Proceedings of the World Congress on Engineering 2011 Vol II
WCE 2011, July 6 - 8, 2011, London, U.K.

Fuzzy Logic Control for DVR to Counter Voltage Sag on a Distribution Network

Puneet Chawla, Rintu Khanna, Abinash Singh

Abstract - In recent years, utilities have been faced with rising number of complaints about the quality of power due to sags and interruptions. There are a number of reasons for this, the most important being that with influx of digital computers and other types of electronic controls customers in all sectors (residential, commercial and industrial) have more sensitive loads. Dynamic Voltage Restorer (DVR) is a series connected power electronic based device that can quickly mitigate the voltage sags in the system and restore the load voltage to the pre-fault value. It is recognized to be the best effective solution to overcome this problem. The primary advantage of the DVR is keeping the users always on-line with high quality constant voltage maintaining the continuity of production. In this paper a fuzzy logic control method for DVR that protects a sensitive load, to counter voltage sag under unbalanced loading conditions is presented. DVR along with other parts of the distribution system are simulated using Matlab/ Simulink
Keywords: DVR (Dynamic voltage restorer), FLC (Fuzzy logic controller), VSC (Voltage source converter), Power Quality

I. INTRODUCTION

The advancement in the power electronics devices and their use has led to a greater awareness of power quality. Voltage sags, swells, harmonics etc are different power quality problems which can cause equipment to fail, misoperate or even shut down, as well as create huge current imbalances which could blow fuses or open the circuit breakers. Voltage sag is considered the most severe power quality problem at the consumer end[2] ,[15]. The voltage sag is defined as a short duration reduction in the rms supply voltage that can last a few milliseconds to a few cycles. The voltage sag can also be defined as a sudden short duration reduction in voltage magnitude between 10% and 90% compared to nominal voltage[15].

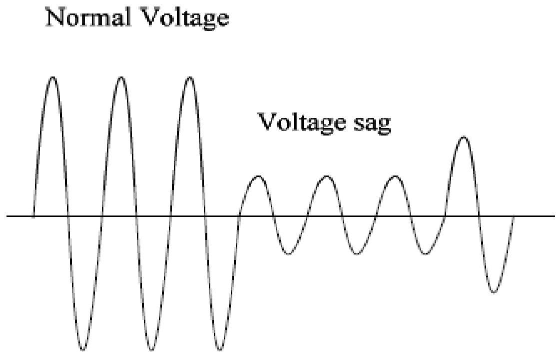


Fig.1.1 Power quality problem: Voltage sag

Manuscript received March 6, 2011 revised April 13, 2011. This work was submitted by Abinash Singh as ME Thesis to PEC University of Technology under guidance of Puneet Chawla.
Puneet Chawla is Assistant Professor in the Department of Electrical Engineering of PEC University of Technology, (Formerly Punjab Engineering College), Chandigarh, India; (phone 91-988817104, email: puneetishaan@yahoo.co.in).
Rintu Khanna is Assistant Professor in the Department of Electrical Engineering of PEC University of Technology, (Formerly Punjab Engineering College), Chandigarh, India; (email: rintukhanna@rediffmail.com).
Abinash Singh is Assistant Professor in SUSCET Tangori Distt. Mohali, (Punjab), India. (email : abinashsingh1986@gmail.com).

There are different methods which have been proposed to mitigate the voltage sags like Uninterruptible Power Supplies (UPS), network reconfiguration devices like Static Transfer Switches (STS), DSTATCOM and series compensating devices like Dynamic Voltage Restorers (DVR). The DVR protects the load from voltage sag coming from the network by supplying the missing voltage.

Dynamic voltage restorer consists of a dc to ac converter, controller, series transformer and a energy storage device. DVR can be controlled by various linear and non-linear control methods, like feed forward control, feedback control, composite control, ANN control, Fuzzy control, no deadbeat control and space vector control[6],[8]. The conventional proportional integrator controller requires precise linear mathematical models, which are difficult to obtain and fail to perform satisfactorily under parameter variations, nonlinearity, load disturbance, etc. The Fuzzy logic controllers (FLCs) have obtained great attention in such applications. The advantages of FLCs over conventional controllers are that they do not need an accurate mathematical model, they can work with imprecise inputs, can handle non-linearity, and they are more robust than conventional nonlinear controllers[16].

