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ROLE OF DVR DEVICE WITH FLYING CAPACITOR FOR VOLTAGE SAG AND SWELL MITIGATION

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Abstract: Power Quality problem in a system leads to various disturbances such as voltage fluctuations, transients and waveform distortions those results in a mis operation or a failure of end user equipment. There are different types of custom power devices like Distribution Static Compensator (D-STATCOM) and Dynamic Voltage Restorer (DVR) which can effectively use for mitigation of different type of power quality problems. This paper describes the technique of correcting the supply voltage sag distributed system and also describes performance comparison are presented between DVR to know how the device successfully been applied to power system for regulating system voltage effectively. DVR working is based on VSI principle. A DVR is a series compensation device which injects a voltage in series to correct the power quality problems. This paper presents a power system operation with PI controller with abc to dq0 convertor approach. In this paper we represent the voltage sag and swell problem simulation results.

I. INTRODUCTION

Power distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the ideal magnitude level and frequency but in practical power systems especially the distribution systems 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 like voltage sag, voltage swell, distortion in waveform, harmonics, etc. Power quality phenomenon or power quality disturbance can be defined as the deviation of the voltage and the current from its ideal waveform. Faults at either the transmission or distribution level may cause voltage sag or swell in the entire system or a large part of it. Also under heavy load conditions, a significant voltage drop may occur in the system. Voltage sag and swell can cause sensitive equipment to fail, shutdown and create a large current unbalance. Two types of VSI-based compensators have been commonly used for mitigation of the voltage sags and swells and regulating the load voltage. The power provided by generating station must be improved for delivering pure and clean power to the end users. For delivering a good quality of power Flexible AC Transmission System (FACTS) devices like static synchronous series compensator (SSSC), static synchronous compensator (STATCOM), interline power flow controller (IPFC), unified power flow controller (UPFC) etc. were used. Generally FACTS devices are modified to be used in electrical distribution system known as Custom Power Devices. Some of the widely used custom power devices are Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Active filter (AF), Unified power quality conditioner (UPQC). These devices are used to reduce power quality problems. DVR is one of the most efficient and effective custom power devices due to its fast response, lower cost and smaller size. Control Unit is the main part of the DVR and D-STATCOM. The function of the control unit is to detect the voltage differences (sag or swell) in the electrical distribution system and generate gate signal to operate the Voltage Source Converter (VSC) for supplying required amount of compensating voltage. Proportional Integral (PI) Controller is used to generate control signal and a PWM Generator is used for generating switching signal, which control the output of DSTATCOM & DVR. PI controller is used as feedback controller operates with a weighted sum of error signal and generates the desired signal for the PWM generator. The first one is a shunt device, which is commonly called DSTATCOM and the second one is a series device, which is commonly called DVR.

These compensators can address other PQ issues, such as load voltage harmonics, source current harmonics, unbalancing, etc., under steady state to obtain more benefits out of their continuous operation. There have been a variety of control strategies proposed for load voltage control using the aforementioned two devices.

II. POWER QUALITY PROBLEMS & SOLUTIONS

DEFINITION OF POWER QUALITY:-

The definition of power quality is different for the different users. As per the Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 is "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment." The effects on load and faulty condition occur in the system create the power quality (pq) problem. The PQ problems will affect on electrical equipments like transformer, motors, generators and home appliances.

A simple definition is that "Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy." The above definition of power quality gives us two functions for electrical devices. The first one is performance and second one is life expectancy. This chapter provides information regarding power quality. In this chapter we also discuss about how we can improve the power quality in the system.

The important things which are concerned regarding the power quality are given below:-
(1) Long duration voltage variation: - Over voltage, under voltage, Sustained Interruption
(2) Short duration voltage variation: - Interruption, Voltage unbalance, Sag, Swell, harmonics distortion, voltage fluctuation and power frequency variations, etc.
In the electrical system there are two types of loads:-
(1) Linear load: The load in which the voltage and current is related to each other and linearly varies. The examples of linear load are motors, heaters, incandescent lamp, etc.
(2) Non linear load: The load in which the voltage and current is not related to each other and their value also not dependent to each other. The examples of non linear loads are Arc furnace, welding, Resistance welding, etc. The nonlinear load uses high-speed power electronics switching devices for A.C to D.C conversion in internal circuits.
Due to this harmonics are produced at the point of common coupling and some other problems of heating and line interference are also occurred. The different non linear loads which produce power quality problems like waveform distortion and harmonics are PC, fax machines, printers, Drives, UPS, lighting Ballasts etc.

Power Quality Issues and Its Consequences:-
The power quality problem is a problem as imbalance in voltage, current, frequency, due to that equipment failure or malfunctioning of the equipment occurred. The latest electronics equipment consumes power and electricity different compare to other conventional appliances. The power quality problems and resulting consequences are occurred due to the increase of use of switching devices, non linear loads, and sensitive loads.

