A Study on DVR Control for Unbalanced Voltage Compensation

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Abstract – This paper presents a new control scheme for a DVR (Dynamic Voltage Restorer) system consisting of series voltage source PWM converters. To control the negative sequence components of the source, it is necessary to detect the negative sequence components. Generally, a filtering process is used which has some undesirable effects. This paper suggests a new method for separating positive and negative sequences components. This control system is designed using differential controllers and digital filters. The positive and negative sequences are extracted and controlled individually. The performance of the presented controller and scheme are confirmed through simulation and actual experiment with a 2.5kVA prototype DVR system.

Keywords – DVR, Positive Sequence, Negative Sequence, Differential Controller

1. INTRODUCTION

Office automation, process automation, medical, and communication equipment used in everyday life are sensitive to disturbances such as momentary interruptions, momentary sags, overvoltages, and harmonics in electrical distribution systems. If these disturbances are not properly mitigated, they can be the cause of equipment breakdown or misoperation resulting in equipment damage or production loss. One of the most widely used equipments to protect critical loads is the uninterruptible power system (UPS), which has limited applications due to its high steady state loss and initial investment cost. Thus research in DVR (Dynamic Voltage Restorer) systems, as an economical and highly efficient compensator for momentary voltage sags that can be applied in place of the UPS, has been gaining interest.

The DVR is a series connected compensator that instantaneously compensates voltage sags and swells. When there is a disturbance within the distribution system, the three phase voltage generally becomes unbalanced, resulting in both the positive and negative sequence components existing in the distribution system. To remove the steady state phase lag, the positive and negative sequence components need to be detected as a DC component and controlled. To separate the positive and negative sequence components, LPF(Low Pass Filter)s are used after the d-q transformation. To separate only the negative sequence components, the large positive sequence components with 120Hz frequency that exist in the d-q transformed negative sequence components must be removed. For effective removal, the cut-off frequency of the filter must be reduced, but has the side effect of reducing the controller response time.

This paper presents a method that ensures the stability and precision of control by passing the positive and negative sequence components through a differentiator for effective compensation of both the positive and negative sequence components. The resulting values are then crisscrossed with the original positive and negative signals and calculated to extract the real positive and negative sequence component signals. The validity of the proposed method is shown through simulation and actual test results.

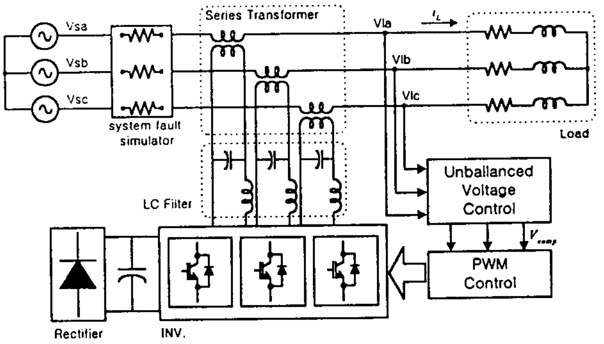


Fig. 1 DVR system configuration

2. THE CONTROL OF DVR SYSTEM

The DVR system configuration is shown in Fig. 1. The system fault simulator in front of the DVR system is configured with magnetic contactors and wound type resistors to simulate voltage sages seen from the DVR input. The inverter, which is connected in series with the network, compensates the voltage drop when voltage sags occur. An unbalanced voltage sag of one or two phases causes negative sequence components to appear in the source voltage. This can be expressed as follows. When the matrix C and R(θ) are defined as follows,

$$C=\begin{bmatrix}1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix},\quad R(\theta)=\begin{bmatrix}\cos(\theta) & -\sin(\theta)\\ \sin(\theta) & \cos(\theta)\end{bmatrix}$$

the 3-phase load voltage is transformed into the d-q values of positive sequence SRF(Synchronous Reference Frame) as shown in eq. (1).

