Control Strategies for Electronic Power Quality Enhancement Equipment

Gerald T. Heydt
Arizona State University
Tempe, Arizona
USA

Siddharth Suryanarayanan
Florida State University
Tallahassee, Florida
USA

Abstract—**This paper describes several concepts for power quality enhancement utilizing electronic devices. The controls for the electronic devices are discussed. The focus of the paper is on the dynamic voltage restorer (DVR) which has been used in a number of cases involving sensitive loads.**

Index Terms-- **Power quality, *dq0* transform, dynamic voltage restorer, feed forward control, phasor domain, voltage sags.**

I. INTRODUCTION

POWER quality engineering often resorts to devices for the enhancement of service to distribution customers. Examples include tapped transformers, lightning arresters, and shunt capacitors. In modern power systems, these passive elements often are unable to provide sufficient conditioning for sensitive loads. Also, some disturbances in the distribution system may have very high bandwidth (e.g., well above 1 kHz) and therefore fast controls are needed to provide the needed power quality enhancement. As an example, an AC electric arc furnace may have load current components over 20 times the power frequency, and therefore to attenuate these signals, controls are needed that can act in, for example, 1/20 times the period of one AC cycle. One way to accomplish this power conditioning is through the use of electronic controls. The main electronic power quality enhancement equipment types are:

- The dynamic voltage restorer
- The transient voltage regulator
- The subcycle transfer switch
- The static var compensator.

II. STATIC VAR COMPENSATORS

Voltage support at a load is usually accomplished by reactive power injection at the load point of common coupling (PCC). The traditional method to support voltage is by installing mechanically switched shunt capacitors at the distribution primary end. The mechanical switching may be on a schedule, via signals from a supervisory control and data acquisition (SCADA) system, on some timing schedule, or with no switching at all (i.e., permanently online). The disadvantage of mechanically switched capacitors is that high speed transients can not be compensated. Mechanical switching operates in the order of 300 ms or (much) more, and sags are not usually corrected in this time frame. Transformer taps may be used, but these too have speed limitations, and tap changing under load has its disadvantages.

Electronic solutions include static var compensators (SVCs) which are effectively electronically switched capacitors (and inductors) [4]. The control of a static var compensator is usually based on root-mean-square (RMS) voltage. That is, a sliding window is used to calculate the RMS value of voltage, and this is compared to a reference voltage set point. The capacitor is switched on in a greater duty cycle when a higher voltage is needed, and the duty cycle is lessened when the bus voltage is higher than the set point. The RMS voltage is simply calculated as

$$V_{rms} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} v^2(t)dt} \qquad (1)$$

where $v(t)$ is a time signal and T is either the period of the time signal or a suitably long time. For the periodic case, when T is an integer multiple of the period of $v(t)$, and t_0 is a fixed point on the wave, the RMS value is termed a *synchronous RMS* (*s*-RMS). The *s*-RMS operation maps a time signal to a single point and can be visualized as an information concentrator. It is a simple matter to demonstrate that the s-RMS quantifies the Joule effect of a sinusoidal voltage or current. Reference [1] contains a discussion of applications and calculation procedures. In electric power engineering, the RMS operation is in widespread use, and for some applications there may be misuse. As an example, in power quality studies, the decrement of the AC voltage amplitude at some buses is known as a voltage sag or dip; the effects on consumers are often quantified in terms of the deviation of secondary distribution voltage RMS values. However when sag events are of short duration, the RMS values may have a problematic interpretation. The most common RMS operator is the m-RMS which entails the use of a moving window of width T to obtain the RMS value. When seen as a filtering operation, the RMS process has a frequency response itself. If the period T_o of the signal is known, by a synchronous averaging of the time data only frequency components at integer multiples of $f_o=1/T_o$ will remain in the output signal. All asynchronous frequencies (irrational multiples of f_o) average to zero [2].

