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Research Article

Performance Analysis of Voltage Sag Compensation to less Fault Current Interruption by DVR

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Abstract

Power quality is a very important issue due to its impact on electricity suppliers, equipment manufactures and customers. Power quality is described as the variation of voltage, current and frequency in a power system. It refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location in the power system. A Voltage Sag is a momentary decrease in the root mean square (RMS) voltage between 0.1 to 0.9 per unit, with a duration ranging from half cycle up to 1 min. It is considered as the most serious problem of power quality. It is caused by faults in the power system or by the starting of large induction motor The problem of voltage sags and its severe impact on sensitive loads is well known. To solve this problem, The DVR is a modern and important custom power device for compensation voltage sags in power distribution systems. The Dynamic Voltage Restorer (DVR) is fast, flexible and efficient solution to voltage sag problem. The DVR is a series compensator used to mitigate voltage sags and to restore load voltage to its rated value. The main focus behind this paper is to analyse the downstream fault current problem and reduce the impact of noise and voltage sag in distribution system.

Keywords: *Voltage Sag, Dynamic Voltage Restorer (DVR, fault current interruption, Power quality.*

1. Introduction

In the early days of power transmission voltage deviation during load changes, power transfer limitation was observed due to reactive power unbalances. Modern power systems are complex networks, where hundreds of generating stations and thousand of load centers are interconnected through long power transmission and distribution networks. The main concern of customer is the quality and reliability of power supply at various load centers. Even though power generation in most well-developed countries is fairly reliable, the quality of supply is not. Power distribution system should ideally provide their customers an uninterrupted flow of energy with smooth. sinusoidal voltage at the contracted magnitude and frequency. However, in practice power system especially the distribution system, have numerous non-linear loads, which are significantly affect the quality of power supply. As a result, the purity of waveform of supply lost. This ends up producing many power quality problems. To improve power quality, custom power devices are used (Zhan *et al.2000*).The thought of custom power (CP) identifies with the utilization of electronic controllers for power system network. There are number of custom power units which are given below, Distribution Statcom (DSTATCOM), Dynamic Voltage Restorer (DVR), Unified power quality conditioner (UPQC), Active Power Filters, Battery Systems (BESS), Distribution Series Capacitors (DSC), Surge Arresters (SA), Un-interruptible Power Supplies (UPS), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), and Static Electronic Tap Changers (SETC) (Jurado *et al.2003*).Power quality issues have become an increasing concern with an increase in the use of sensitive loads. Many crucial production processes face huge economical losses with improper quality in distribution of power. Different power quality surveys done by researchers identify voltage sags as the most serious power quality problem for industrial customers. A Voltage Sag is a momentary decrease in the root mean square (RMS) voltage between 0.1 to 0.9 per unit, with a duration ranging from half cycle up to 1 min (3).

It is considered as the most serious problem of power quality. It is caused by faults in the power system or by the starting of large induction motor. Voltage sag can cause serious problem to sensitive loads that use voltage sensitive components such as adjustable speed drives, process control equipment, and computers and voltage sags last until network faults are cleared (Amrita *et al.2008*).

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Voltage Swell: Voltage swell is defined as an increase in the root mean square (RMS) voltage from 1.1 to 1.8 per unit for duration from 0.5 cycles to 1 min. Voltage swells are not as important as voltage sags because they are less common in distribution systems. The main causes for voltage swell are switching of large capacitors or start/stop of heavy loads (Omar *et al.2008*).

Harmonics: The fundamental frequency of the AC electric power distribution system is 50 Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency. The main causes for harmonic distortion are rectifiers and all non-linear loads, such as power electronics equipment including VSDs.

Voltage transients: They are temporary and undesirable voltages that appear on the power supply line. Transients are high over-voltage disturbances (up to 20kV) that last for a very short time.

Flicker: Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. The main causes are frequent start/stop of electric motors (for instance elevators), oscillating loads (Almeida *et al.2003*).

Figure 1.1 shows the sketch of a voltage waveform with physical power- quality problems.

