Research Journal of Applied Sciences 9 (12): 901-908, 2014
ISSN: 1815-932X

Realization of LC Filter for Fuzzy Controller Based Dynamic Voltage Restorer

[1]S. Arumugom and [2]M. Rajaram
[1]A.R. College of Engineering and Technology, Tamilnadu, India
[2]Anna University, Tamilnadu, India

Abstract: This study discusses the operating principles and control characteristics of a Dynamic Voltage Restorer (DVR) for power quality improvement. The power quality disturbance includes voltage sag, swell, notch, spike and transients, etc. Dynamic Voltage Restorer (DVR) proved as a suitable device that deals with power quality disturbances. The DVR is connected in series with the power lines. The design issues of the output LC filter in fuzzy controller based DVR System. The LC Output Filter System not only could reduce the switching frequency harmonics and improves the system efficiency. The LC filter is also series connected between the converter and the grid. The use of inverter in the DVR would introduce switching harmonics in the grid, therefore, LC filter is proposed to eliminate the high-frequency inverter switching noise and pass through the fundamental component, also could achieve the same performance of damping the switching harmonics using smaller inductance. The fuzzy controller added in the system improves the system performance and the design issues of output LC filter are carried out and realized.

Key words: Dynamic voltage restorer, injection transformer, voltage source inverter, structure and control technique for DVR, DVR Test System, power quality

INTRODUCTION

Power quality improvement is one of the vital areas of research in recent years. In certain commercial and industrial electrical applications, it is critical that high quality and uninterrupted power be supplied; for fear that significant economic losses can be incurred. The reason for demanding high quality un-interruptible power during production process is mainly because of the modern manufacturing and process equipment that operate at high efficiency requires stable and defect free power supply for the successful operation of their machines. Machines, sensitive to power supply variations are to be designed more precisely (Fitzer *et al*., 2004).

There has been significant progress in the application of FACTS devices in power systems during the past decade. Many studies on the application of FACTS devices for power flow control and enhancement of damping of power system oscillations have been reported in the literature. A number of practical implementations have also been reported. One of the directions of the advancement of FACTS technology is the introduction of many different topologies (TCSC, SVC, UPFC, SSSC, STATCOM, etc.).

Dynamic Voltage Restorer (DVR) has become very popular in recent years for compensation of voltage sag and swell. The voltage sag and swell is a very severe problem of power quality for an industrial customer which needs urgent attention for its compensation (Nielsen *et al*., 2004). There are various methods for the compensation of voltage sag and swell. One of the most popular methods of sag and swell compensation is Dynamic Voltage Restorer (DVR) which is used in both low voltage and medium voltage applications (Nielsen and Blaabjerg, 2005). In this research, the main focus is on the DVR. DVR compensates the voltage sag by injecting voltage as well as power into the system. The compensation capability DVR mainly influenced by the various load conditions and voltage dip to be compensated. Efficient control technique (Park's Transformations) is used for mitigation of voltage sag through which optimized performance of DVR is obtained (Li *et al*., 2007). The performance of DVR is analyzed on various conditions of active and reactive power of load at a particular level of dc energy storage. Parameters of load are varied and the results are analyzed on the basis of output voltages (Roncero-Sanchez *et al*., 2009; Araujo *et al*., 2007).

Dynamic Voltage Restorer (DVR) is a custom power device that is used to improve voltage disturbances in electrical distribution system (Ghosh and Ledwich, 2002). The components of the DVR consist of Voltage Source Inverter (VSI), injection transformers, passive filters and energy storage (Malinowski *et al*., 2009). The main function of the DVR is used to inject three phase voltage in series and in synchronism with the grid voltages in

Corresponding Author: S. Arumugom, A.R. College of Engineering and Technology, Tamilnadu, India

order to compensate voltage disturbances (Liserre *et al*., 2006). The development of (DVR) has been proposed by many researchers. This study presents a review of the researches on the DVR application for power quality improvement in electrical distribution network. The types of DVR control strategies and its configuration has been discussed and may assist the researchers in this area to develop and proposed their new idea in order to build the prototype and controller.