Cost of poor power quality:-
The poor Power Quality can create lots of problems in the operating system. Due to that equipment failure, damage, reduce the quality of power, finally due to all these problems cost of the system is increased. The different consequences due to poor power quality are given as below:-

- Equipment failure or malfunctioning.
- Equipment overheating (transformers, motors) leading to their lifetime reduction.
- Damage to sensitive equipment (PC's, production line control systems).
- Electronic communication interferences.
- Increase of system losses.
- Need to oversize installations to cope with additional electrical stress with consequential increase of installation and running costs and associated higher carbon footprint.
- Penalties imposed by utilities because the site pollutes the supply network too much.

The main contributors for poor power quality are given as below: -

- **Reactive power**: -The reactive power creates the unnecessary loads to supply system. Due to that Harmonics, unnecessary load and stress and decrement in efficiency of the system occurs.
- **Load imbalance**: The unbalanced in loads may result in excessive voltage imbalance causes the stress on load and over load problems occurs. So the power quality problems are increased.
- The higher voltage variation causes to flicker.

All of these problems create the power quality issues due to which system down time and equipment life is reduced. Due to that the cost of the system is increased. The solution for power quality issues is that at load side power controlling devices and FACTs devices are connected. Due to these solutions the harmonics, power quality problems, waveform distortions are reduced. To fulfil these solutions for power quality problems the custom power devices and FACTS devices are used with different topologies and control for power quality improvement. According to power quality issues the operation, controlling of the FACTs devices are varied. For reliable and simple operation different control strategy based custom power devices are used easily in the system.

Voltage Sag
Voltage sags and momentary electric power interruptions are the most important Power quality problem affecting to system and large commercial customers. These kinds of events are usually associated with a fault a few location in the supplying power system. Disturbances occur when the problem is on the signal supplying the customer. Although voltage sags occur even if the faults are really far away from the customer's site. Voltage sags lasting only 4-5 periods can cause very sensitive customer equipment to drop out. To industrial customers voltage sag and a momentary interruption are equivalent if both shut their process down. A typical example of voltage sag is shown in fig.3.1

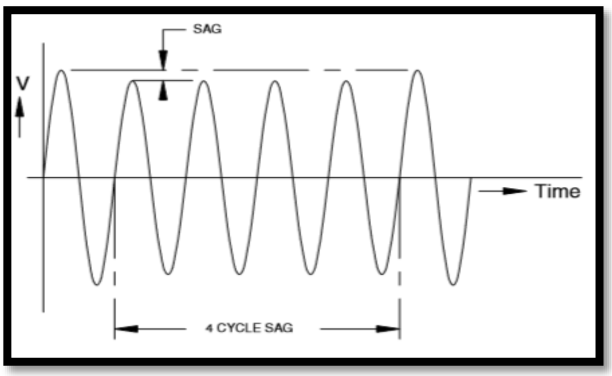

Fig.3.1- Voltage Sag condition

Voltage Swell
A voltage swell is the opposite form voltage Sag, having an increase in Voltage for duration of 0.5 cycles to 1 minute's

time. Intended for swells, high-impedance neutral contacts sudden large load savings and a single-phase problem on a three phase system are common resources. Swells can cause data errors, light flickering, electric power contact degradation, and semiconductor damage in electronics leading to hard server failures. The power conditioners and UPS Solutions are routine solutions for swells.

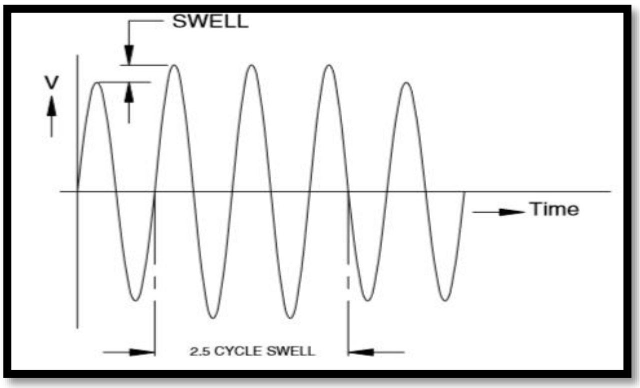

Fig.3.2-Voltage swells condition

III. DYNAMIC VOLTAGE RESTORER

Basic configuration of DVR

Among the several type of power quality problems (sags, swells, harmonics) voltage sags are the most severe type of disturbances. In order to overcome problems associated with power quality, the concept of custom power devices is introduced in recent times. The main function of a DVR is the protection of sensitive loads from voltage sags/swells coming from the network. One of those devices most recognizable and good in performance is the Dynamic Voltage Restorer, which is the most efficient and effective modern custom power device used in power distribution networks. The general arrangement of the DVR is composition of Injection transformer, Harmonic filter, Storage Devices, Voltage Source Converter (VSC), and DC charging circuit, Control and Protection system.

