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Power Quality Improvement Using Dynamic Voltage Restorer

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ABSTRACT Power Quality is an essential concern in the modern power system that can affect consumers and utility. The integration of renewable energy sources, smart grid systems and extensive use of power electronics equipment caused myriad problems in the modern electric power system. Current and voltage harmonics, voltage sag, and swell can damage the sensitive equipment. These devices are susceptible to input voltage variations created by interference with other parts of the system. Hence, in the modern age, with an increase in sensitive and expensive electronic equipment, power quality is essential for the power system's reliable and safe operation. Dynamic Voltage Restorer (DVR) is a potential Distribution Flexible AC Transmission System (D-FACTS) device widely adopted to surmount the problems of non-standard voltage, current, or frequency in the distribution grid. It injects voltages in the distribution line to maintain the voltage profile and assures constant load voltage. The simulations were conducted in MATLAB/Simulink to show the DVR-based proposed strategy's effectiveness to smooth the distorted voltage due to harmonics. A power system model with a programmable power source is used to include 3rd and 5th harmonics. The systems' response for load voltage is evaluated for with and without DVR scenarios. It has been noted that the proposed DVR based strategy has effectively managed the voltage distortion, and a smooth compensated load voltage was achieved. The load voltage THD percentage was approximately 18% and 23% with insertion 3rd and 5th harmonics in the supply voltage, respectively. The inclusion of the proposed DVR has reduced THD around less than 4% in both cases.

INDEX TERMS Dynamic voltage restorer, FACTS, total harmonic distortion, sag, swell, harmonics.

I. INTRODUCTION

Electrical Energy is invisible, a universal commodity that is immediately available in most of the world, and it has now been recognized as everyday consumer need [1]. Renewable Energy Systems (RESs) is used to aid the primary energy demand in solar, Solar thermal, wind energy, etc. The intermittent nature of RESs, harmonics, and reactive power problems halt the power system's performance by originating stability concerns in the power system [2], [3]. The Flexible AC Transmission Systems (FACTS) devices are widely adapted for reactive power compensation, voltage stability, and power quality in distribution grids around the world [4], [5]. However, FACT devices also alter different parameters on the transmission and distribution system [6].

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This work presents a study of the power quality and aims at identifying the causes of poor power quality and provide the solutions to these power quality problems. Some equipment like computers, laptops, relays, solid-state devices, adjustable speed drives, and optical devices are known as sensitive equipment. These devices are susceptible to input voltage variations created by interference with other parts of the system.

The power system is divided into the following parts as generation, transmission, distribution, and by using other transmission line power systems is fed to different loads on the distribution side. Power quality plays a vital role in the power system when variable power is supplied to the load. Subsequently, the domestic and industrial customers with delicate loads are affected by the poor quality of power. Even there is various type of load on the distribution side, but poor power quality affects the sensitive loads more than others.

There are many applications where the sensitive load has an increasing demand, like in hospital's operation theatres, semiconductor systems in processing plants, database systems, instruments to control air pollution in crowded areas, precise and accurate equipment are required by data processing, and service providers. If the power system causes the dips and distorted voltages, these devices may fail, and such a device's failure leads to wastage of a significant amount of money. Therefore, the distribution side is dependent on power quality. Electrical characteristics are set by the power system that does not disturb the system's performance and perform its function in a controlled manner. In this article, voltage swell and distorted voltage with high harmonics in it are discussed.

When the load voltage being disturbed, it causes voltage sag, transient, swell, and high distorted voltage with harmonics and Total Harmonic Distortion (THD) due to the occurrence of the faults. The vulnerability of voltage sags and harmonics problems is mostly to the delicate instruments. Few problems occur in the result of voltage sag that may also cause disturbance of torques in the motors, device burning, misfiring in the device, etc. The harmonic is an essential issue for power quality to be solved effectively.

When the faults occur in the power system that causes a large current drawn from the power system, a short duration reduction RMS voltage appears, commonly known as voltage sag or Dips [7]. For example, when someone starts an air conditioner or a heavy motor, the startup of the load and remote fault clearance done by utility instrument, are the fundamental cause of sag production. When the motor starts, it causes six times more current than actual current. While the motor's startup, a substantial amount of reactive power is absorbed that will lead to the introduction of voltage sag. The voltage profile of the voltage sag is presented in Figure 1.

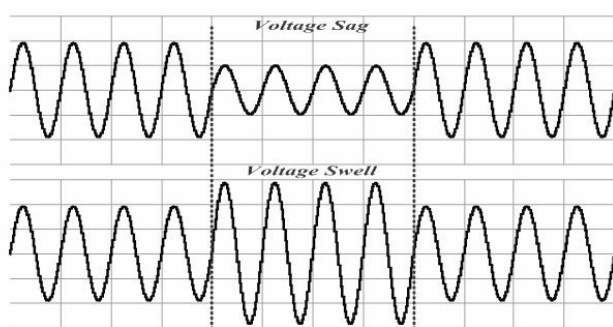


FIGURE 1. Voltage waveform with sag and swell [7].

Voltage swell is defined as the increase in the voltage value from its fundamental value, e.g., during the half-cycle to 1-minute time, the change in voltage from 10 to 80 %. Similarly, it causes overvoltage when voltage sag, continued increasing voltage profile. There are different types of voltage swell, including i. Instantaneous swell, ii. Momentary swell, and iii. Temporary swell. When the connection of large loads being disturbed, it also causes voltage swell. An increase in voltage of the faulted phase and natural wire's

loose connection causes resultant to Single Line to Ground fault (SLG). Overheating and destruction of electrical instruments and insulation breakdown are consequences of voltage swells. Figure 1 shows the voltage swell in voltage profile.

Harmonic distortion is the problem of voltage produced by the variation in fundamental frequencies by three times, for example, 50Hz fundamental frequency when multiplying with three as $3 \times 50 = 150\text{Hz}$. That is the 3rd harmonic of the fundamental frequency, as Figure 2 shows the waveform with harmonic content. The function of switching in power electronics causes harmonics creation. The tripping of circuit breakers, overheating of neutral conductors, transformers, and other power distribution instruments, destruction of circuits without proper management based on clear sine wave activates at zero crossover point are the indicators of a harmonic issue [3], [8].

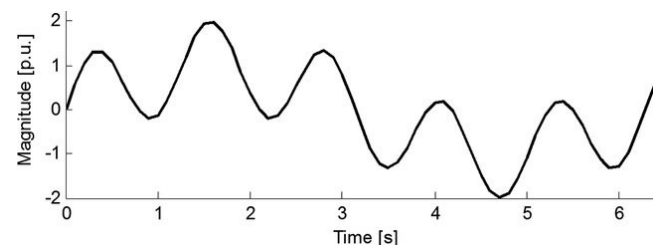


FIGURE 2. Waveform with harmonic content [7].

The main contributions of this research work are summarized below:

- to decrease the THD lower than 5% by mitigating the problem of distorted voltage due to sags, swell or, harmonics.
- to access and analyze the performance of the suggested model with the use of MATLAB / SIMULINK along with the use of DVR and without it too.
- to investigate the power system with the insertion of 3rd and 5th harmonics in the input voltage profile.
- to evaluate the performance of the DVR based power system with same 3rd and 5th harmonics insertion by comparing its results with without DVR based system.

The rest of the paper is organized as; an extensive literature review about the use of DVR is presented in section II. The mechanism, operating principle, and working of DVR are shown in section III; the simulation results are presented and discussed in section IV, and in last, a conclusion is drawn with a focus on the key findings of this work.

II. LITERATURE REVIEW OF DVR

The transmission and distribution system problems were addressed in some countries using the FACTS and D-FACTS devices. As per IEEE recommendations, FACTS can be expressed as [9], "AC transmission systems containing static and power electronics-based controllers to increase power transfer capability and more immeasurable controllability." Today, electricity demand has risen considerably while the development of generation and transmission systems is not

adequate by the limited resources, economic issues, and some environmental limitations. The present transmission system cannot be easily extended due to limited resources. Therefore, the expansion in transmission capacity is a viable solution. Transmission lines are not being fully utilized due to some limiting factors affecting the loading capability of the transmission line. These factors are perceived as the thermal limit, dielectric, and stability. FACTS controllers can control power and enhance the usable capacity of present lines. The FACTS controllers enable the power to flow through line under normal conditions and when subjected to faults and allow a line to transport power close to its thermal ratings [10], [11].

