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The Effectiveness of Dynamic Voltage Restorer with the Distribution Networks for Voltage Sag Compensation

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Abstract

This paper discusses the Dynamic voltage restorer (DVR) operation and control for Voltage sags compensation. DVR is a series connected power electronic based device that can quickly mitigate the voltage sags in the system and restore the load voltage to the pre-fault value. Voltage sag associated with faults in transmission and distribution systems, energizing of transformers, and starting of large induction motor are considered as most important power quality disturbances (PQD). The most of the industries uses the power electronics conversion and switching for manufacturing and processing. These technologies are needs high quality and reliable power supply. Not only the industries, but also the electric power utilities and customers are becoming increasingly anxious about the electric power quality. Sensitive loads such as digital computers, programmable logic controllers (PLC), consumer electronics and variable frequency motor drives need high quality power supplies. DVR is recognized to be the best effective solution to overcome this problem. The primary advantage of the DVR is keeping the users always on-line with high quality constant voltage maintaining the continuity of production. Also, this paper simulates the DVR with the power system using MATLAB/Simulink are demonstrated to prove the usefulness of this DVR to enhance the power system quality.

Keywords: Dynamic Voltage Restorer, Faults, Power Quality, Voltage Sag.
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1. Introduction

A voltage sag is a short-duration reduction in the RMS voltages and it is usually characterized by its magnitude and duration [1,4,6,7]. Good quality of electric power is necessary for right functioning of industrial processes as well as protection to the industrial machines and its long usage. According to IEEE std. 1159/95, the magnitude of voltage sag ranges from 10 to 90 % of nominal voltage and duration from half cycles to one minute [8,9]. However, the short interruptions where the RMS voltage is below 0.1 pu of the nominal voltage can also be considered as voltage sag event. Despite its very short duration, it can cause serious problems to a wide range of industrial loads. Hence, the characterization, classification, and detection of the voltage sag have become essential requirements for PQ monitoring. In order to characterize the voltage sag through magnitude, several methods have been documented. Alternative methods have been also developed to characterize the voltage sag through one parameter [7–10]. These methods quantify the severity of the voltage sag through only one parameter resulting from either magnitude or combination of the magnitude and duration. Moreover, to quantify the magnitude of the voltage sag from recorded waveform or sample data, numbers of methods were documented in the paper. The magnitude of the voltage sag is accepted as one of the most important parameters for its characterization, classification, and the detection. Hence, the selection of most suitable method to quantify the magnitude of voltage sag is a basic requirement of the power quality (PQ) monitoring. DVR Its function is detecting the voltage sag and injecting the voltage difference between the pre-sag and post-sag voltage, so the voltage is maintained and reaches the load side as pre-sag voltage magnitude, however the phase angle is not crucial to return it back to the pre-sag condition. This is done by injecting the active and reactive power. Fig. 1 describes the power circuit of the DVR; it is small in size and best economical solution compared to other methods. This work shows the need to use this standard in the analysis of the impact of voltage sags in industrial distribution systems; and additionally, the need to considering the actual conditions of the connections of end-user loads. This paper introduces the DVR control module that can to uses for voltage sag mitigation. Also, this paper uses MATLAB/Simulink are demonstrated to prove the usefulness of this DVR design and operation to enhance the power system quality.

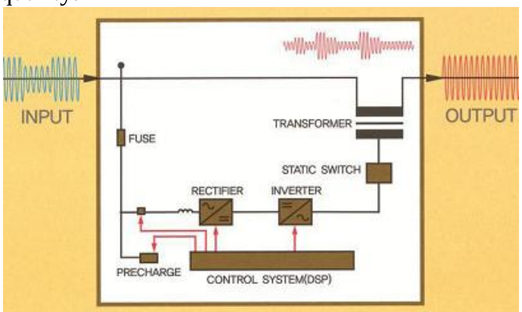

Fig. 1. Scheme logic for dynamic voltage regulator with transmission system

2. Sensitivity Analysis

The sensitivity study is made to analyze how affected loads could be when voltage sags are produced at Utility bus bar. The sensitivity of a plant is depending upon the types of equipment's are installed in the plant. Analyzing the uncertain behavior of the voltage sag literature, sensitivity is classified in four zones.

