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# DVR with Auxiliary DC Voltage Source Provided by A High Power Diode Based Rectifier Used in MV Connection Substations

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*Abstract* - **This paper presents the Dynamic Voltage Restorer (DVR) response study in cases of voltage sags occurrence in the electrical distribution networks with connection substation topology. Usually, these voltage disturbances are caused by faults that can occur on the lines connected to the same bus bar as the main feeder or even on main feeder of connection substation. A DVR that uses a diode based rectifier as a DC voltage source, supplied by the back-up feeder of connection substation, has been modeled in Matlab/Simulink. Severe faults on the lines adjacent to main feeder and back-up feeder and also faults on main feeder, with real impact for the magnitude of voltage supplied to end-users connected to the electrical network downstream of the connection substation bus bars, have been simulated. The DVR response has been studied for these fault conditions. The obtained results prove the effectiveness of the chosen topology of this series Custom Power device for voltage magnitude disturbances mitigation in distribution networks.**

*Keywords*: **dynamic voltage restorer (DVR), diode based rectifier, series custom power device, voltage magnitude disturbances.**

## I. INTRODUCTION

Electricity is a special product whose quality cannot be evaluated before its use. Usually, it is transported on long distances through transmission and distribution networks and, due to power system complexity and because other thousands of consumers, with different electrical characteristics, absorb simultaneously electricity from the network, there are many factors that are influencing the quality of this product [1]

Nowadays, an important process that occurs in the electricity distribution domain is the replacement of old equipments from electricity user plants. The replacement occurs in industrial, residential and public lighting sector. This replacement of old equipment is determined, on the one hand by the fast development of information technology equipment and, on the other hand by saving energy and improving electrical performances process. Changing the equipments in the user plans affects power quality and influences the performance of electrical classic networks. Also, the widespread use of renewable energy sources and the new equipments used to convert the primary energy into electricity has required the use of new classes of static power devices able to respond to the new energy sources dynamism. The continuous development of electronics has enabled the realization of some of equipments able to limit disturbances, equipments that incorporate in their structure high power electronic components called power converters. In order to transfer energy efficiently, a power converter must operate in a switching mode and not with a linear operation. Therefore, in electricity sector, power converters are also called "power sources operating in a switching mode". In order to control and transfer the energy flow through converter, the idea beyond each power converter is to split the continuous energy flow in small packets, to process these packets and deliver energy into another form, in a continuous mode. That’s why the converters topology must respect the main principles of electric circuit theory [2].

For protecting both sources and loads, the power flow at the input and output terminals of converter must be continuous and without any harmonics and noise signals [3]. Also, the choosing of switching frequency for converter is very important. A higher frequency requires the use of smaller passive elements and filters. That’s why, all converter producers tend to increase the switching frequency in order to reduce the production costs. But, using high frequency may negatively influence the converter efficiency. So, a balance between the materials cost, production cost and efficiency must be found, because the efficiency influences the price of energy loss during conversion process for entire operation life of converter [4].

The purpose of this study is to describe the effectiveness of DVR with auxiliary dc voltage source provided by a diode based power rectifier.

## II. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer was developed by Westinghouse as part of EPRI Custom Power program for advanced electric distribution networks [5] and it is a series grid connected device. In fact, this equipment is an AC-DC solid state power converter, which injects a three-phase alternative voltage set in series with the electric distribution line voltage. This voltage set is synchronized with the distribution network voltage. By injecting into the grid these voltages, real-time controlled in amplitude, phase and frequency, the Dynamic Voltage Restorer is able to improve the voltage quality at the users' terminals when the voltage provided by power supply is not adequate in terms of quality, in order to ensure the correct operation for sensitive loads.

