DVR Based Mitigation of Voltage Sag

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***Abstract* - The quality of electrical power is an important contributing factor to the development of any country. Power quality is highly newsworthy issue as it has attained considerable attention in the last few decades due to large penetration of power electronic based loads or microprocessor based controlled loads. In order to avoid the unexpected disruptions and damage in the power system it becomes necessary to overcome power quality issues and to have reliable power performance. Mitigation of power quality event helps the power system to overcome the power quality issues to a great extent. To enhance the quality of power and to reduce the issues related to it, mitigation of power quality events is preferred. Mitigation of power quality event not only provides the control over the power related problems but also maintains it. Therefore, this paperwork proposes dynamic voltage restorer (DVR) as a mitigation tool for the most common power quality problem of voltage sag. Dynamic voltage restorer (DVR) shows the effective result in sag mitigation. The DVR used in this paper uses the feed forward linear control method for the voltage sag mitigation. The voltage injection method used is the pre -sag method. This work has been performed using MATLAB Simulink. Before and after sag mitigation results are provided.**

I.INTRODUCTION

Voltage disturbances are the most common power quality (PQ) problem in industrial distribution systems. The voltage disturbances mainly encompass the voltage sags, swells, harmonics, unbalances, and flickers. These disturbances can cause the malfunction of voltage-sensitive loads in factories, buildings, and hospitals and sever process disruptions resulting in substantial economic and data losses. Voltage sag is a momentary decrease in the rms ac voltage (10%–90% of the nominal voltage) at the power frequency of duration from 0.5 cycles to a few seconds [4].
Voltage sag is normally caused by short-circuit faults, such as a single-line-to-ground fault in a power system and by the start-up of induction motors of large ratings.
Voltage swell is defined as a short duration increase in rms supply with an increase in voltage ranging from 1.1 p.u. to 1.8 p.u. of nominal
supply. The main reasons for voltage swells are switching large capacitors or the removal of large loads [4].
Out of the different methods for voltage sag and swell compensation, the installation of custom power device in distribution system is regarded as the most accomplished one. The custom Power concept was put forward by N.G. Hingorani in the year 1995. Flexible AC Transmission Systems (FACTS) deals with various power problems in transmission systems like improvement in power transfer capabilities and stability margins, whereas the custom power devices involves the utilization of power electronics controllers in a distribution system and deals with various power quality problems and it make sure that the users get a good quality and trustworthy supply.[7]
Some examples of Custom power devices are as follows: Battery Energy Storage System (BESS), Distribution Static synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Surge Arrester (SA), Super-conducting Magnetic Energy Storage (SMES), Solid-State Transfer switch (SSTS), Static Var Compensator (SVC), Uninterruptible Power Supply (UPS) etc [7].

A. The Basics of DVR

Dynamic voltage restoration (DVR) is a method of overcoming voltage sags that occur in electrical power distribution. These are a problem because spikes consume power and sags reduce efficiency of some devices. DVR saves energy through voltage injections that can affect the phase and wave-shape of the power being supplied. Devices used for DVR include static var devices, which are series compensation devices that use voltage source converters (VSC). The first such system in North America was installed in 1996 -

a 12.47 kV system located in Anderson, South Carolina. The basic principle of dynamic voltage restoration is to inject a voltage of the magnitude and frequency necessary to restore the load side voltage to the desired amplitude and waveform, even when the source voltage is unbalanced or distorted. Generally, devices for dynamic voltage restoration employ gate turn off thyristors (GTO), solid state power electronic switches in a pulse-width modulated (PWM) inverter structure. The DVR can generate or absorb independently controllable real and reactive power at the load side. In other words, the DVR is a solid-state DC to AC switching power converter that injects a set of three phase AC output voltages in series and synchronicity with the distribution and transmission line voltages.

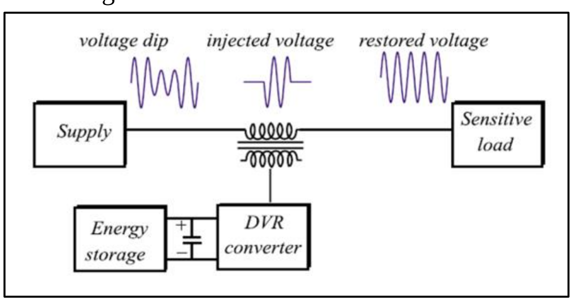

Fig. 1 Schematic diagram of dynamic voltage restorer

B. Principle of DVR

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. 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.