A) Low sensitivity

Exponential distributions assumed to be reverse exponential distributions will represent equipment with low sensitivity means having very good ride through capabilities against voltage sags.

$$f(t) = \begin{cases} 0 & oherwise \\ 1 - e^{-\lambda t} & 0 \le t < \infty \end{cases} \quad (1)$$

Where λ = arrival rate of sag, which can be calculate from no. of sag events in a particular period (from survey)

B) Uniform sensitivity

If there is an equal probability that the equipment voltage tolerance curve may assume any location within the region of uncertainty.

$$f(t) = \frac{1}{t_1 - t_2} \qquad t_1 < t < t_2 \quad (2)$$

$$f(v) = \frac{1}{v_1 - v_2} \qquad v_1 < v <, v_2 \quad (3)$$

Where f(t) and f(v) are the functions of independent variable t i.e time and v i.e magnitude respectively.

C) Moderate sensitivity

This type of sensitivity can be expressed by normal probability density functions. There is higher probability that the knee of the equipment's sensitivity curve will occur in the center of the region of uncertainty

$$f(t) = \frac{1}{\sigma 2\pi} e^{-\frac{1}{2}\left[\frac{t-\mu}{\sigma}\right]^2} \quad (4)$$

Where $\sigma > 0$, $-\infty < \mu < \infty$, σ, μ are the mean and standard deviation of distribution respectively.

D) High sensitivity

If probabilities are assumed in exponentially decreasing order from high-voltage threshold to low-voltage threshold and from low duration threshold to high duration threshold, it will represent highly sensitive equipment having very poor ride through capabilities against voltage sags.

$$f(t) = \begin{cases} 1 - e^{-\lambda t} & 0 \le t < \infty \\ 0 & oherwise \end{cases} \quad (5)$$

Where λ = arrival rate of sag.

3. DVR Operation Strategies

The power circuit of the studied DVR is a three-phase Hybridge PWM converter having a dc battery group. The battery group can be recharged using an external battery charger. In the studied system the associated control system does not require to regulate the dc link voltage. The ac side of the voltage source inverter (VSI) is connected to the point of common coupling (PCC) through an inductor and three single-phase transformers. The primary side of the transformers is connected in series between the utility and the load. The secondary sides of the transformers are connected in a delta or star [11-15] configuration to the VSI. This type of connection is very useful during the compensation of unbalanced utility voltages [10-14]. Since the system is used for compensation of unbalances, the use of a grounded star point prevents zero-sequence voltages. Energy storage: it could be batteries or capacitor bank to provide the real power required during the restoration process of the DVR. Voltage source inverter: to invert from DC-AC, where batteries or capacitor banks will supply it. Passive filter: low pass filter LPF filters out the switching harmonic components from the injected voltage, in other words convert PWM waveform into a sinusoidal waveform. The LPF is an LC series circuit placed either at the inverter side or at the high voltage side of the injecting transformer. Placing the LPF at the inverter side will prevent the higher order harmonics from passing through the transformer and therefore it reduces the voltage stress on the injection transformer. While placing the LPF at the HV side of the injection transformer will result in the need of a higher rating transformer, since now the high harmonic will pass through the injecting transformer. Voltage injection transformer: its function is to step up the low AC voltage supplied by the VSI to the required level of the injected voltage.

A) Principles of DVR Operation

DVR is a solid-state power electronics switching device which comprises of either GTO or IGBT, a capacitor bank as energy storage device and injection transformers. From the fig. 2 it can be seen that DVR is connected in between the distribution system and the load. The basic idea of DVR is that by means of an injecting transformer a control voltage is generated by a forced commuted convertor which is in series to the bus voltage. A regulated DC voltage source is provided by a DC capacitor bank which acts an energy storage device. Fig. 2 shows the principle of DVR with a Response Time of Less Than One Millisecond. Under normal operating conditions when there is no voltage sag, DVR provides very less magnitude of voltage to compensate for the voltage drop of transformer and device losses. But when there is a voltage sag in distribution system, DVR will generate a required controlled voltage of high magnitude and desired phase angle which ensures that load voltage is uninterrupted and is maintained. In this case the capacitor will be discharged to keep the load supply constant [11-15]. Note that the DVR capable of generating or absorbing reactive power but the reactive power injection of the device must be provided by an external energy source or energy storage system. The response time of DVD is very short and is limited by the power electronics devices and the voltage sag detection time. The expected 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.