The main parameters that should be analyzed when choosing a DVR are: its ability to inject voltage, the maximum current supported by its components and the size of energy storage system [6]. In order to reduce the implementation costs and losses in the blank operation, the capacity to inject voltage should be chosen as low as possible, following an accurate analysis regarding the amplitude of voltage dips that may occur at the point of common coupling. The main factors that determine the choosing of rated electrical current of DVR are the maximum power supported by the voltage source converter and the effective value of electrical current through the network. Choosing connection transformers is another important aspect. Transformation ratio can be sized according to the rated voltage of converter from DVR structure and rated voltage value for the network at the point of common coupling. Also, the winding inductive impedance must be chosen carefully, closely related to inductive and capacitive impedances of the filters placed at the inverter terminals, in order to compensate harmonic pollution generated by static switching elements. Making filters is tightly coordinated to their sizing and how their implementation affects the performance of Dynamic Voltage Restorer.

## III. THE STRUCTURE OF TEST SYSTEM

In order to prove the beneficial impact of the DVRs' use, the chosen test system has represented as a medium voltage network with a looped structure, but with a radial operation. The DVR has been implemented in electricity distribution network into a node known as connection substation.

The connection substation has two sources represented as double line underground feeders and five distributor lines are supplied by the MV bus bar of connection substation.

The MV feeders are connected to MV bus bar of two different HV/MV power substations. Two medium voltage/low voltage power transformers installed in connection substation, were providing power for low voltage loads from surrounding area of connection substation location and for auxiliary services of connection substation. The single-phase diagram of test electricity distribution system is shown in Fig. 1.

Due to the fact that the energy necessary for DC link is provided from distribution electricity network through a rectifier bridge, the equivalent capacity for capacitors bank, connected to the DC link of DVR, may be reduced. A reactor with a proper value of inductance, chosen to provide a fast recharging of capacitor banks, is mounted at DC terminals of rectifiers' bridge, in order to ensure the protection of capacitor banks. In order to obtain an efficient mitigation of severs voltage sags, DVR must be equipped with a DC voltage source, for this case, this DC voltage source being provided by a high power diode based rectifier which is supplied from the back up bus bar of connection substation, through a power transformer used to reduce the voltage to a level supported by the rectifier. The single-phase diagram of DVRs' implementation into the test shown in Fig. 2.

In case of severe incidents as two phase or three phase faults, occurred on different MV lines fed from the same power substation bus bar as the main feeder of connection substation, end-users supplied through connection substation suffer voltage sag disturbances. This study scenario will be analyzed in terms of DVR implementation in the connection substation.

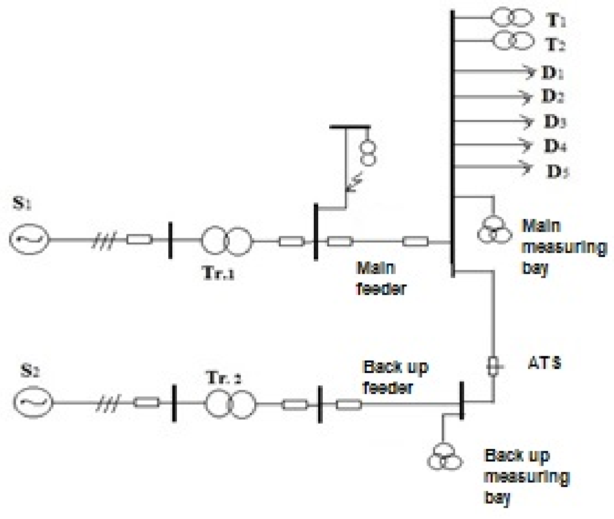


Fig. 1. Single-phase diagram of electricity distribution test.

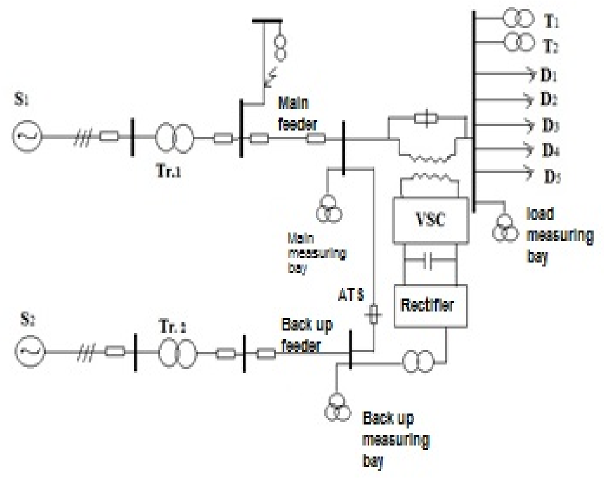


Fig. 2. Connection diagram for DVR having the DC voltage provided by a diode based rectifier, supplied from back up bus bar of connection substation.