The significance of the foregoing is that careful design of the SVC controls is needed to ensure that the SVC will operate suitably quickly for the case of wide bandwidth signals. This is needed, for example, in the case of

AC electric arc furnaces in which the load current bandwidth can reach 20 times the power frequency. If the RMS calculation can not 'see' the high frequency signal, it can not be used to set the SVC operating point. Sensory issues for a static transfer switch.

A static subcycle transfer switch (SCTS) is a solid state switch that is capable of transferring the load from one feeder to a second, independently derived feeder. This is accomplished generally by closing both the normal and the alternate feeders and permitting 'reverse feed' for a few milliseconds, and then opening the 'normal' feed. There are two sensory and system issues: the first relates to the sufficiency of the system reactance to withstand the paralleling of both feeds; and the second is the sensory question itself: when is the voltage on the normal feeder low enough to warrant transferral to the auxiliary feed?

The paralleling of both the normal and auxiliary feeders will occur for approximately 1.0 ms or less in an SCR based SCTS. In a 50 Hz system, this is less than 18^{o} overlap. The worst case occurs when the normal feeder is faulted and appears at zero volts. Even if the short circuit ratio at the normal feeder is very high (i.e., a stiff bus), if the voltage at the load appears to be zero for 18^{o}, the CBEMA [2] criterion would be satisfied. The CBEMA criterion is that a short circuited bus at zero volts should be withstood for as long as 8.3 ms (about 143^{o} in a 50 Hz system).

The issue of sensory speed relates to how fast the SCTS can detect a low voltage condition. This is generally accomplished by passing the three phase supply voltage from the normal supply feeder through a low pass filter, and then obtaining the integral of the resultant. The integral of the three signals will pass through peaks as the signal itself pass through a zero. And, vice-versa, the signal passes through a peak as the integral passes through a zero. In this way, it is claimed by manufacturers that low voltages can be detected within one-quarter cycle (5.0 ms in a 50 Hz system). The sensory time is added to the switching time to obtain the load transfer time – in the order of 6.0 ms. This concept has been commercialized to the 40 MVA class at 32.5 kV subtransmission.

III. THE DYNAMIC VOLTAGE RESTORER

Dynamic voltage restorers (DVRs) are a class of custom power devices for providing reliable distribution power quality. The DVR is a power electronics based solution that employs series voltage boost technology for compensating voltage sags / swells. The DVR applications are mainly for sensitive loads that may be drastically affected by fluctuations in system voltage. The basic concept of a DVR is shown in Fig. 1 in which the distribution supply voltage, V_S is augmented by a series voltage, V_{SER} . The series voltage provides boost compensation during sags to deliver rated voltage to the load, V_L. DVR technology has been commercialized for serving sensitive loads [3]. The operation, power electronic requirements and topologies of a DVR are described in [5]-[8]. A generic DVR is required to detect voltage sags/swells and produce a corresponding compensation voltage for injection in series to the distribution supply voltage, so that the voltage at a sensitive/critical load is within certain limits of reliability. To perform the above functions, the DVR is equipped with the components shown in Fig. 1.

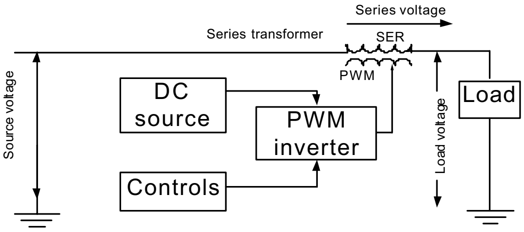

Fig. 1 Components of a generic DVR

The DVR employs power electronics for compensation of the distribution side voltage. A controller detects the sag / swell in the supply voltage and computes a corresponding signal for triggering pulses to a pulse width modulated (PWM) inverter. A controller is feed forward type if it receives inputs from only the supply or the load side; and is feedback type if the error in the output is minimized by using measurements from both the supply and load sides. A DC source, usually capacitors, provides the energy input to the inverter for producing the AC compensation voltage. The series boost voltage is implemented by inserting a transformer in the DVR design: the 'PWM' winding of that transformer is energized by the PWM inverter, and the 'SER' winding is in series with the supply voltage V_S. Note too that the SER winding must carry full load current.

