

Control of Reduced Rating Dynamic Voltage Restorer with Battery Energy Storage System Using Fuzzy Logic

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ABSTRACT: In this paper, different voltage injection schemes for dynamic voltage restorers (DVRs) are analyzed with particular focus on a new method used to minimize the rating of the voltage source converter (VSC) used in DVR. A new control technique is proposed to control the capacitor-supported DVR. The control of a DVR is demonstrated with a reduced-rating VSC. The reference load voltage is estimated using the unit vectors. The synchronous reference frame theory is used for the conversion of voltages from rotating vectors to the stationary frame. The compensation of the voltage sag, swell, and harmonics is demonstrated using a reduced-rating DVR. . Result shows that this method can compensate voltage sag with a compensation error of 0.99%. Using this method, DVR may reduce voltage THD from 10.22% to 0.66%.

KEYWORDS: Dynamic voltage restorer (DVR), power quality, unit vector, voltage harmonics, voltage sag, voltage swell. Harmonics, Fuzzy Logic Controller.

1. INTRODUCTION

POWER QUALITY problems in the present-day distribution systems are addressed in the literature. Due to the increased use of sensitive and critical equipment pieces such as communication network, process industries, and precise manufacturing processes. Power quality problems such as transients, sags, swells, and other distortions to the sinusoidal waveform of the supply voltage affect the performance of these equipment pieces. Technologies such as custom power devices are emerged to provide protection against power quality problems. Custom power devices are mainly of three categories such as series-connected compensators known as dynamic voltage restorers (DVRs), shunt-connected compensators such as distribution static compensators, and a combination of series-and shunt-connected compensators known as unified power quality conditioner. The DVR can regulate the load. Two of the main problems in the field of power quality are voltage sag and instantaneous power loss. In addition, voltage sag has two main parameters including magnitude and time duration. Typically, DVR voltage injection method is used to compensate the difference between voltage when sag occurs and when before sag occurs, using AC voltage in series.

Another method is to inject voltage in phase with supply voltage when sag occurs. The advantage of both methods is that it uses economical energy storage, yet it has disadvantage of the occurrence of phase shift. Voltage sag caused by symmetrical 3 phase fault can be overcome by DVR employing back propagation neural network control. This method compensates very well, but it needs a relatively long time. Conventional fuzzy logic controller can reduce the time needs; however this controller needs many membership functions. Some researchers have been done to decrease the number of membership functions, for example by the use of fuzzy controller. Fuzzy polar controller method could decrease the number of conventional fuzzy logic membership functions. Many previous researchers used zero sequence blocking system, by installing wye-delta transformer to block zero current or voltage so that the sensitive load will not be affected. This was done because of the difficulty to eliminate zero sequence. Using the blocking transformer will make it easier to eliminate zero sequence effect, but this solution is relatively expensive. For this reason, another

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solution without blocking transformer is developed. This paper presents DVR with fuzzy polar controller which concerns on zero sequence voltage compensation to compensate voltage sag in low voltage distribution system by employing zero sequence unblocking system. This paper also compensates voltage distortion caused by harmonics. Simulation result shows that this controller could compensate voltage sag and harmonics very well under the condition of symmetrical and unsymmetrical fault without using zero sequence blocking .

II. DYNAMIC VOLTAGE RESTORER (DVR)

Dynamic Voltage Restorer (DVR) is power electronic device installed in series with distribution system line as can be seen in Figure 1. DVR uses semiconductor device to maintain voltage of sensitive load by injecting voltage whose magnitude, phase, and frequency can be controlled. How a DVR works to compensate harmonics is shown in Figure 2. From Figure 1 and Figure 2 it can be seen that, the topology of DVR as voltage sag compensator is similar to that of as harmonics compensator. Therefore, the DVR can compensate both voltage sag and voltage distortion caused by harmonics.