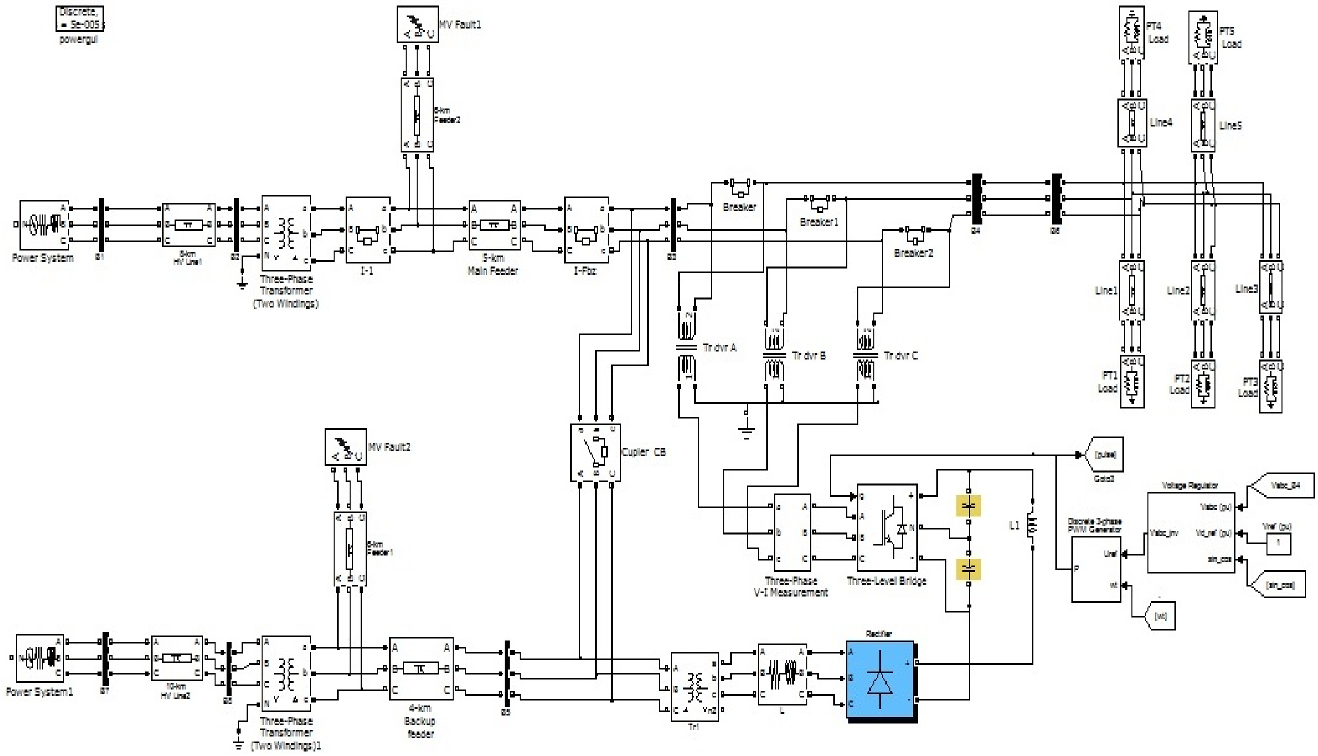


Fig. 3. Matlab/Simulink implementation of test system with DVR.

The proposed topology of DVR has an auxiliary DC voltage source provided by a high power diode based rectifier supplied by the back-up feeders' bus bar.

The DVR capability to mitigate voltage dip is studied using Matlab/Simulink. Each element of the test electrical network was been represented using blocks already implemented in the simulation software library. The Simulink implementation of the test system is shown in Fig. 3.

