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Study of Basic Properties of an Enhanced Controller for DVR Compensation Capabilities

Abstract. *This paper deals with the development of an enhanced controller for investigation of dynamic voltage restorer (DVR) compensation capabilities. Two levels, 24-pulse DVR is modeled with a new control scheme to control the switch signal in the voltage sourced converter. A study on voltage sag compensation capability, harmonic elimination, effect of phase shift on DVR sizing, influence of induction motor load and effect of capacitor value on DVR performance have been investigated. Results proved that the DVR is a suitable device for maximum power quality (PQ) compensation. Thus, the developed model and controller will be useful for further power quality studies in a distribution system.*

Streszczenie. *Opisano ulepszony sterownik system dynamicznego odzyskiwania napięcia DVR. Przeanalizowano przypadki możliwości kompensacji zapadów napięcia, eliminacji harmonicznych oraz wpływ indukcyjności obciążenia. Symulacje potwierdziły przydatność układu w systemach poprawy jakości energii. (**Właściwości ulepszonego sterownika systemu DVR – dynamicznego odzyskiwania napięcia**)*

Keywords: Control strategy, DVR, Voltage sag, Power quality.
Słowa kluczowe: jakośc energii, zapady napięcia, odzyskiwanie napięcia.

Introduction

The increased concern for power quality has resulted a complete shutdown of an entire production line, in particular at high-tech industries like semiconductor plants, with severe economic consequence to the affected industries [1]-[2]. Many concepts have been developed in measuring power quality variations, studying the characteristics of power disturbances and providing solutions to the power quality problems [3]-[5]. Custom power is a concept based on the application of power electronic controllers in the distribution systems aimed at achieving a reliable and high quality power [6]-[11].

Dynamic voltage restorer (DVR) is custom power device, which has excellent dynamic capability for compensating short duration voltage sags [12]. It can tightly regulate critical load voltage and also perform the primary functions of the restorer that is, to protect critical loads from momentary voltage sags and swells [13]-[14]. The world first prototype DVR was built by Westinghouse for Electric Power Research Institute in 1996 and installed by the Duke Power Company at North Carolina [15]. A DVR is usually housed in a tractor-trailer or skid-mounted in order to provide complete site-to-site mobility and quick access for upgrades and modification. The equipment is also easy to install, requiring only minimal support for system installation, site preparation and hook-up [16].

The basic operation of a DVR is to inject a controlled voltage generated by a forced-commutated converter which is connected in series to the load voltage by means of a booster transformer [17]. The series connection is required to allow insertion of voltages of controllable amplitude, phase angle and frequency into the distribution feeder. The sum of the line voltage and the insertion voltage becomes the restored voltage as seen by a critical load [18]. It is explained that a DVR provides not only the missing voltage but also compensates for phase shift during a voltage sag event [19].

Fast controlled force commutated high frequency power electronic devices such as GTO, IGCT (Integrated Gate Commutated Thyristor) and IGBT are normally used in DVR [20]-[21]. The preferred power electronic device for a DVR is the MOSFET which has a relatively low current rating and faster switching as compared to IGBT. But due to low conducting losses, IGCT is sometimes used for DVR as proposed by [17].

The main components of parts of a DVR are inverter, injection transformer, dc energy storage device and control system. There are variations in the inverter configuration in which the common inverter configurations are either a three-level or conventional three-phase Graetz inverters. The injection transformer is either with Y-Y winding or Y-Δ windings depending on the way it is connected in a distribution system. The energy storage devices used are usually dc devices, which may be lead acid batteries, flywheel super-conducting magnetic energy storage device and capacitors [22]. A DVR is controlled in four different states namely known as active, standby, by passed and disconnected states [23]. In the active state, a DVR generates a voltage to compensate for voltage sag. In the Standby state, a DVR is said to be in standby mode and no voltage sag occurs. However, in the by passed state, current is too high for DVR converter to conduct and it has to wait until the current is reduced. Finally, in the disconnected state, a DVR is disconnected from the system during the operation.

The rating and control of a DVR is influenced by voltage sag accompanied with a phase jump. Barros et al. [24] proposed two control methods for compensating voltage sag with a phase jump, and they are known the in-phase compensation and pre-phase compensation.