IV. CONTROL TECHNIQUES FOR A DVR

The basic functions of a controller in a DVR are the following:

- Detection of voltage sag/swell events in the system
- Computation of the correcting voltage
- Generation of trigger pulses to the sinusoidal PWM based DC-AC inverter
- Correction of any anomalies in the series voltage injection
- Termination of the trigger pulses when the system event has passed.

The controller may also be used to shift the DC-AC inverter into rectifier mode to charge the capacitors in the DC energy link in the absence of voltage sags.

The different types of control techniques available are classified as feed forward and feedback modes. A feed forward control technique is achieved by sensing either the supply end voltage, V_S, or the load end voltage, V_L. The control logic for the feed forward method is easier to implement than for a feedback method. The disadvantages of phase jump and transformer saturation may arise when the feed forward method is employed [7]. A feedback control technique is implemented by sensing both V_S and V_L and minimizing the error. The control logic is complicated as compared to that of the feed forward method. The type of control technique and the response time of the controller are largely dependant on the requirements of the critical load. In this paper, two different methods of feed forward control with significantly different response times are described. The first control method based on the *dq0* transformation is a faster technique than the second method which is based on the RMS or moving average computation. The same issues as discussed above in connection with the SVC apply here: note that the RMS process is essentially a low pass filter, and this band limitation can adversely impact the DVR operation.

The *dq0* transformation or Park's transformation [9-11] refers to the transformation of the phase quantities associated with a synchronous machine to a new coordinate system,

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & 1 \\ -sin(\theta) & -sin(\theta - \frac{2\pi}{3}) & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2)$$

where the phase and transformed voltages are shown, and ? is selected on the basis of a reference phasor (usually the *a*-phase (red-phase) supply line-neutral voltage and the power flow in the DVR). Note that

$$\theta = \omega_r t + \theta_o$$

where $?_r$ refers to the power frequency, and $?_o$ can be nominally chosen as zero in this application. Since (1) is a purely real transformation, there is no assumption of sinusoidal steady state (as needed in phasor controls). The use of the *dq0* transformation is very similar to Clarke's *a, ß, 0* transformation, and both transformations yield a low bandwidth signal that effectively decouples the modes of the electrical supply. The latter is deduced by inspection of (2) and noting that

$$V_{dq0}(j\omega) = T(j\omega) * V_{abc}(j\omega). \quad (3)$$

In (3), the upper case voltages are in the Fourier frequency domain, *T* refers to the Fourier transform (term-by-term) of the transformation, and (*) refers to frequency domain convolution. Because *T* contains only DC and single frequency terms (i.e., sines and cosines), the frequency spectrum T contains only delta functions. Therefore, the convolution integral in (3) is simply an integration of the phase variable frequency spectra with delta functions located at ? = 0 and the power frequency. An integral of delta function in this configuration results in zero everywhere except at DC and the sum and differences of the frequency components of V_{abc} ('the sifting property'). The conclusion is that if the sum frequency terms are ignored, the bandwidth of the *dq0* variables is basically concentrated near DC.

The *dq0* variables have the advantage over complex transformations (e.g., symmetrical components) because there is no requirement of sinusoidal steady state operation as need by symmetrical components. The *dq0* based control for DVR is seemingly a popular method and a feedback method of control based on this transformation is described in [5]. This transform may also be insensitive to harmonics in the sensory signals, and there are potentially many applications in control of power electronic devices. Fig. 2 illustrates a flowchart of the feed forward *dq0* transformation based control used in this research.

