



A Simple Method for Detection of Voltage Sags and their Mitigation using a Dynamic Voltage Restorer

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Abstract. Power quality is the major focus of progressive nations. In the era of smart grid, power quality receives a lot of thrust at all voltage levels namely, medium, high and low. The objective of this paper is to present a simple and cost effective method of sag detection and mitigation in three phase systems at the consumer's end.

The use of the concept of space vector representation of three phase quantities, effectively in the detection, quantification and mitigation of short duration voltage disturbances such as sags in three phase supply systems under both balanced and unbalanced conditions of operation is presented. Three phase balanced quantities can be represented by a synchronously rotating space vector of constant magnitude. The two phase equivalent of which on a stationary reference frame are orthogonal to each other. When balanced sags occur, the magnitude of the rotating space vector obtained as a resultant of its orthogonal components is sensed for magnitude deviations from its constant nominal value. A trigger signal of varying amplitude is generated in proportional response to the detection of the deviation in its magnitude.

In case of sags occurring on one or two phases of the supply, (unbalanced), the positive sequence components of the unbalanced three phase quantities are determined using mathematical transformations and the magnitude of the resultant is found out. This resultant is sensed and its deviations from nominal value are measured and used to generate the trigger after processing. The trigger thus generated, initiates the control system of a Dynamic Voltage Restorer (DVR). When a sag is detected, the trigger signal generated, switches on the control circuit of the inverter which uses the space vector PWM control using sampled phase amplitudes of the control signal to generate the modulating wave in proportion to the deviation of the sag voltage from the reference value. The fundamental component of the output voltage which in proportion to the deviation from the nominal value is injected in series with the three phase disturbed signal through a transformer of suitable gain. The results show the successful operation of the DVR in maintaining nominal value of the voltage across the load throughout the duration of the disturbance for all cases of balanced and unbalanced operation. The paper presents the detection algorithm as well as the control algorithm for restoration of voltage which are simple and easy to implement.

Key words

Positive sequence components, sag detection, dynamic voltage restorer (DVR), space vector PWM using sampled reference phase amplitudes.

1. Introduction

Any power problem that results in voltage, current or frequency deviations is a power quality (PQ) problem [1]. Disturbances in the supply system prevent end-user equipment from operating properly. The need to supply distortion and disturbance free voltages to the end user loads has been the motivation for the study on PQ.

By IEC standard [2], a voltage sag is defined as a short duration (half a cycle to one minute) decrease in the supply voltage between 0.1 p.u. and 0.9 p.u. at rated power frequency. In most cases, the duration of the sag is between 10ms and 1 minute. Voltage sags are the most common which impact sensitive equipment that lack sufficient internal energy storage to ride through the sag.

Computers and most other consumer electronics equipment, which consist of low-power electronic devices, are highly sensitive to voltage disturbances. Even if the equipment does tolerate the sag at some instances, repeated operation of under voltage relays unbalanced relays or quick-acting relays in emergency off (EMO) circuits can cause unnecessary shutdown of the entire system. The main source of sags are large increase in current due to faults, large starting currents drawn by motor loads, and operation of different types of load such as welding units connected to the supply system. The main characteristics of voltage sags are its magnitude and duration.

Temporary voltage sag is bound to have a greater impact on the industrial customers. The increasing competition in the market and the declining profits has made it pertinent for the industries to realize the significance of high power quality. This is possible only by ensuring that

uninterrupted flow of power is maintained at proper voltage levels. Electric utilities are also looking for solutions to ensure high quality power supply to their customers. All this can be solved by using custom power devices such as Dynamic Voltage Restorer (DVR).

A dynamic voltage restorer (DVR) is a custom power device for mitigating voltage sags. The DVR is a three-phase voltage source converter (VSC) primarily used at the distribution level. The DVR injects the load voltage in series with the supply line when an upstream fault is detected. Loads connected downstream of the DVR are thus protected from any voltage sag caused by faults elsewhere on the network. The DVR utilizes an energy storage device to supply the required real power. Sag estimation is one of the most critical parts in the DVR compensation performance.

