Design of Three Phase Dynamic Voltage Restorer to Mitigate Voltage Sag

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Abstract: Power quality is the major concern in distributed power system. Consumer always demands for reliable and good power quality supply. Voltage sag is a common and undesirable power quality glitch in the distribution system which causes sensitive loads to misoperate. Dynamic Voltage Restorer (DVR) is a custom power quality device used for mitigation of voltage sag by injecting voltage as well as power into the system. This work shows the hardware implementation of three phase DVR to mitigate voltage sag for balanced three phase system. DVR is implemented to test small scale laboratory equipment with rating up to 1KW power. The three phase DVR can be used for the restoration of voltage for single phase as well as three phase equipment. This work presents the hardware laboratory testing for the three phase DVR. Three phase DVR is designed to operate for almost 78% voltage sag restoration i.e. voltage magnitude more than 50V input voltage is restored. Hardware results are analyzed with the signal analyzer and multi-meter for single phase and three phase loads. For three phase load, a three phase squirrel cage induction motor is tested in laboratory to demonstrate the functioning of three phase DVR. The demonstration showed that the three phase induction motor did not trip over due to the presence of voltage sag in the input supply.

Keywords: Active Power Filters (APF), Custom Power Devices (CPD), Dynamic Voltage Restorer (DVR), Injection Transformer, Power Quality, Voltage Sag, Voltage Source Inverter (VSI).

1. Introduction

Due to faults on power distribution system, consumers suffer various power quality problems. Voltage sags, Outages, Interruptions, Transients and Harmonics are the main disturbances in electrical power system that can disrupt a process at the utility and the customer end. Amongst the disturbances voltage sag is the greatest frequently occurring power quality problem in a network. It origins problems associated to the procedure of electrical and electronic devices. There are different ways to minimize voltage sag from the distribution system, but the use of custom power devices is considered to be the most efficient method. For this aim, we will be using the custom power device such as Dynamic Voltage Restorer. The use of custom power devices fall in the category of customer based results. This paper consists of simulation and hardware implementation of a three phase DVR between supply and load. This DVR designed is for a small scale laboratory testing purpose. This DVR is considered to minimize voltage sags, improve power quality and contribute towards effectively managed power distribution system.

This study is performed as a further step for improving previous disturbance mitigation methods. One of the published papers [1] represents a new topology of two three phase DVRs. The topology used is based on a direct AC / AC converter. Therefore, there is no need for large and expensive DC links and energy storage components. This work uses a new control method for the converter. The direct converter control method is based on PWM technology. In the approach adopted by the authors in [2], the PI controller is designed for dynamic voltage restorer and can reduce power quality problems such as sag and swell. The DVR control circuit in this paper is a combination of PWM-based technology, dq0 conversion and PI controller. The load point voltage and the reference voltage are first converted to the dq0 reference frame. The voltage of these dq0 transforms is then compared to each other, fed to the PI controller; the PI controller minimizes the error, and then passes the signal to the dq0 to the ABC transformer, further converting the voltage in its original reference frame. This paper is simulation based. In the approach adopted by authors in [3], the control modules of single phase DVR consist of PIC microcontroller which is used to compensate for voltage dips and swells. This is a hardware based paper. This helps to quickly reduce power quality problems and, to a large extent, improve power quality issues.

In this work, the control method is based on Atmega 328P programming because it can be easily used with an Arduino board. The inverter topology used is the half bridge DC to AC voltage source inverter topology. In this paper, physical hardware design of three phase DVR for

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balanced system is implemented for voltage sag affecting single phase and three phase loads. In this paper, a three phase DVR is designed on a small scale platform for laboratory testing purpose. The test results of the hardware implementation of the DVR show that we can design a similar DVR on a large scale platform which can be used anywhere on the transmission/ distribution lines in a power system to mitigate voltage sag in the system. The results are analyzed with single phase and three phase loads and these results show the restoration of voltage sag.

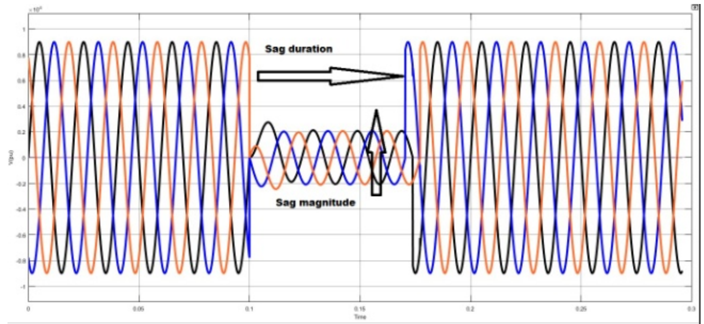

Figure 1: Voltage Sag Three Phase Waveform

2. Voltage Sag

Sag is defined as, "A decrease to between 0.1 and 0.9 P.U in RMS voltage or current at the power frequency for durations of 0.5 cycles to 1 minute" [6].
Conferring to the IEEE Stand, voltage sag is "A decrease in RMS voltage or current at the power frequency for duration of 0.5 cycles to 1 minute" [6].