Daehler and Affolter [17] demonstrated that a DVR would generate high order harmonics under boost mode due to switching of inverter. Although harmonic distortion may not be as onerous a problem as sag, it is still important to maintain the harmonic level to an acceptable level so as to avoid nuisance tripping of sensitive loads and other harmonic induced problems. Therefore, harmonic filtering is indispensable when installing a DVR as suggested by Li et al. [25]. The filtering scheme in a DVR can be placed at the high voltage side or the low voltage side of the series injection transformer. The advantage of placing filters at the low voltage side of a series transformer is that it is closer to a harmonic source [22] and high order harmonic currents can be prevented from penetrating into the series transformer. However, the filter inductor placed at the low voltage side causes a voltage drop and phase angle shift in the inverter output which may affect the control scheme of a DVR. While a high voltage side filter avoids these problems, high order harmonic currents then do penetrate into the series transformer, thus necessitating a higher rating of the transformer.

This paper studies on an enhanced controller for investigation the compatibility issues between the DVR in a distribution system and the end-use loads so as to ensure proper integration and compensation capabilities of the DVR.

Dynamic Voltage Restorer

A DVR is a series custom power device designed especially to improve power quality at the distribution level [26]. It is also a series reactive power compensation device that generates an ac compensating voltage and injects it in series with the supply voltage through an injecting transformer. The injected voltage and the load current determine the power injection of the DVR. In this section, the concept of series reactive power compensation which is the basis of DVR operation is explained. The theory behind the operation of DVR and its control system is also described.

Series Reactive Power Compensation

A series reactive power compensator is functionally a controlled voltage source which is connected in series with transmission or distribution system to control its current [26]. It can be considered as controlled reactive impedance connected in series with a line for the purpose of developing a compensating voltage. Thus, attainable reactive compensating voltage is a function of the prevailing line current [27]-[28]. One of the functions of series reactive power compensation is to minimize the end-voltage variation of radial lines so as to prevent a voltage collapse. Series compensation, if appropriately controlled can also provide significant transient stability improvement for post-fault systems and can be highly effective in machine oscillation damping. The basic idea behind series compensation concept in DVR can be explained by referring to a simplified two machine system with a series compensating injected voltage of DVR as shown in Fig. 1.

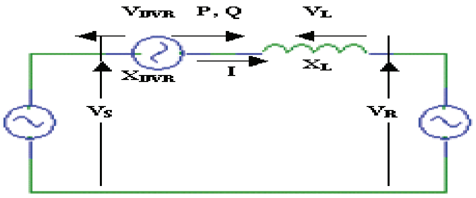

Fig. 1. DVR as a Series Reactive Power Compensator

By assuming that the sending voltage, VS and the receiving voltage, VR have similar magnitudes (VS = VR = V) with a phase difference of δ, the voltage phasor diagram can be drawn as shown in Fig. 2.

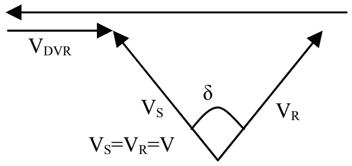

Fig. 2. Phasor diagram of DVR series compensation

From Fig. 1, the real and reactive powers at the receiving end can be expressed as,

$$P = \frac{V^2}{X_L - X_{DVR}} \sin\delta = \frac{V^2}{X_L - \frac{V_{DVR}}{I}} \sin\delta \tag{1}$$

$$Q = \frac{V^2}{X_L - X_{DVR}} \cos\delta = \frac{V^2}{X_L - \frac{V_{DVR}}{I}} \cos\delta \tag{2}$$

The above phasor diagram shows that at a given current the voltage injected by the DVR forces the opposite polarity voltage across the series line reactance to increase by the magnitude of the DVR voltage. DVR voltage injection can be used to change the effective line reactance and therefore controlling the power flow. From equations (1) and (2), by increasing the DVR voltage and the reactance X_{DVR}, the effective line reactance (X_L - X_{DVR}) will decrease and the transmitted powers will increase. Thus, the series compensation works by increasing the voltage across the reactance of a given physical line, which in turn increases the corresponding line current and the transmitted power.

The injected voltage magnitude of the DVR is also dependent on the phase angle of the line current. If the DVR injects a voltage which is leading a line current, it emulates an inductive reactance which is in series with a line and it is considered to be operating in inductive mode. On the other hand, if an injected voltage lags behind a line current, a capacitive mode is emulated.

DVR Principle Operation

Fig. 3 shows a schematic diagram of a typical DVR connected in series with a source and a load in a distribution system. The main components of a DVR are consists of an inverter, transformer and dc capacitor.