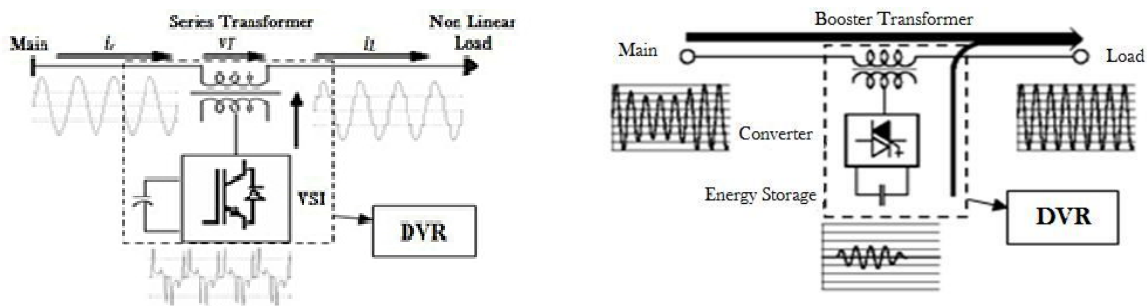


Fig 3: Schematic Diagram of DVR Configuration Fig.3. (a) Basic circuit of DVR.
3. (b) Phasor diagram of the DVR voltage injection schemes

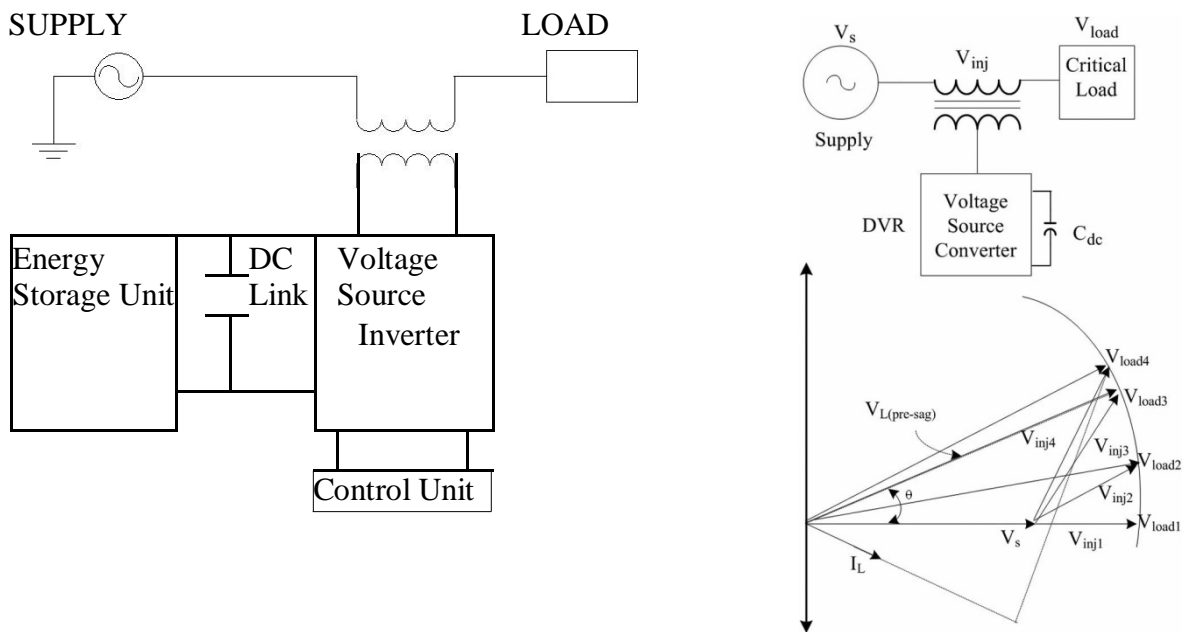
2.1 Configuration of DVR

The general configuration of the DVR consists of an Injection transformer, a Harmonic filter, a Voltage Source Converter (VSC), Energy Storage Unit and a Control and Protection unit as shown in Fig 3. Energy Storage Unit in DVR can be external batteries or capacitors charged from the supply line feeder through a rectifier. Generally the energy storage unit of a DVR can be divided into two parts (i.e. Storage devices and DC Charging Circuit). The purpose of energy storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. Energy Storage Unit in DVR can be external batteries or capacitors charged from the supply line feeder through a rectifier. Generally the energy storage unit of a DVR can be divided into two parts (i.e. Storage devices and DC Charging Circuit). The purpose of energy storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages.