DYNAMIC VOLTAGE RESTORER (DVR)

The conventional circuit configuration of the DVR is shown in Fig. 1. Dynamic voltage restorer is a series connected device is used for mitigating voltage disturbances in the distribution system. The DVRs can be used and are already in operation. DVR maintains the load voltage at a nominal magnitude and phase by compensating the voltage sag/swell, voltage unbalance and voltage harmonics presented at the point of common coupling. These systems are able to compensate voltage sags by increasing the appropriate voltages in series with the supply voltage and therefore avoid a loss of power. Gyugi (1994) (Patent No. 5329222) proposed an apparatus and a method for dynamic voltage restoration of utility distribution network. This method uses real power in order to inject the faulted supply voltages and is commonly known as the dynamic voltage restorer (Gyugi, 1994). The DVR should capable to react as fast as possible to inject the missing voltage to the system due to sensitive loads are very sensitive to voltage variations (Chan *et al*., 2006).

The DVR is a series conditioner based on a pulse width modulated voltage source inverter which is generating or absorbing real or reactive power independently. Voltage sags caused by unsymmetrical line-to-line, line to ground, double-line-to-ground and symmetrical three phase faults is affected to sensitive loads, the DVR injects the independent voltages to restore and maintained sensitive to its nominal value. The compensation of harmonics and mitigates voltage

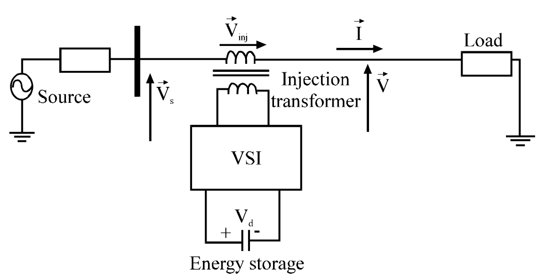

Fig. 1: DVR general configuration

transients has been discussed by Li *et al*. (2007). The capacitor-supported Dynamic Voltage Restorer (DVR) is a power electronic converter-based device that has been proposed to protect critical and sensitive loads from supply side disturbances, except outages. It is connected in series with a distribution feeder and is capable of generating or absorbing reactive power at its AC terminals and interchange real power with the AC network under transient conditions.

The operation principle of the DVR is simple; it injects a voltage in series with the feeder. Ideally, this injected voltage is in quadrature with the line current so that the DVR behaves like an inductor or a capacitor for the purpose of increasing or reducing the overall reactive voltage drop across the feeder. In this operating mode, the DVR does not interchange real power with the system in steady-state. The DVR can restore the load-side voltage to the desired amplitude and waveform. The DVR is based on a Voltage Source Converter (VSC). The output of the VSC is connected in series with a distribution feeder through a transformer. This device uses IGBTs that are operated in a Pulse-Width Modulated (PWM) fashion. The VSC is supplied by a dc capacitor (Silva, 2002). The DVR including the control system, the compensation algorithm, the loads and the switching elements, constitutes a nonlinear circuit. In general, a nonlinear circuit can show many interesting phenomena. In this type of circuits, it is frequently found that a steady-state response such as a limit cycle, abruptly changes its qualitative property by a continuous variation of the system parameters. Such a phenomenon is known as bifurcation of the state and is important in the analysis of nonlinear circuits. Upon obtaining the global feature of the bifurcation set, various non-linear phenomena such as the coexistence of many stable modes, the jumping behavior of periodic responses, the phenomenon of hysteresis and the appearance of chaotic states, etc. can be observed. In a dynamic nonlinear system, there are mainly two ways to determine the location and stability type of its limit sets. The easiest way to locate a limit set is to integrate the system set of equations until the steady-state is reached. This method is called Brute Force (BF) approach. The commonly adopted technique of BF is frequently limited to the investigation of asymptotically stable steady states. Thus, to explore both stable and unstable periodic orbits, it is necessary to resort to additional properties of differential equations.

There has been significant progress in the application of FACTS devices in power systems during the past decade. Many studies on the application of FACTS devices for power flow control and enhancement of damping of power system oscillations have been reported in the literature. A number of practical implementations have also been reported. One of the directions of the advancement of FACTS technology is the introduction of many different topologies (TCSC, SVC, UPFC, SSSC, STATCOM, etc.).

The dynamic voltage restorer is used in the system to compensate voltage sags and swells and eliminating harmonics when sudden voltage faults happen in the grid. The DVR System is designed to protect the consumers especially the sensitive load. The DVR System is essentially composed of a series-connected transformer, a voltage source inverter, an inverter output filter and an energy storage device. The operation of the dynamic voltage restorer is injecting a proper series voltage with the supply through a transformer when sudden sags and swells happen and make the voltage level of the grid remains in the present status. In the experiments, the system is equal to the series connection of a voltage source and impedance. The use of inverter in the dynamic voltage restorer would introduce switching harmonics in the grid, therefore, L filter and LC filter are proposed to eliminate the high-frequency inverter switching noises and pass through the fundamental component. Compared with the traditional L filter, the LC filter could achieve the same performance of damping the switching harmonics using smaller inductance. The filter has the features of better attenuation for switching frequency harmonic and low cost; it is widely used for grid connected power electronic systems.