The voltage regulator that represents the DVR control system is described in [7] and [8]. The transformation of the tree-phase instantaneous voltage frame into synchronous-rotating *dq* reference frame and PI controllers have been used to obtain the voltage necessary to be injected by DVR into the network. The injected voltage is synchronized with the system voltage using a phase locked loop (PLL) module. The PWM technique was used to modulate the signal provided by voltage controller [7], [8]. The firing pulses for the inverters' insulated gate bipolar transistors are provided by a PWM generator.

## IV. DVRs' Response Analysis

The system response for the chosen topology of Dynamic Voltage Restorer, in case of a fault occurrence in a line adjacent to main feeder of connection substation, is presented in Fig. 4. A three-phase fault occurs into a line adjacent to main feeder at time t = 0. 2 s and is removed by the protection systems from VH/MV substation after 0.8 s. The PI controllers' coefficients used for this simulation are $K_P$=0.4 and $K_I$=5000.

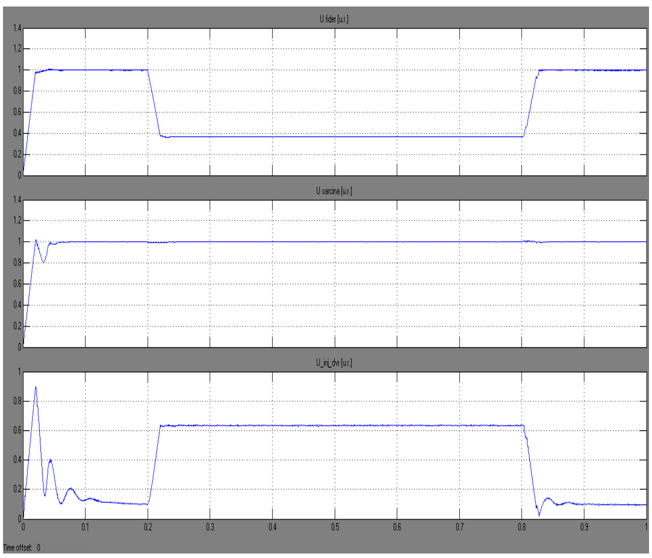

Fig. 4. The voltage magnitude variation for a three-phase fault occurrence in an electrical line adjacent to main feeder, with $K_P$=0,4, $K_I$=5000, for the rectifier-inverter topology of DVR: a) the main feeder voltage magnitude; b) voltage magnitude of loads bus bar of connection substation; c) magnitude of series voltage injected by DVR.

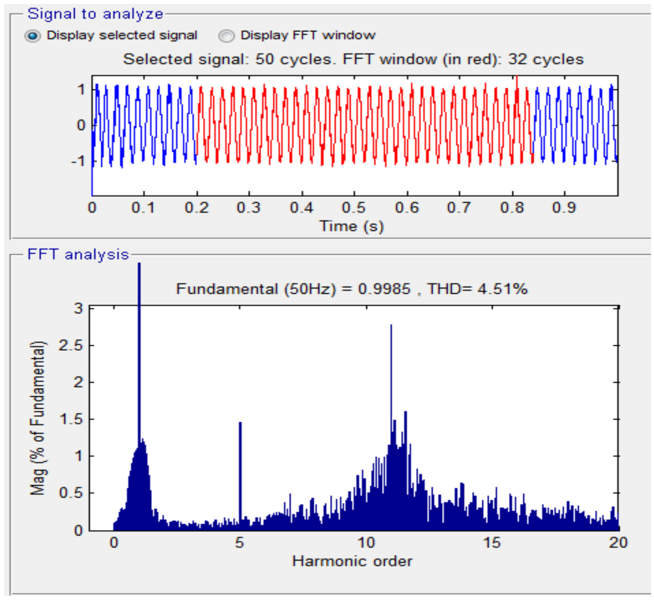


Fig. 5. Harmonic analysis for voltage wave, measured on loads bus bar of connection substation, in case of a three-phase fault occurrence in the electrical line adjacent to main feeder, for the rectifier-inverter topology of DVR, with $K_P$=0.4 and $K_I$=5000.