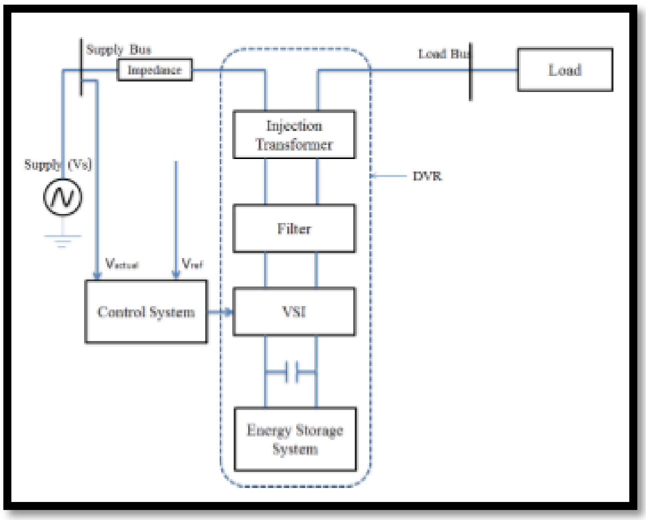

Fig. 4.1 Schematic diagram of DVR [2]

Therefore as shown in Figure 4.1, the DVR is located on approach of sensitive loads. If a fault occurs on other lines, DVR inserts series voltage VDVR and compensate load voltage to pre fault value. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage VL. This means that any differential voltages caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer.

Construction of DVR

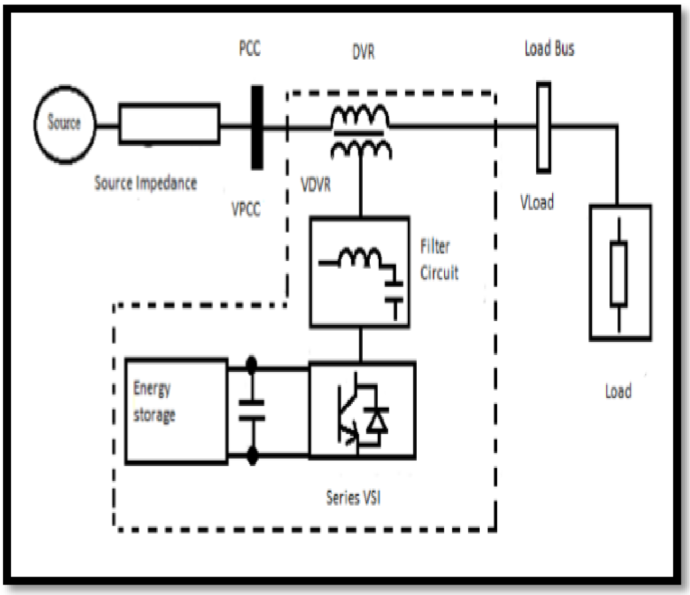

Fig. 4.2 Working Construction of DVR [1]

The DVR is capable to generate or absorb reactive power but the active power injection of the device must be provided by an external energy source or energy storage system. It is linked in series between a distribution and a load. The response time of DVR is very short and is limited by the power electronics devices and the voltage sag detection time.

Energy Storage Unit

The main function of these energy storage units is to provide the desired real power during voltage sag. The amount of active power generated by the energy storage device is a key factor, as it decides the compensation ability of DVR. Among all others, lead batteries are popular because of their high response during charging and discharging.

But the discharge rate is dependent on the chemical reaction rate of the battery so that the available energy inside the battery is determined by its discharge rate.

Voltage Source Inverter

Generally Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used. In the previous section we saw that an energy storage device generates a DC voltage. To convert this DC voltage into an AC voltage a Voltage Source Inverter is used. In order to boost the magnitude of voltage during sag, in DVR power circuit a step up voltage injection transformer is used. Thus a VSI with a low voltage rating is sufficient.

Passive Filters

To convert the PWM inverted pulse waveform into a sinusoidal waveform, low pass passive filters are used. In order to achieve this it is necessary to eliminate the higher order harmonic components during DC to AC conversion in Voltage Source Inverter which will also distort the compensated output voltage. These filters which play a vital role can be placed either on high voltage side i.e. load side or on low voltage side i.e. inverter side of the injection transformers. We can avoid higher order harmonics from passing through the voltage transformer by placing the filters in the inverter side. Thus it also reduces the stress on the injection transformer. One of the problems which arise when placing the filter in the inverter side is that there might be a phase shift and voltage drop in the inverted output. So this could be resolved by placing the filter in the load side.