DVR SIMPLIFIED MODEL

The DVR System is consisted by the energy storage, power converter, inverter and the output filter. In the simplified model of DVR System, the inverter could be considered as a voltage source, the power system upstream to the DVR is represented by an equivalent voltage source and source impedance connected in series. The simplified model of DVR System is shown in Fig. 2. In the simplified model of the system, in order to analyze the voltage ratio of the output filter and the sensitive load, the impedance of the upstream power system and the load with the equivalent impedance of the transformer are equal to one impedance which is set as Z. The transformer ratio is 1:1 and is simplified as a series of inductors and resistors. For an easy analysis of the system, transfer the Thevenin's circuit to Norton's circuit, the voltage source at the grid side is transferred to a current source which gives a constant current (Fig. 3).

However, the LC filter also has following issues worth considering. The first issue is parameters design of LC filter. The LC filter should pass lower frequency components and the fundamental voltage drop on L or C should be relatively small. At the same time, LC filter should cut off the high frequency harmonics. Besides, considering the cost, the inductance should be as small as possible. The second issue is for a converter with LC filter, another issue is the resonance problem of LC filter. If the system is not carefully designed, the control system would have transient distortions and steady-state harmonic around the LC resonant frequency or even affect the overall system stability. The third one is for the LC filter is usually series connected in system with isolated transformer and bypass switch. So, it is also an issue to design the all output systems to achieve high efficiency and low cost.

This has been recognized that among the many types of disturbances that can appear in power systems, voltage sags can lead to the highest level of undesirable impact on sensitive loads. Several devices have been proposed to alleviate the problem, among which the Dynamic Voltage Restorer (DVR) also referred to as the Static Series Compensator (SSC) is shown to be very promising. The DVR is a series compensation device, typically installed in a distribution system and the function of the restorer is to rapidly boost up the load-side voltage in the

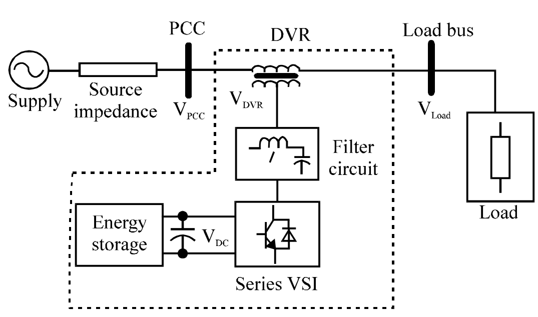

Fig. 2: Diagram representation for LC filter added fuzzy based DVR

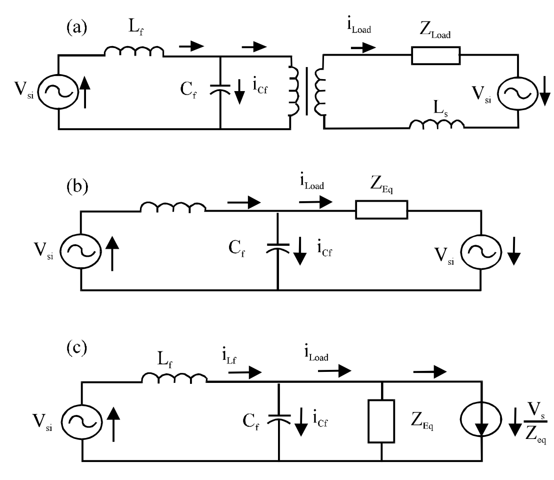

Fig. 3: Simplified model circuit for DVR

event of upstream voltage sags. The restorer consists of an energy storage device which supplies the required power over the limited duration of the sags. The storage device can be made up of capacitor banks, batteries or flywheels, the capacity of which is in accordance to the sag duration and magnitude.