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 following fig. 3 shows the location of DVR.

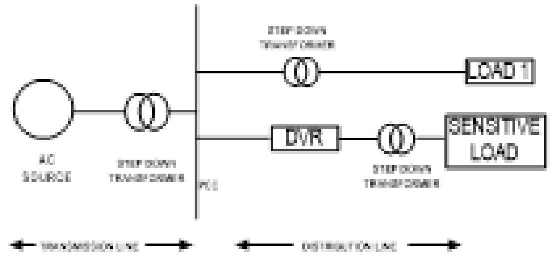

Fig. 3 Location of DVR

C. Basic configuration

The basic configuration of DVR is shown in fig.4.

The DVR consists of:

1. An Injection transformer
2. A Harmonic filter
3. Storage Devices
4. A Voltage Source Converter (VSC)
5. DC charging circuit

1) Injection transformer

Three single phase transformers are connected in series with the distribution feeder to couple the VSC (at the lower 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).[15]

2) Ripple Filter

The output of the inverter contains high frequency switching harmonics. To remove these switching harmonics, a three-phase ripple filter (Electro Magnetic Interference-EMI) filter is used. [15]

3) Voltage Source Converter (VSC)

A VSC is a power electronic device consists of a storage device and switching devices which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSC is used to inject the voltage or part of the voltage into the system to maintain load voltage balanced.

4) DC Charging Circuit

The dc charging circuit has two main tasks.

1. The first task is to charge the energy source after sag /swell Injection.
2. The second task is to maintain dc link voltage at the nominal dc link voltage.

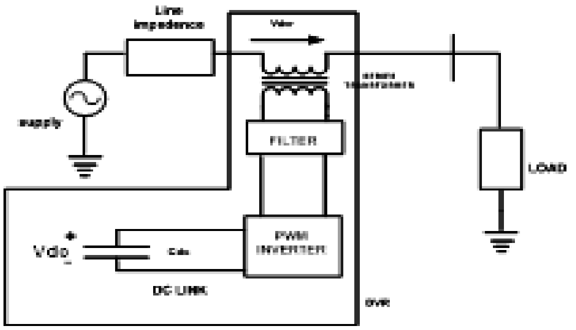

Fig. 4 Basic configuration of DVR

D.DVR operating states

The DVR is designed to inject a dynamically controlled voltage i.e. Vdvr, which is generated by a forced commutated converter. This voltage is injected in series to the bus voltage by means of an injection transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to remove any harmful 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 injection transformer. The DVR has three modes of operation which are: protection mode, standby mode, injection/boost mode [15].

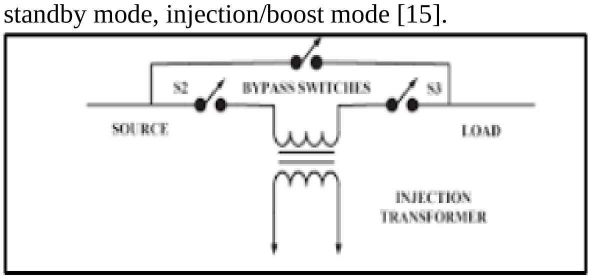

Fig.5 Mode of operation

1) Protection mode

During fault, the DVR is protected from the high current in the load side due to short circuit on the load or large inrush currents the DVR will be isolated from the system by using bypass switches (S2 and S3 will open) and providing an alternative path for current (S1 will be closed) as shown in fig.5.[15].

2) Standby mode (VDVR = 0)

During normal operation, the DVR may either go into short circuit operation which is called standby mode or inject small voltage to compensate the voltage drops on transformer reactance or losses. Generally standby mode is preferred [15].

3) Injection/boost mode (VDVR>0)

As soon as sag is detected the DVR goes into injection mode. AC voltage is injected in series with required magnitude, phase, and wave shape for compensation.

E.DVR Control Methods

There are several techniques to implement and control methods of DVR for power quality enhancement. The control of DVR is very important factor. Control methods involve the detection of any disturbance in voltage by using the suitable detection algorithms. The control system only measures the RMS voltage at the load point. It means there are no measurement of reactive power. The performance of DVR directly affected by the control technique used for driving the inverter, because inverter is the most valuable part of DVR [13].