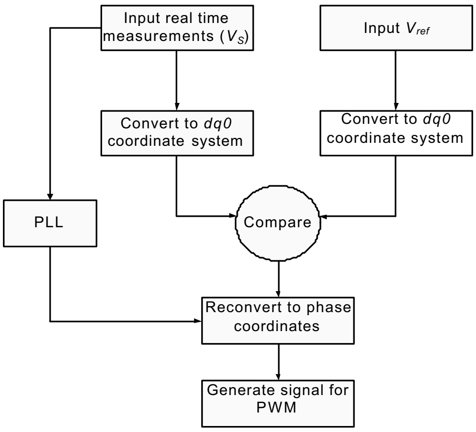

Fig. 2 Flow chart of feed forward control technique for DVR based on *dq0* transformation.

The *dq0* transform based feed forward control method for compensating sags in this research functions almost instantaneously with a time delay of 20% of a cycle (3.33 ms in a 60 Hz system). A potential disadvantage of the *dq0* transform based method is that there is no straightforward mechanism for minimizing the active power taken from the DC energy storage link of the PWM inverter. A slower control method based on RMS values which optimizes the injection of active power during voltage compensation is described below. However, that method has the disadvantage of the assumption of sinusoidal steady state operation (common to all phasor analysis).

There may be some disadvantages to the *dq0* based control. Among these are sensitivity to noise (as opposed to phasor based methods in which high frequency terms are readily eliminated), and simplicity in the design of the controller. The RMS based feed forward control method is a simpler alternative and this is described here. The RMS control is performed by sensing the RMS value of the supply side voltage V_s. In this method, the compensation voltage is controlled using either the magnitude or the phase angle of the series voltage produced by the PWM inverter. The RMS based control method is a combination of two techniques: *all quadrature* and *all maximum* series voltage injection. Prior to the explanation of the novel control method, a brief description of the phasor domain parameters of a DVR is given below [13].

Fig. 3 depicts the phasor diagram in a voltage sag scenario where V_S, V_L, and V_{SER} are the supply, load, and the injected series voltages respectively. I_L is the load current,

F_L is the load power factor and f_S and f_L are the phase differences between V_S and V_{SER} and V_L and V_{SER} respectively. The circumference of the dotted circle in Fig. 3 corresponds to the maximum series voltage that can be injected, $\left|V_{SER}^{\max}\right|$ [9].

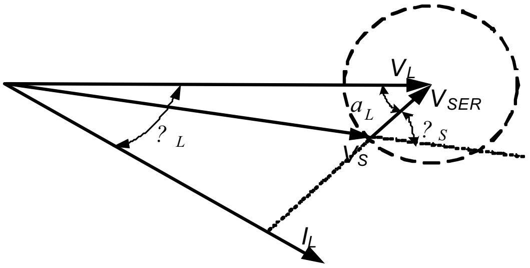

Fig. 3 Phasor diagram of DVR in a voltage sag scenario

During supply side voltage sags, there exists the need to boost the load voltage to acceptable limits, especially for industrial customers possessing sensitive loads. A DVR installed near the load centre offers the capability to maintain the load voltage at a rated value during voltage sags. However, the operational limitation of employing the DVR is attributed to the magnitude and duration of the voltage sag. Based on the magnitude of the voltage sag, there are two distinct cases that can be compensated using a DVR,

$$\begin{aligned} |V_S| &\geq |V_L|\cos\Phi_L \\ |V_S| &< |V_L|\cos\Phi_L\,. \end{aligned} \tag{4}$$

As nomenclature used here, the upper inequality (4) is called *category I* and the lower is *category II*. Voltage compensation to the required level may not be achieved by the DVR when the magnitude of the voltage sag is such that,

$$|V_S| < |V_L| - \left|V_{SER}^{\max}\right|, \tag{5}$$

where $\left|V_{SER}^{\max}\right|$ is the magnitude of the maximum series voltage that can be injected by the series transformer [9].

