

One-Cycle Control Strategy for Dual-Converter Three-Phase PWM Rectifier under Unbalanced Grid Voltage Conditions

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Abstract

In this paper, a dual-converter three-phase pulse width modulation (PWM) rectifier based on unbalanced one-cycle control (OCC) strategy is proposed. The proposed rectifier is used to eliminate the second harmonic waves of DC voltage and distortion of line currents under unbalanced input grid voltage conditions. The dual-converter PWM rectifier employs two converters, which are called positive-sequence converter and negative-sequence converter. The unbalanced OCC system compensates feedback currents of positive-sequence converter via grid negative-sequence voltages, as well as compensates feedback currents of negative-sequence converter via grid positive-sequence voltages. The AC currents of positive- and negative-sequence converter are controlled to be symmetrical. Thus, the workload of every switching device of converter is balanced. Only one conventional PI controller is adopted to achieve invariant power control. Then, the parameter tuning is simplified, and the extraction for positive- and negative-sequence currents is not needed anymore. The effectiveness and the viability of the control strategy are demonstrated through detailed experimental verification.

Key words: Invariant power control, Negative-sequence converter, One-cycle control, Positive-sequence converter, Voltage sag

I. INTRODUCTION

Public power systems are frequently under unbalanced voltage conditions, and single-phase grid voltage sag happens occasionally. Moreover, even harmonic waves appear on DC voltage, as well as distortion on line currents of traditional three-phase PWM rectifiers. Therefore, public power systems could be polluted by harmonics, and power loss of PWM rectifier could be increased dramatically. New control strategy and topology for three-phase PWM rectifier under unbalanced input voltage conditions must be developed. The control goal is to keep DC voltage constant and sinusoidal currents symmetrical together with unity-power factor. Several control methods have been reported for three-phase

PWM rectifier under unbalanced input voltage conditions. Relevant experts and scholars have conducted numerous analyses and research.

Proportional resonant (PR) controller was adopted to realize control of current under two-phase static coordinate that is free from static error [1]-[6]. However, the analysis and design of PR controller are difficult, and the control performance is affected by grid frequency. Furthermore, a DC voltage outer loop PI controller and two PR current inner loop controllers are required. Given that a single-converter structure is adopted, the three-phase grid currents of converter are unsymmetrical, and the workload of the converter switching device is unbalanced. Positive- and negative-sequence dual-current inner loop PI control structures were presented [7]-[11], and static error-free control for the grid positive- and negative-sequence currents could effectively prevent DC voltage fluctuation and grid current distortion. However, the control structure and algorithm are complicated. The structure requires four current inner loop controllers and one voltage outer loop controller,

Manuscript received Apr. 27, 2014; accepted Aug. 26, 2014

Recommended for publication by Associate Editor Jae-Do Park.

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namely, five PI controllers. Thus, a large amount of calculation is required. Parameter tuning is also difficult, and the design uses the single-converter structure as well. Therefore, the converter could not achieve symmetrical three-phase currents, thereby leading to unbalanced workload of converter switching devices.

In view of the preceding analysis, the goal of unbalanced control strategy for three-phase PWM rectifier under unbalanced grid voltage conditions lies in the following factors: the stability of DC voltage, the sinusoidal AC current, and the three-phase symmetric currents, which can balance the workload of the switching devices. The traditional control strategy and the topology could not achieve the three control targets simultaneously.

On the basis of the comprehensive analysis of the preceding papers and research achievements, a novel unbalanced one-cycle control (OCC) strategy for dual-converter PWM rectifier under unbalanced voltage conditions is proposed in this paper according to the perspective of the preceding three control targets. The dual-converter PWM rectifier employs two converters, which are called positive-sequence converter and negative-sequence converter. This unbalanced OCC strategy compensates feedback currents of positive-sequence converter via grid negative-sequence voltages and compensates feedback currents of negative-sequence converter via grid positive-sequence voltages. Therefore, the positive-sequence currents flow through the positive-sequence converter, and the negative-sequence currents flow through the negative-sequence converter. The currents of every converter are symmetrical, and the workload of every switching device is balanced. The harmonic of DC voltage and the distortion of line currents of three-phase PWM rectifier have been eliminated effectively under unbalanced voltage conditions. Unlike the above unbalanced control strategies, the proposed unbalanced OCC strategy uses only one conventional outer loop PI controller, which regulates power to be constant and requires no parameter tuning for current inner loops. The calculations for the AC positive- and negative-sequence currents are also not required. Thus, the proposed unbalanced OCC strategy achieves high performance with reduced calculation.