This chosen topology of DVR succeeds to mitigate voltage sags produced by faults occurrence in electrical lines adjacent to main feeder of connection substation. The frequencies spectrum of voltage wave measured on loads bus bar of connection substation, is presented in Fig. 5. It can be observed that total harmonic distortion reaches the 4.51% value, due to the high level of the $5^{th}$,$11^{th}$ and $12^{th}$ range harmonics.

The system response in case of a three-phase fault occurrence on the main feeder of connection substation is shown in Fig. 6.

After the fault occurrence time, the automatic transfer switch installed in the connection substation transfers the power supply from main feeder to the back-up feeder, with a 3.5 seconds timing. During this break time, the end users suffer an interruption.

The power supply interruption can be eliminated using a directional over-current protection installed in connection substation in order to operate the main feeder circuit breaker from the connection substation. The timing of this protection must be equal with the timing of protection installed in the main feeder bay from the HV/MV power substation.

The test system response assuming the solution previously presented is shown in Fig. 7. In order to test the DVR ability to compensate the voltage sags, it is supposed that, after the accelerated operation of the automatic transfer switch, due to opening command provided by the directional protection system of the main feeder bay from connection substation, another three-phase fault occurs in a line adjacent to back up feeder. At this moment, the back-up feeder represents the supply of connection substation, after the automatic transfer switch system operation.

Analyzing system response, it can be seen that, after the accelerated operation of automatic transfer switch system, the voltage magnitude enters into a maintained oscillations area and, after the fault occurrence on the line adjacent to back up feeder, the DVR response, provided during disturbance manifestation, is improved. After the fault insulation, the voltage magnitude starts a new instability domain.

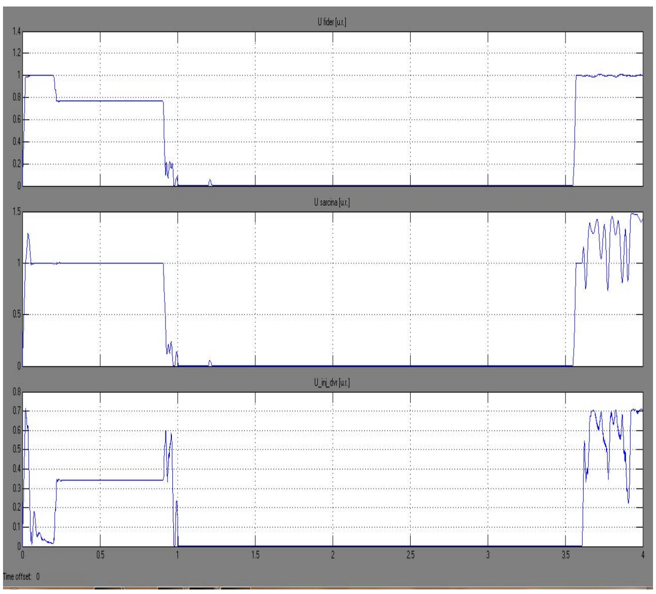

Fig. 6. The voltage magnitude variation for a three-phase fault occurrence on the main feeder, with $K_P$=0.4, $K_I$=5000, for the rectifier-inverter topology of DVR: a) the main feeder voltage magnitude; b) voltage magnitude of loads bus bar of connection substation; c) magnitude of series voltage injected by DVR.