There are many approaches reported on real-time disturbance detection in three phase supply systems. Some of them are based on the conversion of ac voltages to a dc voltage that is obtained from a rectifier-filter arrangement. Any disturbance in the ac supply is reflected as a change in the dc level. When the disturbance is unbalanced, some ripple accompanies the change in the dc level which requires additional stages to convert the change to a trigger signal. The drawback of the above method is in the delay brought about by the filter. There are numerous methods reported based on wavelet analysis of voltage signals such as in [3]. The wavelet transform is a complex, time-consuming algorithm very useful when the disturbances have to be classified into families, according to their characteristics. This can be done off line with algorithms for analysis of the disturbed signal after detection and needs lots of processing time and memory. This leads to an increase in cost. The closest method reported in literature to the algorithm proposed in this work is in [4] based on resultant space vector on a rotating reference frame. However, delays are observed in the detection time due to additional stages of processing needed especially in the case of unbalanced sag detection.

A simple detection algorithm based on the method of Space Vectors that facilitates a real-time detection, quantification of the magnitude of the disturbance, time of occurrence, quickly and accurately in both balanced and unbalanced cases of sag occurrence is presented. Since this method of detection involves quantization of the deviation of the value of the resultant from the standard reference value, it is more robust in the presence of noise. This method of sag detection is shown to be best suited and is used in conjunction with the control system of a DVR. The inverter of the DVR is switched on in response to the detection of the sag using the proposed algorithm.

There are numerous methods of DVR operation reported in literature based on space vector PWM technique [6],[7]. However, the results obtained for the DVR using the sampled phase amplitudes of the control signal [5], in conjunction with the proposed sag detection algorithm, clearly confirms its effectiveness and simplicity. First the detection algorithm is explained along with the results obtained for various cases of sag.

This is followed by the method of operation of the DVR in quick response to the detection and the results of the DVR response.

2. The Detection Algorithm

The disturbance detection algorithm must accomplish the following [4].

1. Detect all the disturbances whether occurring on one of the phases or on all the three phases immediately. Quick detection facilitates initiation of quick mitigation responses.
2. Clearly distinguish a disturbance from other variations by delivering a trip signal only if the disturbance is beyond specified ranges for that disturbance.

This algorithm is based on obtaining the equivalent space vector of three phase quantities. The three phase voltages namely, V_a , V_b and V_c of a three phase supply can be transformed mathematically into three vectors V_{sa} , V_{sb} , V_{sc} along the three spatial axes displaced by 120° . The resultant of these spatial components can be represented by a single equivalent rotating space vector [8], rotating at an uniform angular velocity of ω radians per second, called the resultant space vector \vec{V}_{res} . This can be resolved into components along the two orthogonal axes on a stationary reference frame namely, α and β . These orthogonal components namely, V_α and V_β , can be obtained from the knowledge of the three phase values by means of a simple transformation given by,

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

The magnitude of the resultant space vector can hence be found as,

$$|\vec{V}_{res}| = \sqrt{V_\alpha^2 + V_\beta^2} \quad (2)$$

Under balanced conditions, the phase voltages have a fixed peak value of V p.u. and hence the resultant space vector has a fixed value given by,

$$|\vec{V}_{res}| = 3 \frac{V}{2} \quad (3)$$

Under normal conditions with V as 1p.u.,

$$|\vec{V}_{res}| = |\vec{V}_{ref}| = 1.5 \text{ p.u.} \quad (4)$$

Let the deviation in magnitude of the resultant space vector from its nominal reference value be,

$$|\vec{V}_{diff}| = |\vec{V}_{ref}| - |\vec{V}_{res}| \quad (5)$$

The magnitude of the resultant space vector $|\vec{V}_{res}|$, is a value which can be determined at every instant by sensing the three phase voltages of the utility using equations (1) and (2). This value varies with changes in the level of the phase voltages (which happens during a disturbance). This value is compared with $|\vec{V}_{ref}|$ at every instant as in (5). The deviation $|\vec{V}_{diff}|$, is utilized in further processing to generate the trigger signal which quantifies the instants of start and end of the disturbance as well as the magnitude and type of the disturbance.