4. Construction of DVR

Fig. 3 Shows the DVR power circuit and the control circuit, where 2 main parts of the DVR. There are various critical parameters of control signals such as magnitude, phase shift, frequency etc. which are injected by DVR. These parameters are derived by the control circuit. This injected voltage is generated by the switches in the power circuit based on the control signals. Furthermore, the basic structure of DVR is described by the power circuit and is discussed in this section. The 5 main important parts of power circuit, their function and requirements are discussed ahead.

A) Energy Storage Unit

Various devices such as Flywheels, Lead acid batteries, Superconducting Magnetic energy storage (SMES) and Super-Capacitors can be used as energy storage devices. The main function of these energy storage units is to provide the desired real power during voltage sag. The amount of active power generated by the energy storage device is a key factor, as it decides the compensation ability of DVR. Among all others, lead batteries are popular because of their high response during charging and discharging. But the discharge rate is dependent on the chemical reaction rate of the battery so that the available energy inside the battery is determined by its discharge rate [5-9].

B) Voltage Source Inverter

Generally, Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used. In the previous section we saw that an energy storage device generates a DC voltage. To convert this DC voltage into an AC voltage a Voltage Source Inverter is used. In order to boost the magnitude of voltage during sag, in DVR power circuit a step-up voltage injection transformer is used. Thus, a VSI with a low voltage rating is sufficient.

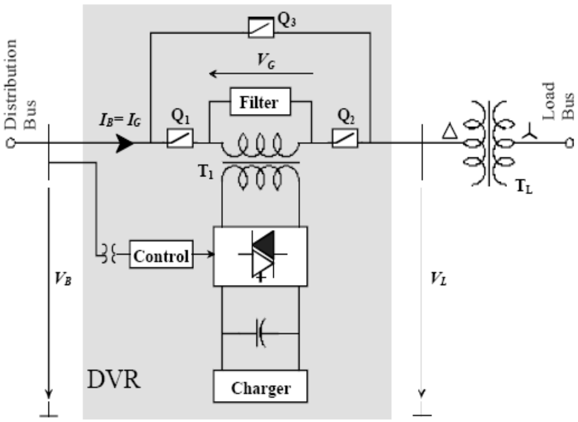

Fig. 2. Principle of DVR with a Response Time of Less Than One Millisecond

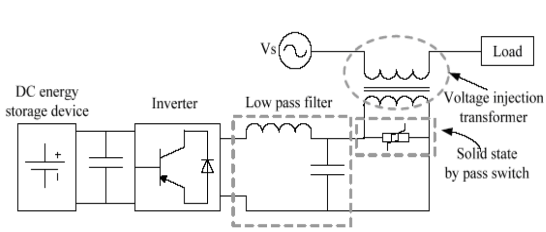

Fig. 3. DVR Power Circuit

C) Passive Filters

Fig. 4 shows the different filter placements. To convert the PWM inverted pulse waveform into a sinusoidal waveform, low pass passive filters are used. In order to achieve this. It is necessary to eliminate the higher order harmonic components during DC to AC conversion in Voltage Source Inverter which will also distort the compensated output voltage. These filters which play a vital role can be placed either on high voltage side i.e. load side or on low voltage side i.e. inverter side of the injection transformers. it can avoid higher order harmonics from passing through the voltage transformer by placing the filters in the inverter side. Thus, it also reduces the stress on the injection transformer. One of the problems which arise when placing the filter in the inverter side is that there might be a phase shift and voltage drop in the inverted output. So, this could be resolved by placing the filter in the load side. But this would allow higher order harmonic currents to penetrate to the secondary side of the transformer, so transformer with higher rating is essential.

