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# Operation of Unified Constant-frequency Integration Controlled Three-phase Power Factor Correction in Unbalanced System

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## ABSTRACT

In recent years, the power quality of the AC system has become a great concern due to the rapidly increased numbers of electronic equipment. In order to reduce harmonic contamination in power lines and improve the transmission efficiency, power factor correction research became a hot topic. Many control methods for the Power Factor Correction (PFC) were proposed. The theory and experiments have demonstrated that Unified Constant-frequency Integration (UCI) controller features excellent performance, simple circuitry, and low cost for three-phase PFC under three-phase balanced conditions. In this paper, a three-phase PFC working in an unbalanced condition with a UCI controller are studied. Analysis and simulation show that with UCI control sinusoidal input current can be realized, whether the input voltages are balanced or unbalanced.

## KEY WORDS

PFC, Unified Constant-frequency Integration (UCI), One Cycle Control, Power Quality.

## 1. INTRODUCTION

To obtain low AC line current THD; passive and active three-phase Power Factor Correction (PFC) rectifier techniques are used. Passive techniques look straightforward, but they rely on low-frequency transformers and/or reactive elements. The large size and weight of these elements are objectionable in many applications [1]. On the contrary active techniques can reduce the size and weight of whole rectifier with complicated controller. Thus the research to simplify the controller in active PFC rectifier becomes a hot point in this field.

Three-phase boost PFC rectifiers are preferred topologies for high power application due to their symmetric and high efficiency characteristics. In recent years, many control methods such as Single-switch constant-duty-ratio control method [2], third harmonic injection method [3], hysteretic control, and d-q transformation control were proposed, nevertheless all those control methods result in complex implementation [4]. Based on one-cycle-control, a new control method was proposed in [4-5], which is named Unified Constant-frequency Integration (UCI) controller. The theory and experiment have proven that the UCI controller is a high performance and low cost solution under three-phase balanced conditions. In this paper, the three-phase PFC working in the unbalanced power system with UCI controller is studied. Analysis, simulation, and experiments have shown that UCI controlled PFC realizes sinusoidal input current in either balanced or unbalanced power systems with a very simple circuit.

## 2. REVIEW OF UCI CONTROLLER FOR PFC IN THREE-PHASE BALANCED SYSTEMS

According to [4-5], most of boost-derived three-phase rectifiers can be categorized into two groups: one group of them can be decoupled into a series-connected duel-boost topology that features central-tapped or split dc output capacitors. The other group can be decoupled into a parallel-connected dual-boost topology that features