A combination of two distinct strategies is offered as illustration of the control needed for a DVR. The two control variables for both the strategies are the magnitude of the series voltage, $|V_{SER}|$, and the angle between V_{SER} and V_L. The first is a control strategy in which the energy taken from the DC supply is minimized by injecting the series voltage in quadrature with the load current– and this strategy is denominated as *all quadrature* series voltage injection. The second control strategy is a much simpler strategy in which the maximum series voltage, $V_{SER}^{\max}$ is injected at an angle other than quadrature with the load current I_L. The simpler 'maximum series voltage' strategy is denominated as *all series maximum* series voltage injection. Both the methods are based on feed forward control and developing the V_{SER} by sensing the supply voltage V_S on a cycle by cycle basis.

The control technique for compensating a *category I* voltage sag is by injecting the series voltage of predetermined magnitude in quadrature with I_L. The magnitude of the injected series voltage is obtained as,

$$\left|\mathrm{V_{SER}}\right| = |V_L|\sin\,\Phi_L - \sqrt{|V_S|^2 - |V_L|^2\cos\Phi_L}\,. \tag{6}$$

Alluding to Fig. 4, the magnitude of the injected series voltage lies with the confines of the circumference of the dotted circle. The calculation of the phase of the injected series voltage is redundant in this case as the injection is performed in quadrature to the load current. According to the quadrature strategy, the series transformer injects only reactive power to the load, thus obeying the 'minimum energy' criterion of the control scheme.

Voltage sags in which the quadrature operation described above is unattainable are compensated using a different strategy. In *category II* sags, the magnitude of the injected series voltage corresponding to $\left|V_{SER}^{\max}\right|$ lies on the circumference of the dotted circle shown in Fig. 5.

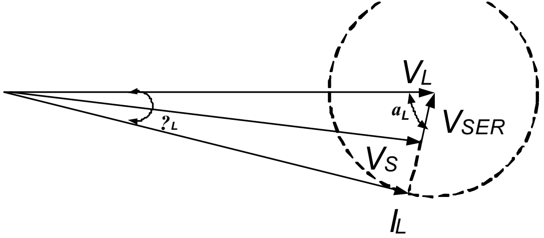

Fig. 4 Phasor diagram of DVR for compensating a voltage sag in which the series compensating voltage can be made in quadrature to the load current

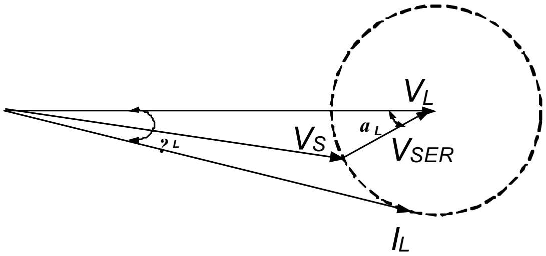

Fig. 5 Phasor diagram of DVR for compensating *category II* voltage sag

In order to minimize the active power injected by the series transformer, it is required to control f_L, the phase difference V_L and V_{SER}, according to the law of cosines,

$$\Theta_L = a\cos\left(\frac{|V_L|^2 + \left|V_{SER}^{\max}\right|^2 - |V_S|^2}{2|V_L|\left|V_{SER}^{\max}\right|}\right). \tag{7}$$

The *all series maximum* control strategy always involves the transfer of real power from the PWM winding to the SER winding of the injection transformer. The maximum active power transfer occurs when the maximum series voltage is injected in phase with V_S. This point also marks the limit of voltage compensation obtainable by the DVR. Figures 6 and 7 show operating results for the case that quadrature control can be achieved.

The differences between the two approaches to controlling the DVR, the *dq0* transform method and the moving average (RMS) based method, are illustrated in Table I.