Voltage Injection Transformers

The primary side of the injection transformer is connected in series to the distribution line, while the secondary side is connected to the DVR power circuit. Now 3 single phase transformers or 1 three phase transformer can be used for 3 phase DVR whereas 1 single phase transformer can be used for 1 phase DVR. The type of connection used for 3 phase DVR if 3 single phase transformers are used is called “Delta-Delta” type connection. The winding configuration of the injection transformer is very important and it mainly depends on the upstream distribution transformer. In case of a Δ-Y connection with the grounded neutral there will not be any zero sequence current flowing into the secondary during an unbalance fault or an earth fault in the high voltage side. Thus only the positive and negative sequence components are compensated by the DVR.

If a winding is missing on primary and secondary side then such a connection is called “Open-Delta” connection which is as widely used in DVR systems Basically the injection transformer is a step up transformer which increases the voltage supplied by filtered VSI output to a desired level and it also isolates the DVR circuit from the distribution network. Winding ratios are very important and it is predetermined according to the required voltage at the secondary side.

DVR Operating Modes

The operating modes of DVR can be classified into three as below:

Protection mode: In case of short circuit fault on load and high inrush current, the over current on the load side exceeds an allowable limit. Then the DVR will get cut off from the systems by using the bypass switches and providing alternate path for current flow.

Standby mode: Switching of semiconductors of VSI will not occur in this mode and the full load current will pass through the primary winding of injection transformer. The low voltage winding of the injection transformer is shorted through the converter in this mode.

Injection mode: DVR injects voltage through the injection transformer to compensate for any disturbance detected in the supply voltage.

Compensation Techniques

Compensation is achieved via real power and Reactive power injection. Based on the compensation level required by the load, there are three types of compensation methods as discussed below:

Pre-sag compensation:

Non linear loads need both magnitude as well as phase angle compensation. In pre-sag compensation technique, DVR supplies the difference between pre-sag and sag voltage thus restoring the voltage magnitude as well as the phase angle to that of the pre-sag value. Therefore this method is suited for nonlinear loads. However this technique needs a higher rated energy storage device and voltage injection transformers.

In Phase compensation:

The DVR compensates only for the voltage magnitude in this particular compensation method, i.e. the compensated voltage has the same phase as that of sagged voltage and it only compensates for the voltage magnitude therefore this technique minimizes the voltage injected by the DVR hence it is suited for the linear loads, which do not need phase angle compensation.

Energy optimization technique:

In this particular control technique the use of real power is minimized (or made equal to zero) by injecting the required voltage by the DVR at a 90’ phase angle to the load current. However in this technique the injected voltage will become higher than that of the in-phase compensation technique. Hence, this technique needs a higher rated transformer and an inverter, compared with the earlier cases.

Further, the compensated voltage is equal in magnitude to the pre sag voltage, but with a phase shift.

Control Strategy

3-Phase sequence analyzer

The Three-Phase Sequence Analyzer block outputs the magnitude and phase of the positive- (denoted by the index 1), negative- (index 2), and zero-sequence (index 0) components of a set of three balanced or unbalanced signals. The signals can contain harmonics or not.

PI Controller

PI controller is a closed loop controller, which drives the plant to be controlled with a weighted sum of the error and the integral of that value. An advantage of a proportional plus integral controller is that the integral term in a PI controller causes the steady state error to be zero for a step input. The aim of the control scheme is to maintain a constant voltage magnitude at the sensitive load point, under the system disturbance. The control system only measures the RMS voltage at load point; for example, no reactive power measurement is required in the DVR controller scheme implemented in MATLAB/SIMULINK. Fig. 4.3 shows that The PI controller process the error signal generates the required angle to drive the error to zero, i.e., the load RMS voltage is brought back to the reference voltage

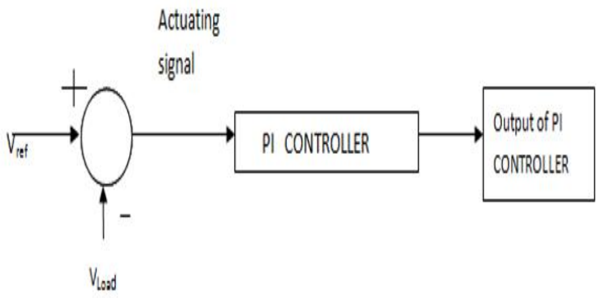

Fig. 4.3 PI Controller

Control Algorithm
The basic functions of a controller in a DVR are the detection of voltage sag/swell events in the system; computation of the correcting voltage, generation of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalous in the series voltage injection and termination of the trigger pulses when the event has passed. The dqo transformation or Park's transformation is used to control of DVR.