LC FILTER REALIZATION

The parameters design of LC filter is based on the fundamental voltage drop on the LC filer, the switching cutoff frequency and the low inductance value (low cost). Assuming the worst condition for DVR System is that the ground fault happens and dynamic voltage restorer should V. Supply all the system voltages as the leakage inductor of the transformer is relatively large and could not be ignored, thus, the leakage inductor should be calculated and taken into account. Thus, the leakage inductor and the output LC filter consists an LCL filter at all. Calculating the leakage inductor, the basic resistance and inductance is:

$$R_b = \frac{U_n}{P} \tag{1}$$

$$L_b = \frac{R_b}{2\times pi\times f} \tag{2}$$

$$L_{leak} = 0.004L_b \tag{3}$$

$$Z_{leak} = Z_t = 2\times pi\times f\times L_{leak} \tag{4}$$

$$i_{cf} = i_{Lf} + i_{load} \tag{5}$$

$$i_{cf} < i_{load} \tag{6}$$

The second step is to design the value of inductor. The fundamental voltage on the inductor should be far less than that of the transformer. Also, considering the worst condition, DVR provides the peak voltage to the system, the voltage shared by the filter inductor should be far less than the voltage provided to the sensitive load. The equivalent inductance of the transformer is relatively smaller than the chosen impedance of the sensitive load, thus the voltage of Z could be considered as the voltage of the sensitive load:

$$\frac{y_1}{100}\left(\frac{Z_{Eq}}{Z_{cf}}\right) \le Z_{cf} \le \frac{y_2}{100}\left(\frac{Z_{Eq}}{Z_{cf}}\right) \tag{7}$$

$$\frac{f_{sw}}{3} \le f_{cut\text{-}off} \le \frac{f_{sw}}{2} \tag{8}$$

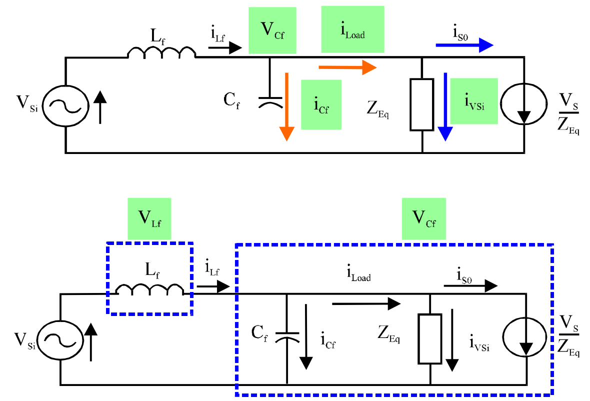

Fig. 4: Circuit for LC filter analysis

$$f_{cut\text{-}off} = \frac{1}{2\pi\sqrt{L_f C_f}} \tag{9}$$

After determining the value of the capacitor and inductor, the cut-off frequency of the filter should be designed considering the elimination of the harmonics. As the output LC filter should filter high-order harmonics such as switching harmonics, the cutoff frequency of LC filter could be designed according to condition (Fig. 4).

FUZZY LOGIC CONTROLLER

Fuzzy logic theory is considered as a mathematical approach combining multi-valued logic, probability theory and artificial intelligence to replicate the human approach in reaching the solution of a specific problem by using approximate reasoning to relate different data sets and to make decisions.

The performance of fuzzy logic controllers is well documented in the field of control theory since it provides robustness to Dynamic System parameter variations as well as improved transient and steady state performances (Fig. 5). In this study, a fuzzy logic based feedback controller is employed for controlling the voltage injection of the proposed Dynamic Voltage Restorer (DVR). Fuzzy logic controller is preferred over the conventional PI and PID controller because of its robustness to system parameter variations during operation and its simplicity of implementation (Nandam and Sen, 1986; Raviraj and Sen, 1997). Since, the proposed DVR uses an Energy Storage System consisting of capacitors charged directly from the supply lines through the rectifier and the output of the inverter depends upon the energy stored in the DC link capacitors. But as the amount of energy stored varies with the voltage sag/swell events, the conventional PI and PID controllers are susceptible to these parameter variations of the Energy Storage System, hence, the control of

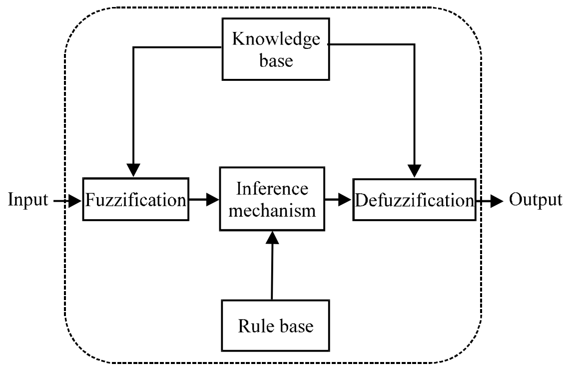

Fig. 5: Fuzzy controller design diagram

Table 1: Rule base for fuzzy logic controller

	e						
ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

voltage injection becomes difficult. The proposed FLC scheme exploits the simplicity of the Mamdani type fuzzy systems that are used in the design of the controller and adaptation mechanism.