II. DYNAMIC VOLTAGE RESTORER

Principle and Operation Of DVR

A dynamic voltage restorer uses a series-connected topology (Fig. 2.1) to add voltage to the supply in the case when a sag is detected. This aims to protect critical loads against voltage sags.

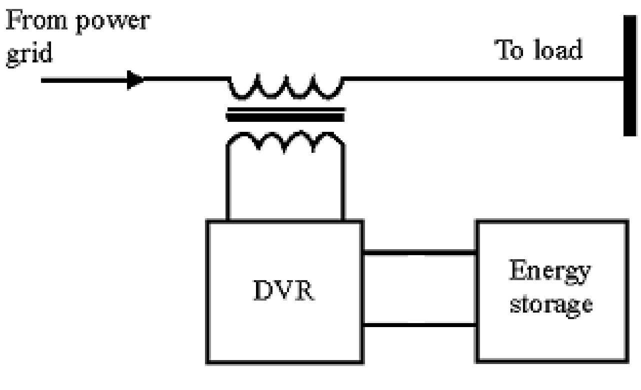


Fig. 2.1 Dynamic voltage restorer connected in series with the distribution network

DVR protects loads against voltage sags by series injection of the missing portion of the utility voltage. A DVR is a power-electronic controller and is realized using voltage source inverters . It injects three independent single-phase voltages in the distribution feeder such that the load voltage is perfectly regulated at system nominal frequency[18].

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Using a DVR is more reliable and quick solution to maintain a clean supply of electricity for customers.The DVR was first installed in 1996. It is normally installed in a distribution system between the supply and the critical load feeder[3]. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load. The basic operating principle of a DVR is to insert a voltage of required magnitude and frequency in series with a distribution feeder. Thus the DVR can restore the voltage on the load side to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. The output of the voltage source converter is connected in series with a distribution network through coupling transformer. Voltage source converter (VSC) employs IGBTs that are operated in a pulse-width modulated (PWM) scheme. The voltage source converter is supplied by a dc source as shown in Fig. 2.2 .

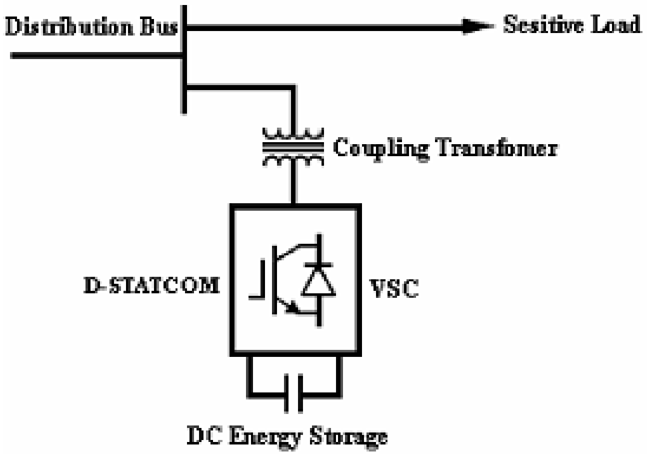


Fig. 2.2 Basic conFig.uration of DVR

Voltage restoration done by DVR means to inject energy from DVR to distribution system. The required energy for injection during sag may be supplied from the grid or energy storage devices such as batteries or super conducting magnetic energy storage systems[5] [6].

Components of DVR

The DVR usually consists of an injection transformer, which is connected in series with the distribution line, a voltage sourced PWM inverter bridge which is connected to the secondary of the injection transformer and an energy storage device connected at the dc-link of the inverter bridge. The core element in DVR design is the three-phase voltage converter[9]. This inverter utilizes solid-state power electronics (insulated gate bipolar transistors, IGBTs) to convert DC to AC and back again during operation.