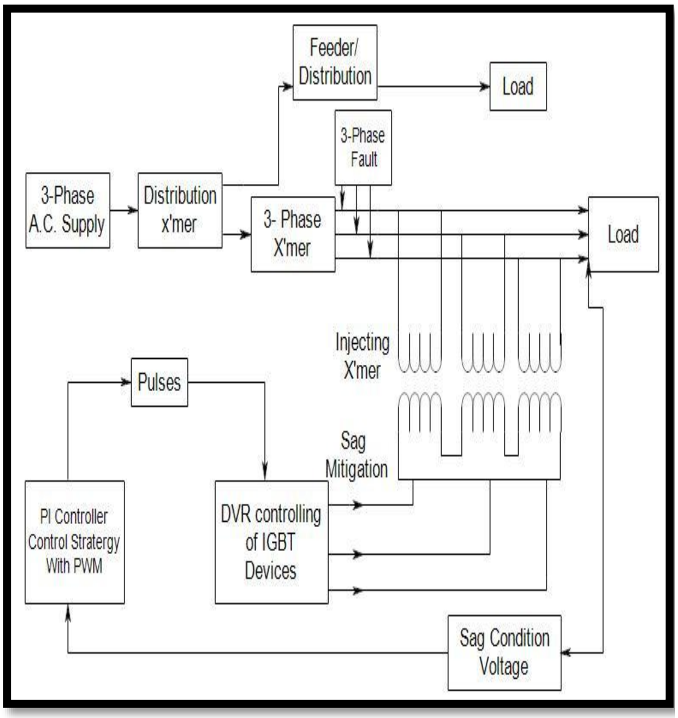

Fig. 4.4 Block Diagram for Sag Mitigation using PI Controller

In order to mitigate the simulated voltage sags in the test system of each compensation technique, also to compensate voltage sags in practical application, a discrete PWM-based control scheme is implemented, with reference to DVR. The IGBT inverter is controlled with PI controller in order to maintain voltage at the load terminals. A proportional-integral (PI) controller drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. The controller output when compared at PWM signal generator results in the desired firing sequence. The sinusoidal voltage V control is phase-modulated by means of the angle δ or delta and the modulated three-phase voltages are given by

$V_A = \text{Sin}(\omega t + \delta)$
$V_B = \text{Sin}(\omega t + \delta - 2\pi/3)$
$V_C = \text{Sin}(\omega t + \delta + 2\pi/3)$

IV. PROPOSED WORK

One of the major concerns in electricity industry today is power quality problems to sensitive loads. The disturbances introduced by nonlinear loads and the rapid growth of renewable energy sources. Majority of power quality problems also affect the end user.
The DVR is promising and effective device for power quality enhancement due to its quick response and high reliability. Multilevel converters based on DVR are the most accepted topology in industry for medium voltage (MV) applications such as medium voltage drive systems. Which allow high power-handling capability with lower harmonic distortion and lower switching power losses than the two-level converter.

Recently, modular multilevel converters topology has been reported as an alternative to conventional multilevel inverters in medium and high voltage applications. It is able to overcome most of difficulties of conventional multilevel inverter and provides new set of features such as – Modular construction; it has fault management capability and better fault ride through capability, with increased number of levels, it generates high voltage with reduced voltage stress on switching device, and extremely low total harmonic distortion. (THD) The balancing of FC voltages is quite important and dictates both the safe and efficient operation of the converter.

There are three types of multilevel converter topologies namely, the neutral point- clamped (NPC) converter, the flying capacitor (FC) converter, and the cascaded converter with separate dc voltage sources (also called H bridge converter). The FC converter has attracted a great deal of interest in recent years mainly due to a number of advantageous features. For instance, it seems that the extension of the converter to higher than three levels is possibly easier than the NPC alternative in commercial applications. This paper focuses on the design of a closed

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loop control system for a DVR by using a five-level flying capacitor converter, based on the so-called repetitive control.

