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Performance of Dynamic Voltage Restorer by Using Fuzzy Controller With Battery Energy Storage System

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***Abstract*—Inthis paper the dynamic Voltage Restorer (DVR) has as of late been acquainted with shield the touchy mechanical burdens from the impeding impacts of voltage lists/swells and other voltage aggravations. Different injection schemes for DVR are analyzed with particular focus on new method used to minimize the rating of voltage source converter(VSC) used in DVR. Anew control technique is proposed to control the capacitor-supported DVR. The control of 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. In this control scheme fuzzy logic controller is used to activate the Pulse Width Converter. The compensation of the voltage sag,swell and hormonics is demonstrated using a reduced-rating DVR.Results shows that this method can compensate voltage sag, swell and harmonics.**

***Index Terms* – Dynamic Voltage Restorer (DVR), Power Quality, unit vector, voltage harmonics, voltage sag, voltage swell, fuzzy Logic Controller.**

I INTRODUCTION

POWER QUALITY problems in the present day distribution systems are addressed in the literature [1]–[6] 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 [2]. 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 [2]–[6]. The DVR can regulate the load voltage from the problems such as sag, swell, and harmonics in the supply voltages. Hence, it can protect the critical consumer loads from tripping and consequent losses [2]. The custom power devices are developed and installed at consumer point to meet the power quality standards such as IEEE-519 [7].

Voltage sags in an electrical grid are not always possible to avoid because of the finite clearing time of the faults that cause the voltage sags and the propagation of sags from the transmission and distribution systems to the low-voltage loads.Voltage sags are the common reasons for interruption in production plants and for end-user equipment malfunctions in general. In particular, tripping of equipment in a production line can cause production interruption and significant costs due to loss of production. One solution to this problem is to make the equipment itself more tolerant to sags, either by intelligent control or by storing "ride-through" energy in the equipment. An alternative solution, instead of modifying each component in a plant to be tolerant against voltage sags, is to install a plantwide uninterruptible power supply system for longer power interruptions or a DVR on the incoming supply to mitigate voltage sags for shorter periods [8]–[23]. DVRs can eliminate most of the sags and minimize the risk of load tripping for very deep sags, but their main drawbacks are their standby losses, the equipment cost, and also the protection scheme required for downstream short circuits.

Many solutions and their problems using DVRs are reported, such as the voltages in a three-phase system are balanced [8] and an energy-optimized control of DVR is discussed in [10]. Industrial examples of DVRs are given in [11], and different control methods are analyzed for different types of voltage sags in [12]–[18]. A comparison of different topologies and control methods is presented for a DVR in [19]. The design of a capacitor-supported DVR that protects sag, swell, distortion or unbalance in the supply voltages is discussed in [17]. The performance of a DVR with the high-frequency-link transformer is discussed in [24]. In this paper, the control and performance of a DVR are demonstrated with a reduced-rating voltage source converter (VSC). The synchronous reference frame (SRF) theory is used for the control of DVR.

II. OPERATION OF DVR

The schematic of a DVR-connected system is shown in Fig. 1(a). The voltage V_{inj} is inserted such that the load voltage V_L load is constant in magnitude and is undistorted, although the supply voltage V_s is not constant in magnitude or is distorted. Fig 1(b) shows phasor diagram of different voltage injection schemes of DVR.

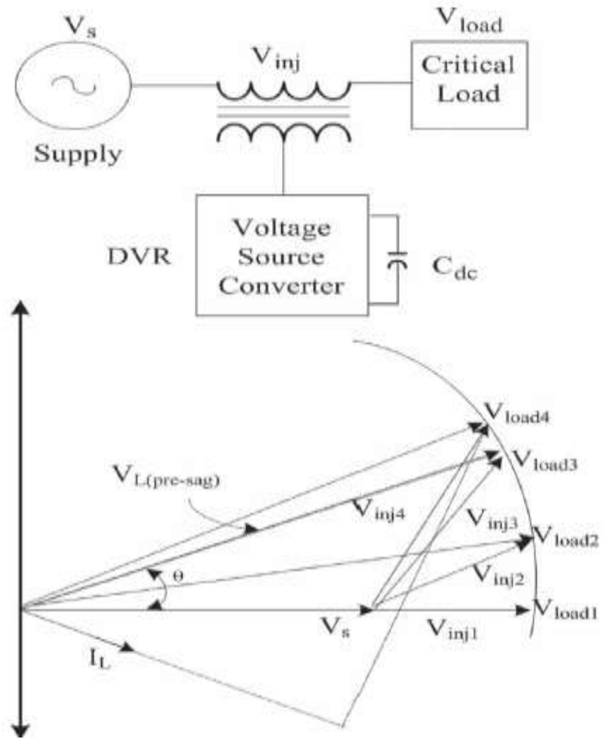

Fig: 1(a) basic circuit of DVR (b) phasor diagram of the DVR voltage injection schemes