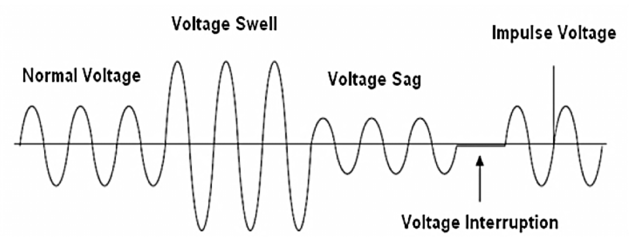

Fig1.1 Power- quality problems in power system

2. Power Quality

The contemporary container crane industry, like many other industry segments, is often enamored by the bells and whistles, colorful diagnostic displays, high speed performance, and levels of automation that can be achieved. Although these features and their indirectly related computer based enhancements are key issues to an efficient terminal operation

2.1 Power Quality Problems

Any power problem that results in failure operation of customer equipment, manifests itself as an economic burden to the user, or produces negative impacts on the environment.'

When applied to the container crane industry, the power issues which degrade power quality include:

• Power Factor
• Harmonic Distortion
• Voltage Transients
• Voltage Sags or Dips

Power quality problem solutions are available. Although the solutions are not free, in most cases, they do represent a good return on investment. However, if power quality is not specified, it most likely will not be delivered. Power quality can be improved through:

• Power factor correction,
• Harmonic filtering,
• Special line notch filtering,
• Transient voltage surge suppression,
• Proper earthing systems.

3. Dynamic Voltage Restorer (DVR) System

Among the power quality problems (sags, swells, harmonics…) voltage sags are probably the most severe disturbances (Ferdi *et al.2008*). In order to overcome these problems the concept of custom power device has become introduced recently. One of those devices is the Dynamic Voltage Restorer (DVR), which is one of the most efficient and modern custom power device used in power distribution networks. A DVR is a 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 a critical load feeder at the so-called point of common coupling (PCC).Its primary function is to rapidly boost up the load-side voltage in the event of a voltage sag in order to avoid any power disruption to that load. There are various circuit topologies and control schemes that can be used to implement a DVR Together with voltage sags and swells compensation, DVR can also have other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

Figure 3.1 shows the location of dynamic voltage restorer (DVR) in an electrical power system. The DVR is a power-electronic-converter-based device capable of protecting sensitive loads from most supply-side disturbances.

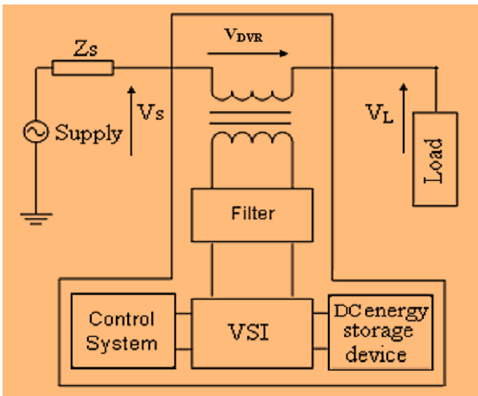

Fig.3.1. Schematic diagram of a DVR with a line-side harmonic filter

The DVR has three modes of operation which are: protection mode, standby mode (during steady state), and injection/boost mode (during sag).

Protection Mode If the current on the load side exceeds a permissible limit due to a short circuit on the load or large inrush current, the DVR will be isolated from the systems by using the bypass switches as shown in Figure 5, S2 and S3 will open and S1 will be closed to provide an alternative path for the load current.

Standby Mode: (VDVR = 0) In the standby mode the booster transformers low-voltage winding is shorted through the converter as shown in Figure 6. No switching of semiconductors occurs in this mode of operation and the full load current will pass through the transformer primary

Injection/Boost Mode: (VDVR≠0) In the Injection/Boost mode the DVR is injecting a compensating voltage through the booster transformer after the detection of a disturbance in the supply voltage.

4. Proposed technique

The problem of voltage sags and its severe impact on sensitive loads can solve through a proposed control strategy for the DVR that provides: voltage-sag compensation under balanced and unbalanced conditions and a fault current interruption (FCI) function. The FCI function requires 100% voltage injection capability. Thus, the power ratings of the series transformer and the VSC would be about three times those of a conventional DVR with about 30%–40% voltage injection capability. This leads to a more expensive DVR system. Economic feasibility of such a DVR system depends on the importance of the sensitive load protected by the DVR and the cost of the DVR itself. The performance of the proposed control scheme is evaluated through various simulation studies in the PSCAD/EMTDC platform. The study results indicate that the proposed control strategy: 1) limits the fault current to less than the nominal load current and restores the PCC voltage within less than 10 ms, and interrupts the fault current within two cycles. it can be used in four- and three-wired distribution systems, and single-phase configurations; 3) does not require phase-locked loops; 4) is not sensitive to noise, harmonics, and disturbances and provides effective fault current interruption even under arcing fault conditions; and 5) can interrupt the downstream fault current under low dc-link voltage conditions.