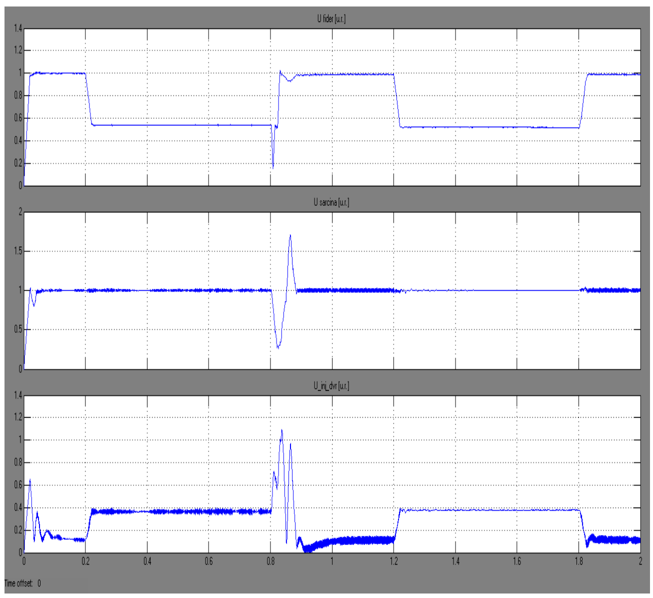

Fig. 7. The voltage magnitude variation for a three-phase fault occurrence in the main feeder, followed by a fault occurrence on an electrical line adjacent to back up feeder, after the ATS system operation, for the rectifier-inverter topology of DVR with $K_P$=0.4 and $K_I$=5000: a) the main feeder voltage magnitude; b) voltage magnitude for loads bus bar of connection substation; c) magnitude of series voltage injected by DVR.

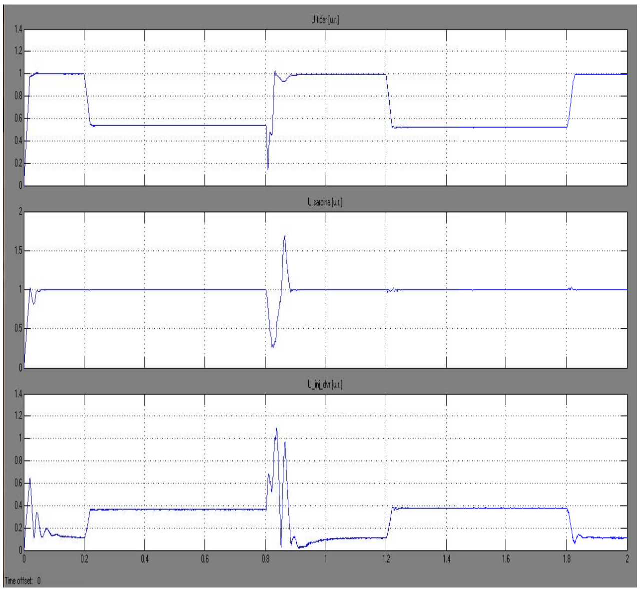

Fig. 8. The voltage magnitude variation for a three-phase fault occurrence in the main feeder, followed by a fault occurrence on an electrical line adjacent to back up feeder, after the ATS system operation, for the rectifier-inverter topology of DVR with $K_P$=0.4 and $K_I$=5000: a) the main feeder voltage magnitude; b) voltage magnitude for loads bus bar of connection substation; c) magnitude of series voltage injected by DVR.

An improvement of system response is obtained after modifying the voltage controller parameters, by increasing the $K_P$ to the value $K_P=1$, this improvement being observed in Fig. 8.

The frequencies spectrum for voltage waves on loads bus bar of connection substation, after the ATS system operation, is presented in Fig. 9.

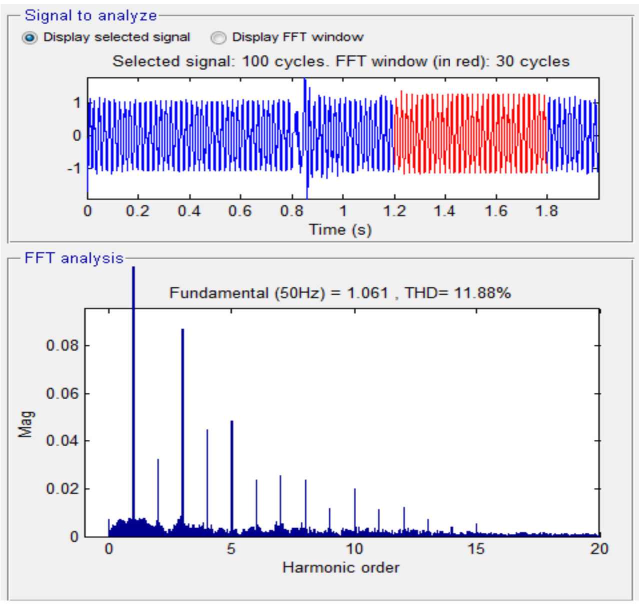


Fig. 9. Harmonic analysis for voltage wave, measured on loads bus bar of connection substation, in case of a three-phase fault occurrence on the electrical line adjacent to main feeder, for the rectifier-inverter topology of DVR with $K_P$=1 and $K_I$=5000.

