Voltage Profile Enhancement using Dynamic Voltage Restorer (DVR) Under Three Phase Balance Load

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Abstract - *To improve power quality in low voltage electric power distribution network the inadequate operation of the conventional compensation devices to mitigate the poor power quality problems have prompted the use of custom power device such as Dynamic Voltage Restorer (DVR). DVR aimed at improving the voltage profile, enhancing the reliability and good quality of power flows in low voltage electric power distribution networks. The DVR is highly efficient device, the principle is based on the voltage source inverter (VSI) which injects the appropriate missing voltage in series with the system voltage to correct the voltage variations experienced in the distribution feeder lengths. The power scheme in respect of the response to voltage disturbances at normal mode operation of three phase balanced loads is presented using the MATLAB simulation. This dissertation gives recommendations on effective methods for improving the voltage profile and reducing the voltage variation to an allowable standard.*

Key Words: Dynamic voltage restorer, voltage source inverter, voltage profile, power quality, distribution networks, distribution feeder

1. INTRODUCTION

The electric power system serves to generate, transport, and distribute electrical energy to consumers in an efficient, economical and reliable manner. Failure operation of electrical equipment cause inadequate power quality and therefore there is power losses in the distribution system [6]. Load voltage variation, three phase voltage unbalance, waveform distortions, voltage sag, voltage swell, these are the various disturbances in the electric power network. Maintaining the voltage and frequency within the statutory limits that is ±5% voltage and ±1% frequency at the end user's terminal is a major challenge for distribution companies. The quality of electrical power, which is given to the end users, can be assessed or estimated in terms of constant voltage magnitude. Different kinds of techniques have been utilized over the years to mitigate voltage variation, voltage unbalance and improve the voltage profile along electric power distribution networks. The earlier stated techniques mostly focus on medium voltage side distribution systems. Hence, it is not enough to obtain the statutory voltage limits of ±5% of the nominal voltage value on the end-user side. Therefore, there is an urgent need to support secondary distribution systems with modern techniques. 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). DVR has been effectively used to find a solution to the power quality problems in the distribution network. The DVR has appeared as a promising device not only to provide voltage profile enhancement, but a fast solution to other power quality problems such as flicker suppression, power factor correction and harmonics control [8]. DVR insert a controlled voltage in distribution networks to correct the load voltage [3].

This paper presents a MATLAB/simulink model of DVR for voltage sag, voltage swell, voltage variations and voltage unbalance mitigation in low voltage electric power distribution network for different feeder lengths using control technique of VSI switching method based on sinusoidal pulse width modulation offers simplicity and better response.

2. DYNAMIC VOLTAGE RESTORER

The block diagram of DVR is shown in Fig.1. It consists of three important parts: measuring unit, control unit, and power unit.

A. Series Voltage Injection Transformer

The utmost function of series voltage injection transformer which is employed in secondary distribution system is that to step up the supply voltage from the output of the ac line filter to the desired nominal voltage level required by the customer load For DVR to properly compensate for the missing voltage, the secondary side of the series voltage injection transformer must be equal to the main source voltage and must be properly matched to the power system network [11].

B. AC Filter

Essentially, filters are employed to decrease or get rid of the switching harmonics produced by the voltage inverter system. This is done to keep a standard permissible harmonic distortion level of the sinusoidal voltage waveform that is supplied to a series voltage injection transformer.

C. DC Charging Unit

This charges the energy source after voltage fluctuation and the variation compensation event, and it also maintains dc link voltage at the nominal dc link voltage and provides a discharge circuit and grounding equipment for maintenance purposes.

D. Pass Switch

A pass switch is employed primarily in a secondary distribution system to safeguard the entire DVR system from fault currents caused by faults in the secondary distribution system.

E. Voltage Source Inverter

VSI comprises six pulses with their ac outputs linked to the secondary windings of the series voltage injection transformer through ac line filter. The VSI circuit generates the injected voltages to compensate for the voltage disturbances. The rating of the VSI is comparatively low in voltage and high in current; this is due to the presence of the step up series voltage injection transformer employed in the design of DVR systems.

F. Energy Storage

This supply the necessary energy to the VSI via a dc link for the generation of needed voltages during disturbances in the network, and most of the DVR application, the energy source can be an electrolytic capacitor bank.