$$\begin{bmatrix}v_{lde}^{(p)}\\ v_{lqe}^{(p)}\end{bmatrix}=\frac{2}{3}R(-\omega t)C^{T}\begin{bmatrix}v_{la}\\ v_{lb}\\ v_{lc}\end{bmatrix} \tag{1}$$

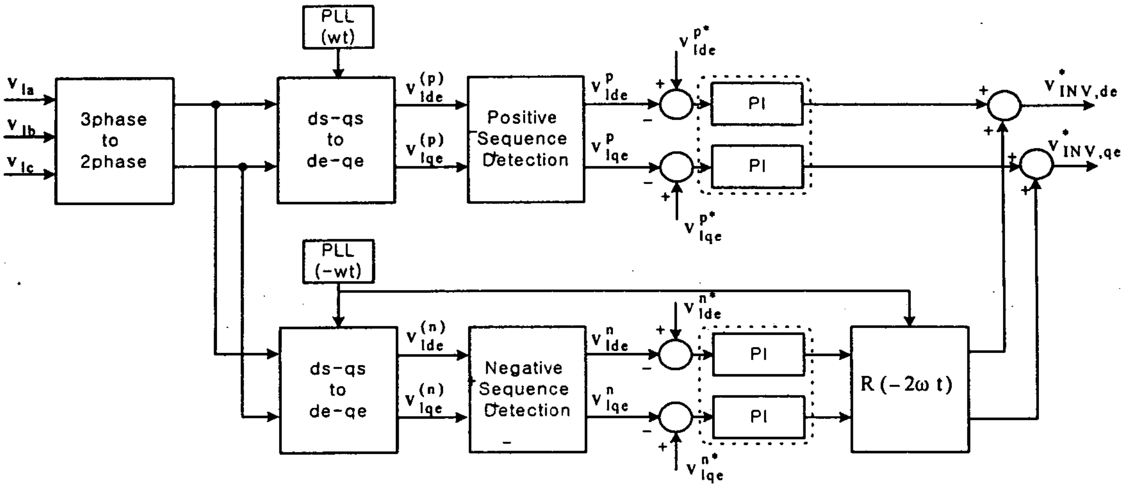


Fig. 2 The control block diagram.

R(θ) is the matrix that rotates a vector by phase angel θ. The superscript, (p) represents that this is the value in positive sequence SRF. The subscript, de and qe represent d-axis and q-axis values in SRF respectively. The subscript, l represents that this is the load voltage. Eq. (1) is composed of both of positive and negative sequence components. This is expressed as eq. (2).

$$\begin{bmatrix} v_{lde}^{(p)} \\ v_{lqe}^{(p)} \end{bmatrix} = \begin{bmatrix} v_{lde}^{p} \\ v_{lqe}^{p} \end{bmatrix} + R(-2\omega t)\begin{bmatrix} v_{lde}^{n} \\ v_{lqe}^{n} \end{bmatrix} \qquad (2)$$

The superscript, p and n shows that this is the value of positive and negative sequence components respectively at t=0. Thus this vector is a constant value. Since the positive sequence rotates counterclockwise and the negative sequence rotates clockwise direction in the stationary reference frame, when they are shown in positive sequence SRF, the positive sequence becomes a DC component and the negative sequence a 120Hz component as expressed in eq. (2). Also, the 3-phase load voltage can be transformed into d-q values of negative sequence SRF as shown in eq. (3).

$$\begin{bmatrix} v_{lde}^{(n)} \\ v_{lqe}^{(n)} \end{bmatrix} = \frac{2}{3}R(\omega t)C^{T}\begin{bmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{bmatrix} \qquad (3)$$

The superscript, (n) represents that it is the value in negative sequence SRF. In this case, the negative sequence becomes a DC component and the positive sequence becomes a 120Hz component as follows.

