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# Voltage Control using DVR under Large Frequency Variation with DFT and Kalman Filter

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**Abstract:** The paper discusses the voltage control of a critical load bus using dynamic voltage restorer (DVR) in a distribution system. The critical load requires a balanced sinusoidal waveform across its terminals preferably at system nominal frequency of 50Hz .It is assumed that the frequency of the supply voltage can be varied and it is different from the system nominal frequency. The DVR is operated such that it holds the voltage across critical load bus terminals constant at system nominal frequency irrespective of the frequency of the source voltage. In case of a frequency mismatch, the total real power requirement of the critical load bus has to be supplied by the DVR. Proposed method used to compensate for frequency variation, the DC link of the DVR is supplied through an uncontrolled rectifier that provides a path for the real power required by the critical load to flow .A simple frequency estimation technique is discussed which are Discrete Fourier transform (DFT), Kalman Filter and ANN controller. The present work study the compensation principle and different control strategies of DVR used here are based on DFT,and kalman Filter.Through detailed analysis and simulation studies using MATLAB. It is shown that the voltage is completely controlled across the critical load.

*Keywords :* Critical load; DVR; Distribution system; Nominal frequency; Power quality; Voltage control; VSI
DFT, kalman Filter and ANN Controller.

## 1. INTRODUCTION

The power quality (PQ) characteristics fall into two major categories: steady-state PQ variations and disturbances. The steady-state PQ characteristics of the supply voltage include frequency variations, voltage variations, voltage fluctuations, unbalance in the three-phase voltages, and flicker in harmonic distortion. There are many devices, such as power electronic equipment and arc furnaces, etc., those generate harmonics and noise in modern power systems. Power frequency variations are defined as deviation of the power system fundamental frequency from its specified nominal values (e.g., 50Hz or 60Hz). The duration of a frequency deviation can range between several cycles to several hours. These variations are usually caused by rapid changes in the load connected to the system. The maxim tolerable variation in supply frequency is often limited within +ve or –ve 0.5Hz. Voltage notching can be sometimes mistaken for frequency deviation.

Accurate frequency estimation is often problematic and may yield incorrect results. A number of numerical methods are available for frequency estimation from the digitized samples of the supply voltage. These methods assumed that the power system voltage waveform is purely sinusoidal and therefore the time between two zero crossing is an indication of system frequency. Digital signal processing techniques are used for frequency measurement of power system signals. These techniques provide accurate estimation near-nominal, nominal and off-nominal frequencies. The application of enhanced phase locked loop(EPLL) system for the online estimation of stationary and instantaneous symmetrical components.

The well known custom power devices such as distribution STATCOM (DSTATCOM), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC) are available for protection of a critical load from disturbances occurring in the distribution system. In this paper we will discuss voltage control of a critical load bus using DVR. The critical load requires balanced sinusoidal waveforms across its terminals preferably at system nominal frequency of 50Hz. It is assumed that the frequency of the supply voltage can vary and it is different from the system nominal frequency. A DVR is a power electronic controller and it is realized using voltage source inverter (VSIs). It injects three independent single phase voltages in the distribution feeder such that load voltage is perfectly regulated at system nominal frequency.

In general, the DVR is operated in such a fashion that it does not supply or absorb any real power during study state operation [12].In case of a frequency mismatch; the total real power requirement of the load has to be supplied by the DVR. To provide this amount of real power, the dc link of the DVR is supplied through an uncontrolled rectifier connected to the distribution feeder. First of all, the analysis of the DVR operation supported through a dc battery has been discussed. A simple frequency estimation technique is discussed which uses a moving average process along with a zero-crossing detector. The reference voltages injected by the DVR are tracked in the closed loop output feedback switching control. A simple frequency estimation technique is discussed which are Discrete Fourier transform (DFT), Kalman Filter and ANN controller. The present work study the compensation principle and different control strategies of DVR used here are based on DFT, kalman Filter & ANN Controller .Through detailed analysis and simulation studies using MATLAB/PSCAD.

## 2. DVR Structure and Control

The single-line diagram of a DVR compensated distribution system is shown in figure 1. The source voltage and PCC (or terminal) voltages are denoted by $v_s$ and $v_t$ respectively. Note that the variables in the small case letter indicate instantaneous values. The three-phase source, $v_s$ is connected to the DVR terminals by a feeder with an impedance of $R_s$+j$X_s$. The instantaneous powers flowing in the different parts of the distribution system are indicated. These are PCC power ($P_{s1}$), DVR injected power ($P_{sd}$) and load power ($P_{12}$) . Using KVL at PCC we get $\mathbf{v_t + v_k = v}$------------------- **(1)**

The DVR is operated in voltage regulation mode. The DVR injects a voltage, $v_k$ in the distribution system such that it regulates the critical load bus voltage, $v_1$ to a reference $v_1^*$ having a prespecified magnitude and angle at system nominal frequency. The reference voltage of the DVR $v_k^*$ is then given by

$\mathbf{v_k^* = v_1^* - v_t}$----------------**(2)**

The DVR structure is shown in fig.2. It contains three H-bridge inverter. The dc bus of all the three inverters is supplied through a common dc energy storage capacitor Cdc [12].

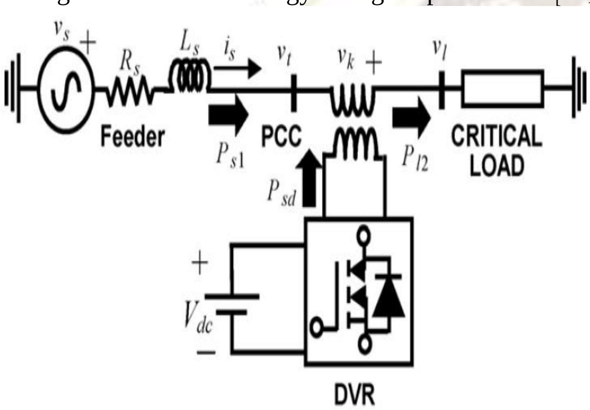


Fig. 1. Single-line diagram of a DVR connected distribution system.

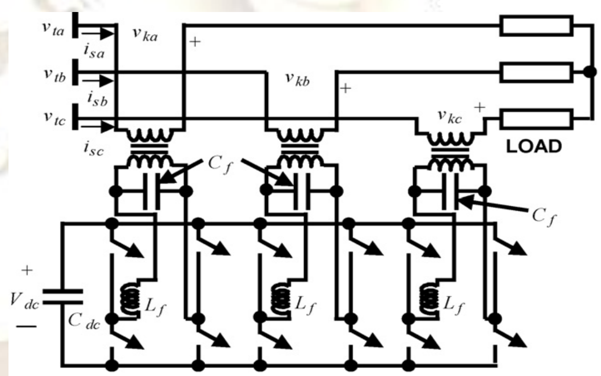


Fig. 2. DVR H-bridge with LC filter.

The voltage across the dc capacitor is indicated as $V_{dc}$ .Note that the each switch represents a power semiconductor device and an anti-parallel diode combination. Each VSI is connected to the distribution feeder through a transformer. The transformer not only reduces the voltage rating of the inverter but also provide isolation between the inverter and the ac system. In this, a switch frequency LC filter ($L_f$ _$C_f$) is placed in the transformer primary (inverter side). The secondary of each transformer is directly connected to the distribution feeder. This will constrain the switch frequency harmonics too mainly in the primary side of the transformer. The three H-bridge inverter are controlled independently. The technique of output feedback control is incorporated to determine the switching actions of the inverters. The controller is designed in discrete-time using pole shifting law in the polynomial domain that radically shifts the open-loop system poles towards the origin. The controller is used to track the reference injected voltages ( $v_k$*) given by (2).

## 3. Normal operation of DVR

The DVR operation using above structure and control has been discussed here. A detailed simulation has been carried out using MATLAB/PSCAD software to verify the efficacy of the DVR system. Let us assume that the source frequency is constant at the distribution system nominal frequency, i.e., at 50Hz. The DVR is connected between the PCC and the critical load. The distribution system and the DVR parameters used for the simulation studies are given in table 1. The dc link of the inverter is supplied through a dc battery. The DVR is operated such that the load voltage is maintained with 9KV peak at system nominal frequency of 50Hz. Note that this value is same as the peak of the source voltage.

