Enrichment of Voltage Profile in Secondary Distribution System using DVR

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Abstract— The power quality issues affect customers directly or indirectly in terms of economic losses due to the equipment damage, process interruption, production loss, data loss, wastage of material etc. Different kinds of techniques have been utilized over the years in industry to compensate voltage unbalance along electric power distribution networks such as booster transformers, series capacitors, shunt reactors, and most recently Volt-VAR reactive power compensation, phase rearrangement, phase balancing between specific medium voltage feeder and the power distribution energy converter banks with a radial arrangement system. Hence, the simple, effective and cheapest device for voltage profile correction in distribution network compared to other custom power devices is the dynamic voltage restorer (DVR). A DVR is connected between the secondary distribution transformer and the customer load along a feeder with a radial arrangement. An innovative new design-model of the DVR has been proposed and developed using dq0 controller and the proportional integral (PI) controller method. Model simulations were carried out using MATLAB/Simulink in Sim Power System tool box.

Keywords: voltage profile, power quality, power distribution, proportional control

I. INTRODUCTION

The technological advancements have proven a path to the modern industries to extract and develop the innovative technologies within the limits of their industries for the fulfilment of their industrial goals and their ultimate objective is to optimize the production while minimizing the production cost and thereby achieving maximized profits while ensuring continuous production throughout the period.

As such a stable supply of un-interruptible power has to be guaranteed during the production process. The reason for demanding high quality power is basically the modern manufacturing and process equipment, which operates at high efficiency, requires high quality defect free power supply for the successful operation of their machines. More precisely most of those machine components are designed to be very sensitive for the power supply variations. Adjustable speed drives, automation devices, power electronic components are examples for such equipment.

Failure to provide the required quality power output may sometimes cause complete shutdown of the industries which will make a major financial loss to the industry concerned. Thus the industries always demands for high quality power from the supplier or the utility. Following shows some abnormal electrical conditions caused both in the utility end and the customer end that can disrupt a process.

1) Voltage sags & swells.
2) Voltage interruptions.
3) Transients due to Lighting loads, capacitor switching, nonlinear loads, etc.
4) Harmonics.
5) Voltage unbalances, etc.

As a result of above abnormalities the industries may undergo burned-out motors, lost data on volatile memories, erroneous motion of robotics, increased maintenance costs and burning core materials especially in plastic industries, paper mills & semiconductor plants. Among those power quality abnormalities voltage sags and swells or simply the fluctuating voltage situations are considered to be one of the most frequent type of abnormality. As the power quality problems are originated from utility and customer side, the solutions should come from both and are named as utility based solutions and customer based solutions respectively. The best examples for those two types of solutions are FACTS devices (Flexible AC Transmission Systems) and Custom power devices. FACTS devices are those controlled by the utility, whereas the Custom power devices are operated, maintained and controlled by the customer itself and installed at the customer premises. Both the FACTS devices and Custom power devices are based on solid state power electronic components.

Uninterruptible Power Supplies (UPS), Dynamic Voltage Restorers (DVR) and Active Power Filters (APF) are examples for commonly used custom power devices. Among those APF is used to mitigate harmonic problems occurring due to non-linear loading conditions, whereas UPS and DVR are used to compensate for voltage sag, voltage swell and voltage unbalance conditions. In this report the control of a Dynamic voltage restorer (DVR) for supply voltage disturbances has been studied.

II. DYNAMIC VOLTAGE RESTORER

Among the power quality problems (sags, swells, harmonics…) voltage sags, swells and supply voltage unbalances are the most severe disturbances. In order to overcome these problems the concept of custom power devices is introduced recently. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells Injection, DVR can also be added other features like: line voltage harmonics Injection, reduction of transients in voltage and fault current limitations.

A DVR is a solid state power electronics switching device consisting of either GTO or IGBT, a capacitor bank as an energy storage device and injection transformers. It is linked in series between a distribution system and a load that shown in Fig. 1. The basic idea of the DVR is to inject a controlled voltage generated by a forced commuted converter in a series to the bus voltage by means of an injecting transformer. A DC to AC inverter regulates this voltage by sinusoidal PWM technique. All through normal operating condition, the DVR injects only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag occurs in the distribution system, the DVR control system calculates and synthesizes the voltage required to preserve output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the distribution system to the critical load.

Note that the DVR capable of generating or absorbing reactive power but the active power injection of the device must be provided by an external energy source or energy storage system. The response time of DVR is very short and is limited by the power electronics devices and the voltage sag detection time. The predictable response time is about 25 milliseconds, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers.