DVR is used on the distribution feeder to protect the load from faults due to the voltage sags and voltage swells. DVR is mounted in series with the load, and a battery energy storage system (BESS) is connected with a transformer and inverter are also connected with DVR, which compensate the active and reactive power requirement for the reduction in voltage sags and voltage swells [12]. For the voltages stability, DVR injects voltage into the distribution system, the DVR to the system through the transformer. DVR is the FACTS device, which compensates the disturbances like the voltage sags, swells, and voltages harmonics from the loads. DVR injects the voltages in series with the transmission lines and injects a small amount of voltages in normal conditions. But, when a disturbance occurs, DVR calculates the voltages required to protect the load through the sinusoidal pulse width modulation (SPWM). Then after those voltages are injected in the system to maintain the situation. In the steady-state, DVR either absorbs or delivers the active or reactive power, but when a disturbance occurs, DVR delivers or absorbed the active or reactive power from the dc-link [13].

Martiningsih *et al.* have recommended the installation of DVR are PT DSS power plant, the DVR acts as a compensator and connected in series with the distribution line. The proposed PI-based DVR is competent in restoring the power quality restraint. [14]. Eltamaly *et al.* have proposed a DVR based strategy for mitigation of voltage sag through DVR to enhance the power systems quality. To degradation in the performance of electrical equipment. The results determine that DVR compensate sag/swell adequately and implement proper voltage adjustment [15].

Ali *et al.* have proposed a novel DVR with a power electronic transformer (PET) to mitigate the symmetrical and asymmetrical sags and swells. The results depict that the novel design is effectively alleviates the symmetrical and asymmetrical voltage sag and voltage swell on the distribution line [16].

A nonlinear adaptive control (NAC) with DVR is proposed to recover the Low Voltage Ride Through (LVRT) for a renewable power system. Real perturbation of the system is compensated by the estimating the perturbation with the NAC in which the parameter which includes measurement of the noise, uncertainties, and disturbances such as the intermittent effect of the renewable sources and grid faults. Through the NAC, no precise model and complete measurement are

required for robust and adaptive control. The DVR is embedded with the energy storage system (ESS). ESS-DVR compensates the grid voltage dips for supporting the voltages. In that scenario, the fuzzy logic controller (FLC) can be used, and both FLC and NAC based controller enhance the LVRT capability [17]. The main thing is that a high rating of the ESS-DVR is required if it is low. The performance will be reduced. Another FLC based power quality improvement strategy for DVR was proposed was Benali *et al.* [18]. Dambumruntrakul *et al.* have presented a using zero active power technique for enhancing the performance of DVR [19]. They have obtained superior results with their prospered method than the conventional In-Phase Compensation with DVR. A power quality improvement technique using a Grasshopper Optimization Algorithm (GOA) based DVR is presented in [20]. A GOA based technique is recommended to tune the parameters of convention Proportional Integral Derivative (PID) controller.

A comparison of literature available on DVR and its applications is presented in Table 1.

TABLE 1. A comparison of various DVR based approaches.

Type	Control Strategy	Application	Reference
DVR-ESS	FLC and NAC	LVRT	[17]
DVR-OLTC	On-load tap changing transformer	Regulation of voltages, power flow	[21]
DVR	DVR system with DSP control board	Power source, SW5250A/ELGAR	[15]
DVR	PI	PT. DSS Power Plant	[14]
Novel DVR	No control	Power electronic transformer (PET) based DVR	[16]
DVR	FLC	Hybrid Wind-PV LVRT	[18]
DVR	Zero-real power tracking technique	Power system voltage sag and swell	[19]
DVR	GOA based PID	voltage sag and swell	[20]

III. PROPOSED DYNAMIC VOLTAGE RESTORER

The frequency of the supplied voltage can determine the power supply quality that is a significant indicator of power quality. The voltage sag is interpreted as a drop in the Root Mean Square (RMS) value of the voltage that can happen from 10 ms to 60 seconds with the depth of the falling voltage of 0.9 per unit (p.u) 0.1 p.u of a nominal p.u based on the IEEE standards [22]–[24]. Regular voltage sags are usually checked for the load at the distribution level due to different reasons. The voltage sags are highly unbearable for a few delicate loads in high technology sectors. The load voltage requirements could be maintained by the complicated tasks with a specific frequency and exact value of voltage sag while distortion and oscillation.

Usually, the destruction of the production sector and its downtime is the result of voltage sag that is costly and leads to harsh problems among consumers. A specific amount of

energy and voltage is supplied to the distribution system by using electric devices that are also named consumer power devices. The complex problem could be mitigated. As compared to the conventional methods of voltage sags problem solving, the DVR is supposed to be an efficient method to control the voltage sag and distortion. In this work, the power system's performance is evaluated by removing voltage sag through a DVR at the distribution level.

A. PRINCIPLES OF DVR OPERATION

A DVR consists of GTO or IGBT based Voltage Source Inverter (VSI), an energy storage instrument, a capacitor bank, and an injection transformer. The DVR is also called solid-state power electronic switching device. A DVR connected to a distribution bus is illustrated in Figure 3. The practical guideline of the DVR as it works by methods for an injecting transformer; a control voltage is created by a forced commuted converter, which is in arrangement to the bus voltage. Different converter control topologies for droop-controlled converter are presented in [25], [26]. DC voltage source behaves like a device of energy storage given by the DC capacitor, as shown in Figure 4.

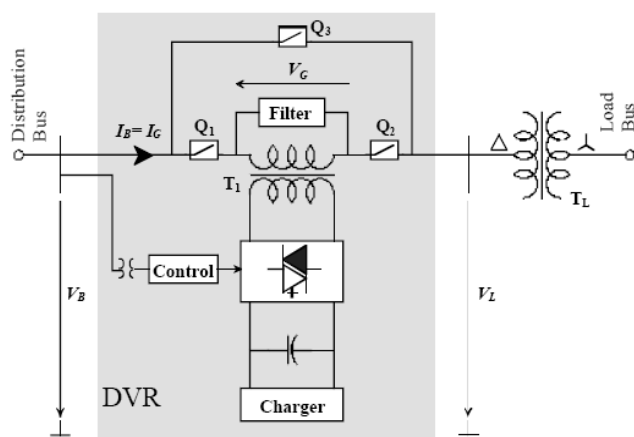


FIGURE 3. Principle design of DVR connected at distribution end [15].

To mitigate the problem of voltage drop is not efficiently done by the DVR when there is no voltage sag issue under optimal conditions. DVR will produce a needed controlled voltage of high frequency with the existence of a distribution system, a required phase angle that will ensure that load is perfect and maintained. For keeping the consistency in the load supply of voltage in this situation, the capacitor will be discharged. Here is needed to note that the DVR can absorb and produce reactive power, but an external source of energy is used to provide reactive power injection. The voltage sag detection time and the devices of power electronics shorten the response time of DVR. As compared to the conventional methods of voltage correlation, for example, the tap-changing transformers response time of DVR is less than 25 milliseconds.

B. CONSTRUCTION OF DVR

There are two parts of the DVR: one is the power circuit, and the other is the control circuit. The control signal consists of magnitude, phase shift, the frequency that are complex parameters of it, and injected by the DVR system. In the power circuit, the switches are used to generate a voltage-dependent on control signals. Additionally, this section will describe the fundamental structure of the DVR by the power circuit. The construction and basic Configuration of the DVR are shown in Figure 4 [27].

1) ENERGY STORAGE UNIT

Different devices are used to store energy like Flywheels, Lead-acid batteries, Superconducting Magnetic energy storage (SMES), and Super-Capacitors [28]. While the occurrence voltage sags, the storage unit provides the required real power as it is its primary function. The compensation capability of DVR is defined by the active power produced the device of energy storage. Instead of using other storage devices, the devices of the high response time of charging and discharging are being used that are lead batteries. The rate of discharge determines the internal space available for the storage of energy, and this discharging rate is based on a chemical reaction [29], [30].

2) VOLTAGE SOURCE INVERTER

The use is of Pulse-Width Modulated VSI (PWMVSI) widespread. A DC voltage has been created through a device of energy storage, as discussed in the previous section. A VSI is the source of the conversion of voltage from DC-AC voltage. At the time of sag occurrence, a step-up voltage injection transformer of the DVR power circuit has been used to increase the magnitude of voltage. So, a minimum voltage value with VSI is enough.

3) PASSIVE FILTERS

The use of low passive filters in this method in which the PWM inverted pulse waveform converted into a sinusoidal waveform. In VSI for the achievement of this conversion, it is compulsory to remove high-value harmonic components while DC-AC transformation, and it will also change the compensated output voltage. A passive filter is an essential source in voltage inverter. That is why it uses either on the side of low voltage like the inverter side of the injection transformer and side of high voltage like load side, as shown in Figure 5.

If we put the filters on the inverter side, it can overcome maximum value harmonics from passing through the voltage transformer. So, the stress on the injection transformer is also decreased by it. When the filter is placed in the inverter side and causes phase shift and voltage drop in inverted, that is the disadvantage of the filter. Thus, by putting the filter on the load side, this problem can be solved. The secondary side of the transformer permits the high valued harmonics currents because the transformer with high values is necessary.

