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A novel control strategy for load converter of DC isolated distribution system under unbalanced loading conditions

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Abstract: A novel control strategy for the load converter supplying the unbalanced AC load in a DC isolated distribution system is presented. The control algorithm results in balanced and sinusoidal load voltages under unbalanced AC loading. The unbalanced load is characterized in the d-q-0 rotating coordinate based on symmetrical sequence components. Also, the mathematical model of the load converter in both a-b-c and d-q-0 coordinates is derived by using the average large signal model. Then, two control strategies for the load converter are presented. The first one uses the conventional d-q-0 controller to ensure the voltage and current regulation. The second one is a newly proposed control strategy based on the decomposition of the voltage and current into instantaneous positive, negative, and zero sequences. These three sequences are controlled independently in their own reference frames as DC signals. The performance of the load converter using these two control strategies is compared. Simulation results show the validity and capability of the newly proposed control strategy.

Key words: Unbalanced load, Power quality, Symmetrical components, Control strategy
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INTRODUCTION

Renewable energy resources are attractive options for loads supplying places where a connection to the utility network is either impossible or unduly expensive (Daniel and AmmasaiGounden, 2004). Unbalanced AC loading could occur at different current levels among phases or at the same current level but with different phase shifts, or both. The unbalanced loading results in unbalanced voltage, a poor power factor, power losses and other power quality disturbances. The aim of this paper is to supply the unbalanced AC load in a DC isolated distribution system by an autonomous DC/AC load converter. The load converter should deliver constant balanced AC voltage magnitude and frequency. In other research, the load converter controller has used a conventional d-q-0 rotating frame (Thandi *et al*., 1999), space vector modulation (Zhang, 1998), and simple *V*-*f* voltage regulator schemes (Saisho *et al*., 2002; Lu and Ooi, 2005). In a conventional d-q-0 controller, the compensation of the unbalanced voltage has used current and voltage regulation in a d-q-0 reference frame rotating at the fundamental frequency. However, the voltage and current give rise to 2ω voltage and current ripples in the d-q channels. The 0 channel is similarly affected by the disturbance at ω. As a result, the performances of the conventional d-q-0 control strategy are insufficient (Lin and Lee, 2004; Blazic and Papic, 2004; Vechiu *et al*., 2007). Existing simple *V*-*f* voltage regulator schemes cannot deal with the zero sequence component caused by unbalanced loads (Saisho *et al*., 2002; Lu and Ooi, 2005). The space vector modulation schemes are implemented in a 2D space, and are therefore unable to deal with the zero sequence component caused by an unbalanced load. However, the developed d-q-0 rotating frame based on symmetrical components has been proposed. This controller is based on the decomposition of the voltage and current into instantaneous positive, negative, and zero sequence components using phasor representation. These three sequences are controlled independently in their own reference frames as DC signals. The positive sequence, which rotates counterclockwise, is regulated by the proportional integral (PI) controllers in a positive reference frame. The negative sequence, which rotates clockwise at the same angular frequency, is regulated by the PI controllers in a negative reference frame. Also, the zero sequence is regulated by the PI controller in a zero reference frame.

In this paper, the unbalanced load is characterized in the d-q-0 rotating coordinate. The large-signal models of the three-leg DC/AC converter are presented in both a-b-c stationary and d-q-0 rotating coordinates. The conventional d-q-0 controller and developed d-q-0 controller based on symmetrical sequence components have been applied to the reference voltages generation of the load converter. The theoretical formulation of these controllers has been analyzed and developed. It has been shown that the load converter can handle the unbalanced load.

SYSTEM DESCRIPTION

Fig.1 shows the diagram of a DC isolated distribution system with unbalanced AC load. This could be the model for a small off-grid distribution system. In Fig.1, the unbalanced AC load is connected to the DC bus via a three-phase, three-leg DC/AC load converter with neutral clamped DC capacitors. This topology is characterized by the connection of the neutral point of the load to the midpoint of this DC/AC converter. As a result, the phase voltage can be controlled independently. The battery may be sized to cover the load consumed power for different operating conditions, while the DC/DC converter provides the power balancing in a DC bus. The DC voltage regulator of the DC/DC converter can adjust the DC bus voltage, V_{dc}, in the acceptable voltage range. The renewable energy units can inject DC power to the DC bus.

UNBALANCED LOAD IN d-q-0 COORDINATE

An unbalanced load could produce negative and zero sequence currents. In Fig.1, the unbalanced AC load has been supplied by balanced sinusoidal voltages:

$$\begin{bmatrix} v_{\mathrm{la}} \\ v_{\mathrm{lb}} \\ v_{\mathrm{lc}} \end{bmatrix} = \begin{bmatrix} V_{\mathrm{m}}\sin(\omega t) \\ V_{\mathrm{m}}\sin(\omega t - 120°) \\ V_{\mathrm{m}}\sin(\omega t + 120°) \end{bmatrix}, \tag{1}$$

where v_{la}, v_{lb} and v_{lc} are the load phase voltages, V_{m} is the peak value of load voltages, and ω is the fundamental angular frequency. If the load is linear and unbalanced (i.e., $R_{\mathrm{la}} \neq R_{\mathrm{lb}} \neq R_{\mathrm{lc}}$ and/or $X_{\mathrm{la}} \neq X_{\mathrm{lb}} \neq X_{\mathrm{lc}}$), the amplitudes and phase shifts are different in each phase current and the neutral current will flow between the neutral of the load side and that of the source side. The three-phase currents are expressed by the following equation:

$$\begin{bmatrix} i_{\mathrm{la}} \\ i_{\mathrm{lb}} \\ i_{\mathrm{lc}} \end{bmatrix} = \begin{bmatrix} I_{\mathrm{am}}\sin(\omega t - \theta_{\mathrm{a}}) \\ I_{\mathrm{bm}}\sin(\omega t - 120^{\circ} - \theta_{\mathrm{b}}) \\ I_{\mathrm{cm}}\sin(\omega t + 120^{\circ} - \theta_{\mathrm{c}}) \end{bmatrix}. \tag{2}$$