IEC explanation for a dip (IEC 61000-2-1, 1990) "A voltage dip is a sudden reduction of the voltage at a point in the electrical system, followed by a voltage recovery after a short period of time, from half a cycle to a few seconds" [6]. Table 1 describes the type of sag with their possible duration and magnitude.

Table 1: Types of sag with their possible duration and magnitude

Categories	Typical Duration	Typical Magnitude
Instantaneous		
Sag	0.5 – 30 cycles	0.1p.u – 0.9p.u
Swell	0.5 – 30 cycles	1.1p.u – 1.8p.u
Momentary		
Interruption	0.5 cycles – 3 sec	< 0.1p.u
Sag	0.5 cycles – 3 sec	0.1p.u – 0.9p.u
Swell	0.5 cycles – 3 sec	1.1p.u – 1.8p.u
Temporary		
Interruption	3 sec – 1 min	< 0.1p.u
Sag	3 sec – 1 min	0.1p.u – 0.9p.u
Swell	3 sec – 1 min	1.1p.u – 1.8p.u

Today, customers are using a large number of electronic, digital and information technology (IT) equipment. The device produces harmonics that are more sensitive to voltage dips and voltage expansion. These devices operate at high frequencies (MHz - GHz), microprocessor-based devices run at very high speeds (MHz-GHz) and make these decisions in microseconds or nanoseconds, so these devices are susceptible to the effect of voltage sag and voltage swell. These devices may switch off, misoperate or make decision incorrectly. Figure 1 shows voltage sag waveform for a three phase system.

Voltage sag occurs due to:

- Fault on same feeders
- Fault on parallel feeder
- Sudden change in load current
- Starting of large loads such as motor
- Switching of large capacitor banks
- Due to lightning

Figure 2 shows the point of common coupling (PCC) and sag due to fault on PCC. The voltage drop at the PCC is given in equation 1.

$$V_{sag} = V_s \frac{Z_f}{Z_f + Z_S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

V_s = Source Voltage
Z_s = Series impedance of the transmission circuit
Z_f = impedance of fault affected line [7] [8]
The voltage sag at PCC will remain till circuit breaker opening or fault clearing

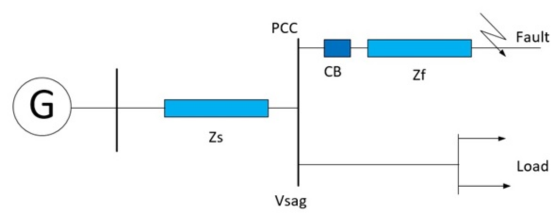

Figure 2: Sag due to fault

The extent of the voltage drop can be governed by the following parameters: the number of feed lines supplied from the PCC, the average length of the feeder, the average feed reactance; the PCC short-circuit equivalent reactance (X_{eq}), fault impedance (Z_f), resistance (X / R) , Fault type, fault distance, pre-suspended voltage level, system configuration and transformer connection [9].
In the power system, the three-phase fault is the most serious, but relatively unusual. Single-wire-to-ground

faults in power systems are the maximum mutual cause of voltage dips in industrial processes.

3. Operational Principle and Construction of DVR

DVR is a Custom power electronic device [4]. It consists of different parts such as Voltage source inverter (consisting of MOSFET and IGBT's), Injection transformer, Energy storage device (such as a battery), Control module and a Filter unit.

DVR is attached in series with the distribution system and load. It injects the control voltage through the injection transformer. The energy storage element (external battery) is used to inject the required voltage for restoration through the injection transformer into the system.

If the PWM signal from the controller is greater (i.e. PWM width is greater), then it means that the voltage magnitude is less and the external battery will inject greater voltage into the system to compensate for the sag. Figure 3 shows the basic principle of DVR operation.

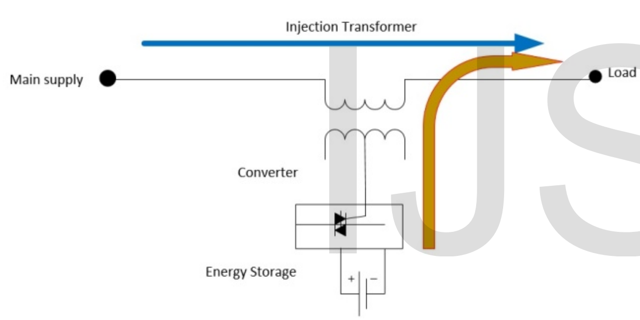

Figure 3: Principle of DVR

Construction of DVR:

The DVR is fast, flexible and efficient solution to voltage sag problems. DVR consists of energy storage unit, inverter (DC to AC), and filter unit and injection transformer as shown in Figure 4.