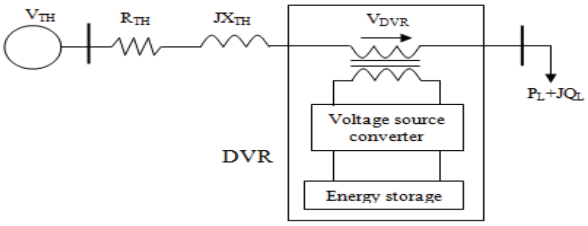

Fig. 3. Principle operation of DVR

The basic idea in the operation of a DVR is to inject a controlled voltage generated by an inverter in series to the bus voltage by means of an injecting transformer. A dc capacitor bank which acts as an energy storage device, provides a regulated dc voltage source. An inverter regulates this dc voltage and converts it into a synchronous ac voltage of controllable amplitude and phase angle.

A DVR is designed to inject a compensating voltage into a distribution line through an injecting transformer so as to restore the load voltage to an acceptable level during the period of voltage sags [26]. The ideal DVR injection voltage can be derived by representing the left hand side of the DVR circuit shown in Fig. 3 with a Thevenin equivalent circuit of the system. The system impedance given by Z_{th} = (R_{th} + jX_{th}) depends on the fault level of the load bus. When the system voltage (V_{th}) drops, the DVR injects a series voltage, V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be determined. The series injected voltage of DVR can be written as

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \tag{3}$$

Here I_L is the load current and is given as,

$$I_L = \left(\frac{P_L + jQ_L}{V_L} \right) \tag{4}$$

When V_L is considered as a reference, equation (3) can be rewritten as,

$$V_{DVR}\angle\alpha = V_L\angle 0 + Z_{th} I_L \angle(\beta - \theta) - V_S\angle\delta \tag{5}$$

where,

$$\theta = \tan^{-1}(Q_L / P_L) \tag{6}$$

It may be mentioned here that when the injected voltage V_{DVR} is kept in quadrature with I_L, no active power injection by the DVR is required to correct the voltage. It requires the injection of only reactive power and the DVR itself is capable of generating the reactive power. However, the DVR can be kept in quadrature with I_L only up to a certain value of voltage sag and beyond which the quadrature relationship cannot be maintained to correct the voltage sag. For such a case, injection of active power into the system is essential. The injected active power must be provided by the energy storage system of the DVR. On the other hand, when the magnitude of the DVR injected voltage is minimized, the desired voltage correction can be achieved with minimum apparent power injection into the system. This aspect of voltage correction is also very important because it minimizes the size of the injection transformer.

DVR Control Algorithm

To maximize dynamic performance, there are different types of DVR control. Hingorani and Gyugyi [27] proposed a control scheme for the operation of a DVR in which it is shown in Fig. 4 in terms of a simplified control block diagram. The inputs to the control are line current IL, the injected compensating voltage V_{DVR} and the reference voltage V_q. The control is synchronized to the line current by a PLL and a phase shifter to provide the basic synchronizing signal θ. The phase shifter is operated from the output of a polarity detector which determines whether the reference voltage V_q is capacitive or inductive. The absolute value of the reference voltage V_q is compared to the measured magnitude of the injected voltage V_{DVR}. An error is observed and then amplified so as to provide a phase displacement angle δ, which is the phase shift between the system voltage and the DVR voltage.

Depending on the polarity δ and θ, the inverter gate drive signals for the GTOs will be advanced or retarded. Thereby, the compensating voltage V_{DVR} will be shifted with respect to the prevailing line current from its original +π/2 or - π/2 phase position. This phase shift will cause the inverter to absorb real power from the ac system to the dc capacitor or supply that to the ac system from the dc capacitor. As a result voltage of the dc capacitor will increase or decrease causing a corresponding change in the magnitude of the compensating voltage and subsequently the quadrature relationship between the line current and the compensating voltage re-established.

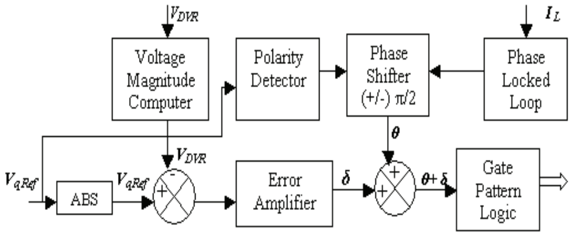

Fig. 4. DVR control scheme

Chung et al. [29] proposed a SPWM control scheme for the operation of a DVR as illustrated in Fig. 5. The three-phase ac voltages at DVR input are converted into d, q components through Parks transformation theory and fed to the Phase Locked loop (PLL). The difference between the output of PLL voltages through low pass filter and the output of PLL voltages is used for fault detection [30]-[31]. When a fault is detected, the PLL locks the pre-fault voltages and the difference between the pre-fault voltages and actual voltage becomes the modulating sine wave. The sine wave is then compared with a triangular signal so as to generate firing signals of the GTO switches of the inverter. This firing signal is also dependent on the phase angle of the system voltage. The proposed SPWM control method is concerned with only d and q components and the disadvantage of this inverter is that it cannot compensate for zero sequence components.