V. SIMULATION MODEL FOR A DVR UNDER *dq0* CONTROL

Manufacturers of complex power quality equipment utilize a number of proprietary techniques to design their products. However, the authors have had the good fortune to examine a real DVR under *dq0* control. Utilizing the control strategies described in the previous section, and MATLAB Simulink models for basic circuit elements, a DVR model was developed to perform case studies similar to voltage events recorded in the field. Fig. 8 illustrates the model designed using the *dq0* controller.

TABLE I
DIFFERENCES BETWEEN THE *DQ0* AND THE RMS BASED METHODS

Parameter	*dq0* method	RMS based method
Response time	1/5th of a cycle	1 cycle
Type of load served	Sensitive/Critical	Not sensitive/critical
Number of controllers	1	3 (1 for each phase)
Type of measurements	Instantaneous phase values	RMS values
Inputs to controller	V_S, V_{REF}, and desired V_L	V_S, V_{REF}, desired V_L, $\left\|V_{SER}^{\max}\right\|$ and ? $_L$

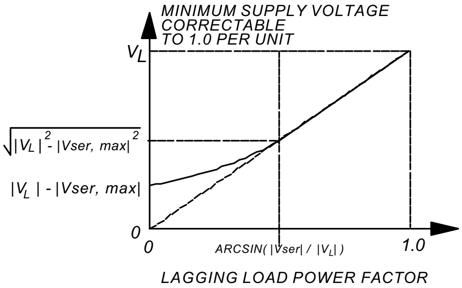

Fig. 6 Minimum value of supply voltage that can be boosted to V_L in quadrature control of a DVR

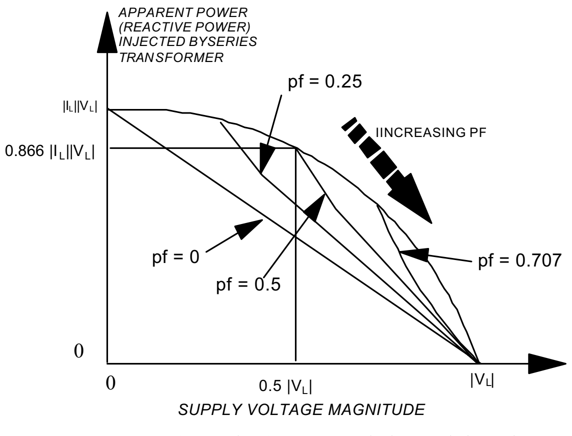

Fig. 7 Apparent (reactive) power injected by the series transformer versus supply voltage V_1 for different load power factors. The upper envelope has ordinate $|I_L||V_L|\sqrt{1-(|V_1|/|V_L|)^2}$. The diagram is for in quadrature control of a DVR

To illustrate a typical response of a DVR, consider a three phase voltage sag of 33% depth lasting 5 cycles. This is for a 60 Hz system in North America. A three phase voltage sag of the same depth and duration from 0.3 s to 0.3833 s is used as a case study to study the validity of the model. Both the control techniques are used to emulate the response of the DVR to the voltage sag. Fig. 9 depicts the waveform of the supply side voltage, V_S, during the voltage sag obtained from computer simulation. Fig. 10 depicts the waveforms of the compensated load side voltage V_L when the DVR models with the *dq0* transform based control are used.

VI. CONCLUSIONS

A general discussion of several power quality enhancement devices, and their controls was presented. These are: the static subcycle transfer switch, the static var compensator, the transient voltage regulator, and the dynamic voltage restorer. The development of a simulation model of a DVR used for regulating the load side voltage of a customer with sensitive loads is described. Two distinct methods of feed forward control for compensation of sags, based on the *dq0* transform and moving average based control method are developed. Case studies with real data similar to one of the largest DVRs operating in the US are provided as examples. The feed forward control based model of the DVR is simpler to design and use than other detailed models. The feed forward RMS controller based model is proposed as a generic model for loads that may not be as critical or sensitive as the semiconductor industry. The frequency domain artefacts of the RMS operation are discussed in mathematical terms.