G. Control Unit

A controller is employed for effective control of DVR systems. DVR detects the presence of voltage disturbances and compensates the voltage problem. The PWM provides an effective method of controlling an inverter to generate ac power from dc power to produce a three-phase 50-Hz sine wave voltage on the load side. The control of compensating device is carried out in three steps: detection of voltage disturbance occasion in the system, compared with the reference value, and the production of gate pulses to the VSI to produce the DVR output voltages, which will mitigate poor voltage profile and other power quality problems in the power system.

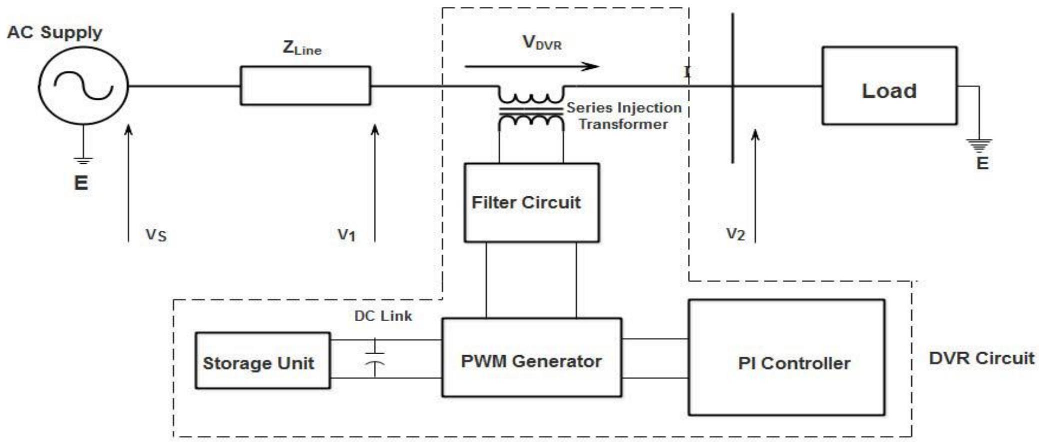

Fig.-1: Block diagram of DVR

2.1 Operation Principle of DVR

A DVR is a solid-state power electronics based custom power device which is connected in series to the load voltage for the purpose of injecting a controlled voltage to the electric distribution network. A DC capacitor bank as an energy storage device is used in DVR, which is connected by coupling transformer. The voltage across the DC link capacitor is control by converter that uses as a common voltage source for the inverters. The IGBT inverter generates a missing voltage, which is added into the electric distribution networks with the help of series step up transformer is also known as coupling transformer. DVR PI controller perform the voltage profile regulation which generates a reference voltage, and compare it with the source voltage of the system in order to inject the missing voltage to keep the load voltage constant. The needed power to synchronize the injected voltage is given by the DC energy storage device. The AC filter connected to the output of the VSI is used to reduce the harmonic generated by the VSI before passing to the step up transformer which carry out proper matching to the distribution network.

3. DVR CONTROL SCHEME

In low voltage electric power distribution network, to keep the voltage magnitude constant at the point of load connection and under system voltage variation disturbances a controller must be introduced. The introduced control scheme is proposed for improvement of DVR operation where they measures the r.m.s voltage at the load point only, the reactive power measurements are not necessary. The voltage source inverter switching method is based on sinusoidal pulse width modulation is used. This method performs a significant role and offers a simplicity, good response and flexible performance than other methods used. The controller performs an excellent control on an error signal obtained from the r.m.s value of the load voltage and the reference voltage value. The error is processed by the discrete PI controller. The proportional integral (PI) controller helps to continuously estimate an error value as the difference between a reference voltages and a load voltage measured on the system. Block diagram of DVR control scheme is shown in figure 2. The two level pulse width modulation generator generates the needed pulse to fire the three phase IGBT inverter with the appropriate triggering sequence, this is to enable the inverter switching to generate three phase 50 cycle per second sinusoidal voltage at the load terminal. A phase-locked loop (PLL) is employed to maintain phases and frequencies matched of output signals with the reference; this is made possible through the use of phase shift detector and frequency oscillator mode of the feedback system in the PLL controller. To reduce the harmonics generated by inverter switching circuit, filter is used and to inject the appropriate missing voltage processed by the control circuit and the power circuit to the electric power distribution network, isolation transformer is used.