Injection Transformers

The injection transformers connect the DVR to the distribution network via the high voltage windings . They transform and couple the injected compensating voltages generated by the VSI to the incoming supply voltage. The ratings of injection transformers are related with the depth of voltage sag, supply current and capacity of DC link. Basically injection transformer used in model are three single phase transformers. The high voltage side of the injection transformer is connected in series to the distribution line, while the low voltage side is connected to the DVR power circuit. For a three-phase DVR, three single-phase or three-phase voltage injection transformers can be connected to the distributionline[10]

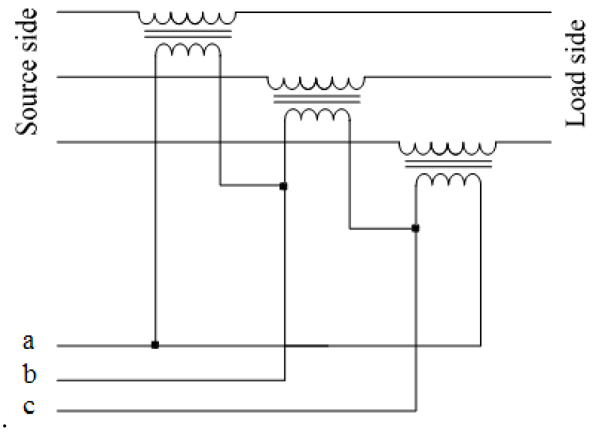


Fig.2.3: Connection method for the primary side of the injection transformer

PWM inverter consisting of IGBT's

The insulated gate bipolar transistor or IGBT is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, variable speed refrigerators, air-conditioners, and even stereo systems with switching amplifiers. Pulse-width modulation (PWM) is a very efficient way of providing intermediate amounts of electrical power between fully on and fully off. The voltage source converter is used to convert the DC to AC and then supply the voltage to distribution feeder through an injection transformer.

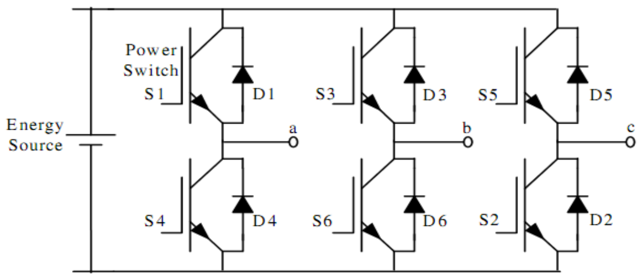


Fig. 2.4 Basic three phase inverter

Energy storage

The energy storage unit supplies the required power for compensation of load voltage during voltage sag. A dc battery is used for this purpose.

Controller

A fuzzy logic controller which controls the inverter of DVR, has been proposed as a substitute for the conventional PI controller.

III. FUZZY LOGIC CONTROL OF DVR

In fuzzy logic, basic control is determined by a set of linguistic rules which are determined by the system. Since numerical variables are converted into linguistic variables, mathematical modelling of the system is not required. The fuzzy logic control is being proposed for controlloing the inverter action. The fuzzy logic controller has two real time

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

inputs measured at every sample time, named error and error rate and one output named actuating signal for each ph. The input signals are fuzzified and represented in fuzzy set notations as membership functions. The defined 'If … Then …' rules produce output (actuating) signal and these signals are defuzzified to analog control signals for comparing with a carrier signal to control PWM inverter[17].

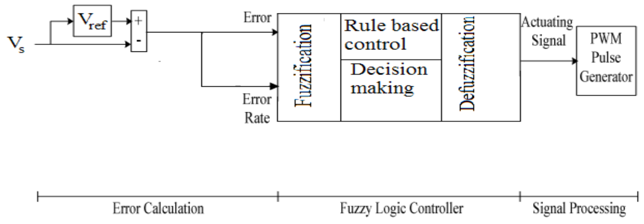


Fig. 3.1 Block diagram of proposed control system

Input Parameters

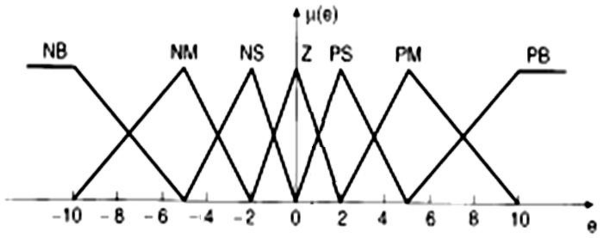
Two variables, error in voltage i.e. difference between supply voltage and the reference voltage and error rate i.e. the rate of change of error of voltage are taken as input to fuzzy logic controller Error and error rate are defined as:

Error = $V_{ref} - V_S$

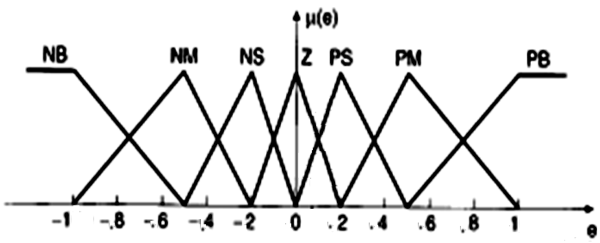
Error rate = error(n) – error (n-1)

Fuzzification

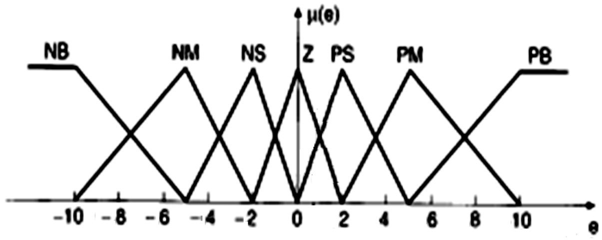
In this simulation study, the error and error rate are defined by linguistic variables such as negative big (NB), negative medium (NM), negative small (NM), zero (Z), positive small (PS), positive medium (PM) and positive big (PB) characterized by triangular membership functions[15]. These functions have been chosen to satisfy the output needs of the fuzzy controller. The output is also defined by seven linguistic variables such as negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB) characterized by membership functions given in fig. 3.2.



Input Variable "Error"



Input Variable "Error Rate"



Output Variable Actuating Signal

Fig 3.2 Membership Functions for inputs and output

Decision Making

Fuzzy process is realized by Mamdani method. Mamdani inference method has been used because it can easily obtain the relationship between its inputs and output[17]. The set of rules for fuzzy controller are represented in Table 1. There are 49 rules for fuzzy controller. The output membership function for each rule is given by the Min (minimum) operator. The Max operator is used to get the combined fuzzy output from the set of outputs of Min operator .The output is produced by the fuzzy sets and fuzzy logic operations by evaluating all the rules.

A simple if-then rule is defined as follows:

If error is Z and error rate is Z then output is Z"

Table 1 Fuzzy rules

Ce\e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

Defuzzification

It is the process of converting the controller outputs in linguistic labels represented by fuzzy set to real control (analog) signals. Centroid method is used for defuzzification in the present studies.

Signal Processing

The outputs of FLC process are the control signals that are used in generation of switching signals of the PWM inverter by comparing with a carrier signal.

IV. SIMULINK MODELING OF DVR

MATLAB software is used for obtaining the simulations[14] [16]. The DVR uses self-commutating IGBT solid-state power electronic switches to mitigate voltage sags in the system. The voltage controlled three single-phase full bridge PWM inverters are used to produce compensating voltage. The switching frequency of the inverters is 3 kHz. Three of single-phase inverters are connected to the common DC voltage source. The DC voltage source is an external source supplying DC voltage to the inverter for AC voltage generation.

The three 600/10000 V (rms) single-phase injection transformers boost the output waveform of the inverter unit and supplies voltage to load side , where the voltage is further stepped down to 0.4 kv for sensitive load (load to be protected).The circuit breakers are placed in the circuit with the injection transformers allowing the protection of the DVR.

A proposed DVR built in MATLAB/Simulink and installed into a simple power system to protect a sensitive load in a distribution system is presented in Fig. 4.1.