$$\begin{bmatrix} v_{lde}^{(n)} \\ v_{lqe}^{(n)} \end{bmatrix} = \begin{bmatrix} v_{lde}^{n} \\ v_{lqe}^{n} \end{bmatrix} + R(2\omega t)\begin{bmatrix} v_{lde}^{p} \\ v_{lqe}^{p} \end{bmatrix} \qquad (4)$$

For effective control without phase shift in steady state, the positive and negative sequence components that have DC values should be separated. Fig.2 shows the block diagram representing this process. Conventionally, LPF (Low Pass Filter) is used in SRF to separate the positive and negative sequence components. In this method, the 120Hz positive sequence components are large compared to the DC negative sequence components in negative sequence SRF. Thus the 120Hz components may not be completely filtered out. Furthermore the controller misinterprets that negative sequence components are present even though the source voltage is balanced and this can be a cause of disturbance in the load voltage. To solve this problem, the cut-off frequency of the LPF should be set to a small value. But this small cut-off frequency results in slow response time of the system and can make the system unstable. To overcome these problems, this paper proposes a method in which differential controllers and noise filters are used to separate the positive and negative sequence components.

3. THE SEPARATION OF POSITIVE AND NEGATIVE SEQUENCE COMPONENTS

3.1 The method using differential controllers

We assume that the positive sequence components in positive sequence SRF and the negative sequence components in negative sequence SRF are constant. Eq. (5) shows eq. (2) differentiated in time domain.

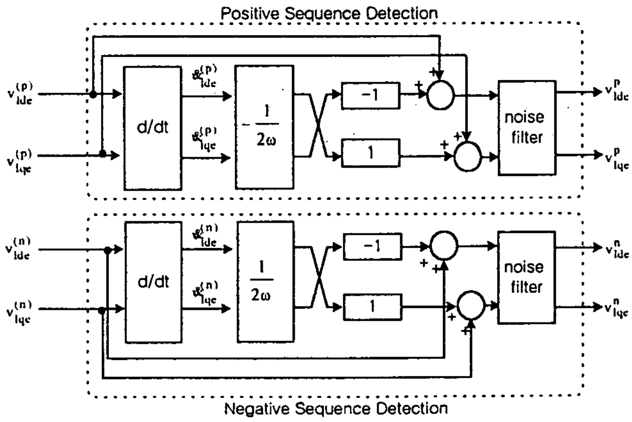


Fig. 3 The proposed method for separating positive and negative sequence components.

$$\begin{bmatrix} \dot{\vec{v}}_{lde}^{(p)} \\ \dot{\vec{v}}_{lqe}^{(p)} \end{bmatrix} = -2\omega \cdot R(\frac{\pi}{2}) \cdot R(-2\omega t) \begin{bmatrix} v_{lde}^{n} \\ v_{lqe}^{n} \end{bmatrix} \tag{5}$$

The differential of $R(-2\omega t)$ becomes $-2\omega \cdot R(\frac{\pi}{2}) \cdot R(-2\omega t)$ and the differential of the positive sequence is zero since it is constant. Eq. (5) is rotated by 90° and divided by -2ω, as follows.

$$-\frac{1}{2\omega} \cdot R(\frac{\pi}{2}) \begin{bmatrix} \dot{\vec{v}}_{lde}^{(p)} \\ \dot{\vec{v}}_{lqe}^{(p)} \end{bmatrix} = R(\pi) \cdot R(-2\omega t) \begin{bmatrix} v_{lde}^{n} \\ v_{lqe}^{n} \end{bmatrix} \tag{6}$$

Since the sum of a vector and the same vector phase shifted by 180° becomes zero, the sum of eq. (2) and (6) leaves only positive sequence components that is a DC component and all negative sequence components are removed.

