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Constant DC Capacitor Voltage Control based Strategy for Active Load Balancer in Three-phase Four-wire Distribution Systems

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Abstract –Three-phase four-wire distribution systems are used for both three-phase three-wire loads and single-phase two-wire consumer appliances in South Korea, Myanmar and other countries. Unbalanced load conditions frequently occur in these distribution systems. These unbalanced load conditions cause unbalanced voltages for three-phase and single-phase loads, and increase the loss in the distribution transformer. In this paper, we propose constant DC capacitor voltage control based strategy for the active load balancer (ALB) in the three-phase four-wire distribution systems. Constant DC capacitor voltage control is always used in active power line conditioners. The proposed control strategy does not require any computation blocks of the active and reactive currents on the distribution systems. Balanced source-side currents with a unity power factor are obtained without any calculation block of the unbalanced active and reactive components on the load side. The basic principle of the constant DC capacitor voltage control based strategy for the ALB is discussed in detail and then confirmed by both digital computer simulations using PSIM software and prototype experimental model. Simulation and experimental results demonstrate that the proposed control strategy for the ALB can balance the source currents with a unity power factor in the three-phase four-wire distribution systems.

Keywords: Active load balancer, Constant DC capacitor voltage control, Four-leg inverter, Three-phase four-wire distribution systems

1. Introduction

Three-phase four-wire distribution systems are widely used in residential and commercial areas because of their economic benefits. Fig. 1 shows a three-phase four-wire distribution system that is used for both three-phase three-wire loads and single-phase two-wire loads. Using single-phase loads on a three-phase system results in unbalanced source currents. The unbalanced source currents cause unbalanced voltage, and affect other loads connected at the same point of common coupling (PCC). Moreover, the unbalanced load conditions cause excessive neutral current, which results in transformer overheating, higher loss and lower system efficiency. To solve these power quality problems, active power line conditioners with several control algorithms have been proposed for the three-phase four-wire distribution systems [1]-[7]. Most of these control algorithms are based on instantaneous active-reactive power theory and its extensions for the calculation of reference currents [1]-[3]. A synchronous reference frame, decomposition in the time domain of the load currents and theory of instantaneous symmetrical component are also used in the control algorithms [4]-[7]. All of these reference current calculation methods require a significant amount of computation steps including transformation blocks.

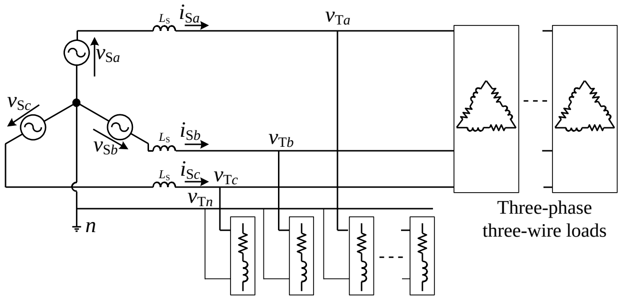

Fig. 1. Three-phase four-wire distribution system

In this paper, a novel constant DC capacitor voltage control based strategy for an active load balancer (ALB) is proposed to reduce the number of computation steps in the reference current calculation. The balanced active source

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current is calculated by the constant DC capacitor voltage control without detecting load currents. Therefore, the proposed control strategy does not require any calculation blocks of balanced active load current. The basic principle of constant DC capacitor voltage control based strategy for the ALB is discussed in detail and then confirmed by digital computer simulation using PSIM software. A reduced-scale experimental model is also constructed and tested. Experimental results demonstrate that balanced source currents with a unity power factor are achieved without any calculation blocks for the unbalanced active and reactive components of load currents.

2. Constant DC Capacitor Voltage Control Based Strategy for Active Load Balancer

2.1 Power Circuit Configuration

Fig. 2 shows a power circuit diagram of the proposed ALB for a three-phase four-wire distribution system. The three unbalanced single-phase loads are used for the unbalanced load condition in three-phase four-wire distribution system. The ALB, which is constructed with four-leg power-switching devices with a common DC capacitor, is connected in parallel to Y-connected three single-phase loads. Thus, the three legs of the ALB are connected with each phase of the distribution transformer and the fourth leg is connected to the neutral line. The unbalanced active and reactive currents drawn by the three single-phase loads are compensated by the ALB, which provides balanced source currents with a unity power factor in the distribution transformer.