The study state system voltages are shown in fig.3.it can be seen from fig.3 (b), that the load bus voltages are perfectly balanced at 50Hz. The PCC bus voltages are also balanced as the source voltages are balanced. It can be seen from fig.3(c), that the magnitude of the injected voltages by the DVR is very small. This is because the DVR is compensating only for the voltage drop across the feeder.

| **System quantities** | **Values** |
|---|---|
| Source voltage | 11KV(L-L),phase angle $0^o$ |
| System normal frequency | 50HZ |
| Feeder Impedance | 0.605+j4.838 ohms |
| Balanced load impedance | 72.6+j54.44 ohms |
| Desired load voltage | 9.0KV peak at nominal frequency, phase angle$0^o$ |
| Single-phase transformers | 1MVA,1.5KV/11KV with leakage inductance of 10% |
| dc-link voltage | 1.5kV |
| Filter parameters(primary side) | L = 61.62µF<br>Ct = 2348.8 µF |
| Pole shift factor(λ) | 0.70 |

## 4. Analysis of DVR operation under frequency variation

Let us now investigate through MATLAB/PSCAD simulation, what happens when the source frequency is not the same as the system nominal frequency. Note that, this is a simulation study to demonstrate the consequences of frequency mismatch the DVR is operated such that it maintains the load voltage at the nominal frequency, of the system, i.e, 50Hz. It is assumed that the source voltage $v_s$ has a frequency of 48Hz. The system current and voltage waveforms are shown in the fig.4.for clarity, only the a-phase waveforms are shown here. It can be seen from fig.4 that the load voltages distortions free and has a fundamental frequency component of 50Hz. Since the load is passive and linear, the load current will also have a frequency of 50Hz.

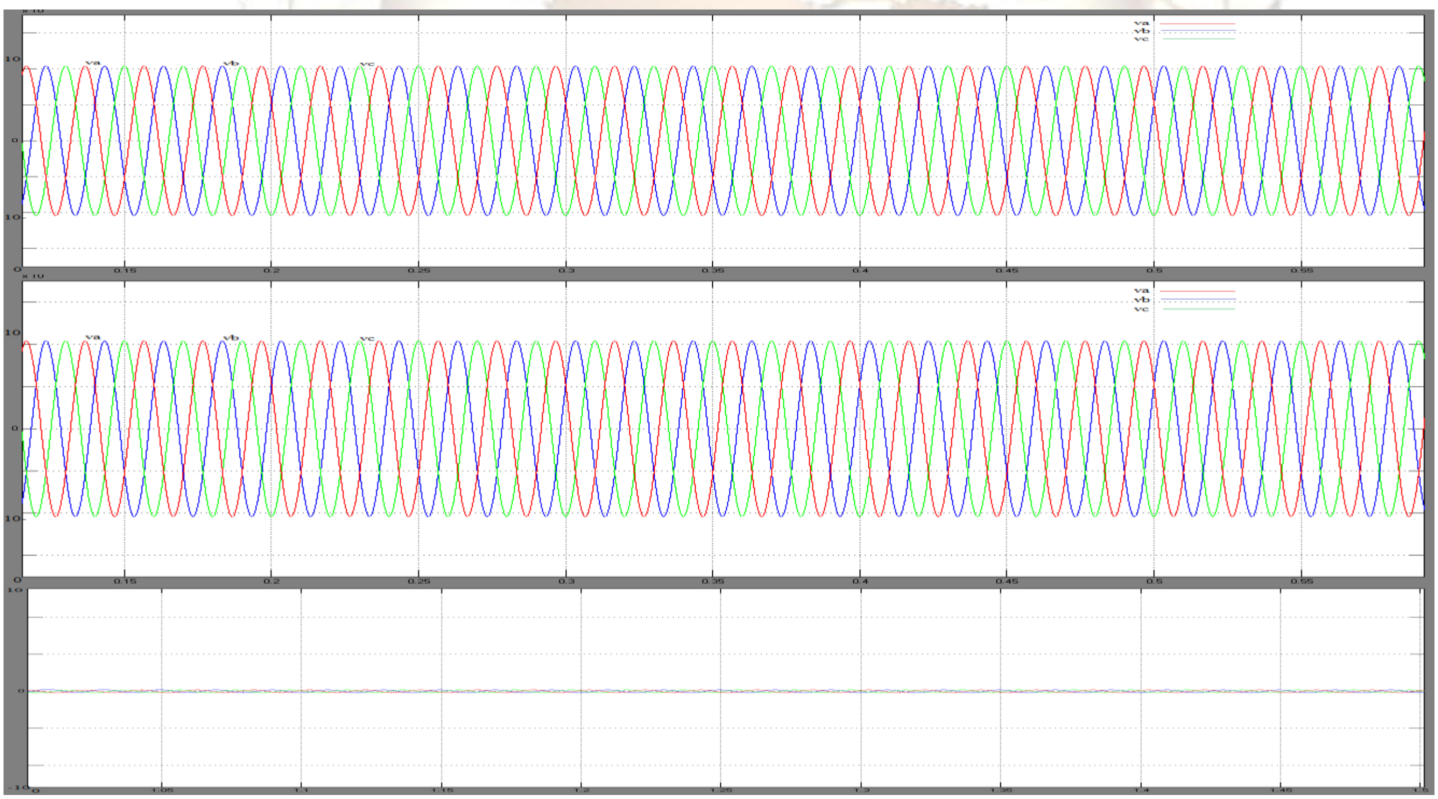

Fig. 3. The system performance using DVR: (a) PCC bus voltages (kV); (b) critical load bus voltages (kV); (c) DVR injected voltages (kV).

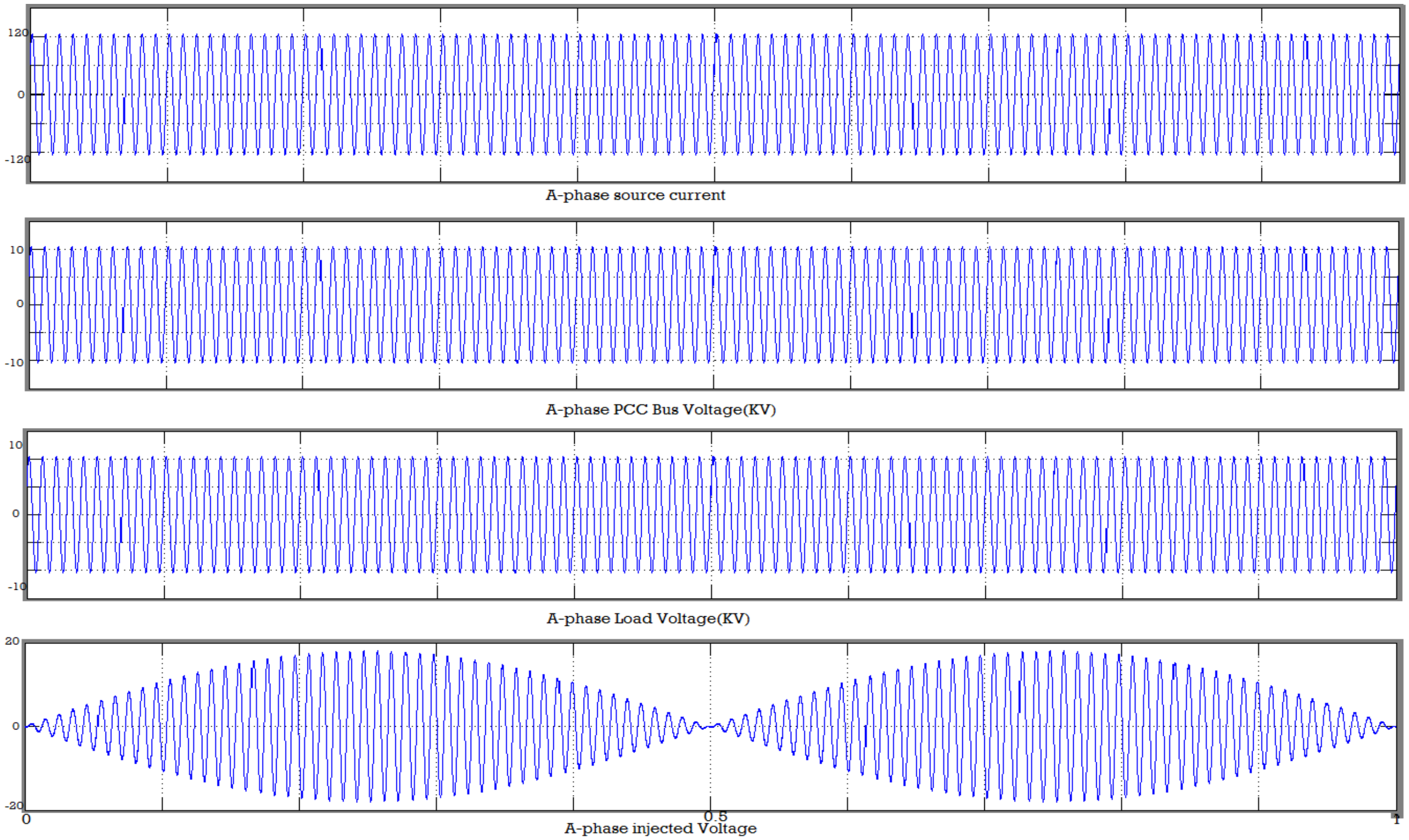

Fig. 4. The source current and the voltages.

