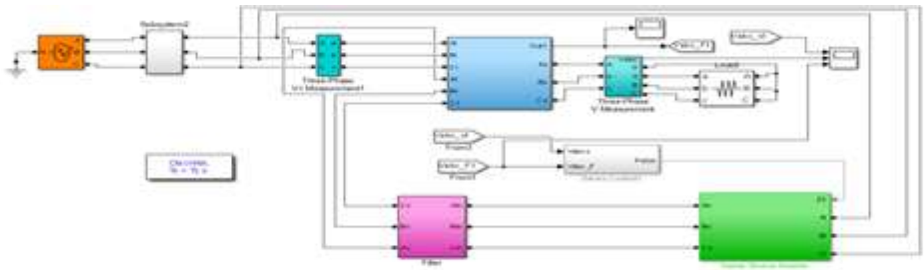


Figure 21. Actual schemes of the proposed structure in the MATLAB /Simulink

Because the inverter output voltages and currents have the components of the switching frequency, usually used a LC filter to remove of high frequency harmonics. LC filter simulated and injection transformer are illustrated in Figure 22 and Figure 23.

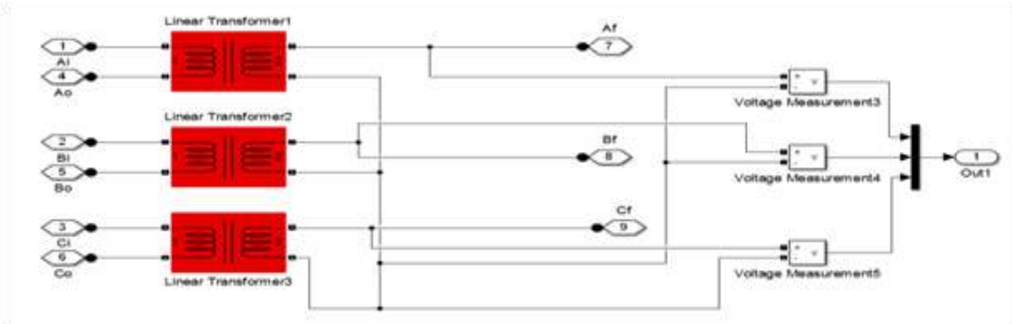


Figure 22. Schematics of simulated in the MATLAB / SIMULINK (LC filter)

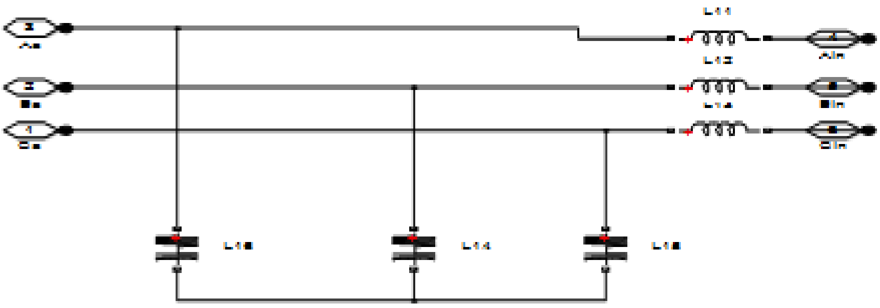


Figure 23. Schematics of simulated in the MATLAB/Simulink (injection transformer)

7. SIMULATION RESULTS

To evaluate the performance of dynamic voltage restorer system proposed by Γ-Source asymmetrical inverter, the system is under severe three-phase voltage sag and voltage asymmetry phenomenon and under harmonic and distortion has been investigated. Simulated network various parameters is shown in Table 1.

