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Load flow Pseudo-inverse and Magnitude Conversions for Mitigation of PQ Problems using DVR

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Abstract

This paper presents, investigation on PQ based problems using DVR. Dynamic Voltage Restorer (DVR) is a series connected flexible AC Transmission System controller used to compensate PQ problems like voltage swells and sags. A DVR used to compensate deep PQ problems and harmonics. The control of DVR has been proposed by using dqo based Pseudo-inverse and Magnitude Conversions transformation for mitigation of PQ problems in power systems. The proposed article explains the load flow dqo transformation algorithm working for mitigation of PQ problems and used for increase power quality in efficient. The control of DVR was achieved by using proposed algorithm. Here the device used to the load with negligible effect on PQ compensation capability. The high oriented graphical representations are facilitates and topology was modeled, simulated using MAT Lab/Sim power systems.

Keywords: *DVR, Flexible AC Transmission System Controller, 'dqo' based Pseudo-inverse and Magnitude Conversions transformation, MAT Lab/Sim power systems*

1. Introduction

Dynamic voltage restorer (DVR) is a series-connected flexible ac transmission systems (FACTS) controller used to compensate voltage sags and swells during abnormal conditions in distribution systems. Different controls of the DVR sophisticated by different topologies [4–10]. In that, there are different control methods for the DVR have been analyzed with emphasis on the compensation of voltage sags with phase jump. Two methods, which are designated as 'in phase compensation' and 'pre-sag compensation' in [4], have been proposed for feasibility of these methods. In [5], a robust control method with an outer H1 voltage control loop and an inner current control loop has been designed and tested and have been performed to validate the proposed control scheme. In [6], the operating principles of the DVR compensating unbalanced or distorted loads. A dc capacitor supported DVR has been proposed so that no active power exchange exists in the system. In [7], a fast dynamic control scheme for capacitor supported for a single-phase DVR has been proposed.

The control scheme has two control loops; the inner loop and the outer loop which are, respectively, responsible for generating the gate signal of the switches of the DVR and the reference voltage signal of the DVR. A DVR prototype has been built and tested with non-linear load. A novel control strategy, which has been validated using time domain simulations, for the capacitor supported DVR has been proposed in [8] to compensate voltage sags.

The possibility of compensating harmonics using DVR at medium voltage level has been investigated in [9]. A control strategy has been included in the main control system of the DVR to compensate selected harmonics during steady state. The topology of the used DVR is

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based on a dc capacitor supported DVR. In this paper, a DVR with the capability to compensate harmonics and deep voltage sags is proposed. The proposed DVR is a DVR with no storage and load-side-connected shunt converter to obtain the maximum benefits from the device [3]. In addition, dc-to-dc step up converter has been introduced in the circuit. The main function of the step up dc-to-dc converter is to maintain and control the dc voltage of the inverter during voltage sag. This configuration allows the DVR to compensate deep and long duration voltage sags and swells.

The capability of compensating harmonics, without affecting sag or swell compensation capability, is added to the controls of the DVR. Extensive time domain simulations, with linear and non-linear loads, have been performed to validate the operation of the proposed DVR system. Digital simulation results have been shown to provide accurate prediction of the behavior of voltage-sourced converter (VSC) based FACTS devices [11].

2. DVR- Physical Phenomenon

The major objectives are to increase the capacity utilization of distribution feeders (by minimizing the rms values of the line currents for a specified power demand), reduce the losses and improve power quality at the load bus. The major assumption was to neglect the variations in the source voltages. This essentially implies that the dynamics of the source voltage is much slower than the load dynamics.

When the fast variations in the source voltage cannot be ignored, these can affect the performance of critical loads such as (a) semiconductor fabrication plants (b) paper mills (c) food processing plants and (d) automotive assembly plants. The most common disturbances in the source voltages are the voltage sags or swells that can be due to

(i) Disturbances arising in the transmission system,

(ii) Adjacent feeder faults and

(iii) Fuse or breaker operation. Voltage sags of even 10% lasting for 5-10 cycles can result in costly damage in critical loads.

The voltage sags can arise due to symmetrical or unsymmetrical faults. In the latter case, negative and zero sequence components are also present. Uncompensated nonlinear loads in the distribution system can cause harmonic components in the quality of power being used. These are called as Dynamic Voltage Restorer (DVR) in the literature as their primary application is to compensate for PQ Problems. Their physical phenomenon is similar to that of SSSC, discussed in past. However, the control techniques are different. Also, a DVR is expected to respond fast (less than 1/4 cycle) and thus employs PWM converters using IGBT or IGCT devices. The first DVR entered commercial service on the Duke Power System in U.S.A. in August 1996. It has a rating of 2 MVA with 660 kJ of energy storage and is capable of compensating 50% voltage sag for a period of 0.5 second (30 cycles). It was installed to protect a highly automated yarn manufacturing and rug weaving facility.

