Voltage Profile Enhancement in Low Voltage 11/0.4 kV Electric Power Distribution Network Using Dynamic Voltage Restorer under Three Phase Balance Load

Ogunboyo Patrick Taiwo
Electrical, Electronic & Computer. Engineering Discipline
University of KwaZulu-Natal, Durban, South Africa
ogunboyopt@gmail.com

Remy Tiako
Electrical, Electronic & Computer. Engineering Discipline
University of KwaZulu-Natal, Durban, South Africa
Tiako@ukzn.ac.za

Innocent E. Davidson
Department of Electrical Power Engineering
Durban University of Technology, Durban, South Africa
Innocentd@dut.ac.za

Abstract-With the global trend of restructuring in electricity market, providing affordable, reliable and quality electric power by service providers to customers the end users of electric energy are of immerse concern. Several initiatives have been taken by utilities to improve power quality in low voltage electric power distribution network but the inadequate operation/performance of the conventional compensation devices to mitigate the poor power quality problems have prompted the use of custom power device such as the dynamic voltage restorer (DVR). Dynamic voltage restorer (DVR) is an advanced power electronics based compensation device which is series connected to the distribution network through boosting transformers. 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 a 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 dependability, robustness and effectiveness of the DVR control and 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 results carried out in Power System Sim Tool box. The balance of the paper gives recommendations on effective methods for improving the voltage profile and reducing the voltage variation to an allowable standard.

Keywords-Dynamic voltage restorer, voltage source inverter, voltage profile, power quality, distribution networks, distribution feeder

I. INTRODUCTION

Ensuring a good electric power quality within the allowable standard limits in electric power distribution network is of great importance [1-5]. Inadequate power quality cause malfunction operation of electrical equipment, intensify power losses in the distribution system [6]. Suppliers and users end disturbances are load voltage variations, three phase voltage unbalance, waveform distortions on the electric network. Power custom devices for electric power distribution networks, are capable of improving the efficient, reliable and excellent quality power that is delivered to the end users [7]. A dynamic voltage restorer (DVR) is a fast response, solid state power electronics controller that gives flexible voltage control at the point of coupling to the electric power distribution networks for better power quality enhancements [8]. 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 [9]. The DVR is specifically designed to inject a controlled voltage in magnitude and phase into electric power distribution networks through an isolating transformer to correct the load voltage [10]. DVR consists an energy storage device, a voltage source inverter, AC filter and an isolating transformer, connected in series to the electric power distribution networks [11].

This paper presents a model of DVR for voltage variations and voltage unbalance mitigation in low voltage electric power distribution network. The control schemes relies on voltage measurements for its effective operation. This technique of VSI switching method based on sinusoidal pulse width modulation offers simplicity and better response.

II. OPERATION PRINCIPLES OF DVR

DVR is a series connected solid based power electronics device. DVR uses a DC capacitor bank as an energy storage device, which is connected by coupling transformer. The converter controls the voltage across the DC link capacitor 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 also known as coupling transformer, the voltage profile regulation is performed by the DVR PI controller, which generates a reference voltage, and compare it with the system source voltage in order to inject the missing voltage to keep the load voltage constant. The DC energy storage devices give the needed power to synchronized injected voltage. 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. The block

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diagram of DVR consisting all the elements is shown in Figure 1.

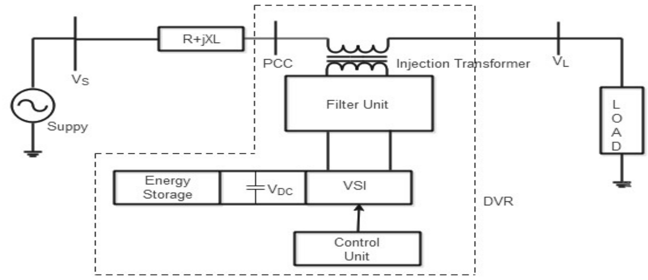

Fig. 1. Block diagram od DVR [12]

III. SYSTEM MODEL

A. Model for LV elecric power distribution networks

The investigation, and analysis of voltage variation was carried out for low voltage electric power distribution network 11/0.4 kV, 500 kVA, urban and rural network. The results are presented under normal operating mode. Voltage variation in LV distribution network 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. The technical data of the distribution network are provided in Table 1. Figure 2 illustrates the proposed Simulink model. The length of the LV electric distribution lines ranges from 0.5 km to 5 km. the voltage levels and conductor type of the LV access network consist of 400 VL-L, 230 VL-N through an 11/0.4 kV, distribution transformer, based on all-aluminum conductor (AAC) standard.