VL (pre−sag) is a voltage across the critical load prior to the voltage sag condition. During thevoltage sag, the voltage is reduced to V_s with a phase lag angleof θ. Now, the DVR injects a voltage such that the load voltage magnitude is maintained at the pre-sag condition. According to the phase angle of the load voltage, the injection of voltages can be realized in four ways [19]. V_{inj1} represents the voltage voltage injected in-phase with the supply voltage. With the injection of V_{inj2}, the load voltage magnitude remains same but it leads V_s by a small angle. In V_{inj3}, the load voltage retains the same phase as that of the pre-sag condition, which may be an optimum angle considering the energy source [10]. V_{inj4} is the condition where the injected voltage is in quadrature with the current, and this case is suitable for a capacitor-supported DVR as this injection involves no active power [17]. However a minimum possible rating of the converter is achieved by V_{inj1}. The DVR is operated in this scheme with a battery energy storage system (BESS).

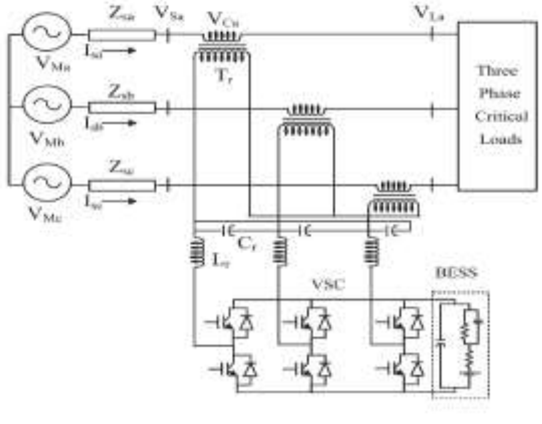

Fig: 2 schematic of DVR connected system

Fig. 2 shows a schematic of a three-phase DVR connected to restore the voltage of a three-phase critical load. A three-phase supply is connected to a critical and sensitive load [2-5] through a three-phase series injection transformer. The equivalent voltage of the supply of phase A$_{vMa}$ is connected to the point of common coupling (PCC) $_{vSa}$ through short-circuits impedance Z_{sa}. The voltage injected by the DVR in phase A$_{vCa}$ is such that the load voltage v_{La} is of rated magnitude and undistorted A three-phase DVR is connected to the line to inject a voltage in series using three single-phase transformers *Tr*. *Lr* and *Cr* represent the filter components used to filter the ripples in the injected voltage. A three-leg VSC with insulated-gate bipolar transistors (IGBTs) is used as a DVR and a BESS is connected is connected to its DC bus.

III. CONTROL METHODS FOR DVR

DVR Control strategies [11] 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-foreword 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-foreword 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.

IV. 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 [11] is simpler and its response time is also faster. Fig 3 shows the block diagram of the proposed controller for the DVR.

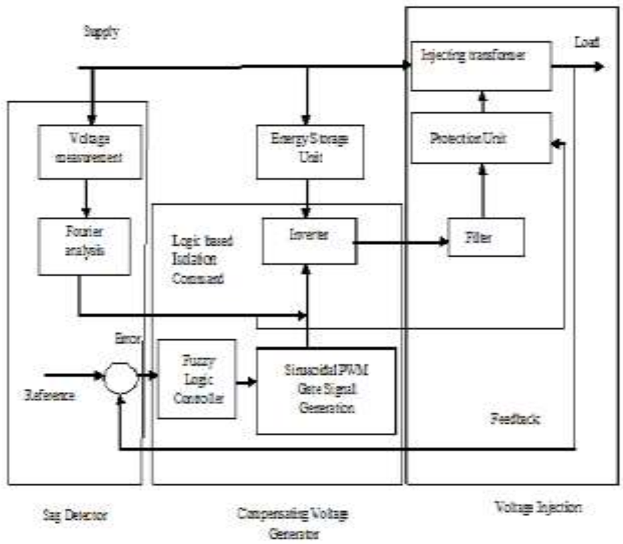

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Fig 3: Block diagram of the proposed DVR control scheme.

