Novel, Simple Reactive Power Control Strategy with DC Capacitor Voltage Control for Active Load Balancer in Three-Phase Four-Wire Distribution Systems

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***Abstract*—This paper proposes a novel, simple reactive power control strategy for the active load balancer (ALB) in three-phase four-wire distribution systems. The proposed reactive power control strategy is applicable for adjustment of the source-side power factor under the balanced load condition. Only DC capacitor voltage control is used in the proposed control strategy. Therefore, the calculation blocks of the active and reactive components of the load currents are not necessary. The authors, thus, offer the simplest control strategy to control reactive power under the balanced load condition on three-phase four-wire distribution feeders. The basic principle of DC capacitor voltage control based reactive power control strategy is discussed in detail, and then confirmed by digital computer simulation. A prototype experimental system was constructed and tested. Experimental results demonstrate that balanced source currents with reactive power control are achieved on three-phase four-wire distribution feeders. These experimental results also demonstrate that controlling the reactive power reduces the required power rating of the ALB compared to that of the existing control strategy, which achieves balanced source currents with unity power factor.**

I. Introduction

Three-phase four-wire distribution systems are widely used in residential and commercial areas, e.g., in South Korea and Myanmar. These distribution systems simultaneously supply both three-phase and single-phase power as shown in Fig. 1. However, unbalanced load conditions frequently occur in these distribution systems and cause excessive neutral line current, which results in transformer overheating, loss, and lower distribution system efficiency. These unbalanced load conditions also lead to unbalanced voltages and affect other loads connected at the same point of common coupling (PCC). To solve these power quality problems, active power line conditioners are proposed in three-phase four-wire distribution systems. The control strategy in these active power line conditioners

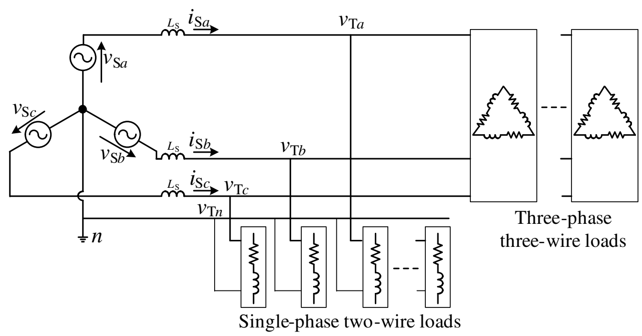

Fig. 1. Three-phase four-wire distribution systems.

is based on active-reactive instantaneous power theory and its extensions for the calculation of the reference source-side current [1]–[3]. The instantaneous symmetrical component theory method and the sample and hold circuit method are also used in [4], [5]. All these control strategies require a significant number of computation steps. Thus, the present authors have proposed a simple control strategy for the ALB that can achieve balanced source currents with unity power factor [6]. The proposed control strategy uses only constant DC capacitor voltage control, which is always used in active power line conditioners. Thus, the computation steps to calculate the unbalanced active and reactive components of the load currents are reduced. However, an ALB with a large power rating is required to obtain unity power factor on the source-side currents. It is imperative that the power rating of the ALB be reduced for practical applications.

In this paper, we propose a power-factor-adjustable reactive power control strategy to reduce the power rating of the ALB. Balanced source currents with a power factor of 0.9, which

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is acceptable in Japanese power distribution systems [7], are achieved without any calculation blocks of the unbalanced active and reactive components of the load currents. The basic principle of power-factor-adjustable reactive power control strategy based on DC capacitor voltage control for the ALB is discussed in detail, and then confirmed with digital computer simulation using PSIM software. A prototype experimental model is constructed and tested to validate the feasibility of the proposed control strategy. Experimental results demonstrate that the proposed reactive power control strategy, which achieves a power factor of 0.9, reduces the ALB's power rating by 26% compared to that of the existing control strategy with unity power factor control.

II. Reactive power control strategy based on DC capacitor voltage control

A. 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 conditions. These three single-phase unbalanced loads are connected through a three-phase four-wire distribution feeder. The ALB, which is constructed with four-leg power-switching devices with a common DC capacitor, is connected in parallel to three single-phase loads. Thus, the three legs of the ALB are connected to each phase of the distribution system, 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 predefined power factor in the distribution transformer.