The inverter control strategy employs following types of controller and the block diagram which shows the various control method is shown in fig 6. below.

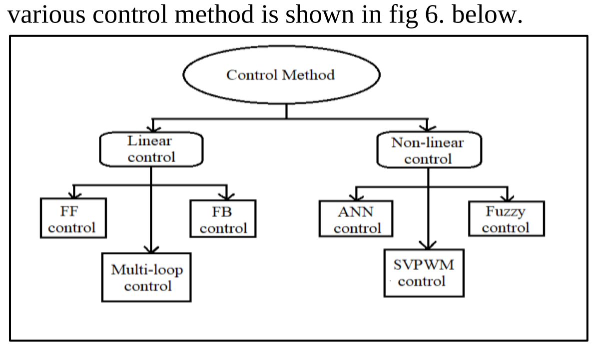

Fig. 6 Control methods of DVR

Voltage Injection Methods

Voltage injection or Injection methods by means of a DVR depend upon the limiting factors such as; DVR power ratings, various conditions of load, and different types of voltage sags. Some loads are sensitive towards phase angel jump and some are sensitive towards change in magnitude and some are sensitive to both magnitude and phase angle change. Therefore, the control strategies depend upon the type of load characteristics. There are three different methods of DVR voltage injection which are:

1. Pre-sag Injection method

2. In-phase Injection method
3. In-phase advance method

1) Pre-sag Injection method

The pre-sag method tracks the supply voltage continuously and if it detects any disturbances in supply voltage it will inject the difference voltage so that the load voltage can be restored back to pre-sag condition. This requires higher rating of the DVR.[7] Before a sag occurs, VS = VL = Vo. VO is pre sag voltage. The voltage sag results in drop in the magnitude of the supply voltage to VS1. The phase angle(δ) of the supply also may shift (see Fig. 7). The DVR injects a voltage Vdvr such that the load voltage (VL = VS1 + Vdvr) remains at Vo i.e. pre sag voltage (both in magnitude and phase).

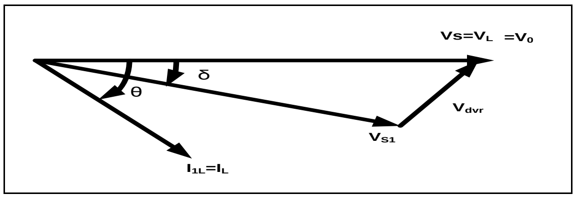

Fig. 7 Pre-sag injection method

Vdvr = V0– Vs1
Where Vs=source voltage
VO = pre sag voltage
IL1=IL=Line current
VS1=source voltage under unbalance condition
Vdvr =injected voltage
θ =load angle.

2) In-phase Injection method

In this method the injected voltage is in phase with the supply voltage irrespective of the load current and pre-sag voltage.[7]

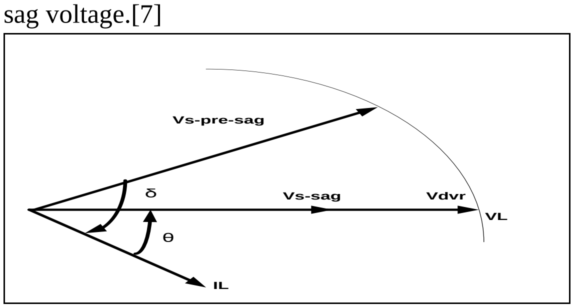

Fig. 8 In-phase injection method

|VL|=|Vs-pre-sag|

3) In-phase advanced method

In this method injected voltage advances the voltage, so the injected voltage phasor and line current are perpendicular. In case of pre-sag and In-phase the DVR is required to insert real power into the faulty line during the compensation period, the capacity of the energy storage device can become a limiting factor in the compensation.[7] The basic idea of energy optimization method is to make the injected real power component zero by having the injection voltage phasor perpendicular to the load current phasor. In this method value of load current and voltage are fixed in the system so we can alter only the phase of sag voltage.