For disturbances which are unbalanced, with respect to magnitude, the resultant space vector is seen to have oscillations superposed on it which needs further

processing to generate the trigger [4]. This introduces an error in the magnitude of deviation measured as well as a time delay in the detection. Apart from this, it fails to detect sag when accompanied with unbalances in phase. Hence there is a need for a method which detects the disturbances under all conditions of balanced magnitude and phase as well as unbalanced magnitude and phase. Fig.1 shows the block diagram representation of the process involved in determining the magnitude of the resultant space vector based on a stationary frame of reference. The first step is to determine the positive sequence components of the three phase input signal. A periodic three phase voltage signal V_a , V_b and V_c with or without neutral conductor, can be decomposed in the following way into sequence components which are well known. The positive sequence components are extracted according to equation(6). Simple calculations are sufficient to extract the fundamental-frequency positive-sequence voltages, eliminating odd and even harmonics. The method is based on obtaining the positive- and negative-sequence components of the grid voltage, by applying the symmetric component theory to the voltage vector transformed into stationary reference frame namely $(\alpha-\beta)$. This is then followed by the process of determining the magnitude of the resultant space vector from the values of these positive sequence components according to equations(1) and (2).

$$\begin{bmatrix} V_a^+(t) \\ V_b^+(t) \\ V_c^+(t) \end{bmatrix} = \frac{-1}{3} \begin{bmatrix} -1 & 1\angle -60^\circ & 1\angle 60^\circ \\ 1\angle 60^\circ & -1 & 1\angle -60^\circ \\ 1\angle -60^\circ & 1\angle 60^\circ & -1 \end{bmatrix} \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} \quad (6)$$

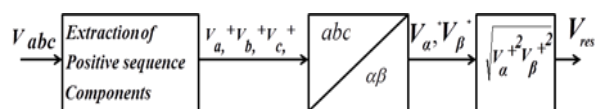


Fig.1. Evaluation process of the resultant space vector

Fig.2 shows the process of generating the trigger after measuring the deviation using equations (4) and (5) in the magnitude of the resultant space vector from its nominal value during a sag under both balanced and unbalanced conditions of magnitude and phase. The processing of the deviation involves operation of the relays when the deviation crosses predefined threshold values (for example for a voltage sag, the value ranges from 0.1p.u to 0.9p.u.). The moment the deviation is detected, the relay operates and the magnitude of deviation is quantified by the multiplier. Relays 1 and 2 operate distinguishing the detection of sag under balanced phase and unbalanced phase conditions. The value of $|\vec{V}_{res}|$ is less than $V_{ref}=1.5p.u$. for all cases accompanied with an unbalance in phase which condition is utilized for the switching operation of relay 2 during sags accompanied with phase unbalance.

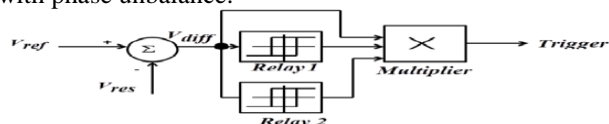


Fig.2. Trigger generation in response to sag

3. Functioning of the detection algorithm for different cases

The algorithm is first tested for its functioning considering test signals corresponding to all cases of sag occurrence. The simulations are done using Matlab/Simulink.

A. Normal Conditions of magnitude and phase, in the presence of Harmonics

In Fig.3 the input signal considered has a peak amplitude of 1.0.p.u, along with the third and fifth harmonic components present in all the three phases. The positive sequence components extracted are observed to be purely sinusoidal of peak amplitude 1.0.p.u and with a frequency equal to the fundamental component of 50Hz. The magnitude of $|\vec{V}_{res}|$ evaluated in this case, has a value equal to that of $V_{ref}=1.5p.u$. at all instants. The trigger signal is found to have a value of zero at all instants since there is no sag. Thus, indicating that the algorithm works successfully in the presence of harmonics in the input signal.

