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Design and Implementation of Dynamic Voltage Restorer for Voltage Sag Mitigation

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***Abstract*— *This paper introduces the terminology and various issues related to 'power quality'. The power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency deviations that result in a failure of end use equipment's. The main occurrence of voltage sag is always considered as one of the major power quality problems and it become severe to industrial customers. Voltage sag can cause mis-operation to several sensitive electronic equipment's. This problem can be mitigated with voltage injection method using custom power device called 'Dynamic Voltage Restorer' (DVR). The performance of the DVR depends on the efficiency of the control technique involved in switching circuit of the inverter. This paper presents hardware implementation of the DVR with Sinusoidal Pulse Width Modulation (SPWM) based PI controller using AT89S51 Microcontroller. A DVR with its excellent dynamic capabilities, when installed between the supply and a critical load feeder, can compensate for voltage sags, restoring line voltage to its nominal value within a few milliseconds and hence avoiding any power disruption to that load.*

***Keywords*— *Dynamic voltage restorer (DVR), AT89S51 microcontroller, sinusoidal pulse width modulation (SPWM), PI controller, voltage sag.*

I. INTRODUCTION

Recently, power quality problems become a major concern of industries due to massive loss in terms of time and money. Hence, there are always demands for good power quality, which positively resulting in reduction of power quality problems like voltage sag, harmonic and flicker, interruptions, harmonic distortion. Preventing such phenomena is particularly important because of the increasing heavy automation in almost all the industrial processes. High quality in the power supply is needed, since failures due to such disturbances usually have a high impact on production costs. There are number of methods to overcome voltage sags. One approach is to use Dynamic Voltage Restorers with energy storage. The DVR is a power electronics device that is able to compensate voltage sags on critical loads dynamically. By injecting an appropriate voltage, the DVR restores a voltage waveform and ensures constant load voltage. The DVR consists of Voltage Source Converter (VSC), injection transformers, passive filters and energy storage (lead acid battery). The Dynamic Voltage Restorer (DVR) with the lead acid battery is an attractive way to provide excellent dynamic voltage compensation capability as well as being economical when compared to shunt-connected devices. The DVR is a custom power device that is connected in series with the distribution system. The DVR employs IGBTs to maintain the voltage applied to the load by injecting single-phase output voltages whose magnitude, phase and frequency can be controlled [1]. The basic function of DVR is to inject dynamically voltage required, V_{DVR} to compensate sagging occurrence. Generally, the operation of DVR can be categorized into two modes; standby mode and injection mode. In standby mode, DVR either in short circuited operation or inject small voltage to cover voltage drop due to transformer reactance losses. The DVR is turn into injection mode as soon as sagging is detected. V_{DVR} is injected in series with load with required magnitude and phase for compensation.

The common causes of voltage sag are faults or short circuit in the system, starting of large loads and faulty wiring. This will lead to increase in both production and financial loss for industries. Therefore, it is vital to mitigate voltage sag. Two main characteristics that explain the voltage sag are depth/magnitude and duration of voltage sag itself. The depth/magnitude and duration of voltage drop that said to be voltage sag is between 0.1 to 0.9 p.u with time interval, t about 0.5 cycles to 1 minute. This classification is based on IEEE standard 1159-1995 [3]. There are various types of voltage sag mitigation equipment that available nowadays such as Uninterrupted Power Supply (UPS), flywheel, and the flexible ac transmission system (FACTS) devices which have been widely used in the power system due to the reliability to maintain power quality control. One of the most FACTS devices that have been created in improvement the performance of power quality is Dynamic Voltage Restorer (DVR) also known as custom power devices. In this project, DVR which consists of the injection transformer, filter unit, PWM inverter, energy storage and control system is used to mitigate the voltage sag in the power distribution system. Control unit is the heart of the DVR where its main function is to detect the presence of voltage sags in the system, calculating the required compensating voltage for the DVR and generate the reference voltage for SPWM generator to trigger on the PWM inverter. The components of control system unit are the dq0-transformation, Phase-lock-loop (PLL) and the PI Controller. PI Controller is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between output and desired set-point) and the integral of that value. [5]

Power Quality in electric networks is one of today's most concerned areas of electric power system. The power quality has serious economic implications for consumers, utilities and electrical equipment manufacturers. The impact of power quality problems is increasingly felt by customers - industrial, commercial and even residential. Some of the main power quality problems are sag, swell, transients, harmonic, and flickers etc [2].