Fig.4.source and voltages

The DVR is a series device, the source current is identical with line current and has only 50Hz component. The system equivalent circuit at the two frequencies is shown in fig.5. from fig5,the injected voltage is given

By $$\mathbf{v_k = v_{k1} + v_{k2}} \text{------------------} \quad \mathbf{(3)}$$

The component $v_{k2}$ is exactly negative of the 48Hz source voltage, $v_s$ such that the line current has no 48Hz component. The component $v_{k1}$ approximately equals the 50Hz reference voltage $v_1$*. It can be seen from fig.4, that a-phase injected voltage by the DVR has modulation due to the frequency components. The PCC bus voltage has a 48Hz component equal to $v_s$ and a small 50Hz component corresponding to feeder drop. Again as per(1),the DVR injected voltage must cancel the 48Hz load voltage. This is obvious from the modulating waveform shown in the fig.4.

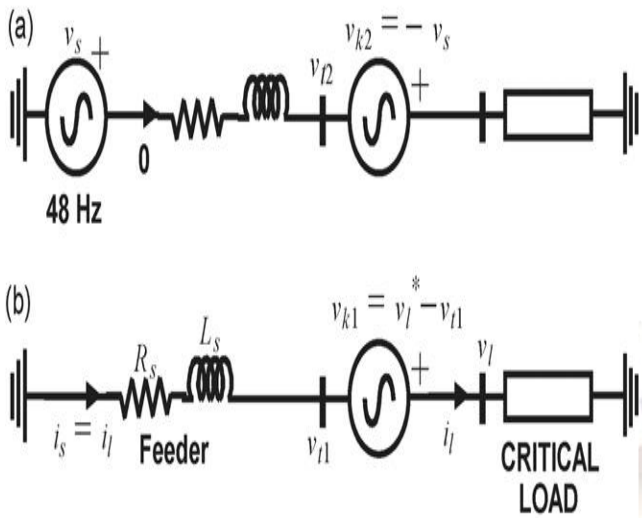


Fig. 5. Equivalent circuits at (a) 48Hz and (b) 50Hz.

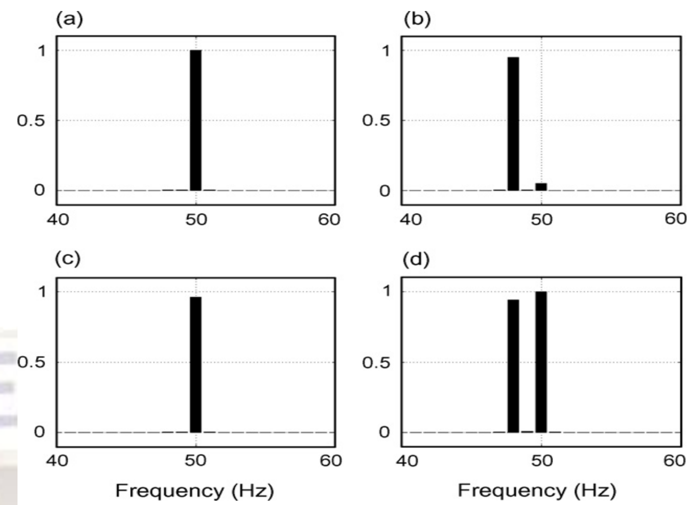


**Fig. 6. The frequency spectrum of current and voltage waveforms: (a) line current; (b) PCC voltage; (c) load voltage; (d) DVR voltage .**

The frequency spectrum of waveforms in fig.4.is shown in fig.6. Note that the spectrum of voltages in fig.6 is normalized with respect to the 50Hz component present in the DVR injected voltage. It can be seen that the line current and the load voltage are at 50Hz component .from (1), the 48Hz component of DVR voltage has the same magnitude as the 48Hz of the PCC voltage, except that they are in phase opposition, which is not shown here. Also, it can be seen from fig.6, that the magnitude of 50Hz load voltage is the different between 50 Hz DVR injected voltage and the corresponding PCC voltage. Let us assume that the PCC voltage contains a component at the fundamental frequency of $\omega_1$ and a component at another frequency $\omega_2$.these three phase voltages ($v_{ta}$,$v_{tb}$,$v_{tc}$) are

Equations

$Vta = Vt_1 \sin(\omega_1 t) + Vt_2 \sin(\omega_2 t)$, $Vtb = Vt_1 \sin(\omega_1 t - 120) + Vt_2 \sin(\omega_2 t - 120)$,

$Vtc = Vt_1 \sin(\omega_1 t + 120^\circ) + Vt \sin(\omega_2 t + 120^\circ)$,______________(4)

The line currents (isa, isb, isc) are at fundamental frequency and are given by

$isa = Is_1 \sin(\omega_1 t - \varphi)$, $isb = Is_1 \sin(\omega_1 t - 120^\circ - \varphi)$, $isc = Is_1 \sin(\omega_1 t + 120 - \varphi)$,__________(5)

From Fig. 1, the instantaneous power (Ps1) entering at the PCC bus is given by

$Ps1 = p_a + p_b + p_c = v_{ta} i_{sa} + v_{tb} i_{sb} + v_{tc} i_{sc}$ ______(6)

Where $pa = Vt_1 Is \sin(\omega_1 t) \sin(\omega_1 t - \varphi) + Vt_2 Is_1 \sin(\omega_2 t) \sin(\omega_1 t - \varphi)$________(7a)

$pb = Vt_1 Is \sin(\omega_1 t - 120) \sin(\omega_1 t - 120 - \varphi) + Vt_2 Is_1 \sin(\omega_2 t - 120) \sin(\omega_1 t - 120 - \varphi)$__________(7b)

$pc = Vt_1 Is \sin(\omega_1 t + 120) \sin(\omega_1 t + 120 - \varphi) + Vt_2 Is_1 \sin(\omega_2 t + 120) \sin(\omega_1 t + 120 - \varphi)$__________(7c)

Expanding (7), we get

$p_a = V_{t1} I_{S1}/2[\cos\phi - \cos(2\omega_{1t} - \phi)] + V_{t2} I_{S1}/2[\cos(\omega_1 - \omega_2)t + \phi] - \cos\{(\omega_1 - \omega_2)t - \phi\}]$

$p_b = V_{t1} I_{S1}/2[\cos\phi - \cos(2\omega_{1t} - 240^0 - \phi)] + V_{t2} I_{S1}/2[\cos(\omega_1 - \omega_2)t + \phi] - \cos\{(\omega_1 - \omega_2)t - 240^0 - \phi\}]$

$p_c = V_{t1} I_{S1}/2[\cos\phi - \cos(2\omega_{1t} + 240^0 - \phi)] + V_{t2} I_{S1}/2[\cos(\omega_1 - \omega_2)t + \phi] - \cos\{(\omega_1 - \omega_2)t + 240^0 - \phi\}]$

Substituting $p_a$, $p_b$, and $p_c$ in, the (6), the instantaneous power $p_{s1}$ is calculated as

$p_{s1}=3/2I_{S1}[V_{t1}\cos\phi+V_{t2}\cos\{(\omega_1-\omega_2)t+\phi\}]$ ---------(8)

Therefore the power entering at the PCC bus ($P_{s1}$) should have a Dc component equal to $1.5*V_{t1}I_{s1}\cos\phi$ and a component at a frequency of ($\omega_1$-$\omega_2$) radian. For the waveforms shown in figure 4,$P_{s1}$ will have a 2 Hz and a dc component. in a similar way power injected by the DVR ($P_{sd}$) will also have these two components. However, the load power ($P_{12}$) will only have a dc component at both the load voltages and load currents are at 50 Hz and the load is balanced. the instantaneous powers are shown in figure7.it can be seen that the load power is constant at about 1.1 MW.