B. Network structure

A low voltage (400V) radial network residential urban/rural electric power distribution network was considered for low voltage variation investigation. In this model, the transformer is delta/star connected. The IEEE Recommendation practice for low voltage distribution 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. The poles are located at a distance of 50 meters from each other. At each pole, houses are supplied from each phase.

TABLE I. PARAMETERS OF LV SYSTEM

S/N	Material	Parameter
1	Distribution transformer	11/0.4 kV, 500 kVA, Δ/Y grounded.
2	MV Feeder	3-Phase 11 kV radial, overhead line.
3	LV Feeder	3–phase 4-wire, 400 V, overhead all-aluminium conductor 100 mm^2
5	Balance load value	Phase A, B and C Load are 120 kW each at 0.9 pf 80% full load capacity.

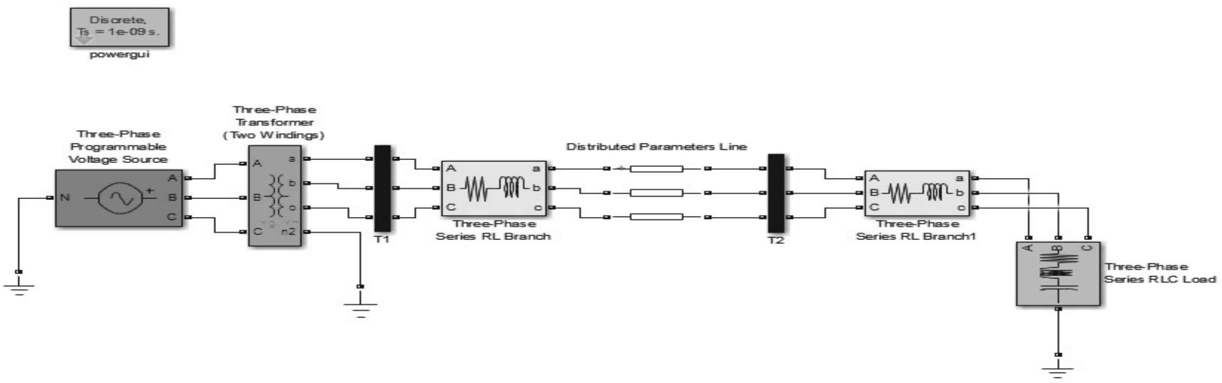

Fig. 2. MATLAB/ Simulink model for LV network without DVR

C. Case studies

Case I: A 3-phase balance load of 360 kW at 80%, 0.9 pf full load transformer rating load capacity without DVR.

Case II: A 3-phase balance load of 360 kW at 80%, 0.9 pf full load transformer rating load capacity with DVR.

IV. CONTROLLER SCHEME OF DVR

In order to keep constant the voltage magnitude at the point of load connection in low voltage electric power distribution network, under system voltage variation disturbances a controller must be introduced. The introduced control scheme 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. This method offers a simplicity, good response and flexible performance than other methods used and preferred in FACTS applications. 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 output which the angle is directed to PWM signal generator as shown in Figure 3. The controller process the error signal generates the required angle to drive the error to zero, the value of the load voltage is returned back to the reference voltage. A simple schematic diagram of PI controller is shown in figure 4. The modulated three phase voltages are given in equation (1), (2), and (3)

$$V_a = \sin(\omega t + \delta) \tag{1}$$

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

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

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

$$V_S = \frac{2}{3}\left((V_{sa})^2 + (V_{sb})^2 + (V_{sc})^2\right)^{0.5} \tag{4}$$

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. The filter is used to reduce the harmonics generated by inverter switching circuit, the isolating transformer is used to inject the appropriate missing voltage processed by the control circuit and the power circuit to the electric power distribution network