The fuzzy logic based control scheme can be divided into four main functional blocks namely knowledge base, fuzzification, inference mechanism and defuzzification.

The knowledge base is composed of data base and rule base. Data base consists of input and output membership functions and provides information for appropriate fuzzification and defuzzification operations. The rule-base consists of a set of linguistic rules relating the fuzzified input variables to the desired control actions. Fuzzification converts a crisp input signal, error (e) and change in error (ce) into fuzzified signals that can be identified by the level of memberships in the fuzzy sets as shown in Table 1.

The inference mechanism uses the collection of linguistic rules to convert the input conditions to fuzzified output. Finally, the defuzzification converts the fuzzified outputs to crisp control signals using the output membership function which in the system acts as the changes in the control input (u). The typical input membership functions for error and change in error are shown in Fig. 6 and 7, respectively whereas the output membership function to change in control input is shown

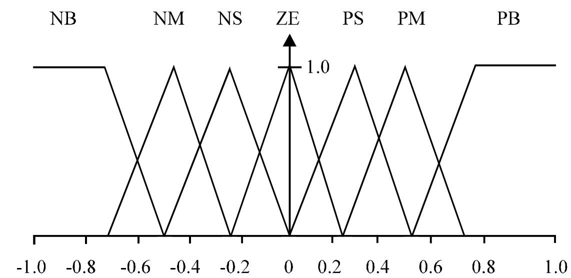

Fig. 6: Membership function for input variable error

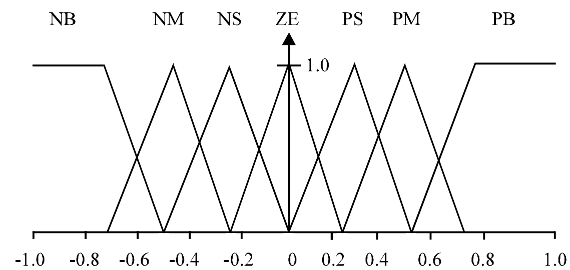

Fig. 7: Membership function for input variable change in error

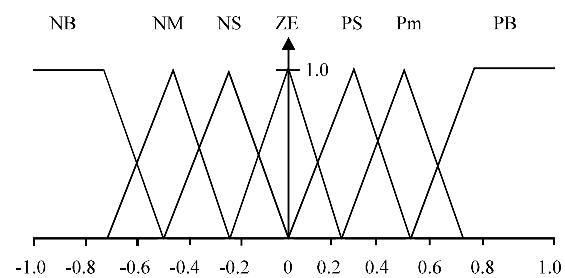

Fig. 8: Membership function for output variable change in control signal

in Fig. 8. The output generated by fuzzy logic controller as shown in Fig. 9 must be crisp which is used to control the PWM generation unit and thus accomplished by the defuzzification block. The defuzzification technique used here is based upon Centroid Method.

SIMULATION AND RESULTS

Dynamic Voltage Restorer (DVR) was proposed for mitigating the problem of voltage sags in industrial distribution systems with a large portion of its load consisting of induction motors. The modeling and simulation of the proposed DVR using Matlab/Simulink have been presented (Fig. 10). Detection and quantization of sags are done using the classical Fourier Transform (FT) technique. Calculation of the compensating voltage

