Novel Control Algorithm for Active Load Balancer in Three-Phase Four-Wire Distribution Systems

Tint Soe Win* Student Member, Eiji Hiraki* Member
Masayuki Okamoto** Member, Seong Ryong Lee*** Non-member
Toshihiko Tanaka* Senior Member

(Manuscript received June 11, 2013, revised Sep. 26, 2013)

Three-phase four-wire distribution systems are widely used in many countries. These distribution systems are used for both three-phase three-wire loads and single-phase two-wire consumer appliances, e.g., in South Korea and Myanmar. Because of the time-dependent load characteristics, unbalanced load conditions frequently occur, resulting in the unbalanced voltages for the three-phase and single-phase loads. In addition, these unbalanced load conditions cause more loss in the distribution transformer. This paper proposes a novel reference current generation method for active load balancer (ALB) in the three-phase four-wire distribution systems. The main advantages of the proposed method is that it uses only a constant DC capacitor voltage control for reference current generation without calculating the active and reactive currents in the three-phase four-wire distribution systems. The basic principle of the novel reference generation method in ALB is discussed and then confirmed on the basis of results of digital computer simulation using PSIM software.

Keywords: active load balancer, three-phase four-wire distribution systems, constant DC capacitor voltage control

1. Introduction

Three-phase four-wire distribution systems are used for both three-phase three-wire loads and single-phase two-wire consumer appliances in Korea, Myanmar and other countries for economical reasons. An active load balancer (ALB) is necessary to avoid unbalanced load conditions in these distribution systems. Many researchers have proposed active power line conditioners with several control algorithms for load balancing in three-phase four-wire distribution systems. These control algorithms are based on the instantaneous reactive power theory and its extensions for reference current generation. Other methods include the sample and hold circuit method and synchronous reference frame method. In the literature, the authors reviewed four control strategies using their reference calculation methods and concluded that the perfect harmonic cancellation method has excellent performance. However, all these control algorithms require a significant number of calculation steps, including transformation blocks for the calculation of the reference currents. This paper proposes a novel control algorithm for an ALB for three-phase four-wire distribution systems. The proposed control algorithm uses the constant DC capacitor voltage control, which is always used in active power line conditioners, for reference signal generation. The basic principle of the novel control algorithm for an ALB is discussed in detail and is confirmed via digital computer simulation using PSIM software.

2. Proposed Control Algorithm for ALB

Figure 1 shows the power circuit diagram of the ALB and the proposed control algorithm. The ALB, which is
constructed with four-leg power switching devices with a common DC capacitor, is connected in parallel to the three different single-phase loads. The three legs of the ALB are connected to each phase, and the fourth leg is connected to the neutral line. The principle of a novel reference generation method using the constant DC capacitor voltage control is discussed. Let the source voltages and three load currents in Fig. 1 be

\[
\begin{align*}
v_{sa}(t) &= \sqrt{2}V_s \cos \omega t, \\
v_{sb}(t) &= \sqrt{2}V_s \cos \left( \omega t - \frac{2\pi}{3} \right), \\
v_{sc}(t) &= \sqrt{2}V_s \cos \left( \omega t - \frac{4\pi}{3} \right). 
\end{align*}
\]

(1)

\[
\begin{align*}
i_{sa}(t) &= \sqrt{2}I_s \cos(\omega t - \phi_a), \\
i_{sb}(t) &= \sqrt{2}I_s \cos \left( \omega t - \frac{2\pi}{3} - \phi_b \right), \\
i_{sc}(t) &= \sqrt{2}I_s \cos \left( \omega t - \frac{4\pi}{3} - \phi_c \right). 
\end{align*}
\]

(2)

