POWER QUALITY IMPROVEMENT USING DYNAMIC VOLTAGE RESTORER

Project report submitted to,

College of Engineering and Technology, Bhubaneswar
in partial fulfilment for the degree
of

Bachelor of Technology
in Electrical Engineering

by

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COLLEGE OF ENGINEERING AND TECHNOLOGY, BHUBANESWAR

CERTIFICATE

This is to certify that the report entitled '**POWER QUALITY IMPROVEMENT USING DYNAMIC VOLTAGE RESTORER'**, submitted by Ms. Aryashree Kajal Priyadarshini (Regd. No.-1601106304), Ms. Sharmila Pal (Regd. No.-1601106364) and Mr. Shashwata Swarupa Sahoo (Regd. No.-1601106366) of the Department of Electrical Engineering, fulfill the requirement of the regulation relating to the nature and standard of the work for the award of the degree of Bachelor of Technology, in Electrical Engineering.

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DECLARATION

We do hereby declare that, the major project report entitled, **'POWER QUALITY IMPROVEMENT USING DYNAMIC VOLTAGE RESTORER'** is a bonafide work of study carried out by us under the guidance of Dr. Ullash Kumar Rout, Associate Professor, Department of Electrical Engineering, College of Engineering and Technology, Bhubaneswar. It has been prepared for the fulfillment of the requirements of the degree of Bachelor of Technology in Electrical Engineering. The work has not been submitted for any other purpose.

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Besides, some technical details enlisted in this report have been taken directly from certain works that have been enlisted in the references provided.

Last but not the least, the timely completion of the project could not have been possible without the moral support extended by our families, friends and the blessings of the Almighty.

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ABSTRACT

With the recent developments in the power sector accompanied by the advancement in semiconductor devices, increase of non-linear loads and rapid growth of renewable energy sources, the power quality has been affected significantly. A decisive factor for the determination of power quality is voltage. Voltage sags and voltage harmonics are the most common causes of the power quality disturbance. Voltage sags occur due to sudden changes in the load or due to faults or short circuits and harmonics are introduced due to the presence of non-linear loads and voltage sensitive loads. Decrement in the voltage level increases transmission losses thus reducing the efficiency of the system and thereby resulting in poor power quality. The poor power quality adversely affects the performance of the whole power system and may damage the various components.

The primary objective of this project entitled 'Power quality improvement by using dynamic voltage restorer' is to mitigate the voltage sag. For this purpose, the FACTS device Dynamic Voltage Restorer (DVR) has been implemented. In order to eliminate the harmonics, RLC filter has been designed and introduced along with the DVR. From the operation point of view, a controller has been designed by cascading the PI controller and Park transformation for the successful mitigation of voltage sag. In this project modeling, analysis, and simulation of DVR has been completed in MATLAB-SIMULINK (vR2017b) software. The variations in voltage and THD has been observed with and without implementation of DVR. The DVR works independent of type of fault or any other event provided that the system is connected to supply. The DVR is one of the most efficient and effective modern custom power devices used in power distribution networks. It is advantageous over other techniques of power quality improvement as it has lower cost, smaller size and fast-dynamic response to the disturbance. It requires less power to operate, thus reduces power consumption.

SYMBOLS AND ABBREVIATIONS

- RMS – Root Mean Square
- PU – per unit
- DVR – Dynamic Voltage Restorer
- SVB – Series Voltage Booster
- SSC – Static Series Compensator
- PCC – Point of Common Coupling
- V_L – Desired Load voltage
- I_L – Load current
- Z_L – Line Impedance
- V_S – Source voltage
- S_{DVR} – Apparent power of DVR
- V_{DVR} – Injected DVR voltage
- P_{DVR} – Active power of DVR
- UPS – Uninterrupted Power Supply
- SSTS – Solid State Transfer Switch
- SMES – Superconducting Magnetic Energy Storage

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CHAPTER 1

INTRODUCTION

The electrical power system is the main area of concern now-a-days. The power quality and continuity of supply is very essential for economic power supply. Reduction in power quality has been due to increased use of power electronic devices and non-linear loads. Different issues related to power quality are: voltage sag, voltage swell, voltage interruptions, transients and harmonic contents. These problems cause degradation of efficiency and shorten the life of end user equipment.

Due to the complex electrical network voltage sag is the major factor for power quality issues and it adversely affects the power distribution and the equipment. Voltage sag is due to sudden connection of heavy loads, fault in the system or due to sudden short circuit phenomenon. Voltage sag is more common as compared to voltage swell. Voltage sag can cause improper functioning and eventual tripping of electrical equipment, resulting in high transmission losses and hamper the network equipment besides reducing efficiency.

There are two general approaches to mitigate voltage sags. One approach is to ensure that the equipment connected are less responsive to the voltage sag, allowing it to ride-through the disturbance. The other approach is to install a custom power device to suppress or neutralize the disturbances at the customer end. Flexible AC Transmission System (FACTS) devices like Distribution Static Compensator (D-STATCOM) and Dynamic Voltage Restorer (DVR) have been recently developed for voltage sag compensation. In this project, the FACTS device DVR is proposed to protect the voltage sensitive load from any sag condition in the supply voltage. It is a series compensating device, can maintain the load voltage profile even when the source side voltage is distorted.

1.1 Literature review

"Voltage Sag/Swell using Z-Source Inverter Based Dynamic Voltage restorer", proceeding of ICETECT 2011, 978-4244-7926-9/11/$26.00,2011 IEEE [1] proposes the role of DVR for mitigating different power quality issues like voltage sag and voltage swell.

“Mitigation of Voltage Sag and Swell Using Dynamic Voltage Restorer”, International Conference on Magnetics, Machine & Drives (AICERA -2014 iCMMD) [2] describes basic model of DVR and describes different voltage compensation techniques of DVR.

“Simulink Model for Mitigation of Sag/Swell by Dynamic Voltage Restorer using SPWM Technique”, International Conference on Intelligent Sustainable System (ICISS 2017),IEEE Xplore Complaint – Part Number: CFP17M19-ART,ISBN:978-1-5386-1959-9 [4] describes different components of DVR.

“PI Controller and Park’s Transformation Based Control of Dynamic Voltage Restorer for Voltage Sag Minimization”, 9th International Forum on Strategic Technology (IFOST), October 21-23,2014, Cox’s Bazar Bangladesh [5] describes about modelling, analysis and simulation of DVR in MATLAB/SIMULINK.

“Analysis, Modeling and Simulation of Dynamic Voltage Restorer (DVR) for Compensation of Voltage for sag-swell Disturbances”, IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE),[6] proposes different control strategies for DVR and mentions the role of DVR for mitigating different power quality issues like voltage sag and voltage swell.

“Dynamic Voltage Restoration with Minimum Energy Injection”, IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 15. NO. I, FEBRUARY 2000 [8] describes the effectiveness of using dynamic voltage restorer (DVR) in order to mitigate voltage sags and swells in low voltage distribution systems. Dynamic Voltage Restorer can provide the most cost-effective solution to mitigate voltage sags and swells.

“Voltage Sag Mitigation by Dynamic Voltage Restorer”, Vol.- 02 ISSN: 0975- 6736, Nov-12 to Oct- 13 [9] proposes implementation of DVR both at a low voltage level as well as medium voltage level and presents modeling and analysis of a dynamic voltage restorer with sinusoidal pulse width modulation- based controller by using MATLAB SIMULINK.

“Voltage Sag Reduction and Power Quality Improvement using DVR”, 2017 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC), [10] describes different power quality issues, provides the idea about different component of DVR and describes different voltage compensation techniques of DVR.

1.2 **Research motivation**

Within the power system, power quality is a crucial topic. Poor power quality not only affects the consumer, but also the producer along with the supplier, that is, it affects the whole system. Moreover, it also damages the equipment. The various reasons for poor power quality can be voltage sag, voltage swell, harmonics, transients, interruptions, failure of equipment and so on. The major issue is voltage sag and the harmonics that may be introduced due to the presence of non – linear loads. Therefore, the voltage sensitive equipment present in the system is prone to poor power quality. The fluctuation in voltage resulting in power quality may damage the equipment. So, in order to minimize the voltage sag, use of FACTS devices is recommended. Dynamic Voltage Restorer is an efficient FACTS device which is proposed in the project. Previously, DVR has been proposed with various control techniques. Here, for sag detection, PLL method is used and for the control of injection voltage a combination of PI controller and Park transformation is used.

1.3 **Objective of the work**

For efficient and economic operation of a power system it is necessary to maintain the power quality. In order to do so, a primary objective to be fulfilled is to mitigate the voltage sag. The main objectives of this project are:

- Accurate and precise detection of voltage sag in the system
- Mitigate the voltage sag by using Dynamic Voltage Restorer
- Proposing a better control scheme for DVR
- Developing a filter to reduce the harmonics convincingly
- Effective operation of the FACTS device proposed to fulfill the objective

CHAPTER-2

POWER QUALITY ISSUES

The latest developments in the power system leading to the increased usage of non–linear loads have made the network highly complex. The power system faces challenges to deliver quality power to the consumers. Poor power quality not only affects the end consumers and industries only but also the distribution units. It may hamper the equipment at times. Further, this also reduces the efficiency of the overall system and increases the transmission losses. Electric power is affected by many factors at the distribution network which are voltage sags, harmonics in current and voltage, transients and interruptions besides failure of equipment. A few of the above can be compensated to improve the quality of power. The recent growth of interest in power quality can be explained by these four major reasons:

- **Increased awareness of consumers:** The end-consumers are now aware of the power quality issues. Unlike before, the look-forward for the reasons of power cuts and want explanations from the officials. Also, changes in the government policies to control electric usage by setting standards and limits have enabled the consumer to get direct information about the happenings very easily.
- **Voltage sensitive equipment:** Latest power electronic devices have microprocessor-based controls and are highly sensitive to voltage changes than the conventional equipment. These devices are much more efficient leading to their vast usage.
- **Increased emphasis on efficiency:** The concerned electricity boards are now emphasising much more on the efficiency of the overall power system than of individual equipment. In order to achieve the above, highly efficient devices have come to the picture. Shunt capacitors and adjustable-speed motor drives are a few to be named. These have managed to attain the efficiency but have introduced harmonics thereby affecting the individual equipment. Also, threatening the operation, reliability and safety.
- **Distributed Generation (DG)**: To increase the reliability, DGs are being installed in the distribution networks. This increases the complexity of the system. The renewable energy sources like solar and wind are a few DGs. Though the reliability is increased, these systems require complex connections and power electronic devices to operate, thereby introducing uncharacteristic harmonics and affecting the operation at times.

2.1 **Power quality**

Power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment. Power quality concerns about the utility to provide uninterrupted power supply. It is one of the major issues in the power system and becomes very important with use of the sophisticated devices whose performance is very sensitive to the quality of power factor. Power quality is influenced by the quality of service. Supply continuity, magnitude variation, voltage and current transients, harmonics are major parameters that characterise power quality.

- **Active power**

The active power is the actual power that is dissipated in the circuit or does useful work. It is denoted by the capital letter P and measured in watts, kilowatts or megawatts. Torque produced in the motor, heat dissipated in heater and the light emitted by lamps are all because of the active power. The active power is the product of the voltage, current and the cosine of the angle between them and it can be represented by the expression.

$P = VI\cos\emptyset = I^2R$ 2.1

- **Reactive power**

The reactive power can be defined as the unused power in an AC network. It is represented by Q, and measured in volt-ampere reactive (VAR). Presence of energy storage elements like capacitor and inductor are responsible for the reactive power in the system. It is the product of voltage and current and the sine of the angle between them and it can be represented by the expression

$P = VI\sin\emptyset = I^2X$ 2.2

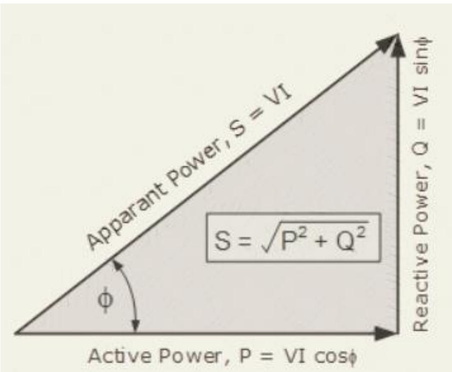


Fig. 2.1: Power triangle

- **Apparent power**

Apparent power is the combination of reactive power and active power. It is denoted by capital letter S and is measured in volt-ampere (VA). When the impedance is a pure resistance, the apparent power is the same as the true power but when reactance exists, the apparent power is greater than the true power. It can be said to be the product of the voltage and current irrespective of the phasor alignment. It is represented by the expression

$$S = VI = I^2Z = \sqrt{P^2 + Q^2} \qquad 2.3$$

2.2 Importance of power quality

The increased usage of power electronic devices, development of renewable resources and introduction of non–linear and voltage sensitive loads lead to generation of characteristic and non-characteristic harmonics which are harmful for the power system.

- If power quality is good then any load connected to the electric network runs efficiently without decreasing its performance.

- If power quality is poor then load connected to the network leads either to the failure of the equipment or reduction in its lifetime and performance.

2.3 Power quality problem

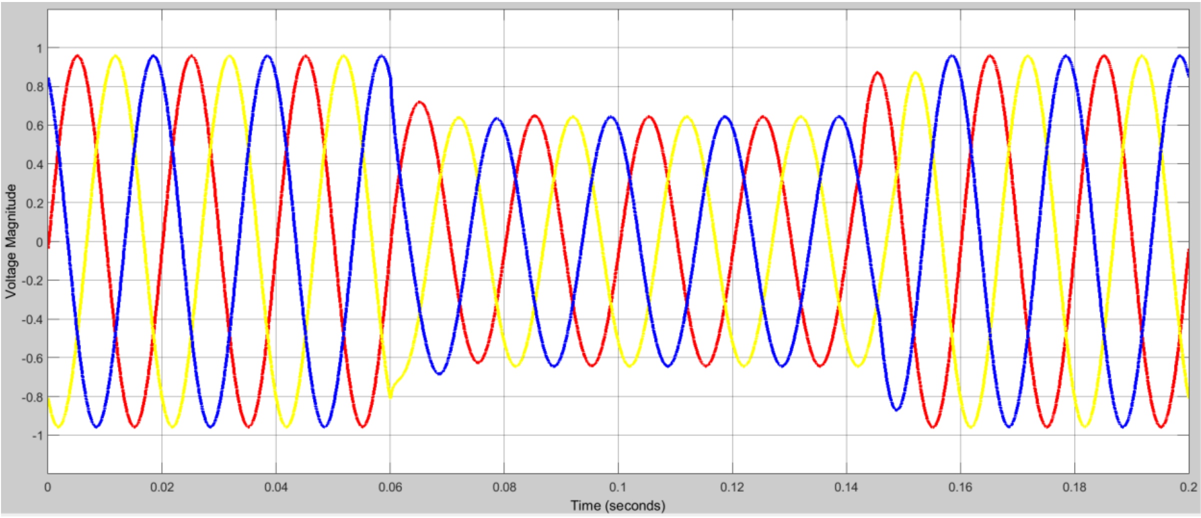
Power quality issues falls into three broad categories.

- **Harmonic voltages and currents** – Most electrical equipment experience harmonic voltage and current that distorts the AC wave form and increases power usage. With the help of harmonic filters or reactors the harmonics are eliminated which increase efficient power usage and cost savings.
- **Poor power factor** – It can be described as excess of reactive power in the system. Power Factor Correction (PFC) eliminates the reactive power, reduce energy costs and stop equipment overheating, tripping and motor failure.
- **Voltage instability**– High or low voltage electricity supplied from the network is the main cause of voltage stability. High voltage does not increase equipment power instead reduces the equipment performance and longevity, and low voltage causes brown outs and decrement on productivity. Voltage optimization ensures the voltage supplied to the system is stable as per the required of the equipment on load side.

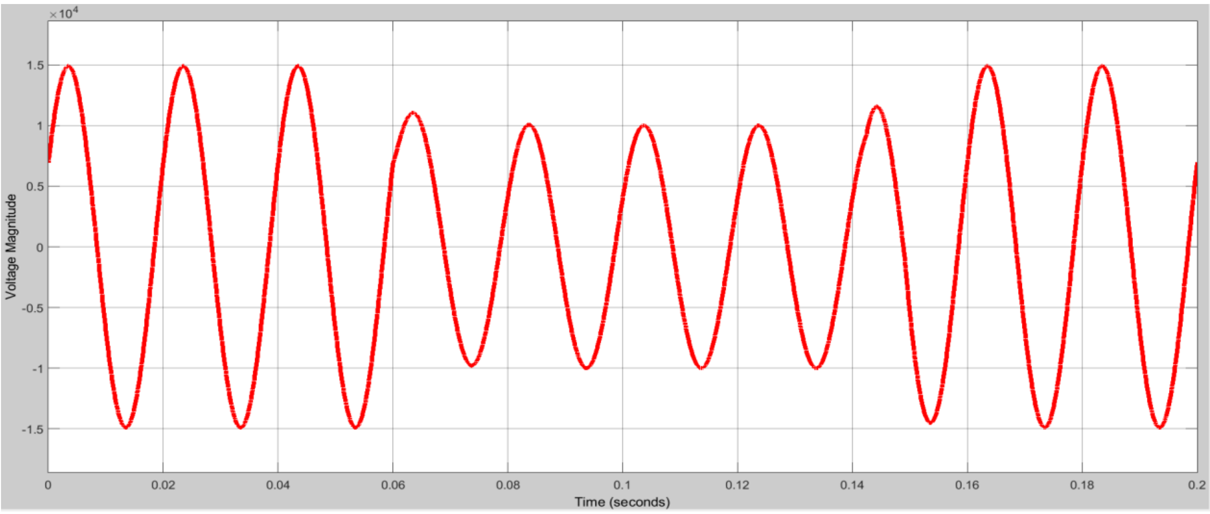
Poor power quality results in economic loss in power system network. Any power problem manifested in voltage, current or frequency deviations that result in failure or maloperation of customer equipment. An overview of many power quality problems along their causes and consequences are presented.

2.3.1 **Voltage sag / dip**

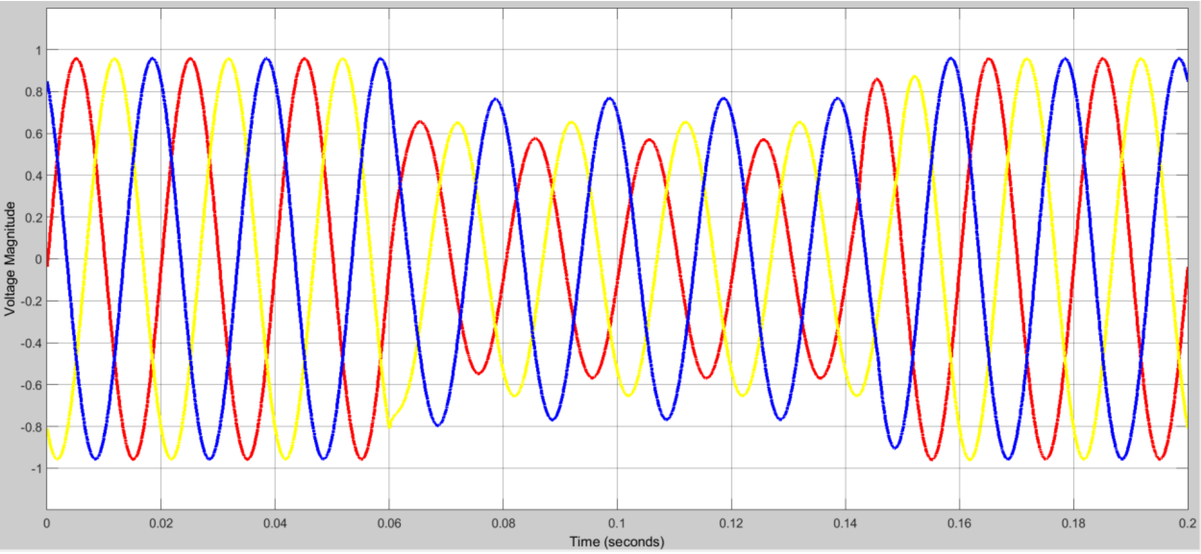
A sag is defined as the decrease in rms voltage or current to a value between 0.1 and 0.9pu at the power frequency duration. It can be stated as reduction in nominal voltage level by 10-90% for short duration for half cycle to one minute, but sometimes last for long duration such prolonged low voltage profile referred as ‘under-voltage’. Voltage sag mainly caused due to starting of large motors, overloading of the electric network, energization of heavy loads, incorrect VAR compensations. Voltage sag in power system results in failure of relays and contactor, dim light, data error, equipment shutdown and fluctuating power.