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

4.1. 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 [1] 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 [5] (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 [1] 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.

4.2 Compensating Voltage Generation

The inverter circuit in DVR [12] 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) [20] for controlling the modulation index hence controlling the output voltage of the inverter

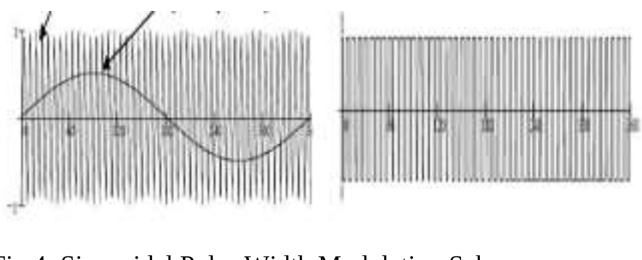


Fig 4: Sinusoidal Pulse Width Modulation Scheme

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 [5] 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.

4.3 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 [25] 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 [15] because of its robustness to system parameter variations during operation and its simplicity of implementation. Since the proposed DVR [11] 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 that can be identified by level of memberships in the fuzzy sets [25]. 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).

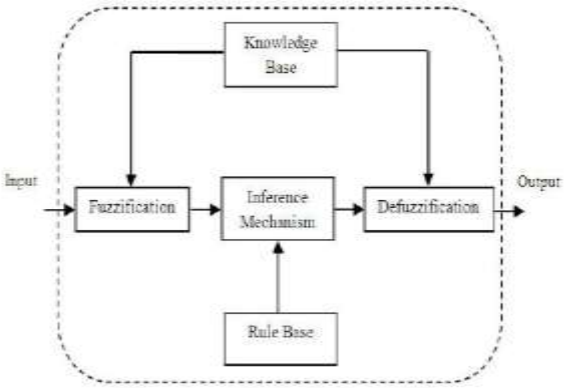


Fig: 5 steps involved in fuzzy logic controller

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 [6] generation unit and thus accomplished by the defuzzification block. Many defuzzification strategies [25] 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.

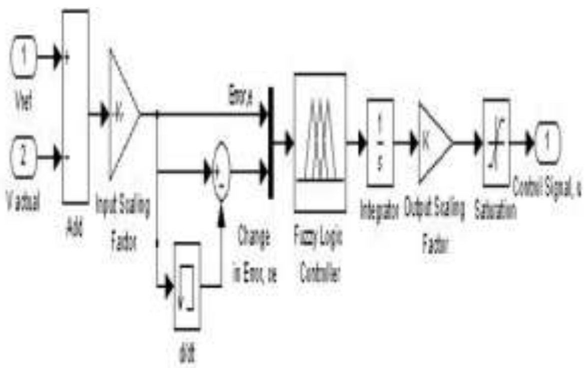


Fig: 6 SIMULINK MODEL of proposed FLC

V. MODELING AND SIMULATION

The DVR-connected system consisting of a three-phase supply, three-phase critical loads, and the series injection transformers shown in Fig. 2 is modelled in MATLAB/Simulink environment along with a sim power system toolbox and is shown in Fig. 5. An equivalent load considered is a 10-kVA, 0.8 lag linear loads. The parameters of the considered system for simulation study are given appendix

VI. PERFORMANCE OF THE DVR SYSTEM

The performance of the DVR is demonstrated for different supply voltage disturbances such as voltage sag and swell. Fig. 6 shows the transient performance of the system under voltage sag and voltage swell conditions. At 0.2 s, a sag in supply voltage is created for five cycles, and at 0.4 s, a swell in the supply voltages is created for five cycles. It is observed that the load voltage is regulated to constant amplitude under both sag and swell conditions.