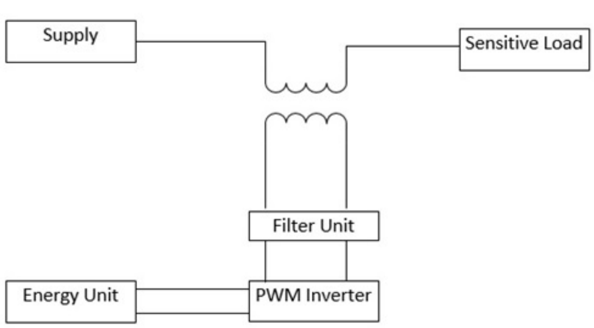

Figure 4: Typical DVR and its outputs

There are two main parts of the DVR. One is the power circuit and the other is the control circuit. DVR can inject key parameters of the control signal through the injection transformer into the line. These parameters include phase shifts, amplitude and frequency etc. DVR injects the voltage magnitude necessary for the system to restore. The power circuit of the DVR is based on the control signal. Power circuit of the DVR is shown in the Figure 5 below.

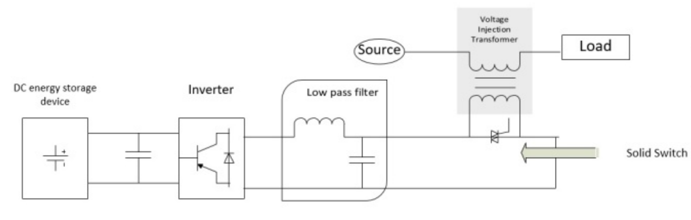

Figure 5: Power Diagram of DVR

Many instruments such lead acid batteries, SMES and super capacitors etc. are used as energy storage units. The energy storage element (external battery) is used to inject the required voltage for restoration through the injection transformer into the system. The main function of the external energy storage element is to inject the voltage necessary to compensate for the sag in the system.

Usually pulse width modulation is used with the VSI. The VSI is used to convert the DC voltage to an AC voltage. The VSI receives the PWM signal through the control circuitry. The voltage injection transformer is used to increase/ boost the voltage amplitude to the load. The GTO, IGBT, or MOSFET is typically used as a switching device in these VSI topologies.

The next part of DVR power circuit is the Injection transformer. This is basically a step up transformer whose primary is connected in series with the distribution line while secondary of the transformer is connected to the DVR power circuit.

Three single phase transformer are used with different ratings in the construction of three phase DVR. The voltage supplied by the voltage source inverter is increased by the injection transformer to the desired level. Injection transformer also acts as an isolating component and separates the distribution network from the DVR power circuit.

4. Operational Modes

There are two different operational modes of DVR. The DVR will operate differently in either of the modes.

4.1 During a voltage sag/swell on the line

The DVR injects the difference between the pre-sag and the sag voltage by providing the actual power demand from the energy storage device composed with the reactive power [5]. Maximum DVR capacity is limited due to the DC energy storage and voltage booster transformer rating. In case of three single-phase DVRs, the size of the restoring voltage can be individually controlled.

4.2 During the normal operation (Standby mode)

During normal process, no sag occurs in the system and the DVR does not deliver any voltage to the load. DVR will be in standby mode and energy storage device is fully charged. The energy storage device may be charged from the power supply itself or from a different source.

5. Techniques used for Compensation

5.1 Pre-sag Compensation

Thyristor control drives (non-linear loads) use the pre-sag compensation process. In the nonlinear load, it is essential to recompense for the voltage amplitude and the phase angle. Figure 6 below depicts this technique. This technology requires an advanced energy storage expedient and a booster transformer (step up transformer).

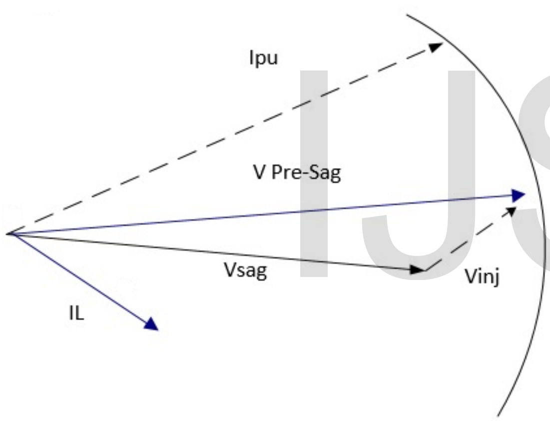

Figure 6: Techniques showing pre-sag compensation [10]

5.2 In phase Compensation

Active loads are used with this compensation technique method. For this technique, the compensated voltage is in phase with the wilted voltage as the name indicates [6]. Figure 7 shows the phase shifts between the voltages before the sag and after the sag.