(a) Three–phase balanced voltage sag



(b) Single–phase voltage sag

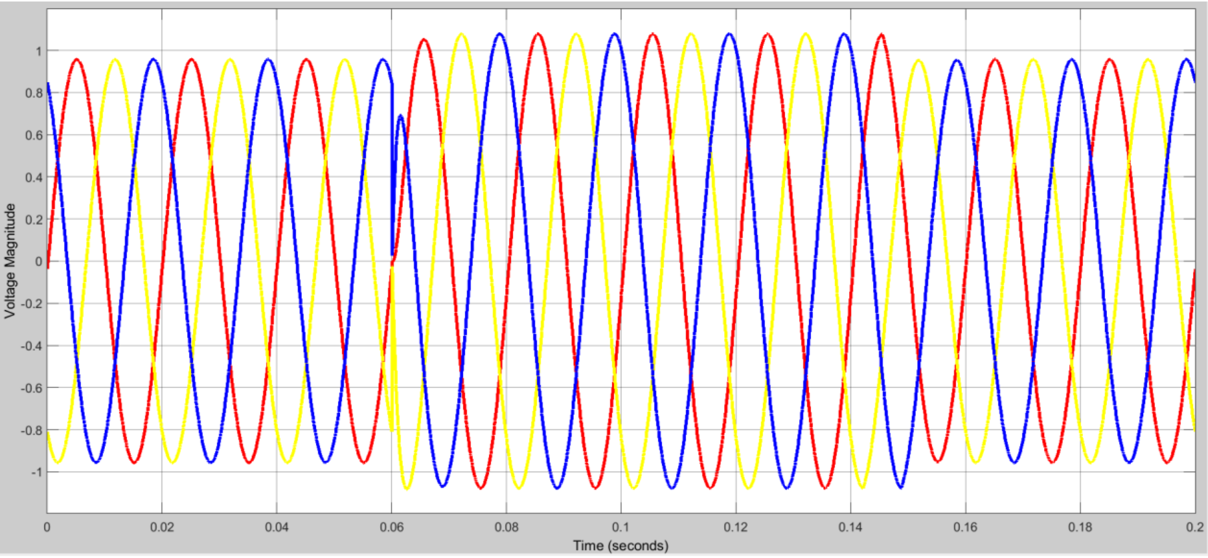


(c) Three–phase unbalanced voltage sag

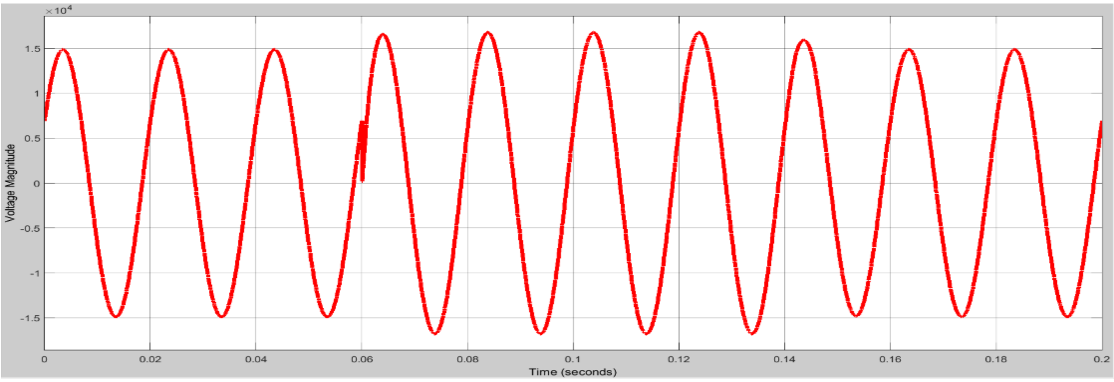
Figure 2.2: Voltage sag waveforms

2.3.2 **Voltage swell**

A swell is defined as an increase in rms voltage or current to between 1.1 and 1.8pu at the power frequency for durations from half cycle to one minute. It can also be stated as voltage rise by 10-80% of normal value for duration of half cycle to one minute. Sometimes voltage swell last for long duration such prolonged high voltage profile is referred as 'over-voltage'. Voltage swell mainly caused due to energizing a large capacitor bank, switching off a large load, incorrect VAR correction, single line to ground fault result in voltage rise in unfaulty phases or loose connection of neutral wire. Voltage swell in power system result in breakdown of insulation, bright light and overheating of electrical equipment.



(a) Three–phase voltage swell waveforms



(b) Single–phase voltage swell

Figure 2.3: Voltage swell waveforms

2.3.3 **Transient**

Transient is a sudden, non-power frequency change in steady state condition of voltage, current or both. Transient results in oscillatory response. It can be further categorized as

- Impulsive transient: Unexpected frequency change in the steady state, change is unidirectional, exist for duration between 5μs to 50ms and specified by their rise and decay time.
- Oscillatory transient: Unexpected frequency change in steady state, change is bidirectional, exist for less than 50ns and specified by magnitude, duration and spectral content.

Transient are produced due to lightning, turning major equipment on or off, back to back capacitor energization or loose connections. Transient result in tripping, overheating of motors and reduce the overall performance and shorten the lifetime of equipment.

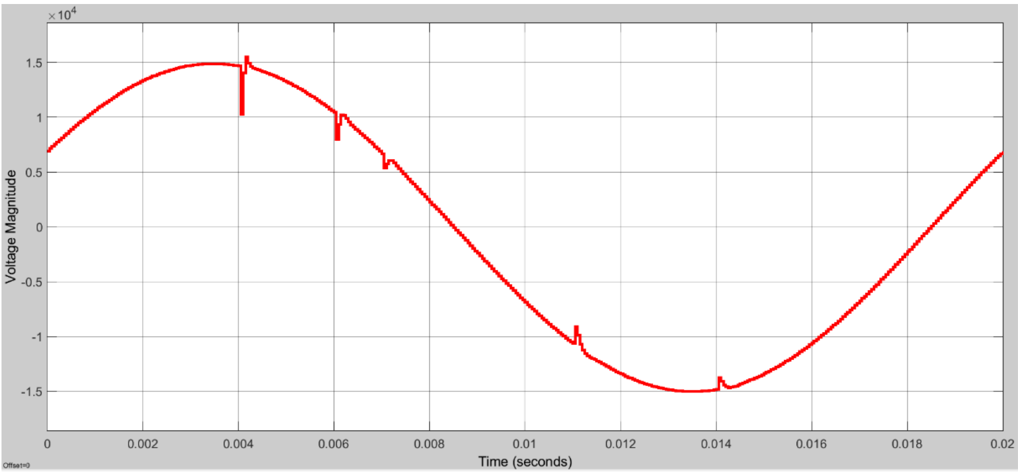


Figure 2.4: Transient waveform

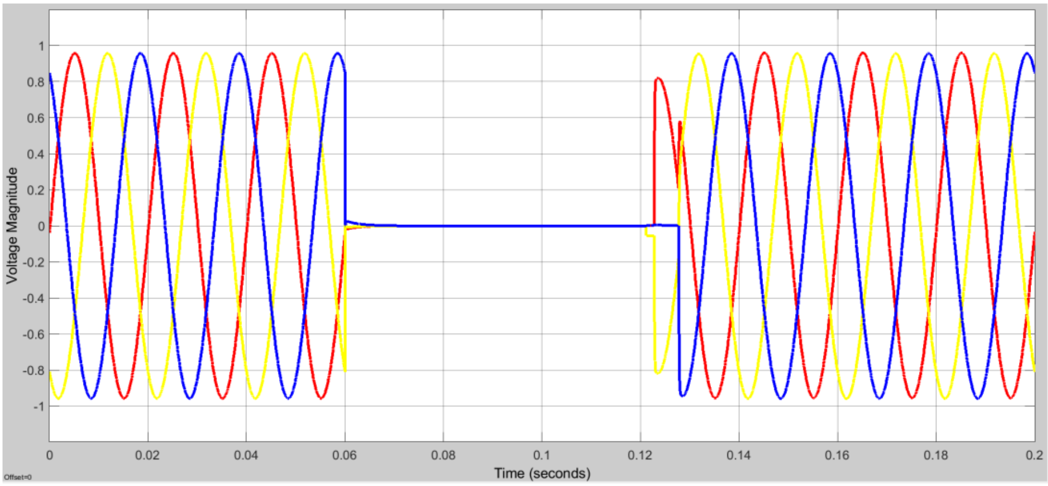
2.3.4 **Voltage interruption:**

An interruption is when the supply voltage or load current decrease to less than 0.1 pu for a period of time not exceeding 1 minute. It can be future divided into two classes based on interruption time period:

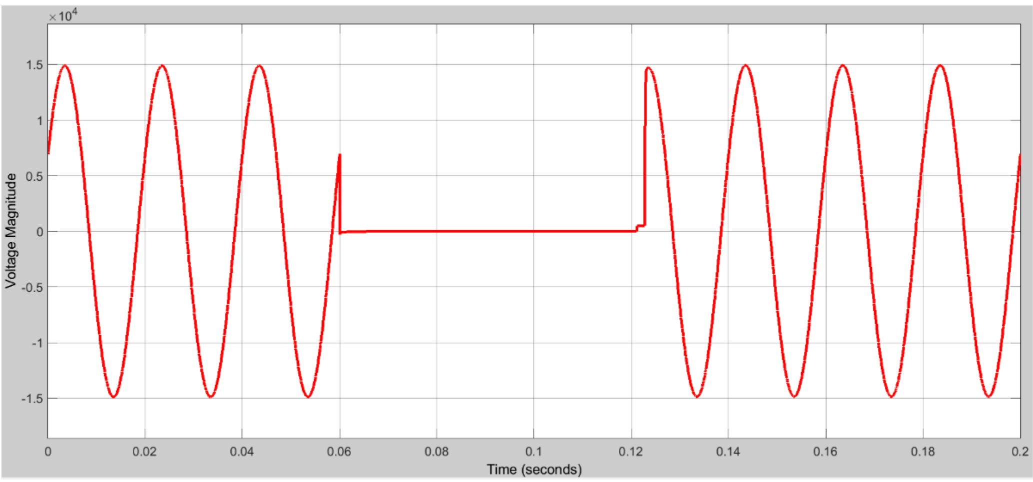
- Short interruption: Interruption occurs for few milli-seconds and due to malfunctioning of switching devices.

- Long interruption: Interruption occurs for range between few milliseconds to several seconds.

Interruption occurs due to faults (short circuit), equipment failures, insulator failure lightning or control malfunctions.



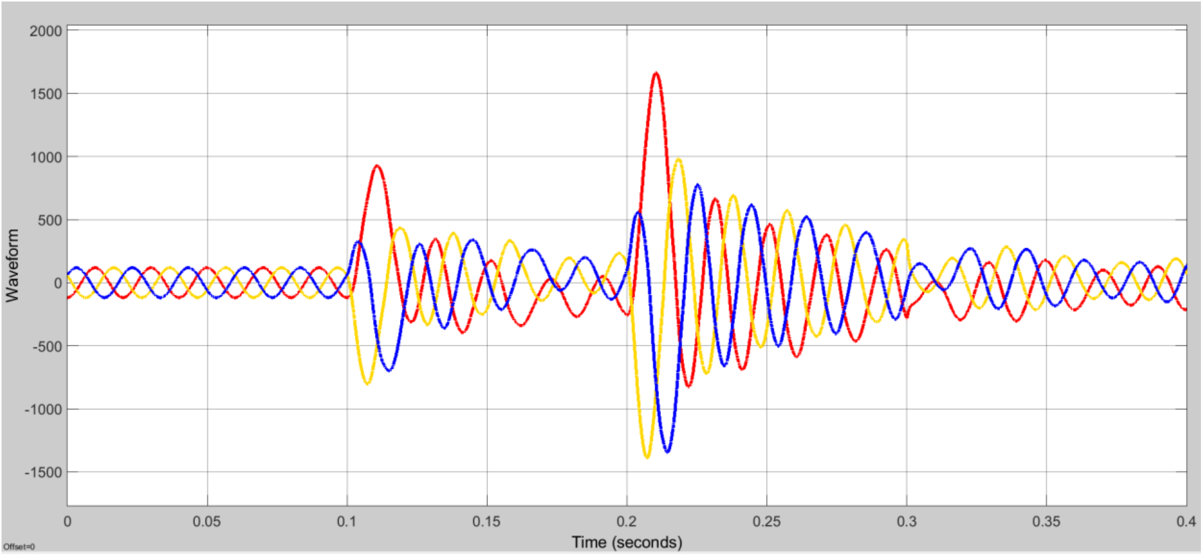
(a) Three–phase voltage sag



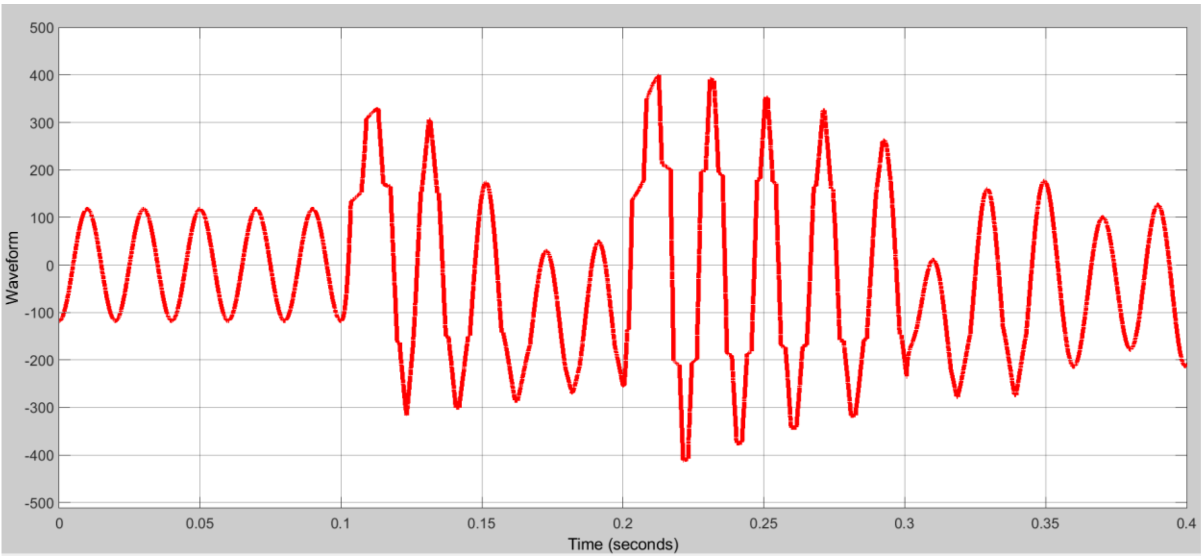
(b) Single–phase voltage sag

Figure 2.5: Voltage interruption waveform

2.3.5 **Harmonics:**



(a) Three–phase voltage sag



(b) Single–phase voltage sag

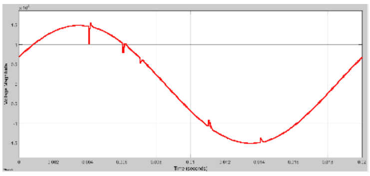
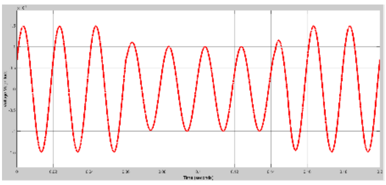
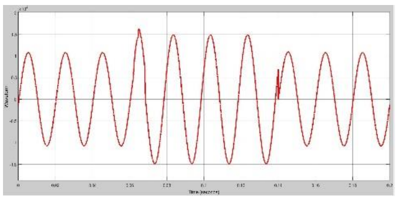
Figure 2.6: Harmonics waveform

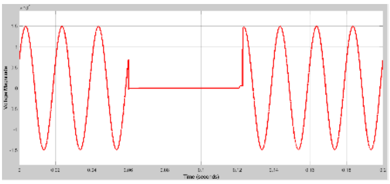
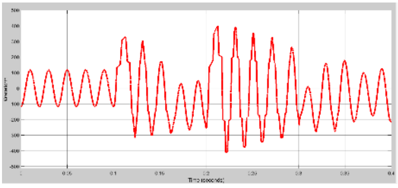
In power systems, harmonics are defined as positive integer multiples of the fundamental frequency. Harmonics are the disturbances in the electric voltages and currents. Current and voltage waveform are distorted and deviate from sinusoidal waveforms due to the presence of harmonics in electrical system. The main cause of harmonic generation is nonlinear loads. There are two types of harmonics:

- Current harmonics: Current harmonic is caused by nonlinear loads connected to the distribution system. When the current draws by load does not have the same waveform as the supply voltage then that load is called non-linear load.

- Voltage harmonics: Voltage harmonics are mostly caused by current harmonics. Due to source impedance the voltage provided by the voltage source will be distorted by current harmonics. If the source impedance of the voltage source is small, current harmonics will cause only small voltage harmonics.

Table 2.1: Different power quality issues, causes and effects

Power Quality Issues		**Causes**	**Effects**
Transient		Lightning, turning major equipment on or off, back to back capacitor energization.	Tripping, Processing error, Data loss, Hardware reboot required, Component failure.
Voltage sag		Starting of large Motors, Energization of heavy loads, Incorrect VAR compensation. Faults on the transmission or distribution network.	Dim lights, Data error, Shrinking display screens, Equipment shutdown, Memory loss.
Voltage swell		Energizing a large capacitor bank, Switching off a large load, incorrect VAR compensation.	Bright lights, Data error, Racing or blinking of digital clock.

Voltage interruptions		Faults (Short circuit), Equipment failures, insulator failure, lightning, Control malfunctions.	Equipment trips off, Programming is lost, Computer shut down, Disk drive crashes.
Harmonics		Electromagnetic interferences from appliances, machines. Interaction of power lines with communication lines.	Continuous distortion of normal voltage, random errors.

CHAPTER -3

DYNAMIC VOLTAGE RESTORER

Power quality is of great importance in all modern environment where electricity is involved, power quality can be essentially influenced by an important factor like quality service. Recent technological advancement lead to rapid growth in number of nonlinear load present in power distribution system which adversely affect the quality of power supply. Voltage sag or swell are considered as one of the major problems to the system network. DVR is one of the effective solutions for compensation voltage sag or swell.

3.1 Dynamic Voltage Restorer

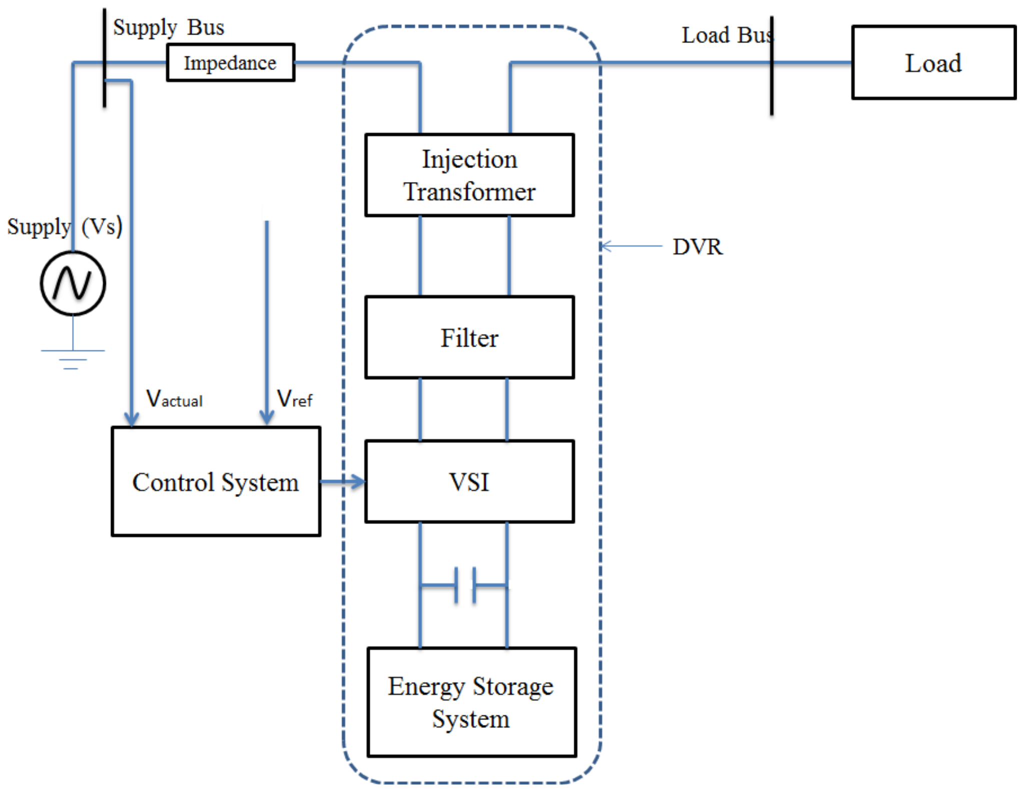


Figure 3.1: Schematic diagram of DVR

DVR is a type of FACTS device. It is also referred as Series Voltage Booster (SVB) or Static Series Compensator (SSC). The Dynamic Voltage Restorer is a series connected solid state device in order to regulate the load side voltage to the desired magnitude and waveform even when the source voltage is unbalanced or distorted that injects additional voltage into the system. Active and reactive power from DVR is injected to a distribution feeder in this process.

The compensating voltage is injected by transformers can be controlled and regulated easily. The load voltage and the DVR injected voltages are in synchronism.

3.2 **Components of DVR**

Dynamic Voltage Restorer is a custom power device mainly consisting of a energy storage unit or an energy source, a filter circuit, control unit, series injection transformer and Voltage Source Inverter.

3.2.1 **Energy Storage Unit**

This energy storing unit is used to store energy in the form of DC. An AC generator can also be used but will not be cost effective. Super capacitors and other devices such as super conducting magnetic energy storage devices are such devices are used to store energy. This unit supplies the required real power of the system when DVR is used for compensation.

3.2.2 **Capacitor:**

The input DC voltage to the inverter is checked by using a large sized DC capacitor to ensure a proper DC voltage input to Inverter. If the energy storage unit used is an ac unit, then there is no requirement for a capacitor.

3.2.3 **Sinusoidal PWM Inverter**

The Voltage Source Inverter is used to convert a DC signal to AC signal. It should be controlled in such a way that it generates voltages which are same as the reference voltages generated by the detection and control block. So SPWM is used as the switching strategy for the inverter. The reference voltages generated by the detection and control block are given as the modulating waveforms for the inverter then the fundamental component of the output of the inverter will be same as the reference voltages generated by detection and control block. The amplitude of modulating waveform is the magnitude of sag. The advantages of using SPWM Inverter are:

- It will have constant switching frequency.
- By choosing the modulation frequency very high, the switching harmonics can be pushed to high frequency side which will make the filter requirement less.

3.2.4 **Passive Filters**

Filters are used to convert the inverted PWM waveform into a sinusoidal waveform. Passive filters are used to filter out the harmonics present in the output of the VSI. Filters can be kept either at the inverter side or at the HV side of the transformer. If placed at the inverter side, switching harmonics are prohibited to enter the injection transformer thereby reduces rating and voltage stress on it. If the filter is placed at HV side of injection transformer, harmonics can enter into HV side hence rating of transformer increases.

3.2.5 **By-Pass Switch**

It is used to protect the inverter from high current in the presence of unwanted conditions. During the occurrence of a fault or a short circuit, DVR changes it into the bypass condition where the VSI inverter is protected against over current flowing through the power semiconductor switches. The rating of the DVR inverters is a limiting factor for normal load current seen in the primary winding and reflected to the secondary winding of the series insertion transformer.