By custom power devices, we refer to power electronic static controllers used for power quality improvement on distribution systems rated from 1 to 38 kV [8], [9]. This interest in the practice of power quality devices (PQDs) arises from the need of growing power quality levels to meet the everyday growing sensitivity of customer needs and expectations [7]. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. Its application includes lower cost, smaller size, and its fast dynamic response to the disturbance [10]. Several research papers and reports addressed the subject of improving power quality in distribution system by the use of custom power devices.

Initially for the improvement of power quality or reliability of the system FACTS devices like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), interline power flow controller (IPFC), and unified power flow controller (UPFC) etc are introduced. These FACTS devices are designed for the transmission system. But now a day as more attention is on the distribution system for the improvement of power quality, these devices are modified and known as custom power devices. The term “custom power” describes the value-added power that electric utilities will offer to their customers. The value addition involves the application of high power electronic controllers to distribution systems, at the supply end of industrial, commercial consumers.

The main custom power devices which are used in distribution system for power quality improvement are distribution static synchronous compensator (DSTATCOM), dynamic voltage Restorer (DVR), active filter (AF), unified power quality conditioner (UPQC) etc. N.G Hingorani [5] was the first to propose FACTS controllers for improving PQ. He termed them as Custom Power Devices (CPD). These are based on VSC and are of 3 types given below.

1. Shunt connected distribution STATCOM (DSTATCOM)
2. Series connected dynamic voltage restorer (DVR)
3. Combined shunt and series, unified power quality conditioner (UPQC).

Custom power devices (CPD). These are based on VSC and are of 3 types given below.

1. Shunt connected Distribution STATCOM (DSTATCOM)
2. Series connected Dynamic Voltage Restorer (DVR)
3. Combined shunt and series, Unified Power Quality Conditioner (UPQC).

The DVR is similar to SSSC while UPQC is similar to UPFC. In spite of the similarities, the control techniques are quite different for improving PQ. A major difference involves the injection of harmonic currents and voltages to separate the source from the load. A DVR can work as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation. A UPQC can be considered as the combination of DSTATCOM and DVR. A DSTATCOM is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation to improve power factor or regulate the load bus voltage. Several power providers have installed custom power devices for mitigating power quality problems. In particular, three major power quality devices (PQDs)—an advanced static VAR compensator, a dynamic voltage restorer, and a high-speed transfer switch are used these days. Over the past ten years, advanced power electronic devices have been the center of various research studies, installation projects, and development technologies. By custom power devices are power electronic static controllers used for power quality development on distribution systems rated 1 through 38 kV. This interest in the usage of power quality devices (PQDs) arises from the need of mounting power quality levels to meet the everyday growing sensitivity of consumer needs and expectations [4]. Power quality levels, if not achieved, can cause costly downtimes and customer dissatisfaction. According to contingency planning research company’s annual study [5], downtime caused by power disturbances results in major financial losses. In order to face these new needs, advanced power electronic devices have developed over the last years. Their performance has been demonstrated at medium distribution levels, and most are available as commercial products [6], [7].