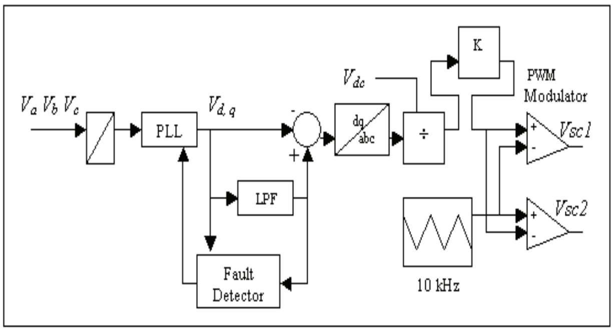

Fig. 5. SPWM DVR control scheme without considering zero-sequence current

To overcome the zero-sequence component problem, three single-phase voltages are fed to PLL separately. However, Fig. 6 shows the control scheme for phase ‘a’ voltage only. In this control scheme, the three-phase voltages are not converted into d-q frame but are controlled independently of each other. Hence, the sum of the three-phase voltages cannot be zero. This means that zero sequence components can be eliminated from restored voltage with the proposed control system.

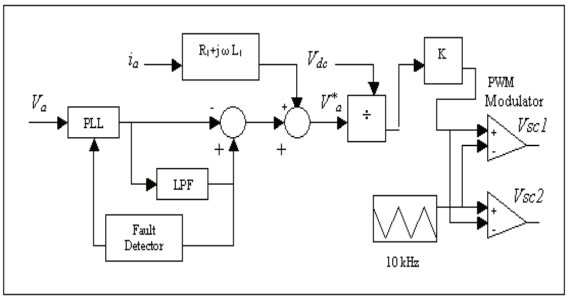

Fig. 6. SPWM DVR control scheme considering zero-sequence current.

DVR Model and Controller

In this section, the simulation model of DVR and its controller are described. A three-phase, 24-pulse DVR model is presented. The simulation model comprises of four 6-pulse inverters, coupling transformers and a dc capacitor as shown in Fig. 7.

The DVR model is quite similar to that of the D-STATCOM. The only differences are that it is connected in series with the distribution system and the transformer arrangement is such that all the secondary windings are delta connected and the primary windings are wye connected. Usually Y-connected secondary windings allow the injection of positive, negative and zero sequence voltages, whereas the delta connected secondary windings allow only the injection of positive and negative sequence voltages. The delta connection prevents zero sequence currents entering into the system from the DVR. The leakage reactance of each single-phase transformer is designed to be 0.01 p.u. in order to reduce its voltage drop. The instantaneous DVR output voltage of the three phases can be computed in this case as,

$$V_a = \frac{1}{\sqrt{3}}[a_1 V_{a1\Delta} + a_2 V_{a2\Delta} + a_3 V_{a3\Delta} + a_4 V_{a4\Delta}] \tag{7}$$

$$V_b = \frac{1}{\sqrt{3}}[a_1 V_{b1\Delta} + a_2 V_{b2\Delta} + a_3 V_{b3\Delta} + a_4 V_{b4\Delta}] \tag{8}$$

$$V_c = \frac{1}{\sqrt{3}}[a_1 V_{c1\Delta} + a_2 V_{c2\Delta} + a_3 V_{c3\Delta} + a_4 V_{c4\Delta}] \tag{9}$$

where, *a1, a2, a3* and *a4* are the voltage ratios of the corresponding transformers

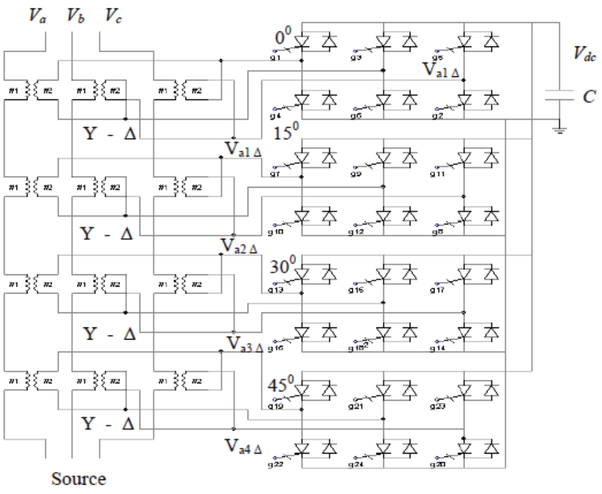

Fig. 7. The three-phase 24-pulse DVR model

DVR Controller

The DVR controller in terms of a block diagram is shown in Fig. 8. In the DVR, the SPWM technique is used to control the magnitude and phase of the ac voltage by synchronizing the GTOs switching to the ac system voltages. The voltage control loop of the DVR, measured phase currents are input to the PLL$_1$ in order to generate the synchronizing signals. The DVR injected voltage is kept in quadrature with the line currents to provide reactive series compensation.