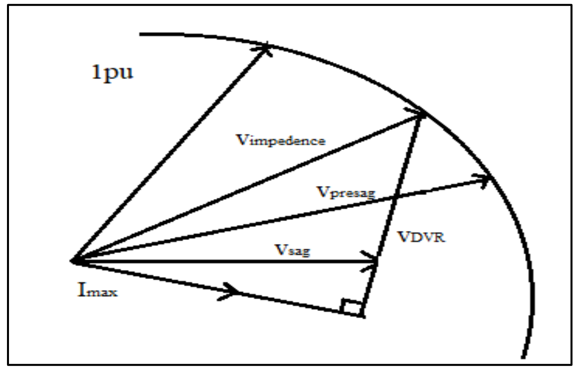

Fig. 9 In-phase advance compensation method

II. THE PROPOSED SYSTEM

The circuit is designed to solve, voltage sag, the most common problem of power quality. This system is designed using power custom device i.e. dynamic voltage restorer commonly known as DVR. The system is designed with the help of MATLAB software version 2013.

Below fig. 11 shows the complete structure of DVR constructed in Simulink MATLAB. The model consists of three phase source that provides the supply to the system, three phase V-I measurement to measure the magnitude of voltage and current of the three phases, pi-section line that provides the impedance of the line also the line length, fault circuit, three phase RLC load and RMS block and display to know the exact values of system. Here in this system we get to know the various faults that causes the power quality problems. These faults can be LG faults due to such fault the system becomes unbalance and the power quality problems such as voltage sag, voltage swell, or interruption comes into effect. So, fault detection is also equally important as fault mitigation. Now, the DVR model consists of source, inverter circuit, control block, series filter, Injection transformer, comparator, and sensitive load. The different supply voltage disturbances are generated by using source. The inverter is used to convert DC supply to AC supply. The output of the inverter contains fundamental voltage and the voltages of switching frequencies and multiples of switching frequencies. The voltages of switching frequencies and multiples of switching frequencies are eliminated by using filter. The pulses are generated by the comparator by comparing sinusoidal signal with triangular signal. The AC voltage of the inverter is injected in phases of the line by using injection transformers. The reference signals to the PWM inverter are generated by using control block.

A. Detection of Voltage Sag

Voltage-sag detection plays an important role in operating DVRs stably and properly. The DVR can eliminate both bandpass filter and average-voltage calculation process from voltage-sag detection, resulting in achieving quick voltage-sag detection. To know the voltage sag detection takes place in three phase distribution line let us first consider the below circuit.

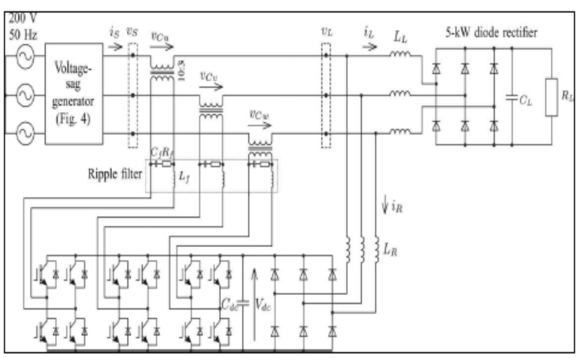

Fig. 10 Circuit configuration of the DVR

At first, the DVR is operated in standby mode under a normal condition. During standby mode, the six upper IGBTs in the series converter remain tuned on, whereas the other six lower IGBTs remain turned off. This means that the compensating voltage in each phase is zero and the DVR produces no switching loss. As soon as ΔV_d gets greater than 5% of VS, the DVR moves to compensation mode and starts compensating. After ΔV_d gets smaller than 2%, it returns to standby mode in a half cycle. A single-phase voltage sag induces a negative-sequence component in the three-phase source voltages, forcing ΔV_d to fluctuate at 100 Hz, i.e., twice the line frequency. If the DVR returned to standby mode as soon as ΔV_d got smaller than 2%, a 100-Hz component present in ΔV_d would make the DVR move to compensation mode again. In other words, the DVR would repeatedly start and stop, half cycle by half cycle. Note that ΔV_d takes 0 V whenever a single-phase voltage sag occurs. To avoid it, the DVR has to stay in compensation mode for a half cycle after the source recovers from the voltage sag. However, this is not a serious problem in the DVR.

B.Circuit Description

Fig. 11 shows the experimental circuit configuration of a DVR for a 220-V 5-kW load. Table 1 summarizes the circuit parameters. Here the simulation is carried out considering a single phase and not the three phases so the voltage sag detection is not performed as voltage sag is already present. The DVR consists of series and shunt converters connected back-to-back and a common dc capacitor.