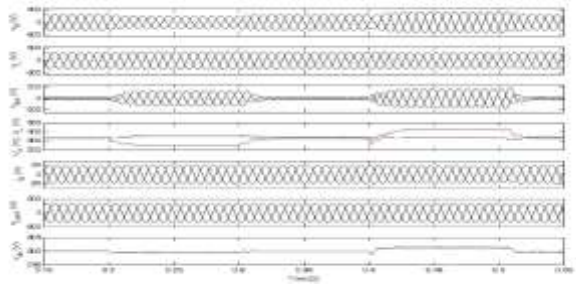


Fig: 7 Dynamic performance of DVR with in phase injection during voltage sag, swell applied to critical load

PCC voltages v_S, load voltages v_L, DVR voltages v_C, amplitude of load voltage V_L and PCC voltage V_s, source currents i_S, reference load voltages $v_{L\mathrm{ref}}$, and dc bus voltage v_{dc} are also depicted in Fig. 6. The load and PCC voltages of phase A are shown in Fig. 7, which shows the in-phase injection of voltage by the DVR. The compensation of harmonics in the supply voltages is demonstrated in Fig. 8. At 0.2 s, the supply voltage is distorted and continued for five cycles. The load voltage is maintained sinusoidal by injecting proper compensation voltage by the DVR. The total harmonics distortions (THDs) of the voltage at the PCC, supply current, and load voltage, respectively. It is observed that the load voltage THD is reduced to a level of 0.66% from the PCC voltage of 6.34%.

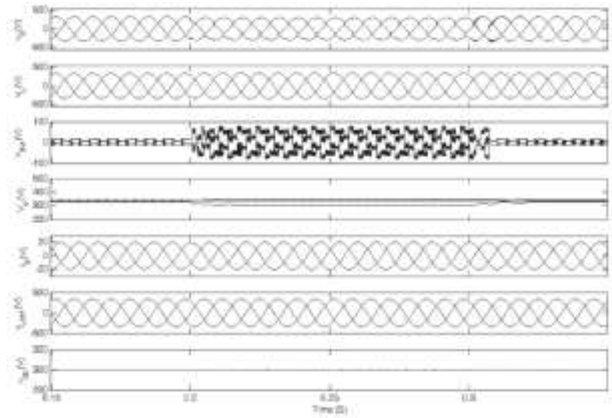


Fig: 8 Dynamic performance of DVR during harmonics in supply voltage applied to critical load