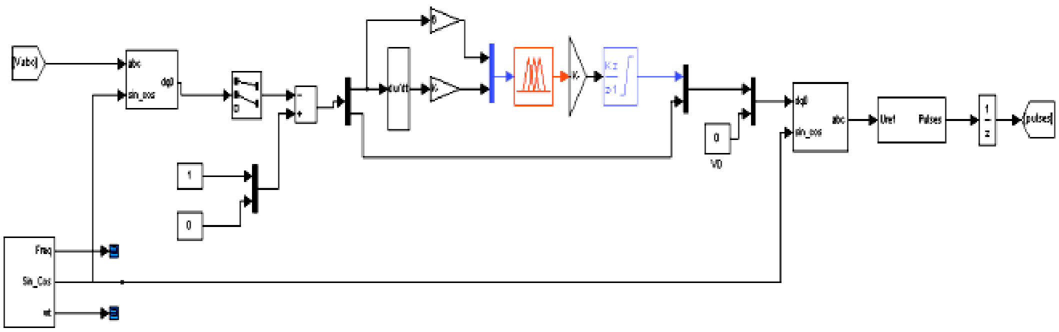

Fig. 9: Fuzzy logic controller

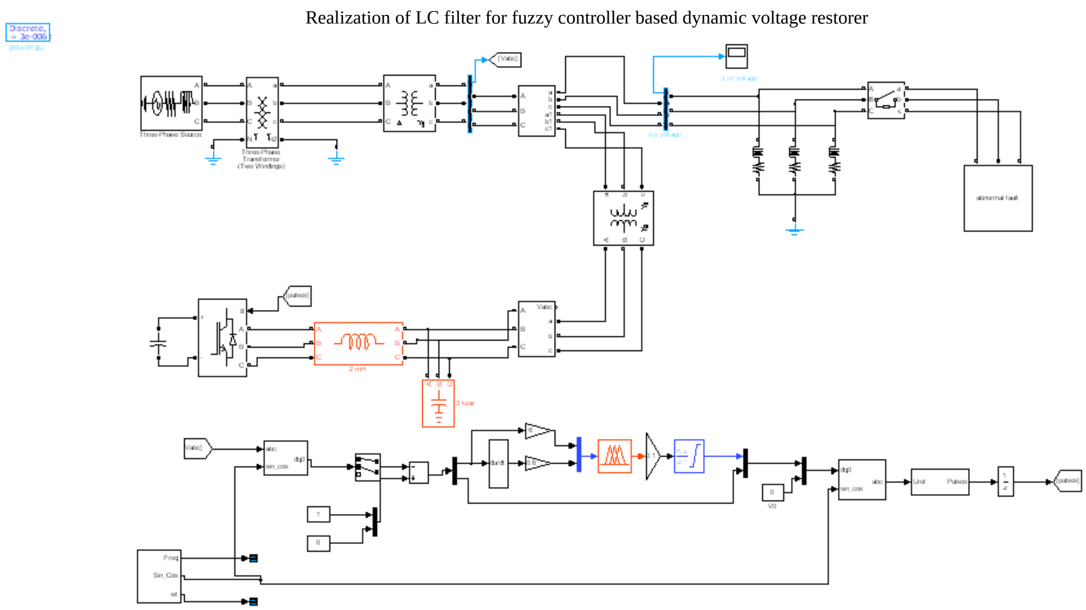

Fig. 10: Matlab/Simulink Model for proposed system

was one with reference to voltage only, since induction motors are not sensitive to changes in phase angle. A controller based on feed-forword technique is used which utilizes the error signal (difference between the reference voltage and actual measured voltage) to trigger the switches of an inverter using a Pulse Width Modulation (PWM) scheme. The proposed DVR utilizes energy drawn from the supply line source during normal operation and stored in capacitors and which is converted to an adjustable three phase AC voltage suitable for mitigation of voltage sags.

Dynamic voltage restorer is simulated using MATLAB SIMULINK and the results are analyzed on the basis of output voltage. Various cases of different active power of load at different DC energy storage are considered to study the impact on sag waveform and compensated waveform as shown in Fig. 11-14. A three-phase fault is created via a fault resistance of 0.55 Ω, load 1 is 5 kW, 100 VAR and load 2 is 10 kW, 100 VAR which results in a voltage sag of 10.07%. Transition time for the fault is considered from 0.1-0.14 sec. The simulation results and DVR performance in presence of DC energy storage reveals that 99.43% of sag is compensated and deviation of 0.57% is attained from three phase source voltage with 600 V of DC energy storage.

When the abnormal fault is effected the system; the sag takes place in the power line. Figure 11 represents the sag conditions in between 0.3-0.7 sec. When swell condition appeared in the line there will be a bulk amount of voltage will go to appear at that particular instant as shown in Fig. 13 in about 0.3-0.7 sec. When the proposed system is activated the sag and swell occurred can be cleared as shown in Fig. 12. Figure 14 shows the stable condition of response.