The adopted DVR converter is comprised of three independent H-bridge VSCs that are connected to a common dc-link capacitor. These VSCs are series connected to the supply grid, each through a single-phase transformer. The proposed FCI control system consists of three independent and identical controllers one for each single-phase VSC of the DVR (Sachdev *et al.*1979). Assume the fundamental frequency components of the supply voltage v_s, load voltage v_l, and the injected voltage v_{inj}.

$\vartheta_s = V_s \, x \, cos(\omega t + \theta_s)$,

$\vartheta_l = V_l \, x \, cos(\omega t + \theta_l)$,

$\vartheta_{inj} = \vartheta_l - \vartheta_s = V_{inj} \, x \, cos(\omega t + \theta_{inj})$

Two identical least error squares (LES) filters are used to estimate the magnitudes and phase angles of the phasors corresponding to v_s, load voltage v_l, and the injected voltage v_{inj}. The FCI function requires a phasor parameter estimator (digital filter) which attenuates the harmonic contents of the measured signal. To attenuate all harmonics, the filter must have a full-cycle data window length which leads to one cycle delay in the DVR response. Thus, a compromise between the voltage injection speed and disturbance attenuation ismade. The designed LES filters utilize a data window length of 50 samples at the sampling rate of 10 kHz and, hence, estimate the voltage phasor parameters in 5 ms.

Fig. 4.1 shows a per-phase block diagram of the proposed DVR control system corresponding to the FCI operation mode, where v_n is the nominal rms phase voltage. The control system of Fig. 4.1 utilizes v_s, v_l, the dc-link voltage V_{DC} , and the harmonic filter capacitor current i_{cap} as the input signals. The reported studies in this paper are based on the overcurrent fault detection method. The fault detection mechanism for each phase is activated when the absolute value of the instantaneous current exceeds twice the rated load current.

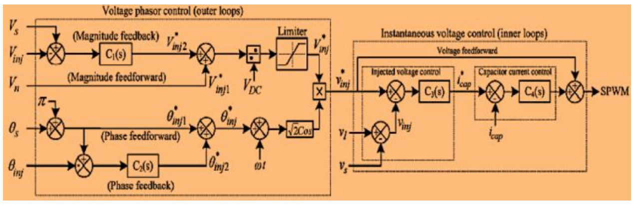

Fig.4.1DVR control system in FCI mode

The proposed multiloop control includes an outer control loop (voltage phasor control) and an inner control loop (instantaneous voltage control). The inner loop provides damping for the transients caused by the DVR harmonic filter and improves the dynamic response and stability of the DVR. The inner loop is shared by the sag compensation and the FCI functions. When a downstream fault is detected, the outer loop controls the injected voltage magnitude and phase angle of the faulty phase(s) and reduces the load-side voltage to zero, to interrupt the fault current and restore the PCC voltage.

5. Simulation Parameter and result

Single-line diagram of a power system depicted in figure 5.1 which is used to evaluate the performance of the proposed DVR control system under different fault scenarios, in the PSCAD/EMTDC software environment. A 525-kVA DVR system is installed on the 0.4-kV feeder, to protect a 500 kVA, 0.90 lagging power factor load against voltage sags.

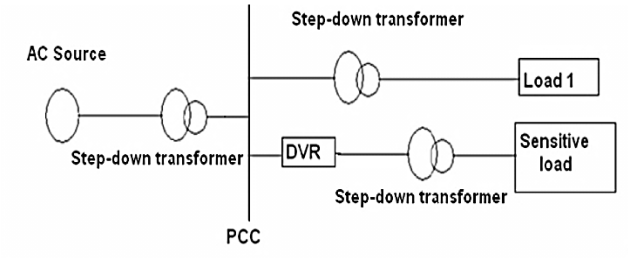

Fig. 5.1 Location of a dynamic voltage restorer (DVR)

Simulation Parameters of power system and the DVR are given in Table.1and 2

Table.1 VSC parameters

VSC Parameters	Value
SPWM (switching frequency)	3KHZ
DC-rated voltage	560V
DC-link capacitor	100mF
Harmonic filter capacitor	300μF
Harmonic filter inductance	56.8μH

Table.2 Transformer parameters

Transformer	T_1,T_2	T_3	T_S
Leakage reactance	.23	.06	.05
Primary voltage rating	230	20	.4
Secondry voltage rating	20	.4	.24
Rated power	95	3	.180
No load losses	.001	.002	.004

Three-Phase Downstream Fault

The system is subjected to a three-phase short circuit with a negligible fault resistance at t= 20 ms at Bus-5. Prior to the fault inception, the DVR is inactive (in standby mode) (i.e., the primary windings of the series transformers are shorted by the DVR).