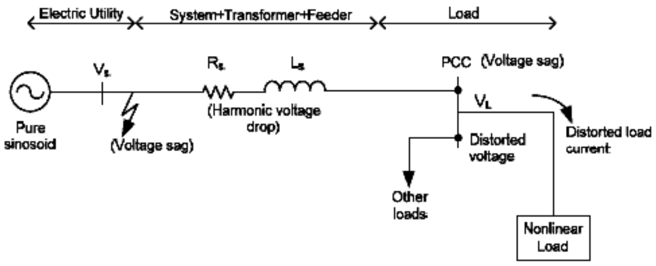

Fig. 1. Single line diagram of a real system without custom power devices

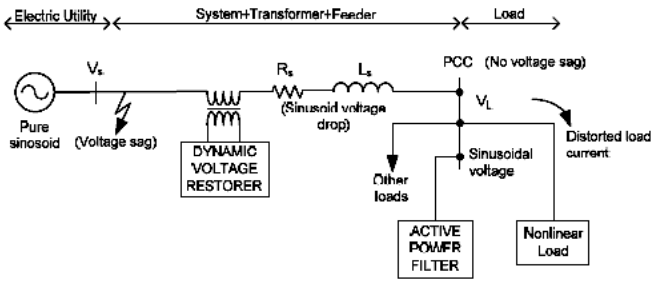

Fig. 2. Single line diagram of a real system with custom power devices

Power quality is one of major concerns in the present era. Distribution system locates the end of power system and is connected to the customer directly, so the reliability of power supply mainly depends on distribution system. It has become important, especially, with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure of end use equipment’s. The electrical distribution network failures account for about 90% of the average customer interruptions. As the customer's demand for the reliability of power supply is increasing day by day, so the reliability of the distribution system has to be increased. One of the major problems dealt here is the power sag. Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in practice, power systems, especially the distribution system, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the purity of the waveform of supplies is lost. This ends up producing many power quality problems. While power disturbances occur on all electrical systems, the sensitivity of today's sophisticated electronic devices makes them more disposed to the quality of power supply. For some sensitive devices, a temporary disturbance can cause scrambled data, interrupted communications, a frozen mouse, system crashes and equipment failure etc. A power voltage spike can damage valuable components.

II. DYNAMIC VOLTAGE RESTORER

Among the power quality problems like sag, swell, harmonic etc, voltage sag is the most severe disturbances in the distribution system. To overcome these problems the concept of custom power devices is introduced lately. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is generally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, DVR can also added other features like line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

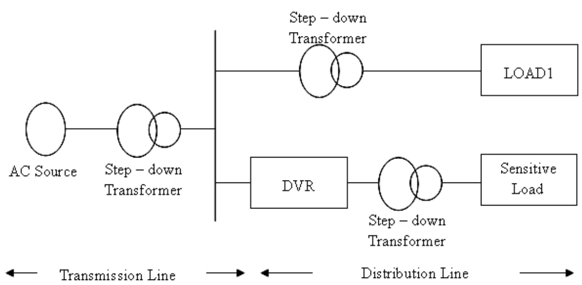

Fig. 3. Location of DVR

Principle of DVR Operation

A DVR is a solid state power electronics switching device consisting of either GTO or IGBT, a capacitor bank as an energy storage device and injection transformers. It is linked in series between a distribution system and a load that shown in figure 4. The basic idea of the DVR is to inject a controlled voltage generated by a forced commuted converter in a series to the bus voltage by means of an injecting transformer. A DC to AC inverter regulates this voltage by sinusoidal PWM technique. All through normal operating condition, the DVR injects only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag occurs in the distribution system, the DVR control system calculates and synthesizes the voltage required to preserve output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the distribution system to the critical load [12].

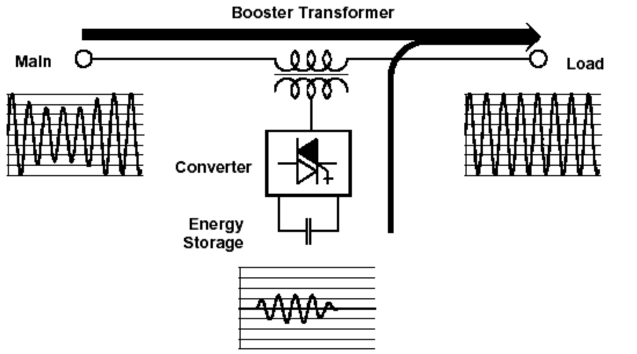

Fig. 4. Principle of DVR system

Note that the DVR capable of generating or absorbing reactive power but the active power injection of the device must be provided by an external energy source or energy storage system. The response time of DVR is very short and is limited by the power electronics devices and the voltage sag detection time. The predictable response time is about 25 milliseconds, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers. [11]

Basic Arrangement of DVR

The DVR mainly consists of the following components:
(a) An Injection transformer
(b) DC charging unit
(c) Storage Devices
(d) A Voltage Source Converter (VSC)
(e) Harmonic filter & (f) A Control and Protection system