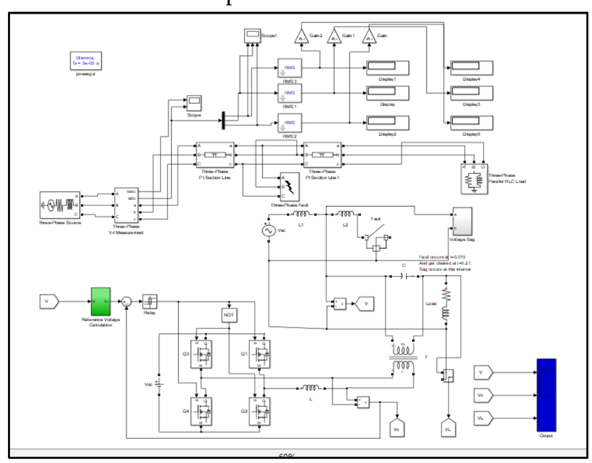

Fig. 11 MATLAB Simulink circuit diagram

The main circuit of the series converter uses voltage-source pulse width-modulation (PWM) converter with a switching frequency of 25 Hz. This single-phase converter is connected in series with the corresponding power line through a single-phase transformer. The turn ratio of the transformer can be determined from the following design concept: The DVR has the capability of compensating for a voltage-sag depth up to 50% in a single-phase sag. The compensating voltage in each phase is as follows:

$311\ V \times 0.5/\sqrt{3} = 53.86\ V$

whereas the maximal ac voltage of the PWM converter is as follows:

$Vdc/\sqrt{2} = 400\ V/\sqrt{2} = 282\ V.$

Therefore, the turns ratio was chosen to be approximately,

300 V : 60 V = 5 : 1.

The filter inductor L_f is installed between the PWM converter and the transformer to eliminate switching ripples produced by the converter. A 50-Hz voltage drop appears across the filter inductor L_f when no voltage sag occurs. Note that here we have used MOSFETs instead of IGBT. The two upper MOSFETs in phase remain turned on, whereas the two lower MOSFETs remain turned off, thus forming a short circuit across the secondary (converter side) windings of the series transformer through L_f.

In this paper, a series RL load rated at 5 kW is used as a sensitive load. The breaker circuit used in the paper. The breaker circuit consists of voltage source connected to breaker. It can intentionally cause a voltage sag to the phase.

The phase-locked-loop circuit detects the three-phase source voltage VS and calculates the phase angle information θ_S. The three-phase source voltages are transformed into d- and q-axis voltages V_d and V_q, respectively. The d-axis voltage V_d is equal to the nominal line-to-line rms voltage of the source VS, and V_q is equal to zero, as long as the source is a three-phase balanced sinusoidal voltage in normal conditions. Thus, the reference voltages can be set as $V*_d$ = VS and $V*_q = 0$, respectively.

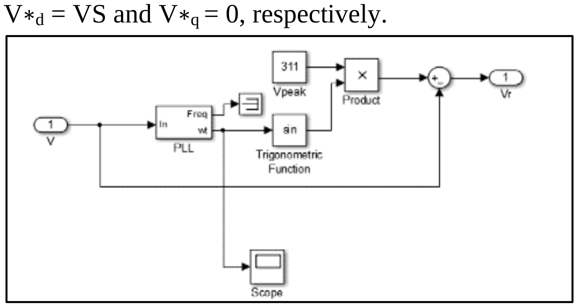

Fig. 12 phase lock loop

Whereas a voltage-sag depth in the three-phase three-wire circuit can be represented by ΔV_d and ΔV_q on the d–q coordinates, which are obtained by subtracting V_d and V_q from $V*_d$ and $V*_q$, respectively. Then, Δ Vu, Δ Vv, and Δ Vw are calculated by applying the inverse d–q transformation to ΔV_d and ΔV_q. Adding a zero-sequence voltage VC0 produces the three-phase voltage references for the series converter, which are $V*_{Cu}$, $V*_{Cv}$, and $V*_{Cw}$, as follows:

$V*_{Cu} = \Delta V_u + V_{C0}$

$V*cv = \Delta V_v + V_{C0}$

$V*cw = \Delta Vw + VC0$

The values of the reference voltages can be calculated using the Park's Transformation.