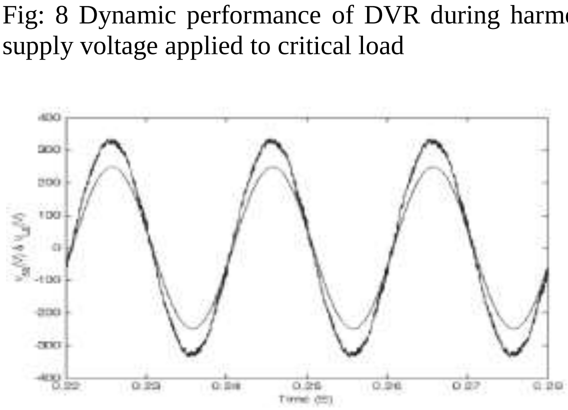


Fig: 8 voltages at PCC and load terminal

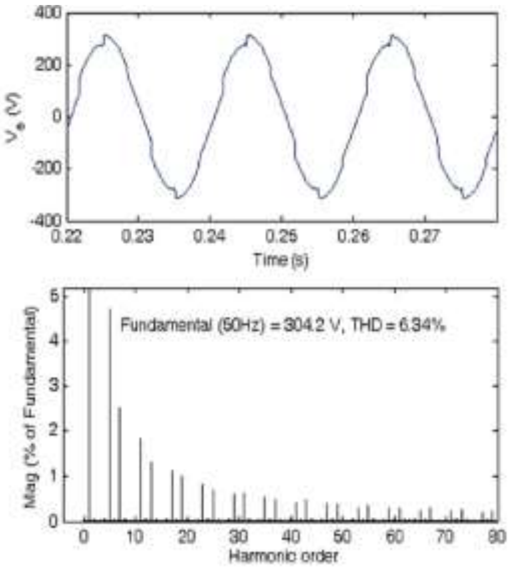
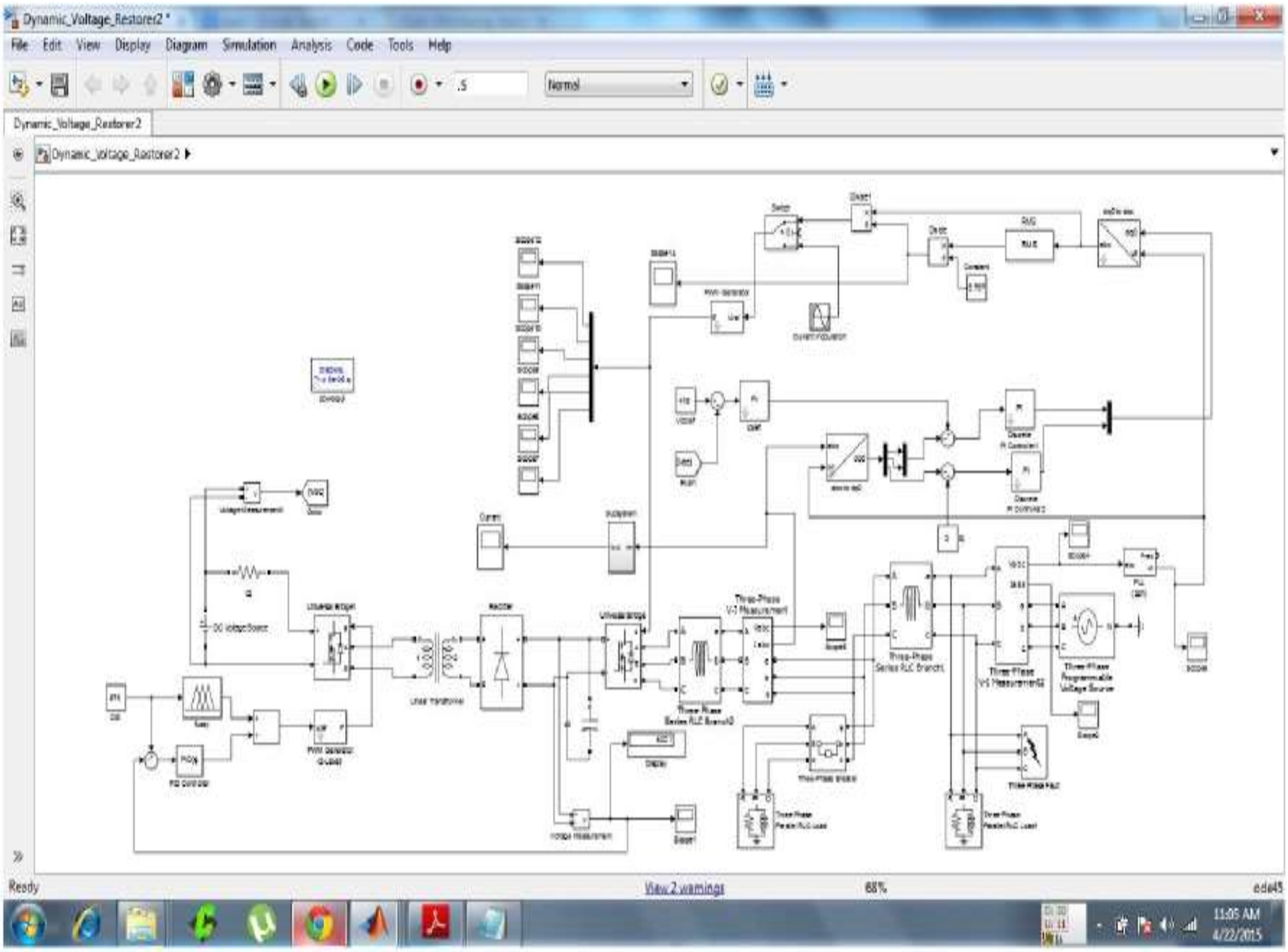


Fig: 9 PCC voltage and harmonic spectrum during the disturbance

VII SIMULINK



VIII 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

APPENDIX

AC line voltage: 415 V, 50 Hz
Line impedance: Ls= 3.0 mH, Rs= 0.01 Ω
Linear loads: 10-kVA 0.80-pf lag
Ripple filter: Cf= 10 μF, Rf= 4.8 Ω
DVR with BESS
DC voltage of DVR: 300 V
AC inductor: 2.0 mH
PWM switching frequency: 10 kHz
DVR with dc bus capacitor supported
DC voltage of DVR: 300 V
AC inductor: 2.0 mH
PWM switching frequency: 10 kHz
Series transformer: three-phase transformer of rating 10 kVA, 200 V/300 V.

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