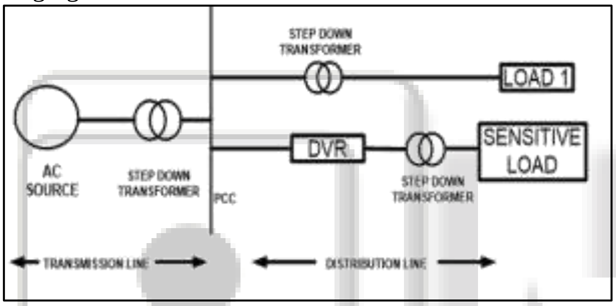


Fig. 1: Location of DVR

The basic configuration of DVR is shown in Fig. 2. The DVR consists of:

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

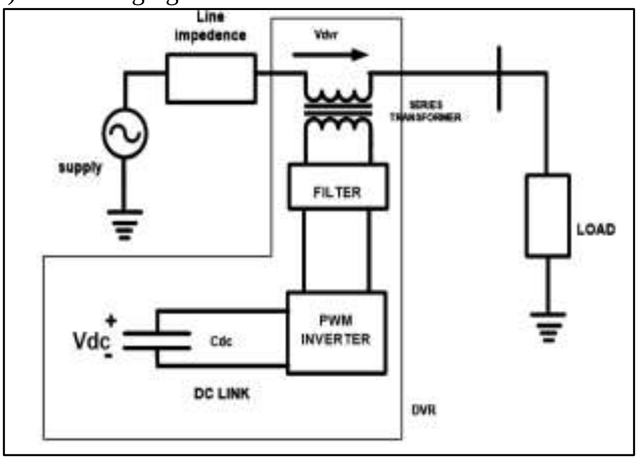


Fig. 2: Basic configuration of DVR

Three single phase transformers are connected in series with the distribution feeder to couple the VSC (at the lower voltage level) to the higher distribution voltage level. It links the DVR system to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection transformer also serves the purpose of isolating the load from the DVR system (VSC and control mechanism). The output of the inverter contains high frequency switching harmonics. To remove these switching harmonics, a three phase ripple filter (Electro Magnetic Interference-EMI) filter is used.

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

The dc charging circuit has two main tasks.

1) The first task is to charge the energy source after sag /swell Injection.

The second task is to maintain dc link voltage at the nominal dc link voltage.

Transformer rating of DVR is the maximum voltage that can be injected to supply, which be determined by specification needed, so transformer rating 1 KVA per phase is the multiplication of maximum voltage injection and current of primary transformer. Maximum injection voltage to system and maximum load current determine capacity of DVR. To Determine capacity of DVR be the needed supply characteristic, including magnitude of voltage sags and load current.

MVA (DVR) = rated MVA (load) x Maximum voltage injection (pu)

So, rating of DVR must not be the same as the rating of load served.

The control and protection of a DVR designed to compensate voltage sags must consider the following functional requirements.

1) When the supply voltage is normal, the DVR operates in a standby mode with zero voltage injection. However if the energy storage device (say batteries) is to be charged, then the DVR can operate in a self-charging control mode.
2) When a voltage sag/swell occurs, the DVR needs to inject three single phase voltages in synchronism with the supply in a very short time. Each phase of the injected voltage can be controlled independently in magnitude and phase. However, zero sequence voltage can be eliminated in situations where it has no effect. The DVR draws active power from the energy source and supplies this along with the reactive power (required) to the load.
3) If there is a fault on the downstream of the DVR, the converter is by-passed temporarily using thyristor switches to protect the DVR against over currents. The threshold is determined by the current ratings of the DVR.

III. Dynamic Voltage Restorer Control Algorithm

The control algorithm is based on synchronously rotating reference frame transformation i.e. abc to dq0 transformation technique or Park’s transformation. The expression of V_{sa},

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

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

Where V_{sa}, V_{sb}, Vsc are the supply voltage, V_0, Vd, Vq are the zero axis, direct and quadrature axis voltages. The supply voltage to the load is given in equation (2). When rated balanced voltage is applied $V_{m1} = V_{m2} = V_{m3} = V_m$ and $\alpha = 0$. The respective V_0, V_d, and V_q are calculated in the following equations.