The frequency spectrum of the instantaneous power is shown in fig.8.it can be seen from fig.8 that the power entering at the PCC, $Ps_1$ has a 2 Hz component and a small dc component. The small dc component Is the feeder loss. As the power $Ps_1$ is oscillating at 2 Hz, it is not contributing anything for the power required by the load. Hence, the entire load power is supplied through the DVR. The power consumed by the load has only a dc component.

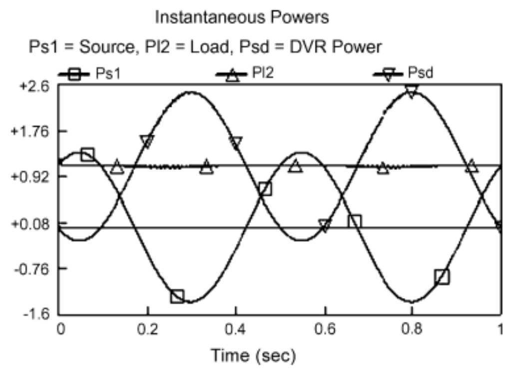

Fig. 7. Various instantaneous powers.

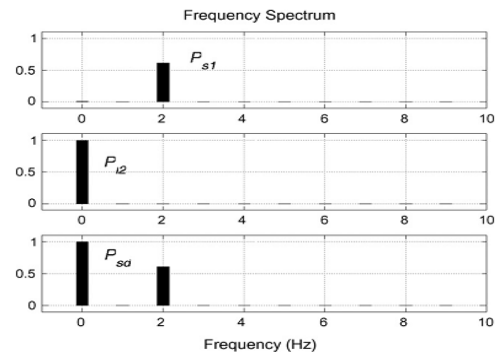

Fig. 8. Frequency spectrum of powers.

The DVR not only supply the load but also supplies the feeder loss, i.e., all 50 Hz components. In addition, DVR also supplies the oscillating 2 Hz component in phase opposition to the 48 Hz component of the source. Therefore, instantaneous maximum value of the DVR injected voltage seems to be very large.

The above discussion clearly demonstrates that the entire real load power has to be supplied by a dc capacitor. The dc capacitor will discharge rapidly if it has to supply this real power irrespective of its size. Hence some alternative arrangement has to be made. It is possible to support the de link through a diode rectifier connected at the PCC bus. We shall now investigate the rectifier-supported DVR operation under frequency mismatch.

## 5. Rectifier-supported DVR

The single line diagram of the distribution system for this connection is shown in Fig. 9 where the power flow

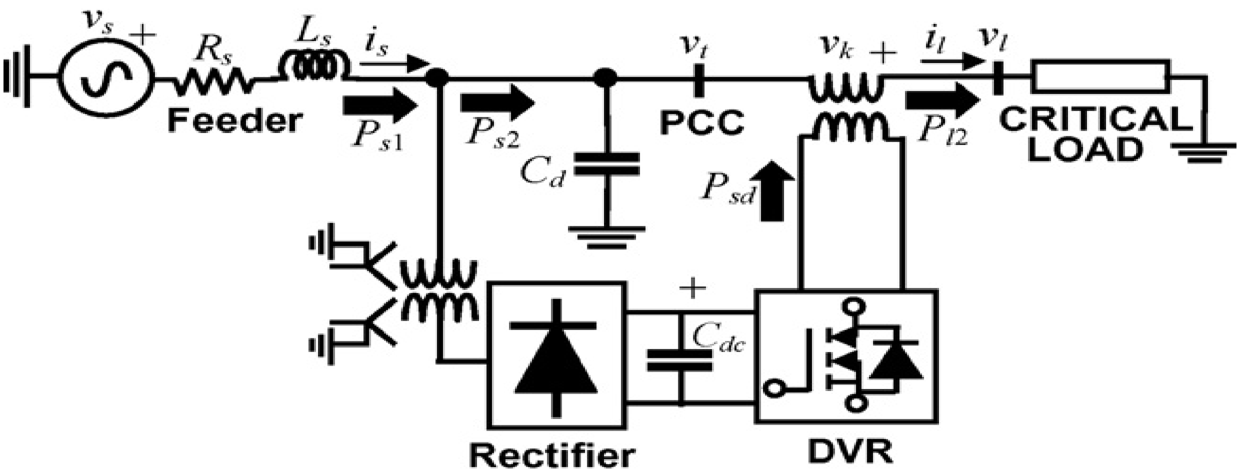


Fig. 9. The rectifier-supported DVR compensated distribution system.

**Table 2**
**Rectifier Parameters**

| System quantities | Values |
|---|---|
| System nominal frequency | 50HZ |
| Source frequency | 48HZ |
| Rectifier transformers | 1MVA, 11KVA/2KV(Y-Y), With Leakage inductance of 10%. |
| Capacitor filter ($C_d$) | 30 µF |
| Dc capacitor ($C_{dc}$) | 4000 µF |
| Reference load voltage ($v_l^*$) | 11KV(L-L) or 9KV Peak at normal frequency ,phase angle0 |

Parts of the system are indicated. The dc bus of the VSIs realizing the DVR is supported from the distribution feeder itself through a three-phase uncontrolled full bridge diode rectifier. The rectifier is supplied by a Y-Y connected to the PCC. Therefore. The DVR can supply real power from the feeder through the dc bus. A shunt capacitor filter, Cd is also connected at the PCC to provide a low impedance path for the harmonic currents generated by the rectifier to flow. Let us assume that the frequency of the source voltage be 48 Hz. The rectifier transformer and capacitor values are given in Table 2 while the rest of the system parameters are the same as given in Table 1.

The PCC voltage, the load and the injected voltage are shown in Fig. 10. It can be seen that the critical load voltage is perfectly regulated to its pre-specified magnitude, i.e., 9 kV. In this connection also a large amount of voltage is injected by the DVR is having a magnitude of about 20 kV at 0.25s. Note from