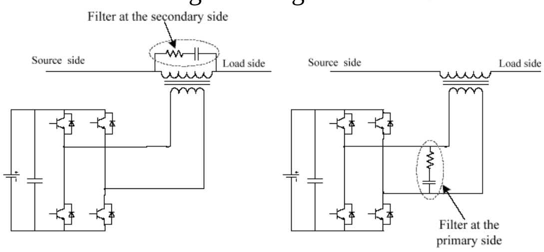

Fig. 4. Different Filter Placements

D) *By-Pass Switch*

Now DVR is a series connected device. If there is a fault current due to fault in the downstream, it will flow through the inverter. Now the power components of inverter are not highly rated but normally rated due to its cost. So, in order to protect the inverter a By-pass switch is used. Generally, a crowbar switch is used which bypasses the inverter circuit. So, crowbar switch will sense the magnitude of the current, if it is normal and within the handling range of inverter components it (the crowbar switch) will be inactive. On the other hand, if current is high it will bypass the components of inverter.

E) *Voltage Injection Transformers*

The primary side of the injection transformer is connected in series to the distribution line, while the secondary side is connected to the DVR power circuit. Now 3 single phase transformers or 1 three phase transformer can be used for 3 phase DVR whereas 1 single phase transformer can be used for 1 phase DVR. The type of connection used for 3 phase DVR if 3 single phase transformers are used is called “Delta-Delta” type connection as shown in Fig. 5 [8-11]. If a winding is missing on primary and secondary side then such a connection is called “Open-Delta” connection which is as widely used in DVR systems as shown in Fig. 6.

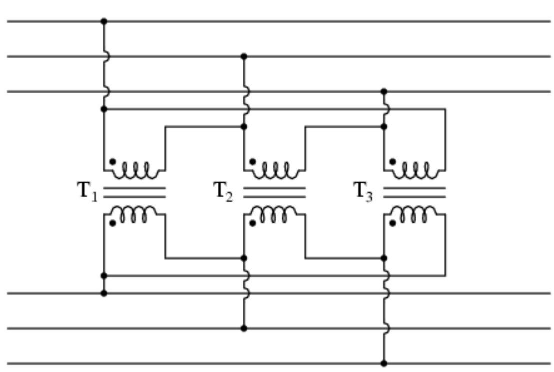

Fig. 5. Connection Method for Injection Transformer Delta-Delta Connection

Basically, the injection transformer is a step-up transformer which increases the voltage supplied by filtered VSI output to a desired level and it also isolates the DVR circuit from the distribution network. Winding ratios are very important and it is predetermined according to the required voltage at the secondary side. High winding ratios would mean high magnitude currents on the primary side which may affect the components of inverter circuit. When deciding the performance of DVR, the rating of the transformer is an important factor. The winding configuration of the injection transformer is very important and it mainly depends on the upstream distribution transformer. In case of a Δ-Y connection with the grounded neutral there will not be any zero-sequence current flowing into the secondary during an unbalance fault or an earth fault in the high voltage side. Thus, only the positive and negative sequence components are compensated by the DVR.

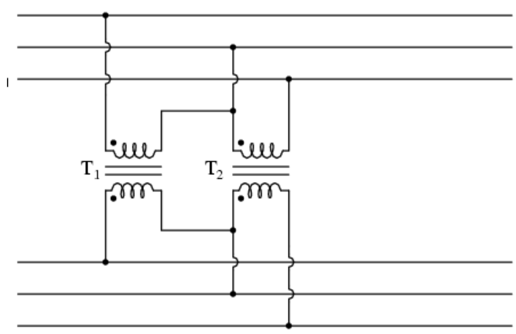

Fig. 6. Connection Method for Injection Transformer Open-Delta Connection

5. Simulation Results

In this section, a DVR's performance in a sample distribution network is investigated. Fig. 7 and Fig. 8 show the simulation results of the proposed DVR control system with the closed loop damping factor of 0.5 when the switching frequency was set to be 10 kHz and 5 kHz respectively. Fig. 7 shows very stable and good dynamics of the output compensation voltage since the switching frequency was set to two times higher than the critical switching frequency. The output compensation voltage is settled around 5Td=500µs which is almost same with the simulation results of Fig. 7, that adopts an ideal linear amplifier model as the inverter this simulation equation and control logic is described in [11]. Although the ripple and the settling time are slightly increased, the output compensation voltage is stable and has good control dynamics when the switching frequency is equal to the minimum switching frequency in Fig. 8.