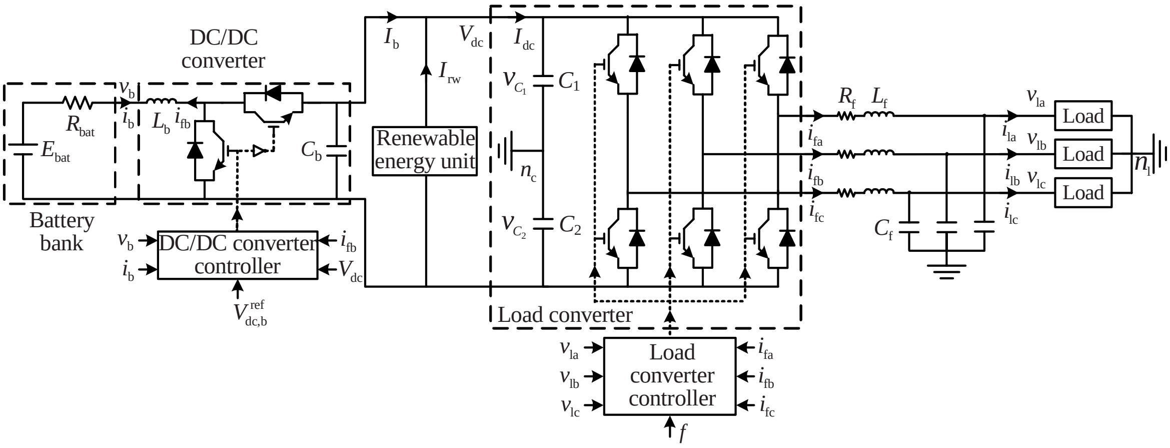


Fig.1 Diagram of the DC isolated distribution system with unbalanced AC load

Using phasor representation, a three-phase unbalanced load current can be expressed by symmetrical components of the positive sequence ($i_{\mathrm{la,p}}$, $i_{\mathrm{lb,p}}$ and $i_{\mathrm{lc,p}}$), negative sequence ($i_{\mathrm{la,n}}$, $i_{\mathrm{lb,n}}$ and $i_{\mathrm{lc,n}}$), and zero sequence ($i_{\mathrm{la,0}}$, $i_{\mathrm{lb,0}}$ and $i_{\mathrm{lc,0}}$), as follows:

$$\begin{bmatrix} i_{\mathrm{la}} \\ i_{\mathrm{lb}} \\ i_{\mathrm{lc}} \end{bmatrix} = \begin{bmatrix} i_{\mathrm{la,p}} + i_{\mathrm{la,n}} + i_{\mathrm{la,0}} \\ i_{\mathrm{lb,p}} + i_{\mathrm{lb,n}} + i_{\mathrm{lb,0}} \\ i_{\mathrm{lc,p}} + i_{\mathrm{lc,n}} + i_{\mathrm{lc,0}} \end{bmatrix}. \tag{3}$$

The load currents can be transformed into the d-q-0 synchronous reference frame, as follows:

$$\begin{bmatrix} i_{\mathrm{ld}} \\ i_{\mathrm{lq}} \\ i_{\mathrm{l0}} \end{bmatrix} = \begin{bmatrix} i_{\mathrm{ld,p}} + i_{\mathrm{ld,n}} + i_{\mathrm{ld,0}} \\ i_{\mathrm{lq,p}} + i_{\mathrm{lq,n}} + i_{\mathrm{lq,0}} \\ i_{\mathrm{l0,p}} + i_{\mathrm{l0,n}} + i_{\mathrm{l0,0}} \end{bmatrix}. \tag{4}$$

In the d-q-0 rotating frame, the load current components in the d-q channels (i_{ld}, i_{lq}) are given rise to 2ω current ripples. The zero component (i_{l0}) appears as a disturbance at ω (Blazic and Papic, 2004; Lin and Lee, 2004; Vechiu *et al*., 2007). The load current decomposed into symmetrical sequence components, the fundamental positive sequence components ($i_{\mathrm{la,p}}$, $i_{\mathrm{lb,p}}$ and $i_{\mathrm{lc,p}}$) rotate counterclockwise with angular frequency, ω. Using this transformation, the positive sequence d-q currents ($i_{\mathrm{ld,p}}$, $i_{\mathrm{lq,p}}$) appear as DC quantities (with ω=0). The negative sequence components ($i_{\mathrm{la,n}}$, $i_{\mathrm{lb,n}}$ and $i_{\mathrm{lc,n}}$) rotate clockwise. Using this transformation, the negative sequence d-q currents ($i_{\mathrm{ld,n}}$, $i_{\mathrm{lq,n}}$) appear as a ripple with the angular frequency of 2ω. The zero sequence current appears as a disturbance on the 0 axes at ω, while the d and q components do not exist. However, the positive, negative, and zero sequences appear as DC signals in their own synchronously rotating reference frames.

LOAD CONVERTER UNDER UNBALANCED LOADING CONDITIONS

The load converter has insulated gate bipolar transistor (IGBT) switches and has been controlled by a pulse-width modulation (PWM) voltage controller. If we assume that the switching frequency is much higher than the fundamental frequency of the AC signals, all voltage and current ripples are negligible and the averaging technique can be used to model the load converter, as shown in Fig.2. The average large signal modeling provides the most efficient way to study the system stability, subsystem interactions and controller's performance in the load converter (Vechiu *et al*., 2007). The load converter voltages and currents in the circuit model can be expressed by

$$\begin{aligned}\begin{bmatrix} v_{\mathrm{fa}} \\ v_{\mathrm{fb}} \\ v_{\mathrm{fc}} \end{bmatrix} &= \begin{bmatrix} v_{\mathrm{la}} \\ v_{\mathrm{lb}} \\ v_{\mathrm{lc}} \end{bmatrix} + \begin{bmatrix} R_{\mathrm{f}} & 0 & 0 \\ 0 & R_{\mathrm{f}} & 0 \\ 0 & 0 & R_{\mathrm{f}} \end{bmatrix} \begin{bmatrix} i_{\mathrm{fa}} \\ i_{\mathrm{fb}} \\ i_{\mathrm{fc}} \end{bmatrix} \\ &+ \begin{bmatrix} L_{\mathrm{f}} & 0 & 0 \\ 0 & L_{\mathrm{f}} & 0 \\ 0 & 0 & L_{\mathrm{f}} \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_{\mathrm{fa}} \\ i_{\mathrm{fb}} \\ i_{\mathrm{fc}} \end{bmatrix},\end{aligned} \tag{5}$$

where v_{fa}, v_{fb} and v_{fc} are line-to-neutral three-phase output voltages for the load converter. i_{fa}, i_{fb} and i_{fc} are three-phase output currents for the load converter. v_{la}, v_{lb} and v_{lc} are line-to-neutral three-phase voltages for the AC loads. The voltages equation can be presented in the d-q-0 reference frame, as follows:

$$\begin{aligned}\begin{bmatrix} v_{\mathrm{fd}} \\ v_{\mathrm{fq}} \\ v_{\mathrm{f0}} \end{bmatrix} &= \begin{bmatrix} v_{\mathrm{ld}} \\ v_{\mathrm{lq}} \\ v_{\mathrm{l0}} \end{bmatrix} + \begin{bmatrix} R_{\mathrm{f}} & 0 & 0 \\ 0 & R_{\mathrm{f}} & 0 \\ 0 & 0 & R_{\mathrm{f}} \end{bmatrix} \begin{bmatrix} i_{\mathrm{fd}} \\ i_{\mathrm{fq}} \\ i_{\mathrm{f0}} \end{bmatrix} \\ &+ \begin{bmatrix} L_{\mathrm{f}} & 0 & 0 \\ 0 & L_{\mathrm{f}} & 0 \\ 0 & 0 & L_{\mathrm{f}} \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_{\mathrm{fd}} \\ i_{\mathrm{fq}} \\ i_{\mathrm{f0}} \end{bmatrix} + \begin{bmatrix} 0 & -\omega L_{\mathrm{f}} & 0 \\ \omega L_{\mathrm{f}} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{\mathrm{fd}} \\ i_{\mathrm{fq}} \\ i_{\mathrm{f0}} \end{bmatrix}.\end{aligned} \tag{6}$$

As can be seen in Eq.(6), the d and q channels are coupled by $\omega L_{\mathrm{f}} i_{\mathrm{q}}$ and $\omega L_{\mathrm{f}} i_{\mathrm{d}}$ terms, respectively. But the 0 channel is completely decoupled from the d and q channels.