II. OCC FOR DUAL-CONVERTER THREE-PHASE PWM RECTIFIER

The topology of OCC for three-phase PWM rectifier is shown in Fig. 1 [12]. In this figure, e_a , e_b , e_c represent the three-phase AC voltages of grid, while i_a , i_b , i_c stand for the grid three-phase AC current; U_{dc} is the DC voltage, R is the equivalent DC load, and S_{xy} is ($x = a, b, c$ and $y = p, n$) the

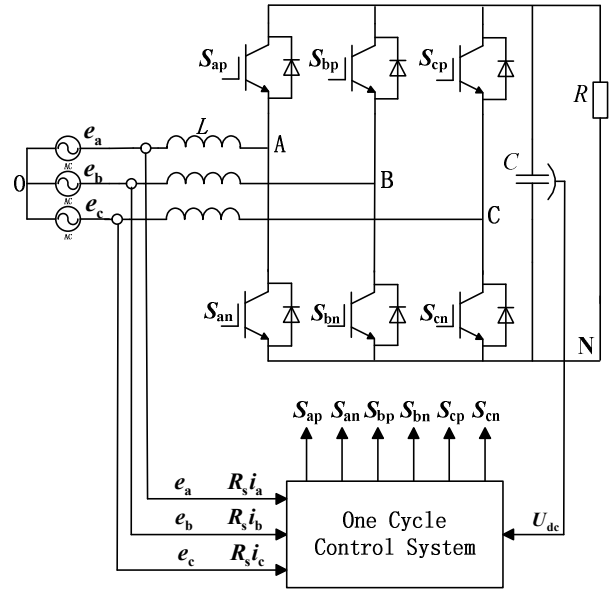


Fig. 1. Topology of OCC for three-phase PWM rectifier.

switching devices of PWM rectifier.

Assuming that grid voltages are under symmetric conditions, the above topology and the traditional OCC system could perform well, and the operating performance would deteriorate sharply under unbalanced grid voltage conditions.

According to the symmetrical component decomposition method, the unbalanced grid voltages could be decomposed into positive- and negative-sequence as well as zero-sequence components. Given that the three-phase PWM rectifier adopts three-wire connection, no zero-sequence components flow through the converter. Therefore, given that the zero-sequence voltages are removed, the unbalanced grid voltages are expressed as follows:

$$e'_x = e_x - (e_a + e_b + e_c) / 3 = e_{x+} + e_{x-} \quad (1)$$

where e_{x+} and e_{x-} ($x = a, b, c$) denote the positive- and negative-sequence voltage component, respectively.

When the grid voltages are under unbalanced condition, the active power of the rectifier must be a constant value by regulating this active power based on power balance principle to restrain the DC voltage second harmonics of the rectifier and the grid currents distortion. In addition, the relationship between positive- and negative-sequence voltages and currents was derived in [13].

$$\begin{cases} [\varphi_{x+}(t) - \theta_{x+}(t)] + [\varphi_{x-}(t) - \theta_{x-}(t)] = 180^\circ \\ \frac{|e_{x+}|}{|i_{x+}|} = \frac{|e_{x-}|}{|i_{x-}|} \end{cases} \quad (2)$$

where $\varphi_{x+}(t)$ and $\varphi_{x-}(t)$ denote the instantaneous phase of the grid positive- and negative-sequence voltages, respectively, $\theta_{x+}(t)$ and $\theta_{x-}(t)$ represent the instantaneous phase of the grid positive- and negative-sequence current, and i_{x+} and i_{x-} are

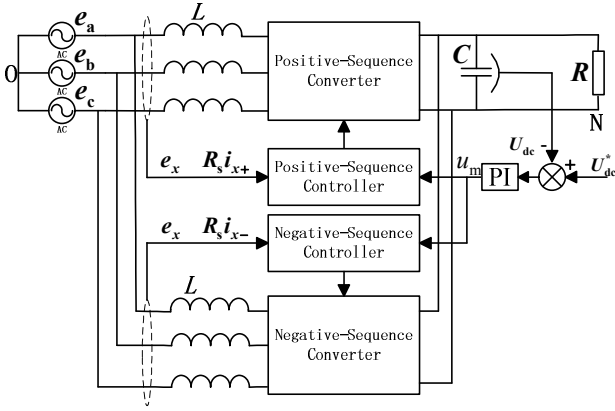


Fig. 2. Topology of unbalanced OCC for dual-converter three-phase PWM rectifier.

the three-phase positive- and negative-sequence currents ($x = a, b, c$).

The unbalanced OCC strategy for dual-converter three-phase PWM rectifier, which is shown in Fig. 2, employs the positive-sequence converter to regulate the grid positive-sequence currents, as well as the negative-sequence converter to regulate grid negative-sequence currents.

According to the relationship shown in (3), the unity-power factor of the rectifier can be achieved by controlling the phase of the grid positive-sequence voltages and currents:

$$\varphi_+(t) = \theta_+(t) \quad (3)$$

From the first item of (2) and (3), the phase relationship between the negative-sequence currents and voltages can be derived as follows:

$$\varphi_-(t) - \theta_-(t) = 180^\circ \quad (4)$$

The grid positive- and negative-sequence voltages and currents are expressed as follows:

$$\begin{cases} e_{x+} = R_{e+} i_{x+} \\ e_{x-} = R_{e-} i_{x-} \end{cases} \quad (5)$$

where R_{e+} and R_{e-} denote the equivalent positive- and negative-sequence power resistors of three-phase PWM rectifier, respectively. From the second item of (2), (3), and (4), the following can be obtained:

$$R_{e-} = -R_{e+} \quad (6)$$

If $R_{e+} = R_{e-}$, then the following can be obtained:

$$R_{e-} = -R_{e+} \quad (7)$$

Three-phase currents of the rectifier can be depicted as follows:

$$i_x = i_{x+} + i_{x-} \quad (8)$$

Fig. 3 shows the equivalent circuit of the positive or negative converter, which is shown in Fig. 1 [12, 16]. In Fig. 3, d_{an} , d_{bn} , d_{cn} are the duty ratios for the converter lower bridge arm switches S_{an} , S_{bn} , S_{cn} , respectively.