$$\begin{bmatrix} v_{lde}^{(p)} \\ v_{lqe}^{(p)} \end{bmatrix} - \frac{1}{2\omega} \cdot R(\frac{\pi}{2}) \begin{bmatrix} \dot{\vec{v}}_{lde}^{(p)} \\ \dot{\vec{v}}_{lqe}^{(p)} \end{bmatrix} = \begin{bmatrix} v_{lde}^{p} \\ v_{lqe}^{p} \end{bmatrix} \tag{7}$$

Eq. (7) shows that positive sequence components can be detected without using LPFs, so the stability and accuracy of control can be obtained. With the same method, the DC negative sequence components can be calculated with the following equation.

$$\begin{bmatrix} v_{lde}^{(n)} \\ v_{lqe}^{(n)} \end{bmatrix} + \frac{1}{2\omega} \cdot R(\frac{\pi}{2}) \begin{bmatrix} \dot{\vec{v}}_{lde}^{(n)} \\ \dot{\vec{v}}_{lqe}^{(n)} \end{bmatrix} = \begin{bmatrix} v_{lde}^{n} \\ v_{lqe}^{n} \end{bmatrix} \tag{8}$$

In conclusion, we can separate the positive and negative sequence components respectively without using LPFs through eq. (7) and (8). Fig. 3 is the block diagram representing the process.

3.2 Realization in digital

For simplicity of expression, the matrix representing the values in SRF can be rewritten as the following vector.

$$\begin{bmatrix} x_{de} \\ x_{qe} \end{bmatrix} = \vec{x}$$

Then eq. (2) can be expressed as the following equation.

$$\vec{V}_l^{(p)} = \vec{V}_l^{p(p)} + \vec{V}_l^{n(p)} \tag{9}$$

The superscript (p) shows that the vector represents the value in positive sequence SRF and p(p), n(p) represent positive sequence and negative sequence respectively in positive sequence SRF. $\vec{V}_l^{p(p)}$ is assumed to be equal with $\vec{V}_l^{p}$ that is the positive sequence vector at t=0 and to be constant. $\vec{V}_l^{n(p)}$ is the vector that rotates in counterclockwise direction with a velocity of 2ωt. Eq. (9) is expressed for the nth sampling case as follows.

$$\vec{V}_l^{(p)}[n] = \vec{V}_l^{p(p)}[n] + \vec{V}_l^{n(p)}[n] \tag{10}$$

To differentiate Eq. (10) for sampling time Tsamp, the subtraction of the nth term and (n-1)th term is performed as shown in eq. (11).

$$\left|\vec{V}_l^{(p)}[n] - \vec{V}_l^{(p)}[n-1]\right| = 2\tan(\omega T_{samp}) \left|\frac{\vec{V}_l^{n(p)}[n] + \vec{V}_l^{n(p)}[n-1]}{2}\right| \tag{11}$$

The direction of that vector is same as the direction of $\vec{V}_l^{n(p)}[n] + \vec{V}_l^{n(p)}[n-1]$ phase shifted by –90°. Thus the differential of eq. (10) is as follows.

$$\frac{\vec{V}_l^{(p)}[n] - \vec{V}_l^{(p)}[n-1]}{T_{samp}} = 2\frac{\tan(\omega T_{samp})}{T_{samp}} \left|\frac{\vec{V}_l^{n(p)}[n] + \vec{V}_l^{n(p)}[n-1]}{2}\right| R(-\frac{\pi}{2}) \frac{(\vec{V}_l^{n(p)}[n] + \vec{V}_l^{n(p)}[n-1])}{\left|(\vec{V}_l^{n(p)}[n] + \vec{V}_l^{n(p)}[n-1])\right|} \tag{12}$$

Thus, eq. (7) can be rewritten as the following equation assuming that T_{samp} is sufficiently small.

$$\vec{V}_l^{(p)}[n] - \frac{1}{2\omega} \cdot R(\frac{\pi}{2}) \dot{\vec{V}}_l^{(p)}[n] \approx \vec{V}_l^{p(p)}[n] + \frac{\vec{V}_l^{n(p)}[n] - \vec{V}_l^{n(p)}[n-1]}{2} \tag{13}$$