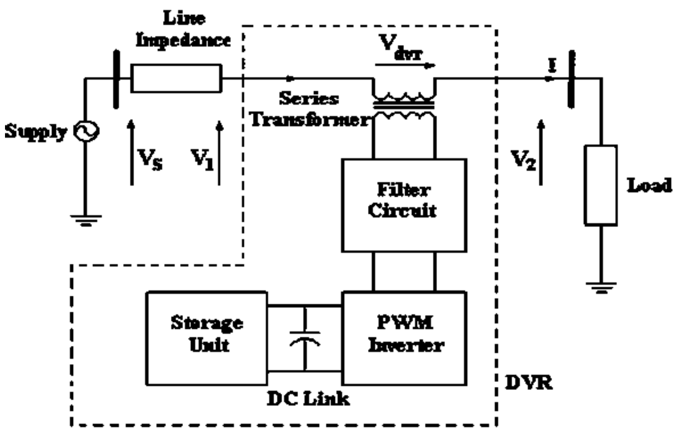

Fig. 5. Schematic diagram of DVR

Injection Transformer

Three single phase transformers are connected in series with the distribution feeder to couple the VSC (at the lower

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voltage level) to the higher distribution voltage level. It links the DVR system to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection transformer also serves the purpose of isolating the load from the DVR system (VSC and control mechanism).

DC Charging Unit

The dc charging circuit is used after sag compensation event the energy source is charged again through dc charging unit. It is also used to maintain dc link voltage at the nominal dc link voltage.

Voltage Source Converter

A VSC is a power electronic system consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. It could be a 3 phase - 3 wires VSC or 3 phases - 4 wires VSC. Either a conventional two level converter or a three level converter is used. For DVR application, the VSC is used to momentarily replace the supply voltage or to generate the part of the supply voltage which is absent. There are four main types of switching devices: Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Gate Turn-Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated thyristors (IGCT).

Each type has its own benefits and drawbacks. The IGCT is a recent compact device with enhanced performance and consistency that allows building VSC with very large power ratings. The function of storage devices is to supply the required energy to the VSC via a dc link for the generation of injected voltages. The different kinds of energy storage devices are Superconductive magnetic energy storage (SMES), batteries and capacitance.

Harmonic Filter

As DVR consist of power electronic devices, the possibility of generation self-harmonics is there so harmonic filter is also become a part of DVR. The main task of harmonic filter is to keep the harmonic voltage content generated by the VSC to the acceptable level.

Control and Protection

A controller is also used for the proper operation of the DVR system. Load voltage is sensed and passed through a sequence analyzer. The magnitude of load voltage is compared with reference voltage. Pulse width modulated (PWM) control technique is applied for inverter switching so as to generate a three phase 50 Hz sinusoidal voltage at the load terminals[14]. Chopping frequency is set aside in the range of a few KHz. PI controller is used with the IGBT inverter to maintain 1 p.u. voltage at the load terminals.

Controller input is an actuating signal which is the difference between the V_{ref} (reference voltage) and V_{in} (actual voltage). An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input [13]. Output from the controller block is in the form of an angled that is used to establish an additional phase-lag/lead in the three-phase voltages. All protective functions of the DVR should be implemented in the software. Differential current protection of the transformer, or short circuit current on the customer load side are only two examples of protection functions possibility. [14]

Block Diagram of a DVR using SPWM Based PI Controller

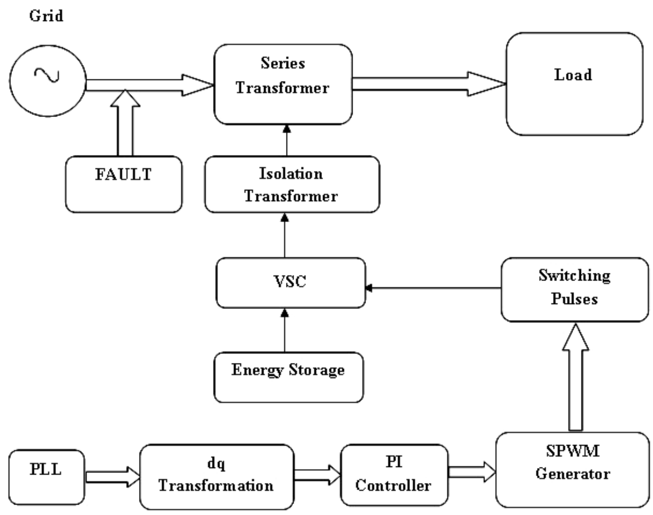

Fig. 6. Block diagram of a DVR using SPWM based PI controller

Block Diagram Description

The input voltage from the grid with three phase fault is fed to the series transformer. The output of Voltage Source Converter (VSC) is given to the series transformer through isolation transformer by injecting voltages. The IGBTs are used for VSC converters with SPWM based PI controller technique. The Phase Locked Loop (PLL) is used to regulate the voltage is given to the dq transformation and compared with desired & measured value. The output of load voltage injection is obtained from transformer due to the voltage sag.