CONFIGURATION OF THE DVR

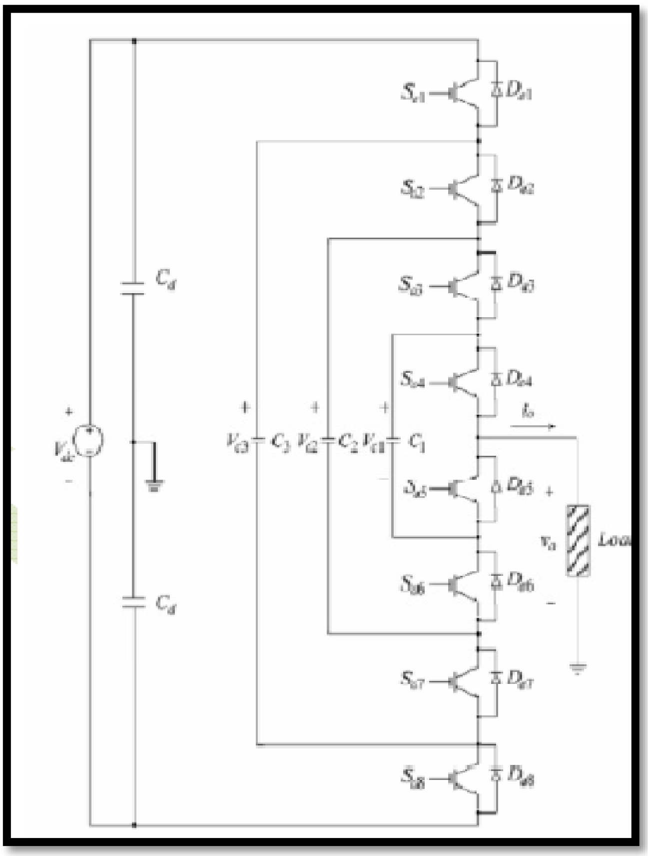

Fig.5.1. Phase-leg of five-level FC multilevel converter

The diode in the diode clamped topology can be replaced by clamping capacitors or floating capacitors to clamp the voltage such topology is called flying capacitor multilevel converter. They are called Flying Capacitor Multilevel Inverter, because the capacitors float with respect to earth's potential. This topology is relative new as compared to H-bridge converter and neutral point- clamped (NPC) converter. Fig.5.1 shows that the Phase-leg of five-level FC multilevel converter and switching table. This topology consists of diodes, capacitors and switching devices.

Each leg consists of switching devices which are generally transistors. Regarding the five-level topology shown in Fig. 5.1 the flying capacitors C1 ,C2 and C3 are charged to, 3Vdc/4, Vdc/2, and Vdc/4 respectively. Therefore, each switch must block only a voltage value equal to Vdc/4 allowing the use of switches with lower-rated voltage compared with those in a conventional two-level converter. There are several switching combinations for the same given output voltage, which is known as switching redundancy.

DYNAMIC VOLTAGE RESTORER (DVR) CONNECTION SYSTEM

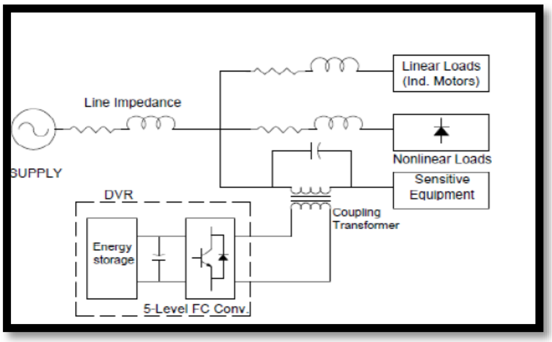

Fig. 5.2 Basic scheme of the system configuration with the DVR

DVR is a Custom Power Device used to eliminate supply side voltage disturbances. DVR also known as Static Series Compensator maintains the load voltage at a desired magnitude and phase by compensating the voltage Sags/swells and voltage unbalances presented at the point of common coupling. The DVR consists of a five-level flying capacitor voltage-source converter and energy storage which provides the necessary voltage to the dc link. The series connection of the DVR is achieved by means of a coupling transformer. A passive LC filter has been used to filter out the high harmonics generated by the PWM process.

FLYING-CAPACITOR VOLTAGE CONTROL

In theory, the phase-shifted PWM method is able to balance the flying-capacitor voltages. Nevertheless, in practical implementations, there may be factors, such as asymmetrical conditions, different characteristic of power switches, etc, that produce voltage imbalances in the flying capacitors. For that reason, a control scheme, which guarantees the balance of the FC voltage, is required. Voltage control is based on a closed-loop control scheme which corrects, for each switch, the modulating signal by adding a square-wave in order to increase or decrease the capacitor voltages. This project focuses on the design of a closed-loop control system for a DVR by using a five-level flying-capacitor converter, based on the so-called repetitive control. Repetitive control was originally applied to eliminate speed fluctuations in electric motors [1], but it has also been successfully used in power-electronics applications, such as power-factor control in three-phase rectifiers and active-filter control [2]. The control system presented in this paper has a wide range of applicability. It is used in a DVR system to eliminate voltage sags, harmonic voltages, and voltage imbalances within a bandwidth. Unlike other control schemes with a comparable range of applicability, only one controller is needed to cancel out all three disturbances simultaneously, while exhibiting good dynamic performance. On the one hand, a closed-loop controller, which consists of a feedback of the load voltage and the repetitive controller, guarantees zero tracking error in steady state. On the other hand, the applied control strategy for the voltage balancing of the flying capacitors, along with a feed forward term of the grid voltage and a controller for the output voltage of the DVR filter, provides excellent transient response.