$$\left.\begin{aligned} v_{sa} &= V_{m1}\sin(wt \pm \alpha) \\ v_{sb} &= V_{m2}\sin(wt - 120 \pm \alpha) \\ v_{sc} &= V_{m3}\sin(wt - 240 \pm \alpha) \end{aligned}\right\} \quad (2)$$

$$v_0 = \frac{1}{3}(v_{sa} + v_{sb} + v_{sc})$$

$$= \frac{1}{3}[V_m\sin(wt) + V_m\sin(wt-120) + V_m\sin(wt-240)]$$

$$= \frac{1}{3}V_m[\sin(wt) + \sin(wt-120) + \sin(wt-240)] \quad (3)$$

$$\therefore v_0 = 0$$

$$v_d = \frac{2}{3}[v_{sa} * \sin(wt) + v_{sb} * \sin(wt-120) + v_{sc} * \sin(wt-240)]$$

$$= \frac{2}{3}[V_m\sin(wt)*\sin(wt) + V_m\sin(wt-120)*\sin(wt-120) + V_m\sin(wt-240)*\sin(wt-240)]$$

$$= \frac{2}{3}[V_m\sin(wt)*\sin(wt) + V_m\sin(wt-120)*\sin(wt-120) + V_m\sin(wt-240)*\sin(wt-240)]$$

$$= \frac{2}{3}[V_m \sin^2(wt) + \sin^2(wt-120) + \sin^2(wt-240)]$$

$$= \frac{1}{3}V_m\left[\left(\frac{1-\cos 2(wt)}{2}\right) + \left(\frac{1-\cos 2(wt-120)}{2}\right) + \left(\frac{1-\cos 2(wt-240)}{2}\right)\right]$$

$$= \frac{1}{3}V_m[(\cos(2wt)) + (\cos(2wt-240)) + (\cos(2wt-480))]$$

$$= \frac{1}{3}V_m[3 - \cos(2wt) + \cos(2wt)$$

$$= \frac{1}{3} * 3V_m$$

$$\therefore v_d = V_m \quad (4)$$

$$v_q = \frac{2}{3}[v_{sa} * \cos(wt) + v_{sb} * \cos(wt-120) + v_{sc} * \cos(wt-240)]$$

$$= \frac{2}{3}[V_m\sin(wt)*\cos(wt) + V_m\sin(wt-120)*\cos(wt-120) + V_m\sin(wt-240)*\cos(wt-240)]$$

$$= \frac{1}{3}V_m[(\sin(2wt)) + (\sin(2wt-240)) + (\sin(2wt-480))]$$

$$= \frac{1}{3}V_m(\sin(2wt) - \sin(2wt))$$

$$\therefore v_q = 0 \quad (5)$$

From equations (3),(4) and (5) we can analyse that quadrature axis voltage and zero axis voltage are of zero value and direct axis voltage is a DC quantity of V_m. When unbalanced voltage is applied $V_{m1} \neq V_{m2} \neq V_{m3} \neq V_m$ and $\alpha = 0$, by solving the equation (2) the quadrature axis voltage and zero axis voltage are not zero value. The quadrature axis voltage is ac voltage with a frequency of twice the supply frequency and zero axis voltage is ac voltage with frequency of supply frequency. The direct axis voltage is a pulsating voltage with DC quantity of average value of V_{m1}, V_{m2}, and V_{m3} and ac quantity with a frequency of twice the supply frequency.

Equations above defines the transformation from three phase abc to dqo reference frame. In this transformation, phase a-axis is aligned to the d-axis which is in quadrature with q-axis. Here ωt is the angle between phase a-axis and the d-axis.

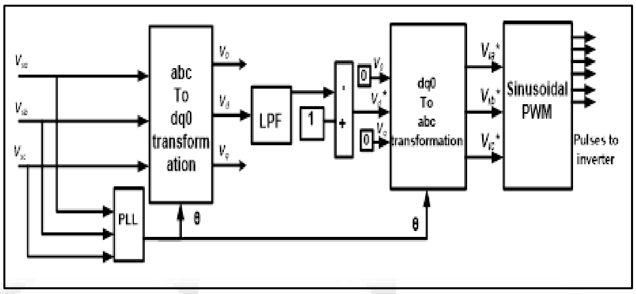


Fig. 3: Reference Voltage Signal Generation Block Diagram

IV. SIMULATION RESULTS

This chapter analyses the performance of the Dynamic voltage Restorer (DVR) with different supply voltage conditions (voltage sag, voltage swell, and voltage unbalance) to R-L load. The complete model of the DVR is constructed in Simulink environment (MATLAB). The specifications of the network is given in the Table 1. In Fig. 4, the distribution network's Simulink model is given. A distance of 5 Km is simulated. In Fig. 5, the DVR controller is shown.