Functional Block Diagram

The main operation principles of DVR as shown in figure 7. Direct feed forward type control model is used to minimize the response time and maximize the dynamic performance. Voltage regulation, low harmonic distortions and no interruptions are realized with this type of control architecture. Using RMS value calculation of the voltages to analyze the sags does not give fast results because at least one half period at the line frequency is required for calculation. In this study, reference signal is obtained from the measured parameters by using the Instantaneous Reactive Power Theory method (d-q theory) that is the most popular waveform correction method based on the time domain.

Compensating Voltage Generation

SPWM or Sinusoidal Pulse Width Modulation is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches. The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and rugged control scheme.

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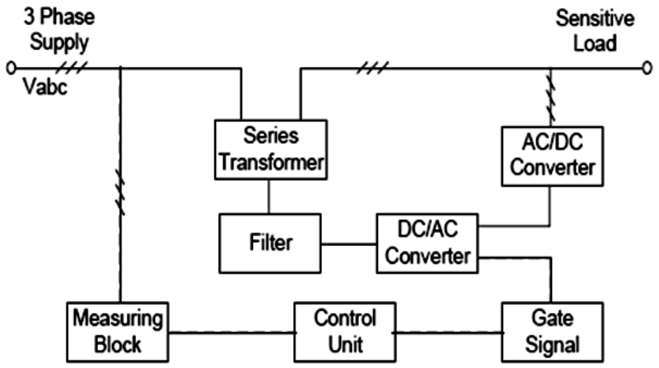

Fig. 7. Function blocks of designed DVR

SPWM switching technique is commonly used in industrial applications. SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period. The width of this pulses are modulated in order to obtain inverter output voltage control and to reduce its harmonic content. Sinusoidal pulse width modulation or SPWM is the most common method in motor control and inverter application.

Conventionally, to generate the signal, triangle wave as a carrier signal is compared with the sinusoidal wave, whose frequency is the desired frequency. The use of the Atmel microcontroller brings flexibility to change the real-time control algorithms without further changes in hardware. It will reduce the overall cost and has a small size of control circuit for the single phase full bridge inverter. 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.

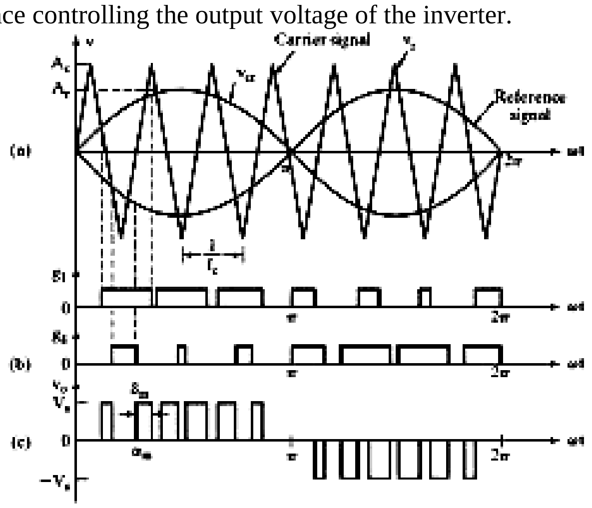

Fig. 8. Sinusoidal pulse width modulation (SPWM)

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 PI 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.

Control Block Diagram of DVR

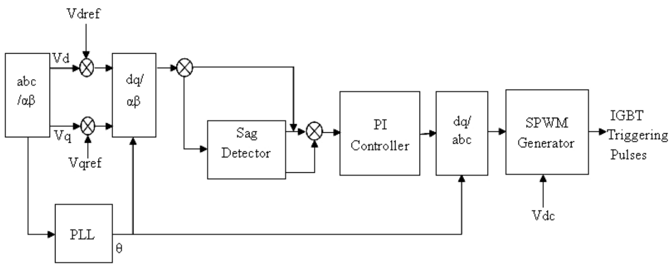

Fig. 9. Block diagram of control strategy for DVR

The control system of a DVR plays an important role, with the requirements of fast response in the face of voltage sags and variations in the connected load. Generally, there are two control schemes, open loop and closed loop which are used in the DVR applications. This project presents an extensive analysis to develop suitable control strategies for the DVRs. The DVR control system consists of a open loop load voltage using phase locked loop (PLL). The PLL circuit is used to generate a unit sinusoidal wave in phase with mains voltage.