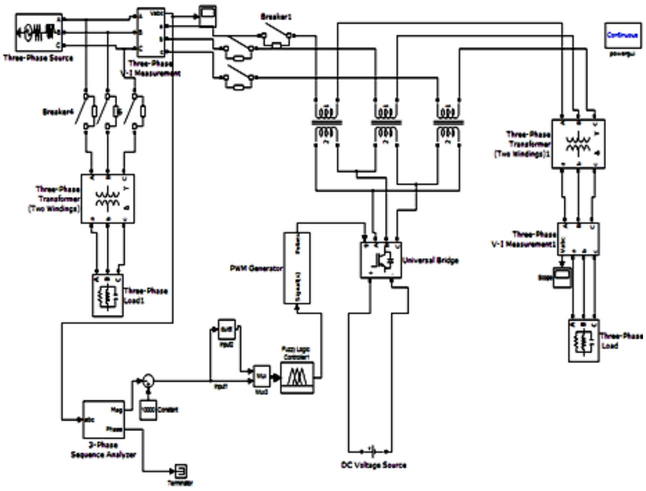


Fig. 4.1. Simulink diagram of DVR connected to a distribution network

Table 2 : Specifications of the test system

Supply voltage	10KV
Load Transformer rating	630 KVA; 10/0.4KV
Single phase transformer voltage rating	0.6/10 KV
Sag duration	50ms to 170ms
DC link voltage	600V
Switching frequency	3khz
System Fundamental Frequency	50 Hz
Typical Cause of Sags	Unbalanced load
Load to be protected	400W

10 kV (rms) main feeder energizes the proposed system. Main feeder is divided into two feeders and each feeder is connected with loads. The unbalanced load (sag source) is connected to feeder 1 and sensitive load is connected to feeder 2. The sensitive load is rated at 400W and receives power from the grid at 10 kV. The grid voltage is reduced to 400 V (rms) by load transformer to allow the utilization of low voltage sensitive load.

The DC link voltage is 600 V. The system runs at 50 Hz frequency. The voltage sags are generated by switching on unbalanced load between 50msec to 170msec. The DVR is designed to mitigate the three-phase voltage sags up to 0.9 pu by controlling its inverter by using fuzzy logic control.

The power circuit of DVR systems can be represented as a three-phase equivalent circuit as shown in Fig. 4.2.

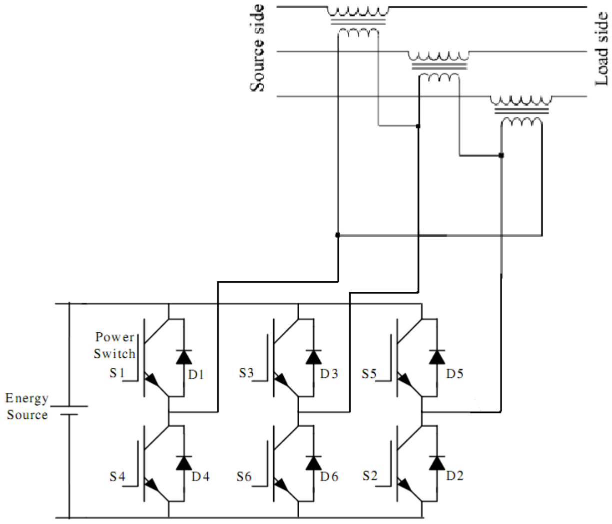


Fig. 4.2. Equivalent three phase circuit diagram for DVR

In Fig. 4.3 equivalent circuit consists of a dc source (energy storage) being connected to inverter i.e six IGBT diodes which are further connected to injection transformer (three single phase transformers). This transformer connects source side to load side. The DVR should be designed to have minimal effect on the system, during faulted and non-faulted system states.

V. SIMULATIONS AND RESULTS

The system runs at 50 Hz frequency and total simulation time is chosen to be 500ms in each case. The scope connected to the V-I measurements at supply side and the load side gives the simulations of supply voltage having sag and the voltage across load.. In Fig.s 5.1, 5.2, and 5.3, it is observed that initially there is no voltage injection and power flow from DVR to the system because no voltage sag is sensed. As soon as the load becomes unbalanced the voltage sag occurs , and the fuzzy controlled PWM inverter produces the missing voltage so that the voltage sag does not affect the sensitive load. The controller inputs are determined by comparing reference signals and measured source data signals. The fuzzy controller output signals are the inputs to the PWM module to generate the required missing voltages . The controller outputs are compared with triangle wave signals to generate the proper switching pulses. Control unit provides the reference voltage for the tracking of source voltage. It controls the inverter to generate pure sinusoidal voltage at the same frequency for the system as shown in simulations. The fuzzy controller operates only for the duration the voltage sag is detected,it starts from 50ms and lasts 170 ms as shown in Fig. 5.1 Once the voltage sag is detected, the DVR (having DC link voltage of 600V) injects voltage through injection transformer to the load and thus restore the critical load voltage and the load voltage is nearly perfect sinusoidal.