From eq. (13), we can see that DC components as well as 120Hz ripples are present. To remove the ripple, the average of $\vec{V}_l^{(p)}[n]$ and $\vec{V}_l^{(p)}[n-1]$ can be used to replace $\vec{V}_l^{(p)}[n]$ because $\vec{V}_l^{p(p)}[n]$, which is a positive component, is constant. Then eq. (13) can be rewritten as eq. (14) with no 120Hz ripple remaining.

$$\frac{\vec{V}_l^{(p)}[n] + \vec{V}_l^{(p)}[n-1]}{2} - \frac{1}{2\omega} \cdot R(\frac{\pi}{2}) \dot{\vec{V}}_l^{(p)}[n] \approx \vec{V}_l^{p(p)}[n] \tag{14}$$

To detect the negative sequence component which is DC, the same process is repeated. Eq. (4) is expressed as eq. (15).

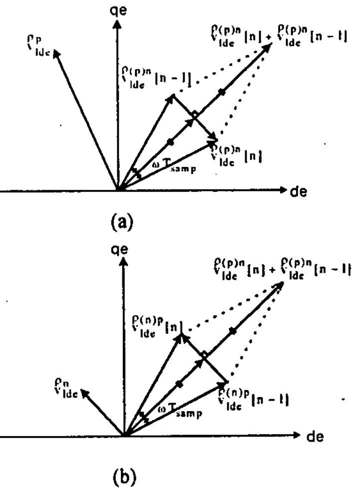
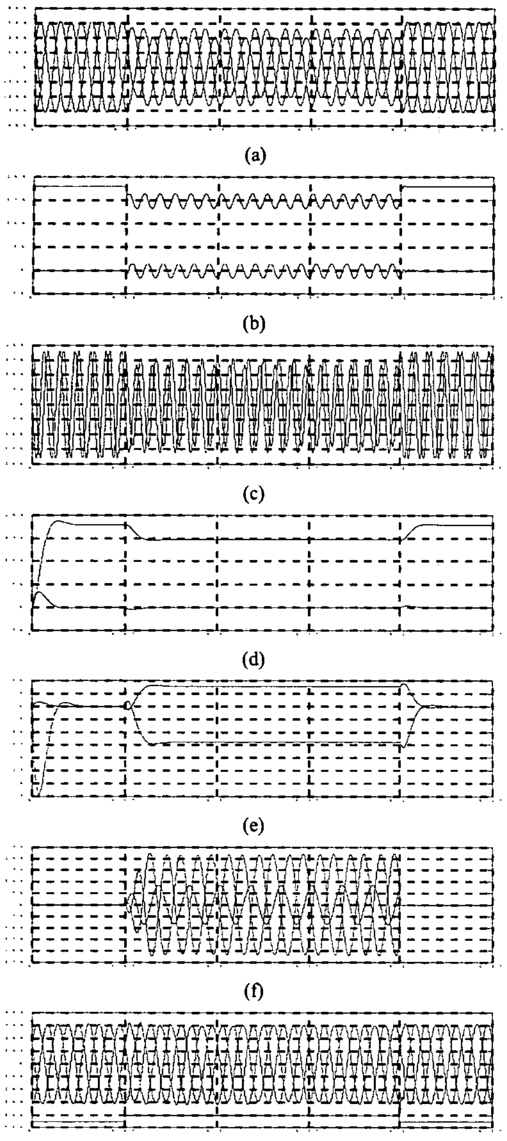


Fig. 4 Vector subtraction of the (n-1)th term from the nth term (a) in positive sequence SRF and (b) in negative sequence SRF.