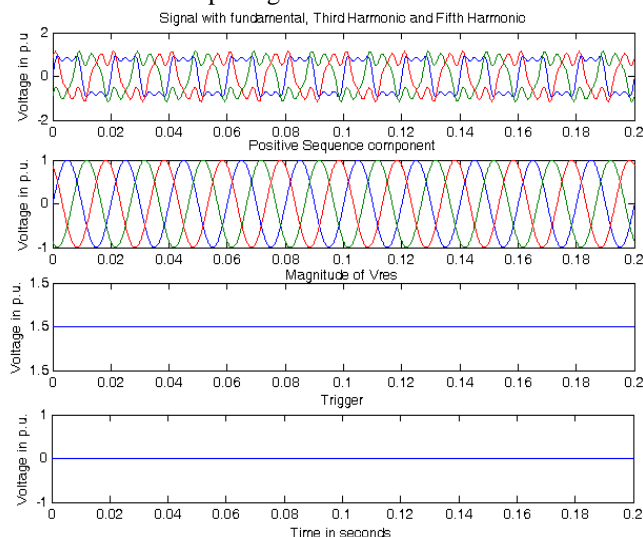


Fig.3. The trigger in the presence of harmonics

B. Balanced Sag of 60%

The Fig.4 shows a signal with a balanced sag of 60% on all phases from 0.05 seconds to 0.5 seconds. The positive sequence components of the signal obtained are not different from the disturbed signal since the signal is balanced in phase and magnitude. The magnitude of the resultant space vector obtained is found to be equal to the value evaluated by equation(3), (which is (1.5×0.4) 0.6p.u in this case). The trigger magnitude obtained is equal to the deviation estimated from the nominal reference value according to equation(5) which is estimated as $(1.5 - 0.6)$, 0.9p.u in this case. There is no time delay observed in the detection of the disturbance. The magnitude of the trigger signal is also given by the expression,

$$|\vec{V}_{trig}| = \frac{1}{2} [(\Delta V_b(t) + \Delta V_c(t))] + \frac{1}{2} (\Delta V_a(t)) \quad (7)$$

Where, $\Delta V_a(t), \Delta V_b(t), \Delta V_c(t) = V - V'$, is the magnitude of the sag level in each phase. V is the phase

voltage under normal conditions which is 1.0.p.u. and V' , is the new value of the phase voltage during the sag. The results obtained indicate accurate and successful detection and quantification of a balanced sag.

C. Detection of Sag one cycle duration in one of the phases:

This signal shown in Fig.5 has a sag of 50% for a duration of one cycle (20msec) from 0.06second to 0.08 seconds. This case is considered to check the effectiveness of the algorithm in the detection of sags of very short duration. Positive sequence components are obtained and magnitudes of these components have dropped from a nominal value of 1.0.p.u.to a value proportional to the level of sag during the duration of the sag. The magnitude of the trigger obtained in this case(sag in only one phase) is given by the expression,

$$|\vec{V}_{trig}| = (\Delta Vc(t))/2, \quad (8)$$

which is apparently half the magnitude of the disturbance level of sag from its nominal value of 1.0.p.u. as given in equation(8).The values obtained do match the estimated values. There is no delay observed in the time of detection. Hence a sag of duration equal to one cycle time of the waveform is detected accurately .The shortest sag that can be detected accurately is of one cycle time duration.

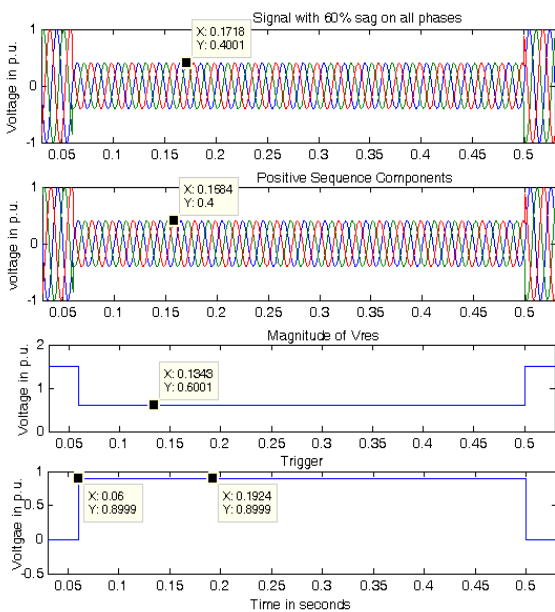


Fig.4.Detection of sag of 60% on all the phases

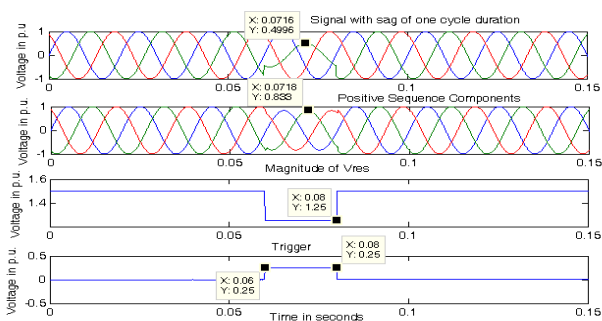


Fig.5.Detection of a sag (50%)one cycle duration in Phase C.