The modulated three phase voltages are given in equation (1), (2), and (3)

$$Va = \sin(\omega t + \delta) \quad (1)$$

$$Vb = \sin\left(\omega t + \delta + \frac{2\pi}{3}\right) \quad (2)$$

$$Vc = \sin\left(\omega t + \delta + \frac{4\pi}{3}\right) \quad (3)$$

The AC amplitude reference voltage can be calculated using equation (4)

$$V_s = \frac{2}{3}((V_{sa})^2 + (V_{sb})^2 + (V_{sc})^2)^{0.5} \quad (4)$$

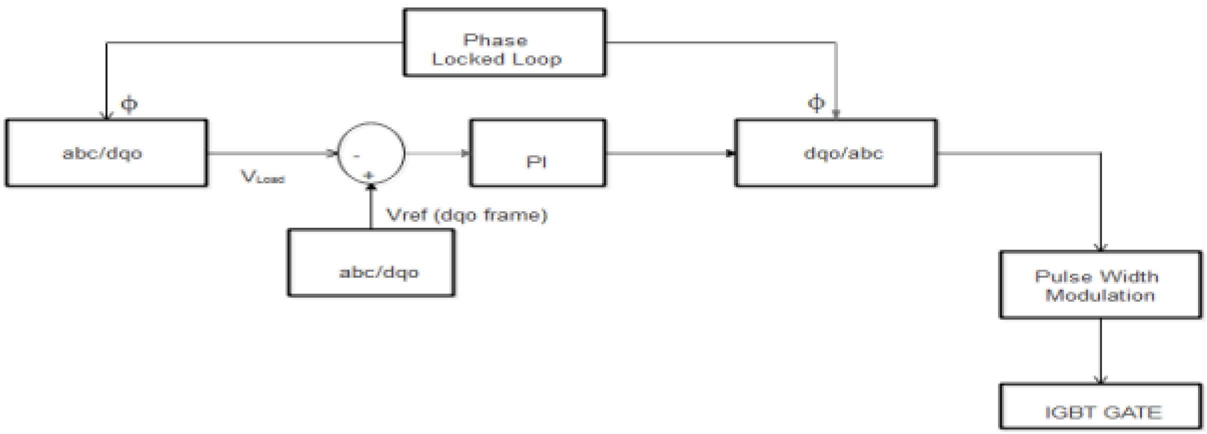

Fig.-2: The block diagram of DVR control scheme

The control algorithm of the DVR can be summarized from the control algorithm of DVR with PI controller.

1) The three-phase load voltage (*abc*) is converted to *dq*0 frame components and is compared with the reference voltage in *dq*0 frame components.

2) The PI controlling system provides accurate and fast responsive solution and correction to a control function. The error signal generated due to the difference between the measured load voltage profile and the reference voltage values and the controller will be active to process the needed voltage required for the mitigation of the voltage disturbance detected. The error signal generated will derive the PI controller, which regulates the system operation depending on the actuating error signal.

3) The output from the PI controller, which is in *dq*0 frame, is converted to three-phase *abc* voltage by the inverse Park's controller; hence, it is directed to the two-level discrete PWM generator.

4) The two level PWM generator produces the needed pulses to fire the PWM inverter with the desire triggering sequence. The PWM generator method is utilized on a voltage source inverter to modulate the carrier signal to produce a three-phase 50-Hz sine wave output ac voltage, which is the same as the reference voltage.

5) The line filter is utilized at the output of the inverter for the purpose of smoothing and for complete removal of switching harmonics produced by the VSI circuit.

6) The PLL circuit is employed in DVR to keep the phase and frequencies of output signals in track with the reference signal.

The 50-Hz *ac* output sinusoidal voltage from the inverter is injected to the step up series voltage boosting transformer matched in series with the three-phase electrical secondary distribution network.