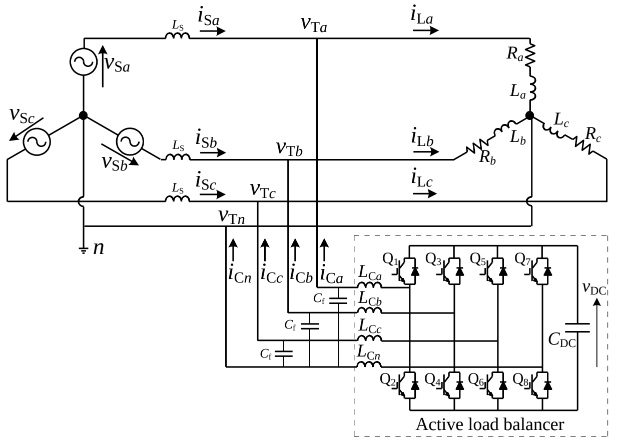

Fig. 2. Power circuit diagram of the proposed active load balancer

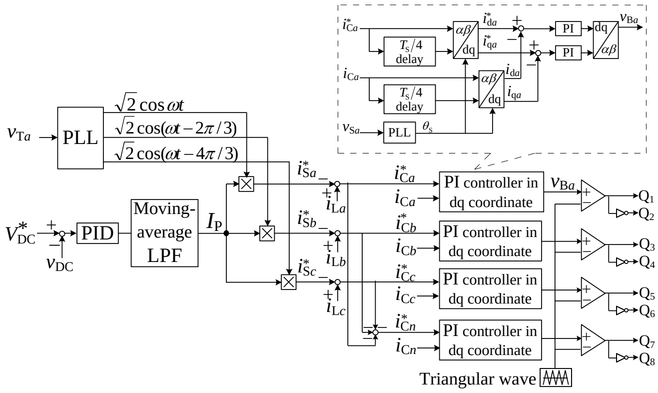

Fig. 3. Power circuit diagram of the proposed active load balancer

2.2 Proposed Control Strategy

Fig. 3 shows the proposed control strategy based on a constant DC capacitor voltage control for the ALB. The basic principle of the reference current calculation using constant DC capacitor voltage control is discussed. The three-phase terminal voltages $v_{\mathrm{T}a}$, $v_{\mathrm{T}b}$ and $v_{\mathrm{T}c}$ of the distribution transformer in Fig. 2 are expressed as

$$\begin{aligned} v_{\mathrm{T}a}(t) &= \sqrt{2}V_{\mathrm{T}}\cos(\omega t), \\ v_{\mathrm{T}b}(t) &= \sqrt{2}V_{\mathrm{T}}\cos(\omega t - \frac{2\pi}{3}), \\ v_{\mathrm{T}c}(t) &= \sqrt{2}V_{\mathrm{T}}\cos(\omega t - \frac{4\pi}{3}). \end{aligned} \tag{1}$$

The three single-phase load currents $i_{\mathrm{L}a}$, $i_{\mathrm{L}b}$ and $i_{\mathrm{L}c}$ are given by

$$\begin{aligned} i_{\mathrm{L}a}(t) &= \sqrt{2}I_a\cos(\omega t - \phi_a), \\ i_{\mathrm{L}b}(t) &= \sqrt{2}I_b\cos(\omega t - \frac{2\pi}{3} - \phi_b), \\ i_{\mathrm{L}c}(t) &= \sqrt{2}I_c\cos(\omega t - \frac{4\pi}{3} - \phi_c). \end{aligned} \tag{2}$$

Let us assume that the three source-side currents are balanced with a unity power factor after compensating the unbalanced active and reactive load currents. The three source-side currents, therefore, can be expressed as

$$\begin{aligned} i_{\mathrm{S}a}(t) &= \sqrt{2}I_{\mathrm{S}}\cos(\omega t), \\ i_{\mathrm{S}b}(t) &= \sqrt{2}I_{\mathrm{S}}\cos(\omega t - \frac{2\pi}{3}), \\ i_{\mathrm{S}c}(t) &= \sqrt{2}I_{\mathrm{S}}\cos(\omega t - \frac{4\pi}{3}), \end{aligned} \tag{3}$$