(g)

Fig. 5 Simulation results. (a) source voltage (b) source voltage in positive sequence SRF (c) source voltage in negative sequence SRF (d) positive sequence detected in DC (e) negative sequence detected in DC (f) DVR injection voltage (g) compensated load voltage

$$\vec{V}_1^{(n)} = \vec{V}_1^{n(n)} + \vec{V}_1^{p(n)} \qquad (15)$$

If eq. (15) is differentiated for sampling time Tsamp,

$$\frac{\vec{V}_1^{(n)}[n] - \vec{V}_1^{(n)}[n-1]}{T_{samp}} = \frac{\tan(\omega T_{samp})}{T_{samp}} R(\frac{\pi}{2})(\vec{V}_1^{p(n)}[n] + \vec{V}_1^{p(n)}[n-1]) \qquad (16)$$

The equation to remove the positive sequence component and the ripple is shown in eq. (17).

$$\frac{\vec{V}_1^{(n)}[n] + \vec{V}_1^{(n)}[n-1]}{2} + \frac{1}{2\omega} \cdot R(\frac{\pi}{2}) \dot{\vec{V}}_1^{(n)}[n] \approx \vec{V}_1^{n(n)}[n] \qquad (17)$$

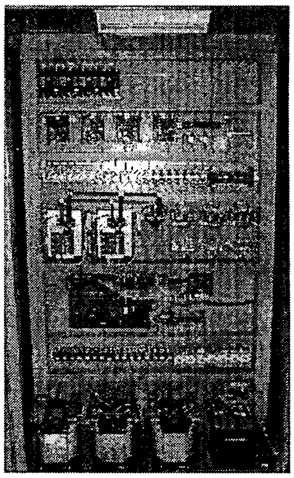


Fig. 6 2.5kVA rating DVR system

Fig. 4 is the phasor diagram, which represents the process of subtracting the (n-1)th vector from the nth vector. So far, the magnitude of positive and negative sequence is regarded as constant. But practically, the magnitude varies when system faults occur and the differential at that point has a large value. other ripples may be present in eq. (14) and (17) depending on the sampling time. Thus a LPF is needed to function as a noise filter. But this noise filter barely has any influence on the control system since the noise filter has a large cut-off frequency.

4. SIMULATION

The proposed controller is modeled with matlab and the source voltage is 220[VLL]. It was confirmed that during a voltage sag, the designed DVR detected changes in positive and negative sequence components and compensated the voltage supply to deliver the required power needed by the load. Simulation waveforms are shown in Fig. 5. Fig. 5(a) shows the source voltage in an unbalanced state. Fig. 5(b) and (c) are the source voltage in positive sequence SRF and negative sequence SRF respectively. The large 120Hz component, which is positive sequence, is present and shown in Fig. 5(c). Fig. 5(d) and (e) show the waveforms after passing through the differential controllers and noise filters proposed in this paper. Fig. 5(d) is the positive sequence component of source voltage in positive SRF and Fig. 5(e) is the negative sequence component of source voltage in negative SRF. Fig. 5(f) shows the DVR injection voltage and the sum with the source voltage is shown in Fig. 5(g). Fig. 5(g) shows that the load voltage is maintained constant.

Table. 1 Parameters

Source voltage (VL-L RMS)	220[V]
Source frequency	60[Hz]
DC Link capacitance	2200[uF]
Switching frequency	5000[Hz]
Inverter output filter L	7.5[mH]
Inverter output filter C	15[uF]