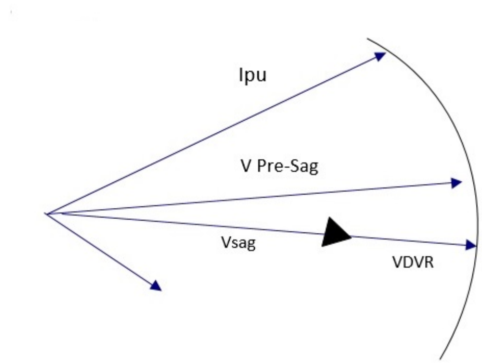

Figure 7: In-Phase Compensation Technique [10]

6. Three Phase Dynamic Voltage Restorer to Mitigate Voltage Sag

When a fault occurs in line, voltage sag will occur. The voltage magnitude will be measured by the control module and the required PWM signal will be generated by the controller which is fed to the inverter module. Energy storage element which is connected to the inverter module will provide the required restoring voltage to the line through the injection transformer. The inverter module topology is DC to AC half bridge voltage source inverter topology.

The block diagram of three phase DVR is shown in Figure 8 below.

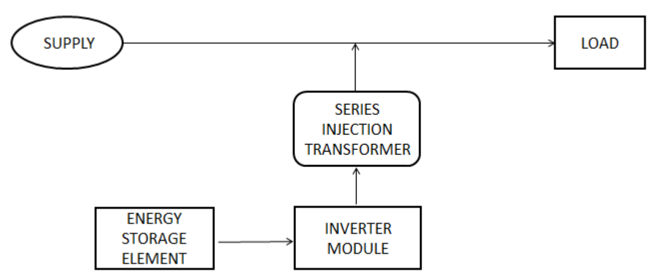

Figure 8: Block Diagram of three phase DVR

The research methodology of a three phase DVR is shown in Figure 9 below.

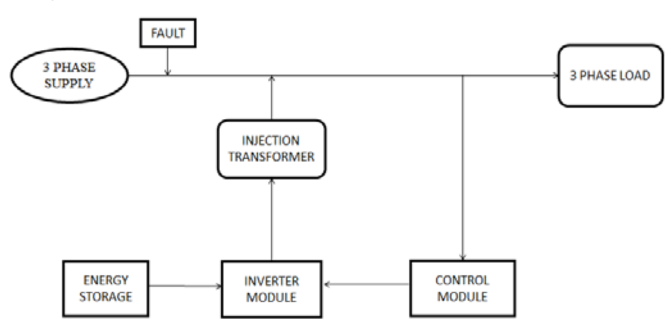

Figure 9: Research Methodology of three phase DVR

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Sag might occur from single phase and three phase faults. Sag in either case is very critical for electrical units. The process sectors whose usage is from one and three phase supply will experience numerous breaks during their manufacture process and hence they need to focus on the use of voltage maintenance equipment. Similarly, the electrical equipments in homes, offices and those for domestic use will get damage or may misoperate during the fault occurring in line. The solution to such problems is three phase DVR.

This project has targeted different single phase and three phase equipment's at the load side with power rating up to 1KW for small scale testing purpose to compensate the three-phase voltage sags for balanced system. The simulation of three phase voltage sags is implemented using MATLAB Simulink. This paper deals with disturbances like voltage sag. The DVR is practically tested in laboratory.

The three phase dynamic voltage restorer consists of two circuits; one is the power circuit and other one is the control circuit. The power circuit consists of power transformer with the rating of 1KVA on each phase. These 1KVA transformers are step up transformers and are center tapped with rating 12/220V AC. These transformers are also known as booster transformers or series injection transformer because they are used to inject the restoring voltage in the line if voltage sag occurs in a system due to a fault. The other part of the power circuit is the MOSFET Inverter circuit. The inverter circuit consist of six 8×8 Array for current boosting on the 12V primary side of the series injection transformers. Two 8×8 arrays are connected per phase to the 12V side of each 1KVA transformer. This inverter module is connected to an external energy source which is a DC 12V battery in this case. The inverter module is used to convert the DC to AC voltage. The inverter topology used here is the half bridge VSI topology. For a single phase operation i.e. red phase MOSFET B1 is turned on for positive half cycle and the switch B2 is turned on for the negative half cycle. One of the switches conducts at a time. If u consider the three phase operation with a three phase load than topology used is named as 6 leg DC to AC voltage source inverter topology. The power circuit is shown in Figure 10.

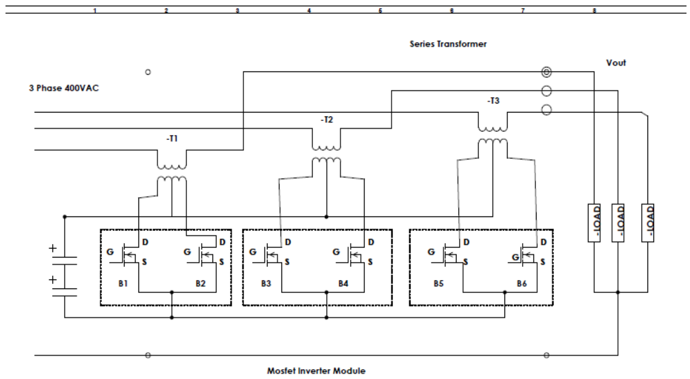

Figure 10: Power circuit of three phase DVR

The control circuit consists of a shunt connected step down transformer (400mVA, 220/24V AC center tapped). The transformer is followed by a half bridge diode circuit which is used for clipping of the signal. D1 diode works for a positive half cycle while D2 diode works during the negative half cycle. The signal from the clipping circuit is passed to the magnitude control circuit (MOSFET driver circuit) which is operated by the PWM signal. The magnitude control circuit consists of a two NPN bipolar junction transistor per phase. The base of the transistors get the PWM signal and it remains on for the time the PWM signal remains on. The gate of the MOSFET of the inverter module receives the signal from the MOSFET driver circuitry. The control circuit is shown in Figure 11.