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The different kinds of energy storage devices are superconductive magnetic energy storage (SMES), batteries, and capacitors. In fact, the capacity of the stored energy directly determines the duration of the sag which can be mitigating by the DVR. Batteries are the common choice and can be highly effective if a high voltage battery configuration is used. However, batteries in general have a short lifetime and often require some type of battery management system, which can be quite costly. An interesting alternative to batteries is the use of supercapacitors, which have a wider voltage range than batteries and can be directly paralleled across the input bus. Supercapacitors have a specific energy density less than that of a battery, but a specific power greater than a battery, making them ideal for short (up to several seconds) pulses of power. Certain supercapacitors can hold charge over extended periods of time, so as to act like a battery. However, unlike batteries, these supercapacitors have a short charging time and much longer lifetime. The purpose of the DC Charging Circuit is to charge the energy storage devices after the compensation of a voltage sag/swell event as well as maintain a nominal dc link voltage. The charging circuit can be an external power supply or a rectifier fed from the supply mains of the distribution network. A Voltage Source Converter is a power electronic system capable of generating a sinusoidal voltage at any required frequency, magnitude, and phase angle. DVR configurations use the VSC to generate the voltage required to compensate for the voltage sag/swell events. Since the majority of the voltage sags/swells observed on distribution systems are unbalanced, the VSC will often be required to operate with unbalanced switching functions for the three phases and must therefore be able to treat each phase independently. Moreover, sag on one phase may result in swell on another phase, so the VSC must be capable of handling both sags and swells simultaneously. The output voltage of the inverter is varied by using different PWM schemes available.

2.2 Compensation Methods

Compensation of voltage sags/swells is dependent upon a number of factors including DVR power rating, different load conditions and different types of voltage sags/swells. Some loads are very sensitive to phase angle jump while others are tolerant to it. Therefore, the compensation strategy depends upon the type and characteristics of the load connected to DVR. There are three different methods for DVR voltage injection which are presented below.

2.2.1 Pre-Fault Compensation

The DVR injects the difference voltage between during fault and pre-fault voltages to the system. In this method the DVR compensates for both magnitude and Phase angle. The main drawback of this technique is it requires a higher capacity energy storage device [23]. Fig 4a shows the vector diagram for the pre-fault control strategy for a

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voltage sag event. This method is best suited to loads sensitive to phase angle jumps as it compensates for both the magnitude and phase angle.

2.3 Control Methods for DVR

DVR Control strategies fall mainly in one of the two categories namely linear control methods and Non-linear control methods. Linear control methods can be employed with the feedback, the feed-forward and the combined feed controllers. Non-Linear control methods comprising the Artificial Neural Networks (ANN), the Fuzzy Logic (FL) and the Space Vector (SV) controllers. Although feedback controllers are popular, they require load and source tracking, whereas feed-forward controllers are much simpler yet open-looped, there is no feedback from the load voltage or current. The proposed DVR utilizes capacitors as the energy storage units fed through the supply mains via the rectifier. The compensation strategy is chosen to be the in phase compensation method due to its simplicity of implementation and induction motor no being sensitive to phase angle jumps. And the control of the proposed DVR is based on a fuzzy logic based feedback controller.

III. MATERIALS AND METHODS

This study proposes a fuzzy logic controlled DVR with in-phase compensation strategy for voltage sag/swell compensation for industrial induction motor loads. Since the in-phase compensation strategy is simpler and efficient, the operation of the proposed DVR is simpler and its response time is also faster. Fig 5 shows the block diagram of the proposed controller for the DVR.

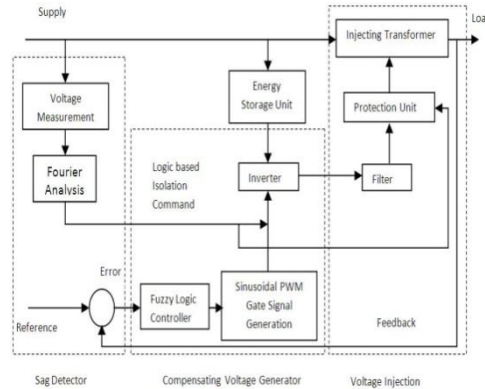


Fig 5: Block diagram of the proposed DVR control scheme.

3. The controller of the proposed DVR consists of the following blocks:

3.1. Detection of Sag and Swell Events: Sag/Swell detection includes determination of the instants when a sag/swell event starts and ends, magnitude of the variation and the phase angle jumps. Several approaches for detection of sag/swell events available are Classical Fourier Transform method, Wavelet analysis, use of RMS values, use of peak values, the transformation of the three phase voltages to a two dimensional frame (dq frame) and therefore to one phasor etc.