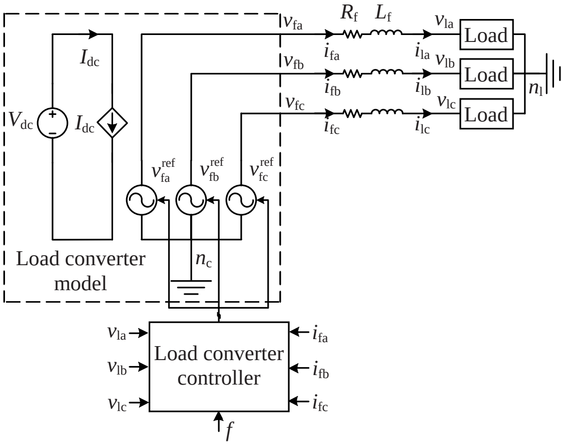


Fig.2 Average large signal model of the load converter

CONVENTIONAL CONTROL STRATEGY

The circuit configuration and conventional control scheme based on d-q-0 coordinate for the load converter has been depicted in Fig.3. The load converter can be controlled by the *V-f* control strategy, which regulates the voltage and the frequency of the AC load.

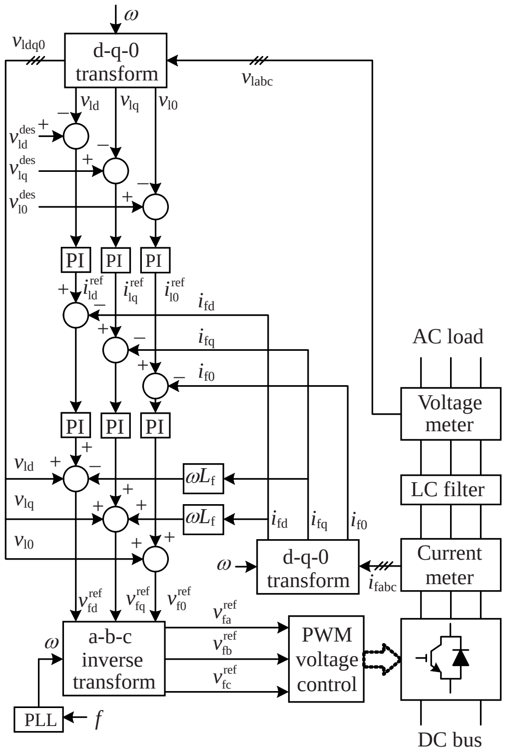


Fig.3 Control strategy of the load converter based on the d-q-0 controller

It is clear that:

(1) The frequency ω can be obtained by phase lock loop (PLL) using a desirable frequency (e.g., 50 Hz);

(2) The load phase voltages (v_{la}, v_{lb} and v_{lc}) can be detected and transformed to the d-q-0 synchronously rotating reference frame by

$$\begin{bmatrix} v_{\mathrm{ld}} \\ v_{\mathrm{lq}} \\ v_{\mathrm{l0}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{dq0}} \begin{bmatrix} v_{\mathrm{la}} \\ v_{\mathrm{lb}} \\ v_{\mathrm{lc}} \end{bmatrix}, \tag{7}$$

where the coordinate transformation matrix, $\boldsymbol{T}_{\mathrm{dq0}}$, is expressed by

$$\boldsymbol{T}_{\mathrm{dq0}} = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos(\omega t-120°) & \cos(\omega t+120°) \\ -\sin(\omega t) & -\sin(\omega t-120°) & -\sin(\omega t+120°) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}.$$

It is obvious that the load phase voltage should be adjusted to the balanced and sinusoidal voltage with constant amplitude and frequency. Therefore, the desired load voltage in the d-q-0 reference frame has only the following values:

$$\begin{bmatrix} v_{\mathrm{ld}}^{\mathrm{des}} \\ v_{\mathrm{lq}}^{\mathrm{des}} \\ v_{\mathrm{l0}}^{\mathrm{des}} \end{bmatrix} = \begin{bmatrix} 0 \\ 0.4\sqrt{2/3} \\ 0 \end{bmatrix}. \tag{8}$$

The reference load currents in the d-q-0 coordinate are

$$\begin{bmatrix} i_{\mathrm{ld}}^{\mathrm{ref}} \\ i_{\mathrm{lq}}^{\mathrm{ref}} \\ i_{\mathrm{l0}}^{\mathrm{ref}} \end{bmatrix} = \begin{bmatrix} \mathrm{PI}(v_{\mathrm{ld}} - v_{\mathrm{ld}}^{\mathrm{des}}) \\ \mathrm{PI}(v_{\mathrm{lq}} - v_{\mathrm{lq}}^{\mathrm{des}}) \\ \mathrm{PI}(v_{\mathrm{l0}} - v_{\mathrm{l0}}^{\mathrm{des}}) \end{bmatrix}. \tag{9}$$

The output voltage of the converter has been compared with a reference value and the error signal is applied to a proportional integrator (PI) controller.

In Fig.3, the reference load currents are compared with the measured output load converter current, in the d-q-0 coordinate (i_{fd}, i_{fq} and i_{f0}).

$$\begin{bmatrix} i_{\mathrm{fd}} \\ i_{\mathrm{fq}} \\ i_{\mathrm{f0}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{dq0}} \begin{bmatrix} i_{\mathrm{fa}} \\ i_{\mathrm{fb}} \\ i_{\mathrm{fc}} \end{bmatrix}. \tag{10}$$

The output signals of the PI controller can be expressed by

$$\begin{bmatrix} v_{\mathrm{fd}}^{\mathrm{ref}} \\ v_{\mathrm{fq}}^{\mathrm{ref}} \\ v_{\mathrm{f0}}^{\mathrm{ref}} \end{bmatrix} = \begin{bmatrix} v_{\mathrm{ld}} \\ v_{\mathrm{lq}} \\ v_{\mathrm{l0}} \end{bmatrix} + \begin{bmatrix} \mathrm{PI}(i_{\mathrm{ld}}^{\mathrm{ref}} - i_{\mathrm{fd}}) \\ \mathrm{PI}(i_{\mathrm{lq}}^{\mathrm{ref}} - i_{\mathrm{fq}}) \\ \mathrm{PI}(i_{\mathrm{l0}}^{\mathrm{ref}} - i_{\mathrm{f0}}) \end{bmatrix} + \begin{bmatrix} -\omega L_{\mathrm{f}} i_{\mathrm{fq}} \\ \omega L_{\mathrm{f}} i_{\mathrm{fd}} \\ 0 \end{bmatrix}. \tag{11}$$