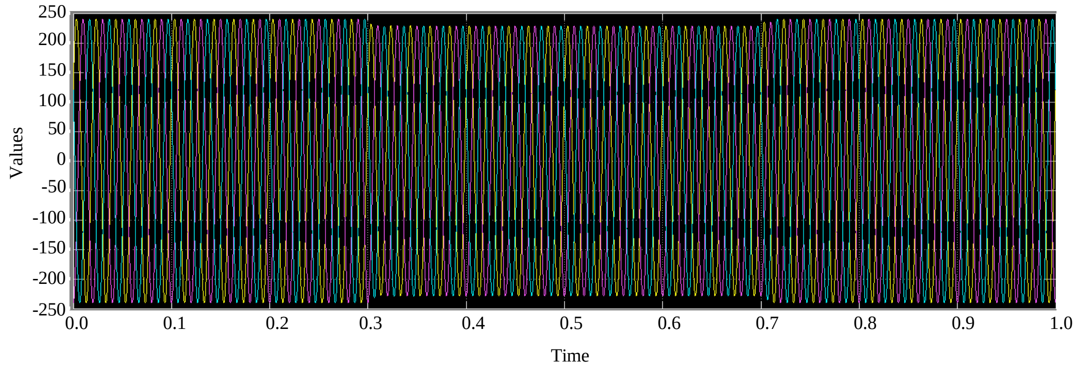

Fig. 11: Sag occurrence when fuzzy based DVR not activated

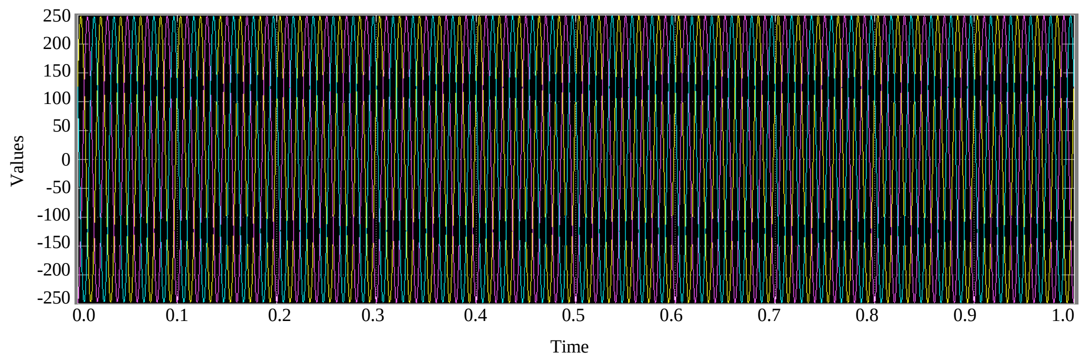

Fig. 12: Sag elimination when fuzzy based DVR activated

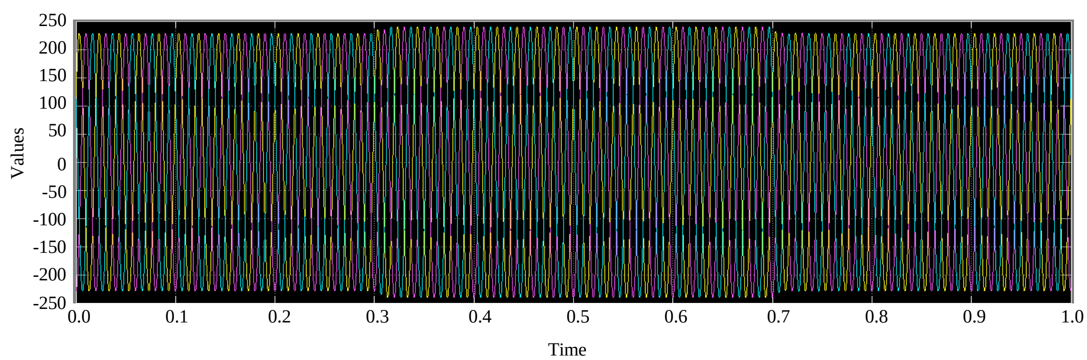

Fig. 13: Swell occurrence when fuzzy based DVR is not activated

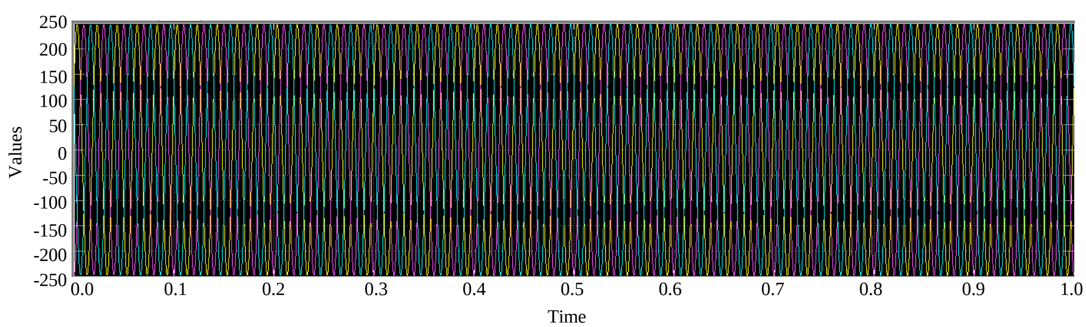

Fig. 14: Swell elimination when fuzzy based DVR is activated

CONCLUSION

This study analysis and design the output filter system with fuzzy based DVR which including the parameter design of LC filter realization. The parameter design includes the power rate of inverter, the cost of inductor and the switching-harmonic elimination performance of LC filter. Considering the resonance issue of LC filter, an addition has proved as a harmonic eliminator. The harmonics caused by the VSC System has been eliminated with LC filter realization. The fuzzy system used has shown in dynamic system response improvement. The response for different conditions like sag and swell has presented and proved as proposed system can eliminate the problem occurring in power system.

The simulation shows that the DVR performance is satisfactory in mitigating voltage sags/swells. The DVR handles both balanced and unbalanced situations without any difficulties and injects the appropriate voltage component to correct rapidly any deviation in the supply voltage to keep the load voltage constant a nominal value. The main advantages of the proposed DVR are simple control, fast response and low cost. Future research will include a comparison with a laboratory experiments on a low voltage DVR in order to compare simulation and experimental results. Further, attention to the filter construction and its parameter selection would be paid in future research. The passive filter is designed to cut off high order harmonics after the inverter circuit and introduce a negligible voltage drop. Another component to be looked for is the injecting transformer. The selection of the transformer parameters and saturation issues require further investigation.

REFERENCES

Araujo, S.V., A. Engler, B. Sahan and F. Antunes, 2007. LCL filter design for grid-connected NPC inverters in offshore wind turbines. Proceedings of the 7th International Conference on Power Electronics, October 22-26, 2007, Daegu, Korea, pp: 1133-1138.