where $I_{\mathrm{S}} = (I_a\cos\phi_a + I_b\cos\phi_b + I_c\cos\phi_c)/3$. I_{S} is the theoretical rms value of the balanced active load current for each phase under any unbalanced load condition in the three-phase power feeding systems. From (2) and (3), the compensation currents of the ALB are calculated as

$$
\begin{aligned}
i_{Ca}(t) &= i_{La}(t) - i_{Sa}(t), \\
&= \sqrt{2}I_a \sin\phi_a \sin\omega t + \frac{\sqrt{2}}{3}(2I_a\cos\phi_a \\
&\quad - I_b\cos\phi_b - I_c\cos\phi_c)\cos\omega t, \\
i_{Cb}(t) &= i_{Lb}(t) - i_{Sb}(t), \\
&= \sqrt{2}I_b \sin\phi_b \sin(\omega t - \frac{2\pi}{3}) + \frac{\sqrt{2}}{3}(2I_b\cos\phi_b \\
&\quad - I_a\cos\phi_a - I_c\cos\phi_c)\cos(\omega t - \frac{2\pi}{3}), \\
i_{Cc}(t) &= i_{Lc}(t) - i_{Sc}(t) \\
&= \sqrt{2}I_c \sin\phi_c \sin(\omega t - \frac{4\pi}{3}) + \frac{\sqrt{2}}{3}(2I_c\cos\phi_c \\
&\quad - I_a\cos\phi_a - I_b\cos\phi_b)\cos(\omega t - \frac{4\pi}{3}). \quad (4)
\end{aligned}
$$

The instantaneous power $p_C(t)$ flowing into the ALB can be calculated as

$$
\begin{aligned}
p_C(t) &= v_{Ta}(t)\cdot i_{Ca}(t) + v_{Tb}(t)\cdot i_{Cb}(t) + v_{Tc}(t)\cdot i_{Cc}(t) \\
&= \left(2I_a\cos\phi_a - I_b\cos\phi_b - I_c\cos\phi_c + \right. \\
&\quad \left.\sqrt{3}I_b\sin\phi_b - \sqrt{3}I_c\sin\phi_c\right)\frac{1}{2}V_T\cos(2\omega t) + \\
&\quad \left(2I_a\sin\phi_a - I_b\sin\phi_b - I_c\sin\phi_c - \right. \\
&\quad \left.\sqrt{3}I_b\cos\phi_b + \sqrt{3}I_c\cos\phi_c\right)\frac{1}{2}V_T\sin(2\omega t).
\end{aligned} \quad (5)
$$

The mean value of the instantaneous power $p_C(t)$ in (5) becomes zero if the source currents are balanced as can be seen in (3). Therefore, maintaining the mean value of DC capacitor voltage at constant in the ALB in Fig. 2 means that the compensation currents are generated from the ALB so that they can satisfy the balanced source-side currents with a unity power factor. Thus, constant DC capacitor voltage control can be used for reference source currents calculation in the ALB.

In the control algorithm of Fig. 3, the DC capacitor voltage v_{DC} is detected from Fig. 2. Then the difference between the detected DC capacitor voltage v_{DC} and the reference value of the DC capacitor voltage V_{DC}^* is amplified by the PID controller as shown in Fig. 3. The output value of the PID controller is input into a moving-average low-pass filter (LPF). The moving-average LPF is designed to remove 2ω frequency component, where ω is the angular frequency of the terminal voltages in (1). The transfer function of the moving-average LPF is expressed as

$$H(z) = \frac{1}{N}\sum_{n=0}^{N-1} z^{-n}, \quad (6)$$

where N is the number of samples and can be expressed as

$$N = \frac{1}{f_C T_S}, \quad (7)$$

T_S is the sampling time interval and set to $83.3\mu s$. f_C is the cutoff frequency. The moving-average LPF is designed to remove 120Hz (2ω component). After filtering with the moving-average LPF, the effective value I_P of the source-side active current is obtained by performing constant DC capacitor voltage control. To calculate the reference source-side currents for the ALB, the *a*-phase terminal voltage is detected and electrical angle $(\theta_S = \omega t)$ is calculated using single-phase phase-locked-loop (PLL). Then $\sqrt{2}\cos(\omega t)$, $\sqrt{2}\cos(\omega t - \frac{2\pi}{3})$ and $\sqrt{2}\cos(\omega t - \frac{4\pi}{3})$ are calculated. Using these calculated values and the effective active source side current I_P, the reference source-side currents are generated as

$$
\begin{aligned}
i_{Sa}^*(t) &= \sqrt{2}I_P\cos(\omega t) \\
i_{Sb}^*(t) &= \sqrt{2}I_P\cos(\omega t - \frac{2\pi}{3}) \\
i_{Sc}^*(t) &= \sqrt{2}I_P\cos(\omega t - \frac{4\pi}{3})
\end{aligned} \quad (8)
$$