Table 1. Parameters of the simulated system

Parameters	Value
Rated voltage	380v
Nominal supply frequency	50Hz
Carrier wave frequency	6Kz
Three-phase load	6Ω
Inverter capacitors	465µf
Inverter inductor	1mh
Inverter transformer windings ratio	1.5
Filter capacitor	60 µf
Filter inductor	2.99 mH

7.1. Voltage sags in all three-phases

In this case study assumes that, voltage in all three phases has dropped 80 percent that this is due to short circuit and any faults in the distribution network. Figure 24 shows the grid voltage, and load voltage and injection voltage by Γ-Source inverter under this voltage disturbance. As expected with appropriate injection of the proposed DVR structure even during severe voltage dips, load this voltage dip has not felt.

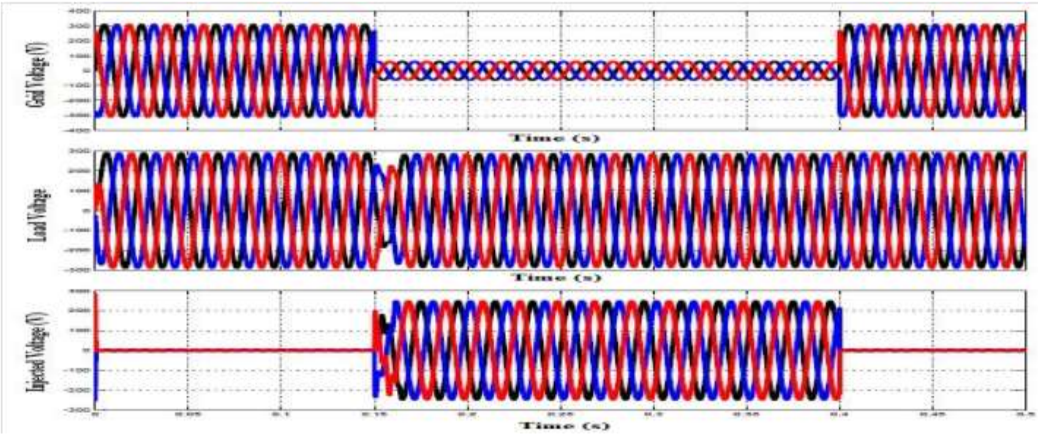


Figure 24. grid voltages, injection load and voltage under severe three-phase voltage sag

7.2. Unbalanced and severe voltage dip

For evaluation the proposed model under a phase voltage unbalance is assumed that the amplitude of a phase has remained unchanged and two other phase one by 50 percent and another 80 percent had a voltage drop. Figure 25 shows grid voltages and injected load voltage under these disturbances and expresses the correct and effective operation of the proposed structure.

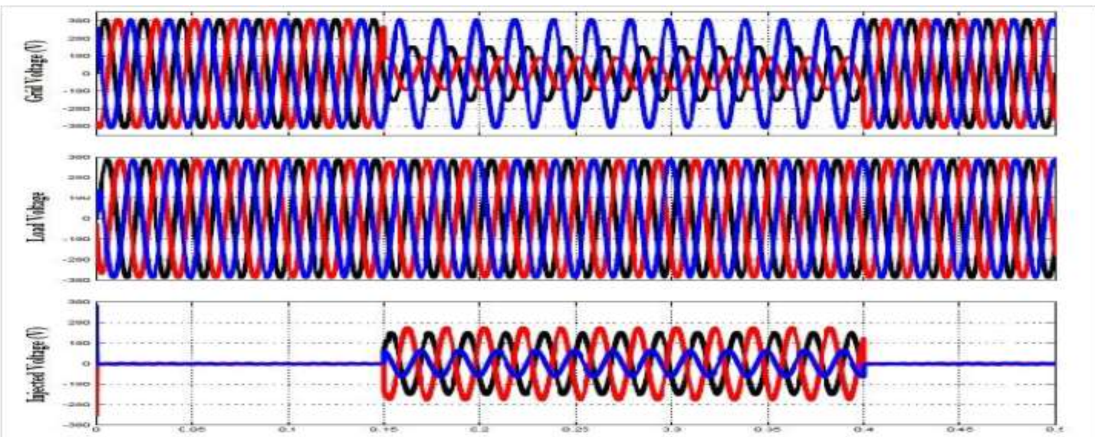


Figure 25. Grid voltages; injection load and voltage under voltage drop and unbalanced Severe voltage