Sr. No.	Quantity	Value
1	Supply Voltage	415V, 50Hz (line-line)
2	Source Impedance	$R_s = 0.5\ \Omega$, $L_s = 0.1$ mH
3	DC Capacitor	5000 uF
4	DC Link Voltage	680V
5	Ripple filter	$L_f = 2$ mH, $C_f = 50$ Uf
6	Series Transformer	1:1
7	Switching Frequency	20 kHz
8	Load	Three Phase Balanced Linear Load 120KW,0.9pf Un balanced load: Phase A 150KW Phase B 110KW Phase C 80KW

9	Three phase transformer	D-Y,500KVA,11000/239.6
10	Pi section line	0.01ohm/km,1mH/km,5km length
11	Circuit breaker on time	40-60 msec

Table 1: Simulation parameters used in simulation

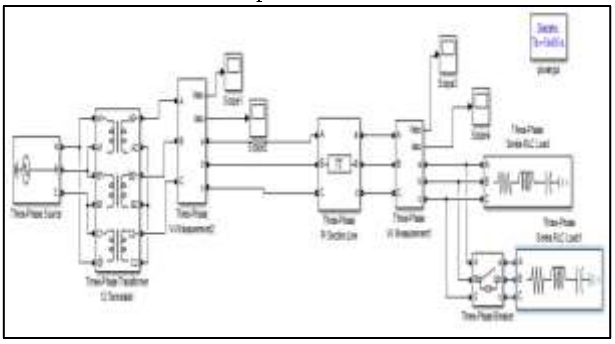


Fig. 3: Simulink model of distribution network of 5km

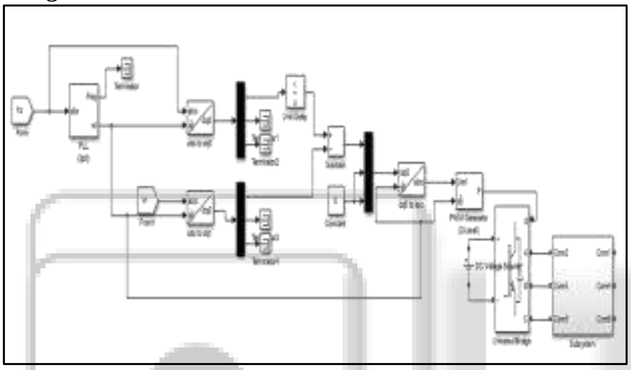


Fig. 4: Simulink model of DVR controller

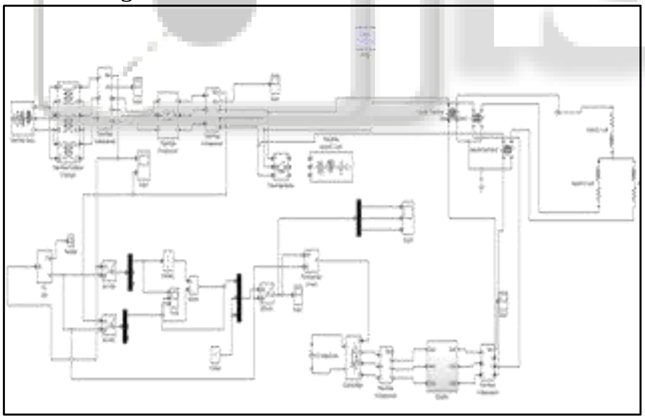


Fig. 5: Simulink model of unbalanced load voltage mitigation by using DVR.