A) Experimental Set-up

Experiments have been performed to verify the proposed control algorithm on a DVR system. Fig. 9 shows the experimental DVR system. The rated line voltage of the grid is 220Vrms/ 60Hz. 50% symmetrical voltage sags were generated by the power source, SW5250A/ELGAR [11-16]. The fault generated over 50 ms. The experimental condition is on Table 1 The DVR consists of a 6-leg inverter, three LC output filters, and three angle-phase matching transformers. The 6-leg inverter has 12 IGBT switches and a dc power supply in the dc link. The switching frequency of the IGBT switches is 10 kHz.

B) Experiment Result

Fig. 9 shows the experimental waveforms of the proposed DVR control system. The DVR compensates the voltage sags over 50ms. Since the control of the output compensation voltage is independent in each phase, only the a-phase voltage waveform is shown for convenience. The waveforms of the upper window of Fig. 10 show the reference compensation voltage and the actual output compensation voltage in relatively long-time interval. The waveforms of the lower window of Fig. 10 show the zooming for the reference compensation voltage and the actual output compensation voltage at the instant of the abrupt change of the reference compensation voltage [11-15]. No over shoot is observed in the output compensation voltage. The output compensation voltage decently converges to the reference compensation voltage within 500µs. This total time delay comes from the pure control delay, the inverter switching, sensing time, and the LC output filters [16-18].

C) Fault ride-through capability

In this subsection, a test is carried out in order to verify the FRT capability of the proposed system against a three-phase fault at the grid. The FRT of the DVR is the capability to restore and maintain the load terminal voltage at desired level in case of a fault occurs in the grid for a short period of time. The simulation results in Fig. 11 shows the grid voltage under three types of fault: a three-phase fault, single-phase to-ground fault and phase-to-phase fault at the grid [16]. The DVR injects the required compensation voltages to minimize the effect of faults at the load terminal as presented in Fig.11b. As a result of this, the voltages at the load terminal are compensated during the faults as seen in Fig.11c. It is obvious that the fault is cleared and the load voltages are restored quickly.

6. Conclusion

There are different definitions for power quality. For instance, electricity companies define power quality as reliability and they can statistically demonstrate how reliable a network is. In contrast, electrical equipment manufacturers define power quality as guaranteeing performance of devices based on power supply characteristics. The Voltage sags of more than 50% and duration of two cycles were compensated by proposed DVR connected system supplying an induction motor. The voltage compensation levels were observed accurately and the line voltages were restored during the sag period precisely since the SPWM pulses were generated at a higher frequency of 5 kHz, thus improves the power quality. Power quality problems, such as sag and swell, can have adverse impact on the performance of critical loads. These power quality problems can even cause undesired turning-off of these loads. Among them voltage unbalance is considered as the major affecting problem leads to degradation in performance of electrical equipment's. The simulation result shows that DVR compensate sag/swell effectively and provide good voltage regulation. The performance of DVR is satisfactory. In this paper DVR has been presented to improve the power system quality. Also, in this paper the guidelines have been verified by an experimental DVR system that shows very good performance as expected by the analysis and simulations. Further study is going on to decrease the time delay of the control system of DVRs.

Table.1.
Experimental Condition

Parameters	Value	Parameters	Value
F	10 kHz	T	100 µsec
R load	40 Ω	Rf	0.4 Ω
Wf	400 µH	Cf	80 µF