Let us assume that the three source currents \( i_{sa}, i_{sb}, \) and \( i_{sc} \) are balanced with a unity power factor after compensating for unbalanced active and reactive load currents. The source currents can be expressed as

\[
\begin{align*}
i_{sa}(t) &= \sqrt{2}I_s \cos \omega t, \\
i_{sb}(t) &= \sqrt{2}I_s \cos \left( \omega t - \frac{2\pi}{3} \right), \\
i_{sc}(t) &= \sqrt{2}I_s \cos \left( \omega t - \frac{4\pi}{3} \right). 
\end{align*}
\]

(3)

where \( I_s = (I_a \cos \phi_a + I_b \cos \phi_b + I_c \cos \phi_c)/3 \). \( I_s \) is the theoretical rms value of the balanced active current for each phase. By (2) and (3), the compensation currents of the ALB are given by

\[
\begin{align*}
i_{ca}(t) &= i_{sa}(t) - i_{sc}(t), \\
i_{cb}(t) &= i_{sa}(t) - i_{sb}(t), \\
i_{cc}(t) &= i_{sb}(t) - i_{sc}(t). 
\end{align*}
\]

(4)

The instantaneous power \( p_c(t) \) flowing into the ALB can be calculated as

\[
p_c(t) = v_{sa}(t) \cdot i_{ca}(t) + v_{sb}(t) \cdot i_{cb}(t) + v_{sc}(t) \cdot i_{cc}(t) \\
= 2V \left[ I_a \sin \phi_a \sin(2\omega t) + I_b \sin \phi_b \sin \left( 2\omega t - \frac{4\pi}{3} \right) \right] \\
+ I_c \sin \phi_c \sin \left( 2\omega t - \frac{2\pi}{3} \right) \\
+ \frac{1}{2} \left( 2I_a \cos \phi_a - I_c \cos \phi_a \right) \cos(2\omega t) \\
+ \left( 2I_b \cos \phi_b - I_c \cos \phi_b \right) \cos \left( 2\omega t - \frac{4\pi}{3} \right) \\
+ \left( 2I_c \cos \phi_c - I_b \cos \phi_c \right) \cos \left( 2\omega t - \frac{2\pi}{3} \right). 
\]

(5)

The mean value of \( p_c(t) \) in (5) becomes zero if the source currents are balanced, as in (3). Therefore, maintaining the DC capacitor voltage at a constant value in Fig. 1 means that the ALB controls the three source currents to be in a balanced condition with a unity power factor. Thus, constant DC capacitor voltage control can achieve reference signal calculation without any calculation blocks of the reactive and unbalanced active currents.

In the control block of Fig. 1, the difference between the detected DC capacitor voltage \( V_{DC} \) and the reference DC capacitor voltage \( V_{DC}^* \) is amplified by the PID controller and input into the moving average low-pass filter. The effective value \( I_p \) of the loads is obtained using constant DC capacitor voltage control. Using this effective value, the compensation signals of the ALB are finally expressed as

\[
\begin{align*}
i_{ca}(t) &= i_{cb}(t) - i_{cc}(t), \\
i_{cb}(t) &= i_{ca}(t) - i_{cc}(t), \\
i_{cc}(t) &= i_{ca}(t) - i_{cb}(t). 
\end{align*}
\]

(6)

Figure 2 shows the simulation results for Fig. 1. The \( a \)-phase load is changed from 0.1 pu to 1.0 pu and vice versa, whereas the \( b \)-phase is 0.5 pu, and the \( c \)-phase is 0.25 pu in the 21.5 kVA, 380 V, 60 Hz rating distribution system. The unbalanced condition of the load is 37% (\( a \)-phase large load) and 41% (\( a \)-phase small load). Before and after the load variation, the three source currents are balanced with a unity power factor. The DC capacitor voltage is well controlled to its reference value with small ripples.

3. Conclusion

In this paper, we have proposed the simplest control algorithm for an ALB in three-phase four-wire distribution systems. The proposed method does not require any calculation blocks for a reference calculation. Thus we concluded that the proposed control algorithm is suitable for an ALB in three-phase four wire distribution systems.

References