Finally, the compensation reference signals for the ALB are expressed as

$$
\begin{aligned}
i_{Ca}^*(t) &= i_{La}(t) - i_{Sa}^*(t), \\
i_{Cb}^*(t) &= i_{Lb}(t) - i_{Sb}^*(t), \\
i_{Cc}^*(t) &= i_{Lc}(t) - i_{Sc}^*(t), \\
i_{Cn}^*(t) &= -\left(i_{Ca}^*(t) + i_{Cb}^*(t) + i_{Cc}^*(t)\right).
\end{aligned} \quad (9)
$$

To reduce the steady-state error in current feedback control, PI controller in dq coordinates is used for the compensation currents i_{Ca}, i_{Cb}, i_{Cc} and i_{Cn} of the ALB. The operation principle of PI controller in dq coordinate is discussed using *a*-phase, for example, in Fig. 4. *a*-phase reference compensation signal i_{Ca}^* is delayed by $T_S/4$, where T_S is the cycle of the *a*-phase terminal voltage. i_{Ca}^* corresponds to the $\alpha-$component, and the delayed signal through $T_S/4$ delay block corresponds to $\beta-$ component. Using the electrical angle of the *a*-phase (θ_S), the $\alpha-$ and $\beta-$components are transformed into i_{da}^* and i_{qa}^*, respectively. Similarly, the compensation output current i_{Ca} is also transformed into i_{da} and i_{qa}. The difference between the reference signals i^*_{da} and i^*_{qa} and the detected signals i_{da} and i_{qa} are amplified by the PI controller in the dq coordinate. The amplified values are retransformed into the *a*-phase component. Then using the pulse width modulation (PWM) technique, the gate signals of power-switching devices for ALB are generated.

3. Simulation Results

To confirm the validity and high practicability of the proposed constant DC capacitor voltage control based strategy for the ALB, digital computer simulation is implemented using PSIM software. The circuit parameters of the distribution transformer in Fig. 2 are shown in Table 1. The rating of the distribution transformer is 21.5 kVA, 3-phase, 380 V and 60 Hz. The line-to-line voltage of 380 V is similar to that for a practical three-phase four-wire distribution system. The base power rating is 7.1 kVA for each single phase system. The three single-phase loads parameter are shown in Table 2. The load condition of *a*-phase includes two different loads, 0.9 per unit (pu) and 0.2 per unit (pu) for the load variation. The unbalanced load percentage is calculated as the ratio of the negative-sequence to positive-sequence values in accordance with the international electrotechnical commission (IEC) standard. Table 3 shows the circuit constants for the ALB in Fig. 2. The reference value of the DC capacitor voltage V^*_{DC} is set to 780 V.

Fig. 4 shows the simulation results for the ALB in Fig. 2 with the proposed control strategy based on constant DC capacitor voltage control. v_{Ta}, v_{Tb} and v_{Tc} are *a*-phase, *b*-phase and *c*-phase terminal voltages. i_{Sa}, i_{Sb} and i_{Sc} are three source-side currents. i_{La}, i_{Lb} and i_{Lc} are three load currents. i_{Ca}, i_{Cb} and i_{Cc} are compensation currents of the ALB. The *a*-phase load current is varied from 0.9 pu to 0.2 pu while the *b*-phase and *c*-phase load currents are kept constant. The unbalanced load percentage is 31% before load variation and 30% after load variation. Before and after load current variation, the three source currents are balanced with a unity power factor as shown in Fig. 4. The source currents i_{Sa}, i_{Sb} and i_{Sc} are settled to their steady state within two periods. In the literature [6], it takes about five periods to settle the currents to their steady state. Therefore, we can confirm that the proposed constant DC capacitor voltage control based strategy enables a good dynamic response of the ALB. The DC capacitor voltage

Table 1. Parameter of distribution transformer

Item	Symbol	Value
Rated power of transformer		21.5 kVA
Rated line-to-line rms voltage	v_o	380 V
Rated line-to-neutral rms voltage	v_{Ta}, v_{Tb}, v_{Tc}	220 V
Rated frequency	f	60 Hz