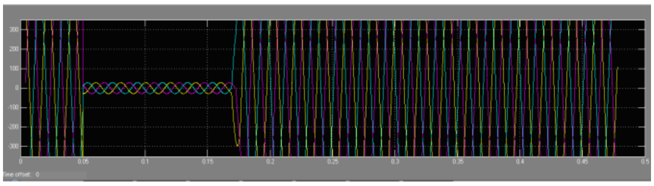


Fig. 5.1 Simulation of supply voltage having voltage sag

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Fig. 5.2 illustrates how quickly the DVR responds for sudden changes to keep the sensitive load voltages at reference value. The calculated injection voltages exactly compensate the sag because the controller exactly calculates the missing voltage. The single-phase PWM inverters managed by the control system generate the three distinct series inverter output voltages to compensate the source voltages at different sag level.

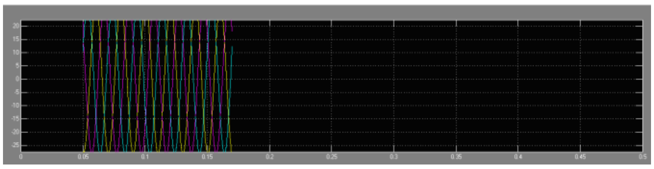


Fig. 5.2 Simulation of DVR injected voltage

The primary task of DVR is providing the high quality voltage to the critical loads. The fuzzy controllers quickly start working in case the measured phase voltages of source are different from the reference values. The fuzzy controllers applied to DVR enable the proposed system for providing a good power and voltage quality to the critical load. The controller output signals stabilize when all the phase voltages of the load attain the desired value. DVR gives high performance in injecting the more in-phase voltage with proper polarity and phase angle. The simulation in Fig. 5.3 shows the load side voltage having no sag because of efficient working of DVR.

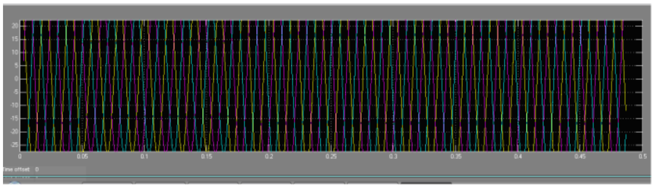


Fig. 5.3 Simulation of voltage across sensitive load after voltage injection

From all the simulations of the three-phase voltage waveforms, it is observed that the new control strategy of DVR quickly responds to sudden changes and a high quality load voltage waveforms are achieved. This ability confirms the results of proposed DVR control technique for the mitigation of voltage sags.

VI. CONCLUSIONS

The proposed DVR for 10 kV distribution line has been assumed to be located in medium voltage distribution network level and it can mitigate three-phase sags . The studied DVR is based on forced commutated series connected voltage source inverter (VSI). Pulse width modulation (PWM) technique with switching frequency 3 kHz has been employed in VSI. The DVR has been designed with special importance at the control of PWM inverter i.e fuzzy logic control.

The fuzzy logic controlled DVR has been developed in this paper to response quickly and obtain a good dynamic performance. The control method does not require a complex computer algorithm. The elimination of transformations, multiplications and divisions makes the control system simple and more reliable. Three phase sequence analyser has satisfactorily tracked the source voltage .The summer compared it with reference signal for fuzzy logic controller and then further for PWM modulation without experiencing a disturbance. The proposed DVR has shown the ability to mitigate the voltage sags . The switching devices have correctly been triggered to make the DVR on-line or off-line and protect the DVR from the voltage drop. The voltage sags have been generated by unbalanced load in the grid. It is concluded that the proposed DVR has successfully mitigated the long duration voltage sags and perfectly restored the critical load voltage to nearly 1 pu. The designed DVR has provided a regulated and sinusoidal voltage across the sensitive load and thus increased efficiency of the system. The nearly perfect sinusoidal output voltages have resulted in improvements in the current and power quality of the sensitive load. The IGBT based VSI technology and dynamic performance capability of fuzzy controlled DVR have improved the quality of critical load quantities by preventing the sags. Thus, the voltage can be restored in a distribution system by controlling the Dynamic Voltage Restorer using Fuzzy logic.