The expression of V_{sa}, V_{sb}, *and Vsc* in terms of V_0, *Vd, and Vq* can be described as follows:

$$\begin{bmatrix} V_0 \\ V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin(wt) & \sin(wt-120) & \sin(wt-240) \\ \cos(wt) & \cos(wt-120) & \cos(wt-240) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}$$

Where V_{sa}, V_{sb}, *Vsc* *are* the supply voltage, V_0, *Vd, Vq* are the zero axis, direct and quadrature axis voltages. The supply voltage to the load is given in equation (1). When rated balanced voltage is applied $V_{m1} = V_{m2} = V_{m3} = V_m$ and $\alpha = 0$.The respective V_0, V_d, *and* V_q are calculated in the following equations.

$$\left.\begin{aligned} v_{sa} &= V_{m1}\sin(wt \pm \alpha) \\ v_{sb} &= V_{m2}\sin(wt - 120 \pm \alpha) \\ v_{sc} &= V_{m3}\sin(wt - 240 \pm \alpha) \end{aligned}\right\} \quad (1)$$

III.RESULTS AND DISCUSSION

In this paperwork, we have developed the system that shows the fault which causes the unbalancing of the load voltage due to which various disturbances occur in the system. These faults can be ground fault, LG fault, LLG fault etc. Also, we have designed the system which mitigate the power quality event (voltage sag) and provides the uninterrupted power supply to the network.

Part I: Fault Analysis

Here we are analyzing different fault conditions. Let us first study the parameters used in the system in the following table 1.

TABLE 1 SIMULINK PARAMETERS OF CIRCUIT

Sr. No.	Parameters	Values
1.	Source voltage	25KV
2.	Source resistance	0.8929 ohm
3.	Source inductance	0.01658 H
4.	Frequency	50Hz
5.	Fault resistance	0.001 ohm
6.	Ground resistance	0.01 ohm
7.	Initial RMS value	120

The entire result of the fault circuit is divided into four different cases depending on the type of fault they observe. The following are the cases:

1. Normal working condition
2. Fault in phase A of the system
3. Fault in phase B of the system
4. Fault in phases C of the system