The voltage source converter is typically one or more converters connected in series to provide the required voltage rating. The DVR can inject a (fundamental frequency) voltage in each phase of required magnitude mode and phase difference. The DVR has two control strategies

1. Standby (also termed as short circuit operation (SCO) mode) where the voltage injected has zero magnitude.
2. Boost (when the DVR injects a required voltage of appropriate magnitude and phase to restore the pre-fault load bus voltage).

2.1. Voltage Source Converter (VSC)

This could be a 3 phase - 3 wires VSC or 3 phases - 4 wires VSC. The latter permits the injection of abrupt voltages or either a conventional multilevel converter is used

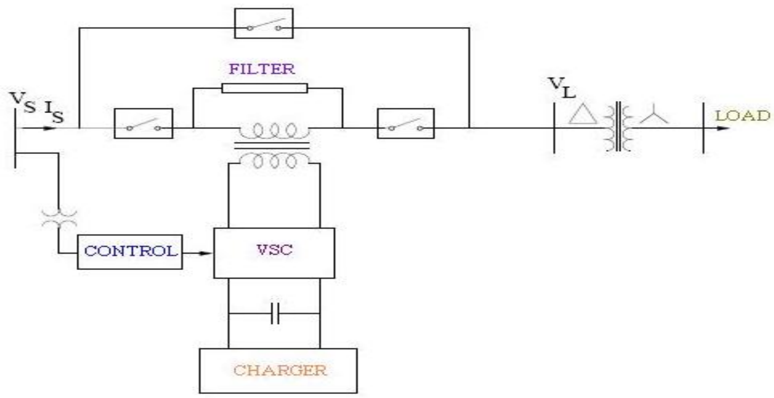


Figure 1. Dynamic Voltage Restorer

2.2. Passive Filters

The passive filters can be placed either on the high voltage side or the converter side of the booster. The additional uses of the converter side filters are (a) the components are rated at lower voltage and (b) higher order harmonic currents (due to the VSC) do not own through the transformer windings. The disadvantages are that the filter inductor causes voltage drop and phase (angle) shift in the (fundamental component of) components injected. The location of the filter o the high voltage side overcomes the drawbacks (the leakage reactance of the transformer can be used as a as high frequency currents can low through the windings.

3. Conventional System Configuration of DVR

Dynamic Voltage Restorer is a series connected device designed to maintain a constant RMS voltage value across a sensitive load. The DVR considered consists of:

1. An Injection / Series Transformer
2. .A Harmonic Filter,
3. A Voltage Source Converter (VSC),
4. An Energy Storage And
5. A Control System , as shown in Figure

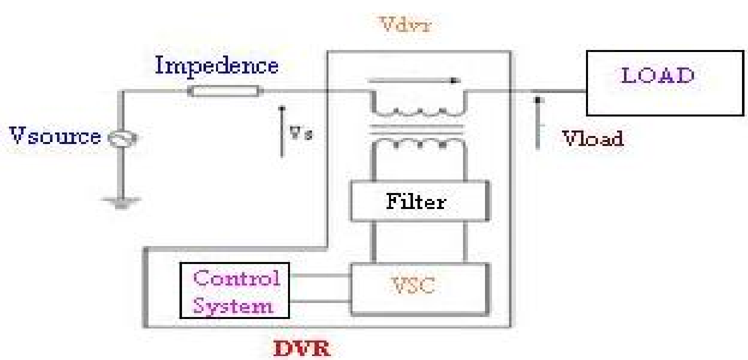


Figure 2. Schematic Diagram of DVR

The main function of a DVR is the protection of sensitive loads from voltage sags/swells coming from the network. From Figure 2 the DVR is located on approach of sensitive loads. The DVR has two modes of operation which are: standby mode and boost mode. In standby mode (V_{DVR}=0), the booster transformer's low voltage winding is shorted through the converter. The losses of the semiconductors in this current loop contribute to the less losses. The DVR will be most of the time in this mode. In boost mode (V_{DVR}>0), the DVR is injecting a compensation voltage through the booster transformer due to a detection of a supply voltage disturbance [4].