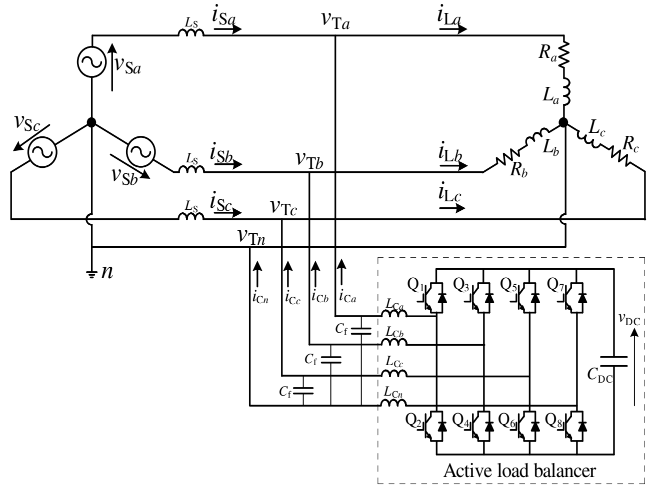


Fig. 2. Power circuit diagram of the proposed active load balancer.

B. Proposed Control Algorithm

Fig. 3 shows a block diagram of the proposed reactive power control strategy for the ALB in three-phase four-wire distribution systems. The basic principle of reactive power control strategy based on DC capacitor voltage control is discussed. The three-phase terminal voltages v_{Ta}, v_{Tb}, and v_{Tc} in Fig. 2 are expressed as

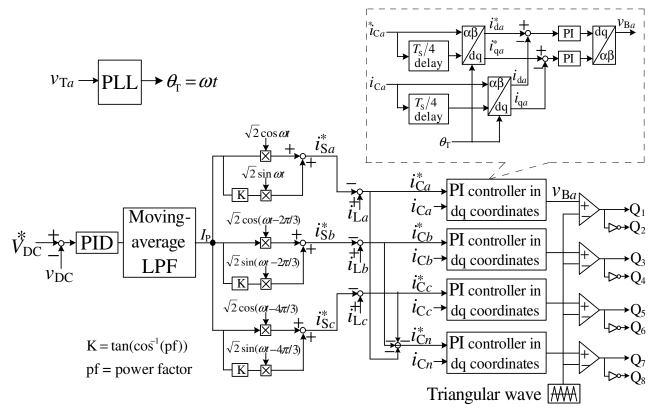


Fig. 3. Proposed reactive power control strategy for the active load balancer.

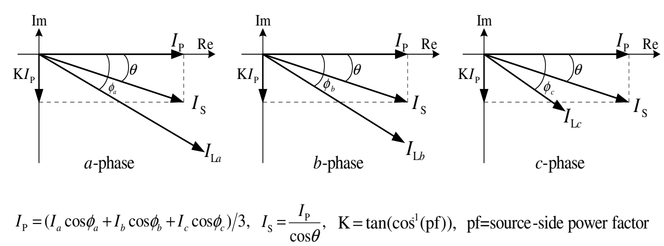


Fig. 4. Phasor diagrams of the proposed control strategy.

$$
\begin{aligned}
v_{Ta} &= \sqrt{2}V_T\cos(\omega t),\\
v_{Tb} &= \sqrt{2}V_T\cos(\omega t - \frac{2\pi}{3}),\\
v_{Tc} &= \sqrt{2}V_T\cos(\omega t - \frac{4\pi}{3}).
\end{aligned} \quad (1)
$$

The load currents i_{La}, i_{Lb}, and i_{Lc} drawn by each single-phase load in Fig. 2 are also expressed as

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

Let us assume that the three-phase source currents i_{Sa}, i_{Sb}, and i_{Sc} are balanced with a power factor of $\cos\theta$ after compensating the unbalanced active components with reactive power control. The three-phase source currents, therefore, can be expressed as

$$
\begin{aligned}
i_{Sa} &= \sqrt{2}I_S\cos(\omega t - \theta),\\
i_{Sb} &= \sqrt{2}I_S\cos(\omega t - \frac{2\pi}{3} - \theta),\\
i_{Sc} &= \sqrt{2}I_S\cos(\omega t - \frac{4\pi}{3} - \theta),
\end{aligned} \quad (3)
$$

where $I_S = (I_a\cos\phi_a + I_b\cos\phi_b + I_c\cos\phi_c)/(3\cos\theta)$ as shown in Fig. 4. I_S is the theoretical rms value of the balanced source current with a power factor of $\cos\theta$ for each phase.