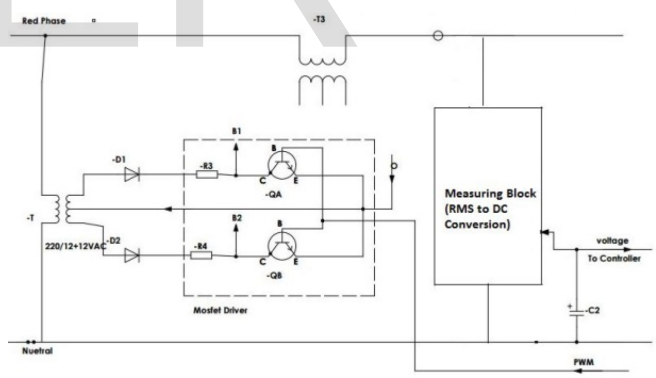

Figure 11: Control circuit of three phase DVR

The voltage magnitude for the three phase balanced voltage sag is measured by the measuring block/ RMS to DC conversion (Op-Amp integrator with negative feedback is used) connected at the load side. This RMS to DC conversion block measures the voltage consisting of the voltage sag at the load side and converts the remaining AC voltage after sag to DC value . The Op-Amp measurement takes about 170μsec for analog read. This DC is fed to the controller (Arduino with Atmega 328P) which controls the value for restoring the required voltage through DVR. The instruction time for statement control is usually 1μsec. Now

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the output PWM signal from the controller is transmitted to the gate of the MOSFET switching circuit (inverter module). The RMS value of an AC voltage is equivalent to a DC voltage that when applied across a given resistor for a certain time dissipates the same amount of heat as the AC voltage applied across the same resistor for the same amount of time. So, for measuring the RMS value using this principle, an instrument using heating effect of the current is required.

Also, it is observed that $1/\sqrt{2}$(=0.707) times its peak value. We have used here this fact to determine the RMS value. The circuit is built around a quad op-amp IC LM324 and operates off a single power supply. The Op-Amp integrator circuit is working with a negative feedback control. The Op-Amp measurement takes about 170μsec for analog read. The RMS to DC conversion circuit is shown in Figure 12.

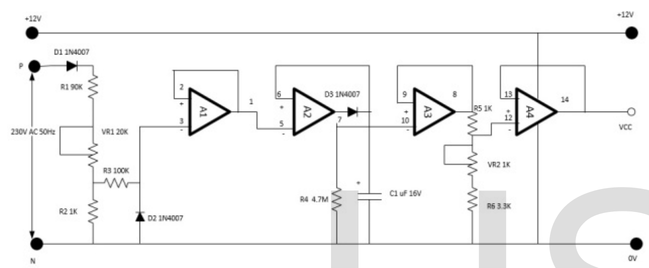

Figure 12: The RMS to DC conversion circuit (Op-Amp Integrator)

The output PWM signal from the controller is transmitted to the gate of the MOSFET switching circuit (inverter module). The duty cycle of PWM depends upon the variation in voltage sag. Depending upon the amount of voltage sag, the PWM generates the required signal for the inverter module in order to restore the required restoring voltage through the injection transformer. If voltage sag is greater, T_{ON} time will be greater while the T_{OFF} time will be smaller and duty cycle 'D' will be greater. This means that PWM signal will remain on for more time so that maximum voltage magnitude can be restored. Therefore, for greater voltage sag in the line, the Duty cycle of the PWM signal will be greater to restore the voltage in the line. PWM sampling frequency is 1 KHz and the instruction time is 1usec. The PWM Duty cycle ranges from 0-255% i.e. Duty cycle can vary from 0-255% range of PWM signal depending upon the sag and swell in line. The equation 2 shows the Duty cycle of PWM signal:

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \ (2)$$

7. Results and Discussions

The software used for simulation is MATLAB Simulink. The simulation of the three phase DVR used to diminish sag is shown in Figure 13.

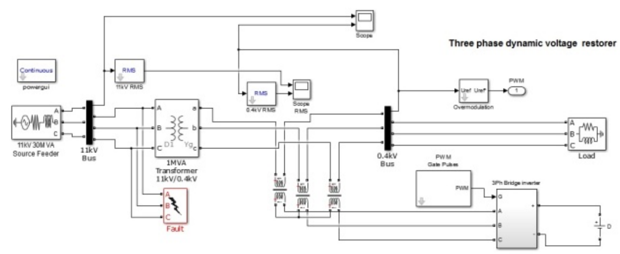

Figure 13: Simulation of three phase DVR

The simulation contains 11KV (30MVA) source. It has two bus bars, one is connected on the 11KV transmission line and other one is connected on the 0.4KV distribution line near the load. A step down power transformer (1MVA) is used to step down the voltage from 11KV to 0.4KV. When a three phase fault occurs on the line near the 11KV bus, the transmission and distribution lines are affected by voltage sag. The effect of voltage sag is greater near the 11KV line, whereas its effect is less near the 0.4 KV line because it is far from the fault.