1.Case I: Normal Working Condition

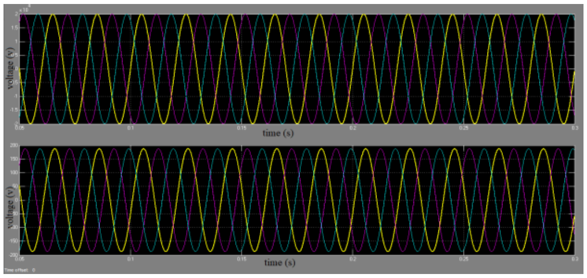

Fig. 13 V-I measurement of three phase during no fault condition

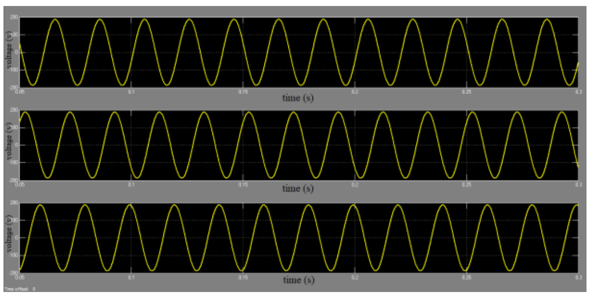

Fig. 14 Individual phase result during no fault condition

2.Case II: Fault in Phase A

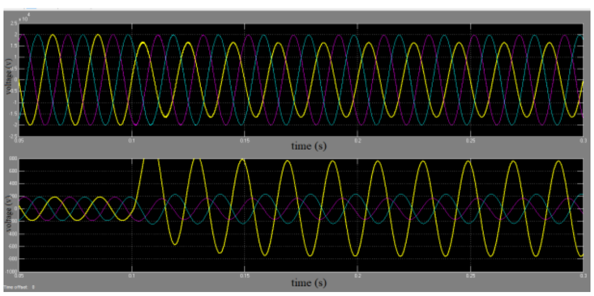

Fig. 14 V-I measurement of three phase result during fault in phase A

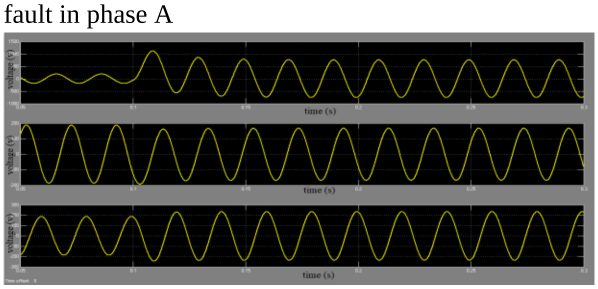

Fig. 15 Individual phase result during fault in phase A

3.Case III: Fault in Phase B

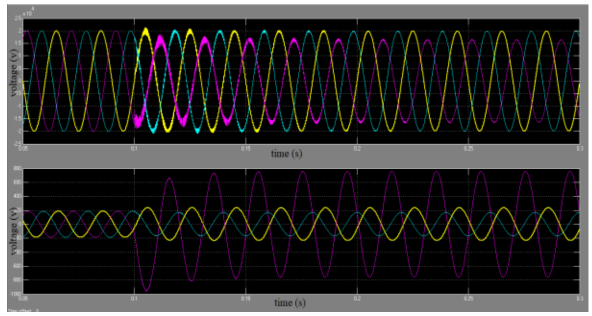

Fig. 16 V-I measurement of three phase result during fault in phase B

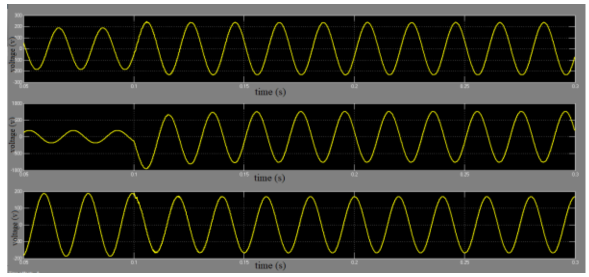

Fig. 17 Individual phase result during fault in phase B

4.Case IV: Fault in Phase C

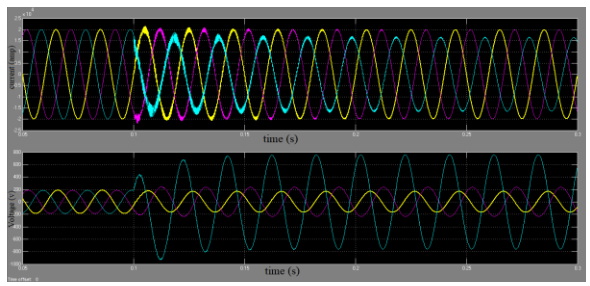

Fig. 18 V-I measurement of three phase result during fault in phase C

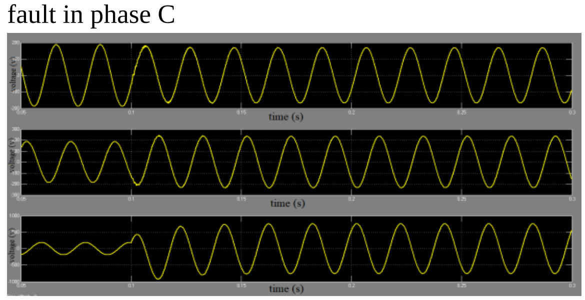

Fig. 19 Individual phase result during fault in phase C

Part II: Voltage Sag Mitigation

The effectiveness of the proposed method is evaluated through MATLAB/Simulink based simulation study. Here we are trying to mitigate the voltage sag condition and provides the system with the required voltage that is need for uninterrupted power in the network. Let us study the parameters used to design the DVR system in the following table.

A simulation model for DVR system, with parameter given in table 2, is developed and simulated for the performance evaluation. The dc link capacitor of 4700µF, is used for this study. As the intention is to maintain the rated voltage across the load terminals without any phase jump, the sensitive load is represented by an R-L load. The simulation results are given in fig. 20 and fig. 21. In this scenario, a sag depth of 50% is considered with a phase jump of +25o. A symmetrical voltage sag, for 10 cycles, is initiated at time t=0.15s. The DVR injected voltage and active-reactive power profiles are shown in Fig. 21 in form of carrier voltage (i.e. injected voltage). It can be noticed that the DVR restores the phase jump by injecting maximum voltage in the line.