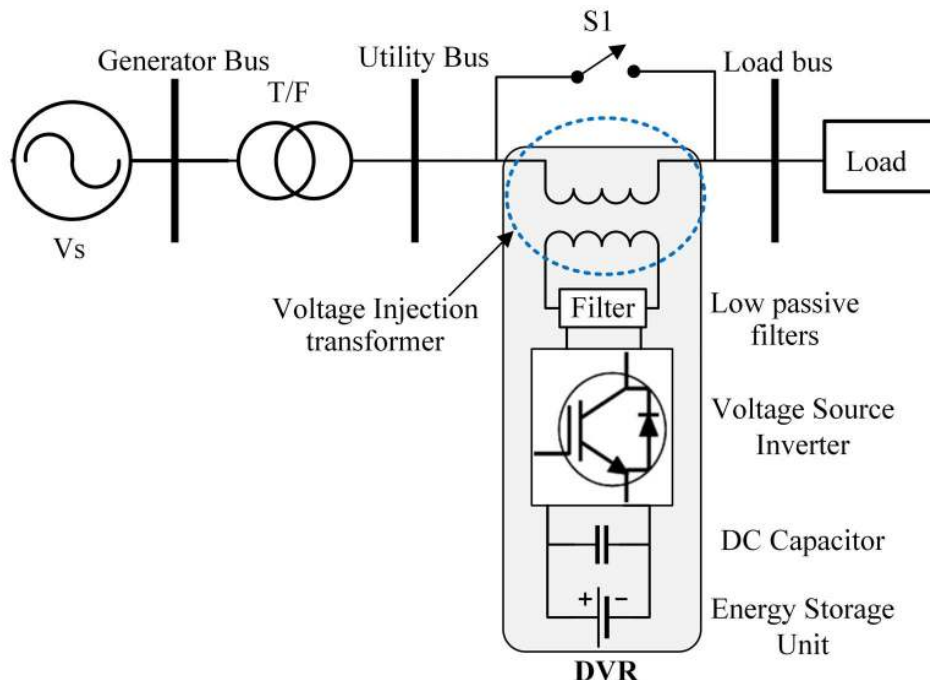


FIGURE 4. Basic Configuration of DVR.

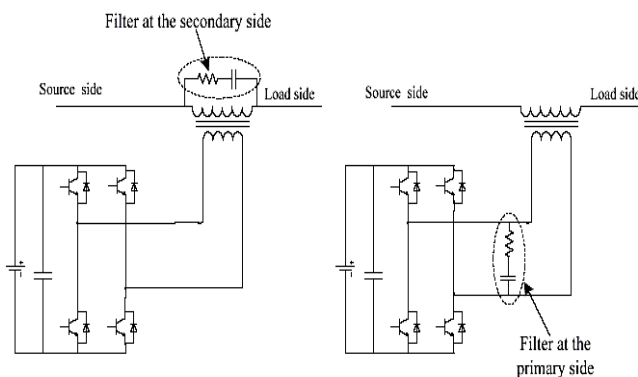


FIGURE 5. Different filter placements in DVR [15].

4) BY-PASS SWITCH

DVR is a series-connected device. The current pass through the inverter if the fault exists in the downstream causes a fault current. For the protection of the inverter, the By-pass switch is being used. Commonly, to bypass the inverter circuit, a crowbar switch is used. Whenever the current is in the range of parts of the inverter, the crowbar would detect the scale of the current and deactivate it in the end. On the other side, it will allow bypassing the components of the inverter if the current is high [15].

5) VOLTAGE INJECTION TRANSFORMERS

There are two sides of the voltage injection transformer, as one is the primary side linked with a distribution line in a series. The other one is the secondary side that is connected with the power circuit of DVR. For the three-phase DVR, one 3-phase transformer or three single-phase transformers

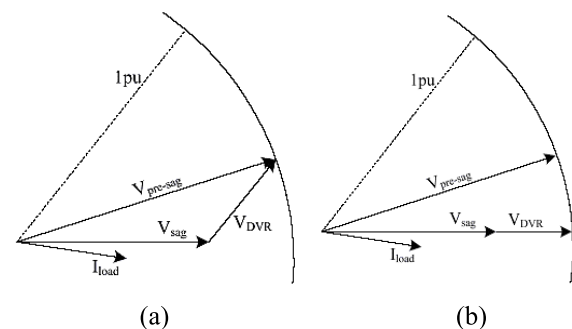


FIGURE 6. (a) Pre-sag compensation techniques, and (b) In-phase compensation techniques.

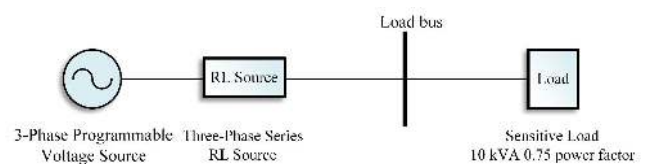


FIGURE 7. Single line diagram of test system without DVR.

could be used, but for one phase DVR, only one single-phase transformer is allowed. The “Delta-Delta” type connection is being used at the time of contact between 3 phase DVR and three single-phase transformers [31].

Usually, the amount of voltage that is supplied by the filtered VSI output to a needed range also simulates the DVR circuit from the transformation network caused by the setup transformer. According to the required voltage at the secondary side of voltage, the pre-examined and significant values are winding ratios. The parts of inverter circuits are affected by the high cost of winding ratio with high-frequency

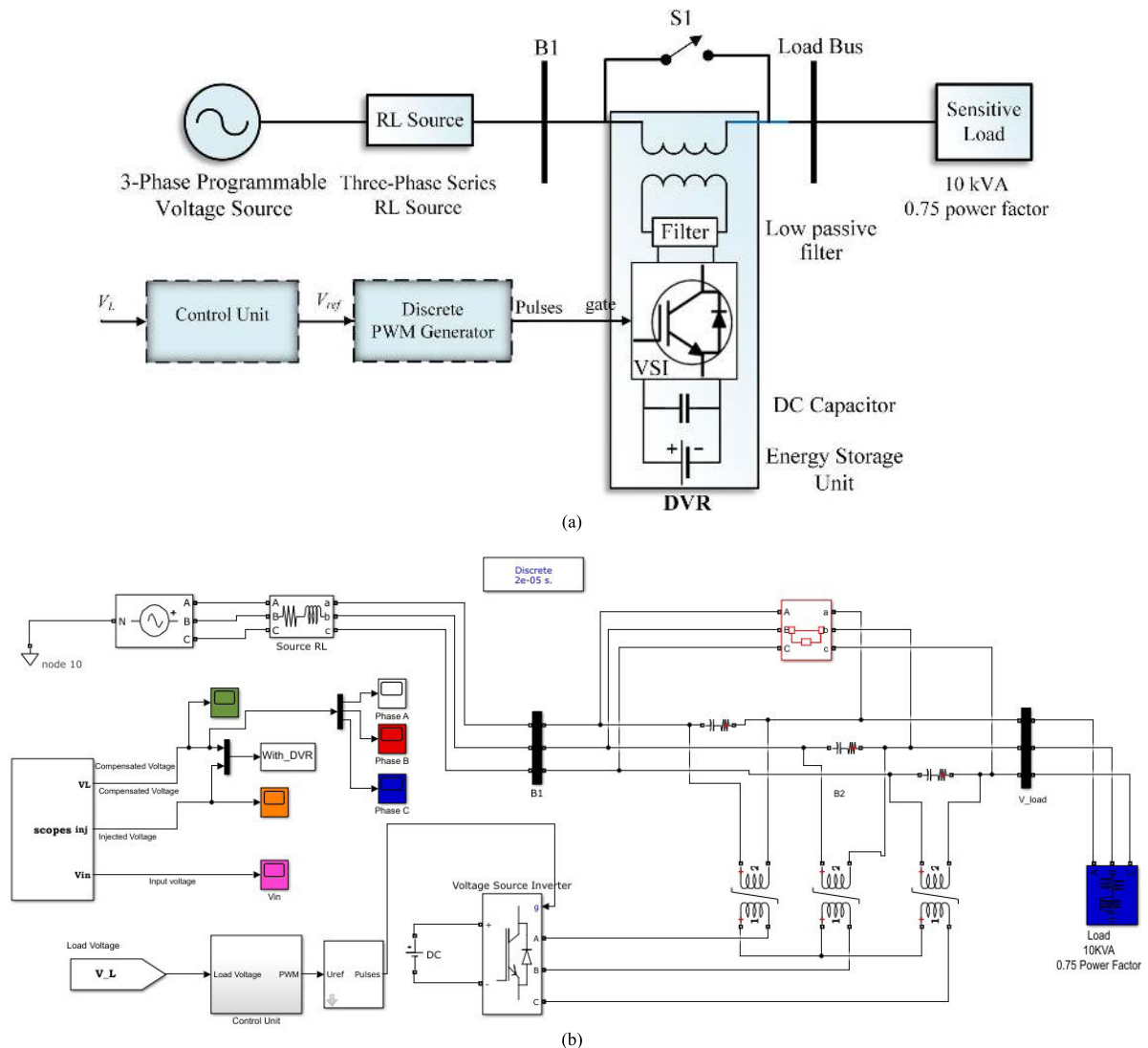


FIGURE 8. (a) Single line diagram of test system with DVR (b) Simulink model of the test system with DVR.