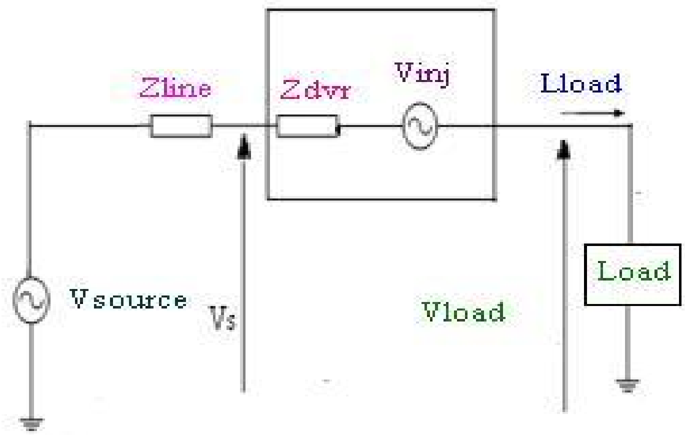


Figure 3. Equivalent Circuit of DVR

Figure 2 shows the equivalent circuit of the DVR when the source voltage is drop or increase; The DVR injects a series voltage V_{inj} through the injection transformer so that the desired load voltage magnitude VL can be maintained. The series injected voltage of the DVR can be written as

$$V_{inj} = V_s + V_{Load} \quad \dots\dots(1)$$

Where,
V_{Load} is the desired load voltage magnitude
Vs is the source voltage during sags/swells condition
The load current I_{Load} is given by,

$$I_{load} = \left(\frac{(P_{load} \pm J * Q_{load})}{V_{load}}\right) \quad \dots\dots\dots.\ (2)$$

4. Control Strategy for DVR

There are three basic control strategies as follows.

4.1. Pre-Sag Compensation

The supply voltage is continuously tracked and the load voltage is compensated to the pre-sag condition. This method results in (nearly) undisturbed load voltage, but generally requires higher rating of the DVR. Before a sag occur, $V_S = V_L = V_o$. The voltage sag results in drop in the magnitude of the supply voltage to VS_1. The phase also gets shifted position. The DVR injects a voltage V_{C1} such that the load voltage ($V_L = V_{S1} + V_{C1}$) remains at V_O.

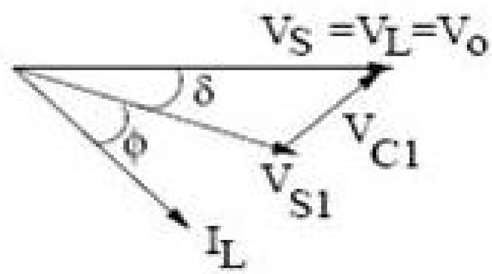


Figure 4. Pre Sag Compensation of DVR

4.2. In -phase Compensation

The voltage injected by the DVR is always in phase with the supply voltage regardless of the load current and the pre-sag voltage (V_o). This control strategy results in the minimum value of the injected voltage (magnitude). However, the phase of the load voltage is differentiated. For Normal loads which are not abnormal to the phase jumps, this control strategy results in optimum utilization of the voltage rating of the DVR. The power requirements for the DVR are not zero for these strategies.

4.3. Minimum Energy Compensation

Neglecting losses, the power requirements of the DVR are zero if the injected voltage (VC) is in quadrature with the load current. To raise the voltage at the load bus, the voltage injected by the DVR is capacitive and VL leads VS1 (see Figure 14.3). Figure 14.3 also shows the in-phase compensation for comparison. It is to be noted that the current phasor is determined by the load.

Implementation of the minimum energy compensation requires the measurement of the load current phasor in addition to the compensating voltage.DVR supplies only reactive power. However, full load voltage compensation is not possible unless the supply voltage is above a minimum value that depends on the load power factor.

When the magnitude of VC is allows full compensation is where Á is the power factor angle and V_o is the required magnitude of the Load bus voltage. If the magnitude of the injected voltage is limited (V_{max}), the mini- mum supply voltage that allows full compensation is given. Note that at the minimum compensating voltage, current is in phase with V_S for the case (a).

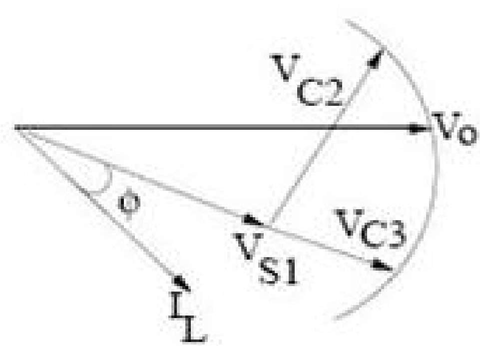


Figure 5. Vector Representation for Energy Consumption using DVR

5. PQ Problems- A Dangerous Scenario

The methodology is outlined in (proposed) of IEEE Gold book (IEEE standard 493, recommended practice for the design of reliable industrial and commercial power system) the methodology basically consists of the following four steps

5.1. Load Flow

A load flow representing the existing or modified system is required with an accurate zero-sequence representation. The machine reactance X_d'' or X_d' is also required. The reactance used is dependent upon the post fault time frame of interest. The machine and zero-sequence reactance are not required to calculate the voltage sag magnitude.