Table 2. Load condition of three-phase four-wire distribution system

Item	Symbol	Value
a-phase load (large load condition) (0.9 pu, power factor 0.8)	R_a	6.1 Ω
	L_a	12 mH
a-phase load (small load condition) (0.2 pu, power factor 0.8)	R_a	25 Ω
	L_a	50 mH
b-phase load (0.5 pu, power factor 0.8)	R_b	10 Ω
	L_b	20 mH
c-phase load (0.25 pu, power factor 0.8)	R_c	20 Ω
	L_c	40 mH
unbalanced load percentage (with *a*-phase large load)		31%
unbalanced load percentage (with *a*-phase large load)		30%

Table 3. Circuit constant for the ALB

Item	Symbol	Value
Reference DC capacitor voltage	V^*_{DC}	780 V
Capacity of capacitor	C_{DC}	2200 μF
Compensation inductances	$L_{Ca}, L_{Cb}, L_{Cc}, L_{Cn}$	2.5 mH
Switching frequency	f_{sw}	12 kHz

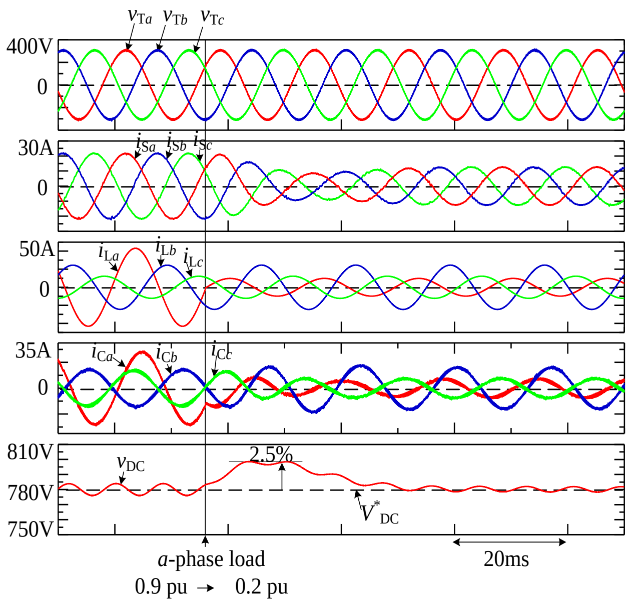

Fig. 4. Simulation results of active load balancer with load variation (heavy to light load)

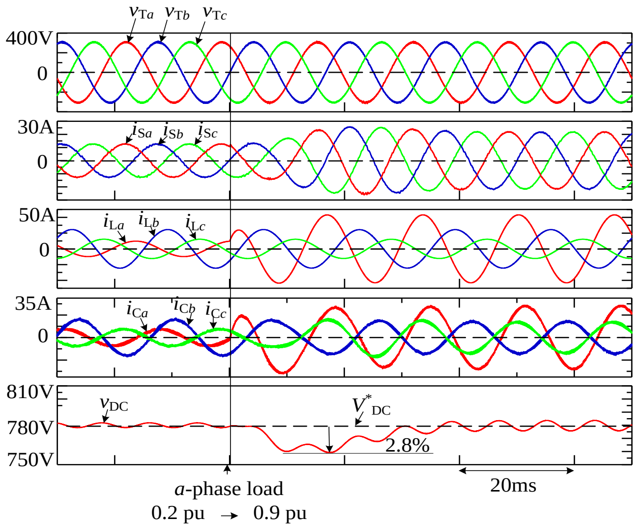

Fig. 5. Simulation results of active load balancer with load variation (light to heavy load)