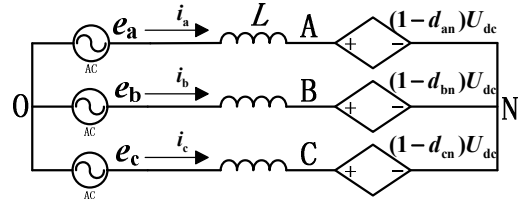


Fig. 3. Equivalent average model of OCC for three-phase PWM rectifier.

The average voltages of rectifier bridge nodes A, B, and C, which are relative to node N, are expressed as follows:

$$u_{XN} = (1 - d_{xn}) U_{dc} \quad (9)$$

where $X = A, B, C$, $x = a, b, c$. Compared with the neutral point O, grid voltage phasor u_{xO} and converter AC side voltage phasor u_{xO} follow that

$$\dot{u}_{xO} = \dot{u}_{xO} - j\omega L i_x \quad (10)$$

According to the analysis in paper [12], the value of the grid side rectifier inductor is actually small (usually approximately 1 mH), and the fundamental wave voltage drops across the inductance can be ignored. Therefore, the converter AC side voltages are approximately equal to the grid voltages:

$$\dot{u}_{xO} \approx \dot{u}_{xO} \Rightarrow u_{xO} \approx u_{xO} = e'_x \quad (11)$$

In Fig. 3, the voltages of nodes A, B, C, node N, and node O must be imposed such that

$$\begin{cases} u_{AO} = u_{AN} + u_{NO} \\ u_{BO} = u_{BN} + u_{NO} \\ u_{CO} = u_{CN} + u_{NO} \end{cases} \quad (12)$$

According to (1), the three-phase converter does not include zero-sequence voltages, and the sum of voltages u_{AO} , u_{BO} , and u_{CO} is equal to zero, that is, $u_{AO} + u_{BO} + u_{CO} = 0$. From (12), we could obtain the voltages between nodes N and O

$$u_{NO} = -\frac{1}{3}(u_{AN} + u_{BN} + u_{CN}) \quad (13)$$

When (13), (11), and (9) are substituted into (12), the relationship between the grid voltages and ratios for rectifier lower bridge arm switches can be derived as follows:

$$\begin{bmatrix} -\frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & -\frac{2}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & -\frac{2}{3} \end{bmatrix} \cdot \begin{bmatrix} d_{an} \\ d_{bn} \\ d_{cn} \end{bmatrix} = \frac{1}{U_{dc}} \cdot \begin{bmatrix} e'_a \\ e'_b \\ e'_c \end{bmatrix} \quad (14)$$

Given that the matrix of (14) is singular, no unique solution exists. Therefore, the following possible solution exists:

$$\begin{cases} d_{an} = k_1 - e'_a / U_{dc} \\ d_{bn} = k_1 - e'_b / U_{dc} \\ d_{cn} = k_1 - e'_c / U_{dc} \end{cases} \quad (15)$$

where k_1 could be a random constant, because the duty ratio d_{xn} must satisfy the inequality, $0 < d_{xn} < 1$ ($x = a, b, c$). When (15) is substituted into this inequality, the following can be obtained:

$$e'_x / U_{dc} < k_1 < 1 + e'_x / U_{dc} \quad (16)$$

From (16), to ensure k_1 is a constant, which would not change along with the grid transient voltages, the following can be acquired:

$$\max(e'_x / U_{dc}) < \min(1 + e'_x / U_{dc}) \quad (17)$$

From (16) and (17), the range of k_1 can be derived as follows:

$$E_{mx} / U_{dc} < k_1 < 1 - E_{mx} / U_{dc} \quad (18)$$

where E_{mx} denotes the grid voltage amplitude.

From (18), the relationship between the DC voltage of three-phase rectifier based on OCC and the grid voltage amplitude can be expressed as follows:

$$E_{mx} / U_{dc} < 1 - E_{mx} / U_{dc} \Rightarrow U_{dc} > 2E_{mx} \quad (19)$$

From (18), the parameter k_1 could be any numerical value in the range of $[E_{mx}/U_{dc}, 1 - E_{mx}/U_{dc}]$, but generally for the sake of increasing application, scope for k_1 , k_1 should be assigned to the middle point value of the range in (18):

$$k_1 = 0.5 \quad (20)$$

Equations (18) and (19) indicate that the essential condition for the OCC system for three-phase PWM rectifier to operate correctly is that the DC voltage is more than double the grid phase voltage amplitude, and then the parameter k_1 could have a solution.