5.2. Voltage Sag Calculation

Sliding faults which include line-line, line to ground, line to line- to ground and three phases are applied to all the lines in the load flow. Each line is divided into equal sections and each section is faulted.

5.3. Voltage Sag Occurrence Calculation

Based upon the utilities reliability data (the number of times each line section will experience a fault) and the results of load flow and voltage sag calculations, the number of voltage sags at the customer site due to remote faults can be calculated. Depending upon the equipment connection, the voltage sag occurrence rate may be calculated in terms of either phase or line voltages dependent upon the load connection. For some facilities, both line and phase voltages may be required. The data thus obtained from load flow, Voltage sag calculation, and voltage sag occurrence calculation can be sorted and tabulated by sag magnitude, fault type, location of fault and nominal system voltage at the fault location.

5.4. Case Study on Sag- Analysis

The results can be tabulated and displayed in many different ways to recognize difficult aspects. The total number of voltage sags with reference to voltage level at fault point, area/zone of fault, or the fault type can be developed to help utilities focus on their system improvements. To examining the existing system, system modifications aimed at mitigating or reducing voltage sags can also be identified, thus enabling cost benefits analysis. Possible such system structural changes that can be identified include.

Reconnection of a customer from one voltage level to another, Installation of Ferro-resonant transformers or time delayed under voltage, drop out relay to facilitate easy ride -through the sag Application of static transfer switch and energy storage system., Application of fast acting synchronous condensers, Neighborhood generation capacity addition, Increase service voltage addition through transformer tap changing, By enhancement of system reliability.

5.5. Solutions to Voltage Sag Problems

Efforts by utilities and customers can reduce the number and severity of sags.

5.5.1. Utility Solutions

Utilities can take two main steps to reduce the detrimental effects of sags –

(1) Prevent fault
(2) Improve fault clearing methods

Fault prevention methods include activities like tree trimming, adding line arrests, washing insulators and installing animal guards. Improved fault clearing practices include activities like adding line recloses, eliminating fast tripping, adding loop schemes and modifying feeder design. These may reduce the number and/or duration of momentary interruptions and voltage sags but faults cannot be eliminated completely.

5.5.2. Customer Solutions

Power conditioning is the general concept behind these methods. They are follows

1. Isolate equipment from high frequency noise and transients.
2. Provide voltage sag ride through capability

5.6. Harmonics

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or/ quantity having a frequency that is an integral multiple of the fundamental frequency.” [1]. some references refer to “clean” or “pure” power as those without any harmonics. But such clean waveforms typically only exist in a laboratory. Harmonics have been around for a long time and will continue to do so. In fact, musicians have been aware of such since the invention of the first string or woodwind instrument. Harmonics (called “overtones” in music) are responsible for what makes a trumpet sound like a trumpet, and a clarinet like a clarinet.
Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it, the fundamental frequency. In the North America, this frequency is 60 Hz, or cycles per second. In European countries and other parts of the world, this frequency is usually 50 Hz. Aircraft often uses 400 Hz as the fundamental frequency. At 60 Hz, this means that sixty times a second, the voltage waveform increases to a maximum positive value, then decreases to zero, further decreasing to a maximum negative value, and then back to zero. The rate at which these changes occur is the trigonometric function called a sine wave, as shown in figure 1. This function occurs in many natural phenomena, such as the speed of a pendulum as it swings back and forth, or the way a string on a violin vibrates when plucked.

6. Proposed Method- ‘dqo’ based Pseudo-inverse and Magnitude Conversion

The configuration of the proposed DVR design using\MATLAB/SIMULINK, where the outputs of a half-bridge inverter are connected to the utility supply via wye-open connected series transformer and Once a voltage disturbance occurs, with the aid of Binomial transformation based control scheme named as Pseudo-inverse and Magnitude Conversions, the inverter output can be steered in phase with the incoming ac source while the load is maintained sustainability. As for the scheme of the proposed method, output of inverter is installed with capacitors and inductors.

6.1. Control Algorithm

The basic orientation and aim of a controller in a DVR are the detection of PQ Problems in the system. The computation of the correcting Phase compensation and generation of trigger pulses to the sinusoidal PWM based inverter, correction of any anomalies in the series voltage injection and termination of the trigger pulses when the 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/swells. The dqo based Pseudo-inverse and Magnitude Conversions transformation or Park's transformation [8-10] is used to control of DVR.

The dqo based Pseudo-inverse and Magnitude Conversions method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from abc reference frame to d-q-o reference. For simplicity zero phase sequence components is ignored. Figure 6 illustrates a flow chart of the feed forward dqo transformation for PQ Problems detection. The detection is carried out in each of the three phases. The control scheme for the proposed system is based on the comparison of a voltage reference and the measured terminal voltage (V_a, V_b, V_c).The voltage sags is detected when the supply drops below 90% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value. The error signal is used as a modulation signal that allows generating a commutation pattern for the power switches (IGBT's) constituting the voltage source converter with binomial conversion for proper magnitude. The pattern is generated by means of the sinusoidal pulse width modulation technique (SPWM); voltages are controlled through the Sinusoidal Pulse width modulation.