III. DVR Test Models

A dynamic voltage restorer (DVR) is a custom power device used to correct the voltage sag by injecting voltage as well power into the system. The mitigation capacity of DVR is generally influenced by the maximum load; power factor and maximum voltage dip to be compensated. The DVR is to transfer the voltage which is required for the compensation from DC side of the inverter to the injected transformer after filter. The compensation capacity of a particular DVR depends on the maximum voltage injection capability and the active power that can be supplied by the DVR. When DVR's voltage disturbance occurs, active power or energy should be injected from DVR to the distribution system. A DC system, which is linked to the inverter input, contains a large capacitor for storage energy.

It provides reactive power to the load during faulty conditions. When the energy is drawn from the energy storage capacitors, the capacitor terminal voltage reduces. Therefore, there is a minimum voltage required below which the inverter of the DVR cannot generate the require voltage thus, size and rating of capacitor is very important for DVR power circuit. The DC capacitor value for a three phase system can be derived. The most important advantage of these capacitors is the potential to supply high current pulses repetitively for hundreds of thousands of cycles. Selection of capacitor rating is discussed on the basis of RMS value of a capacitor current, rated voltage of a capacitor and VA rating of the capacitor. [12]

A controller is required to control or to operate DVR during the fault conditions only. Load voltage is sensed and passed through a sequence analyzer. The magnitude of the actual voltage is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control system is applied for inverter switching so as to generate a three phase 50 Hz sinusoidal voltage at the load terminals.

Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u voltage at the load terminals. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and V_{in}. The output of error detector is V_{ref} - V_{in}. Where V_{ref} equal to 1 p.u. voltage and V_{in} voltage in p.u. at the load terminals. The controller output when compared at PWM signal generator results in the desired firing sequence.

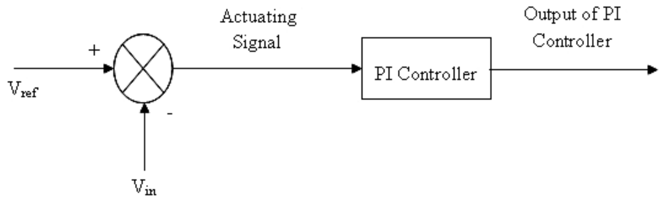

Fig. 10. Schematic of a typical PI controller

IV. AT89S51 MICROCONTROLLER

The AT89S51 is a low-power, high-performance CMOS 8-bit microcontroller with 4K bytes of In-System Programmable Flash memory. The device is manufactured using Atmel's high-density nonvolatile memory technology and is compatible with the industry-standard 80C51 instruction set and pin out. The on-chip Flash allows the program memory to be reprogrammed in-system or by a conventional nonvolatile memory programmer. By combining a versatile 8-bit CPU with In-System Programmable Flash on a monolithic chip, the Atmel AT89S51 is a powerful microcontroller which provides a highly-flexible and cost-effective solution to many embedded control applications.

The AT89S51 provides the following standard features: 4K bytes of Flash, 128 bytes of RAM, 32 I/O lines, Watchdog timer, two data pointers, two 16-bit timer/counters, a five-vector two-level interrupt architecture, a full duplex serial port, on-chip oscillator, and clock circuitry. In addition, the AT89S51 is designed with static logic for operation down to zero frequency and supports two software selectable power saving modes. The Idle Mode stops the CPU while allowing the RAM, timer/counters, serial port, and interrupt system to continue functioning. The Power-down mode saves the RAM contents but freezes the oscillator, disabling all other chip functions until the next external interrupt or hardware reset.