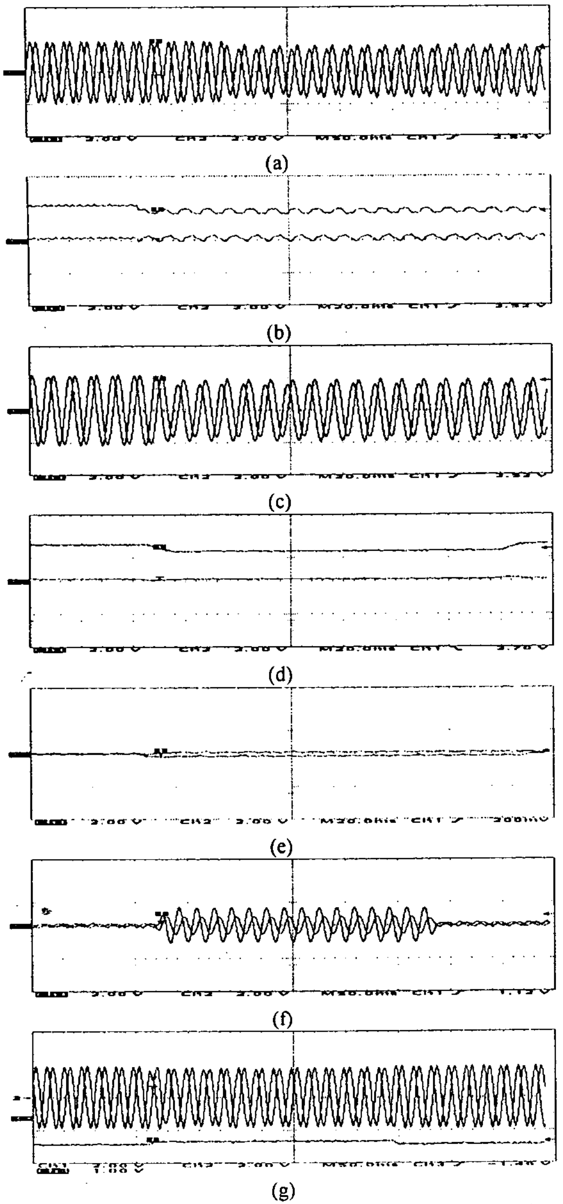


Fig. 7 Experimental results (a) source voltage (b) source voltage in positive sequence SRF (c) source voltage in negative sequence SRF (d) positive sequence detected in DC (e) negative sequence detected in DC (f) DVR injection voltage (g) compensated load voltage

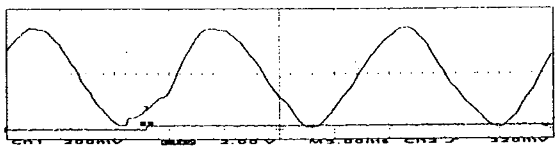


Fig. 8 Magnification of Fig. 7(g) compensated load voltage

5. EXPERIMENTAL RESULTS

Fig. 6 shows the actual hardware configuration of the 2.5kVA DVR prototype which consists of a transformer part, rectifier part, and inverter part. It is connected with the network in series and designed to minimize the leakage inductance. The rectifier part uses a three-phase transformer and energy is stored in the DC-bank through the rectifier. Table 1 shows the parameters used in this DVR system. Fig. 7 shows the experimental waveforms. Fig. 7(a) shows the load voltage dropping instantly due to system fault. Fig. 7(b) and (c) show the source voltage transformed into SRF, and are identical to simulation results. Fig. 7(d) and (e) show that positive and negative sequence component are also detected well in experimental results. Fig. 7(f) shows the actual DVR injection voltage, and Fig. 7(g) shows the load voltage compensated by the DVR. The proportional gain Kp, and integral gain Ki, are set to 2 and 0.02 respectively. The interval that the DVR begins to operate when the signal line at the bottom of Fig. 7(g) goes to high. Fig. 8 is the magnified waveform of Fig. 7(g) and shows that DVR detects the system fault within 2ms and compensates the voltage within half a cycle.

6. CONCLUSION

This paper proposes a DVR controller that compensates unbalanced source voltage caused by faults in the electric supply. The proposed differential controller compensated the fault of source voltage with fast response characteristics and improved the performance compared to a DVR system with only the conventional LPF. The validity of the proposed control method was confirmed with simulation and experimental results. Simulation was performed with Matlab, and the operation and performance of the system was verified. The experiment was performed with a 2.5kVA prototype DVR system.

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