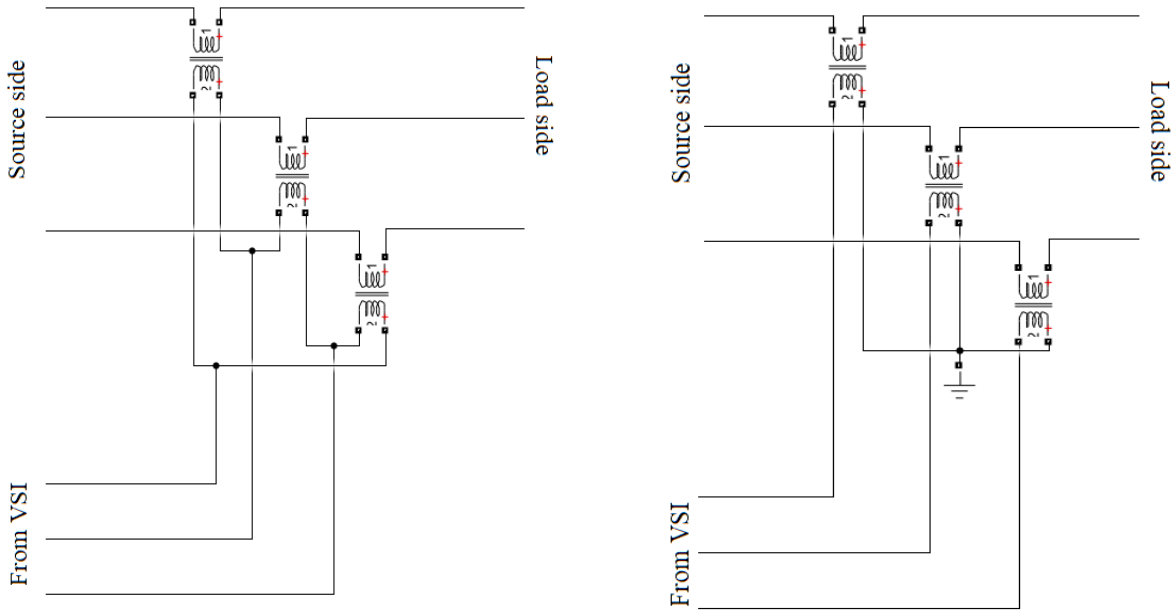
3.2.6 **Voltage Injection Transformers**

The voltage supplied by VSI is stepped up by using injection transformer to the desired voltage level. The HV side is generally connected in series with the distribution network while the power circuit of the DVR is connected to the low voltage side. DVR injects the voltage which is required for the compensation from DC side of the inverter to the distribution network through the series injection transformer. The maximum voltage injection capability and the active power decide the compensation capacity of a particular. When a distortion of DVR's voltage occurs, active power or energy should be injected into the distribution system from DVR. There are two main purposes of transformer.

It connects the DVR to the distribution network and couples the injected compensating voltage generated by the voltage source converter to the incoming supply voltage. It serves the purpose of isolating the load from the system. The winding configuration of the injection transformer is very important and it mainly depends on the upstream distribution transformer.

- If delta-star transformer is used in distribution feeder, zero-sequence voltages will not circulate through the transformer when earth faults occur on the higher voltage level. Therefore, restoration of positive sequence and compensation of negative voltage are necessary. Hence, a delta-open injection transformer can be used. The delta/open winding as shown in Figure 3.2(a) maximizes the utilization of DC link voltage.

- If an earthed star-star distribution circuit transformer is used, zero sequence voltages have to be compensated. For this case, a star-open injection transformer as shown in Figure 3.2(b) is used with injection of zero sequence voltages from the DVR.



(a) **(b)**

Figure 3.2(a): Delta open configuration **(b):** Star open configuration

3.2.7 **Control unit:**

Control circuit steadily observes the system. A controller is used for proper operation of DVR, which detect the presence of voltage disturbance and operate VSI to mitigate the voltage sag/swell. Its function is to detect any disturbance in the system done by comparing the supply voltage with reference voltage then it generates the switching command signals for VSI in order to generate the compensating voltage by DVR.

3.2.7.1 **Sag/Swell Detection Techniques**

The accurate detection and classification of disturbances can help in taking effective countermeasures to maintain adequate power quality. To detect the voltage sag, the starting point and the ending point of sag, depth of sag and phase shift, information are required. The different detection techniques are discussed in the further section.

3.2.7.2 **Control Strategies**

The inverter control strategy includes of two types of control linear and non-linear. Various linear techniques include feed forward, feedback and composite and the non-linear techniques are fuzzy logic and ANN.

3.3 **Sag/Swell Detection Techniques**

3.3.1 **Fourier Transform (FT) Method**

The orthogonal decomposition of installation signal is employed to attain the Fourier Transform. When we apply the FT to each supply phase, it is possible to get the magnitude and phase of each of the frequency components of the supply waveform. It takes one complete cycle to grant the correct data concerning the sag depth and its phase. the belief in real time management is feasible.

3.3.2 **Phase Locked Loop (PLL) method**

Independently PLL is applied to each supply phase. It responds to the phase jump in the supply quickly. It requires freezing the pre-sag magnitude and phase. Supply voltage generated is in the same phase. PLL takes time delay up to half cycle.

3.3.3 **Peak value detection method**

In peak value detection method, a point is found where the gradient of supply voltage phases is zero, and then the supply value is compared at that instant with a reference value and sense the sag. A controller is set to distinguish the deviation. It gives information of start of sag, sag depth and sag end time. It is difficult to extract the phase shift information as a reference waveform is required.

3.3.4 **Root mean square (RMS) method**

It is used to detect the start and end points of sag or swell. RMS is an accurate way to detect the voltage sag or interruption, but it does not give phase angle shift information. It takes more time to calculate the RMS value.

3.3.5 **Space Vector control**

Space Vector Control method gives both voltage magnitude and angle shift information. Three phase voltages Vr, Vy, Vb are transformed into a two-dimension voltage Vd, Vq which in turn can be transformed into magnitude and phase angle. Space vector control method is faster and can be realized in real time but requires complex controller. It is highly.

3.3.6 **Wavelet Transform (WT) method**

WT performs better with non-periodic and non-stationary signals. Change in the state of the supply phases can be detected quickly. In wavelet analysis procedure we design a wavelet prototype function, or the mother wavelet. The disadvantage of this method is selection of appropriate mother wavelet for each application, since the related filter bank coefficients are dependent on selected mother wavelet. There is a delay associated with many mother wavelets as the data at either side of a time instant is required in the convolution process.

3.4 **Control strategies**

3.4.1 **Linear Controller**

The linear controllers used in DVR are

- Feed forward controller
- Feedback controller
- Composite controller

3.4.1.1 **Feed Forward**

Because of ease and fastness, feed forward controller is the prime option for the DVR. It does not sense the load voltage. The injected voltage is calculated on the basis of the difference between the pre-sag and during-sag voltages.

3.4.1.2 **Feedback**

The actual load voltage is injected in the feedback controller by measuring the load voltage and the difference between the voltage reference of the load and. The feedback controller it is complex and time-delayed but has the benefit of exact response.

3.4.1.3 **Composite**

Composite control strategy is a control method where grid voltage feed forward and load side voltage feedback. It had strength of both feed-forward and feedback control strategies. If the feedback control is designed to double-loop, it can improve system stability, system performance and the adaptability of dynamic load. Due to the combination with feed forward control can improve the system dynamic response rate, shortening the time of compensation significantly.

Table 3.1: Comparison of feed forward and feedback controller

Parameter	**Feed forward**	**Feed back**
Measures	Fast, dependent on system	Medium, controllable through controller
Steady state error	High	Can be eliminated
Transient overshoot	Difficult to control	Controllable
Stability	Good	Can be unstable
Compensation of DVR generated voltage	Difficult to control	Can be reduced
Switching harmonics	Do not enter the control	Enter the control
Compensation of non-symmetrical fault	Slow, possible	Good

3.4.2 **Non –Linear Controller**

3.4.2.1 **Fuzzy Logic (FL)**

When precise mathematical formulations are not feasible, FL controllers are an attractive alternative. The tracking error and transient overshoots of PWM and can be significantly reduced. However, the properties of the FL controller are very susceptible to any change of fuzzy sets shapes and overlapping. Consequently, the designing and performance strongly depends on the knowledge and expertise of the designer.

3.4.2.2 **Artificial Neural Network (ANN)**

The artificial neural network has adaptive and self-organizing capacity. It gives improved precision by interpolation. Without the mathematical model, it can constitute the nonlinear relationship based on input and output.

3.4.2.3 **Space Vector Pulse Width Modulation (SVPWM)**

In SVPWM to get quasi-circular rotating magnetic field as an alternative of the original sinusoidal PWM we adopt a voltage inverter space vector of the switch, so that improved performance of the switch over is achieved in low switching frequency conditions. SVPWM is used because of its easier realization and better dc bus utilization. This method is an advanced, computation-intensive PWM method and probably the best among all the PWM techniques.

3.5 **Working of DVR**

When the system voltage (V_S) sags/swells, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. The series injected voltage of the DVR can be written as

$$V_{DVR} = V_L + Z_{LINE} I_{LINE} - V_S \qquad 3.1$$

$$I_L = {}^{(P_L + jQ_L)}/_{V_L} \qquad 3.2$$

$$V_{DVR}\angle\alpha = V_L\angle 0° + Z_{LINE} * I_{LINE}\angle(\beta - \theta) - V_S\angle\delta \qquad 3.3$$

Where, α is angle of V_{DVR}

β is angle of Z_{LINE}

δ is angle of V_S

θ is load power angle

$$\theta = \tan^{-1}\left(\frac{Q_L}{P_L}\right) \qquad 3.4$$

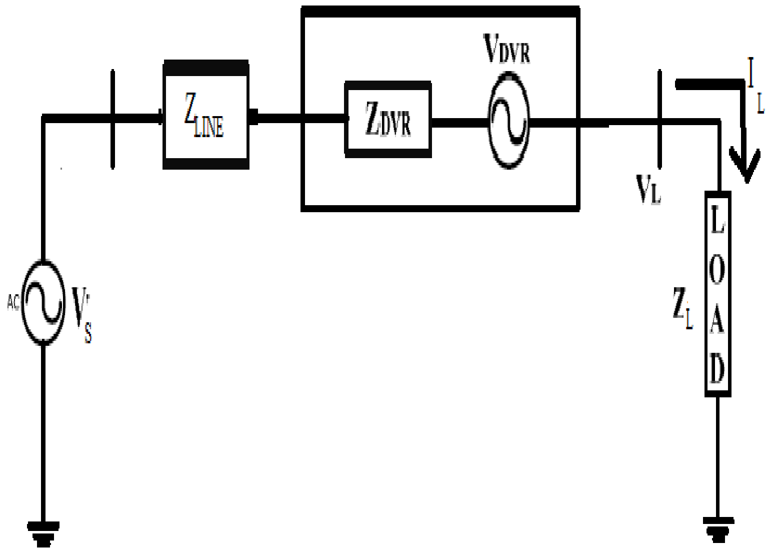


Figure 3.3: Equivalent circuit diagram of DVR

The complex power injected by DVR can be given as,

$S_{DVR} = V_{DVR} I_L{}^*$ 3.5

where, V_L= Desired load voltage

I_L= Load current

Z_L= Line impedance

V_S=Source voltage under unbalance condition

3.6 **Operating modes**

3.6.1 **Protection mode**

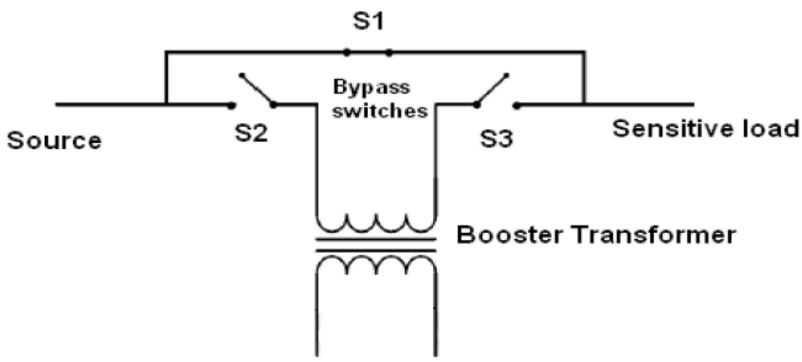


Figure 3.4: DVR in protection mode

The DVR is protected from over current due to short circuit on the load side or large inrush current. The bypass switches isolate the DVR from the system by providing another path for current.

3.6.2 **Standby mode**

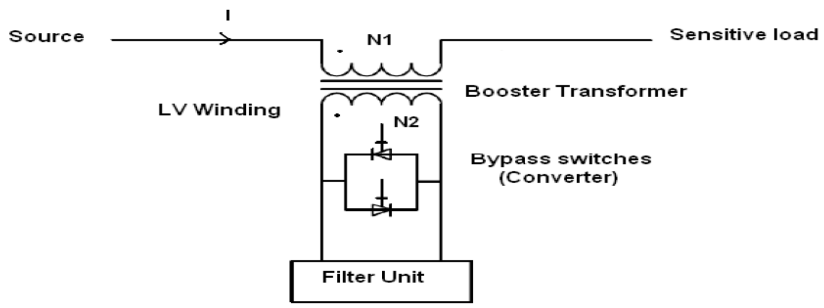


Figure 3.5: DVR in standby mode

In this mode, low voltage winding of injection transformer is shorted; DVR may either go into short circuit operation or may inject small voltage to compensate the voltage drop on transformer reactance or losses.

3.6.3 **Injection mode**

DVR injects the compensating voltage through injection transformer in this mode. When sag or swell is detected the DVR goes into injection mode. For compensation, AC voltage is injected in series with required magnitude and phase. DVR operation in the injection mode is carried out in following steps:

- Comparison of the terminal voltage with reference voltage to find any voltage unbalance in the distribution network. The difference is the desired voltage.
- To initiate switching signals for Voltage Source Inverter (VSI), the desired voltage generated by using satisfactory switching techniques such as PWM. The required signal is generated with the help of the control unit.
- Injection voltages generated from VSI are passed through passive filter to filter harmonics.
- Injection transformers connected in series with the load bus is used to inject the filtered voltage.

3.7 **Voltage Injection Methods**

3.7.1 **Pre-Sag Compensation**

The pre-sag/swell 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/swell condition. Injection of voltage sags/swells in the both phase angle and amplitude to sensitive loads would be achieved by pre-sag/swell injection method. This requires higher rating of the DVR.

The load voltage phasor of DVR injected voltage is unchanged with respect to that before the disturbance. It is recommended for the non-linear loads, sensitive to phase angle jump. Both the voltage sag and the phase jump are restored in this technique. It avoids any circulating or transient current at the load side. It needs active power during compensation.

The apparent power of DVR is:

$$S_{DVR} = V_{DVR} I_L^{*} = I_L^{*}\sqrt{\left(V_L^{\,2} + V_S^{\,2} - 2V_L V_S\cos(\theta_L - \theta_S)\right)} \quad \text{3.6}$$

And the DVR active power is:

$$P_{DVR} = I_L(V_L\cos\theta_L - V_S\cos\theta_S) \quad \text{3.7}$$

The magnitude of injected voltage is:

$$V_{DVR} = \sqrt{\left(V_L^{\,2} + V_S^{\,2} - 2V_L V_S\cos(\theta_L - \theta_S)\right)} \quad \text{3.8}$$

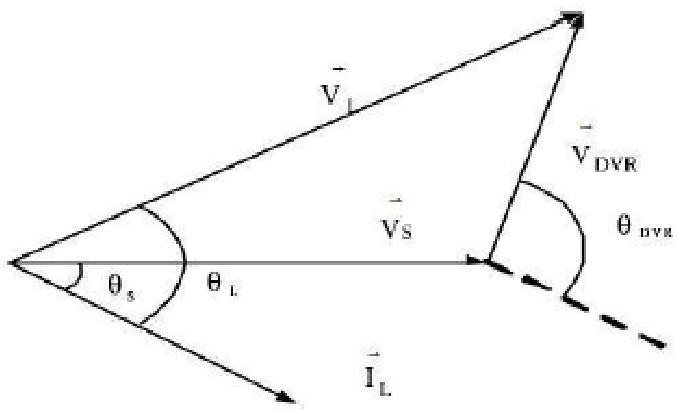


Figure 3.6: Phasor diagram of pre-sag compensation

3.7.2 **In-phase compensation**

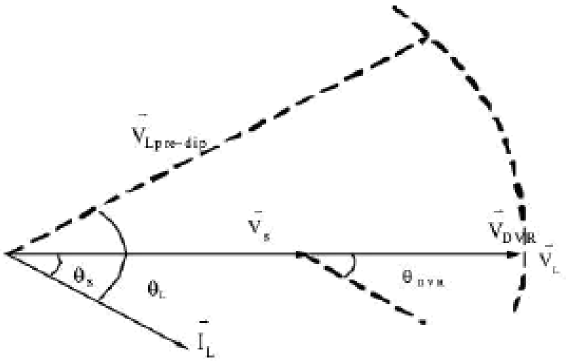


Figure 3.7: Phasor diagram of in-phase compensation

In-phase compensation is the simplest method. In this method the injected voltage is in phase with the supply voltage irrespective of the load current and pre-sag/swell voltage. The phase angles of the pre-sag/swell and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage are satisfied. DVR injected voltage is in phase with the supply voltage. This injection method is recommended for the linear load, where voltage magnitude is only required for compensation. Amount of injected voltage is minimal due to which the voltage rating of the dc link is minimal. It needs active power during compensation. It can't restore the phase jump.

The active and apparent powers of DVR can be given as,

$S_{DVR} = I_L V_{DVR} = I_L(V_L - V_S)$ 3.9

$P_{DVR} = I_L V_{DVR} \cos\theta_S = I_L(V_L - V_S)\cos\theta_S$ 3.10

The magnitude and the angle of the DVR voltage are:

$V_{DVR} = V_L - V_S$ 3.11

$\theta_{DVR} = \theta_S$ 3.12

3.7.3 **In-phase advanced/Energy optimization compensation method**

In in-phase advanced compensation method, the injected voltage advances the voltage, so the injected voltage phasor and line current are perpendicular. In other techniques, pre-sag and in-phase, it is essential to insert real power into the faulty line during the compensation. The main target 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. The value of load current and voltage are fixed in the system, so we can alter only the phase of sag voltage. It uses only reactive power during compensation, hence higher rating of VSI required. All the sags cannot be mitigated without real power, so only suitable for a limited range of sags.

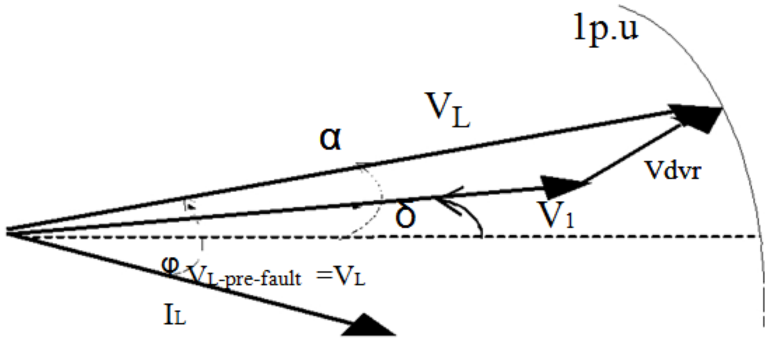
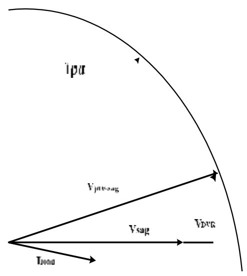
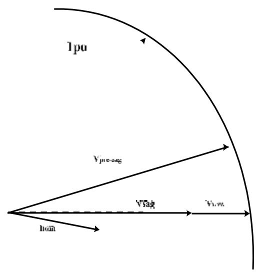
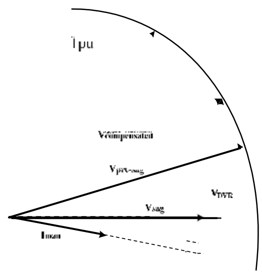


Figure 3.8: Phasor diagram of in-phase advance compensation

Table 3.2: Comparison of the various compensation techniques

Parameters	Pre-sag	In – phase	In – phase advanced
Recommended load	Non-linear load	Linear load	Linear load.
Phasor			
Restore	Voltage magnitude and phase angle	Only voltage magnitude not phase angle	Only voltage magnitude not phase angle.
Rating of storage device/ Voltage injection transformer / Inverter	Higher rated storage device and voltage injection transformer	Minimum rated storage device and voltage injection transformer	Higher rating of inverter.

Performance of PLL during load	PLL is synchronized with load voltage, when a failure occurs, the PLL will be locked and phase angle can be restored as earliest.	PLL has to be synchronized with grid voltage; therefore, PLL will not be locked during the compensation.	PLL has to be synchronized with grid voltage; therefore, PLL will not be locked during the compensation.
Magnitude of injected voltage	High.	Minimum.	Quite high compared to pre-sag and in phase methods.
Distortion	Technique leads to lowest distortion.	Distortion due to phase change is not minimized.	-
Reliability	This technique is reliable to protect sensitive loads without having any transient and circulating current.	This technique leads to transient and circulating current.	This technique sometimes leads to unwanted phase shift when compensated for voltage sag.
Active / Reactive power requirement	Active and reactive power.	Active and reactive power.	Only reactive power.
Outcomes of strategy	It eliminates the voltage disturbance completely even if the phase jumps of voltage in each phase are different.	It does not eliminate voltage disturbance completely	It does not eliminate voltage disturbance completely
Compensation against balanced / unbalanced load	It can compensate both balanced and unbalanced voltage sag.	It can compensate both balanced and unbalanced voltage sag.	-

3.8 **Merits of DVR over other custom power devices**

- The SVC (series VAR compensator) pre-dates the DVR, but the DVR is still favoured because the SVC has no capability to control the active power flow.

- Compared to DSTATCOM and other custom power devices, DVR is small in size and price is less. DSTATCOM is used to compensate the current levels under faulty conditions, so, current harmonics will be reduced considerably.

- The DVR has more energy capacity compared to the UPS (uninterrupted power supply) and SMES (superconducting magnetic energy storage). DVR has many advantages over UPS, like less cost, higher capacity, low losses, injects only the missing part of the supply voltage and less maintenance.

- Economic comparisons of SSTS (solid state transfer switch) and DVR has been investigated and it reveals that SSTS provides better solution in terms of expected savings, cost of solution per KVA, annual operating cost and a higher benefit/cost ratio if, a secondary undisturbed or independent feeder is present otherwise DVR is considered to be the most cost-effective solution.

- SSTS does not regulate voltage neither generate/absorb reactive powers. Its only purpose is to deactivate a faulty feeder in favour of a healthy one.

3.9 **Advantages of DVR**

- DVR is mostly preferred because it is less expensive when compared to DSTATCOM and UPS.

- UPS requires regular maintenance due to problems of battery leakage and replacement. No such trouble is encountered in DVR.

- DVR is small in size and is more efficient custom power device.

- DVR also compensates line voltage harmonics.

- The required installation area is less.

- Voltage drop across DVR in standby mode is very low compared to other custom power devices.

3.10 **Disadvantages of DVR**

- Current conduction and voltage injection capability of DVR is limited. It is due to the design constraints.
- To reduce the cost of DVR, the energy storage size of DVR is kept low. Due to voltage dips, the stored energy can deplete fast and therefore to avoid load tripping due to insufficient stored energy, adequate control is required.
- DVR has higher number of switches.
- Compensation range is limited because operation in case of deep sags may not be successful.
- Current conduction is limited and so is the voltage injection capability.
- It would extend the voltage range if load is a constant power type.

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

In this project, the following three-phase system has been taken into consideration. The various parameters have been mentioned in the following table.