The reference output voltages for the load converter are transformed to the a-b-c coordinate by using an inverse synchronously rotating reference frame, i.e.,

$$\begin{bmatrix} v_{\mathrm{fa}}^{\mathrm{ref}} \\ v_{\mathrm{fb}}^{\mathrm{ref}} \\ v_{\mathrm{fc}}^{\mathrm{ref}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{abc}} \begin{bmatrix} v_{\mathrm{fd}}^{\mathrm{ref}} \\ v_{\mathrm{fq}}^{\mathrm{ref}} \\ v_{\mathrm{f0}}^{\mathrm{ref}} \end{bmatrix}, \tag{12}$$

where

$$\boldsymbol{T}_{\text{abc}}=\begin{bmatrix}\cos(\omega t) & -\sin(\omega t) & 1\\ \cos(\omega t-120°) & -\sin(\omega t-120°) & 1\\ \cos(\omega t+120°) & -\sin(\omega t+120°) & 1\end{bmatrix}.$$

Then, the available voltages in the a-b-c coordinate are compared with the triangular wave provided by the PWM voltage control module. Therefore, the output provides a suitable switching pattern for the load converter.

PROPOSED CONTROL STRATEGY

The objective of the proposed control strategy for the load converter is to provide high power quality, reliability, and efficiency. Fig.4 shows the proposed control strategy based on the transformation of the currents and voltages into the symmetrical components, i.e., positive, negative, and zero sequences. The transformation of the a-b-c signals into the symmetrical components using phasor representation can be expressed by

$$\begin{cases}\begin{bmatrix}g_{\text{a,p}}\\ g_{\text{b,p}}\\ g_{\text{c,p}}\end{bmatrix}=\dfrac{1}{3}\begin{bmatrix}1 & \boldsymbol{a} & \boldsymbol{a}^2\\ \boldsymbol{a}^2 & 1 & \boldsymbol{a}\\ \boldsymbol{a} & \boldsymbol{a}^2 & 1\end{bmatrix}\begin{bmatrix}g_{\text{a}}\\ g_{\text{b}}\\ g_{\text{c}}\end{bmatrix},\\ \begin{bmatrix}g_{\text{a,n}}\\ g_{\text{b,n}}\\ g_{\text{c,n}}\end{bmatrix}=\dfrac{1}{3}\begin{bmatrix}1 & \boldsymbol{a}^2 & \boldsymbol{a}\\ \boldsymbol{a} & 1 & \boldsymbol{a}^2\\ \boldsymbol{a}^2 & \boldsymbol{a} & 1\end{bmatrix}\begin{bmatrix}g_{\text{a}}\\ g_{\text{b}}\\ g_{\text{c}}\end{bmatrix},\\ \begin{bmatrix}g_{\text{a,0}}\\ g_{\text{b,0}}\\ g_{\text{c,0}}\end{bmatrix}=\dfrac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix}\begin{bmatrix}g_{\text{a}}\\ g_{\text{b}}\\ g_{\text{c}}\end{bmatrix},\end{cases}\tag{13}$$

where $\boldsymbol{a}$=exp(j2π/3) and g can be the load voltages or currents. The positive and negative sequences can be determined as shown in Fig.5. The vector operator $\boldsymbol{a}$ can be presented in the control circuit using a 2π/3 phase lead filter (Kouji *et al*., 2004). In order to determine the parameter of the phase lead filter, the following equation must be solved:

$$\arg\left(-\frac{1-\text{j}100\pi T}{1+\text{j}100\pi T}\right)=\frac{2\pi}{3}.\tag{14}$$