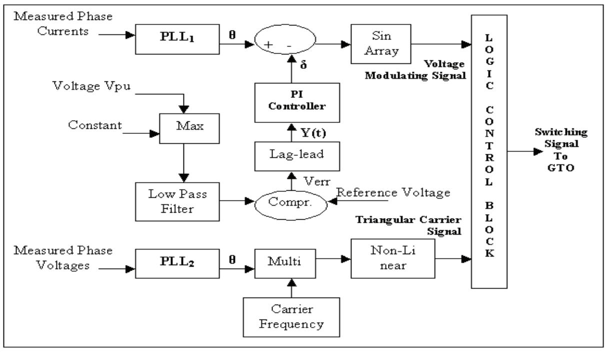

Fig.8. Block diagram of DVR control system in a distribution system

In the DVR control, the generation of the displacement angle δ which is the angle between the system voltage and the reference voltage. If the voltage V p.u. is equal to the reference voltage Vref, then the displacement angle δ = 0, the system voltage and the DVR voltage are synchronized and there is only reactive power in the system. If V p.u < Vref, then δ > 0 and the DVR voltage lags behind the ac system voltage. However, if $V_{p.u} > V_{ref}$, then δ < 0 and the DVR voltage leads the ac system voltage. By changing the displacement angle δ, real power flow through the DVR, the dc capacitor will be charging or discharging and consequently, increasing or decreasing its dc voltage. The increase or decrease in dc voltage will cause an increase or decrease of the DVR ac output voltage, respectively until $V_{p.u.} = V_{ref}$. The DVR control implemented in PSCAD/EMTDC program.

Results and Discussion

To analyze the performance of the designed 24-pulse DVR, simulations were performed on a 22kV distribution system as shown in Appendix B.1. In the system, the single-phase transformers are rated each at 5 MVA, 22/4.16 kV with a leakage reactance of 0.01 p.u. The loads considered are similar to the loads considered in the D-STATCOM simulations. In the simulation studies, various issues have been addressed such as the effectiveness of the DVR in compensating voltage sag, impact of phase shift impact during voltage sag on sizing of DVR, harmonic reduction, influence of induction motor load on the DVR voltage sag compensation capability and the effect of capacitance value on DVR performance. Simulation results are presented for the following cases.

Voltage Sag Compensation Capabilities

To simulate a voltage sag condition, a balanced three-phase fault is created using the three-phase fault generator. The simulation results using the DVR for sag compensation in terms of the phase voltages are shown in Fig. 9. It can be seen that for the system without the DVR, a balanced voltage sag condition is created at time t = 0.08 s for a duration of 80 ms as shown in Fig. 9 (a). For the system with the DVR, a voltage is injected by the DVR as shown in Fig.9 (b). The voltage sag is compensated by the DVR and the load voltage returns to near its rated voltage as shown in Fig. 9 (c). Table I summarizes the voltage sag compensation capabilities of the DVR for sags of different magnitudes. It can be noted that by decreasing the voltage sag magnitudes, the difference between the minimum and the maximum rms voltages is reduced. On the other hand, the steady state rms voltage has less effect with the variation of different voltage sag magnitudes.