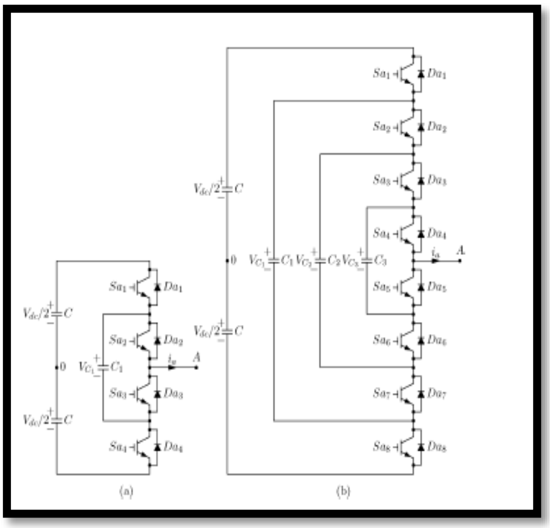

Fig. 5.3 Phase leg of two different flying-capacitor multilevel converter topologies
(a) Three level. (b) Five level.

V. MODELING AND SIMULATION

MATLAB model of DVR for Power Quality Improvement
The PI controller is provided for comparison and relation development between the reference value and running condition value. The PI Controller calculates the value of power angle which is given to trigonometric function calculation of sine and cosine angle value after that it is given for dqo-transformation which compare with the reference value or carrier signal for generating the pulses for IGBT Devices for mitigation of voltage sag condition. The injecting transformers are provided for the distribution line control for compensation using DVR.
The Simulation and results are shown in fig below:-

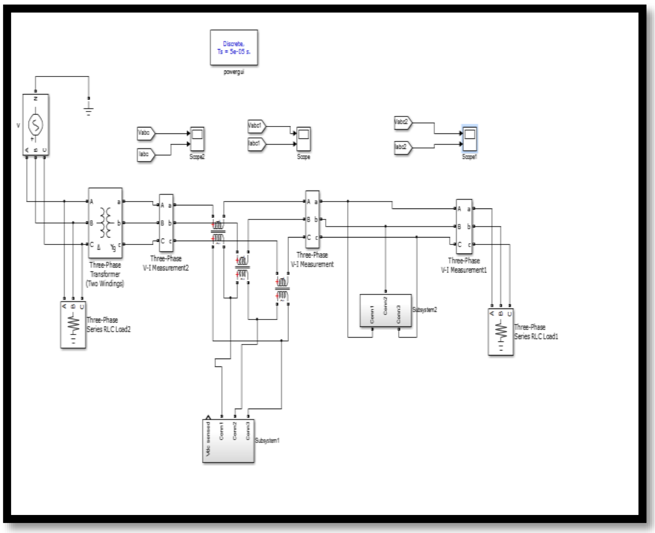

Fig 6.1- Proposed System

The Voltage and current fluctuations are shown in fig below:-

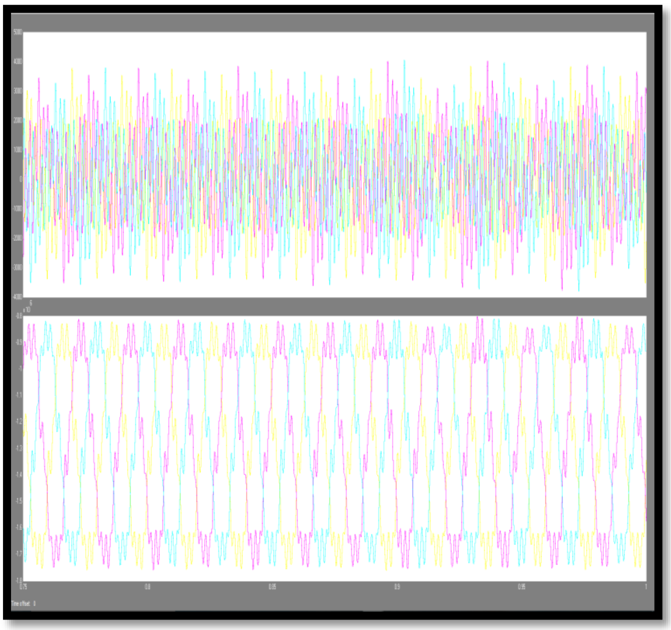

Fig 6.2- Voltage and current fluctuation at Source side

After applying the DVR with the proposed control strategy with Space vector PWM and the VSC converter control of DVR we improve the power quality at PCC side and after apply the subsystem of proposed controlling we improve voltage and current at load side which is shown in the below section:-