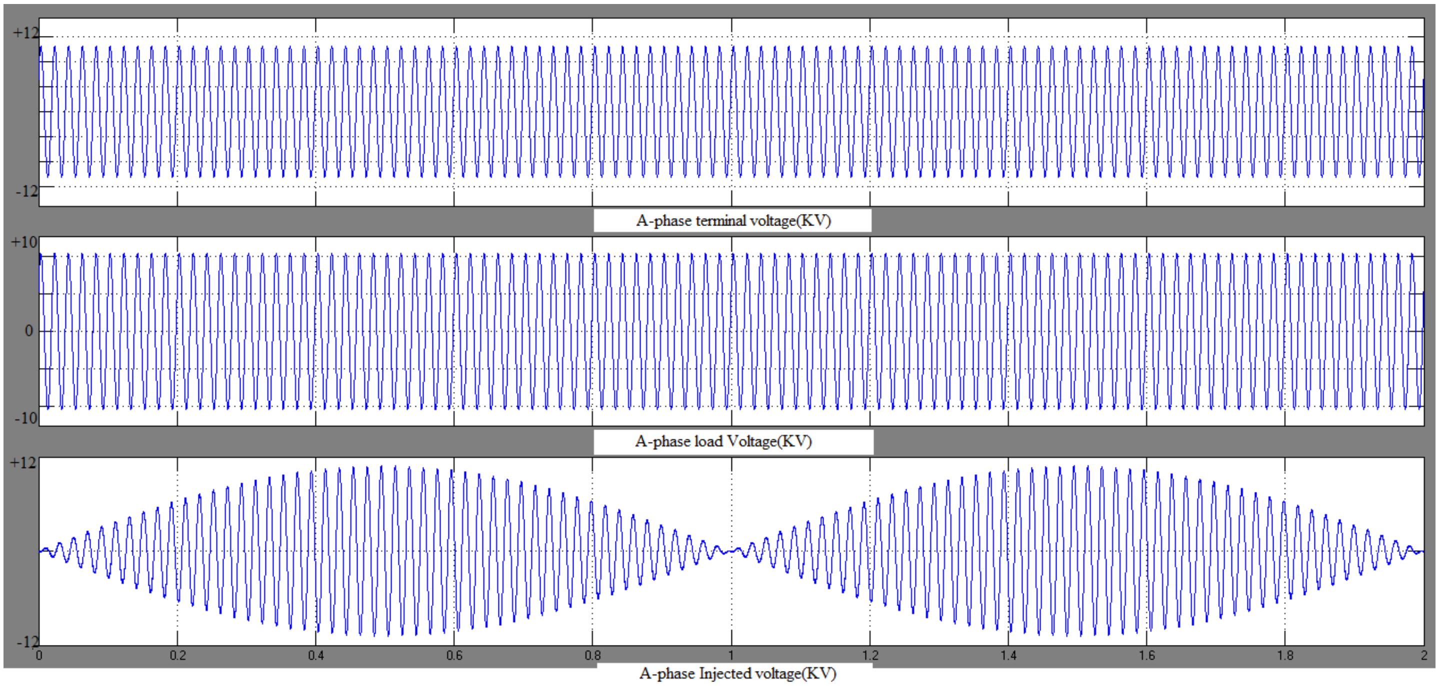


Fig. 10. The system voltage waveforms.

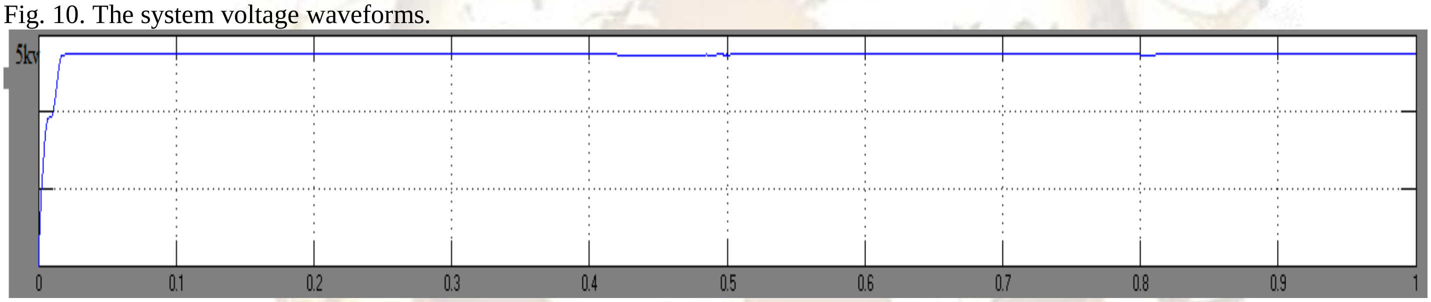


Fig.11.DC capacitor voltage.

Fig. 9, that the load current is not equal to the source current due to the shunt path through the rectifier. The source current, the load current and the dc capacitor voltage waveforms are shown in Fig. 11. Using analysis similar to that in Section 4, we can say that the PCC bus voltage has a large 48Hz component and a very small 50Hz component. The voltage across the dc capacitor supplying the inverters is maintained at about 2.75 kV.The frequency spectrum of the currents and voltages are shown in Fig. 12. Voltages are shown in Fig. 12. Note that the spectrum of the voltages is normalized.

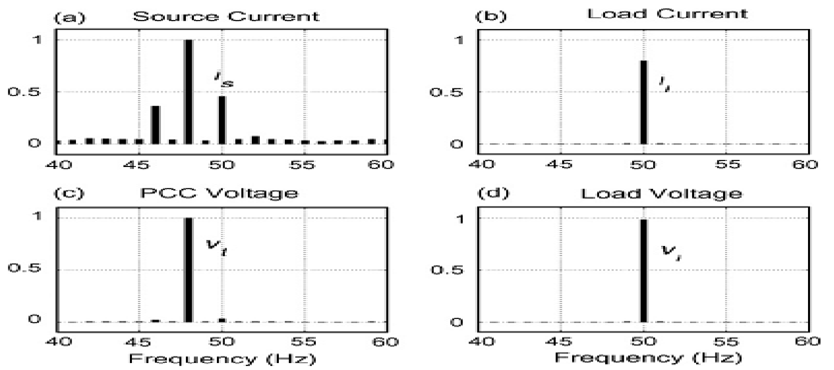

Fig. 12. The frequency spectrum of voltages and current.

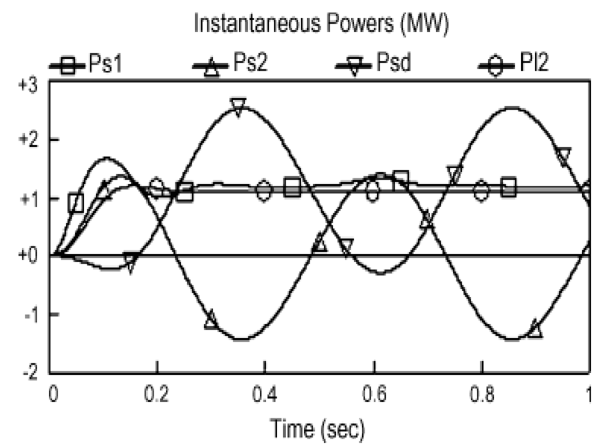

Fig. 13. The instantaneous powers.

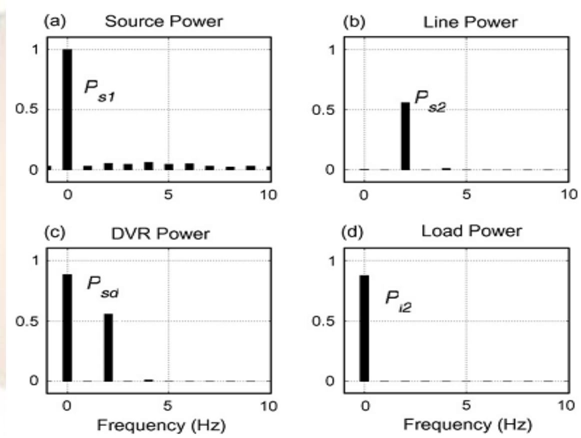

Fig. 14. Frequency spectrum of powers.

With respect to vt. It can be seen that due to the presence of rectifier, the PCC bus voltage has harmonic components n×48 and side bands at frequencies n×48±2Hz where n =1,2,3,.... Hence, the current flowing between the source and the PCC, i.e., is also has these components. As the load voltage is at 50Hz, the load current is also at 50Hz.

The instantaneous powers flowing in the system and their corresponding frequency spectrum (normalized with respect to Ps1) are shown in Figs. 13 and 14, respectively. The load power (Pl2) is constant at about 1.1MW. However, the power flowing in the line, i.e., Ps2 is oscillating at 2Hz and its average over 1 s is nearly zero. The power injected by the DVR (Psd) is oscillating at 2Hz and is riding over a dc value. The dc value being the average critical load power required. The power supplied from the source (Ps1) is having a large dc component and other frequencies of very small magnitudes. The difference in the powers Ps1 and Pl2 is due to the losses occurring in the inverter circuit.

## 6. A new frequency estimation technique

The above discussion clearly shows that it is very important for the power utilities to somehow measure or estimate the supply frequency and accordingly operate the DVR such that it injects the voltage in the distribution system in sympathy with the changes in the source voltage frequency. One possible solution is to phase lock the DVR from the supply.alternatively, through communication channels, information regarding the frequency at the source end can be transferred to the DVR end. However if the communication fails or if the voltage comes out of the phase lock, the dc bus starts supporting the load. This is undesirable.

In order to avoid such a large amount of injected voltages into the distribution system, the numerical methods are available for the online frequency estimation from the samples of the supply voltage. Most of these methods are very effective when the system voltage or current contains one single frequency. for example the extended kalman filter based method has a settling time of only a few samples and can track variations in the system frequency quickly. However the formulation cannot be easily extended for signals containing two frequencies. Given below a new algorithm based on instantaneous symmetrical components for frequency estimation.

Consider the a phase PCC voltage,$v_{ta}$ given in (4).wherever the frequency $\omega_1$ is assumed to know and we have to estimate the unknown frequency $\omega_2$ based on the measurement of the PCC voltages.