TABLE II. DVR MODEL PARAMETERS

Parameter	Value
Distribution Transformer	11/0.4 kV, 500 kVA, Δ/Y grounded.
MV Feeder	Three 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 is 120 kW, each at 0.9 pf, 80% full load capacity.
Line impedance (Ω)	L = 1 mH, R= 0.01 Ω
Line frequency (Hz)	50
Load phase voltage (V)	220
DC supply Voltage (V)	400
Injection transformer turns ratio	1:1
PI controller	Sample time=50 µs, K_P=0.5, K_I=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	7 mH
Filter capacitance	10 µF

Fig. 3. Output of PWM generator to IGBT Inverter gate

Fig. 4. Schematic diagram of PI controller [13]

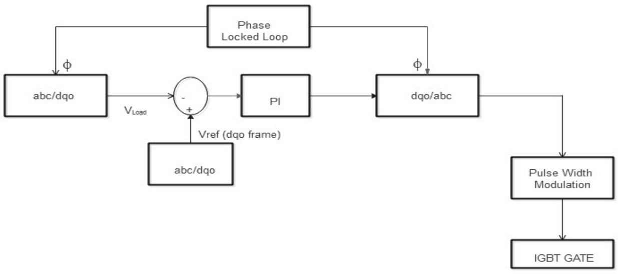

Fig. 5. The block diagram of DVR control scheme

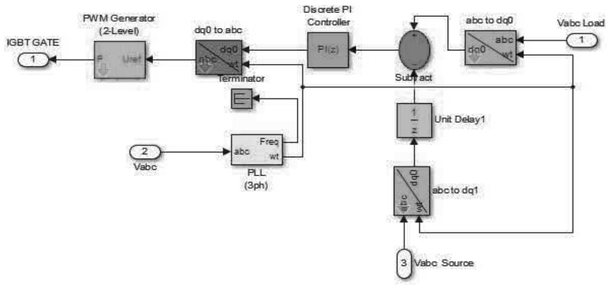

Fig. 6. MATLAB/Simulink configuration of DVR controller

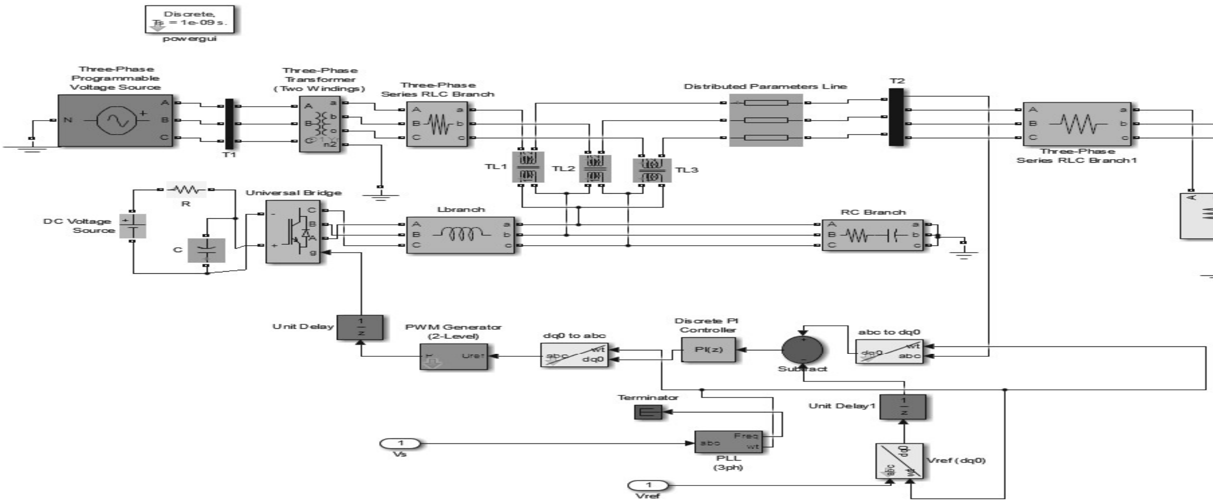

Fig. 7. MATLAB R15b/Simulink model for the proposed network with DVR

V. SIMULATION RESULTS AND DISCUSSIONS

A. Simulation result of case I: 3-phase balance load without DVR

The MATLAB/Simulink model of low voltage electric distribution network without DVR as shown in Figure 2 has been developed to study under different distribution feeder lengths for voltage variation for various parameter settings. The V-I measurement T_1 and T_2 were used to monitor the source voltage and load voltage readings while scopes were used to monitor the various voltage waveforms. The scope attached to T_2 is used to monitor the voltage profile at the customer's load end while scope attached to T_1 is used to monitor the source voltage and also taken as the reference voltage of the system model. Based on the simulation result analysis of LV electric power distribution network standard parameters. It is proved that the voltage profile for 0.5 km distribution feeder length for 3-phase loads are admissible for customers from the beginning to the end of the feeder as designed with engineering standard and judgements. However, it is also established that the voltage profile for distribution network lengths of 0.8 km to 5 km for balance 3-phase