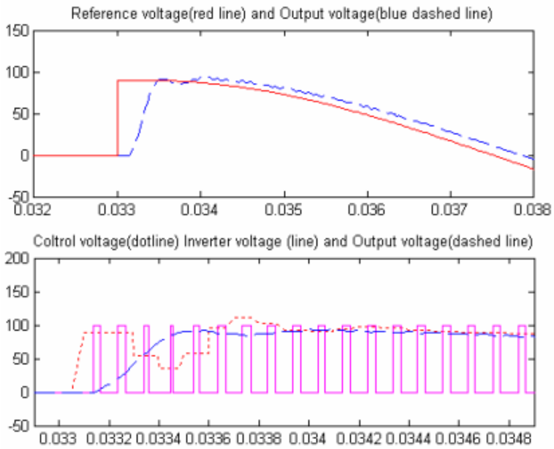

Fig. 7. Voltage response of a digital controlled DVR with time delay

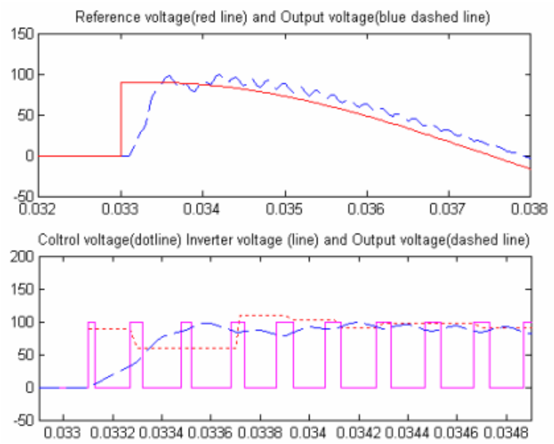

Fig. 8. Voltage response of a digital controlled DVR with time delay

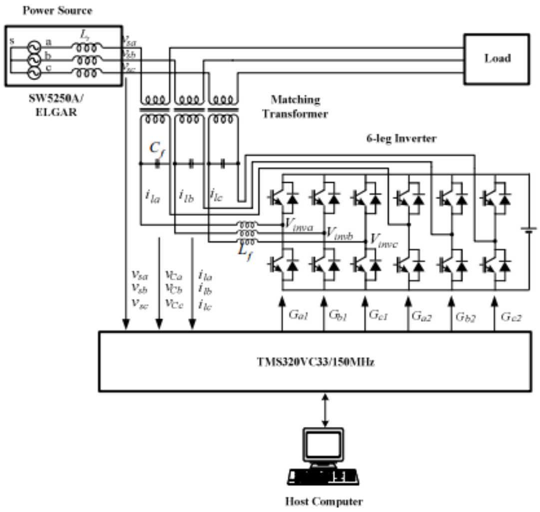

Fig. 9. Experimental DVR system with DSP control board

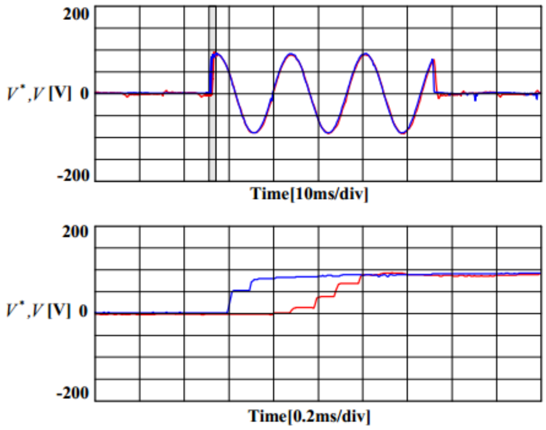

Fig. 10. Experimental voltage response of digital controlled DVR with time delay of Tf /12; fsw=10kHz, ξ=0.5

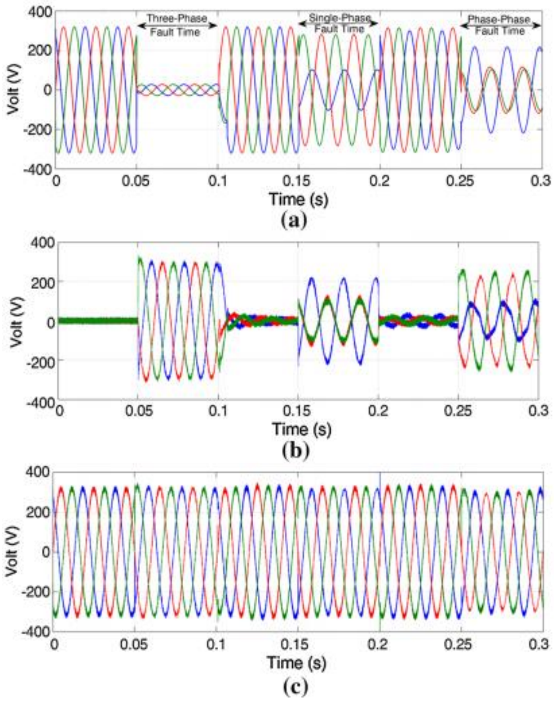

Fig. 11. Performance of the proposed system under three-phase-to ground fault, Single-phase-to-ground fault and phase-to-phase fault three-phase utility voltages, b three-phase voltages injected by the DVR, c resultant three-phase voltages at the load terminal

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