Chan, P.K., K.K. Leung, H.S. Chung and S.Y.R. Hui, 2006. Boundary controller for dynamic voltage restorers to achieve fast dynamic response. Proceedings of the 21st Annual IEEE Applied Power Electronics Conference and Exposition, March 19-23, 2006, Dallas, TX., USA.

Fitzer, C., M. Barnes and P. Green, 2004. Voltage sag detection technique for a dynamic voltage restorer. IEEE Trans. Ind. Applic., 40: 203-212.

Ghosh, A. and G. Ledwich, 2002. Compensation of distribution system voltage using DVR. IEEE Trans. Power Delivery, 17: 1030-1036.

Gyugi, L., 1994. Dynamic compensation of AC transmission lines by solid state synchronous voltage sources. IEEE Trans. Power Delivery, 9: 904-911.

Li, Y.W., D.M. Vilathgamuwa, F. Blaabjerg and P.C. Loh, 2007. A robust control scheme for medium-voltage-level DVR implementation. IEEE Trans. Ind. Electr., 54: 2249-2261.

Liserre, M., R. Teodorescu and F. Blaabjerg, 2006. Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values. IEEE Trans. Power Electron., 21: 263-272.

Malinowski, M., S. Stynski, W. Kolomyjski and M.P. Kazmierkowski, 2009. Control of three-level PWM converter applied to variable-speed-type turbines. IEEE Trans. Ind. Electron., 56: 69-77.

Nandam, P.K. and P.C. Sen, 1986. A comparative study of Proportional-Integral (PI) and Integral-Proportional (IP) controllers for DC motor drives. Int. J. Control, 44: 283-297.

Nielsen, J.G. and F. Blaabjerg, 2005. A detailed comparison of system topologies for dynamic voltage restorers. IEEE Trans. Ind. Applic., 41: 1272-1280.

Nielsen, J.G., M. Newman, H. Nielsen and F. Blaabjerg, 2004. Control and testing of a Dynamic Voltage Restorer (DVR) at medium voltage level. IEEE Trans. Power Electron., 19: 806-813.

Raviraj, V.S.C. and P.C. Sen, 1997. Comparative study of proportional-integral, sliding mode and fuzzy logic controllers for power converters. IEEE Trans. Ind. Applic., 33: 518-524.

Roncero-Sanchez, P., E. Acha, J.E. Ortega-Calderon, V. Feliu and A. Garcia-Cerrada, 2009. A versatile control scheme for a dynamic voltage restorer for power-quality improvement. IEEE Trans. Power Delivery, 24: 277-284.

Silva, J.F., 2002. Control Methods for Power Converters. In: Handbook of Power Electronics, Rashid, M.H. (Ed.). Elsevier, USA., pp: 431-486.