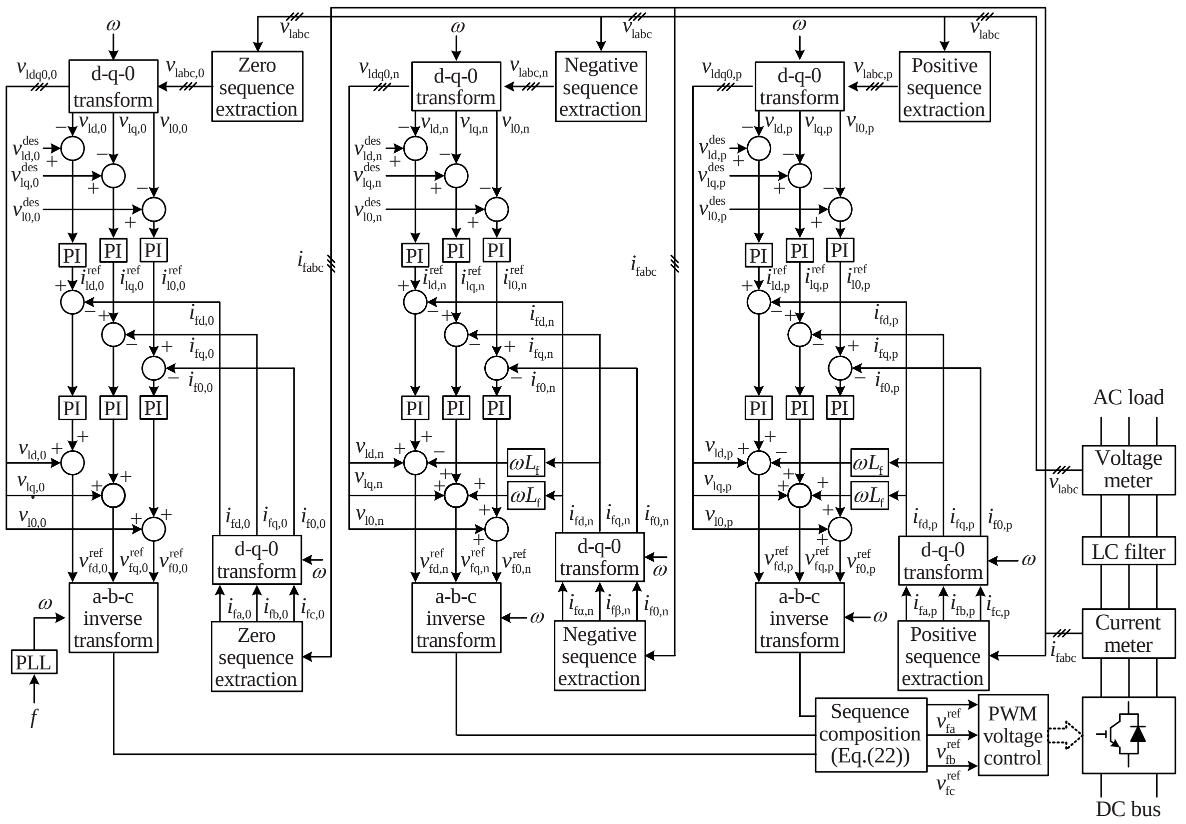


Fig.4 Control strategy of the load converter based on symmetrical components

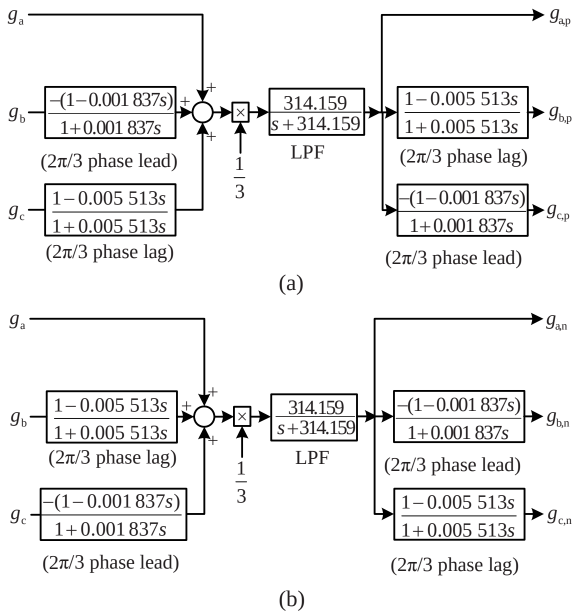


Fig.5 (a) Positive sequence determination; (b) Negative sequence determination

The result is T=0.001 837. The 2π/3 phase lead filter in Fig.5 can fulfill the role of the vector operator $\boldsymbol{a}$. The vector operator $\boldsymbol{a}^2$ can be modeled in the control circuit using a −2π/3 phase lag filter, using the following equation (Kouji *et al.*, 2004):

$$\arg\left(\frac{1-\mathrm{j}100\pi T}{1+\mathrm{j}100\pi T}\right)=-\frac{2\pi}{3}. \tag{15}$$

As a result, T=0.005 513. As shown in Fig.5, Eq.(13) can be obtained for the positive and negative phase components.

In Fig.4, the load phase voltages (v_{la}, v_{lb} and v_{lc}) can be detected and transformed to the d-q-0 synchronously rotating reference frame using the following equations:

$$\begin{bmatrix} v_{ld,p} \\ v_{lq,p} \\ v_{l0,p} \end{bmatrix}=\boldsymbol{T}_{dq0}\begin{bmatrix} v_{la,p} \\ v_{lb,p} \\ v_{lc,p} \end{bmatrix}, \quad \begin{bmatrix} v_{ld,n} \\ v_{lq,n} \\ v_{l0,n} \end{bmatrix}=\boldsymbol{T}_{dq0}\begin{bmatrix} v_{la,n} \\ v_{lb,n} \\ v_{lc,n} \end{bmatrix},$$
$$\begin{bmatrix} v_{ld,0} \\ v_{lq,0} \\ v_{l0,0} \end{bmatrix}=\boldsymbol{T}_{dq0}\begin{bmatrix} v_{la,0} \\ v_{lb,0} \\ v_{lc,0} \end{bmatrix}. \tag{16}$$

The positive sequence voltage, $v_{lq,p}^{des}$, is compared with the desired output voltage amplitude, and the error is processed in a PI controller. All the remaining sequence voltages are set to zero values using the same procedure. The desired load voltage in the d-q-0 reference frame based on symmetrical components has only the following values:

$$\begin{bmatrix} v_{ld,p}^{des} \\ v_{lq,p}^{des} \\ v_{l0,p}^{des} \end{bmatrix}=\begin{bmatrix} 0 \\ 0.4\sqrt{2/3} \\ 0 \end{bmatrix}, \quad \begin{bmatrix} v_{ld,n}^{des} \\ v_{lq,n}^{des} \\ v_{l0,n}^{des} \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad \begin{bmatrix} v_{ld,p}^{des} \\ v_{lq,p}^{des} \\ v_{l0,p}^{des} \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \tag{17}$$

The load converter controller based on the d-q-0 rotating reference frame consists of an inner current loop and an outer voltage loop in a three-channel arrangement.

The current and voltage loops should include independent PI controllers for the d, q and 0 channels to eliminate the current and voltage steady state errors independently. The reference load currents in the d-q-0 coordinate are

$$\begin{cases} \begin{bmatrix} i_{ld,p}^{ref} \\ i_{lq,p}^{ref} \\ i_{l0,p}^{ref} \end{bmatrix}=\begin{bmatrix} \mathrm{PI}(v_{ld,p}-v_{ld,p}^{des}) \\ \mathrm{PI}(v_{lq,p}-v_{lq,p}^{des}) \\ \mathrm{PI}(v_{l0,p}-v_{l0,p}^{des}) \end{bmatrix}, \\ \begin{bmatrix} i_{ld,n}^{ref} \\ i_{lq,n}^{ref} \\ i_{l0,n}^{ref} \end{bmatrix}=\begin{bmatrix} \mathrm{PI}(v_{ld,n}-v_{ld,n}^{exp}) \\ \mathrm{PI}(v_{lq,n}-v_{lq,n}^{exp}) \\ \mathrm{PI}(v_{l0,n}-v_{l0,n}^{exp}) \end{bmatrix}, \\ \begin{bmatrix} i_{ld,0}^{ref} \\ i_{lq,0}^{ref} \\ i_{l0,0}^{ref} \end{bmatrix}=\begin{bmatrix} \mathrm{PI}(v_{ld,0}-v_{ld,0}^{exp}) \\ \mathrm{PI}(v_{lq,0}-v_{lq,0}^{exp}) \\ \mathrm{PI}(v_{l0,0}-v_{l0,0}^{exp}) \end{bmatrix}. \end{cases} \tag{18}$$