From (2) and (3), the compensation currents of the ALB are calculated as

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

The instantaneous power p_C flowing to the ALB can be calculated as

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

The mean value of the instantaneous power p_C in (5) is zero, while the source currents in (3) are balanced with the same phase angle θ. Thus, maintaining a constant DC capacitor voltage in the ALB will result in a balanced condition with a predefined power factor cosθ on the source side. Therefore, the constant DC capacitor voltage control can ideally be used for the reactive power control strategy of the ALB in three-phase four-wire distribution systems. In practical applications, the instantaneous DC capacitor voltage is not constant owing to the 2ω components caused by the unbalanced load conditions. Thus, the constant mean value of the DC capacitor voltage is controlled in the proposed method.

The DC capacitor voltage v_{DC} is detected in Fig. 2. Then the difference between the detected DC capacitor voltage v_{DC} and the reference 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 to a moving-average low-pass filter (LPF). The moving-average LPF is designed to remove the 2ω components, where ω is the angular frequency of the terminal voltage. The transfer function of the moving-average LPF is expressed as

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

where N is the number of samples. 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 compensation currents for the ALB, the a-phase terminal voltage v_{Ta} is detected, and then the electrical angle ($\theta_T = \omega t$) is generated using a single-phase phased-lock loop (PLL) [8]. Next, $\sqrt{2}\cos(\omega t)$, $\sqrt{2}\cos(\omega t-\frac{2\pi}{3})$, $\sqrt{2}\cos(\omega t-\frac{4\pi}{3})$, $\sqrt{2}\sin(\omega t)$, $\sqrt{2}\sin(\omega t-\frac{2\pi}{3})$, and $\sqrt{2}\sin(\omega t-\frac{4\pi}{3})$ are calculated using θ_T. Using these calculated values and the effective value I_P, the reference source currents for each phase are calculated as

$$\begin{aligned} i^*_{Sa} &= \sqrt{2}I_P\cos(\omega t) + K\sqrt{2}I_P\sin(\omega t), \\ i^*_{Sb} &= \sqrt{2}I_P\cos(\omega t - \frac{2\pi}{3}) + K\sqrt{2}I_P\sin(\omega t - \frac{2\pi}{3}), \\ i^*_{Sc} &= \sqrt{2}I_P\cos(\omega t - \frac{4\pi}{3}) + K\sqrt{2}I_P\sin(\omega t - \frac{4\pi}{3}), \end{aligned} \tag{7}$$

where K = tan(cos^{-1}(pf)) as shown in Fig. 4. Therefore, the source side power factor can be adjusted by changing the value of K. Finally, the compensation reference signals for the ALB are expressed as

$$\begin{aligned} i^*_{Ca} &= i_{La} - i^*_{Sa}, \\ i^*_{Cb} &= i_{Lb} - i^*_{Sb}, \\ i^*_{Cc} &= i_{Lc} - i^*_{Sc}, \\ i^*_{Cn} &= -\left(i^*_{Ca} + i^*_{Cb} + i^*_{Cc}\right). \end{aligned} \tag{8}$$

The PI controllers in dq coordinates are used to control the compensation currents i_{Ca}, i_{Cb}, i_{Cc} and i_{Cn} of the ALB [9]. The operating principle of the PI controller in dq coordinates is the same for the phases and the neutral, as shown in Fig. 3. In the a-phase compensation current control, for example, the a-phase reference compensation current 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 α-component, and the delayed current through the $T_S/4$ delay block corresponds to the β-component. Using θ_T, the electrical angle of the a-phase terminal voltage generated by the PLL, the α- and β-components are transformed into i^*_{da} and i^*_{qa}, respectively. The compensation output current i_{Ca} is also transformed into i_{da} and i_{qa} in the same way. The differences between the reference currents i^*_{da}, i^*_{qa} and the detected currents i_{da}, i_{qa} are amplified by the PI controller in dq coordinates. The amplified values are retransformed into a-phase components. Then, using the pulse width modulation (PWM) technique, the gate signals for the power switching devices of the ALB are generated.