In this study, the proposed DVR uses the traditional Fourier Transform method to detect the voltage sag/swell events. The Fourier transform based sag/swell detector associated with the proposed DVR can track the magnitude and the phase angle of the fundamental frequency component of the supply voltage simultaneously in order to make sure that the injected sine wave will be in-phase with the remaining sine wave during the sag/swell events, to have a constructive vector addition of the DVR and the supply voltages. Since the compensation strategy used in the proposed DVR is in-phase method, computation of the compensating voltage magnitude is done using a comparator with one input as the variable load voltage and the other being the reference voltage for each of the three phases independently. The output of the comparator determines the magnitude of the voltage required to be injected by the DVR and is called the error signal which is the input to the fuzzy logic based feedback controller used for controlling the output voltage of the inverter through the control of the modulation index for each of the three phases of the inverter independently.

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3.2 Compensating Voltage Generation

The inverter circuit in DVR is responsible for generation of the compensating voltage. Hence the control of the inverter will directly affect the performance of the DVR. The inverter used in the proposed DVR is a three phase six pulse inverter. The thyristors used in the inverter circuit are chosen to be Insulated Gate Bipolar Transistors (IGBT) for their fast response and robust operation. The inverter uses Sinusoidal Pulse Width Modulation (SPWM) for controlling the modulation index hence controlling the output voltage of the inverter.

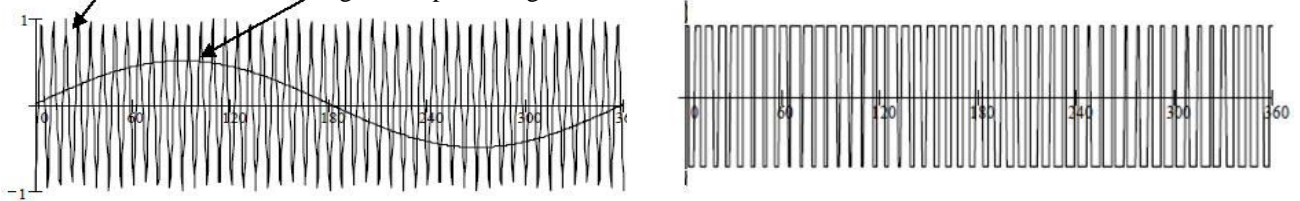
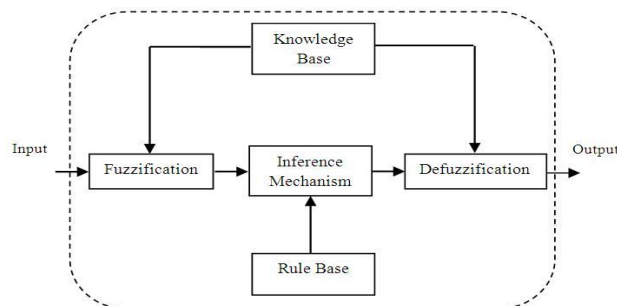


Fig 6: Sinusoidal Pulse Width Modulation Scheme.

In SPWM, a sinusoidal reference signal of supply frequency (i.e. 50 Hz) is compared with a high frequency triangular carrier waveform (i.e. 1080 Hz for this study). When the sinusoidal reference signal is greater than the triangular carrier wave, a batch of three IGBT switches out of the six are turned on and the counter switches are turned off and when the reference sinusoidal signal is smaller than the triangular carrier waveform in magnitude then the second batch of three IGBT switches are turned on and the first batch of switches are turned off. The magnitude of the sinusoidal reference signal determines the modulation index of the PWM signal generator which is dependent upon the error signal. The magnitude of the sinusoidal reference signal is controlled by the fuzzy logic based feedback controller which adjusts the magnitude according to the error magnitude and hence control the modulation index. The proposed DVR utilizes large capacitor banks for storing dc energy. Supply line voltage is rectified and used to charge the capacitor banks. DC voltage from alternative supply sources can also be utilized with the proposed configuration of DVR.

3.3 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. 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. Since the proposed DVR uses energy storage system consisting of capacitors charged directly from the supply lines through 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 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.