$v_ta = Vt_1 \sin(\omega_1 t) + Vt_2 \sin(\omega_2 t)$-------(9)

Let us denote the time periods of two frequencies $\omega_1$and $\omega_2$ as $T_1$and $T_2$ respectively such that

$T_1=2\pi/\omega_1,\quad T_2=2\pi/\omega_2$taking an average of vta (9) over the

$V_{ta,av=}1/T1 \;=\; t_1 \int t_1+T \;\{V_{t1} \sin(\omega_1 t) + V_{t2} \sin(\omega_2\, t)\}\, dt$ ______________ (10)

$Vta,av = 1/T \;\; t_1 \int t_1+T \;\; Vt2 \sin(\omega 2t)\, dt = \gamma \sin(\omega_2\, t1 + \pi\omega\,_2/\omega_1)$________________(11)
$\gamma=v_{t2}\omega_1/ \Pi\, \omega_2 \;\; \sin(\Pi\omega_2/\omega_1)$
now if the average $V_{ta\cdot av}$ is computed using a moving average process with a time window of $T_1$ as time $t_1$ changes, we shall get a sinusoidal waveform that varies with frequency $\omega_2$.two successive zero crossing of this waveform can be used to determine the frequency based on which the frequency $v_k^*$ of (2) is computed.

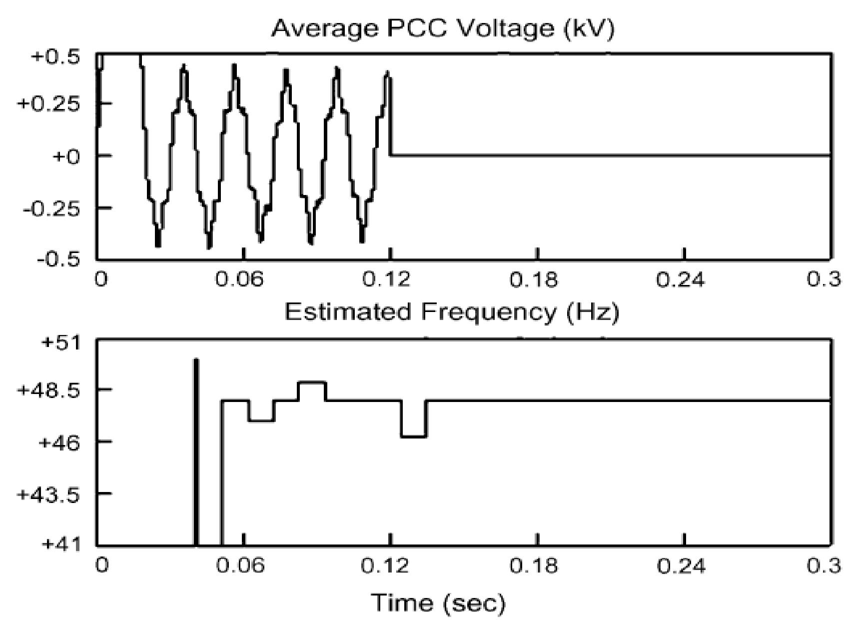


Fig. 15. Average PCC voltage, *V*ta,av and the estimated frequency ($\omega_2/2\pi$).

Consider the same system as discussed in session 4.in which the DVR injects the voltage in the distribution system such that the voltage across the critical load is at a frequency ($\omega_1/2\pi$) of 50 Hz, while the source frequency ($\omega_2/2\pi$) is 48 Hz. The results with the frequency estimation technique mentioned above are shown in fig15 and 16.it can be seen from the fig 15 that a large overshoot (2.5kv) peak arises in the average voltage signal as soon as the frequency mismatch occurs. Note that this is a signal obtained by integration of PCC voltage,$v_{ta}$ over one period. this will cause the zero-crossings of the average voltage to shift for a few successive cycles. Once the variations in the zero-crossings stops, the source frequency estimated to be 48Hz at 0.1s.at this instant, the DVR starts injecting voltages at the estimated frequency. this estimated frequency is then used in the average process of (10) in which both the frequencies are now 48Hz and hence the time window $T_1$ is 1/48s.this will result in average being zero with a delay of one 48 Hz cycle.however,some small variations in the zero-crossings of the average voltage will persist for a few more cycles. The variations in the frequency during this time must be disregarded. if the frequency is allowed to vary in sympathy with the changes in the estimated frequency during this period, the terminal voltage will never be able to settle and the average will not become zero.

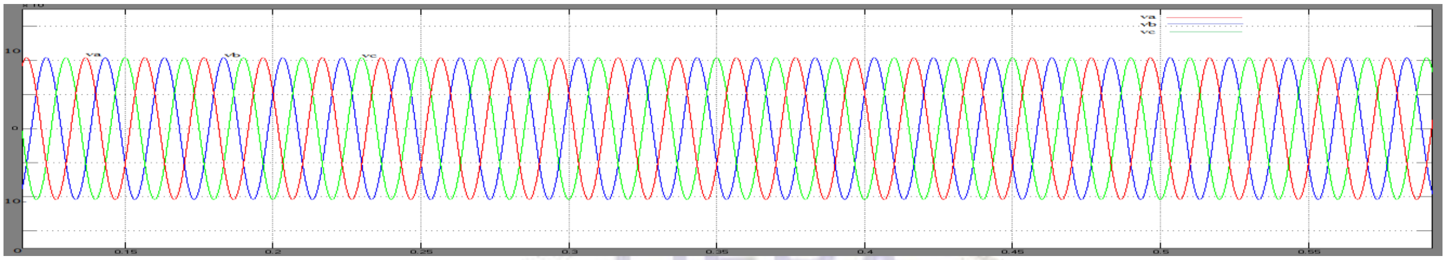
Fig. A. PCC Bus Voltage.