TABLE 2. Parameters and values of test system.

Parameters	Values
Supply Voltage	415 kV
Frequency	50 Hz
Load Power Factor	0.74
Converter	IGBT (3arm-6 pulses)
Load active power	7.5 kW
Load reactive power	6.6 kVA

currents—the primary side current with high-frequency ratios of high windings that could affect the parts of the inverter circuit. The value of the transformer is an important reason when determining the working efficiency of the DVR. The significance of the winding ratio of the injection transformer

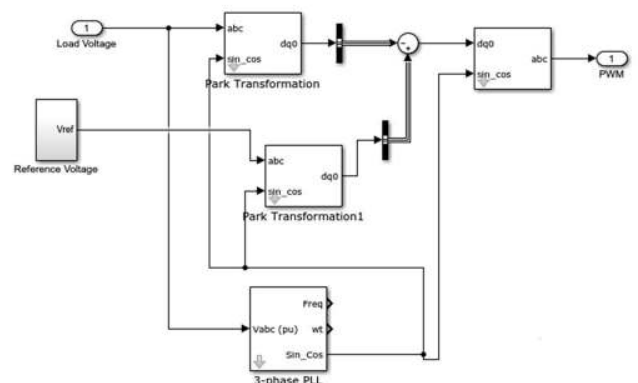


FIGURE 9. Schematic of control circuit for DVR.

concerns on the upward distribution transformer. If there should arise an occurrence of a Δ -Y association with the grounded unbiased, there won't be any zero-grouping current streaming into the auxiliary during an unbalance

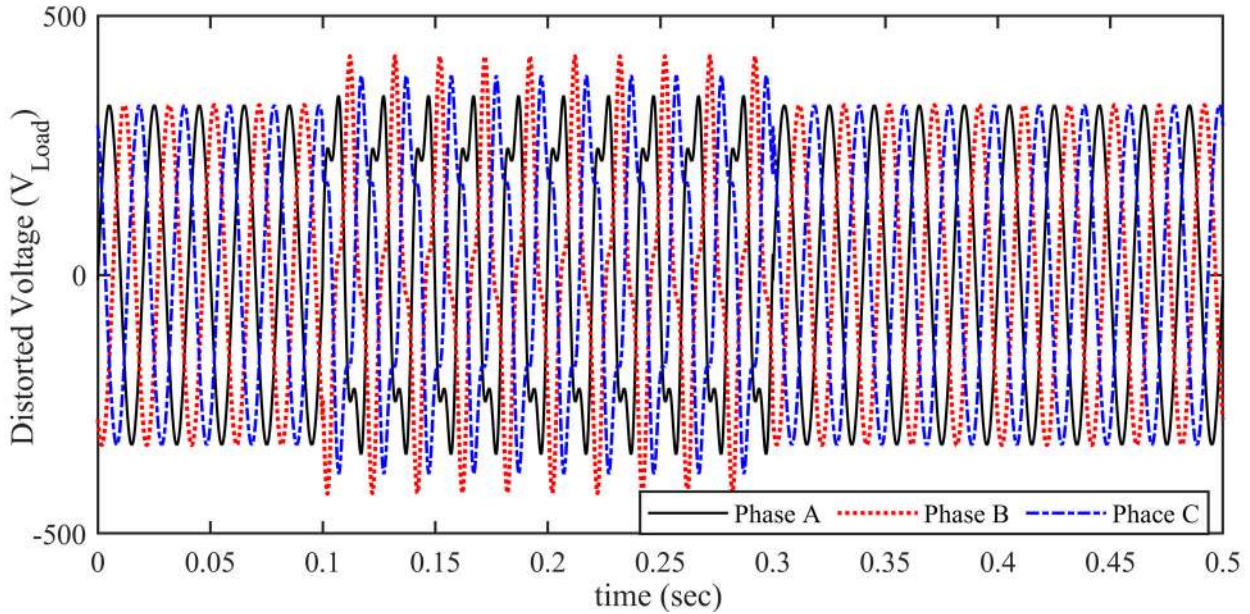


FIGURE 10. Distorted signal (VLoad) in test system without DVR (Scenario 1).

TABLE 3. THD% of test system with and without DVR.

Phases	Scenario 1 THD (%)		Scenario 2 THD (%)	
	without DVR	with DVR	without DVR	with DVR
Phase A	18.49	2.69	22.56	4.06
Phase B	18.49	2.40	22.56	3.55
Phase C	18.50	2.69	22.57	3.74

deficiency or an earth shortcoming in the high voltage side. In this manner, just the positive and negative arrangement segments are rewarded by the DVR [32].

C. OPERATING MODES

1) A VOLTAGE SAG/SWELL ON THE LINE

The energy sources elements are used to supply the store power and use reactive energy to inject the power in DVR when there is variance among the pre sag voltage and the sag voltage. The maximum capacity of DVR is constrained as a result of the estimations of putting away DC energy and the ratio of voltage insertion transformer. In the circumstance of 3 single-phase DVRs, the degree of the injected voltage can be estimated individually. The injected voltages are being composed as comparable frequency and phase angle with the system voltages [33].

2) IN NORMAL FUNCTIONING

DVR would not inject voltage to the load when there is no sag presence during the normal process. The device will run in self-charging means or as standby means if the power storage device is ultimately charged. There are various sources of

self-supply for which the device of energy storage could be charged.

3) A SHORT CIRCUIT OR FAULT

A bypass switch will be simulated during the downstream movement of the distribution line, and to prevent the inverter's electric parts, it will bypass the inverter circuit [15].

D. COMPENSATION TECHNIQUES

1) PRE-SAG COMPENSATION

It is a process that is used for the nonlinear loads, for example, thyristor-controlled drives. The compensation of phase angle and magnitude of voltage is done in nonlinear loads. The method of pre-sag compensation is presented in Figure 6 (a). For this method, a voltage injection transformer and an energy storage device with high value is required.

2) IN-PHASE COMPENSATION

The in-phase compensation method is used for the active loads. There is a requirement of compensation only for voltage magnitude but not for phase angle compensation. The voltage in compensated form is in phase with sagged voltage in this method. For the compensation and support of DVR in terms of power storage devices, the process is suggested in Figure 6 (b), it is used when both the real and reactive powers are required.

IV. GRAPHICAL RESULTS AND DISCUSSION

Simulations are performed on Intel (R) Core(TM) i5-7200U @ 2.5 GHz and window 10 operating system. MATLAB/Simulink software environment is adapted to perform the analysis of the proposed setup.

The load of 10 kVA with 0.75 power factor is considered as a sensitive load. The sensitive load is supplied by the

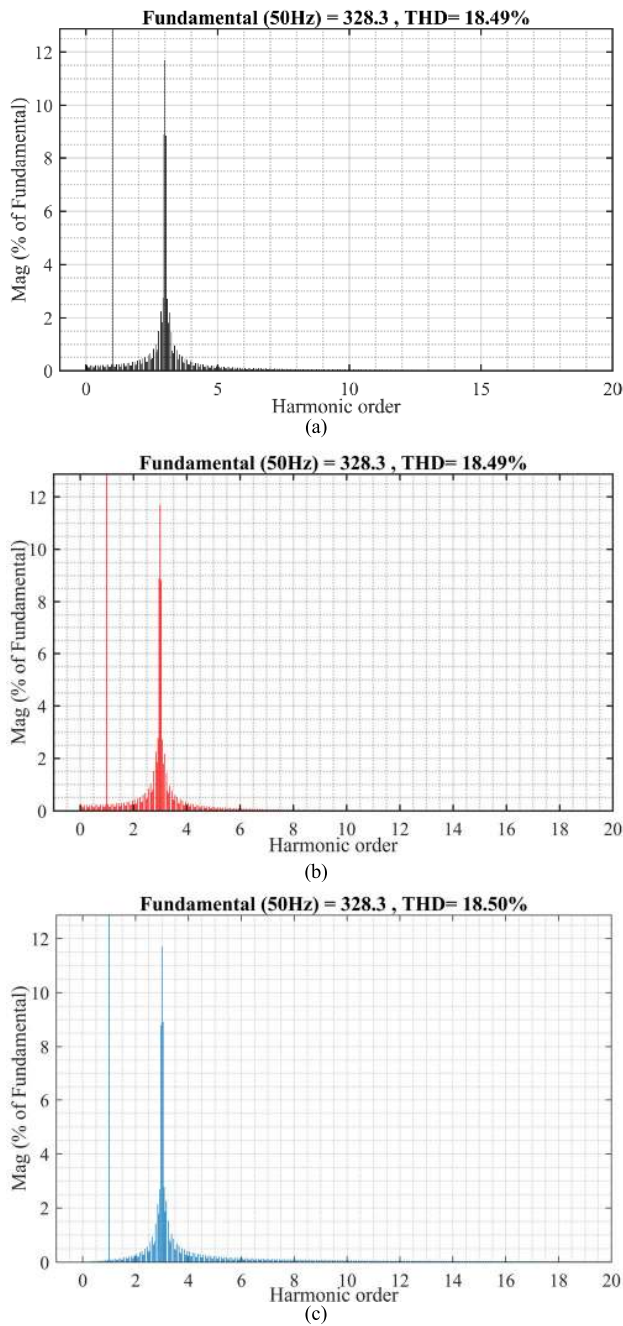


FIGURE 11. Without DVR (Scenario 1): (a) THD in Phase A (b) THD in Phase B (c) THD in Phase C.