D.Detection of Sag unbalanced in Phase and magnitude

The Fig.6 indicates successful detection of sag accompanied by unbalance in phase.The signal considered has a sag level of 40% in Phase A at a phase of 0°, 60% in Phase B at a phase of 60° from the zero crossing and 50% in Phase C occurring at a phase of 210° from the zero crossing .The magnitude of the resultant is found to deviate from a value of $|\vec{V}_{ref}|$ which is less than 1.5.p.u.and is detected by the operation of relay 2 .

E.Results recorded from the experimental set-up

To test the algorithm using a suitable hardware set-up, the execution target for NI LabVIEW real-time applications, NI c-RIO(National Instruments, Compact Reconfigurable Input Output),real time controller is used. It is a small and rugged embedded controller, with 400 MHz, Freescale MPC5200 real-time processor.The block diagram of the set-up is as shown in Fig.7.The c- RIO is configured through the software wizard installed in the personal computer. It is added as real time (RT)target for the code generated in LAB VIEW. The three phase disturbance signals of different types generated are now available at the digital output ports of the RT(real-time) target. These signals are converted into analog signals by the NI9263 D/A module. and the three phase disturbance signals are now available real-time at the analog out put ports of this D/A module. These signals are transferred to A/D NI 9201 A/D input module of the RT controller. This module has the signal conditioning unit as well as anti aliasing filters built in. The sampling frequency chosen is 1KHz.The algorithm which resides in the memory of the real time controller acts on the signals and generates the trigger during the disturbance in the signal which is now available at the output of the D/A module. The results observed on the oscilloscopes are as shown in Fig.7 and Fig.8 which show the disturbed signal, the positive sequence components and the trigger signal generated during an unbalanced sag of 50% in two phases.

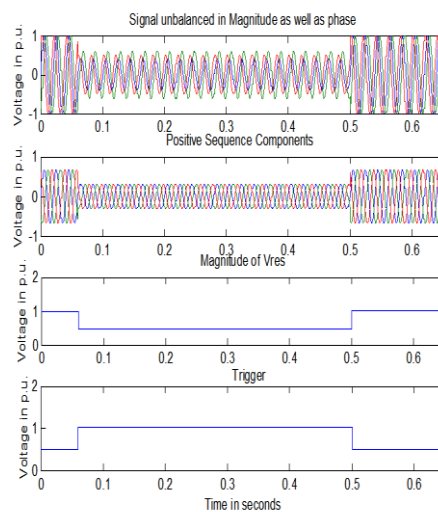


Fig.6.Detection of sag unequal in magnitude and phase.

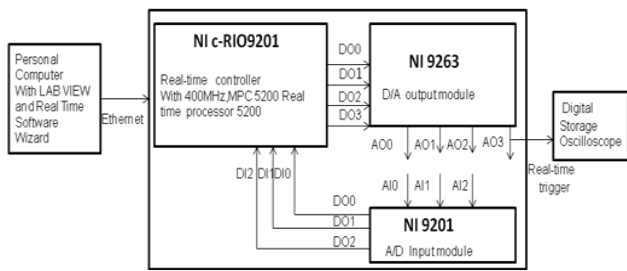


Fig.7. Block Diagram of the hardware set-up used

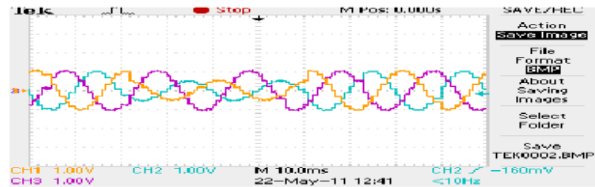


Fig.8. Capture of unbalanced sag (50%) in two phases.

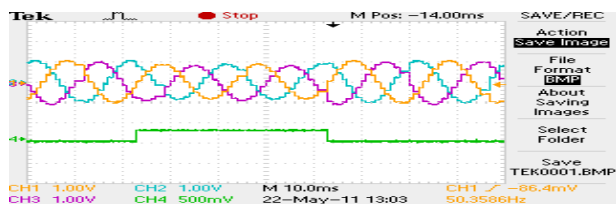


Fig.9. Positive sequence component and trigger(0.25p.u.)