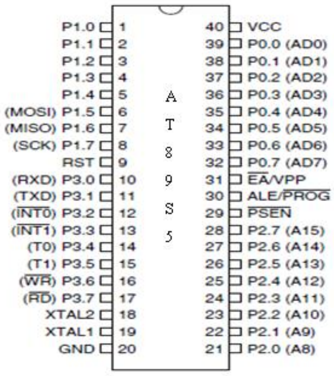

Fig. 11. Pin diagram of AT89S51 microcontroller

Features

- Compatible with MCS®-51 Products
- 4K Bytes of In-System Programmable (ISP) Flash Memory – Endurance: 10,000 Write/Erase Cycles
- 4.0V to 5.5V Operating Range
- Fully Static Operation: 0 Hz to 33 MHz
- Three-level Program Memory Lock
- 128 x 8-bit Internal RAM
- 32 Programmable I/O Lines
- Two 16-bit Timer/Counters
- Six Interrupt Sources
- Full Duplex UART Serial Channel
- Low-power Idle and Power-down Modes
- Interrupt Recovery from Power-down Mode
- Watchdog Timer
- Dual Data Pointer
- Power-off Flag
- Fast Programming Time
- Flexible ISP Programming (Byte and Page Mode)
- Green (Pb/Halide-free) Packaging Option

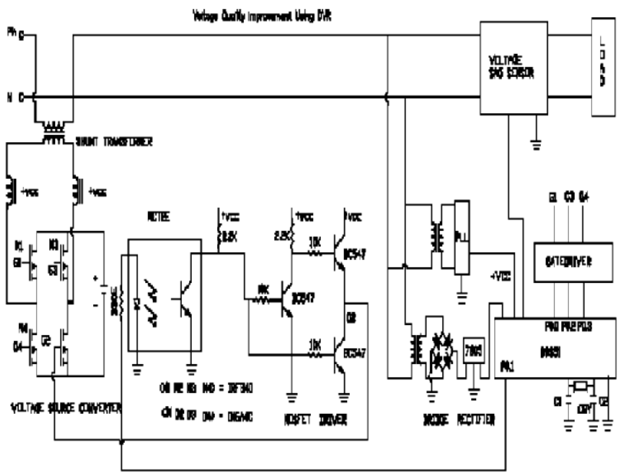

Fig. 12. Circuit diagram

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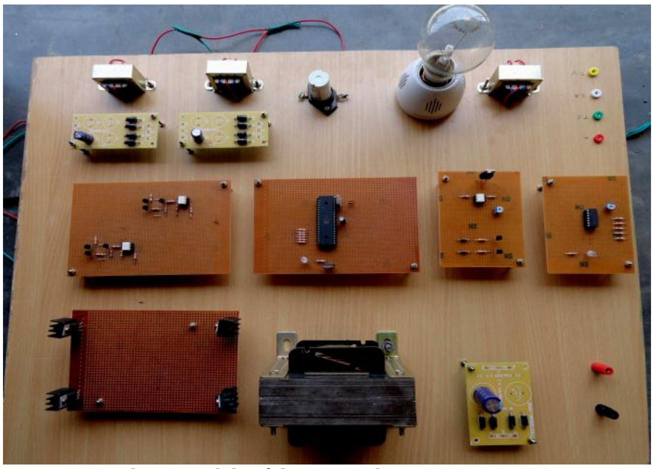

Fig. 13. Hardware module of dynamic voltage restorer (DVR) top view

Output Waveform

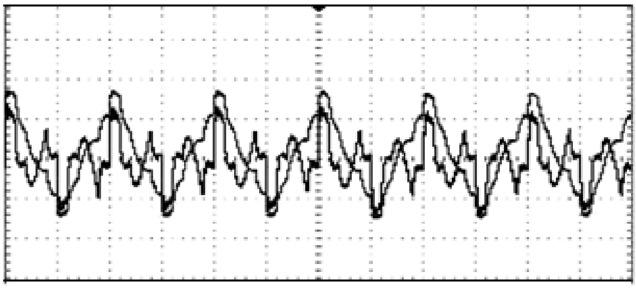

Fig. 14. Voltage sag compensation

V. CONCLUSION

In this paper, a fast and cost effective Dynamic Voltage Restorer (DVR) is proposed for mitigating the problem of voltage sag and other fault conditions in industrial distribution systems. A PI controller is used which utilizes the error signal which is the difference between the reference voltage and actual measured load voltage to trigger the switches of an inverter using a Sinusoidal Pulse Width Modulation (SPWM) scheme. In this paper, the DVR has shown the ability to compensate for voltage sags at the grid side, this can be proved through hardware implementation. The efficiency and the effectiveness in voltage sags compensation showed by the DVR makes it an interesting quality device compared to other custom power devices. The effectiveness of DVR can be investigated and established for active loads like PV source and Wind turbine.

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