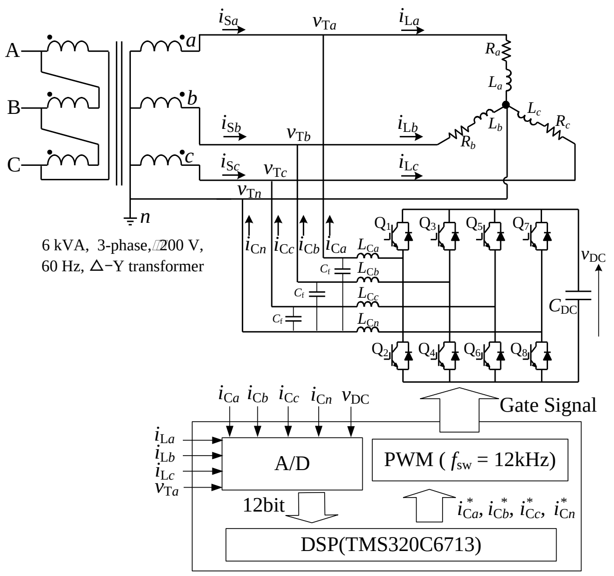

Fig. 6. Constructed experimental model

v_{DC} is well control to its reference value V^*_{DC} in both the transient and steady states. The amount of ripple of the DC capacitor voltage is within the acceptable range of under 2.5% in the both transient and steady states.

Fig. 5 shows the simulation results upon varying the *a*-phase load current i_{La} from 0.2 pu to 0.9 pu while the *b*-phase and *c*-phase load currents are kept constant. The unbalanced load percentage is 30% before load variation and 31% after load variation. Before and after load variation, the source currents i_{Sa}, i_{Sb} and i_{Sc} are balanced with a unity power factor. The DC capacitor voltage v_{DC} is well control to its reference value V^*_{DC} in this load variation. The amount of ripple of the DC capacitor voltage in the transient state is 2.8%.

4. Experimental Results

A reduced-scale experimental model of the ALB is constructed and tested to demonstrate the validity and high practicability of the proposed control algorithm. Fig. 6 shows a block diagram of the constructed experimental model. A $\Delta - \mathrm{Y}$ connected distribution transformer is used in the experiment. The utility three-phase system distributes 200 V in Japan. Therefore, a line-to-line voltage of 200 V is used in the experiment instead of 380 V. The rating of the transformer is 6 kVA, 3-phase, 200 V and 60 Hz as shown in Table 4. The load conditions of the distribution system are the same as those in Table 2. The circuit constants of the

Table 4. Parameter of experimental transformer

Item	Symbol	Value
Rated power of transformer		6 kVA
Rated line-to-line rms voltage	v_o	200 V
Rated line-to-neutral rms voltage	v_{Ta}, v_{Tb}, v_{Tc}	115 V
Rated frequency	f	60 Hz

Table 5. Circuit constant for the ALB in the experiment

Item	Symbol	Value
Reference DC capacitor voltage	V^*_{DC}	385 V
Capacity of capacitor	C_{DC}	2200 μF
Compensation inductances	$L_{Ca}, L_{Cb}, L_{Cc}, L_{Cn}$	1.5 mH
Switching frequency	f_{sw}	12 kHz

ALB in the experiment are shown in Table 5. A digital signal processor (DSP: TMS320C6713, 225 MHz) is used in the experimental setup.

The line-to-neutral voltage v_{Ta} is detected and input to the DSP through a 12-bit A/D converter as shown in the Fig. 6. The other signals detected for the DSP are the three load currents, the three compensation output currents and the DC capacitor voltage through the 12-bit A/D converters. In the DSP, the effective value I_p of the source-side active current is detected using constant DC capacitor voltage control strategy. Then $\sqrt{2}\cos(\omega t)$, which is synchronized with *a*-phase, $\sqrt{2}\cos(\omega t - \frac{2\pi}{3})$, which is synchronized with *b*-

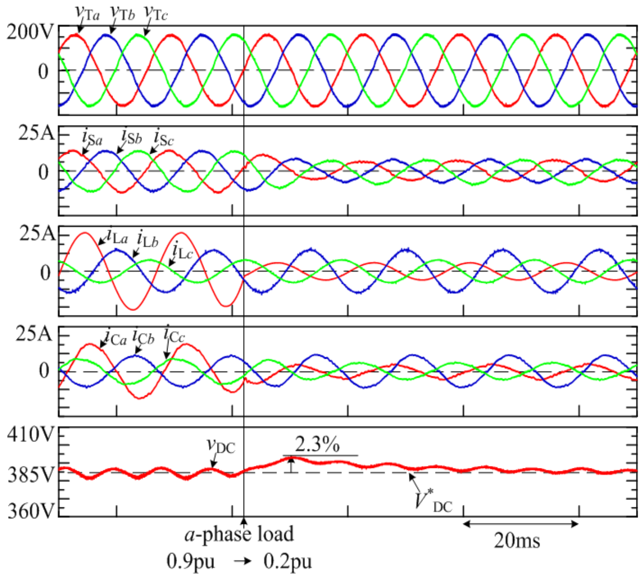

Fig. 7. Experimental results of active load balancer with load variation (heavy to light load)