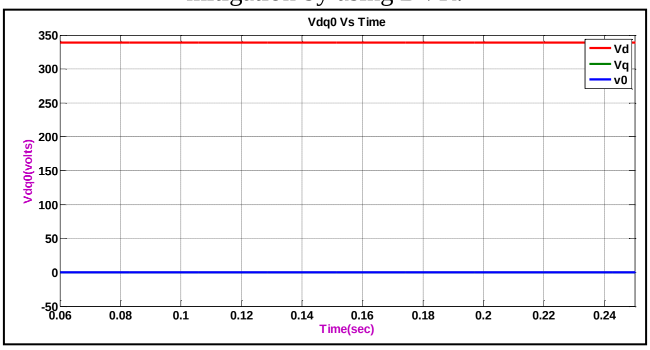
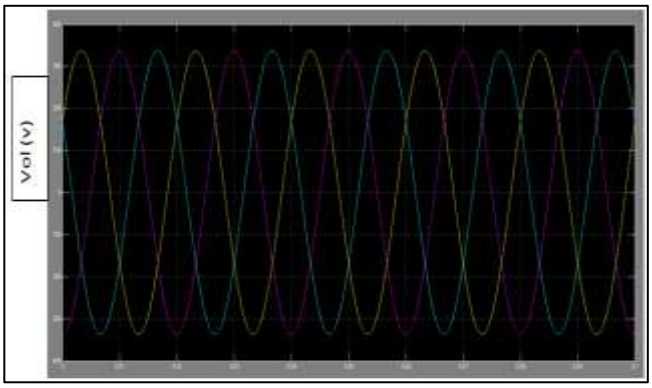


Fig. 6: Direct, Quadrature and Zero axis voltages



Time(sec)

Fig. 7: Sending end voltage. $V_{max} = 337.5V$

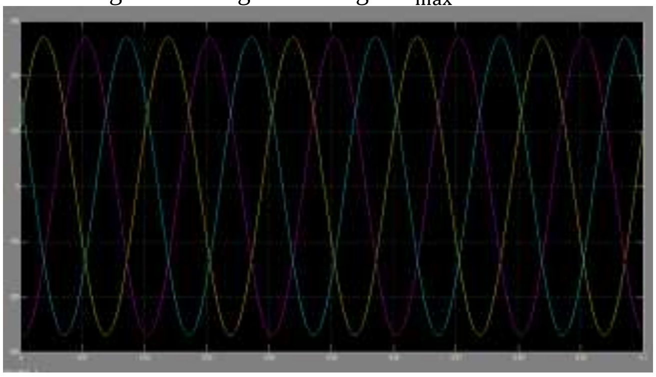


Fig. 8: Receiving end voltage for 5km before compensation. $V_{max} = 270$ V

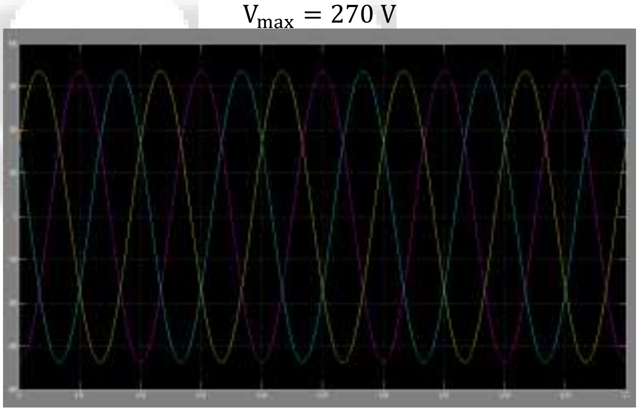


Fig. 9: Receiving end voltage for 5 km after compensation. $V_{max} = 337V$

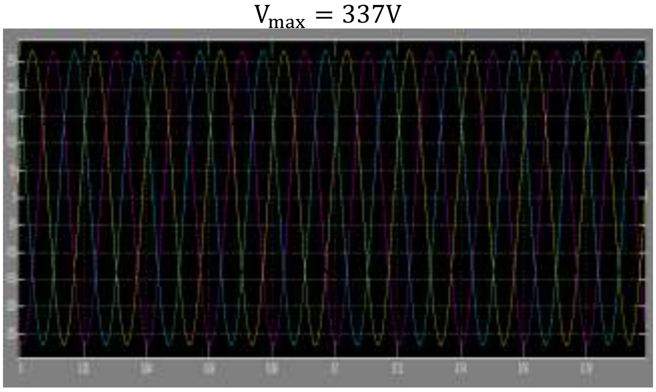


Fig. 10: Receiving end voltage for 2.5 km before compensation. $V_{max} = 300V$

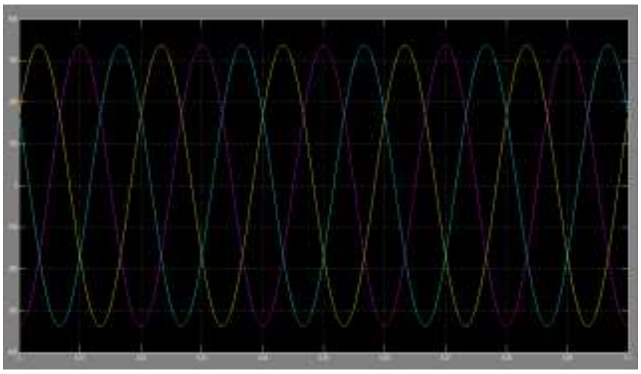


Fig. 11: Receiving end voltage for 2.5 km after compensation. $V_{max} = 337V$.