The DVR is connected near the load on the 0.4 KV distribution side. It consists of a three phase injection transformers, a control circuitry consisting of PWM gate pulses and a voltage source inverter module. The inverter topology used in the simulation is the three phase bridge inverter topology. The restoring voltage is provided by the energy storage element connected to the inverter module and this restoring voltage is injected into the line through the injection transformer. The three phase load connected is inductive load with power rating of 2KW.

Figure 14 shows the voltage sag results in both the 11KV and 0.4KV line during a three phase fault. The results show that the 11KV line has a greater impact of voltage sag as compared to the 0.4KV line. Figure 15 shows the DVR performance after voltage sag mitigation. It can be seen that the voltage sag is mitigated in the 0.4KV line which is connected to the injection transformers of the three phase DVR. Voltage sag can still be seen on the 11KV line. Figure 16 shows the three phase waveform representation results in both the 11KV and 0.4KV line during a three phase fault. Figure 17 shows the RMS waveform post sag restoration results.

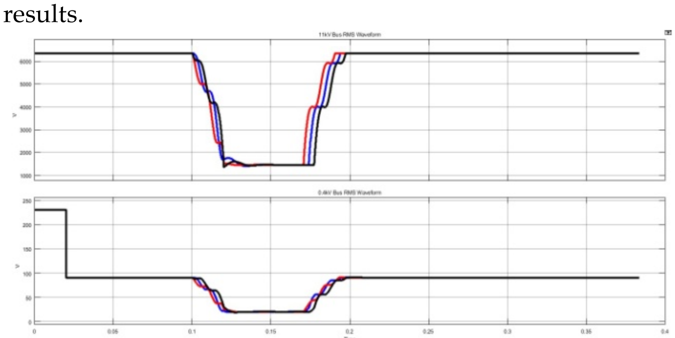

Figure 14: Three phase lines during fault

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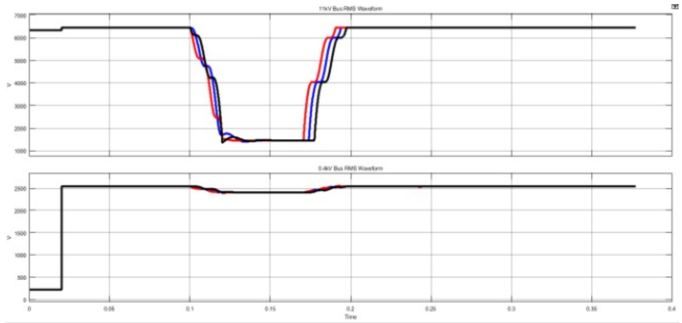

Figure 15: Three phase DVR performance after sag mitigation in 0.4kV line

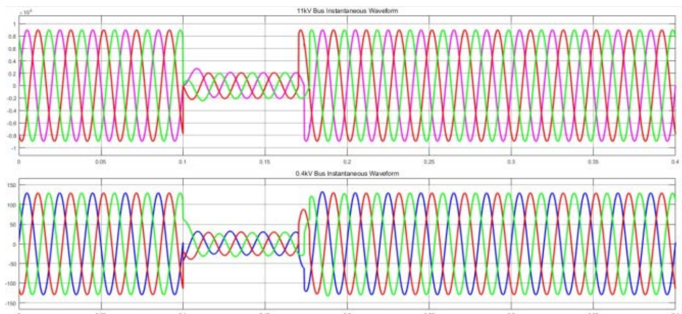

Figure 16: Three phase waveform representation of lines during fault

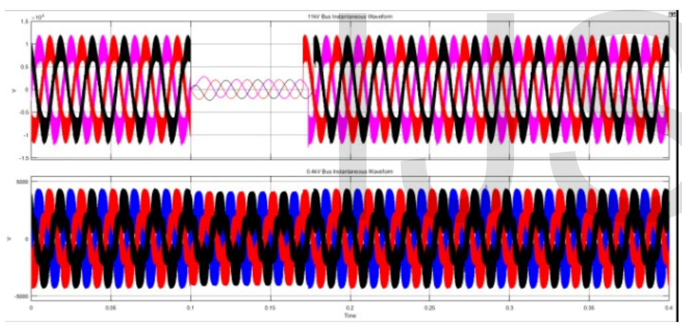

Figure 17: RMS waveform view of post sag restoration in 0.4KV line

The hardware design of a three phase Dynamic Voltage Restorer is shown in Figure 18 below.