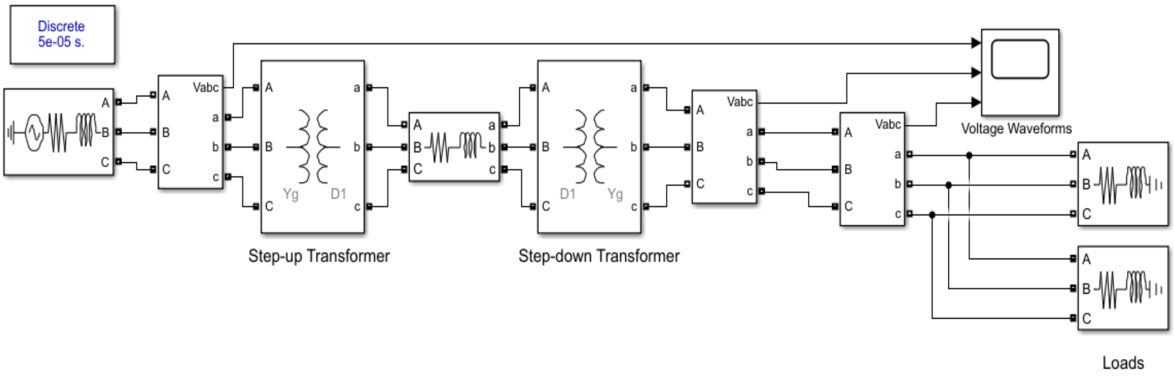


Figure 4.1: Three-phase system taken into consideration for the project

Table 4.1: Three-phase system parameters taken into consideration for the project

Sl. No.	System Quantities	Standards
1	Three- phase source	13 kV, 50 Hz
2	Step – up transformer	Y-Δ, 13/115 kV
3	Line resistance	R_L =0.1ohm
4	Line inductance	L_L = 0.5mH
5	Step – down transformer	Δ – Y, 115/11 kV
6	Loads	Y – connected, 20kW, 4 kVAr

Voltage sag occurs due to sudden connection of load or occurrence of fault. Occurrence of voltage sag is rarer phenomenon as loads are often inductive or resistive and seldomly capacitive. When there is a voltage sag or swell, it may have adverse effect on voltage sensitive loads. Also, due to voltage sag, the power quality is reduced as the load voltage becomes very less compared source voltage thereby increasing the reactive power and reducing the power factor. Hence, to accomplish the above, Dynamic Voltage Restorer is introduced.

DVR is connected in series with the system at the Point of Common Coupling (PCC). It receives the input from the source and load, and accordingly gives the controlled output voltage in order to compensate the sag. In this project, a DC voltage source in form of a battery bank of 400 volts is used. SVPWM inverter gets the gate pulse from a combination of PI controller and Park transformation. A filter is introduced in order to eliminate the harmonics in the three-phase voltage generated from the inverter (sampling frequency of 10 kHz) that is to be fed to the system to eliminate voltage sag. This voltage is then fed to a 2:1 injecting transformer whose HV side is connected to DVR unit and LV side is connected to the PCC.

Table 4.2: Dynamic Voltage Restorer parameters

Sl. No.	System Quantities	Standards
1	DC voltage source	400 volts
2	Inverter	IGBT based, 3 arms, sinusoidal PWM
3	Filter – 1	RLC filter, $R_L = 50\Omega$, L = 7mH; $R_C = 5\Omega$, C = 50μF
4	Filter – 2	RLC filter, $R_L = 20\Omega$, L = 7mH; $R_C = 5\Omega$, C = 50μF
5	Injecting transformer	Δ – open Δ, 22/11 kV

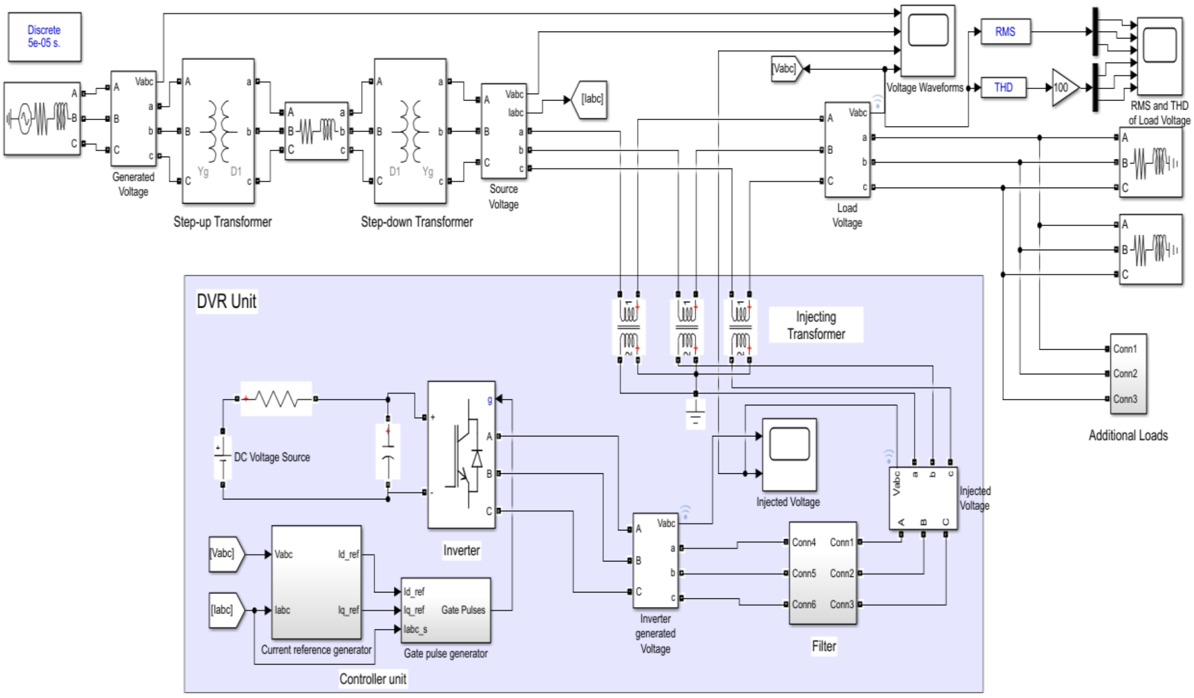


Figure 4.2: Three-phase system along with the Dynamic Voltage Restorer unit

Controller Unit:

Controller is a comparative device used to compare the received input signal from a measured process variable with predetermined value or set point and determines the output signal required to provide corrective action within a control loop. Controllers are used to obtain the desired performance specifications.

Proportional controller: Proportional controller is called as gain controller where the output value is related to deviation of predefined value and measured value. It is a type of linear feedback control system. The output is proportional to error. The output of the controller is multiplication product of the error signal and the proportional gain. This can be mathematically expressed as:

$P_{OUT} = K_P * E(t) + p_0$ 4.1

where, p_o = Controller output with zero error

P_{OUT} = Output of the proportional controller

K_P = Proportional gain

E(t) = Instantaneous process error at time t

It is used to vary the transient response of a system. Proportional controller is usually amplifier with gain K_P. It is easy to implement, low cost, reduces the steady state error. Further, fastens response of the over-damped system and easy to tune. But the response only changes the error increasing the maximum overshoot of the system.

Integral controller: In integral controller the output is directly proportional to the integral of the error signal. It is also known as reset controller. It can be mathematically express as:

$P_{OUT} = K_I * \int_0^t E(t)\,.dt$ 4.2

P_{OUT} = Output of Integral Controller

K_I = Integral gain

E(t) = Instantaneous process error at time t.

PI has a unique ability that, it can return the controlled variable back to exact set point following a disturbance for this it is also known as reset controllers. It is used to decrease the steady state error by increasing the type of the system due to which stability decreases.

Proportional integral (PI) controller: The proportional integral controller produces an output which is the combination of outputs of proportional and integral controller As it is the combination of proportional and integral controller so its output is summation of proportional and integral of error signal. This can mathematically express as:

$P_{OUT} = K_I * \int_0^t e(t).dt + K_P * E(t)$ 4.3

PI controller reduces the overshoot to zero. By adding a pole at origin and zero to open loop transfer function, steady state error decreases. Also, it improves damping. But bandwidth decreases and rise time increases and transient response becomes slower.

Park Transformation: Park transformation is used to convert a three-phase quantity to a two-phase quantity for making the calculation simple. This is simply known as a-b-c to dq0 transformation which is a space vector transformation of three-phase time-domain signals from a stationary phase coordinate system (ABC) to a rotating coordinate system (dq0). The voltage is transformed from a-b-c reference frame to dq0 reference frame. The dq0 transformation computes the direct axis, quadrature axis and zero sequence quantities in a two-axis rotating reference frame for a three-phase quantity. Parke transformation is an extension of Clarke transformation.

The equation that transforms the three-phase a-b-c system to dq0 frame is given by:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad \text{4.4}$$

where,

$\theta = \omega t + \delta_A$, is the angle between the rotating and fixed coordinate system at each time t.

δ_A is an initial phase shift of the voltage

The Inverse Park Transformation is done to obtain the original values of the voltage in a-b-c reference frame.

The equation of Inverse Park Transformation is given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix}\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \quad \text{4.5}$$

The classical Park transform is not power invariant, i.e. the instantaneous power of the variables calculated in the dq0 frame is not the same as the power calculated in the natural coordinate reference frame.

Park Transformation makes the computation easier as two-phases are involved. Also, system operator can independently control the active and reactive components of current. It is easy to design a controller for the dq0 model because it deals with only dc values and the solution of flux and torque is easier.

Combination of PI controller and Park transformation: PI controller cannot take care of the phase difference due to which during injection transients are observed. This problem is solved by Park transformation. In Dynamic Voltage Restorer, Park transformation gives the best injection voltage but overshoot is observed which increases the harmonics. PI reduces the harmonics to zero, thereby eliminating the unwanted frequencies.

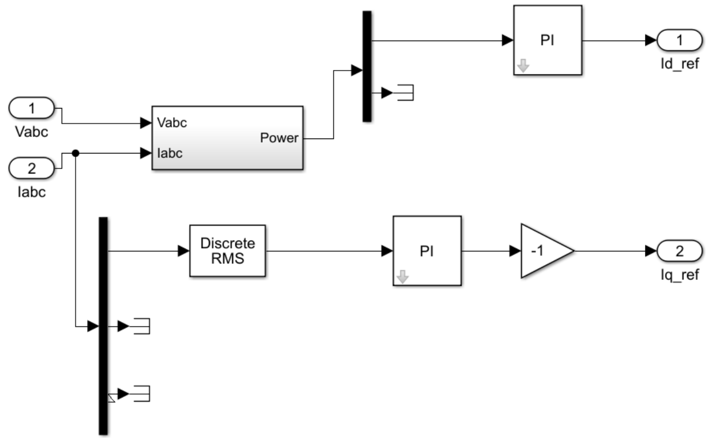


Figure 4.3: Current reference generator unit

Current reference generator unit takes two inputs which are load voltage and source current. The source current and load voltage are given as input to power block from which active and reactive powers are obtained. Active power is used to obtain the reference current for I_d component in Park transformation. This is so because active power is directly proportional to the direct axis component of current. The source current waveform's RMS value is directly used to obtain the I_q reference of Park transformation. PI controller is used to reduce the overshoot and reach the steady state value quickly thereby helping the system to attain stability faster. Also, PI controller reduces steady state errors, thus, reference currents for I_d and I_q are very accurate.

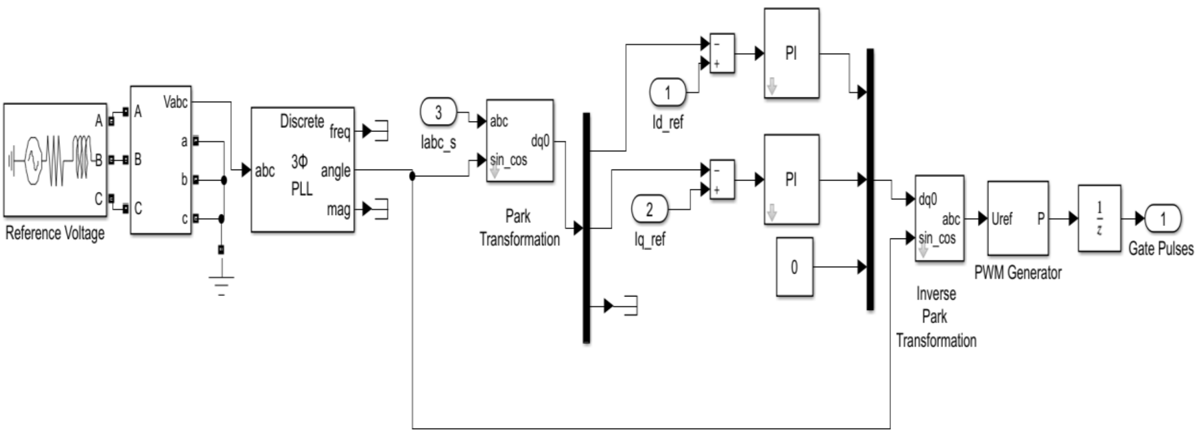


Figure 4.4: Pulse generator unit

The pulse generator unit generates the gate pulses for the inverter. Reference voltage used is the same as the source voltage in order to eliminate any phase difference. The PLL generates the required phase for Park and Inverse Park transformations. Park transformation eliminates any possibility of phase difference in injected voltage and load voltage thus it increases the stability of load voltage when DVR injects the compensation voltage and reduces the possibilities of transients. The output of Park transformation is controlled using PI controller to reduce the steady state error. The inverse Park transformation then generates three-phase voltage which is the reference signal for generation of gate pulses for the inverter.

Filter:

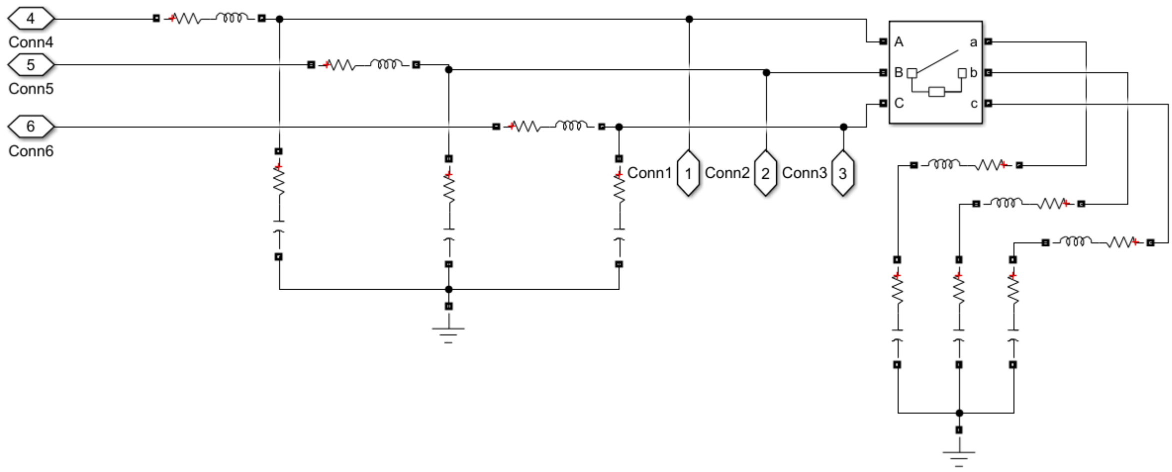


Figure 4.5: Filter to reduce harmonics from the injected voltage

RL-RC Y-connected three-phase RLC filter having values R_L = 50ohm, L = 7mH and R_C = 5ohm, C = 50μF is used initially and then when additional load is increased additional RL-RC Y-connected RLC filter having values R_L = 20ohm and L = 7mH and R_C = 5ohm and C = 50μF is initiated in order to eliminate the harmonics of the voltage to be injected to eliminate the voltage sag.

The voltage generated by the SPWM VSI contains harmonics due to the non–linear elements in form of IGBT and diodes present in the inverter. If this voltage is directly injected to the load side, then due to the harmonics in injected voltage, the load voltage will be distorted which is not suitable for the system and the voltage sensitive loads. Therefore, this RLC filter is used to eliminate these harmonics. Thus, the injected voltage is free of harmonics and on injection to the system doesn't distort the load voltage.

All the results are obtained by using MATLAB SIMULINK R2017b software.

4.1 Non – linear load as additional load

To the existing three-phase system, three-phase series RLC load with active power of 40 kW and inductive reactive power of 60 kVAr is initiated at 0.02 seconds and at 0.04 seconds load with active power 80 kW and inductive reactive power of 60 kVAr is added. The results obtained are as follows.

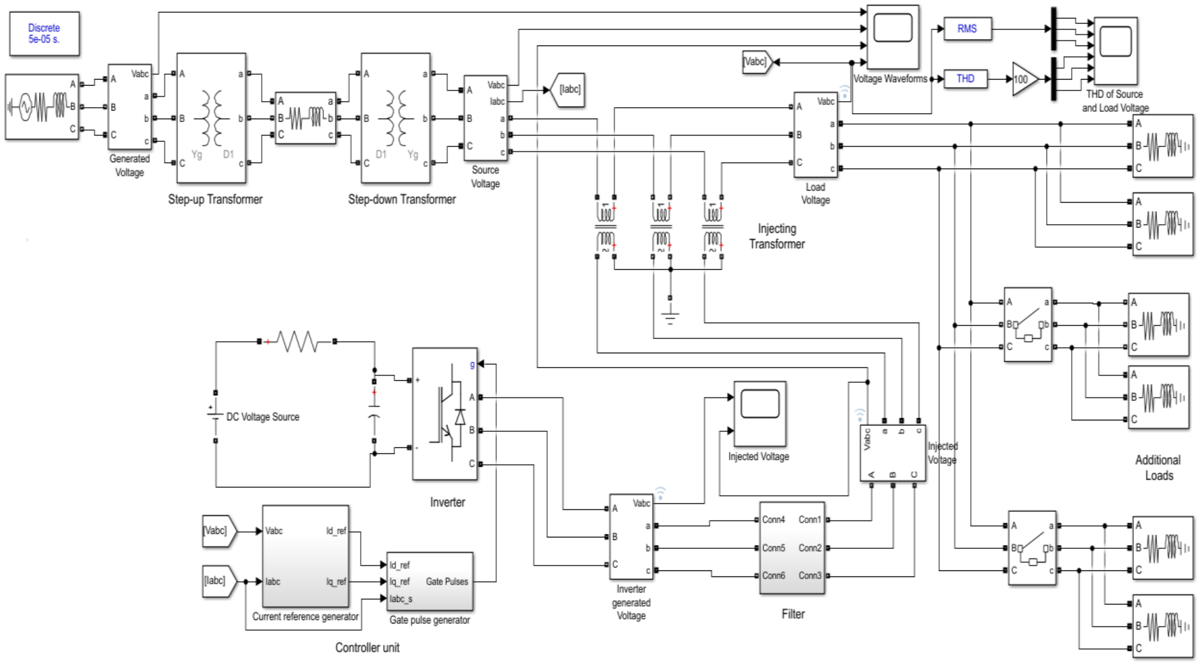


Figure 4.1.1: Three-phase system with non – linear load as additional load

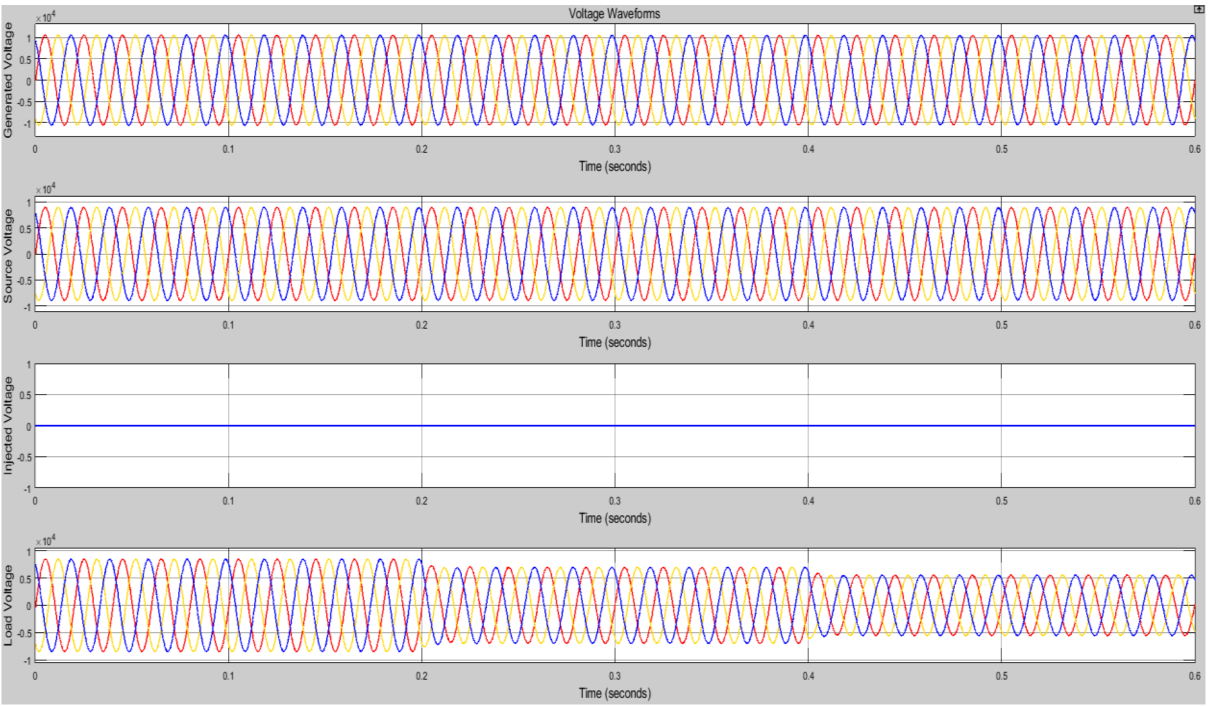


Figure 4.1.2: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage without DVR compensation