III. OCC STRATEGY FOR POSITIVE-SEQUENCE CONVERTER OF PWM RECTIFIER

Only positive-sequence current i_{x+} should flow through the positive-sequence converter to keep three-phase currents of the positive-sequence converter symmetrical and sinusoidal. Thus, the relationship between voltages and currents of the positive-sequence converter is expressed as follows:

$$R_e i_{x+} = e_{x+} \quad (21)$$

According to (21), the control system compensates feedback currents of the positive-sequence converter by grid negative-sequence voltages under unbalanced grid voltage conditions

$$e_{x-} + R_e i_{x+} = e_{x-} + e_{x+} = e'_x \quad (22)$$

According to (22), the currents of the positive-sequence converter are straightforwardly derived as follows:

$$i_{x+} = \frac{e'_x}{R_e} - \frac{e_{x-}}{R_e} \quad (23)$$

If R_s is the equivalent current sampling resistance [14], [15], then Equation (23) could be expressed as follows:

$$R_s i_{x+} = \frac{R_s e'_x}{R_e} - \frac{R_s e_{x-}}{R_e} \quad (24)$$

For the positive-sequence converter, Equation (15) could be rewritten as follows:

$$\begin{cases} d_{an+} = k_1 - e'_a / U_{dc} \\ d_{bn+} = k_1 - e'_b / U_{dc} \\ d_{cn+} = k_1 - e'_c / U_{dc} \end{cases} \quad (25)$$

where d_{xn+} is the duty ratio for the positive-sequence converter lower bridge arm switches. When (25) is substituted into (24), the following is produced:

$$R_s i_{x+} = \frac{k_1 R_s}{R_e} U_{dc} \left(1 - \frac{d_{xn+}}{k_1}\right) - \frac{R_s}{R_e} e_{x-} \quad (26)$$

When $d_{xn+} = 1 - t_{xp+}/T_s$ is substituted into (26), the following can be obtained:

$$R_s i_{x+} = \frac{k_1 R_s}{R_e} U_{dc} \left(\frac{t_{xp+}}{k_1 T_s} - 1 - \frac{e_{x-}}{k_1 U_{dc}}\right) \quad (27)$$

where T_s denotes the switching period of switches, and t_{xp+} is the turn-on time of each positive-sequence converter upper bridge arm switch in one switching period. From (27), OCC key equations for the positive-sequence converter can be obtained:

$$\begin{cases} R_s i_a = u_{m+} \left(\frac{t_{ap+}}{\tau_+} - 1 - \frac{e_{a-}}{U_{dc} \cdot k_1}\right) \\ R_s i_b = u_{m+} \left(\frac{t_{bp+}}{\tau_+} - 1 - \frac{e_{b-}}{U_{dc} \cdot k_1}\right) \\ R_s i_c = u_{m+} \left(\frac{t_{cp+}}{\tau_+} - 1 - \frac{e_{c-}}{U_{dc} \cdot k_1}\right) \end{cases} \quad (28)$$

where

$$\begin{cases} u_{m+} = \frac{R_s k_1}{R_e} U_{dc} \\ \tau_+ = k_1 T_s \end{cases} \quad (29)$$

where u_{m+} denotes the positive-sequence DC error control voltage, which is used to control output power for rectifier; τ_+ stands for the integral time constant of integrator in OCC system, and its value is half the switching period; and $-u_{m+} e_{x-} / (U_{dc} k_1)$ is the grid negative-sequence voltage compensation item. According to (28), the OCC system structure for the positive-sequence converter can be shown as in Fig. 4.

IV. OCC STRATEGY FOR NEGATIVE-SEQUENCE CONVERTER OF PWM RECTIFIER

Only negative-sequence current i_{x-} should flow through the negative-sequence converter to keep three-phase currents of

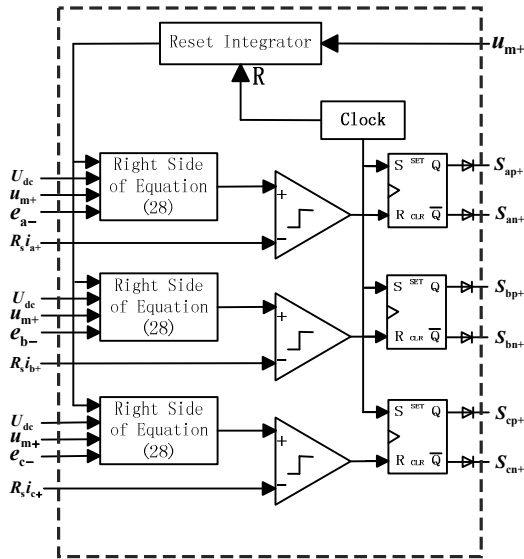


Fig. 4. Unbalanced OCC system for positive-sequence converter.

the positive-sequence converter symmetrical and similar. Thus, the relationship between voltages and currents for the negative-sequence converter is expressed as follows:

$$R_e i_{x-} = -R_e i_{x-} = e_{x-} \quad (30)$$

According to (30), the control system compensates feedback currents of negative-sequence converter via grid positive-sequence voltages under unbalanced grid voltage condition:

$$e_{x+} - R_e i_{x-} = e_{x+} + e_{x-} = e'_x \quad (31)$$

According to (31), the currents of the negative-sequence converter are straightforwardly derived as follows:

$$i_{x-} - \frac{e_{x+}}{R_e} = -\frac{e'_x}{R_e} \quad (32)$$

If R_s is the equivalent current sampling resistance, then Equation (32) could be expressed as follows:

$$\begin{cases} R_s i_{x-} - \frac{R_s}{R_e} e_{x+} = -(k_3 R_s e'_x - k_2 R_s U_{dc} \frac{e'_x}{U_{dc}}) \\ k_3 - k_2 = 1 / R_e \end{cases} \quad (33)$$

where k_2 and k_3 are positive constants that are used to control power for negative-sequence converter and maximum grid currents, respectively. For the negative-sequence converter, Equation (15) could be rewritten as follows:

$$\begin{cases} d_{ap-} = 1 - k_1 + e'_a / U_{dc} \\ d_{bp-} = 1 - k_1 + e'_b / U_{dc} \\ d_{cp-} = 1 - k_1 + e'_c / U_{dc} \end{cases} \quad (34)$$

where d_{xp-} is the duty ratio for the negative-sequence converter upper bridge arm switches. When (34) is substituted into (33), the following can be obtained:

$$R_s i_{x-} - \frac{R_s}{R_e} e_{x+} = -k e'_x + (k - \frac{R_s}{R_e}) U_{dc} [d_{xp-} - (1 - k_1)] \quad (35)$$

where k is similar to k_3 and used to restrain maximum grid currents. Then, substituting the duty ratio $d_{xp-} = t_{xp-} / T_s$ into (35) can obtain the following control key equation:

$$k e_{x-} + R_s i_{x-} = (k - \frac{R_s}{R_e})(1 - k_1) U_{dc} [\frac{t_{xp-}}{(1 - k_1) T_s} - 1 - \frac{e_{x+}}{U_{dc}(1 - k_1)}] \quad (36)$$

where T_s denotes the switching period of switches, and t_{xp-} is the turn-on time of each negative-sequence converter upper bridge arm switch in one switching period. From (36), the OCC key equation for the negative-sequence converter can be obtained:

$$\begin{cases} k e_{a-} + R_s i_{a-} = u_{m-} [\frac{t_{ap-}}{\tau} - 1 - \frac{e_{a+}}{U_{dc}(1 - k_1)}] \\ k e_{b-} + R_s i_{b-} = u_{m-} [\frac{t_{bp-}}{\tau} - 1 - \frac{e_{b+}}{U_{dc}(1 - k_1)}] \\ k e_{c-} + R_s i_{c-} = u_{m-} [\frac{t_{cp-}}{\tau} - 1 - \frac{e_{c+}}{U_{dc}(1 - k_1)}] \end{cases} \quad (37)$$

where

$$\begin{cases} u_{m-} = (k - \frac{R_s}{R_e})(1 - k_1) U_{dc} \\ \tau = (1 - k_1) T_s \end{cases} \quad (38)$$

where u_{m-} denotes the negative-sequence DC error control voltage, which is used to control output power for rectifier. τ is the integral time constant of integrator of OCC system, and its value is half of switching period, and $-u_{m-} e_{x+} / (U_{dc}(1 - k_1))$ is the grid positive-sequence voltage compensation item. According to (37), the OCC system structure for the negative-sequence converter can be shown in Fig. 5.

According to (28) and (37), the positive and negative-sequence converters adopt the same bipolar OCC strategy, and the switching operations of positive- and negative-sequence converter switches are nearly at the same time based on Figs. 4 and 5. Therefore, the high-frequency circulation currents between the positive-sequence converter and the negative-sequence converter can be eliminated [16].

V. UNBALANCED OCC SYSTEM FOR DUAL-CONVERTER PWM RECTIFIER

Grid positive- and negative-sequence voltages could be decomposed under two-phase stationary coordinate system from the retained voltage, which is described by (39).

$$\begin{bmatrix} e_{\alpha+} \\ e_{\beta+} \\ e_{\alpha-} \\ e_{\beta-} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} e_{\alpha} & e_{\beta} & e_{\alpha}^{\perp} & e_{\beta}^{\perp} \end{bmatrix}^T \quad (39)$$

where e_{α} and e_{β} are α and β axis coordinate components of the

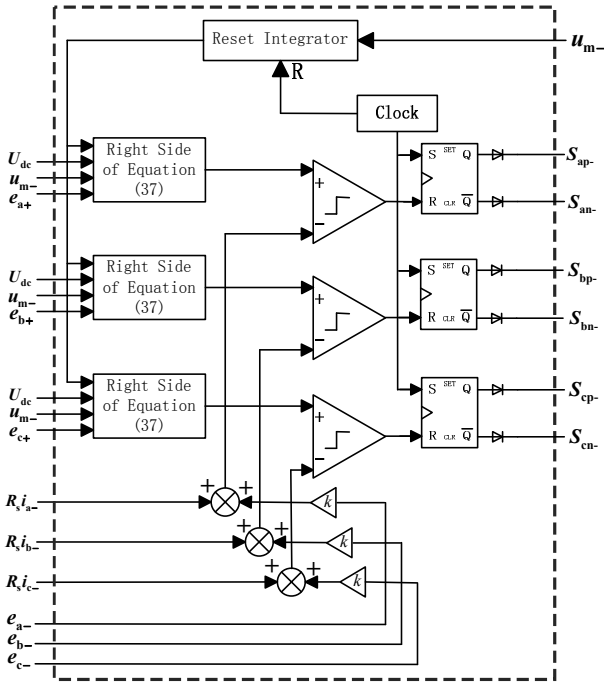


Fig. 5. Unbalanced OCC system for negative-sequence converter.

grid voltages, respectively, and e_{α}^{\perp} and e_{β}^{\perp} denote the α and β axis coordinate components, which delay one-fourth power period. The transient values of the grid positive- and negative-sequence voltages under three-phase stationary coordinate are derived as follows:

$$\begin{bmatrix} e_{a+} \\ e_{b+} \\ e_{c+} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_{\alpha+} \\ e_{\beta+} \end{bmatrix} \quad (40)$$

$$\begin{bmatrix} e_{a-} \\ e_{b-} \\ e_{c-} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_{\alpha-} \\ e_{\beta-} \end{bmatrix} \quad (41)$$