415V load and 50Hz frequency to a 3-phase supply system. The single line diagram of the test system without DVR is shown in Figure 7. It shows that the test system contains a Three-Phase, a programmable voltage source, an RL source, and a sensitive active and reactive load is connected with it. Table 2 below is presenting the parameters and the values of the testing system. Throughout this chapter, a convention of black, red, and blue is adapted for all three phases and with the same line design.

The simulation was conducted with a 3-phase test system without a DVR connected with sensitive loads in

MATLAB/Simulink and then a proposed DVR model with the power system in Simulink is presented in Figure 7. The simulations were conducted with a 3-phase test system with and without a DVR connected with sensitive loads in MATLAB/Simulink. The single line diagram of the test system and DVR are shown in Figure 8 (a), and its Simulink representation is also illustrated in Figure 8 (b).

A. INTERNAL CONTROL OF DVR

For control purposes, the different parameters and internal control of DVR, as shown in Figure 9, are simulated in the MATLAB/ Simulink. At the normal level of the supply voltage, to provide the lower number of losses in the conversion circuits, the DVR should be controlled in the transformer and the filtering circuits. When the voltage unbalance, or distorted voltage is detected in the system, then the required injected voltages are supplied to the test system through the installed DVR. Depend upon the voltage (V_{ref}), the instantaneous value of the supply voltage (V_{supply}), the whole process is accomplished by the feedback control technique.

The reference voltages (V_{ref}) are extracted by the control algorithm from the supply and the load voltages when the gate pulses provide the VSI to regulate the load voltage at the control algorithm's reference voltage.

In this step, the detection of the voltage distortion, including voltage sag and voltage swell, can be done by calculating the problems among the dq-frame voltages of the load voltage (V_{Load}) and the reference voltage (V_{ref}). The abc frame is converted into the $\alpha\beta$ -frames by connecting of the load voltage to a transformation block.

The reference voltage will generate the gate pulses by equating the reference voltage (V_{ref}) with that of the load voltage (V_{Load}) in the case of any detection of the voltage swelling or sag and these pulses received by the VSI and by using the pulse width modulation (PWM), the preferred voltage will be formed in a way to maintain the load voltage at the (V_{ref}) or reference voltage, i.e., 330V.

1) MATHEMATICAL MODEL FOR OPERATING PRINCIPLE OF PROPOSED DYNAMIC VOLTAGE RESTORER

The power (active) that load absorbed is as follows:

$$P_L = V_L I_L \cos \theta \quad (1)$$

While if the active power of the DVR is given,

When DVR gives active power,

$$P_{DVR} > 0 \quad (2)$$

When active power is taken by DVR

$$P_{DVR} < 0 \quad (3)$$

When the active power is not exchanged.

$$P_{DVR} = 0 \quad (4)$$

$$\theta_r = \theta_l + \theta_s - \cos^{-1} \left(V_L \cos \theta_L / V_S \right) \quad (5)$$

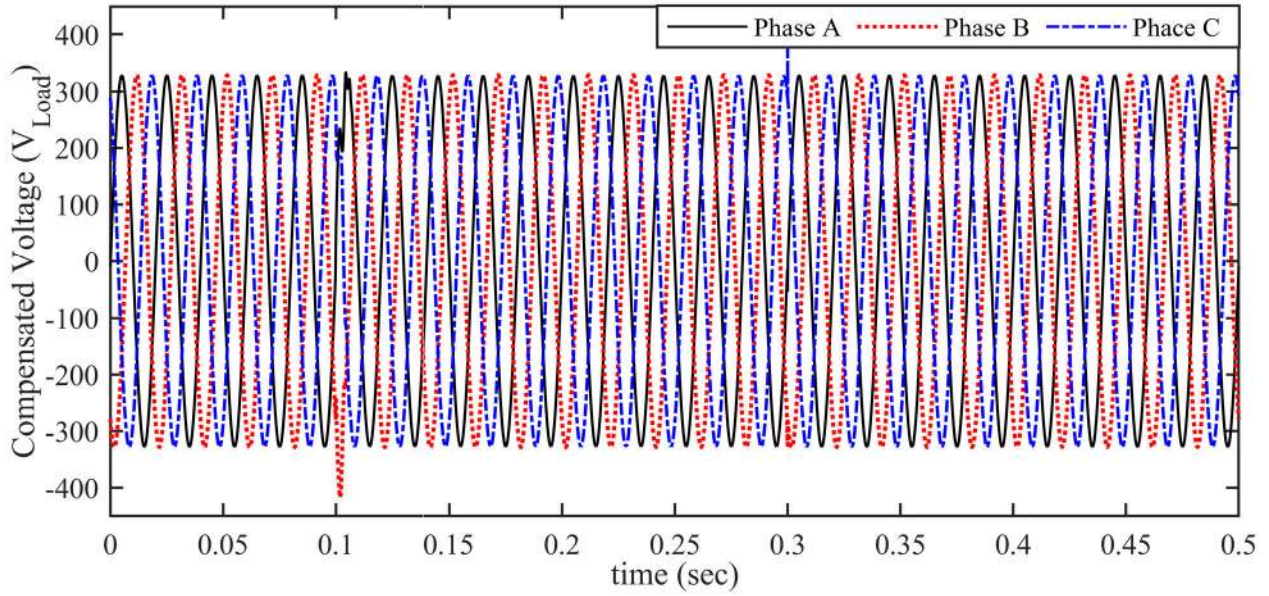


FIGURE 12. Compensated signal (V_{Load}) in test system With DVR (Scenario 1).

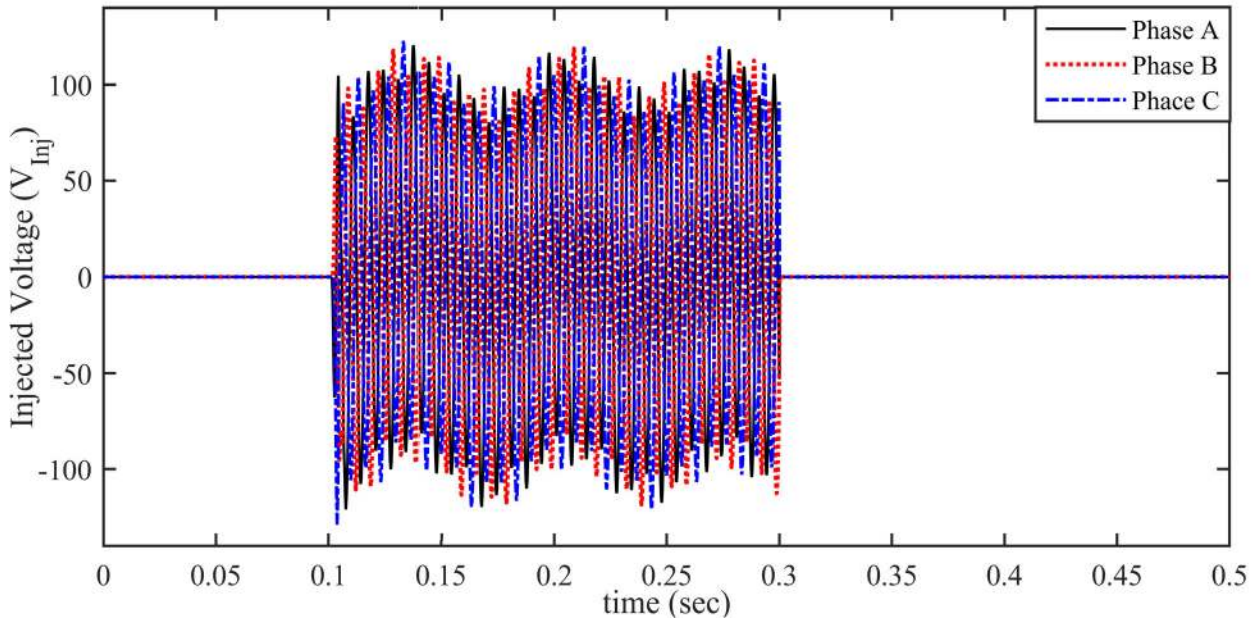


FIGURE 13. Injected voltage (V_{inj}) by DVR in all three phases (Scenario 2).

where, $V_S > V_L \cos \theta_L$, this condition should be satisfied. By ignoring the limitations of the voltage, the exchange of active power for the voltage swell is zero. But in the circumstance of the voltage sag, the active power is supplied by the equipment, and if the voltage sag has a magnitude that is very deep that it could not satisfy the condition, thus injection voltage is as follows. able

$$V_{INJ} > \sqrt{V_s^2 + V_L^2 - 2V_s V_L \cos(\theta_s - \theta_L)} \quad (6)$$

The three-phase injection transformer is used to connect the DVR system to that of the test system's transmission line.