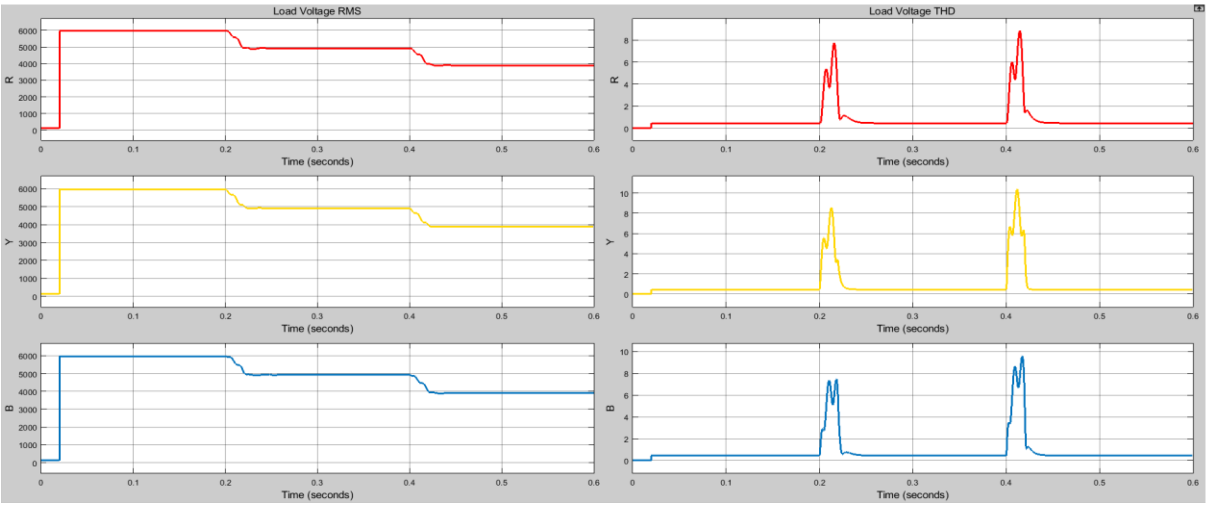


Figure 4.1.3: Load voltage RMS and THD waveforms without DVR compensation

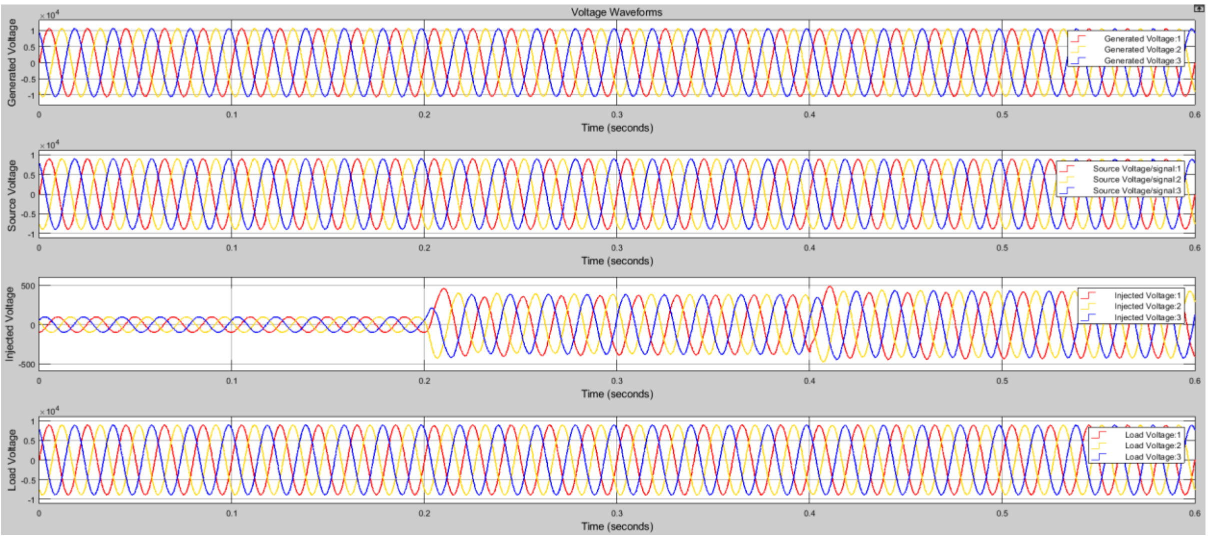


Figure 4.1.4: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage with DVR compensation

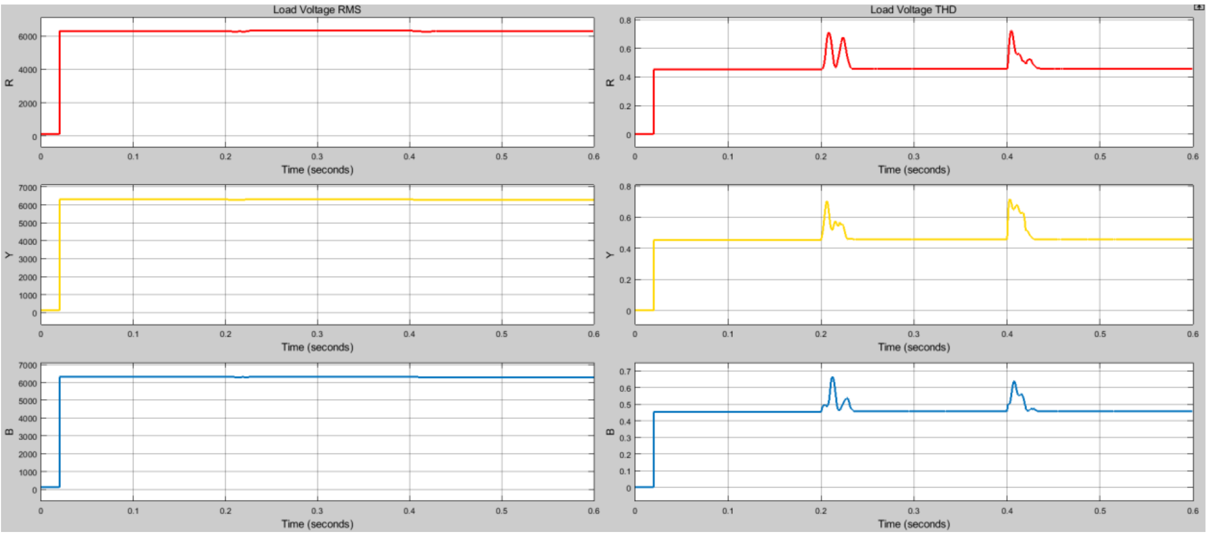


Figure 4.1.5: Load voltage RMS and THD waveforms without DVR compensation

From Figure 4.1.4, it can be observed that the DVR doesn't affect the system when in stand-by mode that is from t = 0s to t = 0.2s. When load is increased and voltage sag is observed as in Figure 4.1.2, the sag is satisfactorily mitigated by DVR as in Figure 4.1.3. Also, it can be observed that the RMS waveforms of the three phases in Figures 4.1.3 and 4.1.5 that with compensation voltage of DVR, THD is reduced and RMS attains nearly constant value. From Figure 4.1.6, it can be observed that the filters make the injected voltage waveform continuous and thereby reducing the harmonics.

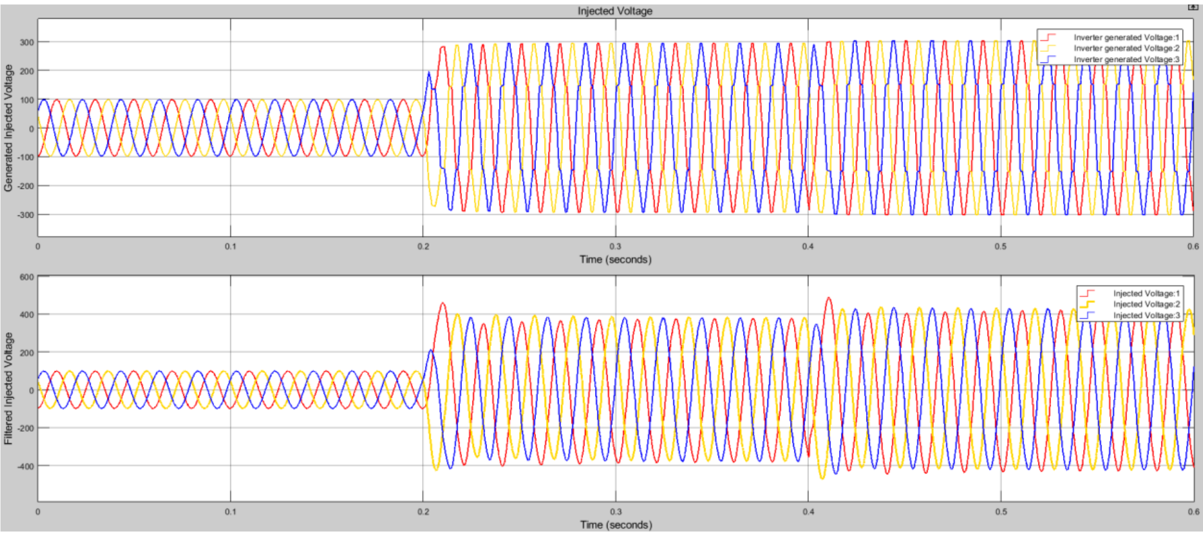


Figure 4.1.6: (a) Inverter generated voltage and (b) Voltage injected as compensation

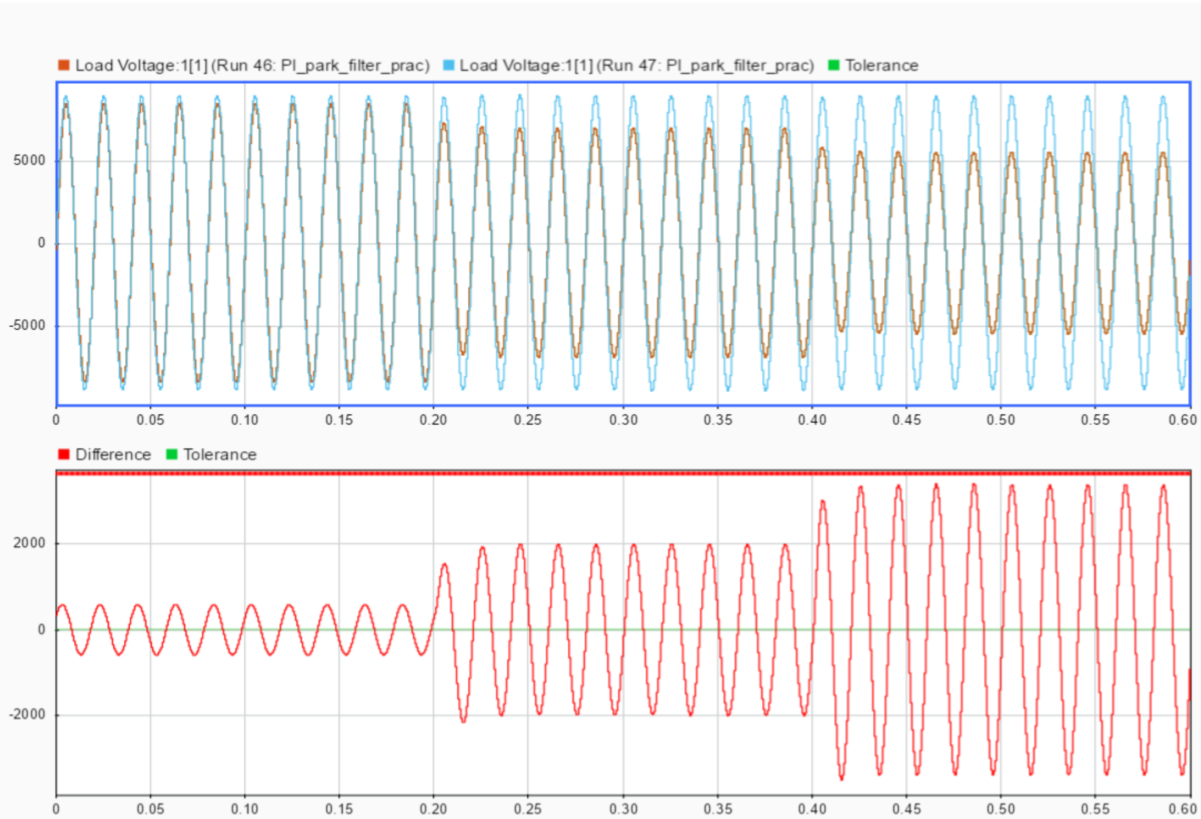


Figure 4.1.7: Comparison of load voltage without compensation and with compensation

Table 4.1.1: THD (in %) of different voltage waveforms at different cases

Phase / Signal	**Load Voltage without compensation**	**Source Voltage**	**Injected Voltage**	**Load Voltage with compensation**
R	12.75	0.38	9.86	0.44
Y	13.29	0.40	7.84	0.45
B	13.49	0.38	6.45	0.44

* THD of 'Load Voltage without compensation', 'Source voltage' and 'Load Voltage with compensation' have been calculated by taking 30 cycles (0.0 to 0.6) into consideration. THD of 'Injected voltage' has been calculated for the interval DVR is in injection mode. Here, for 20 cycles (0.2 to 0.6).

4.2 <u>Linear load as additional load</u>

To the existing three-phase system, three-phase series RLC load with active power of 350 kW is initiated at 0.02 seconds and at 0.04 seconds load with active power 300 kW is added. The results obtained are as follows.

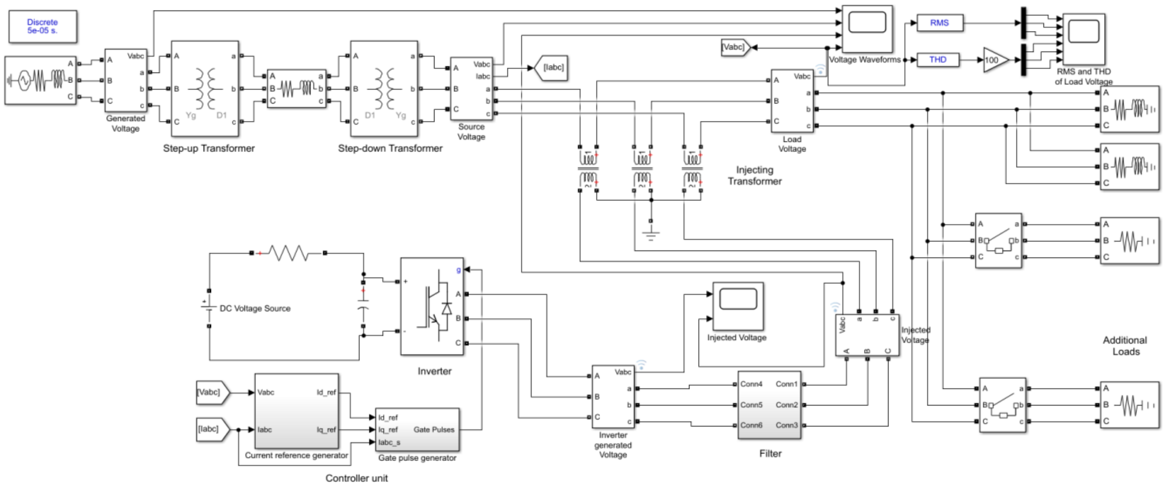


Figure 4.2.1: Three-phase system with linear load as additional load

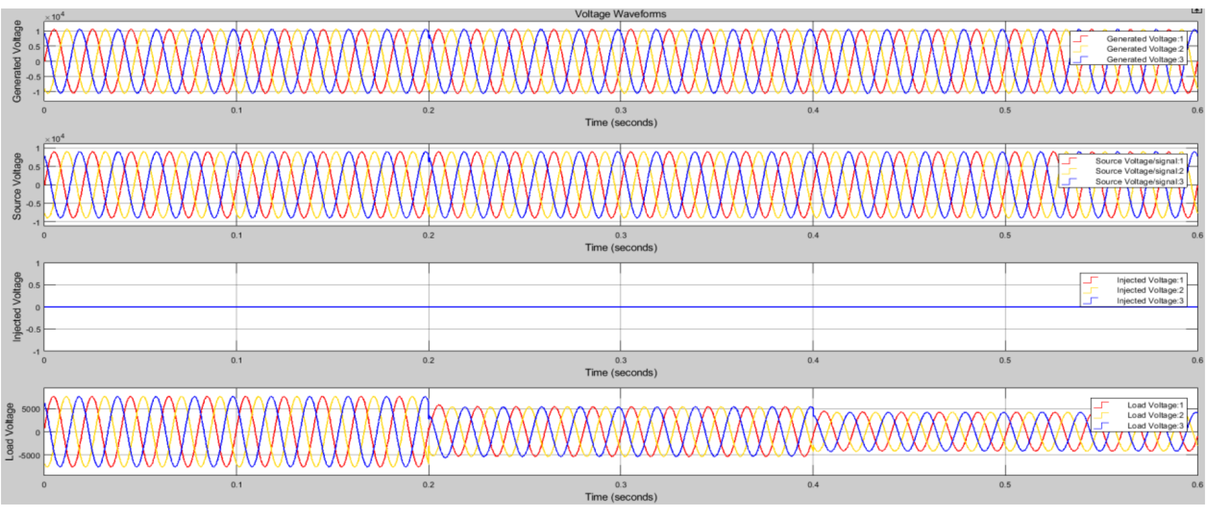


Figure 4.2.2: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage without DVR compensation

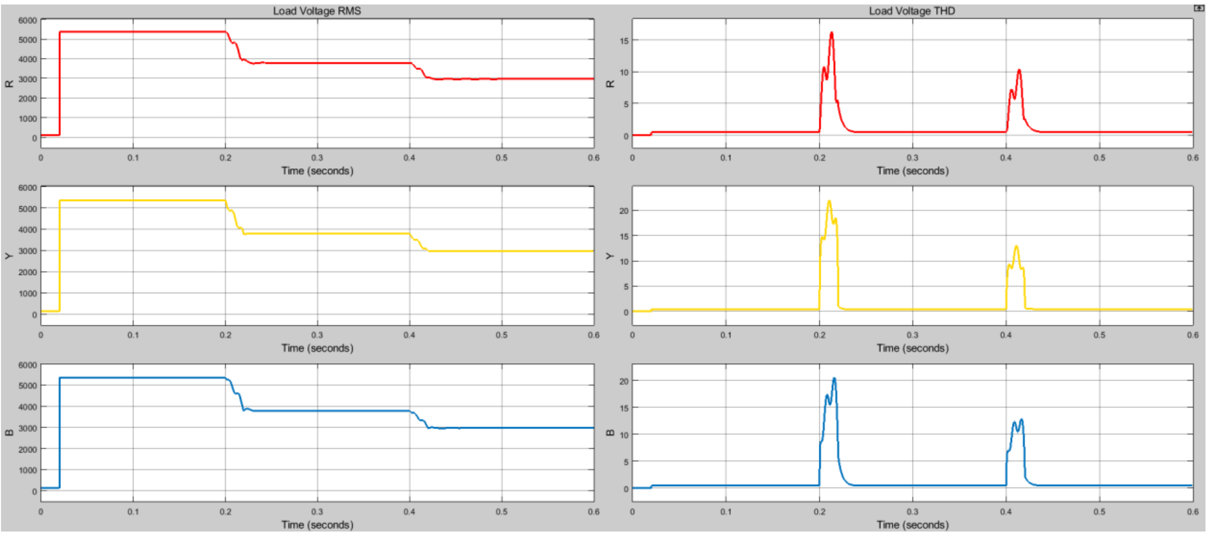


Figure 4.2.3: Load voltage RMS and THD waveforms without DVR compensation

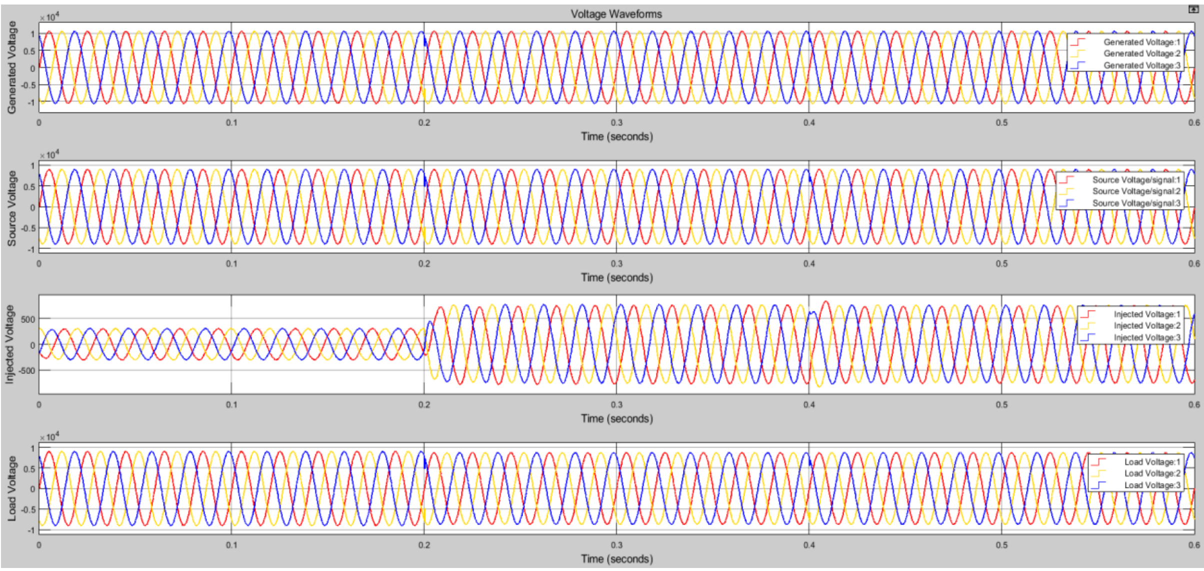


Figure 4.2.4: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage with DVR compensation

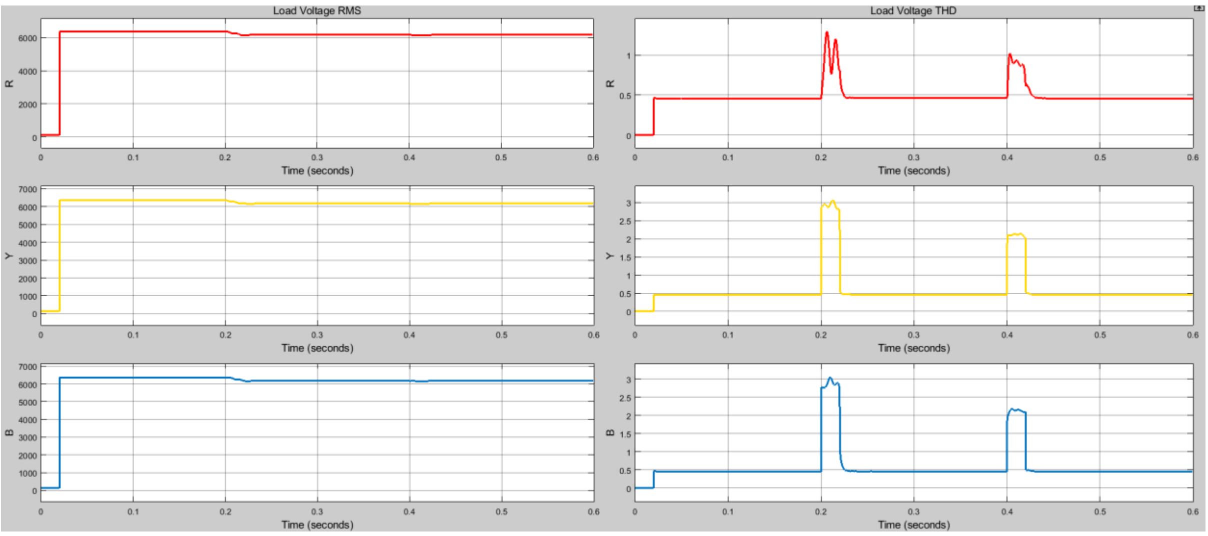


Figure 4.2.5: Load voltage RMS and THD waveforms without DVR compensation

When active power consumption is increased due to addition of resistive loads at instants of t=0.2s and the at t=0.4 s, voltage sag is observed in the load voltage as in Figure 4.2.2 which is satisfactorily mitigated by the DVR as shown in Figure 4.2.3. Similar to non – linear loads, it can be observed that the RMS waveforms of the three phases in Figures 4.2.3 and 4.2.5 that with compensation voltage of DVR, THD is reduced and RMS attains nearly constant value. From Figure 4.1.6, the filters make the injected voltage waveform continuous and thereby reduce the harmonics.