4. Operation of the DVR

The Fig.10. gives the block diagram representation of the DVR for operation subsequent to the detection of the sag. The control unit of the DVR is activated during the sag by the trigger signal generated. The DVR is not switched on under normal conditions. The positive sequence components of the three phase voltage signal during the sag is determined using the mathematical transformation mentioned in equation (6). These positive sequence components of the supply are used for comparison with the nominal (reference) value of positive sequence components. The error which is the voltage to be injected is applied as the control signal to the SVPWM inverter from which the pulses for the inverter operation proportional to the control signal are derived. The inverter output is passed through a low pass filter and the filter output through transformers is applied in series to aid the positive sequence components of the sag voltage that provide the necessary gain. The resultant of this voltage is now available at the load.

5. The SVPWM algorithm used for inverter

A three phase balanced system with sinusoidal variations can be represented by a single resultant space vector, rotating at a uniform angular velocity, the tip of the vector tracing a circular locus. The idea behind space vector PWM technique, is to obtain the switching pattern of the six switches of the inverter in such a way that the average variation in each phase will be sinusoidal such

that the tip of the resultant space vector moves over a circular locus as shown in Fig.11.

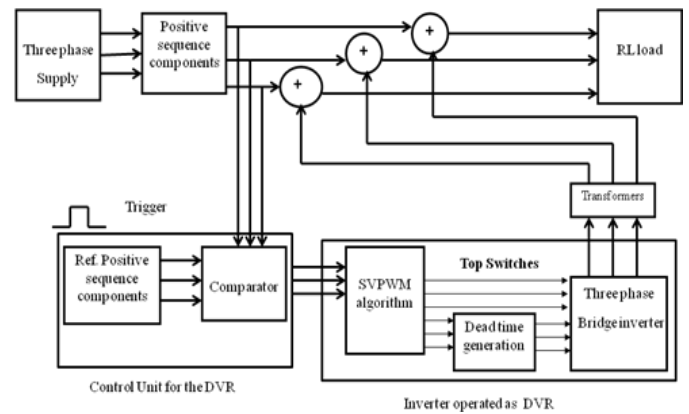


Fig.10. Block Diagram of the DVR set-up.

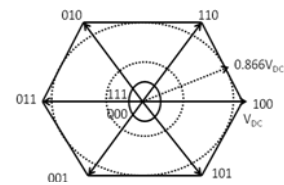


Fig.11. The loci traced by voltage vector during SVPWM control.

In[5], the switching times for active vectors of each sector are derived very easily once the sampled reference phase amplitudes are known. The steps involved in the algorithm are :

1. Sampling the reference phase voltages V_a , V_b and V_c the switching times of the active voltage vector in the different sectors are determined as given by (10), Where T_s is the sampling period.

$$T_{as} = \frac{V_a \cdot T_s}{V_{DC}}, T_{bs} = \frac{V_b \cdot T_s}{V_{DC}}, T_{cs} = \frac{V_c \cdot T_s}{V_{DC}} \tag{10}$$

2. Calculating the value of T_{eff} (effective switching time). which is nothing but the difference of maximum(maximum of T_{as} , T_{bs} and T_{cs}) of the sampled value and the minimum (minimum of T_{as} , T_{bs} and T_{cs}) of the sampled values. This is obtained after sampling the three phase reference amplitudes and applying a three element sorting algorithm.

3. Calculating the Zero time ' T_0 ' where $T_0 = T_s - T_{eff}$. This is the time for which the switching vector is inactive that is the state is 000 or 111. T_1 and T_2 are the switching time intervals for the active switching vectors of the corresponding sectors.

4. The time period should be positive therefore an offset is added to shift it to positive side. The offset time is evaluated as $T_{offset} = \frac{T_0}{2} - T_{min}$.

5. This gives us the corresponding gating signal to the top switches in a sampling period. Therefore, the gating signal duration for the top switches are obtained as,

$$T_{ga} = T_{as} + T_{offset}, T_{gb} = T_{bs} + T_{offset}, T_{gc} = T_{cs} + T_{offset} \quad (11)$$

For the rest of the sampling period the bottom switch is turned on.