The control circuit of the DVR is used for the amplification of the pulses and produced by the PWM. Then through the transformer, the injected of the voltage in the transmission line occurs.

B. SCENARIO 1: INJECTION OF 3rd HARMONIC

In scenario 1, the 3rd harmonic voltage is inserted into the supply voltage programmable source. The 3-phase sensitive loads are connected with this distorted supply and examined with this distortion in all three phases. Figure 10 shows that the insertion causes a distortion in voltage profile,

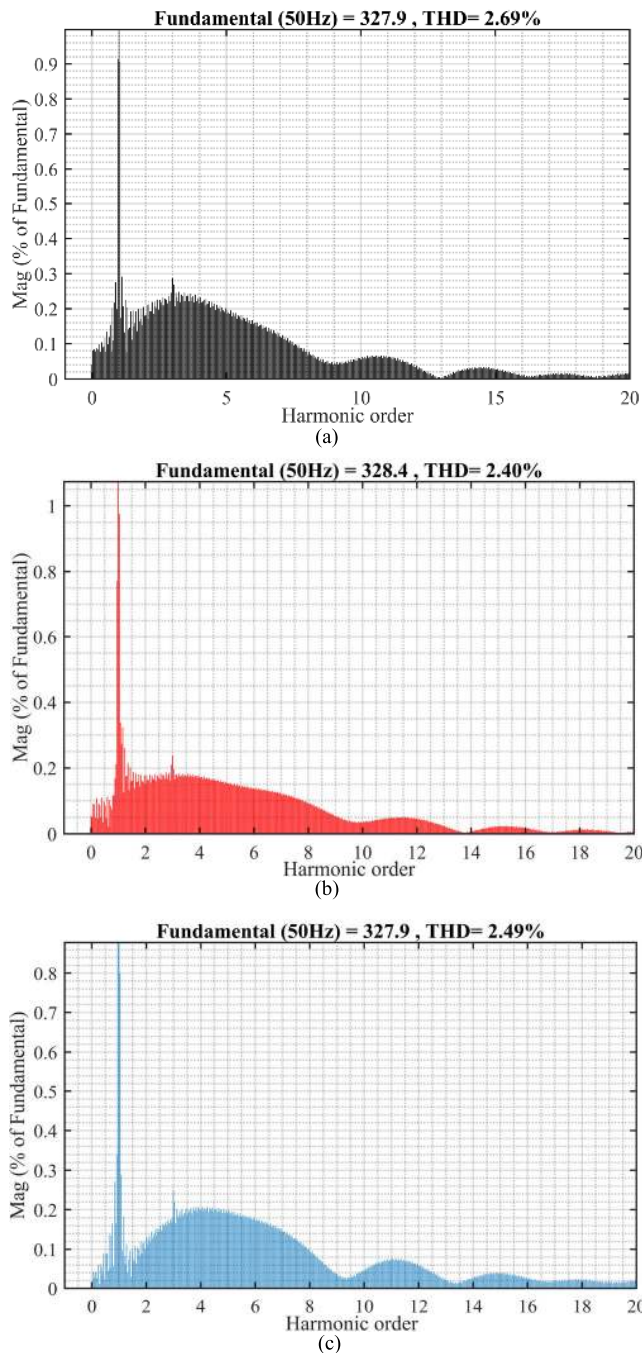


FIGURE 14. With DVR (Scenario 1): (a) THD in Phase A (b) THD in Phase B (c) THD in Phase C.

and load voltage has observed a distorted voltage (V_{Load}) with a disturbing waveform, and some swell in it. The VRMS phase to phase peaks reaches to near 460 V magnitude in voltage profile. The disturbance in the voltage profile may lead to failure or malfunctioning of sensitive equipment.

The THD distortion is calculated for all the three phases and shown in Figure 11 (a), (b), and (c). The impact of THD is lessening the quality of power as phase A (18.49%), phase B (18.49%), and phase C (18.50%) having a high THD because

of distortion of load voltage (V_{Load}). The THD graphs show that the signal has almost 11.5% of 3rd harmonic content in it. As the same magnitude of 3rd harmonics is inserted in the system; therefore, all the phases have shown almost similar THD with almost similar harmonics in it.

Such systems are not accepted because they are not according to the IEEE standards. Referring to the IEEE standard 519 to 1992, the THD rate must be 5% less than the fundamental frequency. The value of THD is way over IEEE Standards. Thus, the disturbance in the voltage source is mitigated by the inclusion of DVR.

To maintain the THD distortion under the IEEE limit and improve the power quality, DVR with a control system is implemented. The load voltage with DVR, along with the control system, is shown in Figure 12. The compensation in the load voltage (V_{Load}) can be seen in all three phases of voltage. This is accomplished with the automatic connection, and the injection of the voltage occurs when the breakers of the circuit open in the presence of the DVR. A significant reduction is seen from $t = 0.1$ to 0.3 sec for the voltage swell as well as the high magnitude of harmonics is removed, and voltage profile is back to normal in all the three cases with a slight flicker at 0.1 sec or 0.3 sec only. A smaller spike has been observed at 0.1 and 0.3 sec. To maintain the power quality, DVR has injected the voltage into the distribution line, the injected voltage for all three phases are shown in Figure 13.

The DVR used the electronic device, transistor, and diodes to protect from the error, convert voltage from AC to DC, correct the voltage in load, and control the flow of the power. Then during operating, the generation of the harmonics takes place through the inverter that is PWM. Then the small amount of effect will occur on the load the supply of the utility, reduction in the harmonics occur. Later in the power system, the filters of the harmonics are used to resolves the above issues.

$$THD = \sum_2^{\infty} C2K/C1 \times 100\% \quad (7)$$

The above equation shows that the $C1$ is considered the essential component magnitude, where the harmonic component magnitude is the Ck (where k is $2, 3, 4, \dots$). Then, for the sensitive loads, the THD's value must be put just below the 5 percent in the power system; to produce the low frequency in the harmonics' constant frequency, the passive filters like the LC filters are used. If the harmonics' frequency is inconsistent and frequencies are different, then the active filters are used to compensate for this.

Figure 14 (a), (b), and (c) shows the THD of the compensated voltage by DVR; the percentage THD has reduced to 2.69%, 2.40%, and 2.49%. This shows a significant improvement in the voltage profile and a reduction in harmonic content in the load voltages.

C. CASE: 2 INJECTION OF 5th HARMONIC

In scenario 2, the parameters of the programmable voltage source are changed with 5th harmonics insertion.

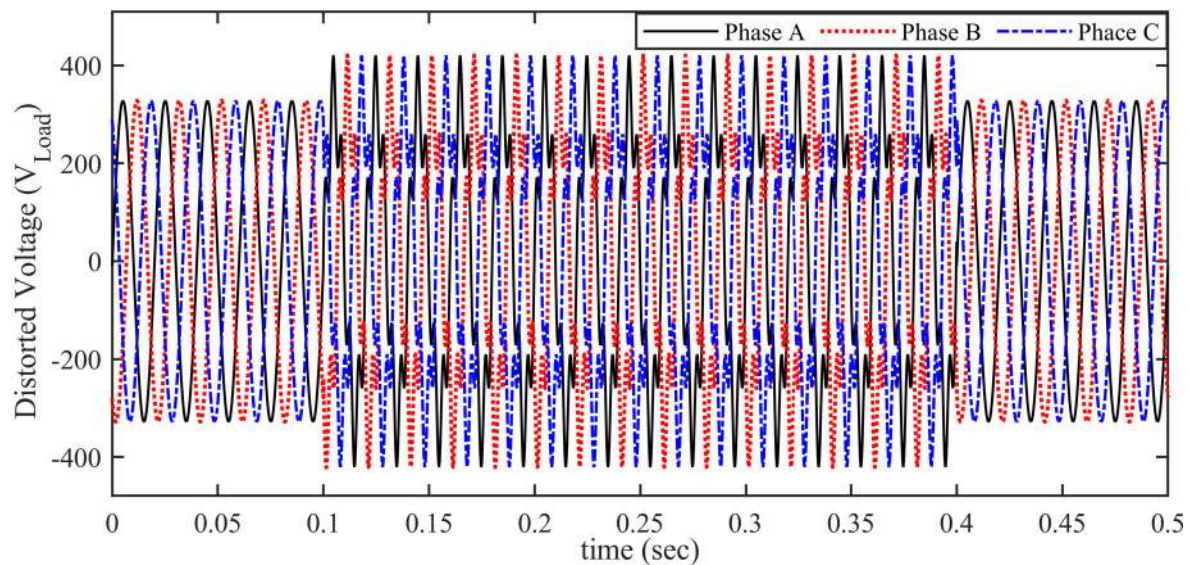


FIGURE 15. Distorted voltages (V_{Load}) profile without DVR (Scenario 2).