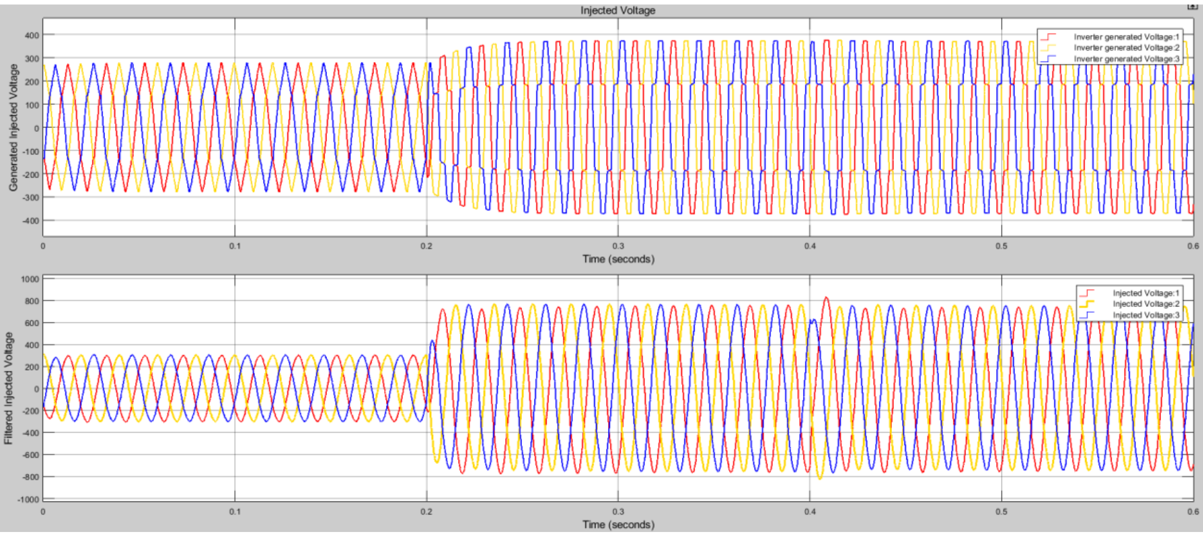


Figure 4.2.6: (a) Inverter generated voltage and (b) Voltage injected as compensation

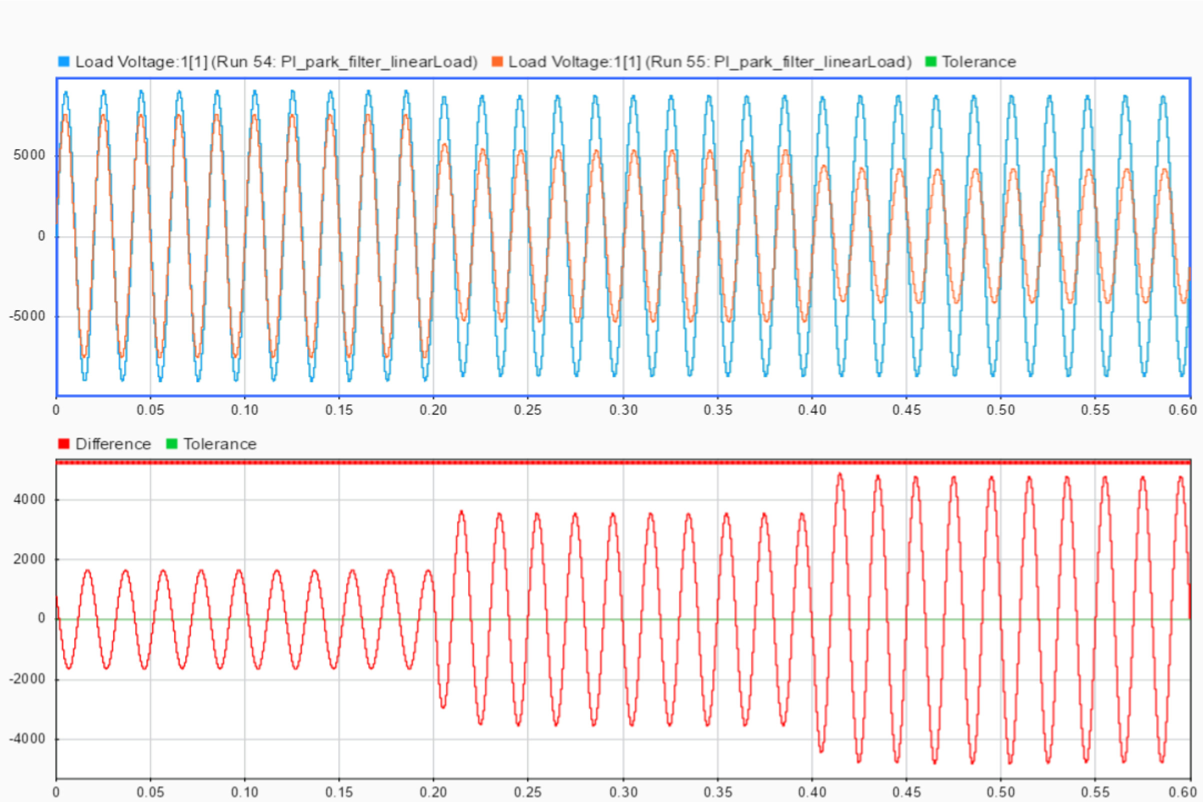


Figure 4.2.7: Comparison of load voltage without compensation and with compensation

Table 4.2.1: THD (in %) of different voltage waveforms at different cases

Phase / Signal	Load Voltage without compensation	Source Voltage	Injected Voltage	Load Voltage with compensation
R	15.88	0.23	5.28	1.24
Y	16.99	0.25	2.63	1.42
B	16.88	0.24	6.04	1.43

* THD of 'Load Voltage without compensation', 'Source voltage' and 'Load Voltage with compensation' have been calculated by taking 30 cycles (0.0 to 0.6) into consideration. THD of 'Injected voltage' has been calculated for the interval DVR is in injection mode. Here, for 20 cycles (0.2 to 0.6).

4.3 <u>Induction motor load as additional load</u>

In this case, two induction motors rated at 400 V, 37 kW, 1480 rpm and 400 V, 75 kW, 1484 rpm are introduced into the system at instants of t = 0.2s and t = 0.4s respectively.

These results in sudden decrease in voltage due to the added loads and also certain recovery can be observed from the load voltage waveform in Figure 4.3.3. Also, from Figure 4.3.4, the unsteadiness of the RMS voltage waveforms of the three phases also supports the above. The THD waveform of the three phases gives a clear picture that the voltage sensitive loads are at a risk in such scenario.

The compensation of the voltage sag by the DVR can be clearly observed in Figure 4.3.7 and the reduction in THD can be observed from Figure 4.3.8. Figures 4.3.6 and 4.3.7 show the current waveforms of stator and rotor of motor1 and motor2 respectively without compensation of the load voltage.

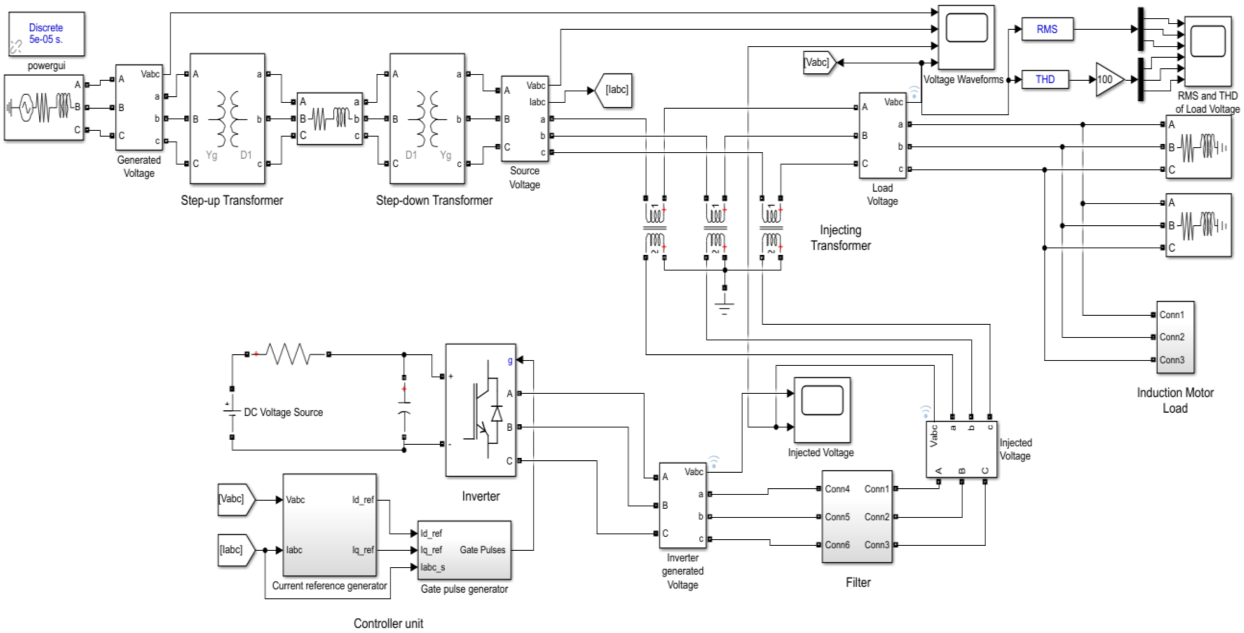


Figure 4.3.1: Three-phase system with induction motor as additional load

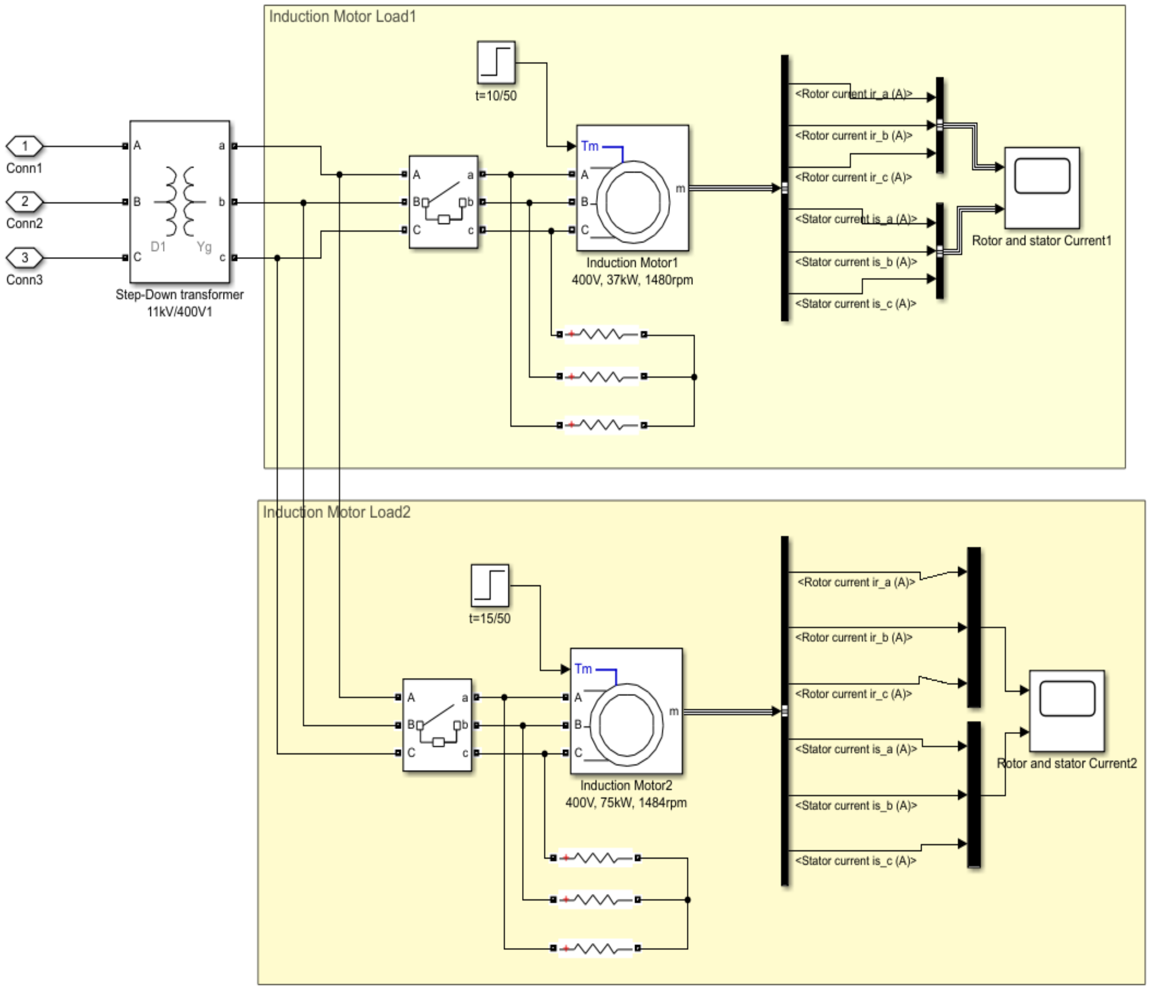


Figure 4.3.2: Induction motor load

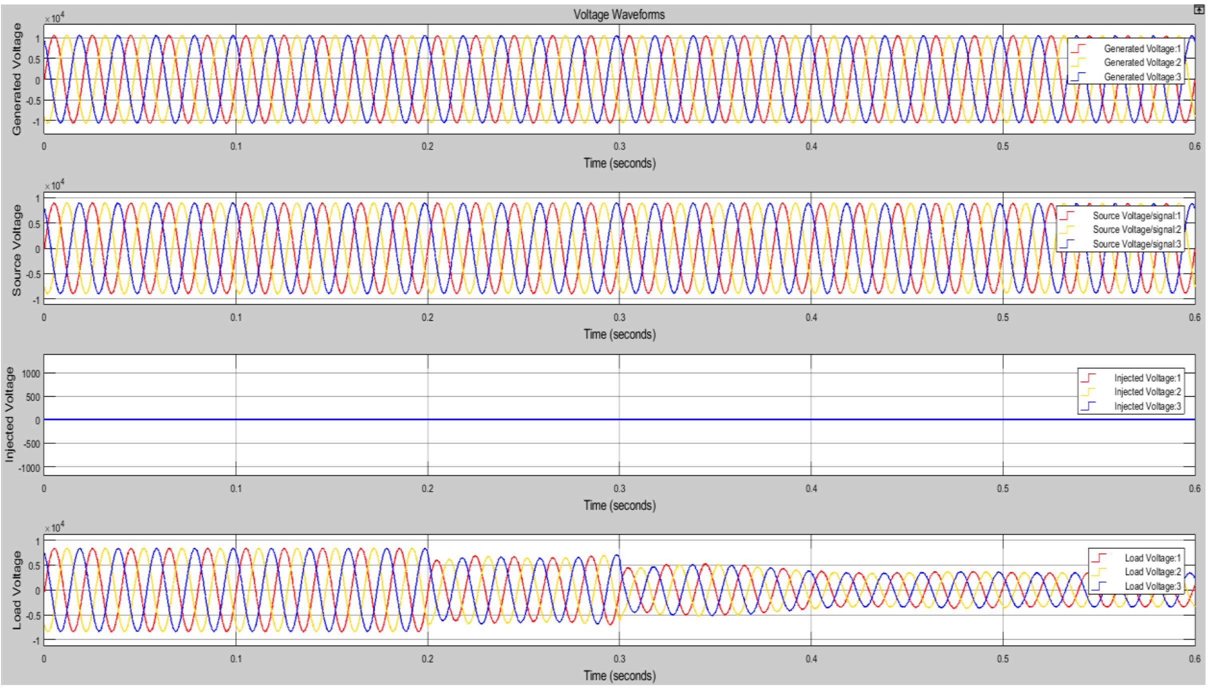


Figure 4.3.3: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage without DVR compensation