7.3. Harmonic disturbances in the network

For various reasons such as the presence of power electronics devices and rectifiers, low-power lamps and drives of electric motors, power systems have distortion in voltage and current. To evaluate the proposed system in this paper, it is assumed that there is the third harmonic with 0.3pu and fifth harmonic with the size of the 0.2pu in network. Figure 26 shows the grid voltage under these harmonics. The proposed DVR system also well apply the symmetric harmonic for neutralization, and you see load, and voltage with constant amplitude and frequency of 50Hz and load voltage is totally sinusoidal.

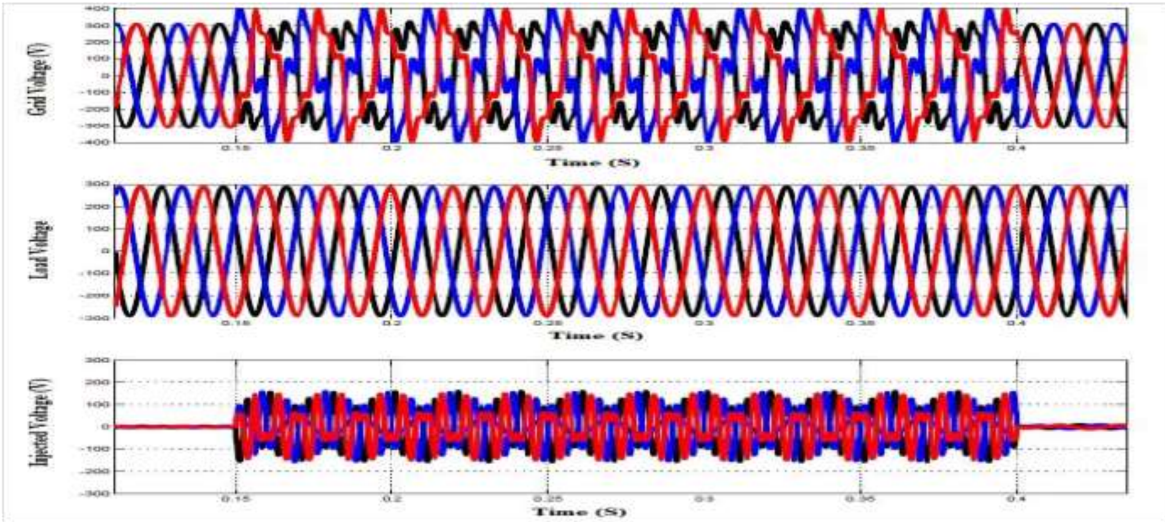


Figure 26. Network voltages, load and injected voltage under the third and fifth harmonics with amplitudes of 0.3pu and 0.2pu