III. Simulation results

To confirm the validity and practicability of the proposed reactive power control strategy for the ALB, digital computer simulation is implemented using PSIM software. The rating of the distribution transformer is three-phase, 380 V, 21.5 kVA, and 60 Hz. A line-to-line voltage of 380 V is used in the simulation for Korea's three-phase four-wire distribution systems. The base power rating is 7.1 kVA for each single-phase system. Three single-phase load parameters and unbalanced load conditions are shown in Table I. The load conditions for the a-phase include two different loads, while the b-phase and c-phase loads are kept constant. 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 II shows the circuit constants for the ALB in Fig. 2. The capacity of the DC capacitor voltage is 2200 μF. The reference value of the DC capacitor voltage V^*_{DC} is set to 780 V.

Fig. 5 shows the simulation waveforms for the ALB in Fig. 2 with the proposed reactive power control strategy. v_{Ta},

TABLE I. Load conditions 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 small-load)		30%

TABLE II. Circuit constants of active load balancer in the simulation.

Item	Symbol	Value
Reference DC capacitor voltage	V^*_{DC}	780 V
Capacity of capacitor	C_{DC}	2200 μF
Compensation inductance	$L_{\mathrm{C}a}$, $L_{\mathrm{C}b}$, $L_{\mathrm{C}c}$, $L_{\mathrm{C}n}$	2.5 mH
Switching frequency	f_{sw}	12 kHz

$v_{\mathrm{T}b}$, and $v_{\mathrm{T}c}$ are the a-phase, b-phase, and c-phase terminal voltages, respectively. The a-phase load current $i_{\mathrm{L}a}$ is varied from 0.9 pu to 0.2 pu, while the b-phase and c-phase load currents, $i_{\mathrm{L}b}$ and $i_{\mathrm{L}c}$, are kept constant. The unbalanced load percentage is 31% before the load variation and 30% after the load variation. The power factor is set to 0.9 in the control strategy in accordance with the Japanese guidelines [7]. Before and after the load current variation, the three source currents $i_{\mathrm{S}a}$, $i_{\mathrm{S}b}$, and $i_{\mathrm{S}c}$ are balanced as shown in Fig. 5. The power factor, $\cos\theta$, is 0.9 under the heavy-load condition and 0.91 under the light-load condition. A slight difference in the power factor occured because of the filter capacitor effect of the ALB. The DC capacitor voltage v_{DC} is well controlled with respect to its reference value V^*_{DC} in both the transient and steady states. The ripple in the DC capacitor voltage is 2.8% in the transient state and less than ±1% in the steady state.

Fig. 6 shows the simulation results for the ALB in Fig. 2 with the proposed reactive power control strategy. The a-phase load current $i_{\mathrm{L}a}$ is changed from 0.2 pu to 0.9 pu, while the b-phase load $i_{\mathrm{L}b}$ and c-phase load $i_{\mathrm{L}c}$ are kept constant. Before and after the load current variation, the source currents $i_{\mathrm{S}a}$, $i_{\mathrm{S}b}$, and $i_{\mathrm{S}c}$ are balanced. The DC capacitor voltage v_{DC} closely follows its reference value V^*_{DC} in this light-load to heavy-load variation. The ripple in the DC capacitor voltage is less than 3.2% in the transient state.