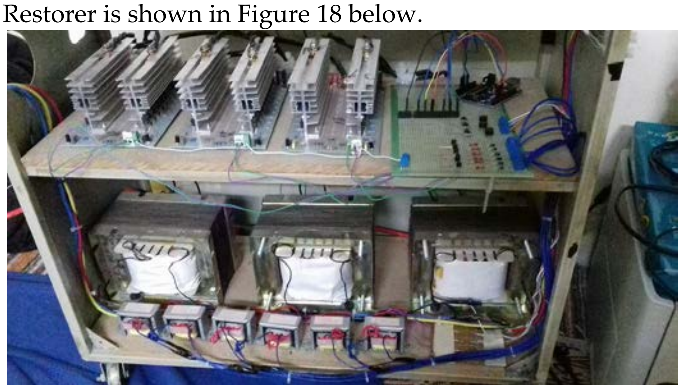

Figure 18: Hardware implementation of three phase DVR

The DVR was tested in the laboratory using the variable AC power supply and a 500W single phase load. The Figure 19 shows result with input voltage magnitude in the range of 140-150V. The result is shown on the multi-meter below. The output voltage to the load is restored by the external battery through the injection transformer which is approximately between the ranges of 200V-205V.

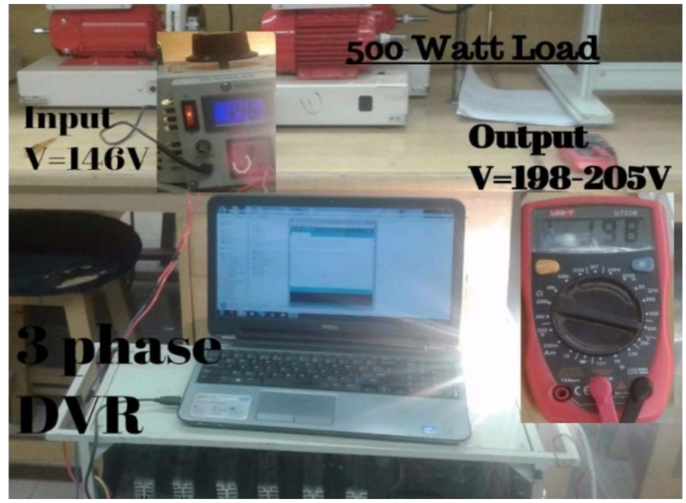

Figure 19: Testing of three phase DVR in the laboratory with a single phase load

The results with single phase 200W bulb at load was taken using the signal analyzer with input voltage magnitude being 180V and 150V as shown in Figure 20 and Figure 21 respectively. Current transformer is connected with the output phase to make the signal available on the signal analyzer. The voltage was being restored at the output between 200-220V which was measured using the multi-meter.

Comparing the output waveforms (blue signal) between the two figures below, it is seen that if the input voltage magnitude is less (voltage sag is greater) than the width of PWM signal from the controller is greater which can be clearly seen in Figure 21. In other case, if the input signal is greater (voltage sag is less) then the width of PWM signal is less as shown in the output signal in Figure 20. So, basically as far as results are concerned this hardware design is not dealing with the variation in magnitude of PWM signal but it is dealing with the variation in the width of PWM signal. Table 2 shows the comparison results in terms of width of PWM signal for two different input voltages at 200W single phase load.

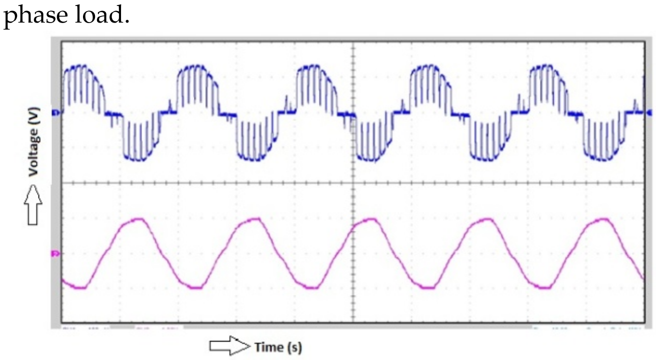

Figure 20: Output signal (blue) with 200W load (input voltage 180V) using signal analyzer

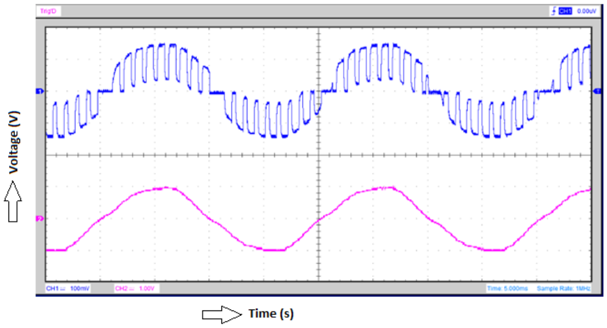

Figure 21: Output signal (blue) with 200W load (input voltage 150V) using signal analyzer.