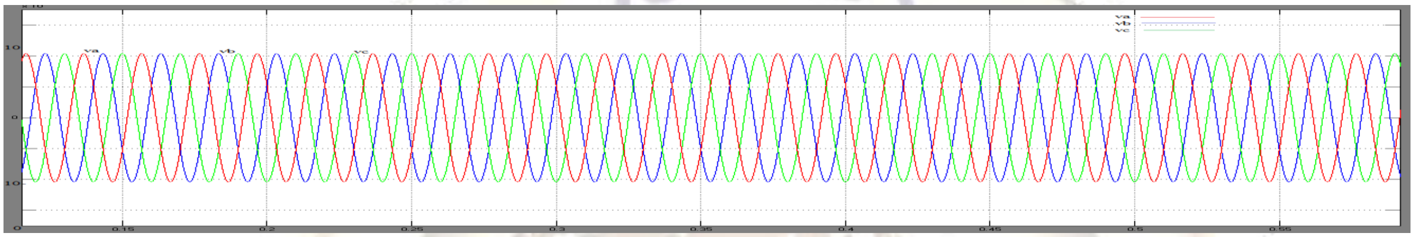
Fig.B. Critical load Bus Voltage

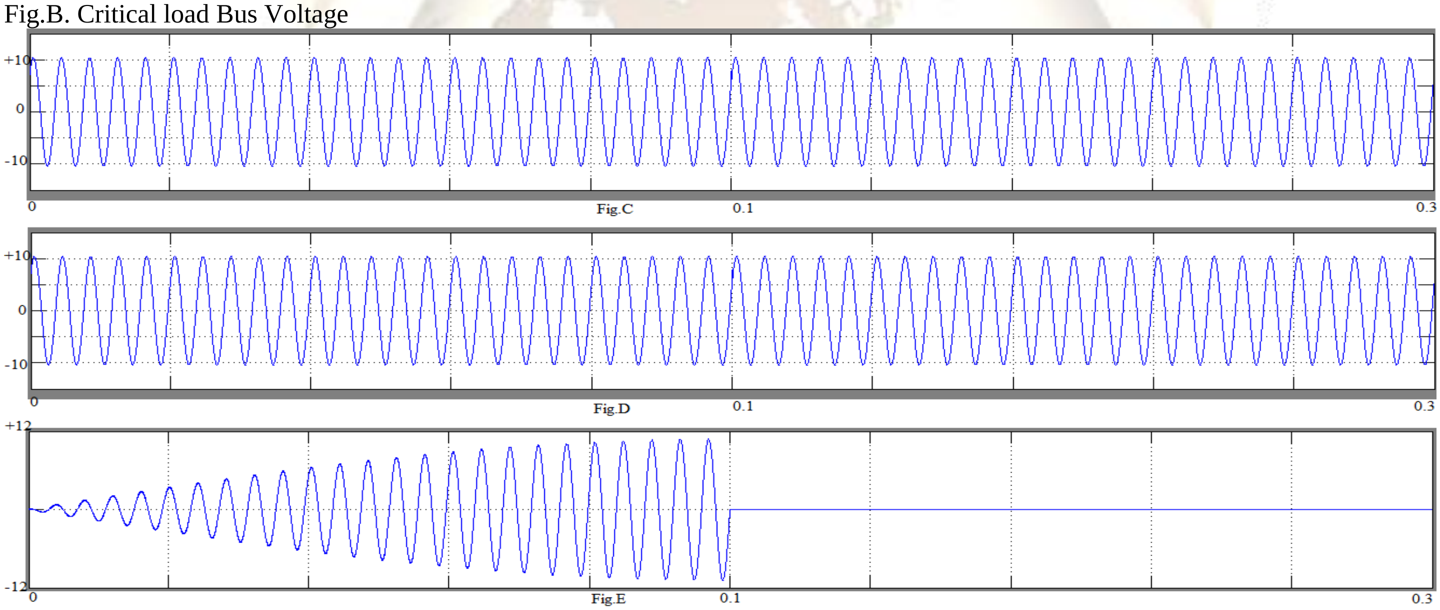


Fig. 16. The system voltage waveforms.

The update of frequency in the reference voltage $v_k^*$ of (2) based on its estimated value therefore must be disabled during this time; the frequency update is enabled once there is a large variation in the average voltage again. the estimated frequency is shown in figure 15.the PCC bus voltages, the critical load bus voltages and DVR injected voltages are shown in fig 16.it can be seen that the DVR injected voltage increases till 0.1sec as seen before in figure 4 and reduce drastically once the frequency is correctly estimated.

So far, we have considered that the source voltages, *v*s (Fig. 1) are balanced and are free from harmonics. Let us assume that *v*s contains 20% fifth harmonic component. Then the a-phase PCC voltage can be written as

$vta = Vt_1 \sin(\omega_1 t) + Vt_2\{\sin(\omega_2 t) + 1/5\sin(5\omega 2t)\}$_______(12)

The average of *v*ta of (12) over the period *T*1 will be

$V$ta,av = $1/T_1 \int_{t1}^{t1+T1} Vt_2\{\sin(\omega_2 t) + 1/5\sin(5\omega_2 t)\}dt$

$= \gamma \sin(\omega_2 t_1 + \pi\omega_2/\omega_1) + \gamma 5 \sin 5(\omega_2 t_1 + \pi\omega_2/\omega_1)$ ______________(13)

Where the constant term $\gamma$ and $\gamma 5$ are given by

$\gamma = Vt_2\omega_1/\pi\omega_2 \sin(\Pi\omega_2/\omega_1)$ , $\gamma 5 = Vt_2\omega_1 \sin(5\Pi\omega_2/\omega_1)$

The procedure for estimating the frequency described above can now be applied to $V$ta,av as per (13). The estimated frequency.

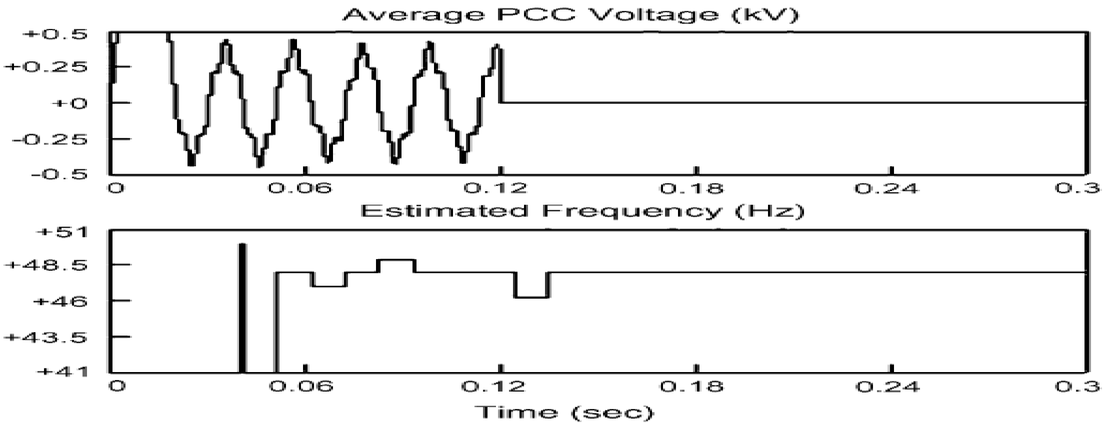


Fig. 17. Average PCC voltage, Vta,av and the estimated frequency

Along with average PCC voltage is shown in Fig. 17. It can be seen that that the harmonic in the source does not affect the Estimation technique, because the zero crossings are unaffected by the addition of an integer harmonics in (12).

In general, addition of integer harmonics whose magnitudes Reduce as harmonic number increases; do not cause a shift in zero crossing. Therefore, the presence of such integer harmonics does not affect the estimation of frequency

**Kalman Filter For Determination Of Sag Beginning**

Kalman algorithm is applied in order to detect the start and finish of the voltage sag as soon as possible. The Kalman filtering performs the following operations. First of all, it is necessary to have a mathematical description both of the system and of the measurement The process will be estimated at time $t_k$, based on the knowledge of the a-priori process at time

$x_k = \phi_{k-1} x_{k-1} + w_{k-1}$ (16)

Next, the state variables and the stochastic system model will be defined. It is assumed that the signal system under study (voltage signal) corresponds to a sinusoidal signal as is expressed in the following equation.

$y_k = A\cos(\omega k\delta t + \upsilon)$ (17)

For the next time step $k+1$:

$y_{k+1} = A\cos(\omega(k+1)\delta t + \upsilon) = A\cos((\omega k\delta t + \upsilon) + \omega\delta t)$ .....(**14**)

Considering the state variables as the following

$x_{1.k} = A\cos(\omega k\delta t + \upsilon)$

$x_{2.k} = A\sin(\omega k\delta t + \upsilon)$ ……………………………(15)

the following relationship can be obtained. Where  (angular frequency=2Π.50 rad/s) and δt =1/fs, where fs is the sampling frequency. Consequently, the measurement at time $k+1$ may be related with the state variables at time $k+1$, as:

$$x_{k+1} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_{k+1} = \begin{bmatrix} \cos(\omega\delta t) & -\sin(\omega\delta t) \\ \sin(\omega\delta t) & \cos(\omega\delta t) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_k \quad \text{……………………… (16)}$$

Consequently, the measurement at time $k+1$ may be related.

$$Y_{k+1} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_{k+1} = Hx_{k+1} \quad \text{……………………… (17)}$$

Where $H$ is the Matrix giving the ideal connection between the measurement and the state vector at time $t_k$.

The measurement of the process is assumed to occur at discrete points in time in accordance with the linear relationship:

$z_k = Hx_k + v_k$ …………………… (18)

where $V_K$ is the measured error assumed to be a white sequence with known covariance and probability distribution, p(v)

$p(v)=N(0,R)$ …………… (19)

The random process can be modeled by:

$x_k=\phi.x_{k-1}+w_{k-1}$ ……(20)

Where is the matrix relating the state variables at instant of time $t_k$ with $t_{k-1}$ :

$$\phi = \begin{bmatrix} cos(\omega\delta t) & -sin(\omega\delta t) \\ sin(\omega\delta t) & cos(\omega\delta t) \end{bmatrix} \quad (21)$$

and ϖ is the vector assumed to be a white sequence with known covariance structure. It has the following probability distribution:

$p(\varpi)=N(0,Q)$ ………………………………. (22)

The estimation of the process covariance, P, in the next time step *k* can be obtained by the following equation:

$P_K^{\sim}=\phi P_{K-1}\phi^T+Q$………………. (23)

and the Kalman gain, *K*, can be computed as:

$K_K = P_K^{\sim}H^T(HP_K^{\sim}H^T+R)^{-1}$ ……….. (24)

With this information the state estimation can be updated knowing the measured $z_k$:

$x_k^{\sim}=x_k\sim+K_K(z_k-Hx_k\sim)$…………………….. (25)

and the process covariance can be updated according to:

$$P_k=(1-K_kH)P_k\sim \quad (26)$$

Kalman filter provides an online estimation of the following signals:

- amplitude of the voltage signal, A(t) of y(t)
- phase angle $\phi(t)$ ωt υ of y(t)

$$A(t)=\sqrt{x_1^2+x_2^2} \quad (31)$$

$$\phi(t)=arctan\ x_2/x_1 \quad (32)$$

One of the weak points of this algorithm is that the process can be very sensitive to noise and disturbances signal. Different performances can be obtained by using different model order , different noise covariance matrixes Q and R or to use the nonlinear Extended Kalman Filter.