loads from the beginning to the end of the feeder are less than standard permissible limit of -5%, hence voltage is inadmissible for customers use. There is therefore a need for a power custom device known as a dynamic voltage restorer (DVR) which provides an efficient and effective means of voltage booster connected along the feeder length in order to improve the voltage profile from the beginning of the network to the end to standard permissible range. The simulation results of network without DVR were presented in Figures 8a to 14a, Table 3 shows the summary of the voltage profile per unit measurement and Figure 15 shows the curves of voltage profiles for balance 3-phase loads.

B. Simulation result of case II: 3-phase balance load with DVR

The MATLAB/Simulink model of low voltage electric distribution network with DVR as shown in Figure 7 has been developed to study under different distribution feeder lengths for voltage variation for various parameter settings. The energy storage system has been realized 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 V-I measurement T_1 and T_2 were used to monitor the source voltage and load voltage readings while scopes were used to monitor the various voltage waveforms. The scope attached to T_2 is used to monitor the voltage profile at the customer's load end while scope attached to T_1 is used to monitor the source voltage and also taken as the reference voltage of the system model. Results obtained from simulation with distribution feeder lengths 0.5 km to 5 km for balanced 3-phase loads with DVR connected to the system model are within the permissible nominal voltage tolerance of ±5% at the customer's terminal. Finally, several simulation results shown in Figure 8b to 14b shown that DVR is capable of effective correct voltage variation in a low voltage electric power distribution feeder length to standard permissible limit. Table 4 shows the summary of the voltage profile per-unit measurement and Figure 16 shows the curves of voltage profiles of balanced three phase loads when a DVR is connected.