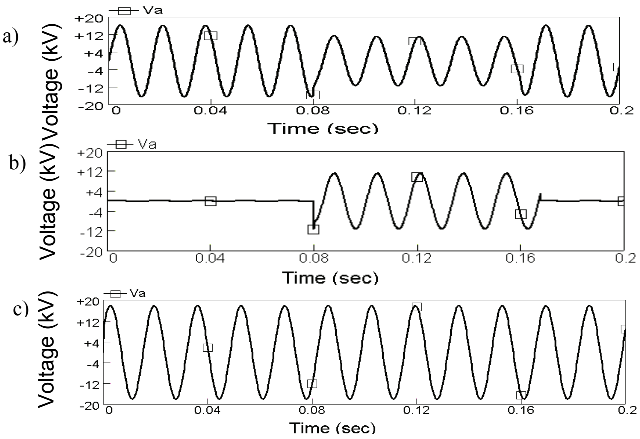

Fig. 9. Load voltage a) without DVR b) DVR injected c) compensated voltage

Harmonic Elimination

Basically, a DVR should not actively generate any harmonics but during the sag period under boost mode, the DVR tends to generate harmonics as shown in Fig.10 (a). To eliminate harmonics generated by the DVR, a passive filter is connected at the inverter side of the series transformer for the attenuation of the high order harmonics. Fig. 10(b) shows the load voltage response with the harmonics eliminated when the system is connected with a passive filter of inductance *L* = 0.2 H and capacitance C = 25 μF. The size of L and C is selected based on the fact that $2\pi f_0 = 1/LC$ where f_0 is the fundamental frequency.

Table I. Compensation effect for sags of different magnitudes

Without DVR	Voltage Sag magnitude (p.u)	0.68	0.82	0.88	0.91
With DVR	Min rms Voltage (p.u)	0.946	0.971	0.980	0.986
	Max rms Voltage (p.u)	0.996	0.999	1.001	0.99
	Steady state rms Voltage (p.u)	0.985	0.987	0.992	0.995

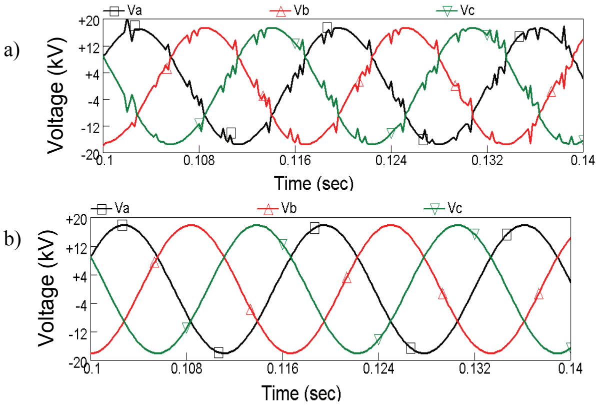

Fig. 10. Load voltage a) without filter b) with filter

To illustrate further the effect of using the passive filter, the total harmonic distortion (THD) of the system is recorded. Fig. 11 (a) and (b) show that the calculated THD for the system without and with the filter connected are 12.68 % and 0.88 %, respectively. It can be observed that with the filter connected, the harmonics are eliminated and the THD of the system is reduced to 0.88 % from 12.68 %. The THD of 0.88 % is far below the THD limit of 5 %. Thus, the harmonics generated in the DVR can be significantly reduced by connecting a passive filter into the system.

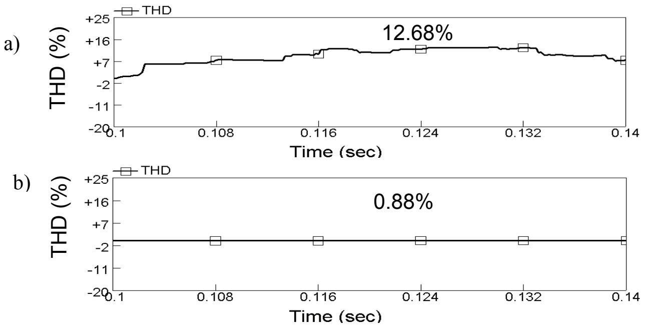

Fig. 11. Total harmonic distortion a) without filter b) with filter

Phase Shift on DVR Compensation Capabilities

Magnitude variations with respect to time are normally used to describe voltage sag. However, some voltage sags are associated with phase shift especially in the case of line-to-line faults. Therefore, the impact of phase angle shift during voltage sags is investigated so as to determine the required compensation capability of the DVR. Voltage sag can be compensated by the DVR injecting a voltage, in which the voltage injection capability of the DVR can be calculated using equation,

$$V_{inj} = \sqrt{\left\{V_{nom}^{2} + V_{sag}^{2} - 2V_{nom}V_{sag}Cos(\beta)\right\}} \tag{10}$$

where: V_{inj} - Injected voltage to the system by the DVR, V_{nom} - Nominal voltage of the system, V_{sag} - Voltage sag of the system, β - Phase shift between the nominal voltage and the voltage sag.

The simulation results shown in Fig. 12 indicate that without a phase shift, the DVR is required to inject 40 % of voltage magnitude so as to compensate voltage sag of 60 %. However, with a 60 degree phase shift, the results shown in Fig. 13 indicate that the DVR is required to inject 87 % of voltage magnitude so as to compensate voltage sag of 60 %. The investigation on the effect of phase angle shift during voltage sags shows that the required injection capability of the DVR is greater when a phase shift is present.