TABLE 2 DVR PARAMETERS

Parameters of source		
	Reference voltage	400V
	Frequency	50Hz
Parameters of DVR		
	Dc voltage	311V
	Transformer turns ratio	5:1
	Diode Resistance	0.01 ohm
	Inductance	0.1mH
	Dc link capacitor value	4700 µF
	Breaker resistance	0.01 ohm
Parameters of non-linear load (RL type)		
	Nominal voltage	220V
	Nominal frequency	50 Hz
	Active power	100 KW
	Inductive reactive power	5 KVAR

The following fig.20 shows us the sinusoidal waveform of the reference voltage where an uninterrupted power is flowing in the network. The fig 21 shows us the final waveform of the mitigated voltage. In this figure the result is shown in three different parts namely input voltage, carrier voltage and load voltage. The input voltage waveform shows us the disrupted voltage that leads to voltage sag. After the disturbance the carries voltage detects the fault and add the required voltage in the network and finally inject voltage to mitigate the problem and we get the un-interrupted power in the system. Here fault occurs at t= 0.015 and gets cleared at t=0.027.

Thus, the per unit value of sag depth can be calculated by the following equation.

$$\Delta V_{sag} = \frac{V_L - V_G'}{V_L}$$

where, V'_G is sagged grid voltage.

The injected voltage in DVR can be expressed as a function of sag depth is

$$V_{DVR} = \sqrt{2}V_L\sqrt{\Delta V_{sag}^{\ 2} + 2(1-\Delta V_{sag}) - 2(1-\Delta V_{sag})\cos(\delta)}$$

Here the injected voltage in DVR is nearly around 135 V that is 40% of the sag which is required for the mitigation.

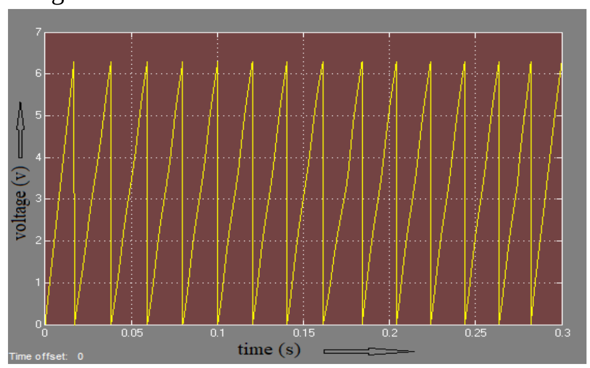

Fig. 20 Input voltage waveform

From the result we can see that the input rated voltage was 311 V and the sag of around 40% was observed which was injected in the line through carrier voltage and the load voltage gets corrected by using DVR. The voltage sag occurred for t=0.15 and lasts up to t=0.27 gets cleared giving uninterrupted supply to the load.

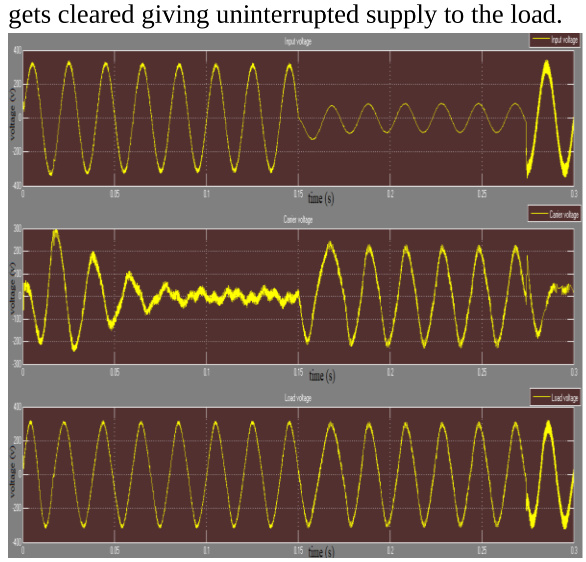

Fig. 21 Mitigated output voltage waveform

IV. CONCLUSION

In this paperwork an enhanced sag compensation scheme is proposed for capacitor supported DVR. The proposed strategy improves the voltage quality of sensitive loads by protecting them against the grid voltage sags involving the phase jump. The effectiveness of the proposed method is evaluated through simulations in MATLAB/Simulink. The scheme can be easily realized by implementing the discrete-time model of the system. The simulation and experimental results confirm the usefulness of this scheme.

Concluding this work, a system has developed that shows the fault which causes the unbalancing of the load voltage due to which various disturbances occur in the system. Also, the mitigation of voltage sag is obtained without any disturbance. This disturbance occurs at t= 0.015 and gets cleared at t=0.027.

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