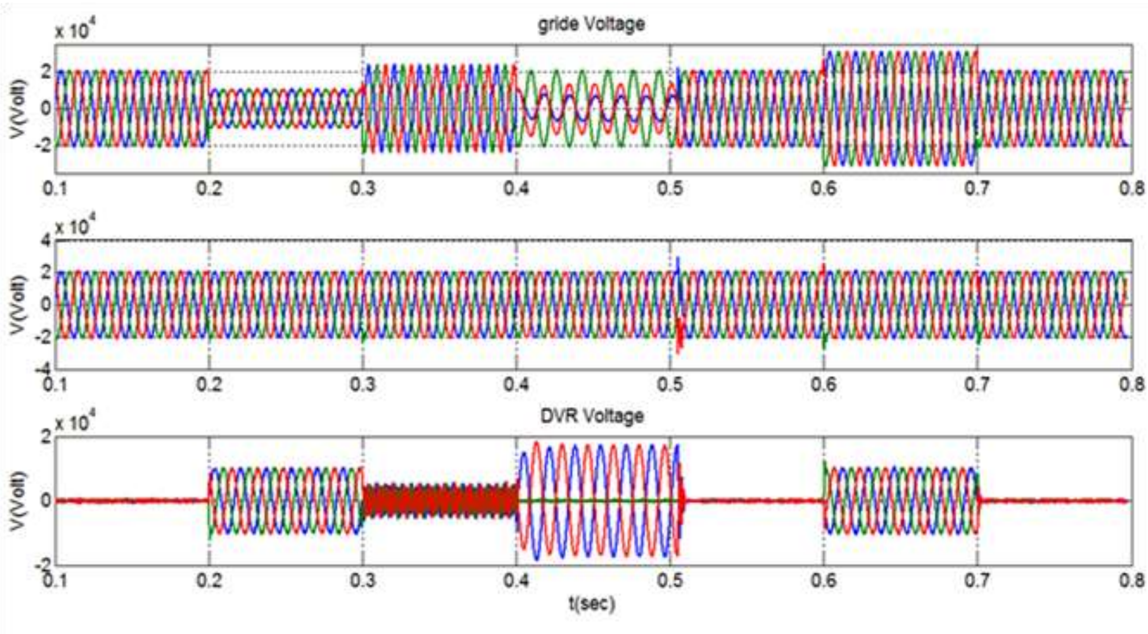


Figure 27. grid voltage, Compensated voltage by DVR , injected voltage by DVR

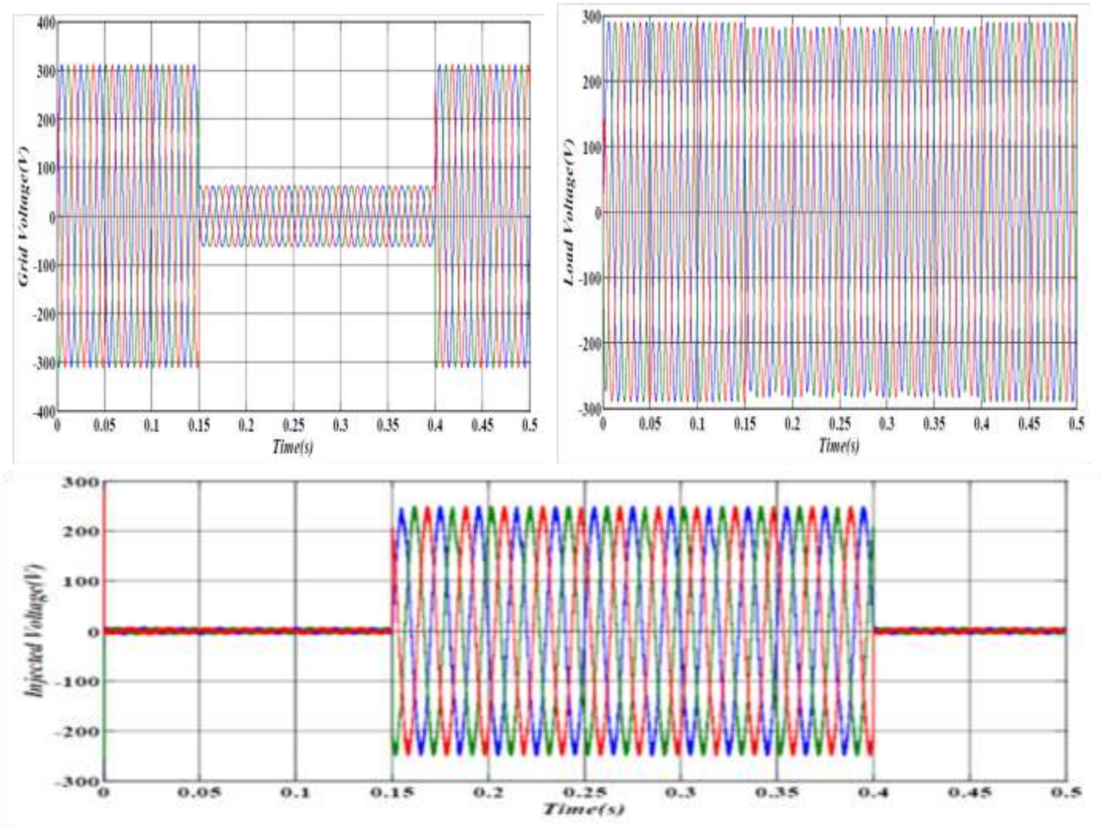


Figure 28. Grid voltages, injection load and voltage under system sever voltage sag (Γ-Source)