IV. Experimental results

A reduced-scale experimental model of the ALB is constructed and tested to demonstrate the validity and practicability of the proposed reactive power control strategy. Fig. 7 shows a block diagram of the constructed experimental model. A Δ-Y connected distribution transformer is used in the experimental setup. Electric power utilities in Japan distribute 200 V for commercial supply. Therefore, the voltage rating (line-to-line) is 200 V in the experiment. The rating of the transformer is three phase, 200 V, 6 kVA, and 60 Hz on both the primary and secondary sides. The line-to-neutral voltage is 115 V for each single-phase system on the secondary side. The circuit constants of the ALB are shown in Table III. The

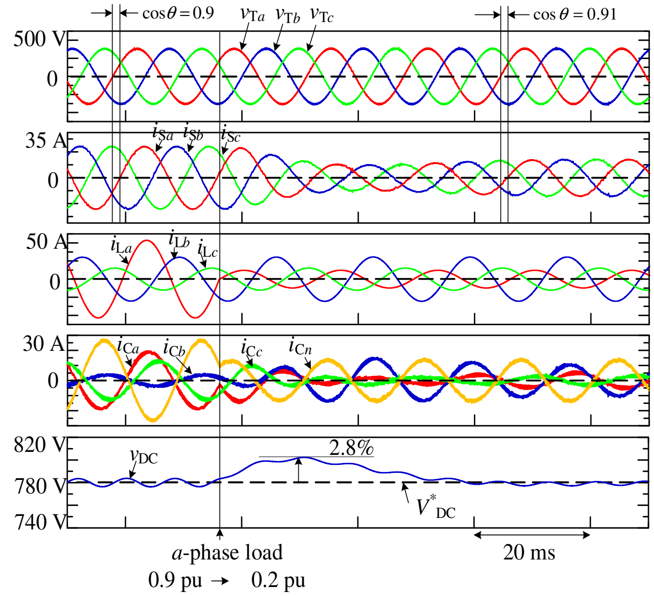


Fig. 5. Simulation waveforms using the proposed reactive power control strategy with heavy-load to light-load variation (power factor is set to 0.9).

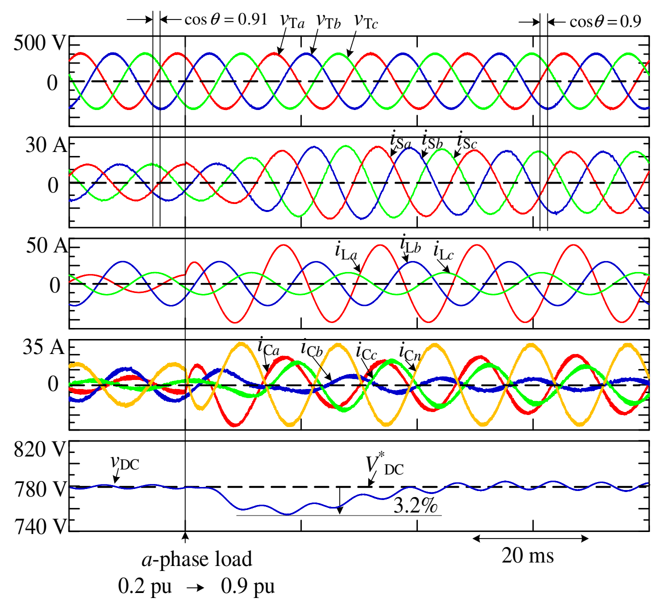


Fig. 6. Simulation waveforms using the proposed reactive power control strategy with light-load to heavy-load variation (power factor is set to 0.9).

reference DC capacitor voltage V^*_{DC} is 385 V in the experiment. The load conditions of the distribution system are the same as those in Table I.

A digital signal processor (DSP: TMS320C6713, 225 MHz) is used in the experimental setup. The line-to-neutral voltage $v_{\mathrm{T}a}$; the three load currents $i_{\mathrm{L}a}$, $i_{\mathrm{L}b}$, and $i_{\mathrm{L}c}$; the four compensation output currents $i_{\mathrm{C}a}$, $i_{\mathrm{C}b}$, $i_{\mathrm{C}c}$, and $i_{\mathrm{C}n}$; and the DC capacitor voltage v_{DC} are detected. These detected