VII. REFERENCES

[1] N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters, Applications, and Design, 2nd ed., New York, John Wiley & Sons, 1995.

[2] G. Heydt, Electric Power Quality, Stars in a Circle Publications, Scottsdale AZ, 1997.

[3] S&C Electric. PureWave™ DVRs Save Microprocessor Manufacturer. S&C Electric Company, Chicago, IL. [Online] Oct 2004. Available: http://www.sandc.com/webzine/030402_1.asp

[4] M. Albu, G. T. Heydt, "On the use of RMS values in power quality assessment," IEEE Trans. on Power Delivery, v. 18, No. 4, October 2003, pp. 1586-1587.

[5] J. G. Nielsen, M. Newman, H. Nielsen, and F. Blaabjerg, "Control and testing of a DVR at medium voltage," IEEE Trans. on Power Electronics, v. 19, no. 3, pp. 806-813, May 2004.

[6] D. M. Vilathgamuwa, A. Perera, and S. S. Choi, "Voltage sag compensation with energy optimized dynamic voltage restorer," *IEEE Trans. Power Delivery*, v. 18, No. 3, pp. 928-936, July 2003.

[7] J. G. Nielsen, F. Blaabjerg, and N. Mohan, "Control strategies for dynamic voltage restorer compensating voltage sags with phase jumps," *Proc. 2001 IEEE Applied Power Electronics Conference and Exposition*, v. 2, pp. 1267-1273.

[8] J. G. Nielsen and F. Blaabjerg, "Comparison of system topologies for dynamic voltage restorers," *Proc. 2001 IEEE Industry Applications Conference*, v. 1, pp. 2397-2403.

[9] S. Suryanarayanan, G. T. Heydt, R. Ayyanar, R. S. Thallam, A. B. Cummings, J. D. Blevins, and S. W. Anderson, "A feed forward control technique of dynamic voltage restorers for voltage

sag compensation," submitted to Power Quality Applications Conference 2005, Vancouver, BC, Canada.

[10] R. H. Park, "Two-reaction theory of synchronous machines," *Trans. AIEE*, Vol. 48, pp-716-730, 1929.

[11] P. M. Anderson and A. A. Fouad, Power System Control and Stability, 2^{nd} Ed., IEEE Press, Piscataway, NJ, 2003 pp. 83-88.

[12] P. Kundur, Power System Stability and Control, EPRI, Palo Alto CA, 1994.

[13] G. T. Heydt, W. Tan, T. LaRose, and M. Negley, "Simulation and analysis of series voltage boost technology for power quality enhancement," *IEEE Trans. on Power Delivery*, v. 13, No. 4, pp. 1335–1341, Oct. 1998.