The PI controller (K_p+1/($T_i s$)) for the voltage controller can be designed using the classic Bode-plot and root-locus method. In this study the parameters of PI controllers of the voltage controller are K_p=25 and T_i=0.01. As shown in Fig.4, the reference load currents are compared with the measured output load converter currents in the d-q-0 reference frame by the symmetrical components, i.e., positive sequence ($i_{fd,p}$, $i_{fq,p}$ and $i_{f0,p}$), negative sequence ($i_{fd,n}$, $i_{fq,n}$ and $i_{f0,n}$) and zero sequence ($i_{fd,0}$, $i_{fq,0}$ and $i_{f0,0}$):

$$\begin{bmatrix} i_{\mathrm{fd,p}} \\ i_{\mathrm{fq,p}} \\ i_{\mathrm{f0,p}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{dq0}} \begin{bmatrix} i_{\mathrm{fa,p}} \\ i_{\mathrm{fb,p}} \\ i_{\mathrm{fc,p}} \end{bmatrix}, \quad \begin{bmatrix} i_{\mathrm{fd,n}} \\ i_{\mathrm{fq,n}} \\ i_{\mathrm{f0,n}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{dq0}} \begin{bmatrix} i_{\mathrm{fa,n}} \\ i_{\mathrm{fb,n}} \\ i_{\mathrm{fc,n}} \end{bmatrix},$$
$$\begin{bmatrix} i_{\mathrm{fd,0}} \\ i_{\mathrm{fq,0}} \\ i_{\mathrm{f0,0}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{dq0}} \begin{bmatrix} i_{\mathrm{fa,0}} \\ i_{\mathrm{fb,0}} \\ i_{\mathrm{fc,0}} \end{bmatrix}. \tag{19}$$

Then the output signals of the PI controller can be expressed by

$$\begin{cases} \begin{bmatrix} v_{\mathrm{fd,p}}^{\mathrm{ref}} \\ v_{\mathrm{fq,p}}^{\mathrm{ref}} \\ v_{\mathrm{f0,p}}^{\mathrm{ref}} \end{bmatrix} = \begin{bmatrix} v_{\mathrm{ld,p}} \\ v_{\mathrm{lq,p}} \\ v_{\mathrm{l0,p}} \end{bmatrix} + \begin{bmatrix} \mathrm{PI}(i_{\mathrm{ld,p}}^{\mathrm{ref}} - i_{\mathrm{fd,p}}) \\ \mathrm{PI}(i_{\mathrm{lq,p}}^{\mathrm{ref}} - i_{\mathrm{fq,p}}) \\ \mathrm{PI}(i_{\mathrm{l0,p}}^{\mathrm{ref}} - i_{\mathrm{f0,p}}) \end{bmatrix} + \begin{bmatrix} -\omega L_f i_{\mathrm{fq,p}} \\ \omega L_{\mathrm{f}} i_{\mathrm{fd,p}} \\ 0 \end{bmatrix}, \\ \begin{bmatrix} v_{\mathrm{fd,n}}^{\mathrm{ref}} \\ v_{\mathrm{fq,n}}^{\mathrm{ref}} \\ v_{\mathrm{f0,n}}^{\mathrm{ref}} \end{bmatrix} = \begin{bmatrix} v_{\mathrm{ld,n}} \\ v_{\mathrm{lq,n}} \\ v_{\mathrm{l0,n}} \end{bmatrix} + \begin{bmatrix} \mathrm{PI}(i_{\mathrm{ld,n}}^{\mathrm{ref}} - i_{\mathrm{fd,n}}) \\ \mathrm{PI}(i_{\mathrm{lq,n}}^{\mathrm{ref}} - i_{\mathrm{fq,n}}) \\ \mathrm{PI}(i_{\mathrm{l0,n}}^{\mathrm{ref}} - i_{\mathrm{f0,n}}) \end{bmatrix} + \begin{bmatrix} -\omega L_{\mathrm{f}} i_{\mathrm{fq,n}} \\ \omega L_{\mathrm{f}} i_{\mathrm{fd,n}} \\ 0 \end{bmatrix}, \\ \begin{bmatrix} v_{\mathrm{fd,0}}^{\mathrm{ref}} \\ v_{\mathrm{fq,0}}^{\mathrm{ref}} \\ v_{\mathrm{f0,0}}^{\mathrm{ref}} \end{bmatrix} = \begin{bmatrix} v_{\mathrm{ld,0}} \\ v_{\mathrm{lq,0}} \\ v_{\mathrm{l0,0}} \end{bmatrix} + \begin{bmatrix} \mathrm{PI}(i_{\mathrm{ld,0}}^{\mathrm{ref}} - i_{\mathrm{fd,0}}) \\ \mathrm{PI}(i_{\mathrm{lq,0}}^{\mathrm{ref}} - i_{\mathrm{fq,0}}) \\ \mathrm{PI}(i_{\mathrm{l0,0}}^{\mathrm{ref}} - i_{\mathrm{f0,0}}) \end{bmatrix}. \end{cases} \tag{20}$$

In this study the parameters of PI controllers for the current controller are K_{p}=12 and T_{i}=0.01. The output signals of the PI controller, the reference output voltages of the load converter in the symmetrical sequence—positive sequence ($v_{\mathrm{fd,p}}^{\mathrm{ref}}$, $v_{\mathrm{fq,p}}^{\mathrm{ref}}$ and $v_{\mathrm{f0,p}}^{\mathrm{ref}}$), negative sequence ($v_{\mathrm{fd,n}}^{\mathrm{ref}}$, $v_{\mathrm{fq,n}}^{\mathrm{ref}}$ and $v_{\mathrm{f0,n}}^{\mathrm{ref}}$) and zero sequence ($v_{\mathrm{fd,0}}^{\mathrm{ref}}$, $v_{\mathrm{fq,0}}^{\mathrm{ref}}$ and $v_{\mathrm{f0,0}}^{\mathrm{ref}}$)—are transformed to the a-b-c coordinate by using the inverse synchronously rotating frame:

$$\begin{bmatrix} v_{\mathrm{fa,p}}^{\mathrm{ref}} \\ v_{\mathrm{fb,p}}^{\mathrm{ref}} \\ v_{\mathrm{fc,p}}^{\mathrm{ref}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{abc}} \begin{bmatrix} v_{\mathrm{fd,p}}^{\mathrm{ref}} \\ v_{\mathrm{fq,p}}^{\mathrm{ref}} \\ v_{\mathrm{f0,p}}^{\mathrm{ref}} \end{bmatrix}, \quad \begin{bmatrix} v_{\mathrm{fa,n}}^{\mathrm{ref}} \\ v_{\mathrm{fb,n}}^{\mathrm{ref}} \\ v_{\mathrm{fc,n}}^{\mathrm{ref}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{abc}} \begin{bmatrix} v_{\mathrm{fd,n}}^{\mathrm{ref}} \\ v_{\mathrm{fq,n}}^{\mathrm{ref}} \\ v_{\mathrm{f0,n}}^{\mathrm{ref}} \end{bmatrix},$$
$$\begin{bmatrix} v_{\mathrm{fa,0}}^{\mathrm{ref}} \\ v_{\mathrm{fb,0}}^{\mathrm{ref}} \\ v_{\mathrm{fc,0}}^{\mathrm{ref}} \end{bmatrix} = \boldsymbol{T}_{\mathrm{abc}} \begin{bmatrix} v_{\mathrm{fd,0}}^{\mathrm{ref}} \\ v_{\mathrm{fq,0}}^{\mathrm{ref}} \\ v_{\mathrm{f0,0}}^{\mathrm{ref}} \end{bmatrix}. \tag{21}$$