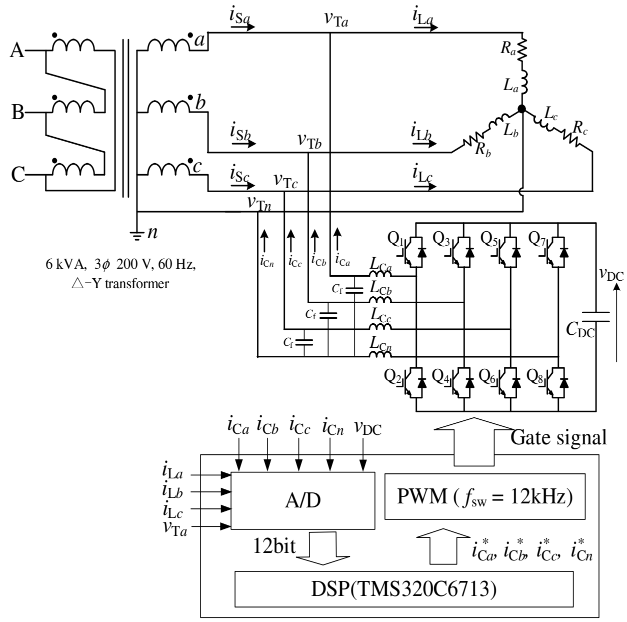


Fig. 7. Constructed experimental model for Fig. 2.

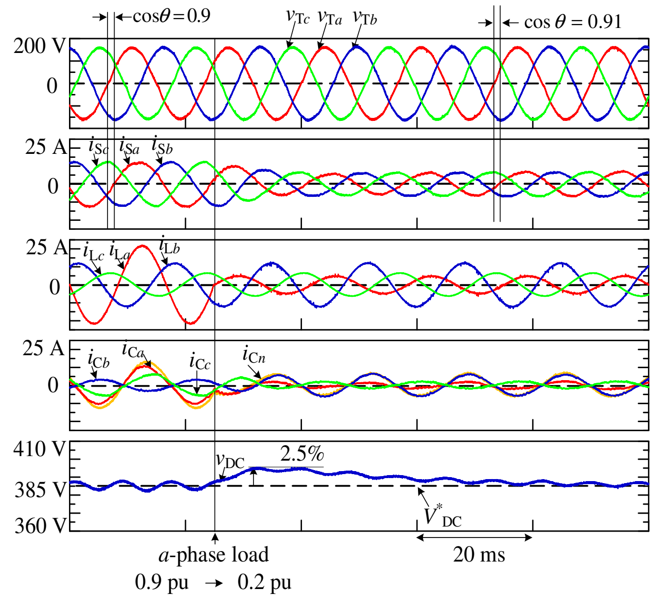


Fig. 8. Experimental results of the proposed reactive power control strategy with heavy-load to light-load variation (power factor is set to 0.9).

TABLE III. CIRCUIT CONSTANTS OF ACTIVE LOAD BALANCER IN THE EXPERIMENT.

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

signals are input to the DSP through 12-bit A/D converters as shown in Fig. 7. In the DSP, the reference compensation currents i^*_{Ca}, i^*_{Cb}, i^*_{Cc}, and i^*_{Cn} are calculated using the proposed reactive power control strategy as in (8). 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 detected by the DSP for current feedback control, where the PI controller in dq coordinates is also constructed. A Yokogawa SL1000 high-speed data acquisition unit with a sampling rate of 5 μs is used for waveform measurement.

Fig. 8 shows the experimental results for the ALB in Fig. 7 with the proposed reactive power 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 load i_{Lb} and the c-phase load i_{Lc} are kept constant. The unbalanced load percentage is 31% before the load variation and 30% after the load variation. The power factor is set to 0.9 in the control algorithm in accordance with the Japanese guidelines [7]. Before and after the load current variation, the source currents i_{Sa}, i_{Sb}, and i_{Sc} are balanced. The power factor cosθ is 0.9 under the heavy-load condition and 0.91 under the light-load condition. A slight difference in the power factor occured because of the filter capacitor effect of the ALB. The DC capacitor voltage v_{DC} closely follows its reference value V^*_{DC} in both transient and steady states. The ripple in the DC capacitor voltage is less than 2.5% in both transient and steady states.