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that can be identified by level of memberships in the fuzzy sets. 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 respectively, whereas the output membership function for change in control input. The output generated by fuzzy logic controller must be crisp which is used to control the PWM generation unit and thus accomplished by the defuzzification block. Many defuzzification strategies are available, such as, the weighted average criterion, the mean-max membership, and center-of-area (centroid) method. The defuzzification technique used here is The set of fuzzy control linguistic rules is given in Table 1. The inference mechanism of fuzzy logic controller utilizes these rules to generate the required output based upon centroid method. DVR is generally connected in feeders having sensitive loads whose terminal voltage has to be regulated. The SIMULINK model of proposed fuzzy logic controller.

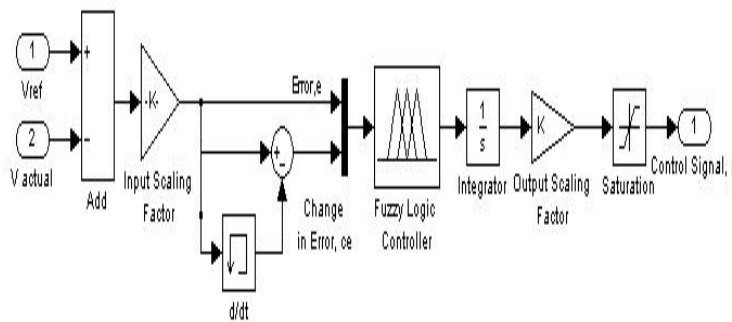


Fig 9: SIMULINK model of proposed FLC.

IV. MODELING AND SIMULATION

The performance of the proposed fuzzy logic based DVR is evaluated by using MATLAB/SIMULINK program as a simulation platform. The DVR is connected in series between a three phase programmable (controllable) voltage source with 400V line to line RMS voltage, 50 Hz and a load of active power $p = 10$ KW and reactive power $Q = 1$ KVAR (with installation of power factor correction capacitors). The Simulink model of the proposed DVR.

V. RESULTS AND DISCUSSIONS

Results are obtained by simulating the proposed DVR system in MATLAB/SIMULINK software. The minimum operation time of the DVR is 1 cycle or 20 milliseconds. Several power quality phenomena associated with voltage sag and swell have been simulated and the results are arranged in the following sequence for all cases: (a) the supply voltage (V_{Supply}), (b) the DVR voltage (V_{DVR}) and (c) the load voltage (V_{Load}).5.1 Simulation Results

5.1.1. Three Phase Balanced Sag

A three phase balanced voltage sag is simulated by reducing the line to line voltage on each phase to 60% of the normal value for a duration of 0.3 seconds from $t=0.4$ sec till $t=0.7$ sec as shown in Fig 10. The simulation duration was 1 second.

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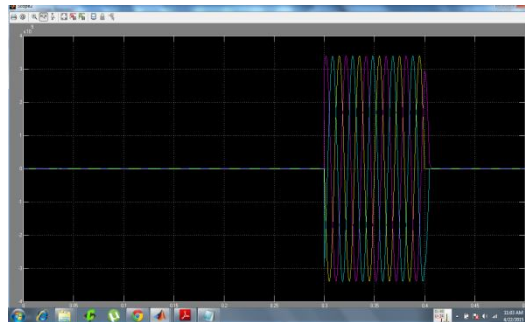
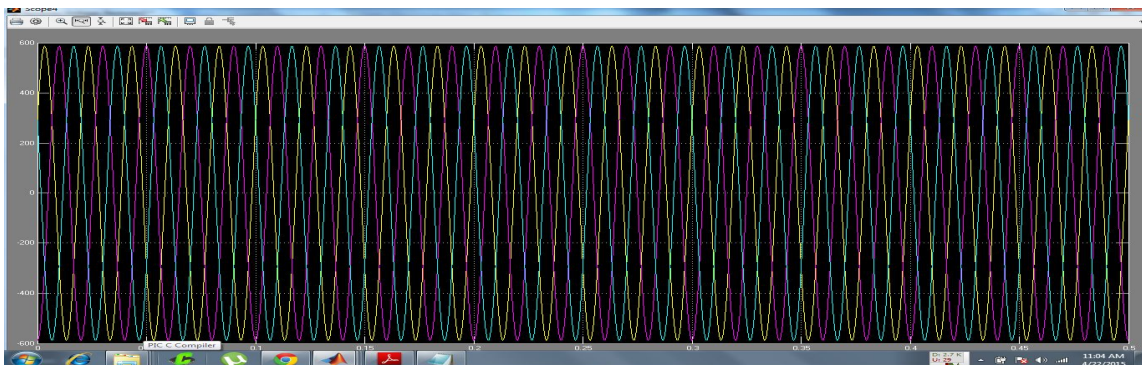