REFERENCES

[1] J.G.Nielsen, M.Newman, H.Nielsen, and F.Blaabjerg “Control and Testing of a Dynamic Voltage Restorer (DVR) at Medium Voltage Level”, IEEE transactions on power electronics, vol. 19, no. 3,pp.1248 – 1253,May.2004

[2] A.Kusko, M.T.Thompson, “Power quality in electrical system” ,third edition, McGraw-Hill,2007

[3] A.Kara, P.Dahler, D.Amhof and H.Gruning , “Power Supply Quality improvement with a Dynamic Voltage Restorer (DVR)” IEEE,Energy Management and Power Delivery, 1998. Proceedings of EMPD, vol.2, pp.518 – 525, 1998.

[4] A.K.Jindal, A.Ghosh , A.Josh “Critical load bus voltage control using DVR under system frequency variation”, Science-Direct, Electric Power Systems Research,. Vol. 78, No. 2, pp. 255-263, Feb. 2008

[5] K.Piatek, “Sliding mode control of DVR with minimized energy injection”, Proceedings of 11th European Conference on Power, EPE Dresden, pp.8, 2005

[6] D.Mahinda, H.M and S.Choi ,“A Novel Technique to Compensate Voltage Sags in Multiline Distribution System—The Interline Dynamic Voltage Restorer “IEEE transactions on industrial electronics, vol. 53, no. 5, Oct.2006

[7] D.Hongfa, G.Jun, D.Xianzhong. “New concepts of dynamic voltage restoration for three-phase distribution systems.” IEEE Power Engineering Society, vol. 3, pp.1427 – 1432,July. 2000.

[8] F.A.LJowder “Design and analysis of dynamic voltage restorer for deep voltage sag and harmonic compensation”, Published in IET Generation, Transmission & Distribution, Oct.2008

[9] M.Tümay , A.Teke , K.Ç. Bayındır ,M.U.Cuma , “Simulation and modeling of a dynamic voltage restorer” Adana, Turkey,vol.3,pp.31-35,2002

[10] G.V.N.Kumar D.D. Chowdary, “DVR with Sliding Mode Control to alleviate Voltage Sags on a Distribution System for Three Phase Short Circuit Fault” , IEEE Region 10 Colloquium and the Third

ISBN: 978-988-19251-4-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

International Conference on Industrial and Information Systems, pp.1-4, Dec.2008.

[11] H.Ezoji, A.Sheikholeslami, M.Tabasi, M.M. Saeednia, "Simulation of Dynamic Voltage Restorer Using Hysteresis Voltage Control", European Journal of Scientific Research ISSN 1450-216X vol.27,no.1 pp.152-166,2009

[12] L.Haichun, X.Lizhi, X.Shaojun, "A New Detection Method of Voltage Sag Based on Period Phase Concept", IEEE Industrial Electronics and Applications, ICIEA 4th IEEE Conference, pp:3333 – 3337,May.2009

[13] J.Zhou, H.Zhou , Z.Qi ,"The Study on a Dual-feed-forward Control of DVR to Mitigate the Impact of Voltage Sags Caused by Induction Motor Starting", IEEE, Electrical Machines and Systems, International Conference,pp.1497 -1500,Oct.2008

[14] P.Boonchiam andN.Mithulananthan , "Understanding of Dynamic Voltage Restorers through MATLAB Simulation" , Thammasat Int. J. Sc. Tech., Vol. 11, No. 3, July-Sep.2006

[15] R.C.Dugan, M. Mcgranaghan, S. Santoso, H.W. Beaty, "Electrical power system quality", second edition, McGraw-Hill,2004

[16] S.N.Sivanandam, S.Sumathi and S.N.Deepa, "Introduction to Fuzzy Logic using MATLAB", Springer-Verlag Berlin Heidelberg 2007

[17] Bayindir K.Q, Teke A., Tumay M., " A robust control of dynamic voltage restorer using fuzzy logic, Electrical Machines and Power Electronics, 2007. ACEMP '07. International Aegean Conference on. 10/2007; DOI: 10.1109/ACEMP.2007.4510483

[18] H.Zhou, T.Z.Wei, Y.Zhao, Z.P.Qi, "Study on Dynamic Matrix Predictive Control of single-phase DVR", Electric Utility Deregulation and Restructuring and Power Technologies, DRPT, pp. 2136 - 2140 April.2008