Fig. 9 shows the experimental results for the ALB in Fig. 7 with the proposed reactive power control strategy. The a-phase load current i_{La} is changed from 0.2 pu to 0.9 pu, while the b-phase load i_{Lb} and the c-phase load i_{Lc} are kept constant. Before and after the load current variation, the source currents i_{Sa}, i_{Sb}, and i_{Sc} are balanced. The DC capacitor voltage v_{DC} closely follows its reference value V^*_{DC} in the transient state in this light-load to heavy-load variation. The ripple in the DC capacitor voltage is less than 2.8% in the transient state.

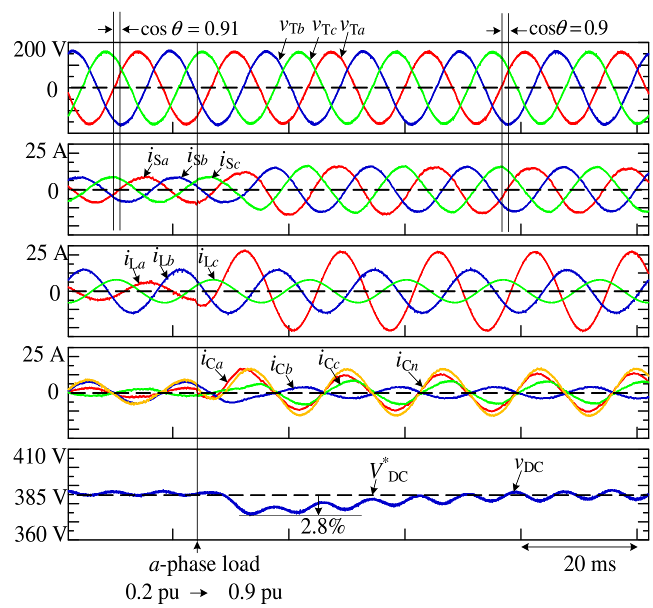


Fig. 9. Experimental results of the proposed reactive power control strategy with light-load to heavy-load variation (power factor is set to 0.9).

V. Required power rating of the ALB

The required power rating S_{ALB} of the ALB with four-leg switching devices is discussed. Fig. 10 shows the equivalent circuit of the ALB in three-phase four-wire distribution systems. Each leg of the ALB is represented by a current source. From the equivalent circuit, it is seen that the neutral-leg current should be included in the required power rating calculation of the ALB. The power rating of the ALB is given by

$$S_{ALB} = V_{Ln}(I_{Ca} + I_{Cb} + I_{Cc} + I_{Cn}). \quad (9)$$

where V_{Ln} is the rms line-to-neutral voltage, and I_{Ca}, I_{Cb}, I_{Cc}, and I_{Cn} are the rms compensation currents of the ALB.

Fig. 11 shows a comparison of the experimental results using two control strategies under the same load condition. Fig. 11(a) shows the experimental results of existing control strategy with a unity power factor control in [6]. The compensation current flowing in each phase is I_{Ca} = 10.642 A, I_{Cb} = 6.113 A, I_{Cc} = 5.035 A and I_{Cn} = 8.712 A. Thus, the required power rating of the ALB is 3.5 kVA. Fig. 11(b) shows the experimental results of the proposed reactive power control strategy with the power factor of 0.9. The compensation current flowing in each phase is I_{Ca} = 7.367 A, I_{Cb} = 2.356 A, I_{Cc} = 4.098 A and I_{Cn} = 8.970 A. The required power rating of the ALB is 2.6 kVA. Therefore, the proposed reactive power control strategy reduces the required power rating of the ALB by 26% compared to the power rating obtained with the existing control strategy.