The duration of change in supply voltage was set to 0.1 sec to 0.4 sec in this scenario. It has also resulted in a distorted voltage waveform with almost identical shapes for all three phases, as shown in Figure 15.

The distortion in the wave shape is more in this scenario; however, voltage peaks are less as compared to the previous case. The THD percentage is shown in Figure 16 (a), (b), and (c), which was around 22.56%, 22.56%, and 22.57% for phases a, b and c, respectively. The THD profiles show that the load voltage waveform has 17% of 5th harmonic content in it. Therefore, it has resulted in more than 22% of THD.

Fig. 17, shows the compensated voltage for the scenario 2, it depicts that only a slight distortion comes at 0.1 seconds and after that When DVR is installed on the power system, it is concluded that in Figure 18 (a), (b), and (c) of the THD, it has been reduced to around 4%. The THD percentage for phase a, b and c are 3.74%, 4.04%, and 3.60%, respectively. The injected voltage by the DVR are shown in Figure 19. The comparison between both scenarios and their THD is presented in table 3.

Most of the world has done work on DVR, and mostly it is for power plants and grid stations. Authors have worked on low voltage distribution lines for controlling voltage fluctuations (sag and swell and harmonics), which is a significant issue in the textile, surgical, and paper industry in Pakistan. All the requisite conditions of DVR are applied according to the requirements of different sectors in Pakistan. Without DVR, THD is almost constant as the significant portion of THD as the input magnitude of inserted harmonics is kept the same for all the phases. When DVR applied, the distorted voltage is minimized, and as the DVR is involved at different phases having different angles with a 120-degree phase shift so the values will differ in THD due to this change of angle, which is prominent after applying DVR.

D. IMPLEMENTATION OF DVR FOR GEPCO SUBDIVISION

Due to these advantages of DVR, a proposal for three DVR systems for the Distribution side at Gujranwala Electric Power Company (GEPCO) subdivision at Sialkot is submitted. This scheme can overcome the undesired voltage sags, swell and harmonic distortion at Sambrial, GEPCO subdivisions Sialkot, to mitigate these problems output. These problems mostly occur due to extensive use of low-power factor equipment like motors at industrial zones of Sambrial and Sialkot, which sometimes causes significant voltage sag, swell, and harmonics problems and could not be directly checked without particular types of equipment.

Thus causes issues to the nearby small industries as well as some domestic customers. The complaints about the failure of electrical equipment like Computers, Laptop, and Mobile chargers are common in some areas of the Sambrial subdivision. A feasibility study has been submitted for its implementation at this subdivision by one of the authors.

The need to integrate renewable energy with the exiting grid of Pakistan is key to enhancing its capability to tackle the increasing demand and efficiently manage the energy system in Pakistan [34]–[36]. Therefore, the research focus is mostly on solar PV [37], [38], solar thermal [39], [40], Net zero energy buildings (NZEB) [41], [42], combined heat and power systems [43], and low global warming impact based on technologies and natural cooling refrigerants [44]. FACTS devices like Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) on its 500 kV and 220 kV high transmission lines [45], [46] and devices like D-STATCOM and DVRs at the distribution level [47]. NTDC is operating sixteen 500 kV and forty-five 220 kV HVAC lines and a grid station. NTDC has already installed an HVDC and connected it with the grid in 2020 [48], [49]. Therefore, the

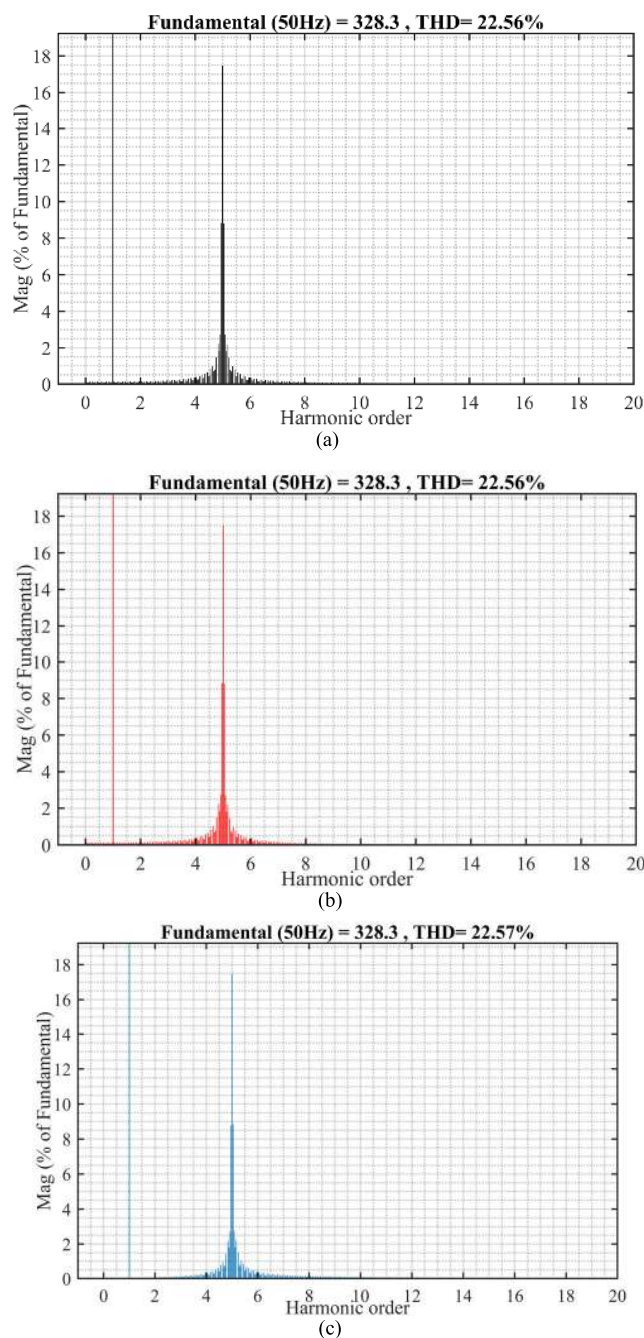


FIGURE 16. Without DVR (Scenario 2): (a) THD in Phase A (b) THD in Phase B (c) THD in Phase C.

Installation of FACTS on existing HVAC lines will definitely increase the capability of these lines. Pakistan cannot only rely on increasing the installed capacity of power systems with the same old power transmission and distribution infrastructure. The transmission capacity should also be improved by adding FACTS devices on the transmission network. This is how electrical utilities can tackle power loss and reactive power compensation in a better way. The installation of FACTS devices requires two types of basic costs; equipment cost and necessary infrastructure costs. The equipment costs significantly rely upon the device's installation rating