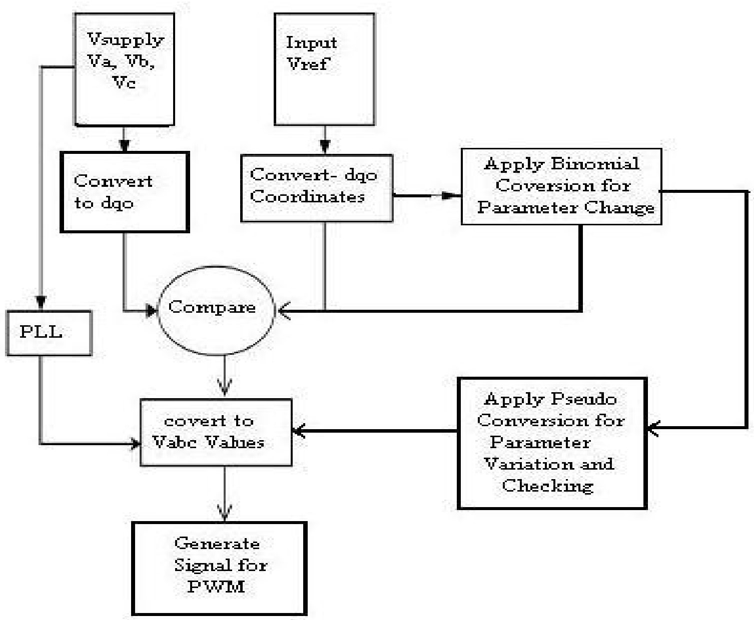


Figure 6.Flow Chart of Feed Forward Control Technique for Dqo based Pseudo and Magnitude Conversions

$$\begin{bmatrix} f\alpha \\ f\beta \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -2/3 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \text{x} \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} \quad \text{......................} (3)$$

$$\begin{bmatrix} fd \\ fq \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix} \text{x} \begin{bmatrix} f\alpha \\ f\beta \end{bmatrix} \quad \text{......................} (4)$$

$$\begin{bmatrix} fd \\ fq \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi-\gamma) & \cos(\phi+\gamma) \\ -\sin(\phi) & \cos(\phi-\gamma) & -\sin(\phi+\gamma) \end{bmatrix} \mathrm{x} \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} \quad \text{......................... (5)}$$

$$f_a+f_b+f_c=0 \quad \text{.......... .... (6)}$$

$$\begin{bmatrix} fd \\ fq \end{bmatrix} = \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix} \mathrm{X} \begin{bmatrix} fd \\ fq \end{bmatrix} \quad \text{......................... (7)}$$

$$\begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \mathrm{x} \begin{bmatrix} fd \\ fq \end{bmatrix} \quad \text{......................... (8)}$$

Where $\gamma = 2\pi/3$

ϕ =Angle between dq and $\alpha\beta$ reference frames

A space vector $\overrightarrow{f0}$ and its time rate of change $\overrightarrow{g0}$ are attached to a $\alpha\beta$ coordinate system rotating at the speed $\frac{d}{dt}$=w_m. The transformation to a dqo coordinate system rotating at the speed wk=$\frac{d}{dt}$ is performed using the rotating matrix $M(\phi)$.

A Matter of Scale In 3 to 2 And 2 to 3phase Transformations

$$\begin{bmatrix} fd \\ fq \end{bmatrix} = K \begin{bmatrix} \cos(\phi) & \sin(\phi-\gamma) & \cos(\phi+\gamma) \\ -\sin(\phi) & \cos(\phi-\gamma) & -\sin(\phi+\gamma) \end{bmatrix} \mathrm{x} \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} \text{ or } f_{dq} = k_t\, f_{abc} \quad \text{................ (8)}$$

Pseudo-inverse conversion

$$F_{abc}=k_i * T_t *fdq \quad \text{......................... (9)}$$

Where $ki=2/3T_t$, $T_t=u_2$

Magnitude conversion

$$f\alpha=k_m f_a \quad \text{......................... (10)}$$

Where km=3/2k

Common conventions:
a: equal magnitude of 2-and3-phase balanced sinusoidal signals
b: equal 2-and3-phase power (power invariant)
c: 2-phase amplitude equals 3/2 3-phase amplitude
d: 2-phase amplitude equals rms of 3-phase signal

The above Equations defines the transformation from three phase system a, b, c to dqo stationary frame. In this transformation, phase A is aligned to the d_{axis} that is in quadrature with the q-axis. The Theta (θ) is defined by the angle between phases A to the d-axis.