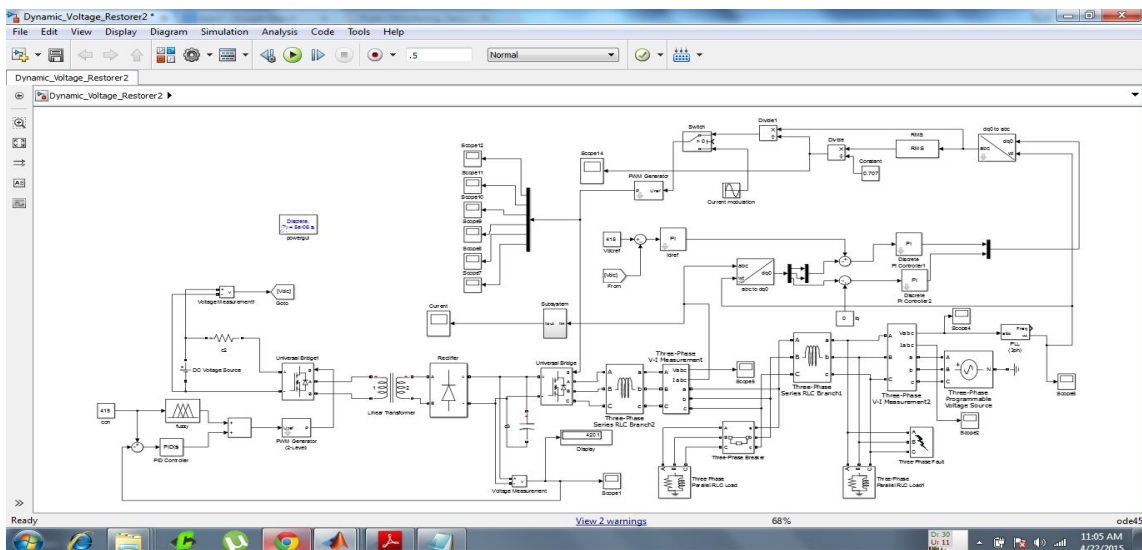
Fig 10: Three Phase Balanced Voltage Sag

5.1.2 Three Phase Balanced Swell

A three phase balanced voltage swell is simulated by increasing the line to line voltage on each phase to 140% of the normal value for a duration of 0.3 seconds from $t=0.4$ sec till $t=0.7$ sec . The simulation time was 1 second.



V. SIMLINK



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VI. CONCLUSION

In this study, a simple, fast and efficient Dynamic Voltage Restorer (DVR) is proposed for mitigation of power quality problem associated with voltage sags/swells in industrial distribution systems with a large portion of its load comprising of induction motors. The proposed DVR employs the classical Fourier Transform technique for detection and quantification of voltage disturbances (sags/swells) events. Since induction motors are not sensitive to changes in phase angle, in phase compensation method is used for calculation of the compensating voltage since it is fast and simple and finally a fuzzy logic based feedback controller is used to control the voltage injection of the proposed DVR system in case of voltage disturbances. The proposed DVR utilizes energy drawn from the supply line source during normal operation and stores in capacitors and which is converted to an adjustable three phase ac voltage suitable for mitigation of voltage sags/swells. The modeling and simulation of the proposed DVR using MATLAB/SIMULINK had been presented. The simulation shows that the DVR performance is efficient and satisfactory in mitigating voltage sags/swells. The DVR handles both balanced and unbalanced situations with sufficient efficiency and accuracy and injects the appropriate voltage component to correct rapidly any deviation in the supply voltage to keep the load voltage constant at the nominal value. The main advantages of the proposed DVR are simple and efficient adaptive control and fast response. Future works will include a comparison with a laboratory experiments on a low voltage DVR in order to compare simulation and experimental results and estimate the cost of the practical system. Further issues associated with low pass filter construction and its parameters selection, injection transformer selection and its saturation and reduction in operational time of the entire DVR system will be investigated in future works

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