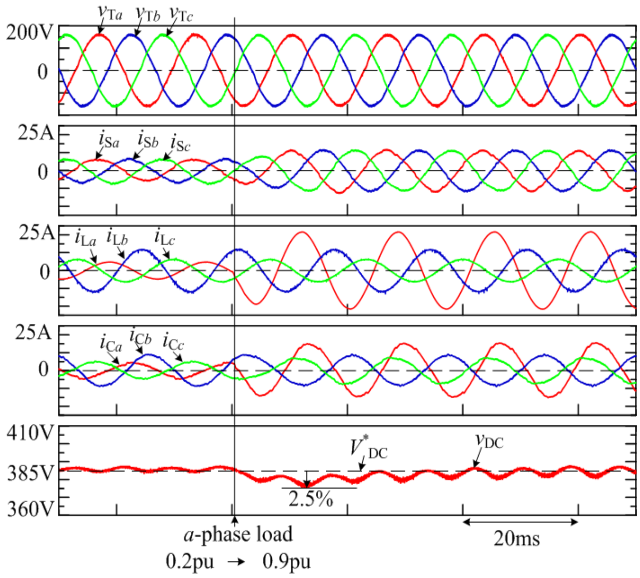

Fig. 8. Experimental results of active load balancer with load variation (light to heavy load)

phase and $\sqrt{2}\cos(\omega t - \frac{4\pi}{3})$, which is synchronized with *c*-phase are calculated using θ_S. Finally, the compensation reference values $i^*_{Ca}, i^*_{Cb}, i^*_{Cc}$ and i^*_{Cn} for the ALB are obtained from (9). The sine triangle intercept technique is used to control the output currents i_{Ca}, i_{Cb}, i_{Cc} and i_{Cn}. These compensation output currents are also input into the DSP for current feedback control, where the PI controller in dq coordinate is also applied. A Yokogawa SL1000 high-speed data acquisition unit with a sampling rate of $5\mu s$ is used for waveforms detection.

Fig. 7 shows the experimental results for the ALB in Fig. 6 with the proposed control strategy based on constant DC capacitor voltage control. The *a*-phase load current i_{La} is changed from 0.9 pu to 0.2 pu while the *b*-phase and *c*-phase load currents are kept constant. Before and after load current variation, the source currents i_{Sa}, i_{Sb} and i_{Sc} are balanced with a unity power factor. The DC capacitor voltage v_{DC} closely follows its reference value V^*_{DC} in the transient and steady states. The amount of ripple of the DC capacitor voltage is less than 2.3% in both transient and steady states.

Fig. 8 shows the experimental results for the ALB in Fig. 6 upon varying the *a*-phase load current from 0.2 pu to 0.9 pu. The source currents i_{Sa}, i_{Sb} and i_{Sc} are balanced with a unity power factor. The DC capacitor voltage v_{DC} closely follows its reference value V^*_{DC} in the transient and steady states. The amount of ripple of the DC capacitor voltage is less than 2.5% in the both transient and steady states.

5. Conclusion

In this paper, we have proposed constant DC capacitor voltage control based strategy for an ALB in a three-phase four-wire distribution system. It was anticipated that constant DC capacitor voltage control can detect balanced active source current without detecting unbalanced load currents from the load sides. The basic principle of the constant DC capacitor voltage control based strategy was discussed in detail by considering the instantaneous power flow into the ALB. The instantaneous power of the ALB suggests that the balanced source currents with a unity power factor are achieved using constant DC capacitor voltage control. A digital computer simulation was performed to verify the proposed constant DC capacitor voltage control based strategy for an ALB in a three-phase four-wire distribution system. Simulation results show that the ALB using the proposed control strategy can balance the source currents with a unity power factor. Therefore, the number of calculation steps required for active current detection can be reduced in the control algorithm of the ALB. A prototype experimental model for the ALB based on the proposed control strategy was constructed and tested to demonstrate its validity and excellent practicability. Both the simulation and experimental results demonstrated that the proposed control strategy well operate on the transient and steady states. Therefore, we have realized the simplest control algorithm for the ALB in three-phase four-wire distribution systems.

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