4. PROPOSED SYSTEM MODEL

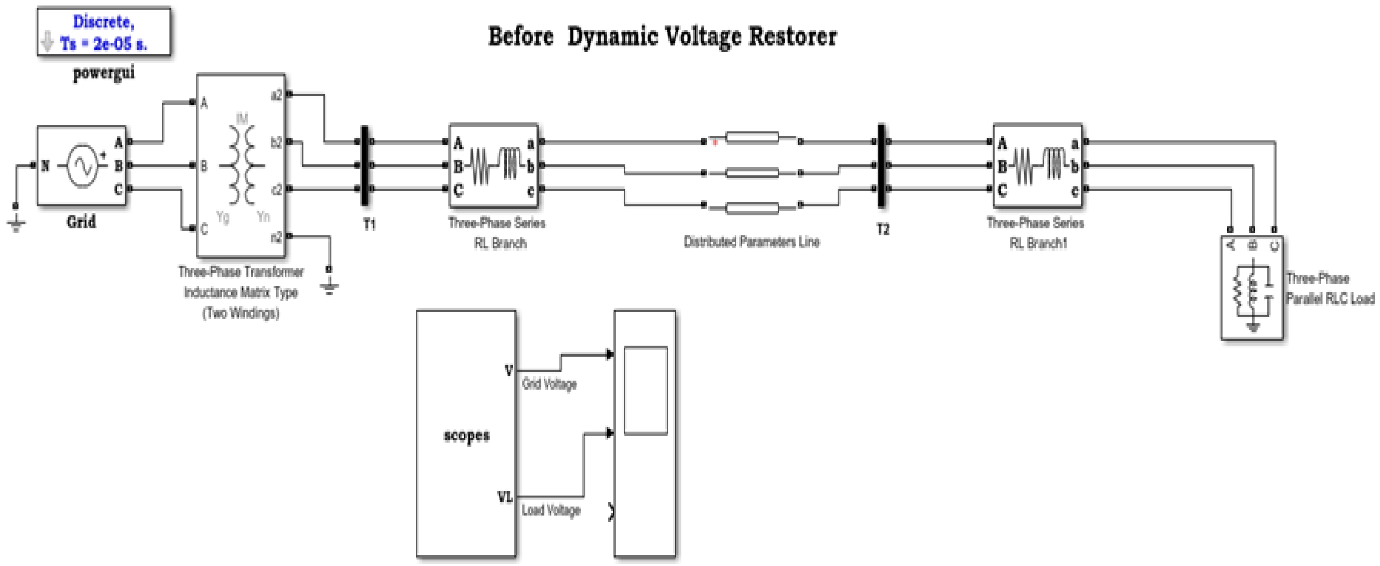

Fig-3: MATLAB/ Simulink model for LV network without DVR

Table-1: DVR Model Parameters

Parameter	Value
Distribution Transformer	11/0.4 kV, 500 kVA, Δ/Y grounded
MV Feeder	3-phase 11 kV radial, overhead line
LV Feeder	3-phase 4-wire, 400 V, overhead all-aluminium conductor 100 mm^2
Balance load	Phase A, B and C load are 1000kW at 0.9 pf 80% full load capacity
Line impedance (Ω)	L=1 mH, R=0.01Ω
Line frequency (Hz)	50
Load phase voltage (V)	220
DC supply voltage(V)	700
Injection transformer turns ratio	1:1
PI controller	Sample time=50μs, K_p=0.5, K_1=50
Inverter specification	Three arms IGBT based, six pulse, sample time 50 μs,carrier frequency 1080 Hz
Linear Transformer	5 kVA, 100/400 V
Filter inductance	7mH
Filter capacitance	10μF