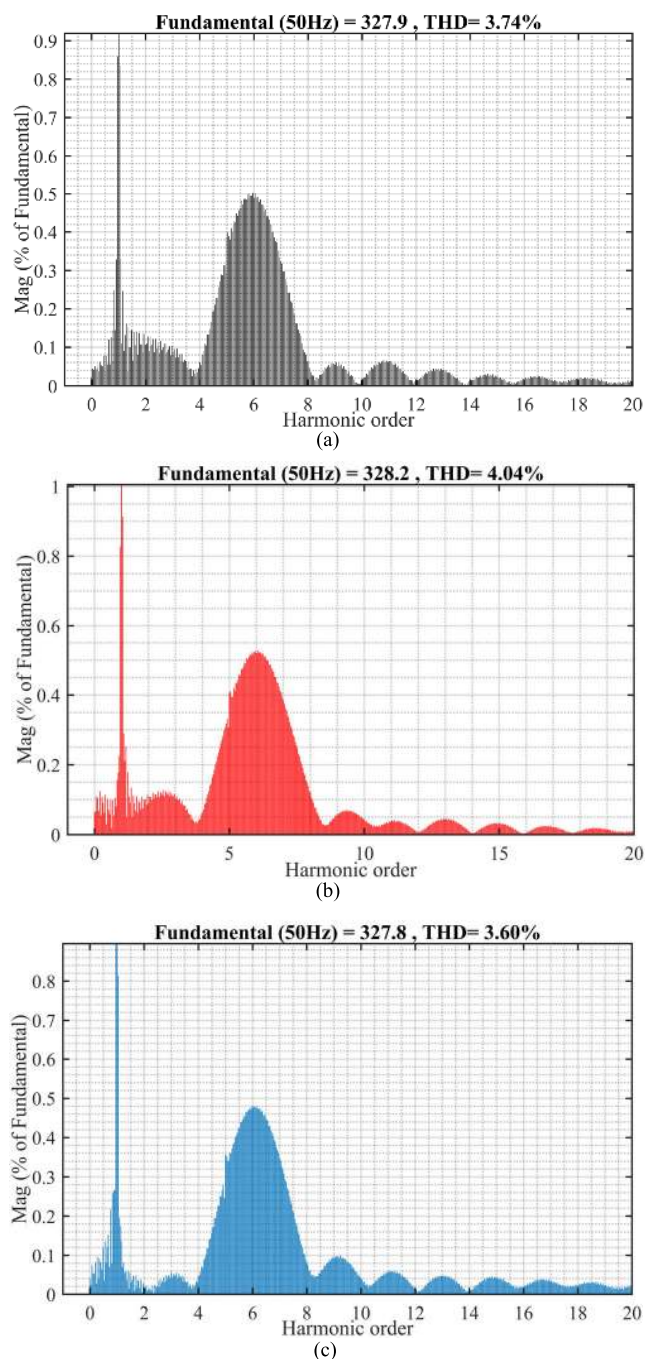


FIGURE 17. With DVR (Scenario 2): (a) THD in Phase A (b) THD in Phase B (c) THD in Phase C.

just as it additionally relies upon other specific necessities like; excess of control and assurance hardware, surrounding conditions, seismic conditions, and correspondence with the substation control framework. The foundation cost relies upon the area at which FACTS should be installed. It comprises of land securing, change in the current substation, development of working for indoor control hardware (insurance thyristor valve, other equipment, and battery banks, and so on.), civil works, and associating the correspondence framework.

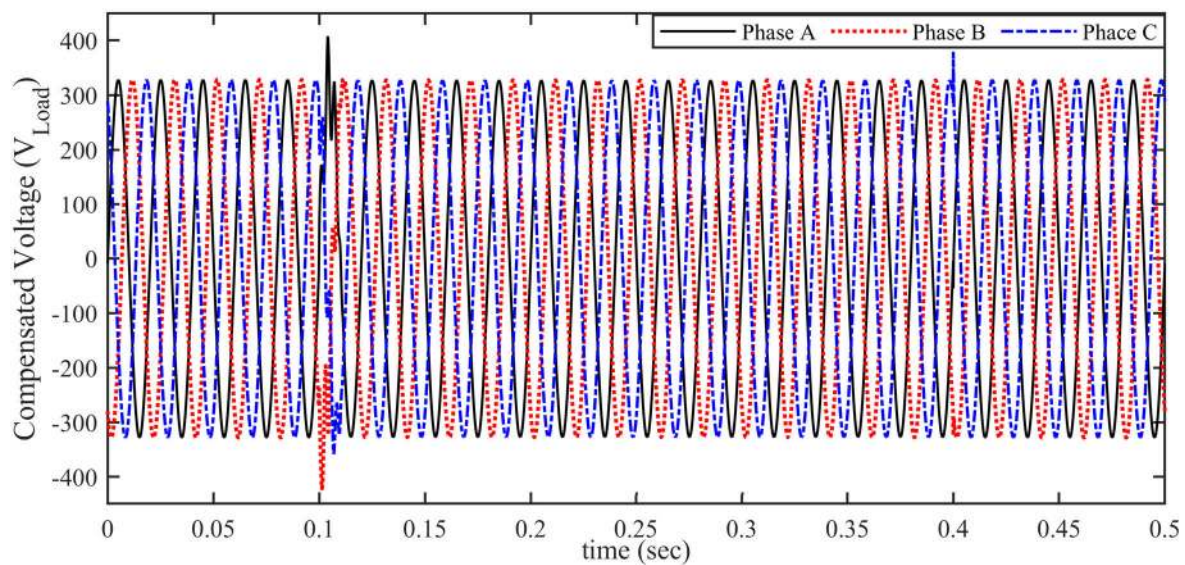


FIGURE 18. Compensated voltages profile with DVR (Scenario 2).

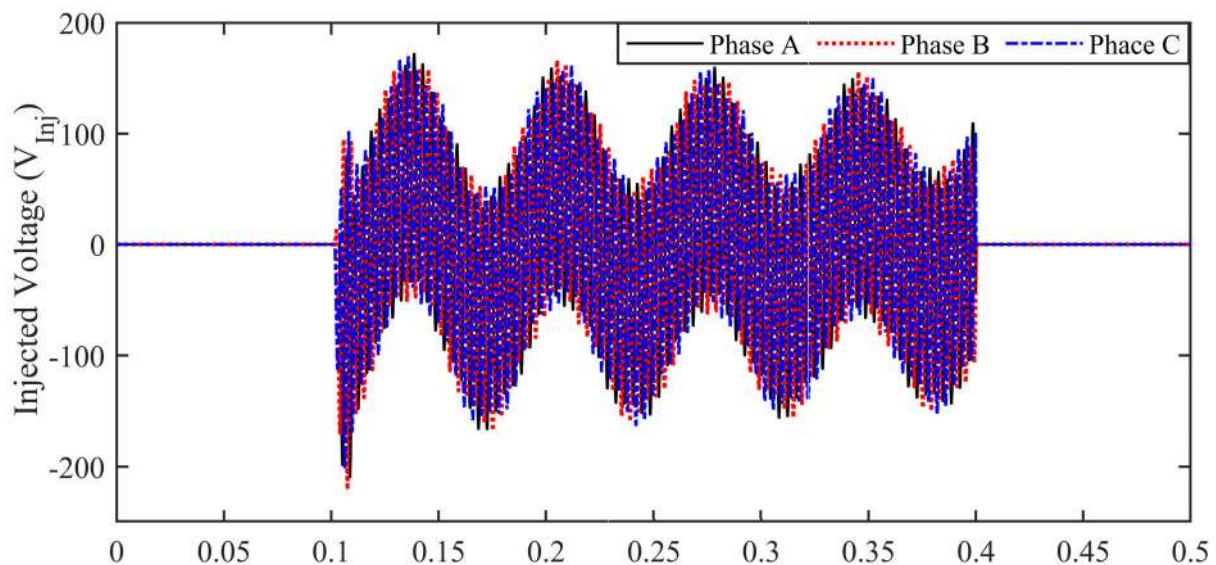


FIGURE 19. Injected voltage by DVR in all three phases (Scenario 2).

Similarly, on the distribution side, DVR is very beneficial in LVRT reduction, voltage and frequency control, reduction in voltage sags, and voltage swells. Some modern algorithm is used which are shown in Table 1 like NAC, using a tap changing transformer PI controller and many others. A DVR based PI controller is used with renewable power sources. It mitigates the problems like distortion in the waveform, current, and voltages [50].

V. CONCLUSION

DVR is proposed as the most noteworthy device to enhance the quality of power and proved to be a useful and well-performing device. Through the platform of MATLAB/Simulink, a simulation of DVR with a power circuit is carried out by structure and modeling of the control circuit and

power system with a sensitive load. The DVR is implemented with the test system and investigated with and without DVR. A programmable voltage source is used to supply a distorted voltage with first with 3rd harmonic content and then with 5th harmonic insertion in the supply voltage. The proposed DVR based control strategy was effective in compensation of the distorted load voltage and maintained a better steady and smooth voltage profile with very less harmonic content in it. To maintain the load voltage normal and steady at the optimal range, the correction of any problem in voltage supply is possible when the DVR injects the suitable voltage component into it. While maintaining the compensation of voltage profile, the THD was reduced to around 4%. Like for scenario 1, the observed THD with DVR case was 2.69%, 2.40%, and 2.69%, and for scenario 2, there were 3.74%,

4.04%, and 3.60% THD in the voltage profile. This improvement and reduction in the THD in load voltage explain the effectiveness of the DVR based control strategy used in this work.

The application of control strategy based on soft computing like adaptive NeuroFuzz controllers for power quality improvement is a promising future perspective of this research. Authors have already implemented Type-2 Neuro-Fuzzy controls for enhancement of power system stability using STATCOM.

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