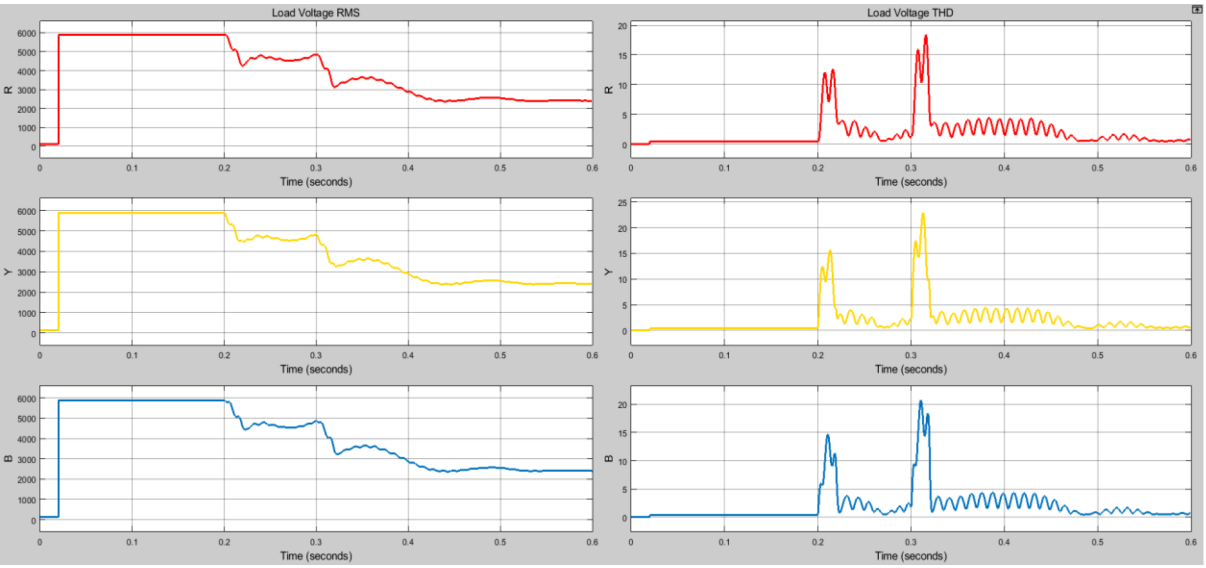


Figure 4.3.4: Load voltage RMS and THD waveforms without DVR compensation

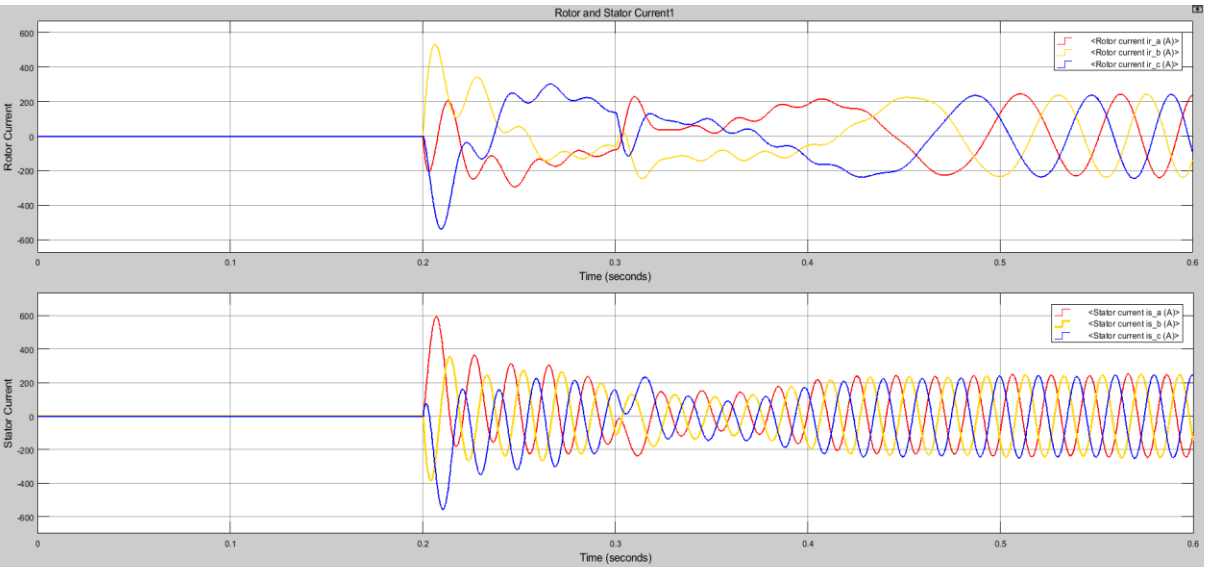


Figure 4.3.5: Rotor and stator current waveforms of motor1 without DVR

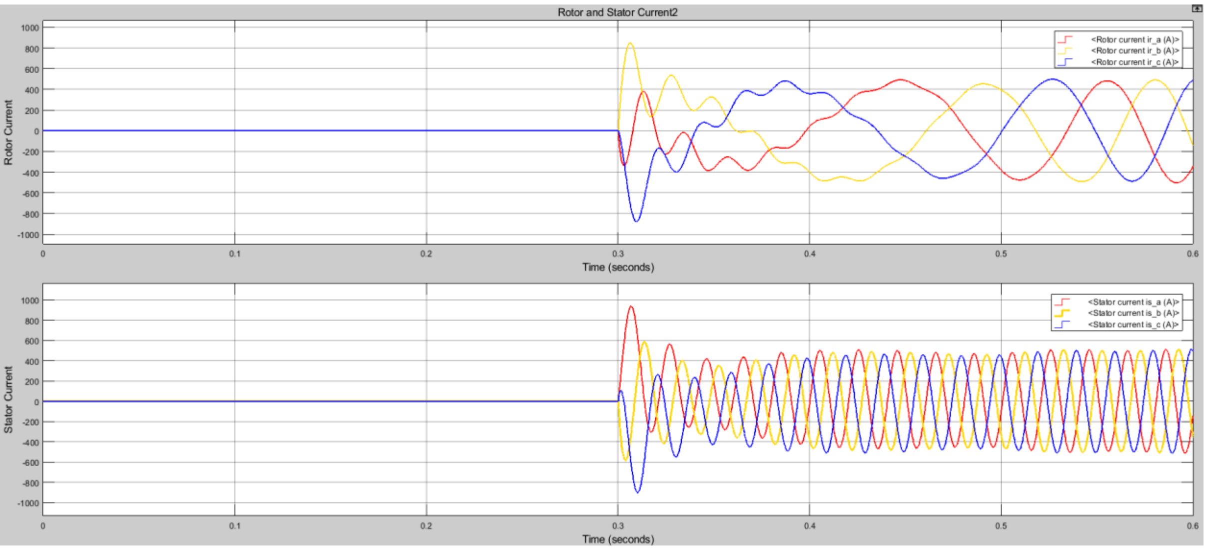


Figure 4.3.6: Rotor and stator current waveforms of motor2 without DVR

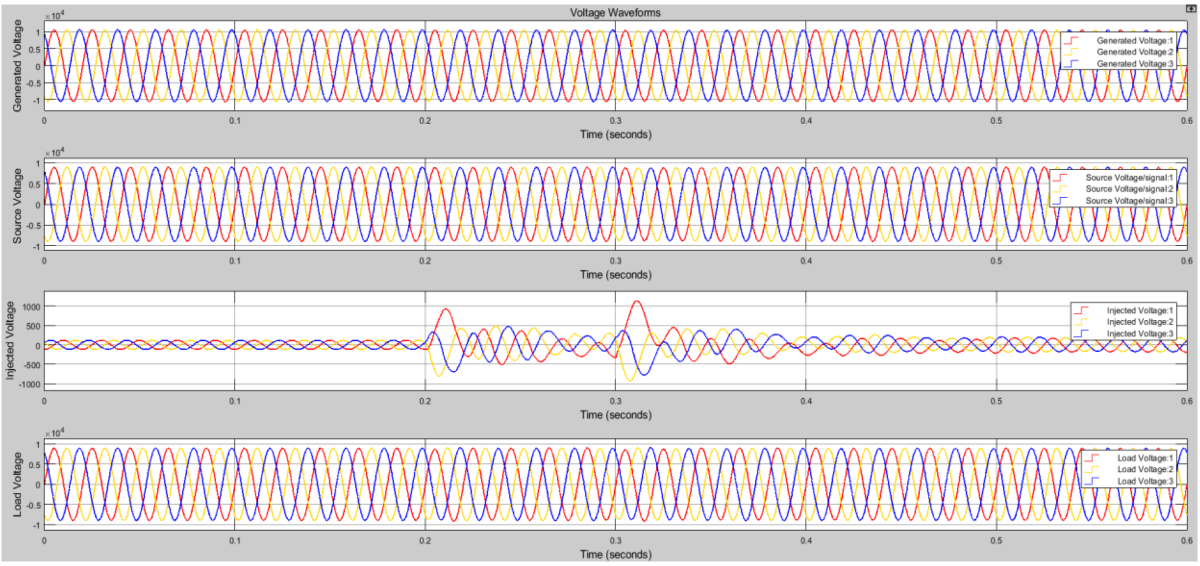


Figure 4.3.7: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage with DVR compensation

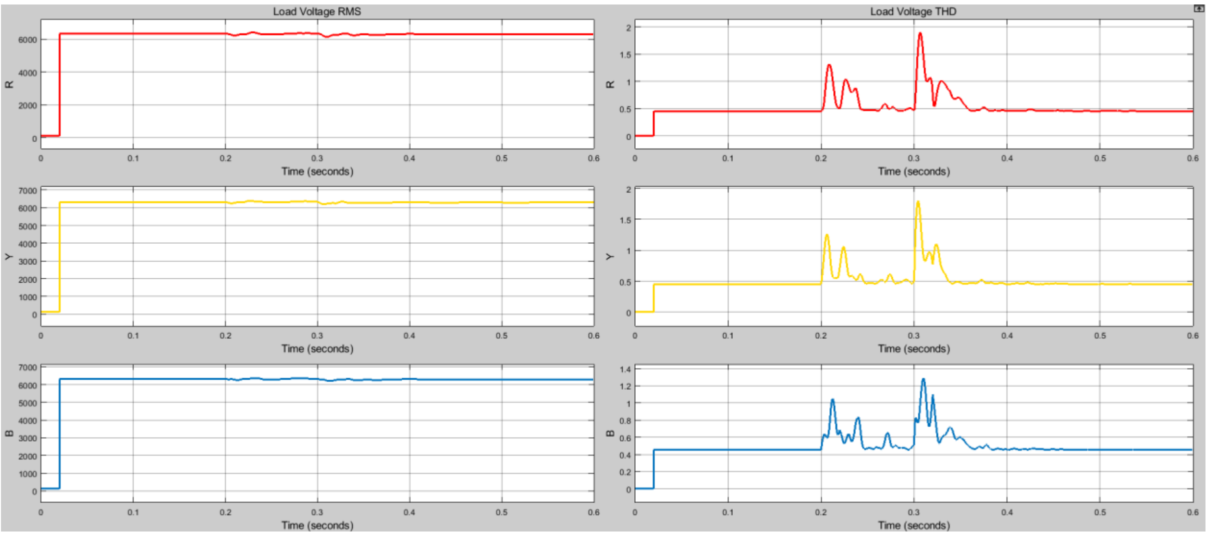


Figure 4.3.8: Load voltage RMS and THD waveforms without DVR compensation

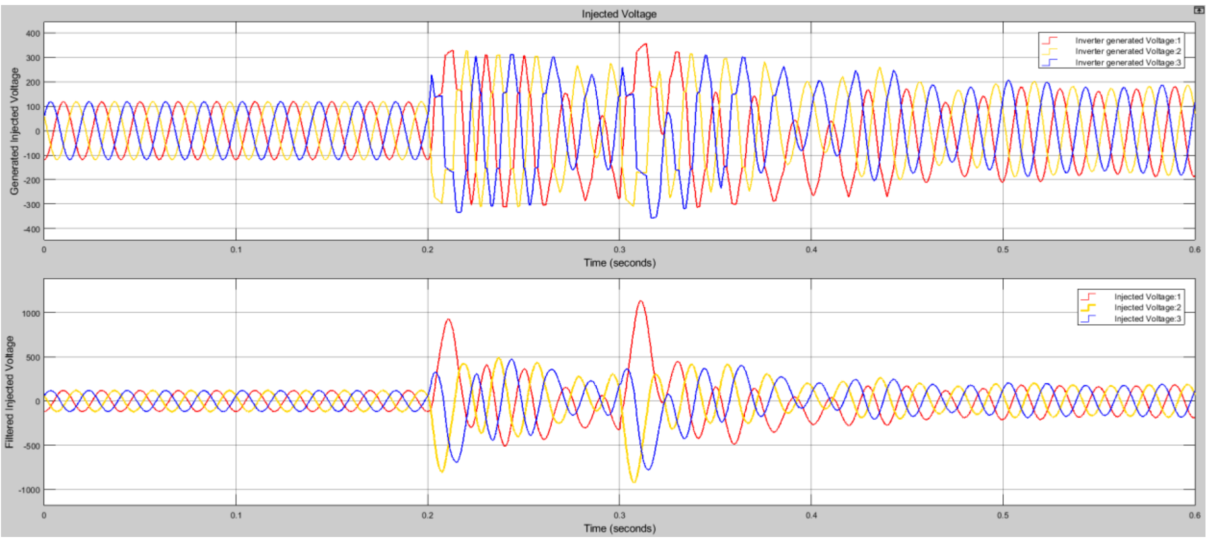


Figure 4.3.9: (a) Inverter generated voltage and (b) Voltage injected as compensation

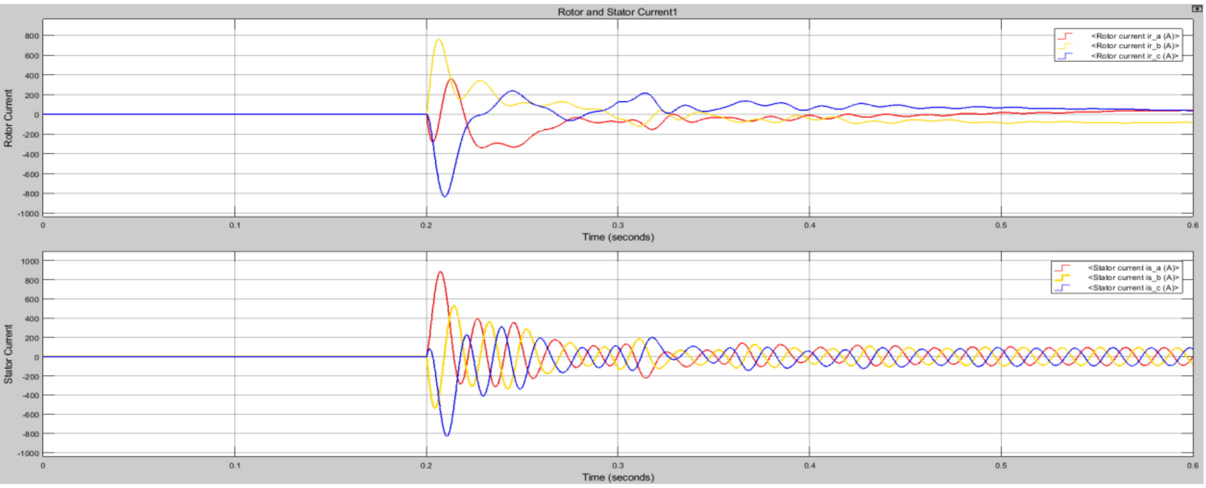


Figure 4.3.10: Rotor and stator current waveforms of motor1 with DVR

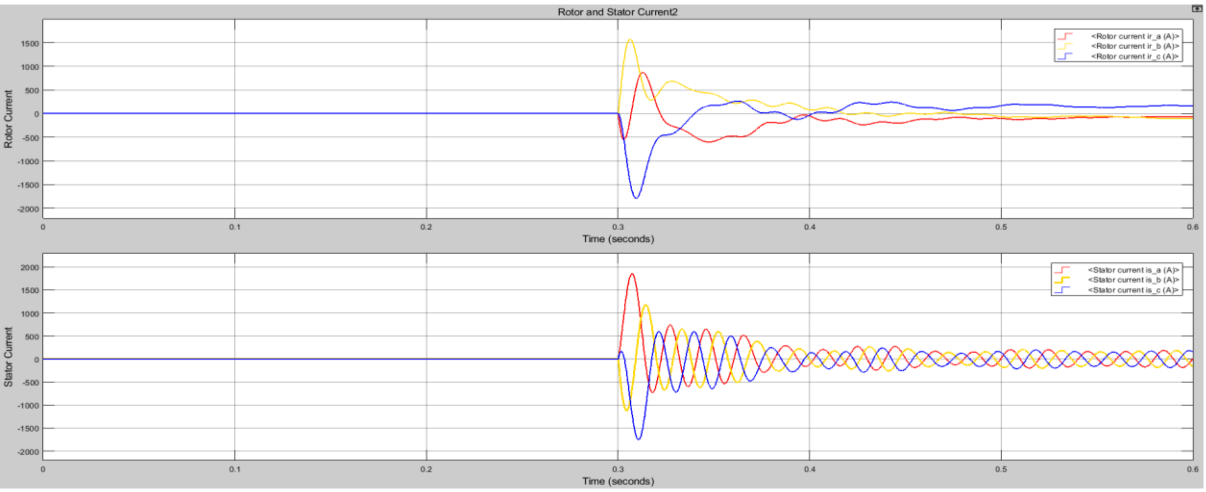


Figure 4.3.11: Rotor and stator current waveforms of motor2 with DVR

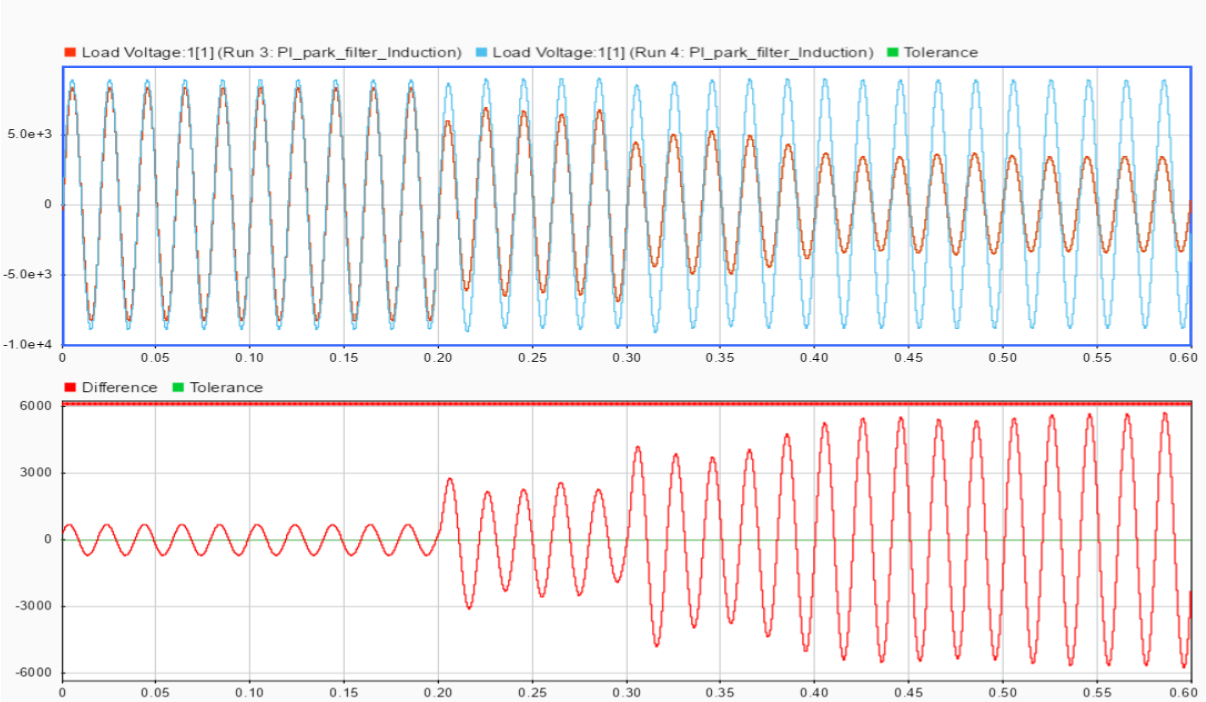


Figure 4.3.12: Comparison of load voltage without compensation and with compensation

Table 4.3.1: THD (in %) of different voltage waveforms at different cases

Phase / Signal	Load Voltage without compensation	Source Voltage	Injected Voltage	Load Voltage with compensation
R	12.75	0.35	27.21	0.48
Y	13.29	0.37	30.69	0.53
B	13.49	0.36	30.41	0.48

* THD of 'Load Voltage without compensation', 'Source voltage' and 'Load Voltage with compensation' have been calculated by taking 30 cycles (0.0 to 0.6) into consideration. THD of 'Injected voltage' has been calculated for the interval DVR is in injection mode. Here, for 20 cycles (0.2 to 0.6).

4.4 <u>Combination of Induction motor, non – linear load and linear load as additional load</u>

Here, a resistive load or linear load is introduced at t = 0.06s having power rating 100 kW. Then, at t = 0.2s inductive load rated at 80 kVAr and at t = 0.3s induction motor rated at 400 V, 75 kW, 1484 rpm are introduced into the system.

Addition of loads cause voltage sags can be observed in the load voltage waveform in Figure 4.4.2 and the effect of loading can be observed in Figure 4.4.3. The voltage sag is mitigated and the compensated voltage waveforms can be observed in Figure 4.4.5. Figures 4.4.4 and 4.4.7 show the current waveforms of stator and rotor of motor without compensation of the load voltage after load voltage sag compensation respectively.

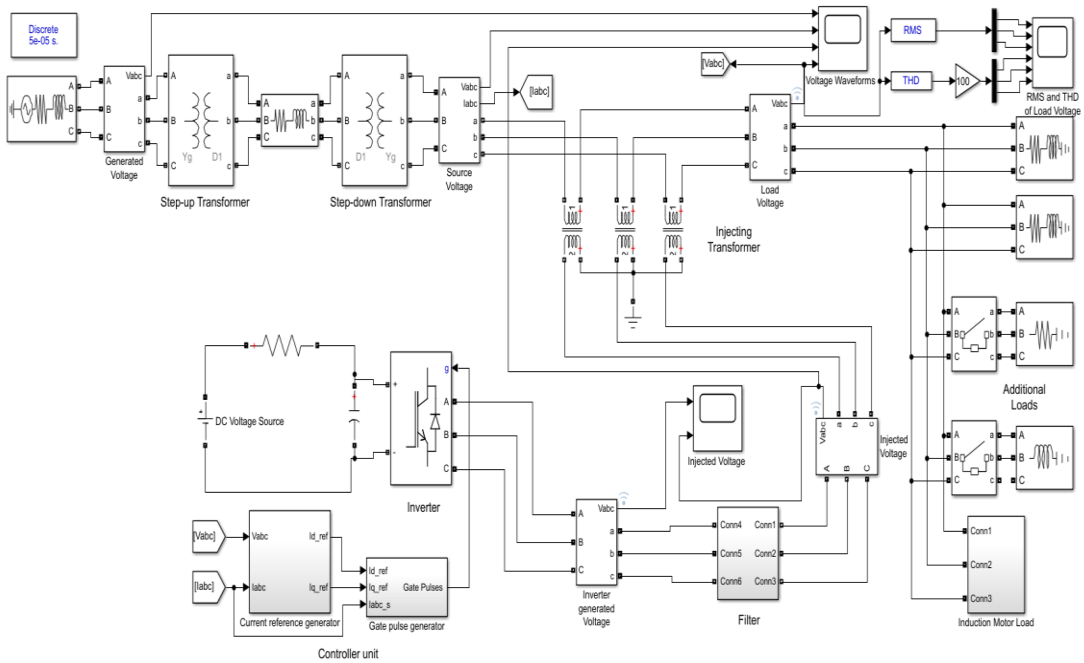


Figure 4.4.1: Three-phase system with induction motor, inductive load and resistive load as additional load

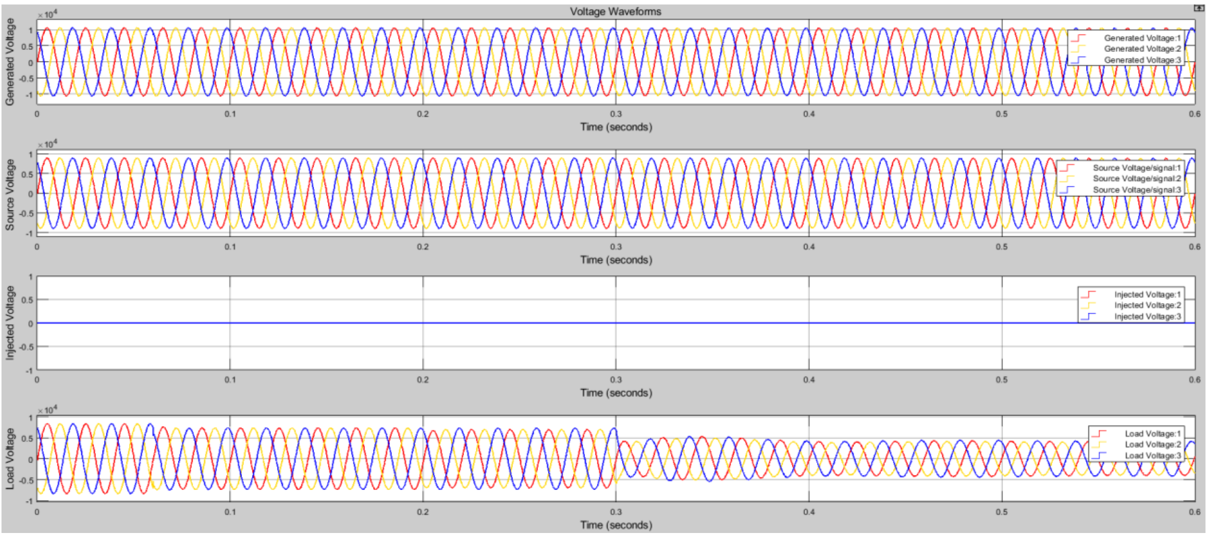


Figure 4.4.2: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage without DVR compensation