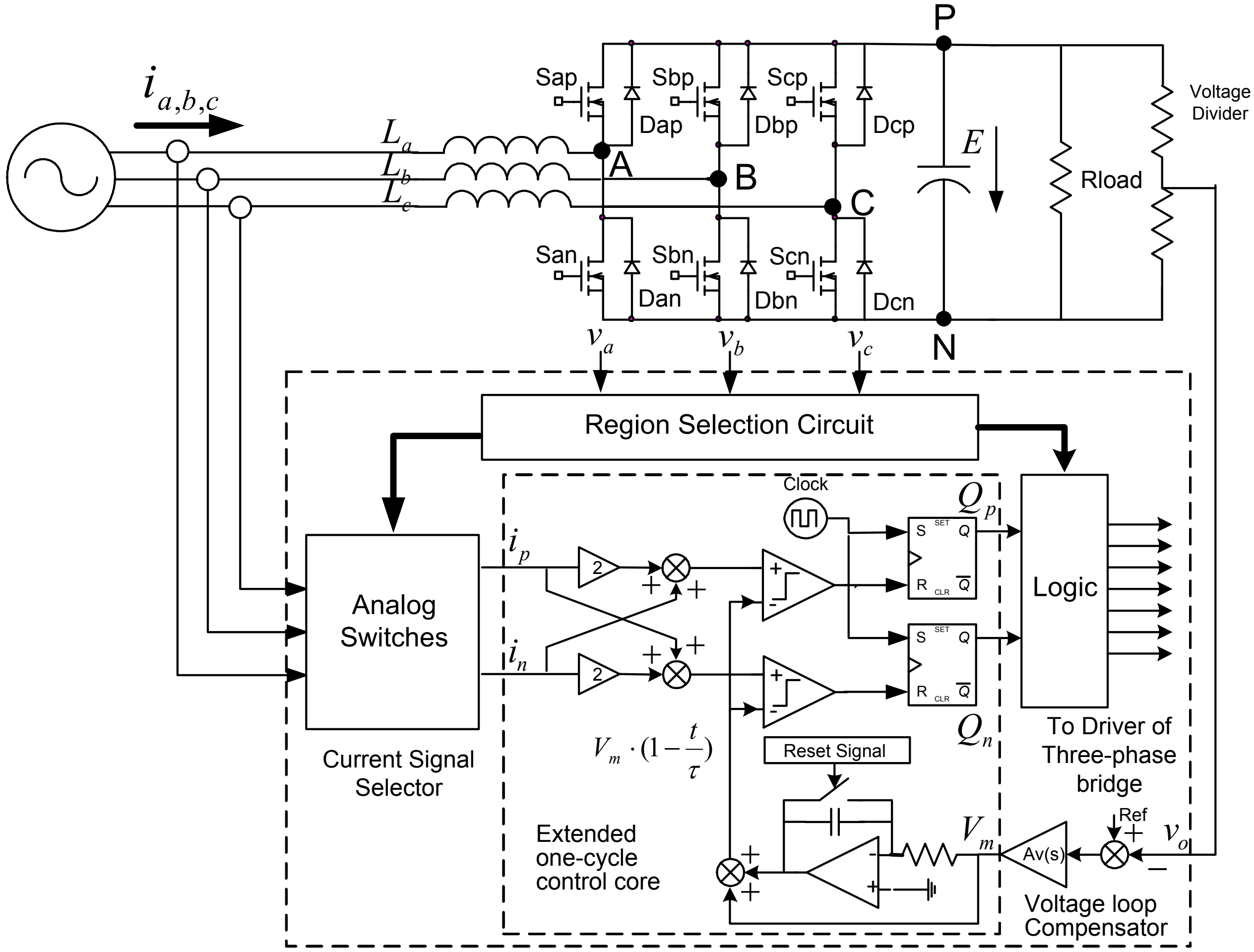


Fig.1 The diagram of the three-phase PFC with UCI controller

a single dc output capacitor. Analysis and experiments in [4-5] proved that UCI controller could control all those boost-derived three-phase rectifiers.

As an example, Fig.1 shows the schematics of the three-phase PFC rectifier, which employs a three-phase bridge boost rectifier and UCI controller, where, $i_a$, $i_b$, $i_c$ and $v_a$, $v_b$, $v_c$ represent the input currents and voltages of phase A, B, C respectively, voltage divider provide feedback signal of DC bus voltage.

In this analysis, one line period is divided into six regions as depicted in Fig. 2. Article [4] points out that if in each region the duty ratio of the switch in the arm with dominant voltage (highest of lowest) is set to on or off according to the polarity of phase voltage, etc. in the first

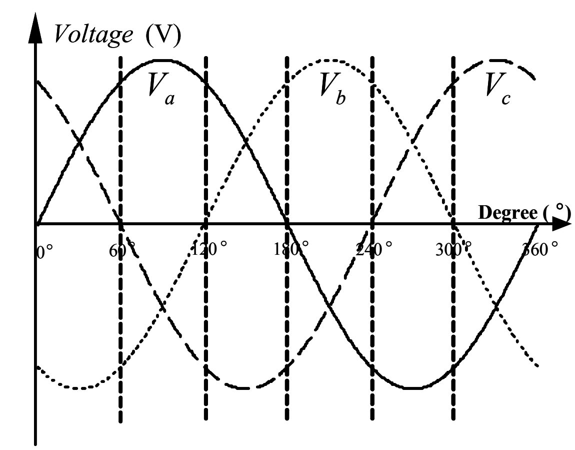


Fig.2 Three-phase voltage waveforms

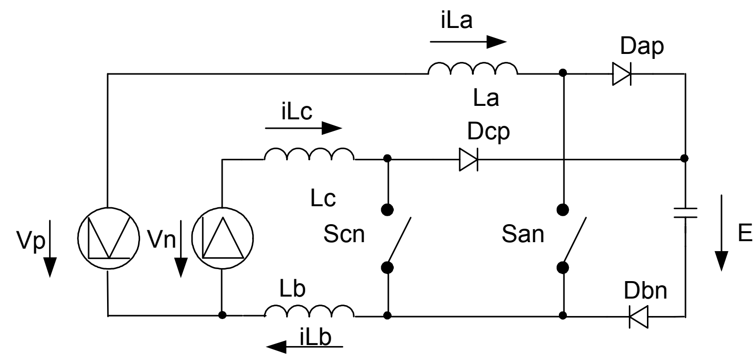


Fig.3 The equivalent parallel-connection dual-boost topology of 3-phase boost rectifier