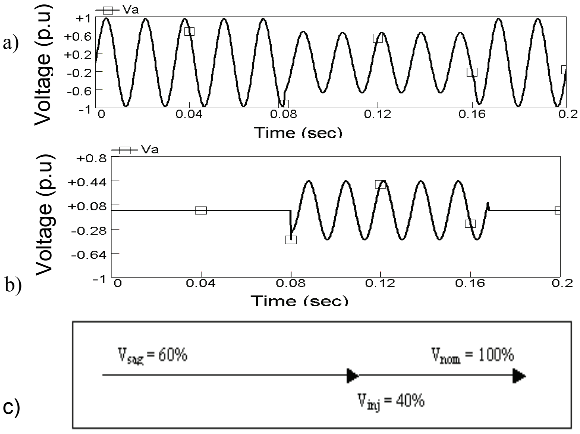

Fig. 12. Without phase shift a) voltage sag b) DVR injected voltage c) voltage phasor diagram.

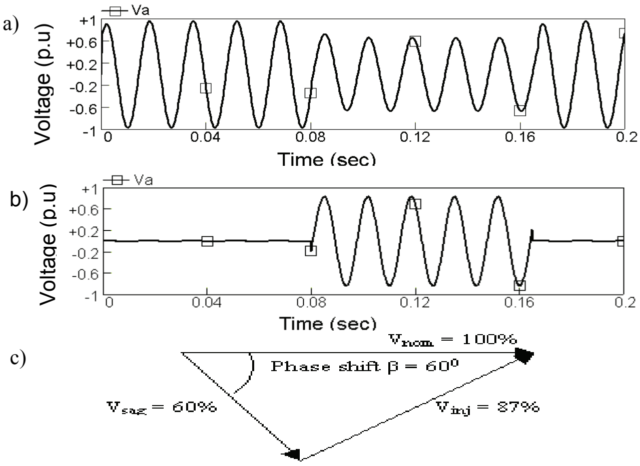

Fig. 13. With 60^0 phase shift a) voltage sag b) DVR injected voltage c) voltage phasor diagram.

Motor Load on Voltage Sag Compensation Capabilities

Due to large numbers of induction motors present in the distribution system, an analysis is made on the influence of induction motor load on the voltage compensation capability of the DVR. Fig. 14 (a) and (b) show the characteristic of voltage sags for the system with static load and with induction motor load, respectively. In Fig. 14 (a) it is shown that without the induction motor load, the voltage sags down to 0.62 p.u almost immediately after fault initiation and returns back immediately to its rated value upon fault clearance. However, due to the induction motor load, the voltage sags down continuously throughout the fault period until it reaches 0.68 p.u and after the fault, the sag remained for almost 0.16 s before the prefault voltage level was regained as shown in Fig. 4 (b). Thus, the deceleration and acceleration of induction motors influence the duration and shape of voltage sags. In the presence of induction motor loads, the assumption of rectangular sags no longer holds.

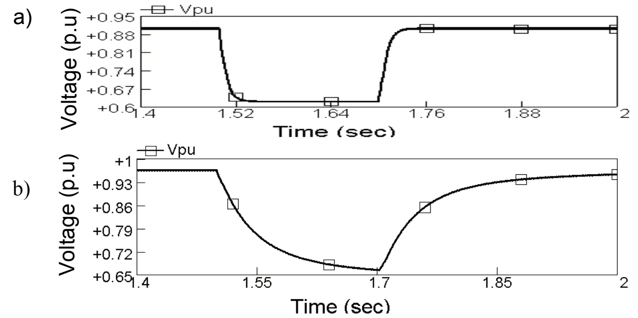

Fig. 14. Voltage sag without DVR a) without induction motor b) with induction motor

Fig. 15(a) and (b) show the compensated load voltage without induction motor load and with induction motor load, respectively. Simulation results shown that the DVR is equally capable of restoring the load voltage to within 90 %-105 % of nominal voltage.

Effect on Capacitance values on DVR Performance

An investigation is made to study the effect of the dc capacitance on the capacitance voltage and the load voltage. By changing the capacitance values according to 500 μF, 1000 μF, 1500 μF and 2430 μF, the dc capacitance voltages are recorded as shown in Fig. 16.