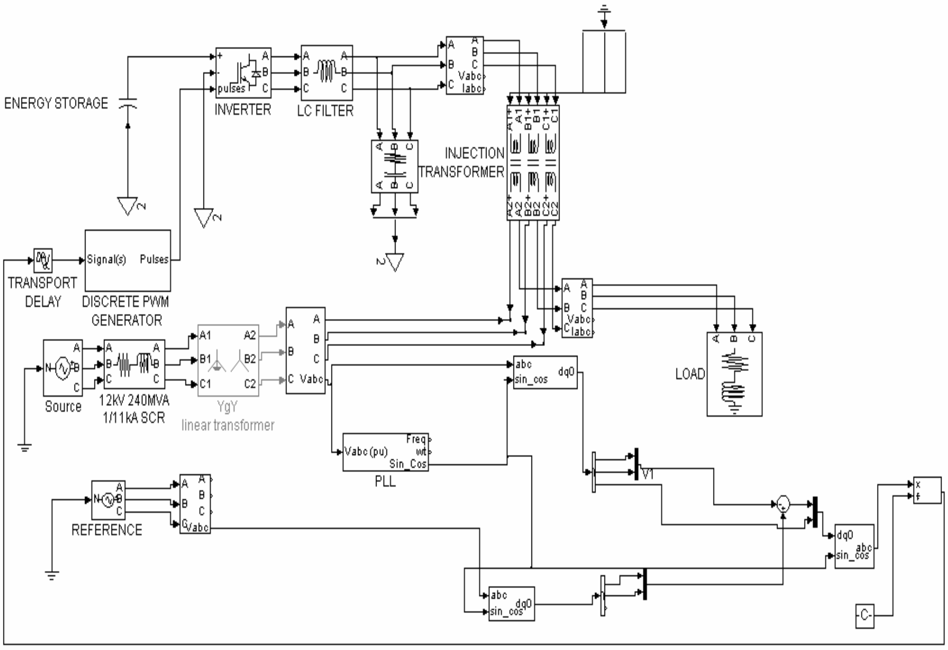

Fig. 8 DVR model with *dq0* controller

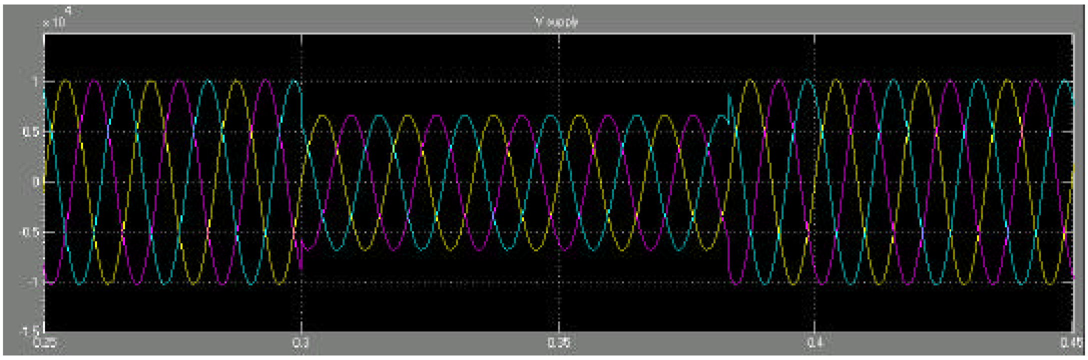

Fig. 9 Supply side voltage waveform for the sag event obtained from computer simulation (vertical scale in instantaneous volts line to neutral, horizontal scale in seconds)

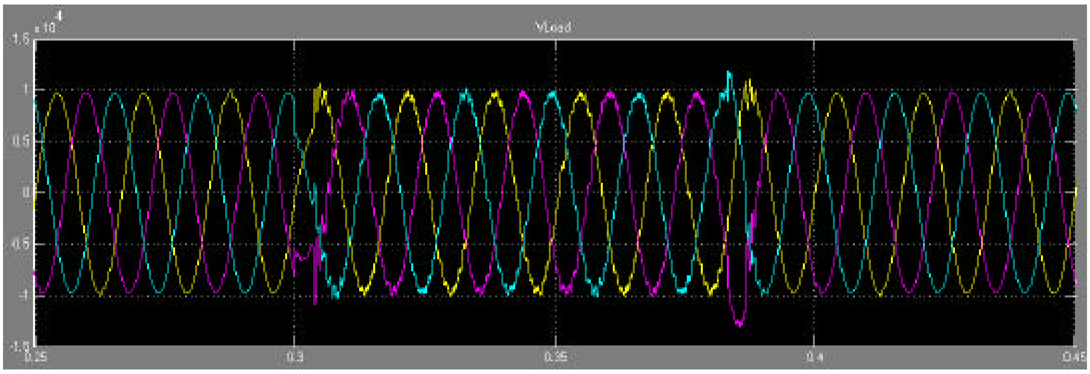

Fig. 10 Load side voltage waveform using a DVR with *dq0* controller obtained from computer simulation (vertical scale in instantaneous volts line to neutral, horizontal scale in seconds)