7. Modeling and Simulation for Test System of DVR Control Using Pseudo-inverse and Magnitude Conversion

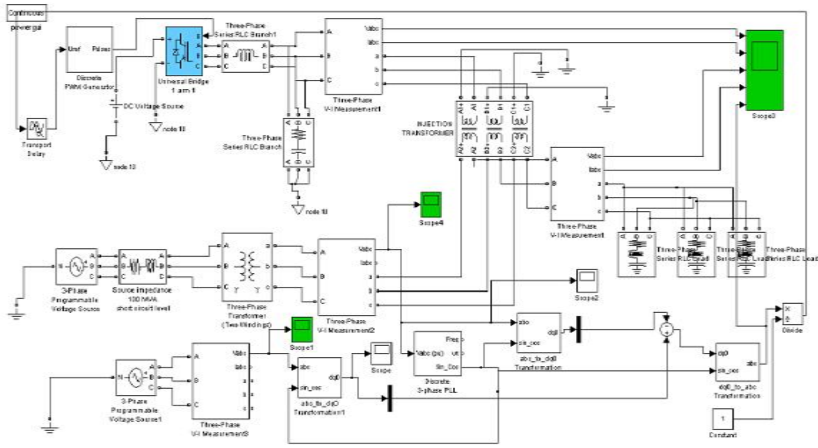
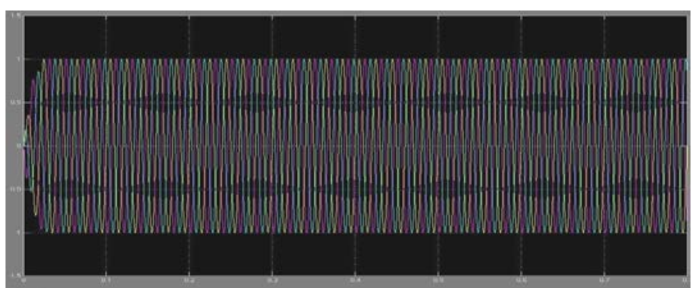


Figure 7. Test System of DVR Control Using Pseudo-inverse and Magnitude Conversion

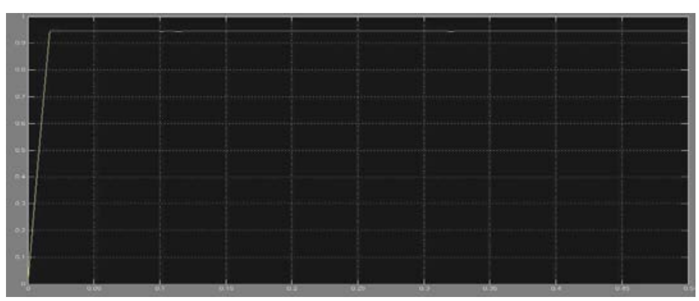
8. Results and Discussions

A detailed system as shown in Figure 2 has been modeled by MATLAB/SIMULINK to study the efficiency of suggested control strategy. It is assumed that the voltage magnitude of the load bus is maintained at 1 pu during the PQ Probable statically approach.

The results of conventional graphical facilities are represented in Figures 8-13. The load has been assumed linear with power factor pf =0.85 lagging and its capacity of 5 KVA.



(a)

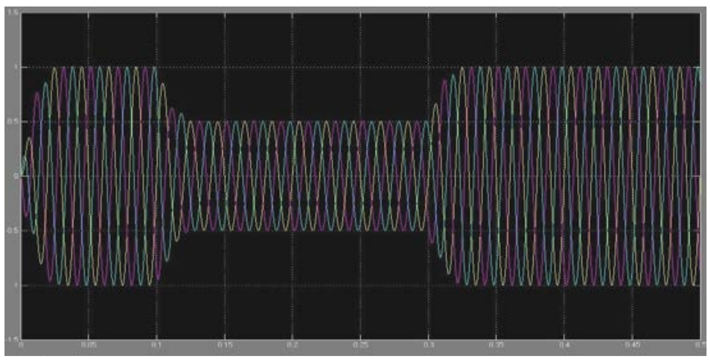


(b)

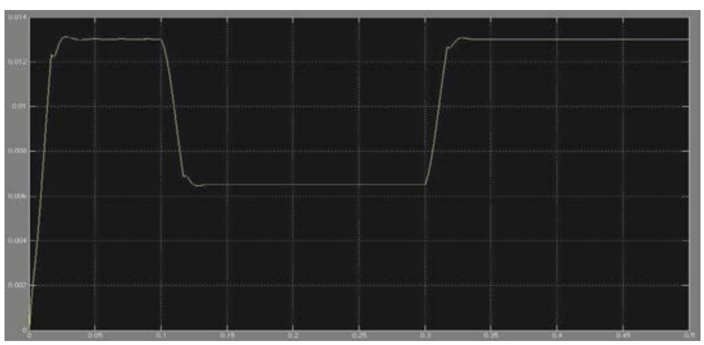
Figure 8. Wave Configurations for (a) Output Voltage (b) RMS Voltage of Test System