An unwanted increase of total harmonic distortion to 11.88 % value can be seen, above than permissible limits by European EN 50160 norm [9], compared to the case of the fault occurrence in an electrical line adjacent to main feeder (seen in figure 5), when the $THD = 4.51$ %.

This increase represents the influence of diode based rectifier on the voltage waves. Also, an important increasing of $3^{th}$,$5^{th}$, and $7^{th}$ range harmonics can be observed.

During the time period when dynamic voltage restorer operation is not required, the total harmonic distortion is 6.19%, this value representing the influence of the diode rectifier to the voltage waves.

## V. CONCLUSIONS

The study for the analysis of DVR capability to compensate voltage sags in the electrical distribution areas with connection substation topology, was realized using the Matlab/Simulink simulation environment.

For this configuration, when the DC voltage provided by a diode based rectifier, supplied from back up bus bar of connection substation, the DVR has demonstrated the ability to compensate voltage sags even for occurrence of a fault in line adjacent to back-up feeder, case when the voltage at the input terminals of the rectifier is severely disturbed. However, the voltage level measured on the loads bus bar is restored to its rated value.

The result obtained during this study proves the fact that using Dynamic Voltage Restorer for mitigation of voltage sags that occur on connection substation bus bars is a good solution, considering the results obtained from a statistical analysis realized for Bucharest area electricity distribution network, during 2012 – 2014. This electricity distribution network is used to supply approximately one million residential and commercial consumers.

The proposed analysis has shown that the fault number in medium voltage underground cables was between 1700 and 2300 fault per years. These fault type causes voltage sags recorded on each line supplied from the same bus bar of power substation as the faulty line. From total number of occured fault, around 400 faults determined the automatic transfer switch system operation, this case being analyzed in this paper.

Over 120 voltage sags occurrence cases were recorded in the medium voltage bus bar of most important high voltage/ medium voltage substation. These disturbances affected tens of thousands residential consumers. The use of the Dynamic Voltage Restorer can provide a high quality distribution service for all these consumers.

## REFERENCES

[1] Electricity Supply Association from Australia Limited – „*Customer Guide to Electricity Supply*”, 2002.

[2] W. E. Newell - „*Introduction to Solid State Power Electronics*”, POWEREX – Semiconductor Division, Editor: John William Motto, Jr., febtuary 1977

[3] J. Lutz, H. Schlangenotto, U. Scheuermann, R. De Doncker – „*Semiconductor power devices. Physics, Characteristics, Reliability*”, Springer-Verlag Berlin Heidelberg 2011, ISBN 978-3-642-11124-2.

[4] PELS Operations Handbook: IEEE PELS Webpages(2005)- http://ewh.ieee.org/soc/pels/pdf/PELSOperationsHandbook.pdf).
[5] T. Devajaru, V.C.Veera Reddy, M. Vijaya Kumar – ”Role of custom power devices in Power Quality Enhancement: A Review”, International Journal of Engineering Science and Technology Vol. 2(8), 2010, page 3628-3634.
[6] J. G. Nielsen – „*Design and control of a Dynamic Voltage Restorer*”, Aalborg University, Denmark, March 2002
[7] Gh. Nicolaescu, H. Andrei, □. Rădulescu – ”Dynamic Voltage Restorer Response Analysis for Voltage Sags Mitigation in MV Networks with Secondary Distribution Configuration”, Proceedings of the IEEE-EEEIC, Krakow, 10-12 May 2014.
[8] Gh. I. Nicolaescu, H. Andrei, □. Rădulescu – ”Modeling and Simulation of Dynamic Voltage Restorer for Voltage Sags Mitigation in Medium Voltage Networks with Secondary Distribution Configuration”, Proceedings of the IEEE-OPTIM 2014, Bra□ov, 22-24 May 2014.
[9] EN 50160/2012 – Voltage characteristics of electricity supplied by public distribution systems