According to the characteristics of the dual-converter PWM rectifier, the positive- and negative-sequence converters must share the same PI outer loop voltage controller. Therefore, the error control voltage of the positive sequence u_{m+} is equal to the error control voltage of the negative sequence u_{m-} . According to (29) and (38), u_{m+} can be made equal to u_{m-} by adjusting the parameters k , R_s , and R_c . If $u_{m+} = u_{m-} = u_m$ and given that $k_1 = 0.5$, namely, $k_1 = 1 - k_1$, then parameter k is expressed as follows:

$$k = \frac{2R_s}{R_c} \quad (42)$$

The mathematical relationship between error control voltage u_m and DC voltage U_{dc} can be derived as follows:

$$u_m = \frac{k}{4} U_{dc} \quad (43)$$

From (43), PI controller can be employed to control the DC voltage for the unbalanced OCC system, and the control equation for DC voltage is expressed as follows:

$$u_m = (K_p + K_I \int dt)(U_{dc}^* - U_{dc}) \quad (44)$$

where U_{dc}^* denotes the set value of DC voltage for rectifier, U_{dc} is the rectifier feedback DC voltage, and K_p and K_I are the proportionality and integral coefficient for PI controller, respectively. From Fig. 2 and (43), the following can be obtained:

$$k = \frac{4u_m}{U_{dc}^*} \quad (45)$$

According to (28) and Fig. 4, the feedback currents of the positive-sequence converter, which are the positive-sequence currents, must be transmitted to the negative inputs of the comparator of the positive-sequence controller to ensure that the three-phase currents, which flow through the positive-sequence converter, are symmetric. According to OCC theory, the positive-sequence currents of the positive-sequence converter could be used to cancel out the grid positive-sequence voltages. The positive- and negative-sequence voltages exist under unbalanced grid voltage conditions simultaneously, and the grid negative-sequence voltage compensation component is transmitted to the positive inputs of comparator of positive-sequence controller to cancel out the negative-sequence voltages. Therefore, the feedback currents of the positive-sequence converter should be compensated by negative-sequence components of grid voltages. Similarly, from (37) and Fig. 5, the feedback currents of the negative-sequence converter, which are the negative-sequence currents, must be transmitted to the positive inputs of comparator of positive-sequence controller to ensure that the three-phase currents, which flow through the negative-sequence converter, are symmetric. According to (6), the positive-sequence converter serves as a rectifier, whereas the negative-sequence converter serves as a grid-connected inverter that inverts the second harmonic power of the DC side back to grid in form of sinusoidal currents. Therefore, the second harmonic waves of DC voltage and distortion of line currents can be eliminated.

According to (28) and (37), the positive- and negative-sequence currents flow through the positive- and negative-sequence converters, respectively, and the unbalanced factor for the grid voltages is defined by [17]:

$$VUF = \frac{|U_-|}{|U_+|} = \sqrt{\frac{6(U_{ab}^2 + U_{bc}^2 + U_{ca}^2)}{(U_{ab} + U_{bc} + U_{ca})^2}} - 2 \quad (46)$$

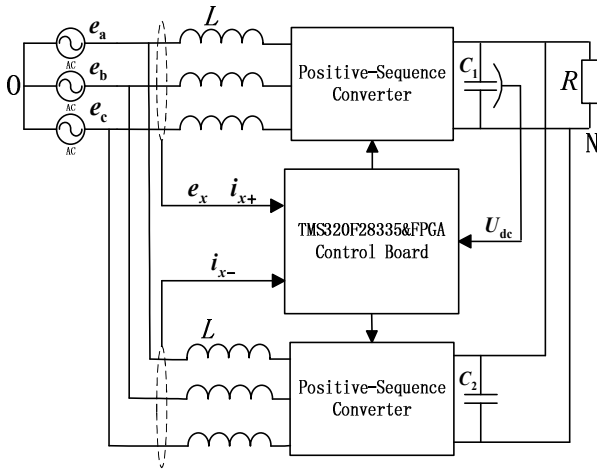


Fig. 6. Experiment system of unbalanced OCC for dual-converter three-phase PWM rectifier.

where U_+ and U_- denote the grid positive- and negative-sequence RMS voltages, respectively, whereas U_{ab} , U_{bc} , and U_{ca} are the grid RMS line voltages. The relationship between positive- and negative-sequence currents can be derived as follows:

$$|i_{x-}| = VUF|i_{x+}| \quad (47)$$

According to (47), the negative-sequence converter is VUF times the capacity of design and the rated currents of switching devices and inductance of positive-sequence converter in engineering applications. To achieve consistency, the inductance of negative-sequence converter should be designed to be $1/VUF$ times the value of the inductance of the positive-sequence converter. The reduction in the rated currents of inductance of negative-sequence converter could reduce the size of inductor magnetic core and then greatly reduce the cost. For example, if the unbalanced factor VUF is 10% for the design, then the negative-sequence converter is 10% the capacity of the positive-sequence converter. In addition, the cost of negative-sequence converter is greatly reduced. According to (47), because i_{x-} is less than i_{x+} , the loss of negative-sequence converter is also less than positive-sequence converter. Therefore, the extra loss caused by the negative-sequence converter increases slightly. In particular, when the grid voltage is under slightly unbalanced condition and VUF is nearly zero, the current of the negative-sequence converter remains nearly zero, and the loss increases slightly.