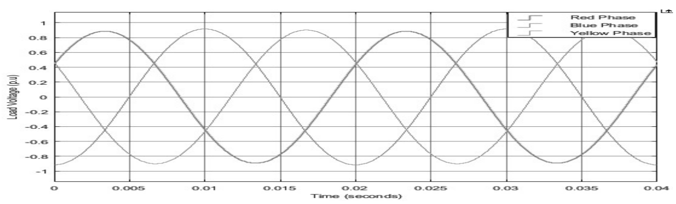

Fig. 8a. p.u voltage profile at 0.5 km for 3-phase balance load without DVR

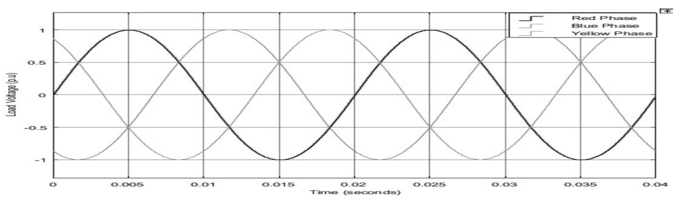

Fig. 8b. p.u voltage profile at 0.5 km for 3-phase balance load with DVR

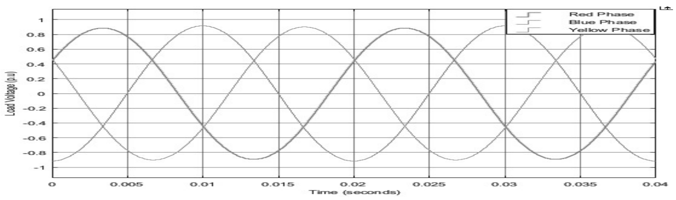

Fig. 9a. p.u voltage profile at 0.8 km for 3-phase balance load without DVR

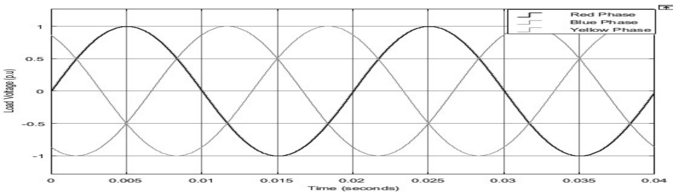

Fig. 9b. p.u voltage profile at 0.8 km for 3-phase balance load with DVR

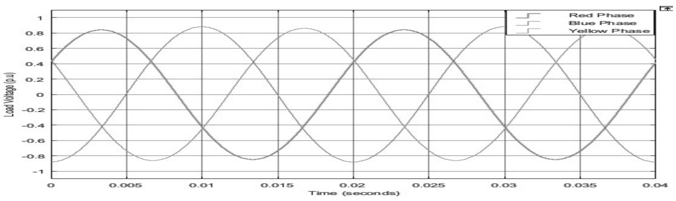

Fig. 10a. p.u voltage profile at 1 km for 3-phase balance load without DVR

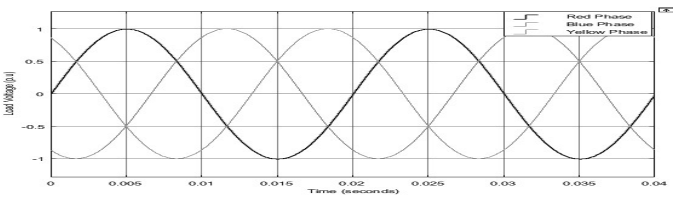

Fig. 10b. p.u voltage profile at 1 km for 3-phase balance load with DVR

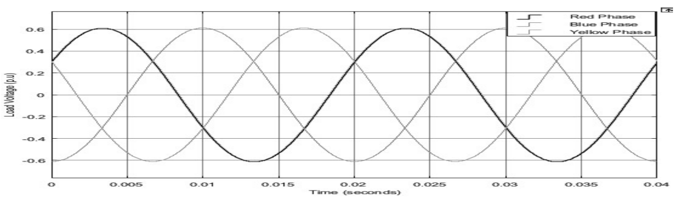

Fig. 11a. p.u voltage profile at 2 km for 3-phase balance load without DVR

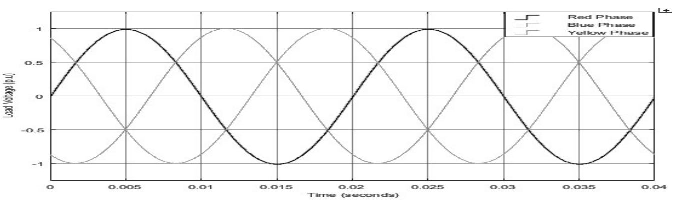

Fig. 11b. p.u voltage profile at 2 km for 3-phase balance load with DVR

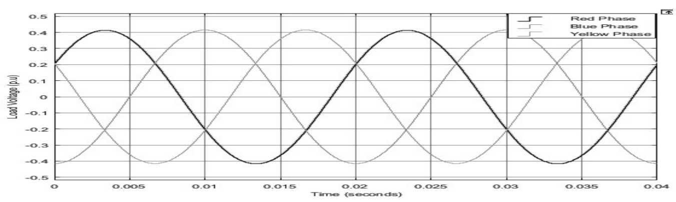

Fig. 12a. p.u voltage profile at 3 km for 3-phase balance load without DVR

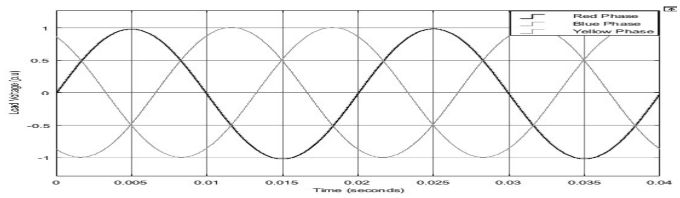

Fig. 12b. p.u voltage profile at 3 km for 3-phase balance load with DVR

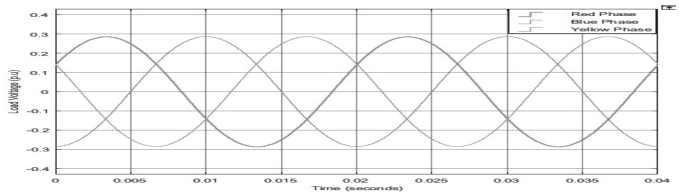

Fig. 13a. p.u voltage profile at 4 km for 3-phase balance load without DVR

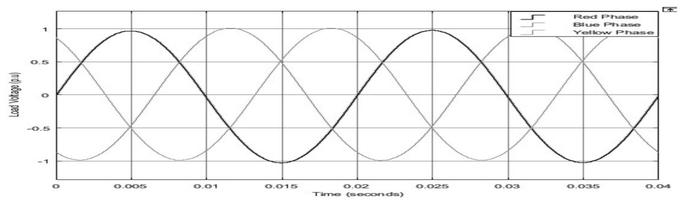

Fig. 13b. p.u voltage profile at 4 km for 3-phase balance load with DVR