8. CONCLUSION

As mentioned before, the existence of sensitive loads in the network needs to challenge with the voltage disturbances and doing this is necessary. This article introduces the structure of the DVRs as a fundamental solution for challenge with voltage disturbances. By evaluating the introduced Structures some notes can be gotten. Topologies without energy storage element used the fact that the remaining voltage on the source side during voltage sags can provide the rated voltage. This approach has the disadvantage that compensation takes more current during the fault of the network and therefore more voltage drop will experience high loads manually. On the other hand, there is no need for energy storage element and the economy will be more cost-effective. In addition, the lack of long-term voltages can be compensated with the typologies. Especially when the DVR is connected to a relatively strong network. Power that required to load in flaw could increase the current drawn from the source and inject the appropriate voltage of the supply network. Different structures of DVR based on impedance converters were introduced and in this regard from a asymmetrical Γ-Source inverter have been added recently to the family of impedance sources converters is used to create new structures in DVR. This structure has a very good performance because of high voltage and as is clear from the simulation results, under severe voltage drop, and even 80% drop in voltage, have the voltage recovers and before the even error operation is located continues with the same voltage range before. It also conducts assessments, the proposed structure in a severe unbalanced voltage, under voltage restorer as well as distortion in the voltage waveform has been successful and load continuously understands the sinusoidal voltage with the constant amplitude and frequency of 50 Hz.

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BIOGRAPHIES OF AUTHORS

Mahmoud Zadehbagheri was born in Yasouj, Iran in October 1979. In 2003 he received his B.S. in Electrical Engineering from Kashan University and in 2008 he received his M.S. in Electrical Engineering from the Islamic Azad University, Najafabad Branch, he is currently pursuing your PhD at Sabzevar university. He is with the faculty of the Electrical Engineering Department, Islamic Azad University of Yasouj. His research interests includes the fields of power electronics, electrical machines and drives, FACTS devices and Power Quality.

Rahim Ildarabadi was born in Sabzevar, Iran in 1975. He received the PhD degree from Ferdowsi University of Mashhad in 2010. He is a full time faculty member at Sabzevar Hkim Sabzevari University. His main area of interest are automation system, electrical machine derive, renewable energy, instruments and measurement. He is currently an Assistant Professor of electrical engineering at Hakim Sabzevari University.

Majid Baghaei Nejad received the B.S. and M.Sc degree in electrical engineering from Ferdowsi University, and Tarbiat Modares University, Iran, in 1996 and 2000 respectively, and his PhD degree in electronic and computer systems from Royal Institute of Technology (KTH), Stockholm, Sweden in 2008. Since 2000 he has been with electronics department at Hakim Sabzevari University, Iran, where currently has an assistance professor position. His current research work includes low power analog/RF integrated circuit design, ultra wideband communication, RFID systems and wireless sensing.

Tole Sutikno (M'07) received the B.Eng. degree in electrical engineering from Diponegoro University (UNDIP), Semarang, Indonesia, in 1999, and the M.Eng. degree in power electronics from Gadjah Mada University (UGM), Yogyakarta, Indonesia, in 2004. He is currently working toward the Ph.D. degree in the Department of Energy Conversion, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Skudai, Malaysia. Since 2001, he has been a Lecturer in the Electrical Engineering Department, Universitas Ahmad Dahlan, Yogyakarta. His research interests include the fields of power electronics, motor drive systems, and field programmable gate array applications.