Fig. 5.2 shows FCI performance of the proposed DVR control system during the fault. Fig. 5.2 (a)–(c), respectively, shows the three-phase injected voltages, the restored three-phase supply-side voltages, and the three-phase load-side voltages which are reduced to zero to interrupt the fault currents. The slightly injected voltage by the DVR before the fault initiation [Fig. 5.2 (a)] is the voltage drop across the series impedance of the DVR series transformer secondary winding. Fig. 5.2 (d) shows the line currents (i.e., the currents passing through the DVR). Fig. 5.2 (d) illustrates that the proposed FCI method limits the maximum fault current to about 2.5 times the nominal value of the load current and interrupts the fault currents in less than 2 cycles. Fig. 5.2 (e) depicts variations of the dc-link voltage during the FCI operation, and indicates that the dc-link voltage rise under the worst case (i.e., a severe three phase fault) is about 15% and occurs during the first 5 ms after fault inception.

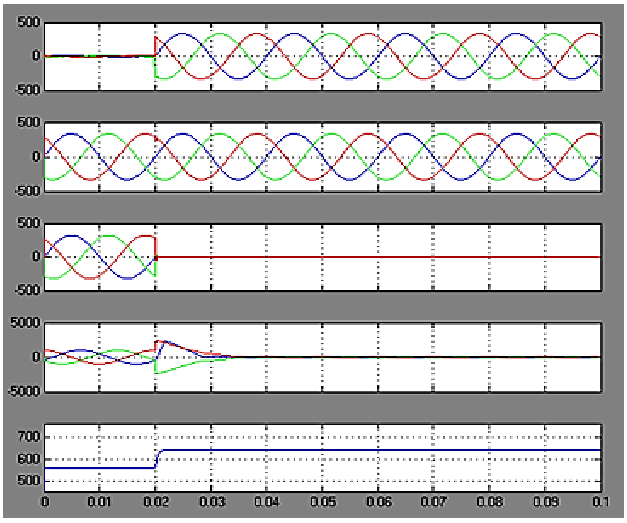

Fig.5.2. (a) Injected voltages. (b) Source voltages. (c) Load voltages. (d) Line currents. (e) DC-link voltage, during the three-phase downstream fault

Phase-to-Phase Downstream Faults

The system of Fig. 4.1 is subjected to a phase-A to phase-C fault with the resistance of 0.05Ω at 10% of the cable length connecting bus-4 to bus-5 , at 20 ms. Fig. 5.3 illustrates that when the DVR is in service, the proposed FCI control successfully interrupts the fault current and restores the PCC voltage of the faulty phases within two cycles. Fig. 5.3 (e) shows that the dc-link voltage rise is less than 7%. Fig. 5.3 also shows that only the two faulty phases of the DVR react, and the healthy phase is not interrupted.

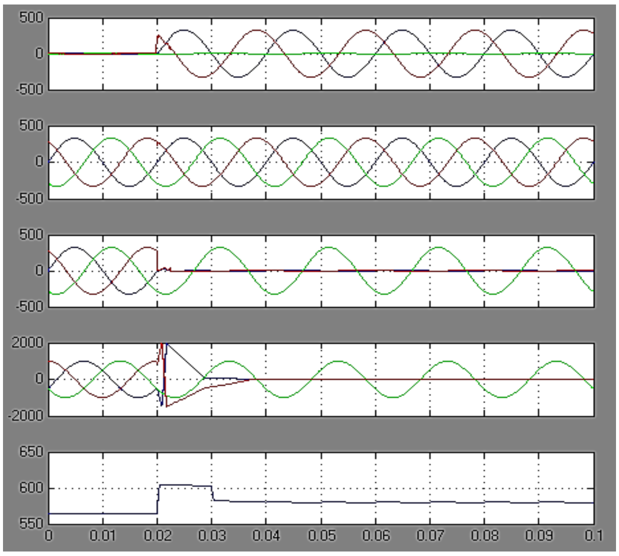

Fig. 5.3. (a) Injected voltages. (b) Source voltages. (c) Load voltages. (d) Line currents. (e) DC-link voltage, during the phase-to-phase downstream fault