VI. EXPERIMENTAL RESULTS

A three-phase dual-converter PWM rectifier based on unbalanced OCC strategy is designed in this study to verify the validity of the theoretical analysis and research. The control system for the rectifier adopts the digital signal processor (DSP) TMS320F28335, and the capacity of the

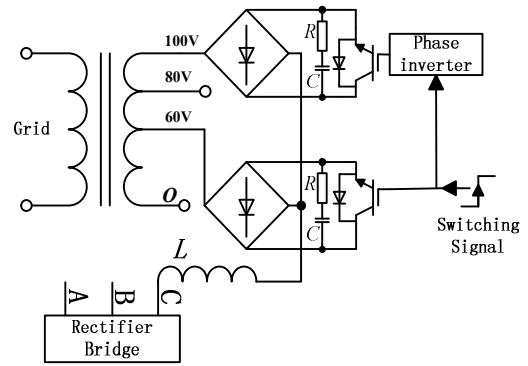


Fig. 7. Voltage sag generator of Phase C.

TABLE I
EXPERIMENTAL PARAMETERS FOR THREE-PHASE PWM RECTIFIER

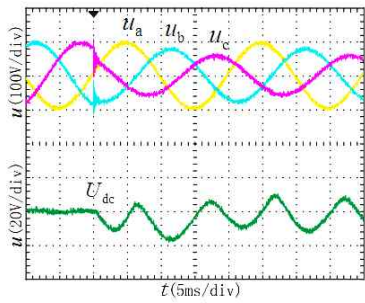
Given DC voltage	U_{dc}^*	250 V
Load resistor	R	20 Ω
Filter inductor of positive- and negative-sequence converter	L_+	1.2 mH
	L_-	5 mH
DC side filter capacitor	C	1360 μ F
PI controller parameters	K_p	1.6
	K_i	100
OCC system parameters	R_s	0.5 Ω
	k	0.2
RS flip-flop clock frequency	f_s	12.8 kHz
Integral time constant of the integrator($\tau_+ = \tau_- = \tau = k_1 T_s$)	τ_+	0.0390625 ms
	τ_-	0.0390625 ms

rectifier is designed as 5 kVA. The experimental system structure is shown in Fig. 6.

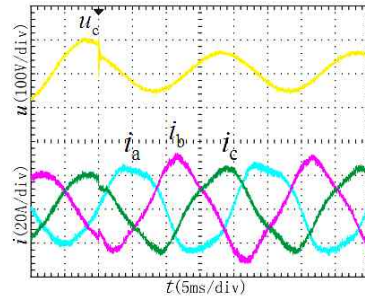
The control software was completed by TMS320F28335 DSP. Moreover, the digital integrator, data comparator, RS flip-flop, and clock generator were completed by using a field programmable gate array. On the basis of the laboratory prototype, we conducted research on the conventional rectifier based on balanced OCC strategy and dual-converter rectifier based on unbalanced OCC strategy.

The grid unbalanced fault was simulated by voltage sag generator, which is shown in Fig. 7. The voltage sag generator employed a three-phase transformer with 9000 VA capacity. Each phase of the transformer output windings had three taps, and the output voltage amplitudes of every tap were 100, 80, and 60 V.

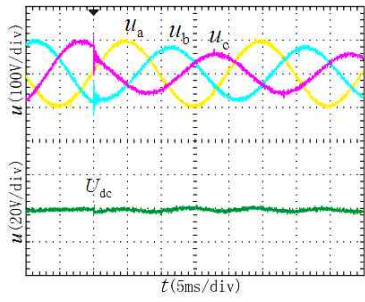
The grid was initially under balanced voltage conditions, and three-phase voltage amplitudes were all 100 V. After the rectifier was running stably, we simulated an unbalanced fault by using voltage sag generator. Moreover, the voltage amplitude of Phase A remained 100 V, the voltage amplitude of Phase B dropped to 80 V, and the voltage amplitude of Phase C dropped to 60 V. Table I lists the experimental parameters for the three-phase PWM rectifier, and the experimental results are shown in Fig. 8.



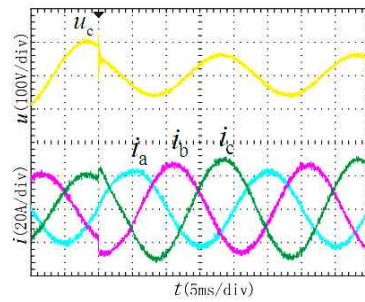
(a) DC voltage waveforms of PWM rectifier based on conventional balanced OCC strategy under Phase B and Phase C voltage sag.



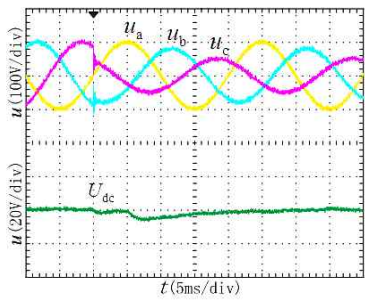
(b) Three-phase current waveforms of PWM rectifier based on conventional balanced OCC strategy under Phase B and Phase C voltage sag.