A. Operation of the DVR during a balanced sag of 60%

The Fig.12, shows the effective restoration of the positive sequence voltage across the load to its nominal value during the balanced sag of 60%. It shows the successful operation of the inverter as a DVR. The voltages injected by the inverter are also shown and it is seen that the voltage across the load is always maintained at the nominal value. The range of voltage deviations that can be compensated by the DVR is actually confined to the linear region of control of the inverter which by the svpwm technique used is restricted to when the peak value of the control signal is 0.577p.u. Hence for operating the DVR in this region it is necessary to choose an appropriate scaling value so as to restrict the peak amplitude of the control signal to be in the linear region of operation. In this work the maximum range for sag magnitude restoration chosen is 100%. Therefore, the scaling chosen in order to see that the magnitude of the control voltages lie in the linear region for successful DVR operation is 0.5p.u. The inverter output magnitude in the linear region is related to the magnitude of the control voltage and this value is 0.699 for the inverter used. Therefore the inverter output voltage is amplified by a value approximately three times ($1/2 \times 1/0.699 = 2.86$ p.u) in order to obtain the necessary p.u. voltage to be added in conjunction with the supply voltage.

B. Operation of the DVR during a sag of 70% in Phase A and 60% in Phase B and C

The proposed DVR effectively restores the voltage across the load even during the occurrence of sag which is unbalanced in magnitude in the three phases. Fig.13. shows the voltage injected by the DVR in response to the deviation of the positive sequence components from its nominal value during the occurrence of 70% sag in A and 60% in B and C phases. The delay in the restoration of the voltage across the load to its nominal value is found to be minimal (2ms).

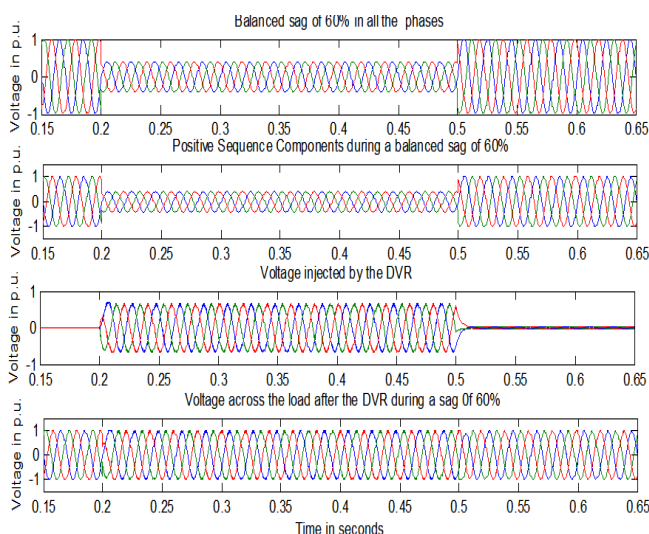


Fig.12. Restoration of voltage during balanced sag of 60%

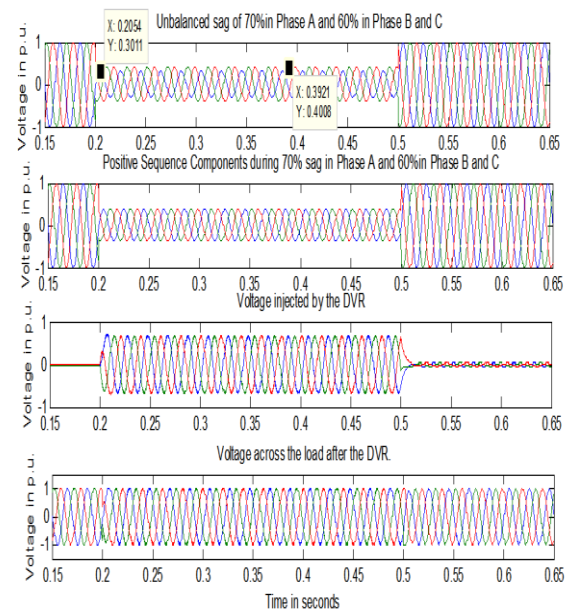


Fig.13. Dynamic restoration during unbalanced sag

6. Conclusion

The results obtained are indicative of accuracy in detection as well as measurement in the levels of disturbance with no time delays. The distinctive feature being the simplicity of the algorithms for detection and restoration with mathematical transformations that can be implemented easily using a micro controller or a digital signal processor and is cost effective.

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