Figure 8 (a) & (b) Shows the output voltage and RMS Voltages of DVR test system with following specifications

Main supply Voltage per phase - 230v
Line Impedance Ls = o.5mH &Rs - 0.1Ω
Series Transformer turns ratio – 1:1
DC bus voltage- 120V
Filter Inductance- 1mH
Filter Capacitance – 1nF
Load Resistance – 60Ω
Load Inductance - 60mH
Frequency -50HZ



(a)

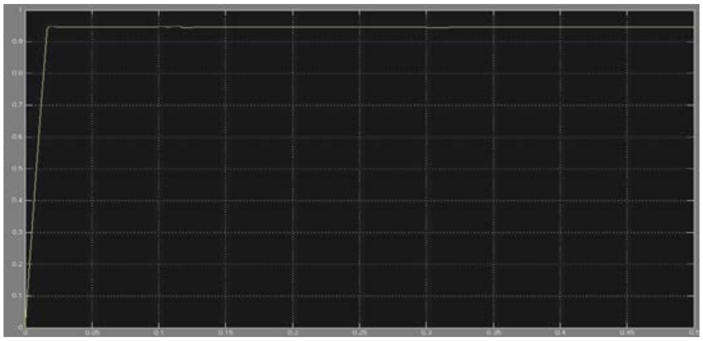


(b)

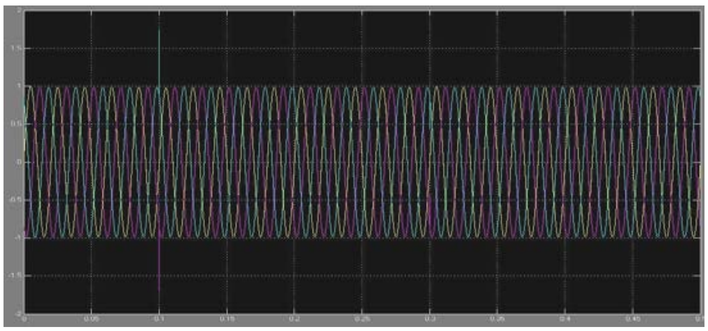
Figure 9. (a) Output Voltage (b) RMS Voltage during Voltage Sag Condition

The Figure 9 Shows three phase voltage sag is simulation. The simulation started with the supply voltage 50% sagging as shown in Figure 9(a).In Figure 8 (a) also shows a 50% voltage sag initiated at 0.18s and it is set until 0.40s, with exisisting voltage sag duration of 0.2s. Figures 10 (a) and (b) show the voltage injected by the DVR and the corresponding load voltage with constant mode magnitude. As a result of the test system of DVR, the load voltage magnitude is kept at 1 pu.

The effectiveness of the DVR is 50% single phase voltage sag on a utility grid only. Through simulation the supply voltage with one phase voltage dropped down to 50% as shown in Figure 10(a). The DVR injected voltage and the load voltage are shown in Figures 10(a) and (b) respectively. The corresponding load voltage magnitude representations are shown in Figure 13 where it is possible to see that the compensation method is keeping the load voltages constant at 1 p.u.

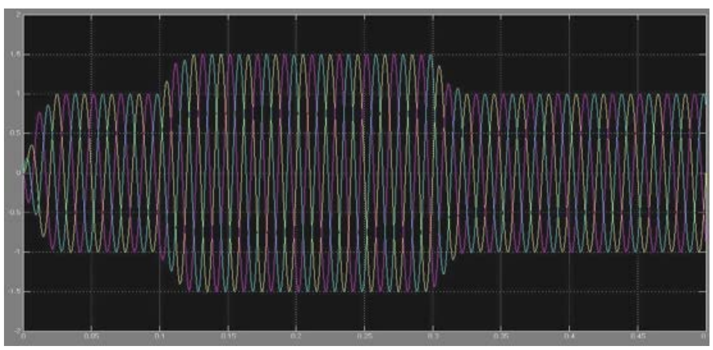


(a)

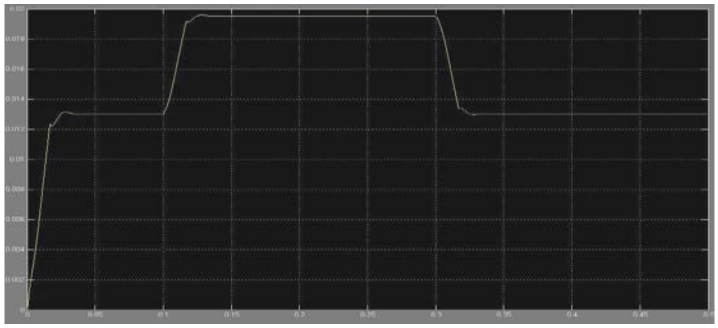


(b)