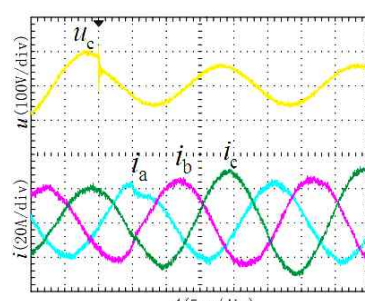
(c) DC voltage waveforms of single-converter PWM rectifier based on PR controller under Phase B and Phase C voltage sag.



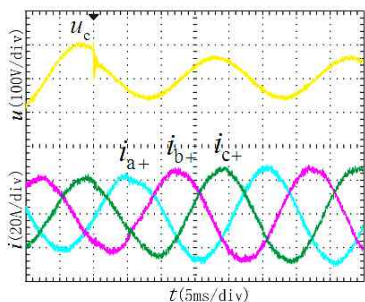
(d) Three-phase current waveforms of single-converter PWM rectifier based on PR controller under Phase B and Phase C voltage sag.



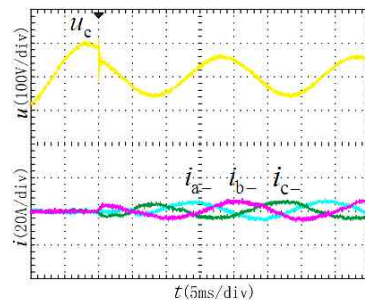
(e) DC voltage waveforms of dual-converter PWM rectifier based on unbalanced OCC strategy under Phase B and Phase C voltage sag.



(f) Three-phase current waveforms of dual-converter PWM rectifier based on unbalanced OCC strategy under Phase B and Phase C voltage sag.



(g) Three-phase current waveforms of positive-sequence converter based on unbalanced OCC strategy under Phase B and Phase C voltage sag.



(h) Three-phase current waveforms of negative-sequence converter based on unbalanced OCC strategy under Phase B and Phase C voltage sag.

Fig. 8. Experimental waveforms of three-phase PWM rectifier under unbalanced grid voltage conditions.

The experimental waveforms of DC voltage and AC currents of the conventional rectifier based on balanced OCC strategy under unbalanced voltage conditions are shown in Figs. 8(a) and 8(b), respectively, where the second harmonic waves of DC voltage and distortion of line currents appeared. The total harmonic distortion (THD) of the AC currents is nearly 13%, and the oscillation of DC voltage is approximately 19 Vpp. The experimental waveforms of DC voltage and AC currents of the single-converter rectifier based on PR controller under unbalanced voltage conditions are shown in Figs. 8(c) and 8(d), respectively, where the DC voltage oscillation is approximately 4 Vpp in steady state, which is less than that of the conventional rectifier. The line current is nearly sinusoidal, and the distortion is restrained. However, the line current is unsymmetrical. Thus, the workload of every switching device is unbalanced, and the power rating of every switching device cannot be used to the fullest. The experimental waveform of the DC voltage of the dual-converter rectifier based on unbalanced OCC strategy under unbalanced voltage conditions is shown in Fig. 8(e), where the DC voltage enters the steady state rapidly with a slight oscillation, which is only approximately 2 Vpp. Fig. 8(f) shows the AC line currents of the dual-converter rectifier, which are the sum of the positive- and negative-sequence currents under unbalanced voltage conditions. The AC line currents of the dual-converter rectifier are not symmetric but sinusoidal. The three-phase AC current waves of the positive- and negative-sequence converter are shown in Figs. 8(g) and 8(h), where the three-phase AC currents are all symmetric sinusoidal waveforms. The distortion of line currents is eliminated, and the THD is only approximately 2.5%. The power factor is approximately 0.97, and the dual-converter PWM rectifier runs nearly in unity-power factor state.

VII. CONCLUSIONS

An unbalanced OCC strategy for dual-converter three-phase PWM rectifier based on grid positive- and negative-sequence voltage feedforward compensation was proposed in this paper to eliminate the second harmonic waves of DC voltage and distortion of line currents for a three-phase PWM rectifier under unbalanced input grid voltage conditions. The unbalanced OCC mathematical model for the positive-sequence converter based on the grid negative-sequence voltage feedforward compensation and the model for the negative-sequence converter based on the grid positive-sequence voltage feedforward compensation were presented. Moreover, the current control and parameter tuning method was investigated. The experimental results indicate that unlike other unbalanced control strategies, the proposed unbalanced OCC strategy for dual-converter three-phase PWM rectifier needs no calculation for the positive- and negative-sequence currents and no designation

for current inner loop controller. Therefore, the control system for the dual-converter three-phase rectifier only has one PI controller, and the control structure is simplified. The second harmonic waves of DC voltage and distortion of AC line currents of rectifier are eliminated, and the harmonic pollution to grid is reduced greatly under unbalanced grid voltage conditions. Moreover, the positive- and negative-sequence converters both achieved symmetrical three-phase sinusoidal currents, which balance the workload of all the switching devices of the converters, and high-power factor can be achieved. With the proposed dual-converter topology and the corresponding unbalanced control strategy, the performance of the three-phase PWM rectifier is ultimately optimized under unbalanced grid voltage conditions.

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