Single-Phase-to-Ground Downstream Fault

Phase-A of the system of Fig. 4.1 is subjected to a fault with the resistance of 0.2Ω at 10% length of the cable connecting bus-4 to bus-5, at 20 ms. If the DVR is inactive, the PCC voltage does not considerably drop and the fault current is about 2.5 p.u. Fig. 5.4 illustrates that the proposed DVR control strategy successfully interrupts the fault current in the faulty phase in about two cycles. Fig. 5.4 (e) shows that the dc-link voltage rises less than 1.8%. Fig. 10 also shows that only the faulty phase of the DVR reacts to fault current, and the healthy phases are not interrupted.

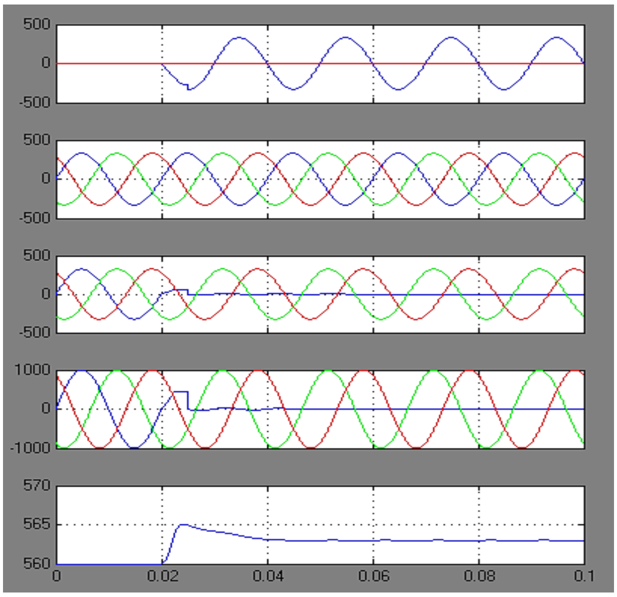

Fig. 5.4 (a) Injected voltages. (b) Source voltages. (c) Load voltages. (d) Line currents. (e) DC-link voltage, during the single-phase-to-ground downstream fault

Simulation studies conclude that the dc-link voltage rise caused by the proposed FCI mode of operation is proportional to the fault current, and depends on the type of fault. The results also indicate that the maximum dc-link voltage rise occurs under the most severe three-phase fault which is about 15%, and can be tolerated based on DVR appropriate design. It must be noted that to prevent operation of three-phase induction motors under unbalanced voltage conditions, they must be equipped with protective devices which detect such conditions and disconnect the load when any of the phases is de-energized by the single-phase operation of the FCI function. Furthermore, disabling the single-phase fault current interruption capability can be provided as an operational option and the operator can decide either to use or disable this function depending on the type of load.

Simultaneous FCI Operation and Sag Compensation

The proposed DVR control system performs two different Function (i.e., sag compensation and FCI). Thus, the mutual effects of these modes on each other must be evaluated. At t=15 ms, the system of Fig. 4.1 is subjected to a phase-A to phase-B fault with the resistance of 1Ω at 90% of the line length from bus-1. The fault causes 87% voltage sag at the PCC. At t= 55 ms, another fault with the resistance of 0.2Ω on phase-A at 10% length of the cable connecting bus-4 to bus-5 occurs. The upstream fault is cleared by relays at t= 93 ms.

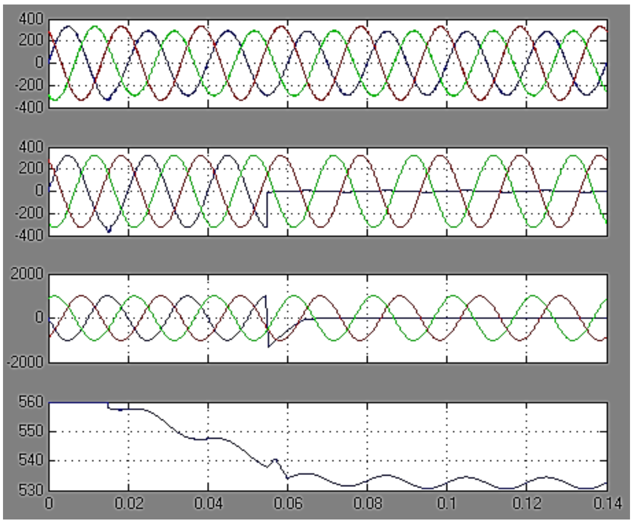

Fig.5.5 (a) Source voltages. (b) Load voltages. (c) Line currents. (d) DC-link voltage, during phase-A to ground downstream fault which takes place during sag compensation in phases A and B