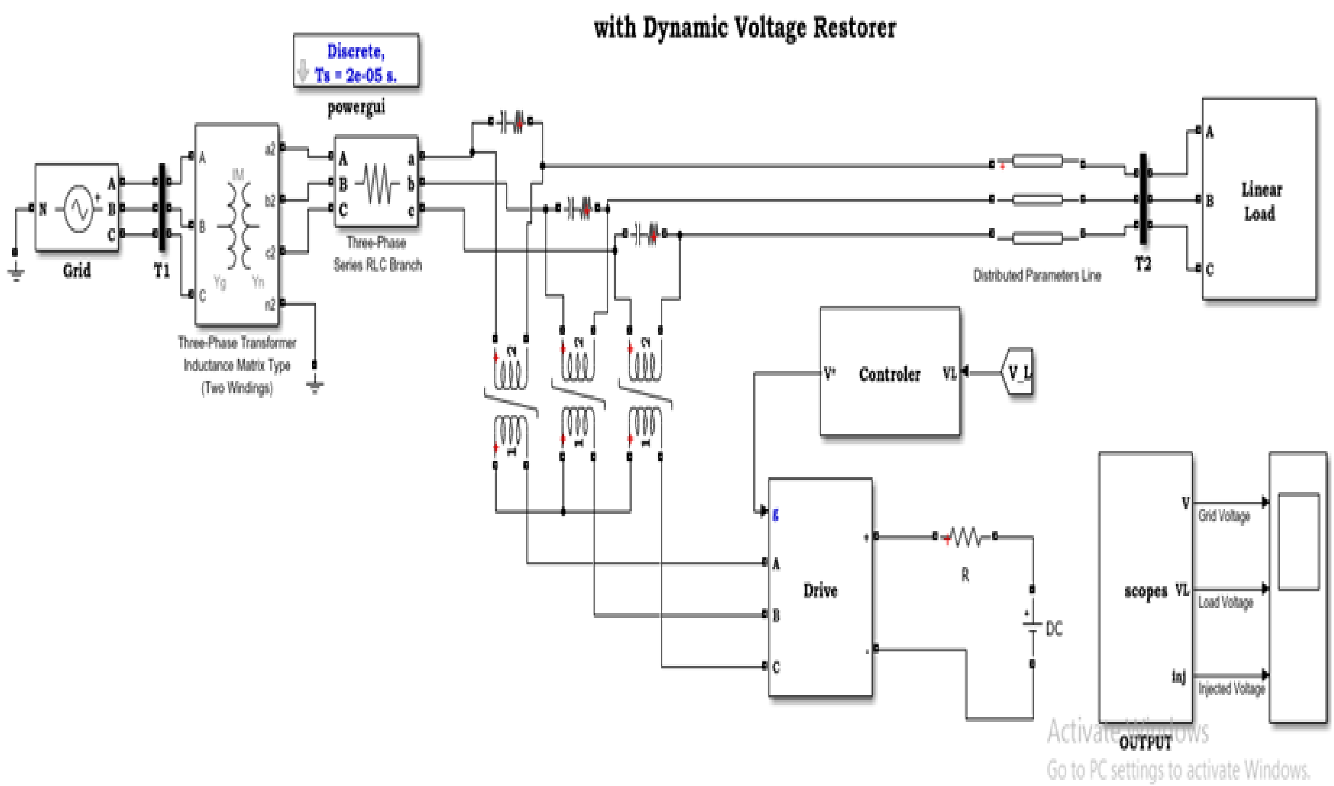

Fig.-4: MATLAB R16b/Simulink model for the proposed network with DVR

The analysis of voltage variation was carried out for low voltage electric power distribution network 11/0.4 kV, 500 kVA, for urban and rural network. This Simulink model shown in figure 3 give results under normal operating mode when DVR is not connected to the system and the simulink model shown in figure 4 give results when DVR connected in the distribution system under different feeder lengths. In LV distribution network, the voltage variation was modelled and simulated in MATLAB/Simulink using Sim Power System tool box. The LV electric power distribution network presented in this model is based on the standard network values obtained from an electric utility and the technical data of the distribution network are shown in Table 1. The length of the LV electric distribution lines ranges from 10 km to 20 km. The voltage levels and conductor type of the LV network consist of 400VL-L, 230 VL-N through an 11/0.4 kV, distribution transformer, based on all-aluminium conductor (AAC) standard. A low voltage (400V) radial network residential urban/rural electric power distribution network was considered for low voltage variation analysis. In this model, delta/star connected transformer is used. Also power factor close to unity was used. The network supplies electricity to both residential and small business customers. The feeder has 3-phase and four wire system with equal length.

4. RESULTS AND DISCUSSION

Case I: 3-phase balance load without DVR

The MATLAB/Simulink model of low voltage electric distribution network without DVR as shown in Figure 3. This DVR model is developed to study under different distribution feeder lengths for voltage variation for various parameter settings. The V-I measurement T1 and T2 are used to monitor the source voltage and load voltage readings while scopes are used to monitor the various voltage waveforms. The voltage profile at the customer's load end is measure using scope which is attached to T_2 while scope attached to T1 is used to measure the source voltage also reference voltage of system model is taken by T_2. Figure 5a and 6a shows the simulated waveforms of the balanced three phase load of radial network in the absence of DVR in LV distribution system. It was noticed that at the beginning of the distribution feeder length of 10km, the voltage profile reaching the electricity to consumer end is 300V which is within the standard allowable range of 300-320V of the nominal voltage value. On the other hand, the voltage measured at the end of the distribution feeder lengths of 11-20km is less than the standard minimum permissible voltage range of nominal voltage; hence, the voltage reaching at the end users are not admissible for customer use. Therefore there is a need of a custom power device known as a dynamic voltage restorer (DVR). DVR effectively improves the voltage profile of distribution network from the beginning to the end of the distribution feeder lengths of 10-20km to standard limits of the nominal voltage value. Table 2 shows the summary of the voltage profile measurement in volts and Figure 10 shows the graph of voltage profiles of balanced three phase loads when a DVR is not connected in the system.