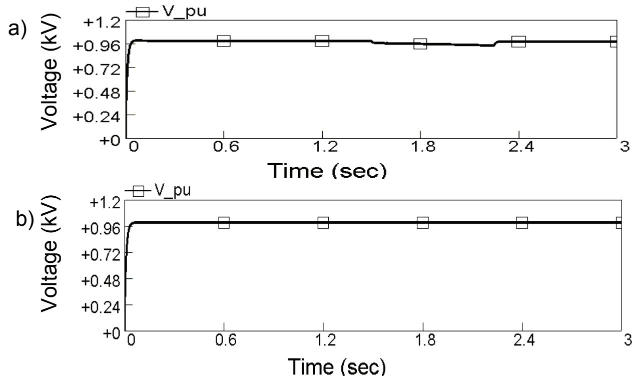

Fig. 15. Compensated load voltage with DVR a) without induction motor b) with induction motor

From the simulation results, it can be seen that by increasing the dc capacitance values, the oscillation in the capacitance voltages are reduced. Table 2 shows the magnitudes of the capacitance voltages and the load voltages for the different dc capacitance values. From Table 2, as the dc capacitance is increased, the trend noted is that the maximum dc voltage decreases while the minimum dc voltage increases, thus making the amount of overshoot to decrease. As for the load voltage, by increasing the capacitance values the load voltage magnitude increases. However, the load voltage variations are small, when the capacitance values are increased from 1500 μF to 2430 μF. Thus, a larger dc capacitance greatly reduces the amount of oscillation in the capacitance voltage and increases the steady-state rms value of the load voltage.

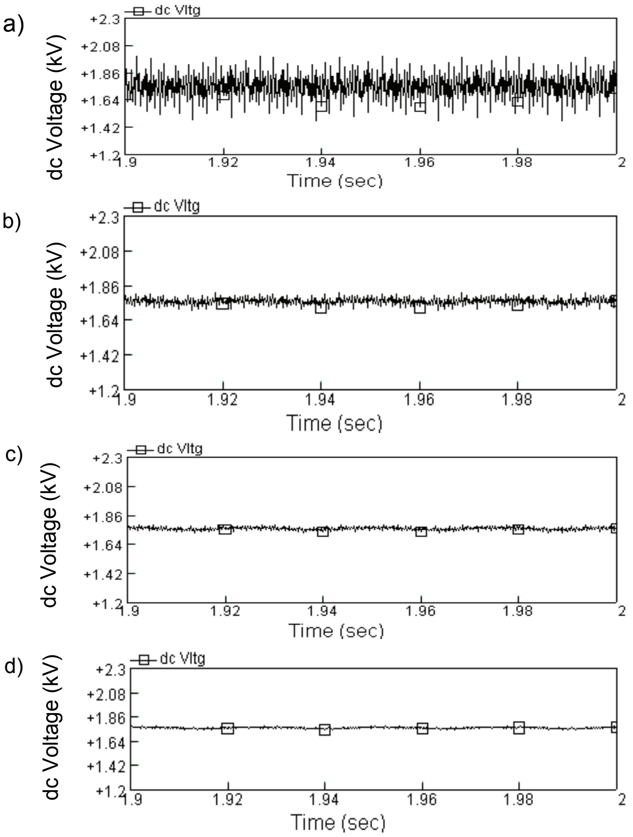

Fig. 16. DC capacitance voltages at a) 500 b) 1000 c) 1500 d) 2430 μF

TABLE 2.performance comparison under different capacitor values

Capacitance μF	Steady -state rms Load Voltage (p.u)	Max dc Voltage (kV)	Min dc Voltage (kV)
500	0.953	3.25	1.52
1000	0.963	2.35	1.72
1500	0.984	2.26	1.76
2430	0.988	2.25	1.78

Conclusion

In this paper, an enhanced controller for DVR is developed for investigation PQ compensation capabilities. The DVR model and the controller were developed using the electromagnetic transient program PSCAD/EMTDC and the developed control strategies were thoroughly verified. In these studies, two level 24-pulse DVR models in a test distribution system was considered to provide better performance than any other level and pulse in terms of voltage sag compensation, harmonic elimination, effect of phase shift, induction motor load and capacitance values. In the DVR control algorithm, a simple control algorithm using an ac current control loop, voltage control loop and PI controller has been designed for fast synchronizing and accurate firing logic signals. Investigations are made on various issues involved in the performance of the DVR as voltage sag compensation capabilities, harmonic elimination, impact of induction motor load, effect of phase shift, inverter pulse-number and dc capacitance which provides a better understanding of the compatibility between the DVR, the distribution system and loads. Thus from the results, it is proven that the DVR can effectively perform maximum PQ mitigation and the developed enhanced model and controller will be useful for future power quality studies as well as basis for the prototype implementation.

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