The reference voltages that should be applied to the load converter are obtained with the addition of the symmetrical components (Fig.4):

$$\begin{bmatrix} v_{\mathrm{fa}}^{\mathrm{ref}} \\ v_{\mathrm{fb}}^{\mathrm{ref}} \\ v_{\mathrm{fc}}^{\mathrm{ref}} \end{bmatrix} = \begin{bmatrix} v_{\mathrm{fa,p}}^{\mathrm{ref}} \\ v_{\mathrm{fb,p}}^{\mathrm{ref}} \\ v_{\mathrm{fc,p}}^{\mathrm{ref}} \end{bmatrix} + \begin{bmatrix} v_{\mathrm{fa,n}}^{\mathrm{ref}} \\ v_{\mathrm{fb,n}}^{\mathrm{ref}} \\ v_{\mathrm{fc,n}}^{\mathrm{ref}} \end{bmatrix} + \begin{bmatrix} v_{\mathrm{fa,0}}^{\mathrm{ref}} \\ v_{\mathrm{fb,0}}^{\mathrm{ref}} \\ v_{\mathrm{fc,0}}^{\mathrm{ref}} \end{bmatrix}. \tag{22}$$

Then, the available voltages in the a-b-c coordinate are compared with the triangular wave provided by the PWM voltage control module. Therefore, the output provides a suitable switching pattern for the load converter.

The nonlinear loads have different harmonic contents and different phase sequences. For example, the fundamental 7th and 13th harmonics are positive-sequence components, the 5th and 11th harmonics are negative-sequence components and the 3rd and 9th are zero-sequence components.

In the d-q-0 rotating frame, odd non-triplen harmonic components become even harmonic components in the d and q channels and they are equal to zero in the 0 channel.

All triplen harmonic components will be preserved in the 0 channel. As a result, each individual harmonic current of nonlinear loads can be decomposed into symmetrical components. Therefore, the proposed control strategy can also provide the balanced sinusoidal voltages for nonlinear loads.

SIMULATION RESULTS

The system shown in Fig.1 has been modeled and simulated by PSCAD/EMTDC software to analyze and compare the performance of the load converter with the two control strategies. The simulation results show that the load converter can supply an unbalanced and nonlinear AC load by balanced sinusoidal voltages. In this simulation, the DC distribution supplied the unbalanced resistive-inductive load by star connection. The system parameters chosen for the simulation shown in Fig.1 are listed in Table 1, which was loaded with 50 kW. The renewable energy units generated 55 kW. The batteries bank, which ensures the power balance of the system, had a rated capacity of 285 A·h.

Table 1 Simulation parameters

Parameter	Value
Rated output load voltage, $V_{\rm la}$ (V)	230
Rated output frequency, f (Hz)	50
Rated DC bus voltage, $V_{\rm dc}$ (V)	750
Filter component	
$L_{\rm f}$ (mH)	3
$R_{\rm f}$ (Ω)	0.1
AC loads (Ω)	
Phase a	1.75+j0.432
Phase b	3.25+j0.812
Phase c	7.5+j3.91

Fig.6a shows the unbalanced load phase currents. As shown in Fig.6a, the load in phase a is disconnected at t=1 s. It is found that the load phase currents are not sinusoidal. Fig.6b shows the simulation results in the case of a load converter with conventional d-q-0 controllers. In Fig.6b, it can be seen that the balanced voltages are not provided for the AC load while the load phase currents are not sinusoidal.

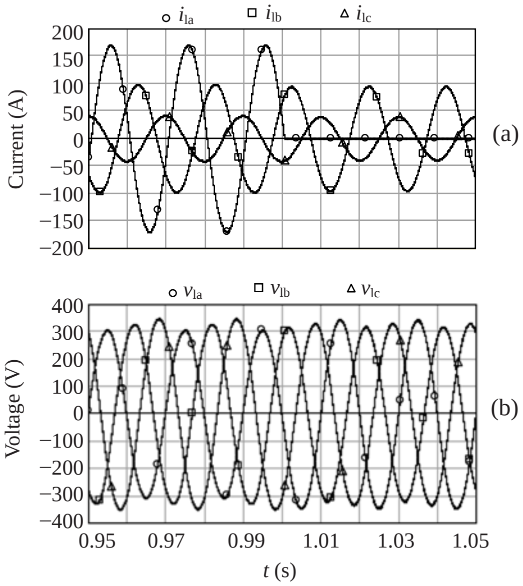


Fig.6 Unbalanced load currents (a) and unbalanced load phase voltages (b) in the case of a load converter with conventional d-q-0 controllers

Fig.7 shows the load phase voltages in the d-q-0 reference frame. As shown in this figure, the reference voltages generated by the d-q-0 controller and the generated voltage by load converters are not matching together, the $v_{\rm ld}$, $v_{\rm lq}$ and $v_{\rm l0}$ have a large ripple. In this case, the negative sequence unbalance is about 10%. It must be noted that the standards accept imbalances lower than 2% (Short, 2004).

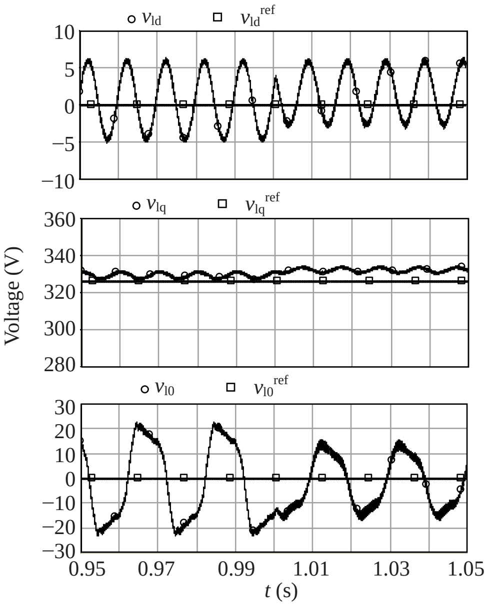


Fig.7 Load voltages in the d-q-0 controller for the load converter with conventional d-q-0 controllers

Figs.8 and 9 show the simulation results for the load converter with the proposed control strategy. As shown in Fig.8a, the load in phase a is disconnected at t=1 s. The balanced voltages are provided for the unbalanced AC load while the load phase currents are not sinusoidal. The load voltages in the developed symmetrical sequence components in the d-q-0 reference frame have been shown in Figs.9a~9c. In this case, the negative sequence imbalance is lower than 1% (Short, 2004).