Fig.-5a: Load Voltage profile at **10 km is 300V** for 3-phase balance load without DVR

Fig.-6a: Load Voltage profile at **15 km is 297.5V** for 3-phase balance load without DVR

Case II: 3-phase balance load with DVR

Figure 4 shows the MATLAB/Simulink model of low voltage electric distribution network with DVR. This model is develop to study voltage variation under different distribution feeder lengths for various parameter settings. The energy storage system has been recognize by connecting a DC voltage source and the three-phase voltage source inverter along with its necessary control circuits have been included in the VSI subsystem of the system model. The source voltage and load voltage readings are measure by using the V-I measurement T_1 and T_2 while scopes are used to monitor the various voltage waveforms. The scope attached to T 2 is used to measure the voltage profile at the customer's load end and the scope attached to T1 is used to measure the source voltage and also taken as the reference voltage of the system model. The voltage waveforms obtained when the DVR controller is introduced to the distribution line network model are shown in figures 5b and 6b. It was observed that DVR effectively improves the voltage profile of the distribution network from the beginning to the end of the distribution feeder lengths of 10-20km to the standard limits of 300-320V of the nominal voltage value. The results when DVR is used are shown in table 2 and Figure 11 shows the graph of voltage profile of balanced three phase loads when a DVR is connected. Moreover, it was observed that the DVR injects the required voltage to compensate the voltage disturbances experienced in distribution network when DVR is introduced into the system. This is an indication that the control system designed for DVR is suitable seeing that it perform the good purpose for which it is designed in the electric power distribution system.

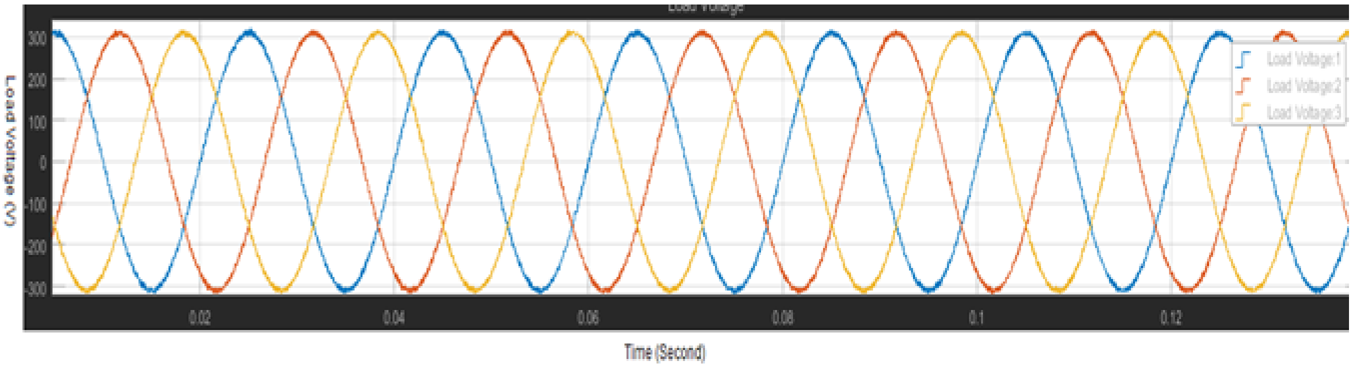

Fig.-5b: Load Voltage profile at **10 km is 320V** for 3-phase balance load with DVR