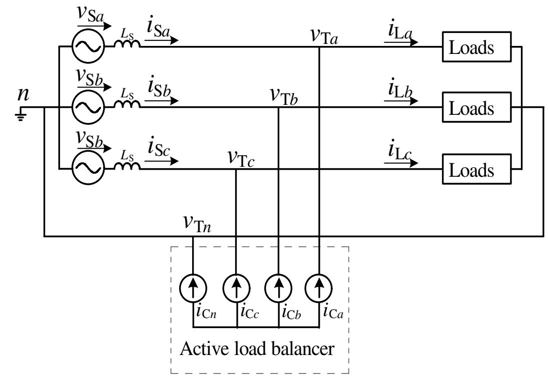
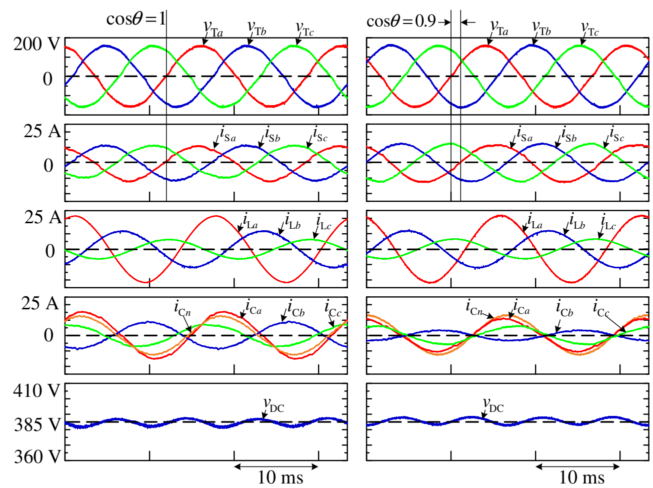


Fig. 10. Equivalent circuit of the ALB in three-phase four-wire distribution systems.



(a) Constant DC capacitor voltage control strategy for unity power factor

(b) Proposed reactive power control strategy for power factor of 0.9

Fig. 11. Comparison of experimental waveforms using two control strategies for the ALB.

VI. Conclusion

In this paper, we have proposed a novel, simple reactive power control strategy based on DC capacitor voltage control for the ALB in three-phase four-wire distribution systems. The proposed control strategy can adjust the source-side power factor in the balanced load condition. Balanced source-side currents with a power factor of 0.9 can be achieved without any calculation blocks of the active and the reactive components of the load currents. A digital computer simulation and experimental results confirm that the proposed reactive power control strategy is well suited to reactive power control to reduce the power rating of the ALB. From the experimental analysis, the reactive power control strategy, which achieves a power factor of 0.9, reduces the ALB's power rating by 26%, whereas the existing control strategy achieves a unity power factor. Therefore, we have offered the simplest and most efficient control strategy for the ALB in three-phase four-wire distribution systems.

References

[1] H. Akagi, Y. Kanazawa, and A. Nabe, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.,* Vol. IA-20, No. 3, May/June 1984.

[2] A. Nava-Segura and G. Mino-Aguilar, "Four-branches-inverter-based-active-filter for unbalanced 3-phase 4-wires electrical distribution systems," *Proc. IEEE Ind. Appl. Conf.,* Vol. 4, pp. 2503-2508, 2000.

[3] A. Adya, A.P. Mittal, and J.R.P. Gupta, "Modeling and control of DSTATCOM for three-phase, four-wire distribution systems," *IEEE-IAS Ann. Meeting,* Vol. 4, pp. 2428-2434, 2005.

[4] N. Geddada, S.B. Karanki, M.K. Mishra, and B.K. Kumar, "Modified four leg DSTATCOM topology for compensation of unbalanced and nonlinear loads in three phase four wire system," *Proc. of EPE'11,* pp. 1-10, 2011.

[5] L.W. Dixon, J.J. Garcia, and L. Moran, "Control system for three-phase active power filter which simultaneously compensates power factor and unbalanced loads," *IEEE Trans. Ind. Electron.,* Vol. 42, pp. 636-641, 1995.

[6] Tint Soe Win, E. Hiraki, M. Okamoto, S.R. Lee and T. Tanaka, "Constant DC capacitor voltage control based strategy for active load balancer in three-phase four-wire distribution system," *Proc. of ICEMS 2013 International Conf.,* pp. 1560-1565, 2013.

[7] Japan Electric Association, Indoor Wiring Guidelines, JESC E0005, p. 32 (2005) (in Japanese).

[8] L.N. Arruda, S.M. Silva, and B.J.C. Filho, "PLL structure for utility connected systems," *Conf. Rec. 36th IEEE-IAS Ann. Meeting,* pp. 2655–2660, Chicago, USA, 2001.

[9] F. S. Zhang,"Control of single phase power converter in D-Q rotating coordinates," U.S Patent 6 621 252 B2, Sep. 16, 2003.