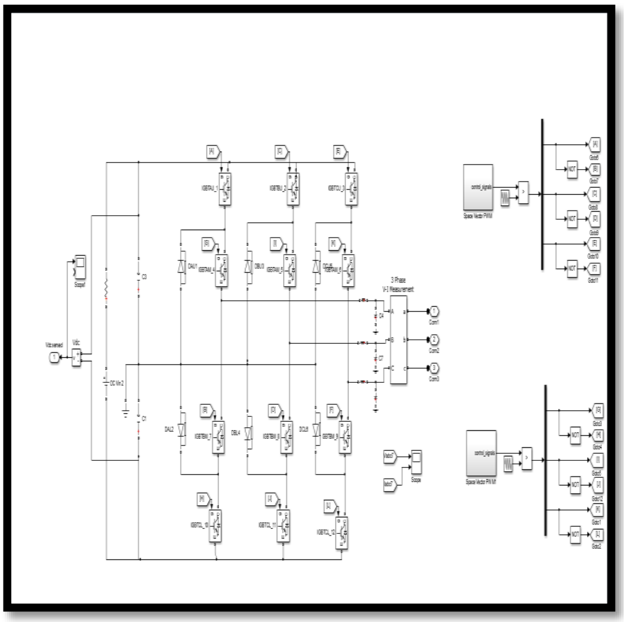

Fig 6.3- Proposed control subsystem

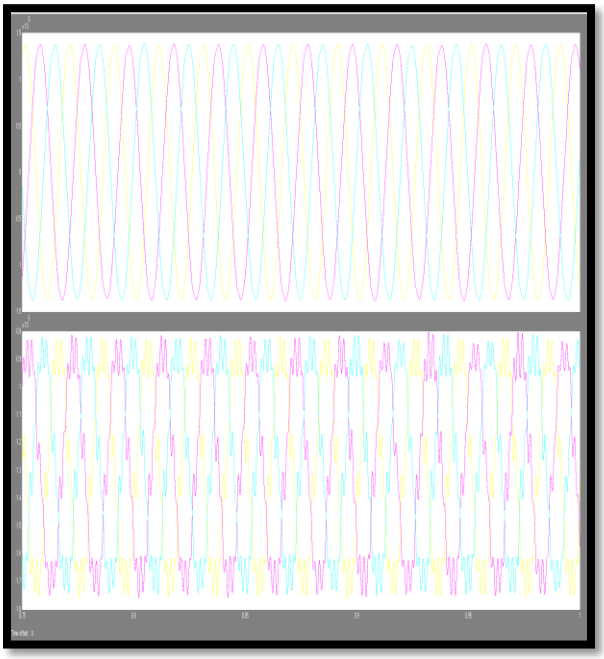

Fig 6.4- Voltage and current at PCC

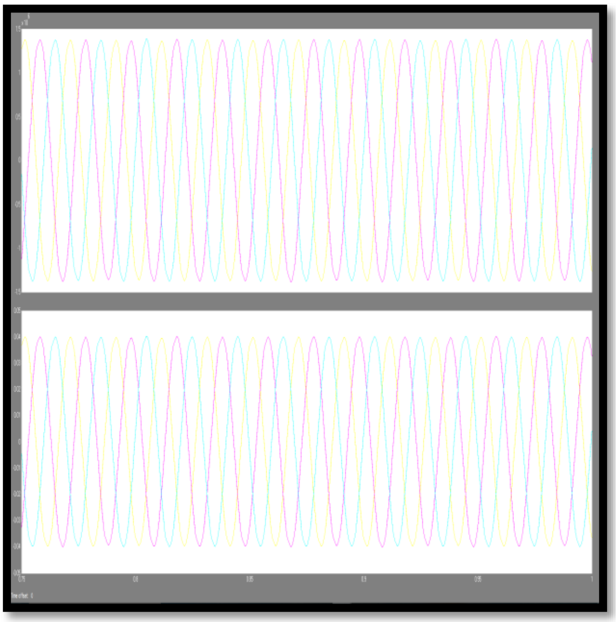

Fig 6.5- Voltage and current at load side

VI. CONCLUSION

In this paper DVR based on conventional converter operated by a proposed control scheme. This control structure simultaneously cancels out voltage sags, voltage imbalances, and voltage harmonics other than high frequency switching harmonics. The control system is split into two subsystems: the first one works to eliminate the resonance peak of the filter used in the converter output voltage; while the second one is the repetitive control, which ensures a fast transient response and zero tracking error in steady-state for any sinusoidal reference and for any sinusoidal disturbance whose frequencies are an integer multiple of the fundamental frequency. We can now develop multi level flying capacitor based DVR system which operated in three subsystems and improve power quality very well compare to conventional DVR system.

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