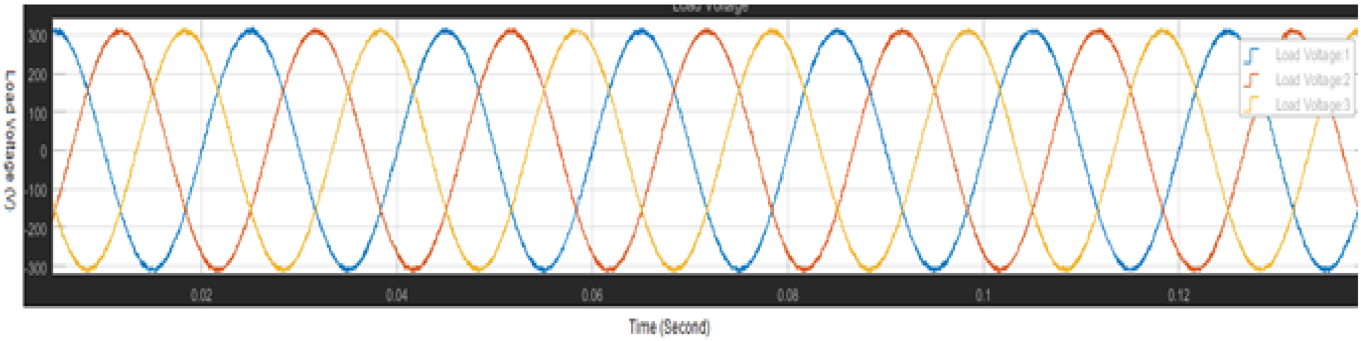

Fig.-6b: Load Voltage profile at **15 km is 320V** for 3-phase balance load with DVR