In this paper, a simple linear model has been applied because it offers good reliability, minimum detection time and low computational complexity. This last factor is especially critical in the final implementation in the DVR control algorithm.

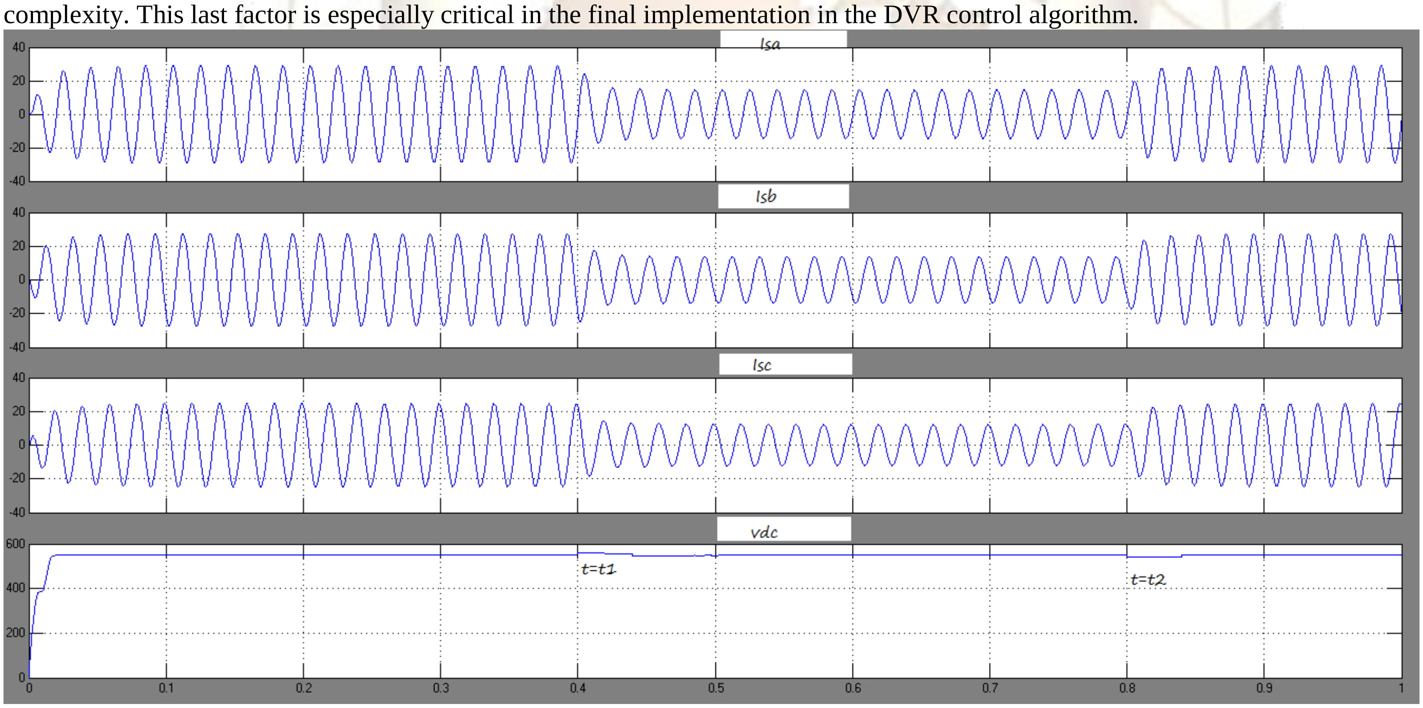


Fig.18. source currents and DC-link voltage with kalman filter and proposed VSI controller

## 7. Conclusions

The critical load bus voltage regulation using a DVR is discussed in this paper. It has been assumed that the source voltage Frequency is not same as the distribution system nominal frequency. It has been shown that in order to maintain the load voltage at system frequency of 50 Hz, a rectifier-supported DVR is able to provide the required amount of real power in the distribution system. The rectifier takes this real power from the distribution feeder itself and maintains the voltage across the dc capacitor supplying the DVR. However, the rectifier power contains a large ac component at the difference frequency. As investigated in Section 5, the injected voltage and magnitude of powers are unacceptably high if the frequency variation is large.

A simple frequency estimation technique is discussed which uses a moving average process along with zero-crossing detector. It has been shown that once the frequency of the injected voltage latches on to that of the source voltage, the DVR injection reduces drastically.

## 8. REFERENCES

[1] A. K. Pradhan, A. Routray, and A. Basak, “Power System Frequency Estimation Using Least Mean Square Technique,” IEEE Trans. Power Delivery, Vol. 20, No. 3, pp. 1812-1816, July 2005.

[2] R. Aghazadeh, H. Lesani, M. Sanaye-Pasand and B. Ganji, “New technique for frequency and amplitude estimation of power system signals,”IEE Proc.-Gener. Transm. Distrib., Vol. 152, No. 3, pp. 435-440, May 2005.

[3] K. Kennedy,G. Lightbody and R. Yacamini, “Power System harmonicanalysis using the Kalman Filter,” in Proc. IEEE Power Eng. Soc. General Meeting, Toronto, Vol. 2, pp. 752-757 , July 2003.

[4] A. G. Phadke, J. S. Thorp and M. G. Adamiak, “A new measurement technique for tracking voltage phasors, local system frequency, and rate of change of frequency,” IEEE Trans. Power App. Syst., Vol. PAS-102, No. 5, pp. 1025–1038, May 1983.

[5] M. M. Begovic, Petar M. Djuric, S. Dunlap and A. G. Phadke, “Frequency tracking in power networks in the presence of harmonics,”IEEE Trans. Power Delivery, Vol. 8, No. 2, pp. 480-486, April 1993.

[6] J. Z. Yang and C. W. Liu, “A precise calculation of power system frequency and phasor,” IEEE Trans. Power Delivery, Vol. 15, No. 2, pp. 494-499, April 2000.

[7] V. V. Terzija, M. B. Djuric, and B. D. Kovacevic, “Voltage phasor and local system frequency estimation using newton type algorithm,” IEEETrans. Power Del., Vol. 9, No. 3, pp. 1368–1374, July 1994.

[8] T. S. Sidhu and M. S. Sachdev, “An iterative technique for fast and accurate measurement of power system frequency,” IEEE Trans. Power Delivery, Vol. 13, No. 1, pp. 109-115, January 1998.

[9] T. S. Sidhu, “Accurate measurement of power system frequency usinga digital signal processing technique,” IEEE Trans. Insrum. Meas., Vol.48, No. 1, pp. 75-81, February 1999.

[10] A. Ghosh, A. K. Jindal and A. Joshi, “Inverter control using output feedback for power compensating devices,” IEEE TENCON 2003 Conf. on Convergent Technologies for Asia-Pacific Region, Vol. 1, pp. 48-52, 14-17 Oct. 2003.

[11] A. K. Jindal, A. Ghosh, and A. Joshi, “Voltage Regulation using Dynamic Voltage Restorer for large frequency Variations,” in Proc. IEEE Power Eng. Soc. Gen. Meeting, San Francisco, CA, pp 1780-1786,June 2005.

[12] A. Ghosh and G. Ledwich, “Structures and control of a dynamic voltage regulator (DVR),” in Proc. IEEE Power Eng. Soc. Winter Meeting,Columbus, OH, 2001.

[13] A. Ghosh and G. Ledwich, Power Quality Enhancement Using Custom Power Devices, Norwell, MA: Kluwer, 2002.