Fig. 5.5 shows the performance of the proposed DVR control system under the aforementioned conditions (i.e., simultaneous FCI operation and sag compensation). Fig. 5.5 shows that when the downstream fault occurs in phase-A, the operation mode of the DVR in phase-A changes from sag compensation to FCI operation. However, the DVR continues to compensate the sag in phase-B to restore the load voltage in this phase. Consequently, phase-A and phase-B of the DVR operate in sag compensation mode during 15< t < 55 ms. During 55 < t < 93 ms, phase-A is in FCI operation mode, and phase-B continues to compensate the sag. During t > 93 ms, phase-B is in standby mode since the upstream fault is cleared and phase-A continues to interrupt the downstream fault current. During the entire process, phase-C is in standby mode.

Fig. 5.5(d) depicts variations of the dc-link voltage and indicates that the dc-link voltage drops during sag compensation, but the FCI operation maintains the dc-link voltage when it is lower than a certain value (the dc-link voltage, which is needed to reduce the load voltage to zero). This continues until the capacitor voltage approaches the aforementioned threshold. The reason is that when the capacitor voltage is lower than a certain value, the magnitude of the voltage injected by the DVR, which must be 180 out of phase with respect to the source voltage, is less than the source voltage magnitude. Thus, small current flows through the DVR until the capacitor is charged. This current results in active power absorption by the DVR.

Fig. 5.6 shows the effect of lower initial dc-link voltage on the FCI operation during a phase-A to ground fault with the resistance of 0.05Ω at 10% length of the cable connecting bus-4 to bus-5 , at t=15 ms. If the DVR is inactive (bypassed) during the fault, the fault current increases to about 7 times the rated load current. Fig. 5.6(a) shows that even under very low dc-link voltage conditions, the FCI control limits the fault current to less than the nominal load current in about one cycle. Fig. 5.6(b)

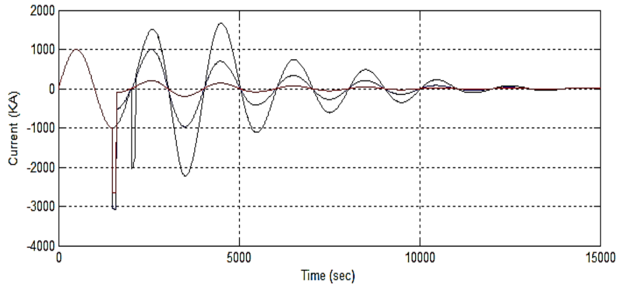

Fig.5.6. (a) Line current of phase-A for different initial values of the dc-link voltage, during downstream phase-A-to-ground fault

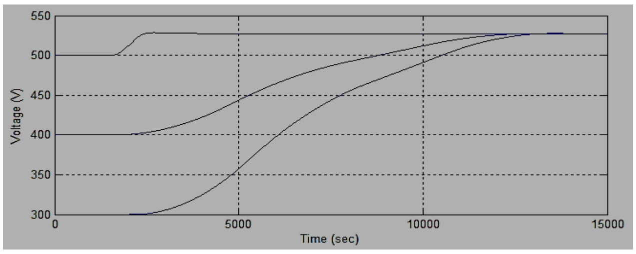

Fig.5.6 (b) dc-link voltage

Conclusion

This paper introduces an auxiliary control mechanism to enable the DVR to interrupt downstream fault currents in a radial distribution feeder. This control function is an addition to the voltage-sag compensation control of the DVR. The performance of the proposed controller, under different fault scenarios, including arcing fault conditions, is investigated based on time-domain simulation studies in the PSCAD/EMTDC environment.

The study results conclude that

- the proposed multiloop control system provides a desirable transient response and steady-state performance and effectively damps the potential resonant oscillations caused by the DVR LC harmonic filter;
- the proposed control system detects and effectively interrupts the various downstream fault currents within two cycles (of 50 Hz)
- The proposed fault current interruption strategy limits the DVR dc-link voltage rise, caused by active power absorption, to less than 15% and enables the DVR to restore the PCC voltage without interruption; in addition, it interrupts the downstream fault currents even under low dc-link voltage conditions.
- The proposed control system also performs satisfactorily under downstream arcing fault conditions.

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