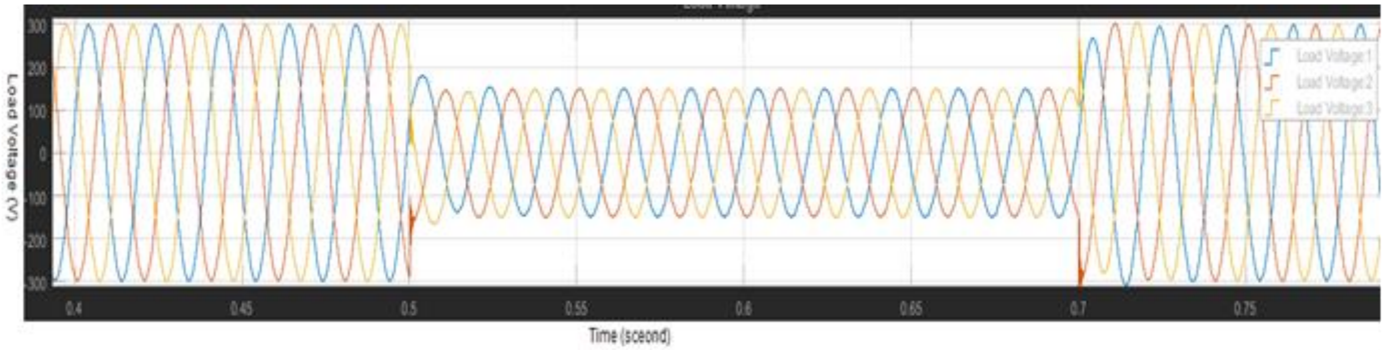

Fig.-7: Simulink Waveform when Voltage Sag occur in the system

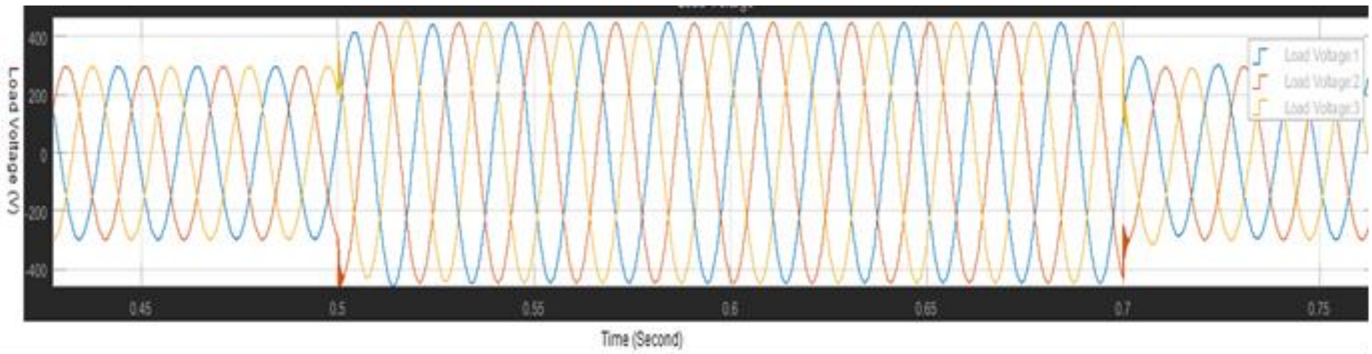

Fig.-8: Simulink Waveform when Voltage Swell occur in the system

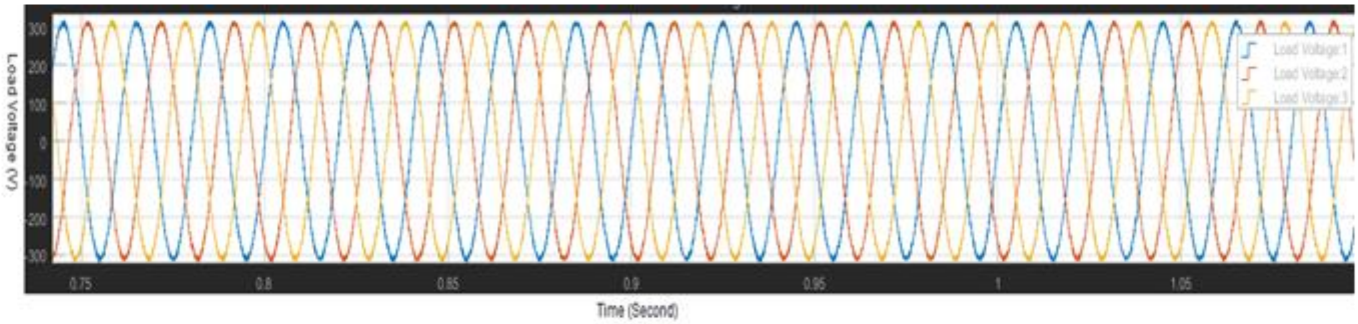

Fig.-9: Simulink Waveform of compensation of voltage sag and voltage swell

Table-2: Comparison of measurement of voltage profile for 3-phase balanced load without DVR and with DVR

Network Length (km)	Voltage Profile (V) without DVR	Voltage Profile (V) with DVR
10	300	320
11	299	320
12	298	320
13	297.8	320
14	297.6	320
15	297.5	320
16	297.3	320
17	297	320
18	296.8	319.9
19	296.5	319.9
20	296	319.9

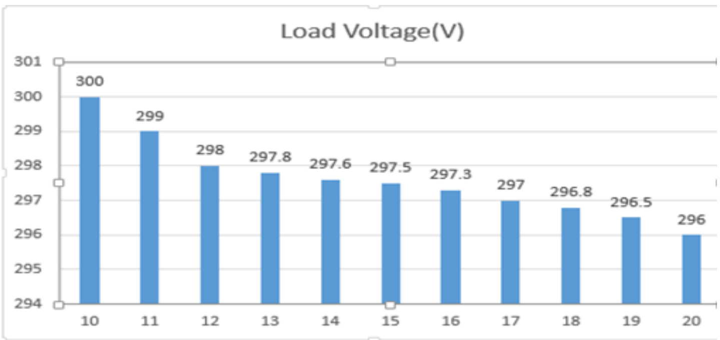

Fig.-10: Graph of voltage profile for 3-phase balance load without DVR

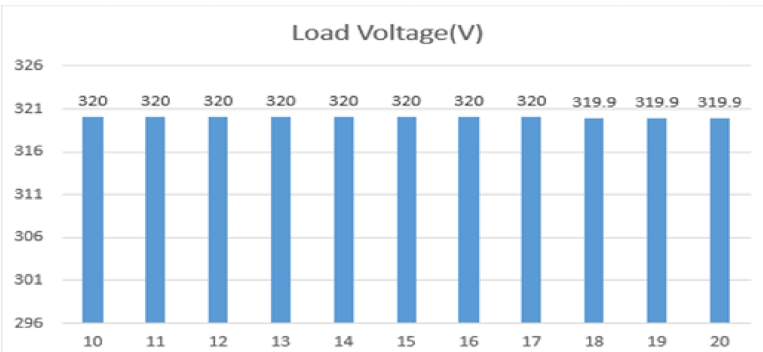

Fig.-11: Graph of voltage profile for 3-phase balance load with DVR

5. CONCLUSION

From the results obtained, it has been conclude that DVR installed in the low voltage electric power distribution networks for the purpose of improving the voltage profile and voltage variation and also compensate voltage sag and voltage swell from the beginning of the distribution feeder line to the end of the feeder gives a better power quality and improve the voltage profile in low voltage electric distribution networks. From the network studies carried out using the proposed DVR model and simulations using MATLAB/Simulink in Sim Power System tool box, show that a dynamic fast response, simple and cost-effective DVR effectively enhance better voltage profile and reduce voltage variation from the beginning to the end of distribution feeder lengths under steady state operation.

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