Figure 10. (a) Output Voltage (b) RMS Voltage in Sag Condition, after Injecting Voltage through DVR

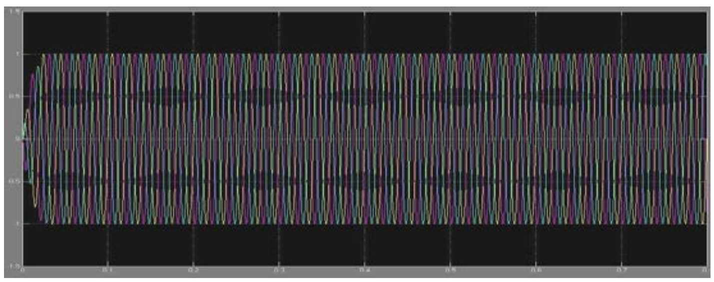


(a)

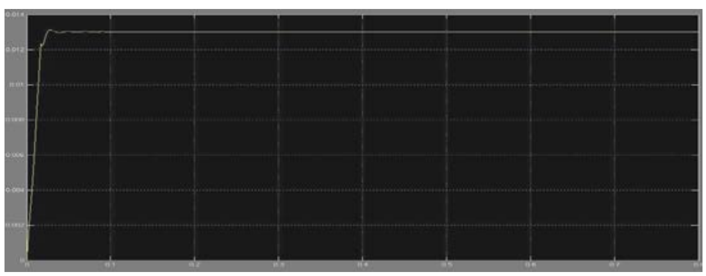


(b)

Figure 11. (a) Output Voltage (b) RMS Voltage during occurrence of Voltage Swell



(a)



(b)

Figure 12. (a) Output Voltage (b) RMS Voltage in Voltage Swell, after injecting Voltage

The Figure 11 (a) & (b) shows the DVR performance during a voltage swell condition. The simulation started with the supply voltage swell is generated as shown in Figure 10(a). As observed from this figure the amplitude of supply voltage is increased about 25% from its nominal voltage. Figures 12(a) and (b) show the injected and the load voltage. From test system of DVR, the load voltage is maintaining statistically initial value with the helping of conventional System configuration. In case of voltage sag, the DVR responds to inject the certain voltage component (negative voltage magnitude) to correct the supply voltage. Figure 10(b) shows that the performance of the DVR with an unbalanced voltage swells. In this case, two of the three phases are higher by 25% than the third phase as shown in Figure 12(a). The injected voltage that is produced by DVR in order to correct the load voltages and the load voltages maintain at the constant are shown in Figures 12(a) and (b) respectively.

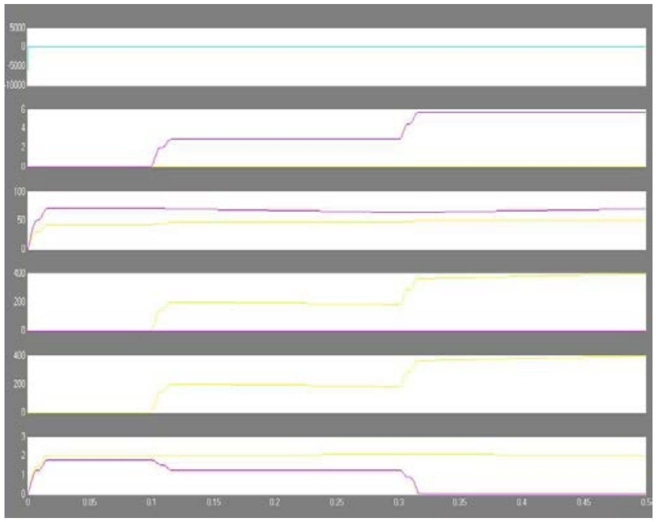


Figure 13.Hybrid Model Graph for PQ Problems in DVR

Figure 13 Shows simulation for the DVR swell and sag improvement hybrid model by applying Pseudo-inverse and Magnitude Conversions transformation to the controlling of attributes of test system.

9. Conclusion

A Control system based dqo depending algorithm initiating by pseudo and magnitude conversion are used for control DVR. The exisisting PQ Problems are performed by test system were eliminated and diagnosis by using DVR. The maximum part of Voltage magnitude per unit assumptions are modified with help advanced controlled technique like pseudo and magnitude conversion. The entire DVR Test system was investigated, modeled and simulated. The entire graphical representations were presented with help of MATLAB/Sim power systems.

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