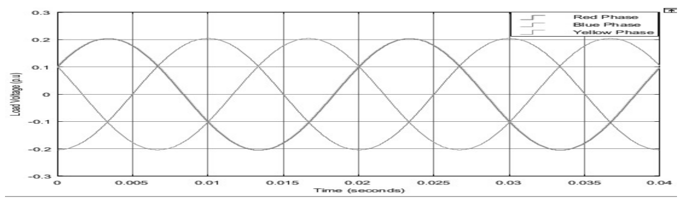

Fig. 14a. p.u voltage profile at 5 km for 3-phase balance load without DVR

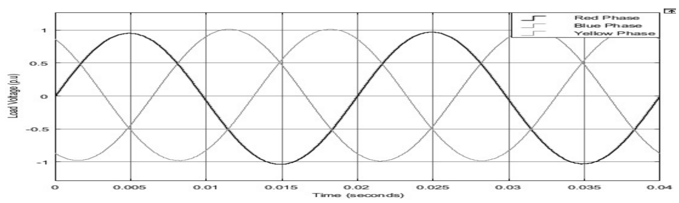

Fig. 14b. p.u voltage profile at 5 km for 3-phase balance load with DVR

TABLE III. P.U MEASUREMENT OF VOLTAGE PROFILEFOR 3-PHASE BALANCED LOAD WITHOUT DVR

Network Length, (km)	Voltage profile (p.u)
0.5	0.95
0.8	0.90
1.0	0.85
1.5	0.73
2.0	0.61
2.5	0.50
3.0	0.41
3.5	0.31
4.0	0.28

4.5	0.23
5.0	0.20

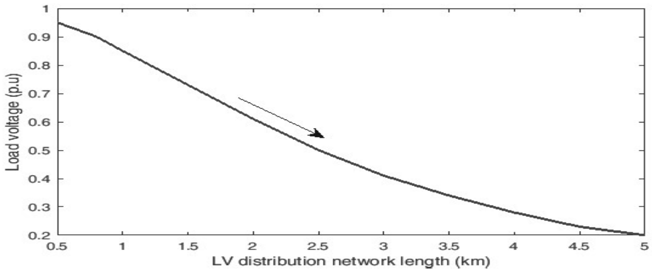

Fig. 15. Curve of voltage profile for 3-phase balance load without DVR

TABLE IV. PER-UNIT MEASUREMENT OF VOLTAGE PROFILE FOR 3-PHASE BALANCED LOAD WITH DVR

Network length, (km)	Load voltage (p.u) for phase A, B and C
0.5	1.0
0.8	1.0
1.0	1.0
1.5	1.0
2.0	1.0
2.5	0.9999
3.0	0.9999
3.5	0.9998
4.0	0.9998
4.5	0.9997
5.0	0.9997

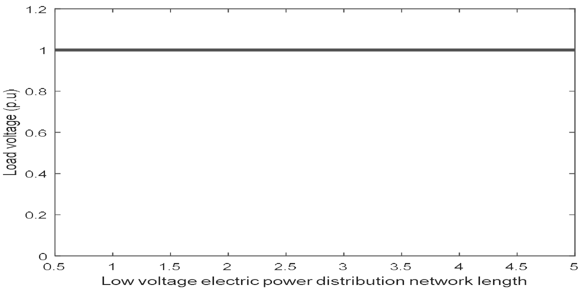

Fig. 16. Curve of voltage profile for 3-phase balance load with DVR

VI. CONCLUSIONS

From the results obtained, it has been demonstrated that DVR installed in the electric power distribution networks with the purpose of improving the voltage profile and reduce voltage variation from the beginning of the distribution feeder line to the end of the feeder provides a better power quality 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 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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