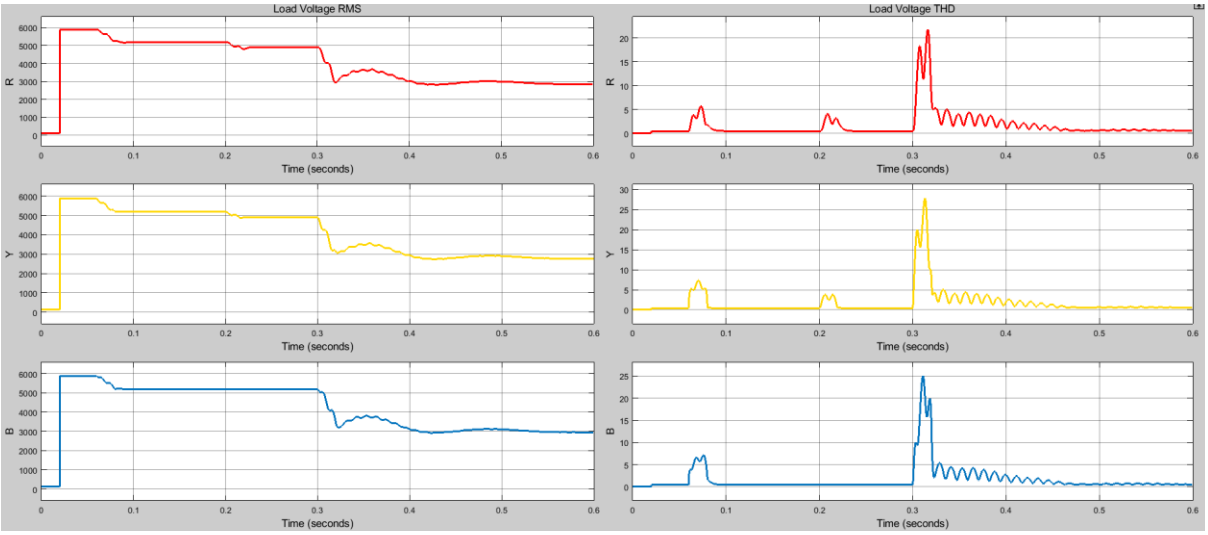


Figure 4.4.3: Load voltage RMS and THD waveforms without DVR compensation

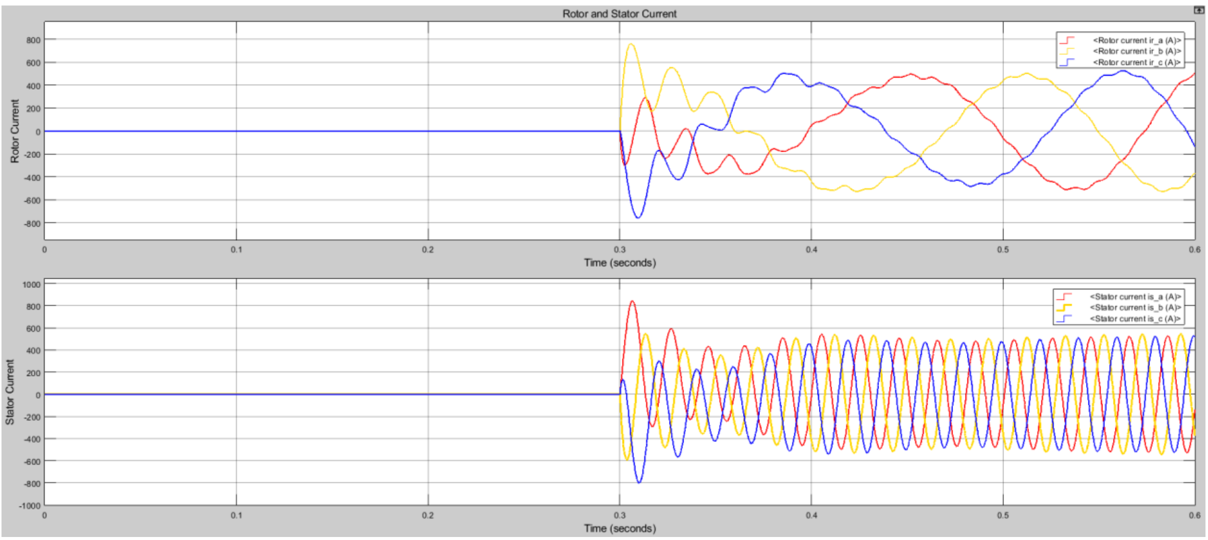


Figure 4.4.4: Rotor and stator current waveforms of motor without DVR

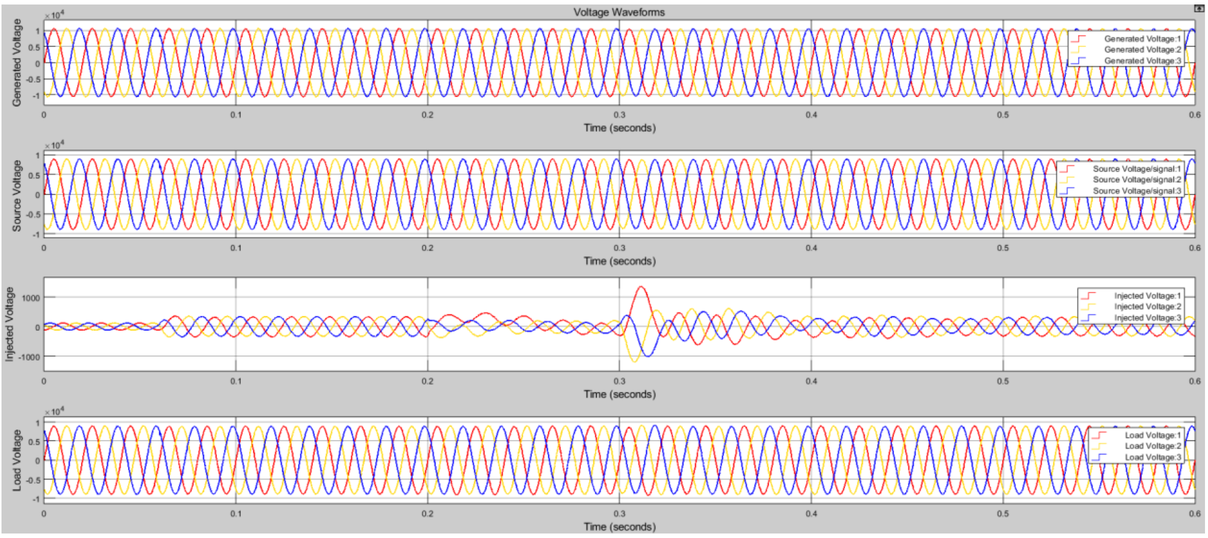


Figure 4.4.5: Voltage waveforms of (a) generated voltage, (b) source voltage, (c) injected voltage and (d) load voltage with DVR compensation

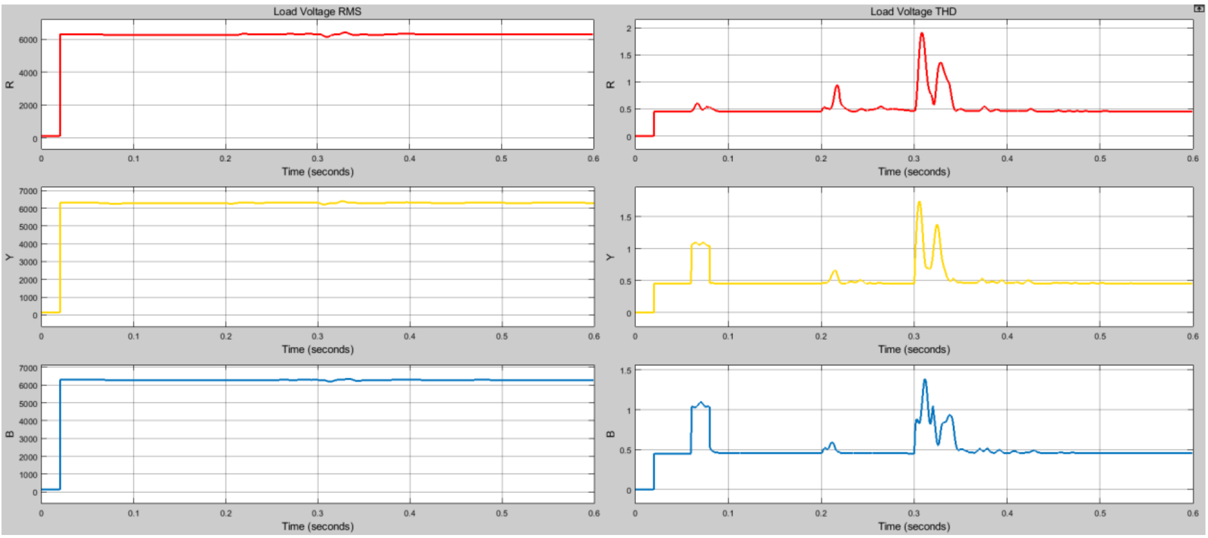


Figure 4.4.6: Load voltage RMS and THD waveforms without DVR compensation

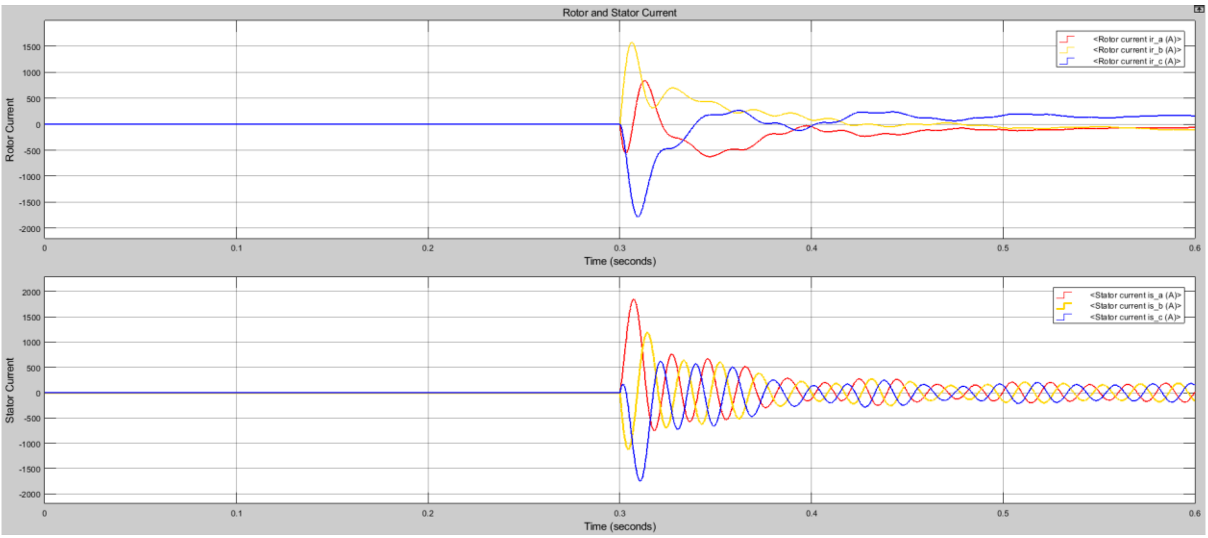


Figure 4.4.7: Rotor and stator current waveforms of motor1 with DVR

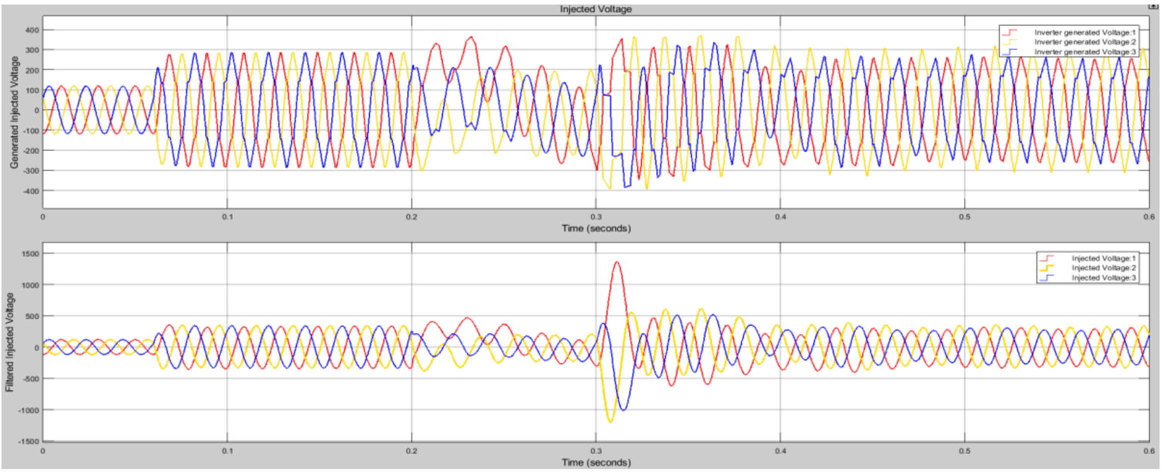


Figure 4.4.8: (a) Inverter generated voltage and (b) Voltage injected as compensation

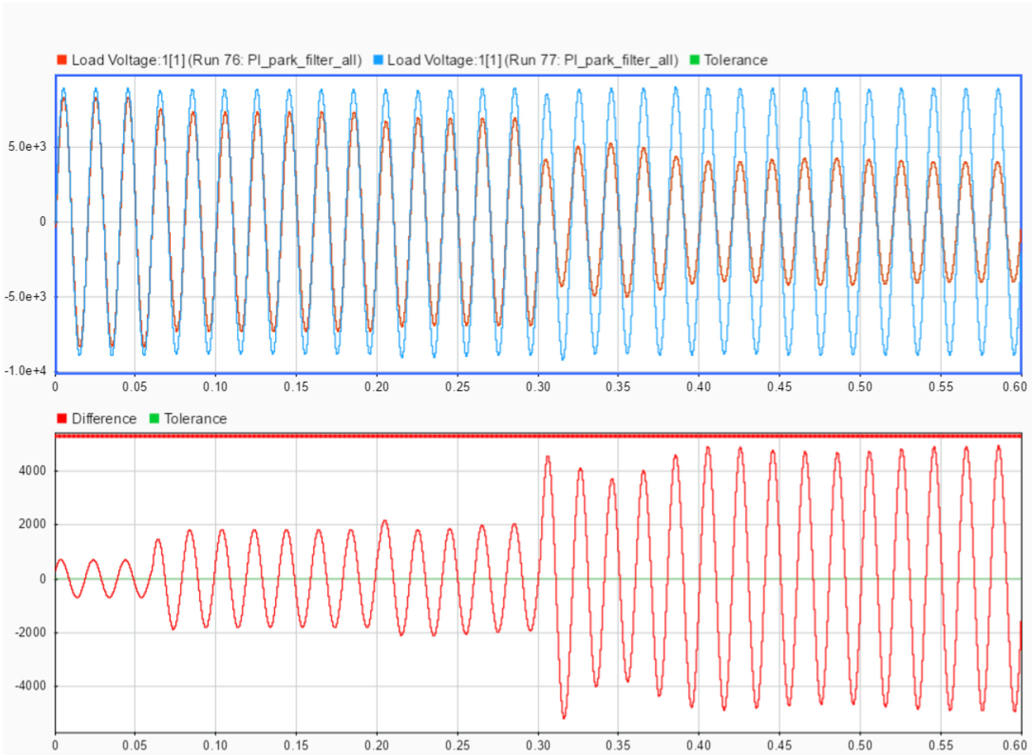


Figure 4.4.9: Comparison of load voltage without compensation and with compensation

Table 4.4.1: THD (in %) of different voltage waveforms at different cases

Phase / Signal	Load Voltage without compensation	Source Voltage	Injected Voltage	Load Voltage with compensation
R	19.82	0.28	31.60	0.31
Y	21.97	0.33	32.90	0.37
B	19.21	0.31	29.50	0.37

* THD of ‘Load Voltage without compensation’, ‘Source voltage’ and ‘Load Voltage with compensation’ have been calculated by taking 30 cycles (0.0 to 0.6) into consideration. THD of ‘Injected voltage’ has been calculated for the interval DVR is in injection mode. Here, for 27 cycles (0.06s to 0.6s).

4.5 Result

Figures 4.1.7, 4.2.7, 4.3.12 and 4.4.9 show the comparison of the load voltage waveform with DVR compensation and without DVR compensation. It can be observed that as DVR has a limitation that it can supply at most 50% of the maximum voltage, in 4.3 and 4.4, it cannot compensate the voltage sag completely.

Tables 4.1.1, 4.2.1, 4.3.1 and 4.4.1 show the THD in the various voltage waveforms (Data collected from ‘Powergui’ block THD analysis). It can be clearly seen that the aim of improving the power quality is clearly achieved as the total harmonic distortion of the load voltage waveforms after compensation in each case is less than 5%. Further, the injected voltage waveform THD in cases of linear and non – linear load is within 5% to 10% but in cases of induction motor load and combination loads, THD of injected voltage waveform is very high. In case of combination of loads, it was observed that the THD when linear and non-linear loads are compensated is within10% range but for induction motor it is very high. The main reason behind this is the transient caused during the starting of the induction motor.

Figures 4.1.6, 4.2.6, 4.3.9 and 4.4.8 show the generated sinusoidal PWM inverter voltage and the filtered voltage that is injected to the system for voltage sag compensation. The discontinuity in the inverter generated voltages can be clearly seen from the waveforms and the RLC filters successfully remove the unwanted harmonics as well. This helps to improve the quality of the mitigation of voltage sag and thereby help to enhance the power quality.

Table 4.3: THD (in %) of load voltage waveforms with different controllers

Phase/Controller	**Type of controller**					
	Without compensation	**Park [6]**	**PI [1]**	**Park2 [1]**	**Park + PI (without filter)**	**Park + PI (with filter)**
R	12.25	8.68	1.10	1.71	1.45	0.95
Y	12.74	7.16	1.20	1.63	1.74	0.96
B	12.63	9.33	1.11	3.32	1.49	0.98

Table 4.3 shows the total harmonic distortion in the load voltage waveforms when different controllers are used. For all the cases the same three-phase system was used with extra load of active power 150 kW and inductive reactive power of 120 kVAr added to the system from t = 0.2s to t = 0.4s. Along with the controller, the filter values as provided in the reference papers were taken into consideration to obtain the results. The above values were obtained from the FFT analysis option present in Powergui block in MATLAB SIMULINK.

Figure 4.6 represents the comparison of the R-phase load voltage waveforms that are mentioned in Table 4.3.

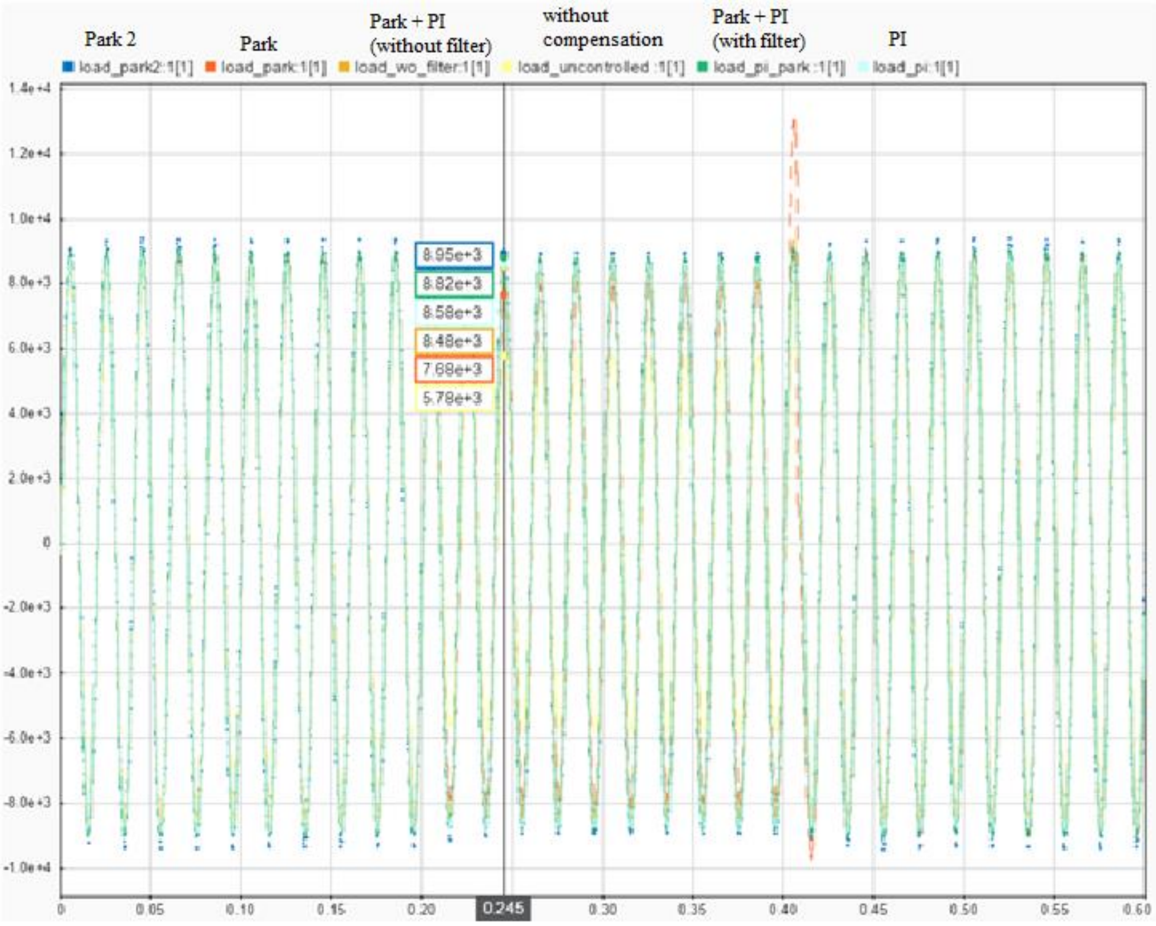


Figure 4.6: Comparison of load voltage waveforms with different controllers

CHAPTER 5

CONCLUSION

5.1 Conclusion

The demand for quality power has become a challenging issue for industrial area and consumers. Among them voltage sag is a major problem that leads to degradation in performance of electrical equipment. Dynamic Voltage Restorer is a power FACTS device that provides satisfactory solution to this problem with the additional advantage of reducing the harmonics by introducing RLC filter. The MATLAB simulation results clearly show the performance of the DVR in mitigating the voltage sags under the different conditions. To fix the load voltage as a constant and balanced one at the basic required value, the DVR injects necessary voltage to the system; in the process protecting the sensitive loads.

In this project Dynamic Voltage Restorer is applied for different sag conditions created by sudden change of load. The simulation result provides the resultant voltage waveform during sag conditions and the compensated voltage waveform when DVR is applied. Also, the THD analysis is done in order to show the efficiency of the method.

This project concludes that Dynamic Voltage Restorer handles both balanced and unbalanced situations without any difficulty and injects appropriate voltage component, maximum up to 50 per cent of the maximum voltage. DVR connected in series to the load side of the power system, compensates the sags swiftly providing excellent voltage regulation. Further, the application of the RLC filters helps to remove the unwanted harmonics from the controlled voltage generated by the inverter that is injected to the system to remove the voltage sag, thereby maintaining the THD levels. Hence, ensuring that power quality is better. Thus, the aim of the project to improve the power quality of the system by the introduction of Dynamic Voltage Restorer is achieved successfully.

When applying DVR, it is vital to consider nature of load so as to set the filter inductance and capacitance values, type of voltage supply for proper application of the PARK transformation and operation of PLL and the transmission system to select the rating of the energy storage system and the injection transformer.

5.2 <u>Future Scope</u>

- Dynamic Voltage Restorer successfully restores the voltage sag when there is sudden increase in the load irrespective of the load. But in case of induction motor, due to very high starting current resulting in introduction of harmonics and the transients, the voltage waveforms are slightly distorted. Certain changes in the system to reduce this effect will further boost the efficiency of the DVR.
- The recent developments in the field of renewable energy sources like solar and wind have led to decrement in the power quality as these sources use non – linear devices for better performance which introduce harmonics. DVR can be implemented for renewable energy-based power system.
- The control circuit of DVR can be further improved by using new complex techniques. This may further boost the performance of the DVR and ensure better voltage regulation and enhance the power quality.
- To remove the harmonics, RLC filter has been used. Certain internal changes and developments in the inverter may help to remove the filter and reduce the cost of the system. Also, RLC filter can be replaced by virtual filter like programmable band-pass filter which will allow only the required frequencies to pass and eliminate the rest. This can further boost the performance of the Dynamic Voltage Restorer.

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