Table 2: Comparison result in terms of width of PWM signal for different input voltages

S. No	Load	Input Voltage	Restoring Voltage	Output Voltage	PWM Width
1.	200W	180V	Lesser (30V)	210V	Smaller
2.	200W	150V	Greater (65V)	215V	Greater

Now, results with single phase 500W bulb at load was taken using the signal analyzer with input voltage being 150V and 160V as shown in the Figure 22 and Figure 23 respectively. Output signal is the signal in blue while the input voltage signal is in pink. Current transformer is connected with the output phase to make the signal available on the signal analyzer. The voltage was being restored at the output between 210-220V which was measured using the multi-meter.

Comparing the output waveforms (blue signal) between the two figures below, it is seen that if the input voltage magnitude is less (restoring voltage is greater) than the width of PWM signal from the controller is greater which can be clearly seen in Figure 22. In other case, if the input signal is greater (restoring voltage is less) then the width of PWM signal is less as shown in the output signal in Figure 23. So, basically as far as results are concerned this hardware design is not dealing with the variation in magnitude of PWM signal but it is dealing with the variation in the width of PWM signal.

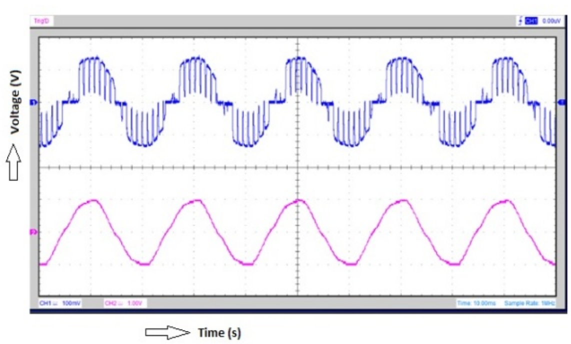

Figure 22: Output signal (in blue) with 500W load (input voltage 150V) using signal analyzer

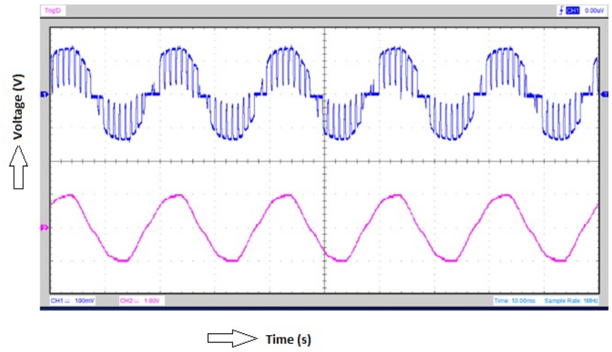

Figure 23: Output signal (in blue) with 500W load (input voltage 160V) using signal analyzer.

Table 3 shows the comparison results in terms of width of PWM signal for two different input voltages at 500W single phase load. The comparison results show that more the restoring voltage, greater will be the width of PWM signal.

Table 3: Comparison result for different input voltages at 500W load

S. No	Load	Input Voltage	Restoring Voltage	Output Voltage	PWM Width
1.	500W	150V	Greater (60V)	210V	Greater
2.	500W	160V	Smaller (45V)	205V	Smaller

The DVR was tested in laboratory with a three phase squirrel cage induction motor of 600W power rating. A variable balanced three phase AC source was used. The results indicated that the input three phase AC voltage magnitude greater than 50V (L-N) was restored at the output. The output voltage was between the ranges of 215V-230V (phase to neutral) which was measured using the multi-meter. Table 4 shows the three phase output restored voltage from DVR for different values of three phase input voltages. The distortion is seen at the output because no filter was used in the hardware design.

Table 4: Three phase results with a 600W load

S. No	Load (600W)	Input Voltage (L-L)	Output Voltage (L-N)
1.	Squirrel cage induction motor	300V	225V
2.	Squirrel cage induction motor	250V	230V
3.	Squirrel cage induction motor	200V	220V
4.	Squirrel cage induction motor	150V	215V
5.	Squirrel cage induction motor	100V	220V
6.	Squirrel cage induction motor	Less than 100V	0V (Load trips)

8. Conclusion

This paper demonstrates the hardware implementation results using single phase and three phase loads. Atmega 328P programming is used in this work because it can be easily used with an Arduino board.

The physical hardware design of three phase DVR for balanced system is implemented for voltage sag affecting single phase and three phase loads. This DVR is designed for small scale laboratory testing purpose. The results are analyzed with single phase and three phase loads and these results show the restoration of voltage sag. The results show that the width of PWM signal is dependent on voltage sag in the system. The hardware results show that method deals with the variation in width of the PWM signal with varying voltage sags. The hardware results are not implemented with respect to the variation in RMS voltage waveform of PWM with varying voltage sag. The simulation results show the sag duration. The sag duration from the simulation results is calculated to be 80 msec.

In case of three phase loads i.e. squirrel cage induction motor, the designed DVR can operate for 78% of voltage sag restoration. Hence, observing the results it can be concluded that the DVR designed has a high efficiency and reliability, fast operating time and low cost.

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