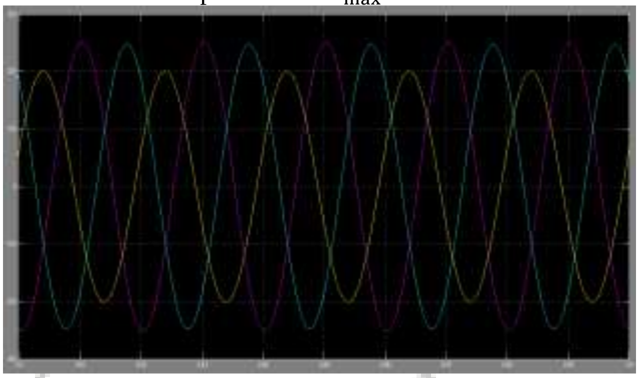


Fig. 12: Receiving end voltage for 5km before compensation for unbalanced load.

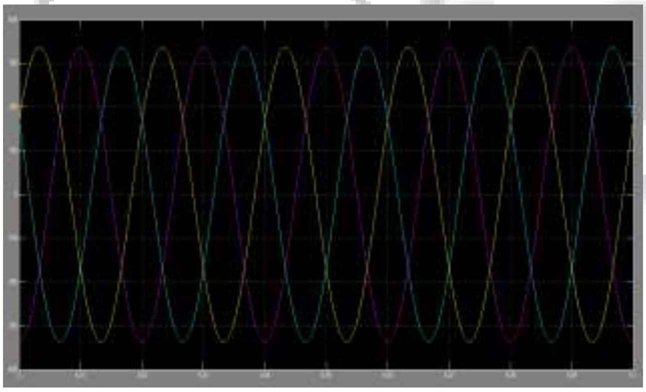


Fig. 13: Receiving end voltage for 5 km after compensation after compensation.

Line length (Km)	Vmax (V)	Vrms (V) [per phase]
0.5	329	232.63
1	321	227
1.5	314	222
2	307	217.08
2.5	300	212.13
3	293	207.18
3.5	287	202.94
4	281	198.7
4.5	275	194.45
5	270	191

Table 2: Receiving end voltages for different lengths

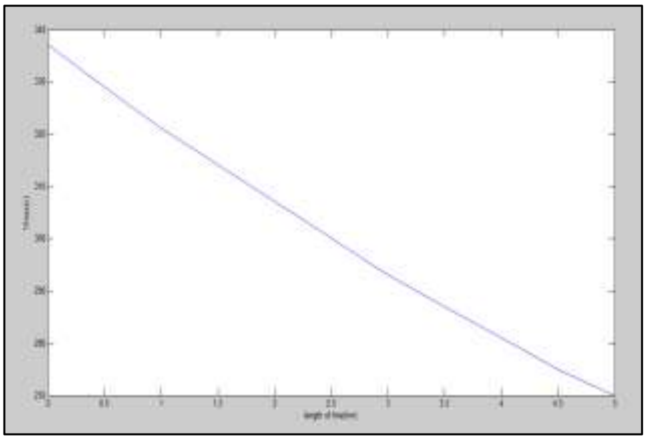


Fig. 14: Graph between Voltage vs Line length

V. CONCLUSION

In this paper, we introduced the Dynamic Voltage Restorer (DVR) for improving power quality that it is considered one of the custom power devices and one of the most efficient and effective solution for improving power quality. The performance and effectiveness of the proposed DVR connected to the system is tested with different case studies. To show the function of the DVR for mitigation of power quality problems, the DVR is connected to system with different loads and applied different faults. The simulation examples and results of the DVR connected to system with different loads are introduced. It is effective in mitigating the power quality problems and provides excellent voltage regulation and harmonics cancelation. The DVR injects the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. The future scope of the work is to mitigate the power quality problems when this load is fed from two different distribution feeders. For mitigation of power quality problems and investigation of power system stability a new device which is named Inter-line Dynamic Voltage Restorer (IDVR) can be employed. This device consists of two conventional DVRs which are installed in two different distribution feeders and the DC link.

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