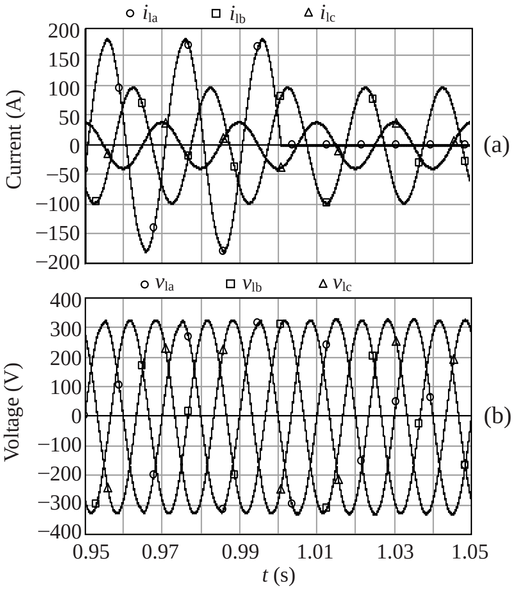


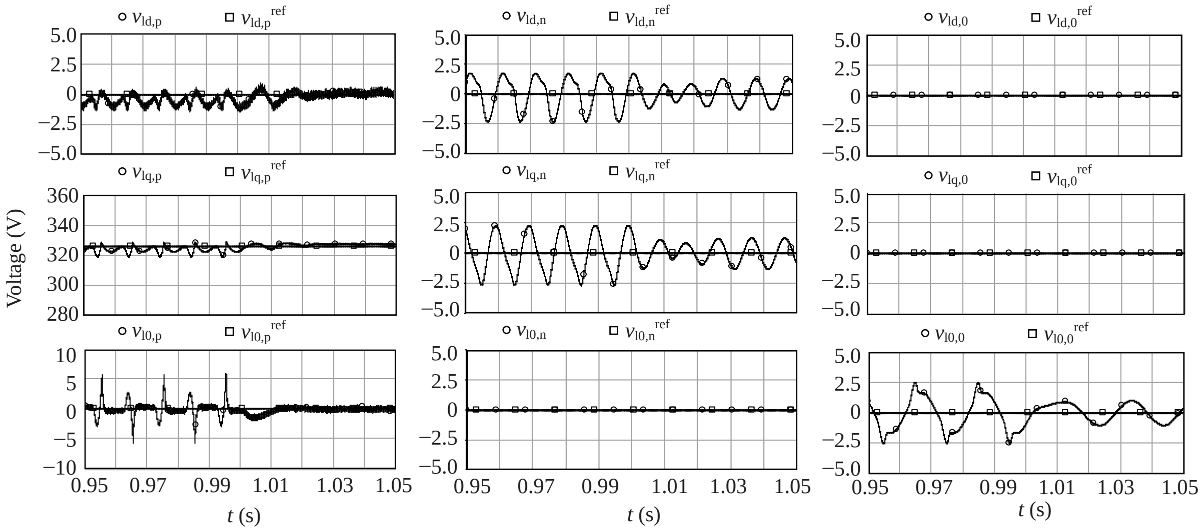
Fig.8 Unbalanced load currents (a) and balanced load phase voltages (b) for the load converter with the proposed control strategy

The aim of the developed symmetrical sequence controllers is to control the positive, negative, and zero sequences separately. In Figs.9a~9c, all voltage signals are constant DC values.

Also, the reference voltages generated by the proposed controller and the generated voltage by the load converter are matching together. It is obvious that the load phase voltages are balanced and sinusoidal with constant amplitude and frequency.

Fig.10a shows the nonlinear load phase currents. The total harmonic distortion (THD) of this current is 33.11%. The output voltage THD is lower than 1%, which satisfies the design target. Therefore, the designed control and voltage loops can present a good performance for nonlinear loads.

Fig.11 shows the instantaneous active and reactive powers of the unbalanced AC loads. In this case the inductance parameter of the unbalanced AC load, presented in Table 1, has been changed to zero during the time period of t=1 s till t=1.3 s. As is shown in this figure, the effect of the reactive power consumption variation on the active power is negligible.



(a) (b) (c)

Fig.9 Load voltages decomposition into positive (a), negative (b), and zero (c) symmetrical components for the load converter with the proposed control strategy

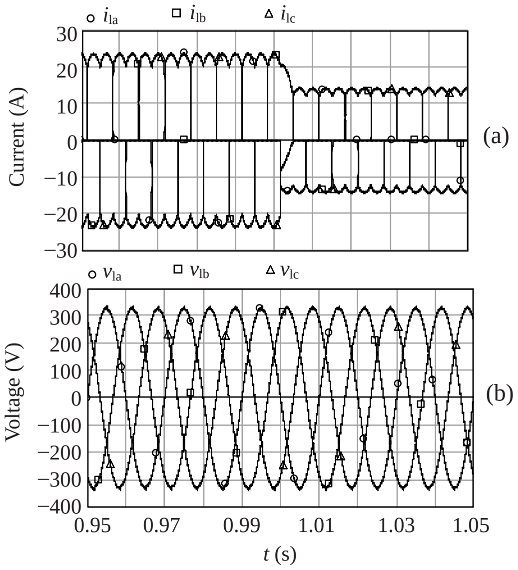


Fig.10 Nonlinear load currents (a) and balanced load phase voltages (b) for the load converter with the proposed control strategy

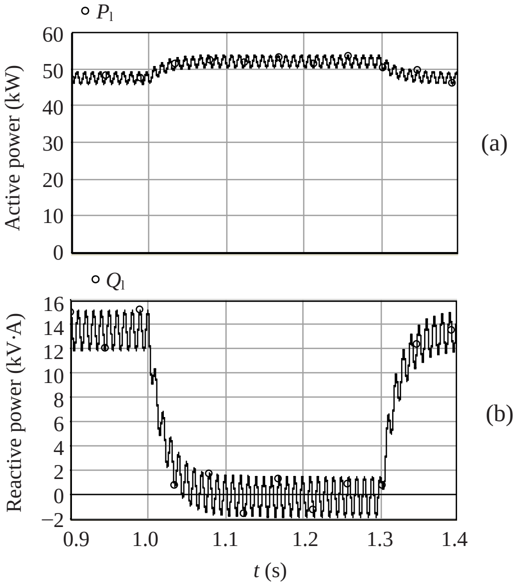


Fig.11 Instantaneous active (a) and reactive (b) powers of the unbalanced AC loads

CONCLUSION

In this paper, the control of the load converter under unbalanced loading conditions for an isolated DC distribution system has been investigated, while the load converter model is presented and two different control strategies are compared. The first one uses the conventional d-q-0 frame rotating controller with ω=314.159 rad/s and PI controllers to regulate the voltages and currents. The performances of this control strategy are insufficient. As a result, in this paper the proposed control strategy has been developed. This strategy is based on the decomposition of the voltages and currents into instantaneous positive, negative, and zero sequence components. The decomposition method uses phasor representation. In this control strategy, the positive, negative, and zero sequences appear as DC signals in their own synchronously rotating reference frames. The independent control strategy makes it possible to eliminate the disturbance of the output voltage caused by the unbalanced load. Simulation results show the effectiveness of the proposed control strategy versus the conventional control strategy.

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