$60^o$ region $V_b$ is the dominant voltage and its polarity is negative, therefore, $S_{bp}$ is off while $S_{bn}$ is on for the entire region, further more in this region the three-phase bridge boost rectifier can be decoupled into a parallel-connected dual-boost topology as depicted in Fig. 3, where $V_p$ and $V_n$ are given by equation (1),

$$\begin{bmatrix} V_p \\ V_n \end{bmatrix} = \begin{bmatrix} v_{ab} \\ v_{cb} \end{bmatrix} = \begin{bmatrix} v_a - v_b \\ v_c - v_b \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad \ldots (1)$$

In other regions, the equivalent circuits with same construction can be derived.

In the three-phase balanced condition $v_a+v_b+v_c=0$. Based on the inductor volt-second balance concept, in the first $60^o$ region the steady state relationship between input phase voltages and output voltage E via the switch duty ratios for CCM operation is shown as below [4]:

$$\begin{bmatrix} 1-d_a \\ 1-d_c \end{bmatrix} = \frac{1}{E} \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \cdot \begin{bmatrix} V_p \\ V_n \end{bmatrix} = \frac{1}{E} \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_c \end{bmatrix} \quad \ldots (2)$$

where $d_a$ and $d_c$ are the duty ratios of $S_{an}$ and $S_{cn}$.

For the three-phase PFC rectifier, the control goal is to achieve unit-power-factor, ie.

$$V_g = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_e \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = R_e \cdot i_g \quad \ldots (3)$$

where $R_e$ is the emulated resistance that reflects the real power of the load. Combination of the above two equations and elimination of input voltage $V_g$ yield the key equation of UCI control in the first $60^o$ region:

$$V_m \cdot \begin{bmatrix} 1-d_a \\ 1-d_c \end{bmatrix} = R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_c \end{bmatrix} \quad \ldots (4)$$

where $R_s$ is the current sensing resistance and $V_m$ is given by

$$V_m = R_s \cdot \frac{E}{R_e} \quad \ldots (5)$$

Similarly, the control equations for the other five regions can be derived [4]. These control equations can be realized by the one cycle control circuit that is composed of one integrator with reset along with some logic and linear components as shown in Fig.1. The operation waveforms of UCI controller are shown in Fig.4, where $i_p$ and $i_n$ represent the currents from the non-dominant phases selected by the current signal selector. In the first $60^o$ region, $i_p=i_a$, $i_n=i_b$ At the beginning of each switching cycle, the clock pulse sets the two flip-flops. The currents $i_p$ and $i_n$ from the analog switches is linearly combined to form an input to each of the two comparators. The value of other input of the two comparators is that $V_m$ minus the integrated value of Vm, ie. $Vm-V_m(t/T_s)$. in the upper comparator $V_m-V_m(t/T_s)$ is compared with $R_s(2i_p+i_n)$

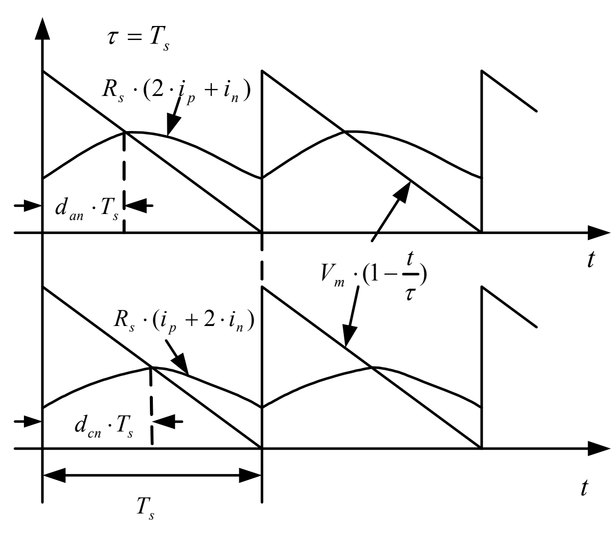


Fig.4 The operation waveform of UCI controller

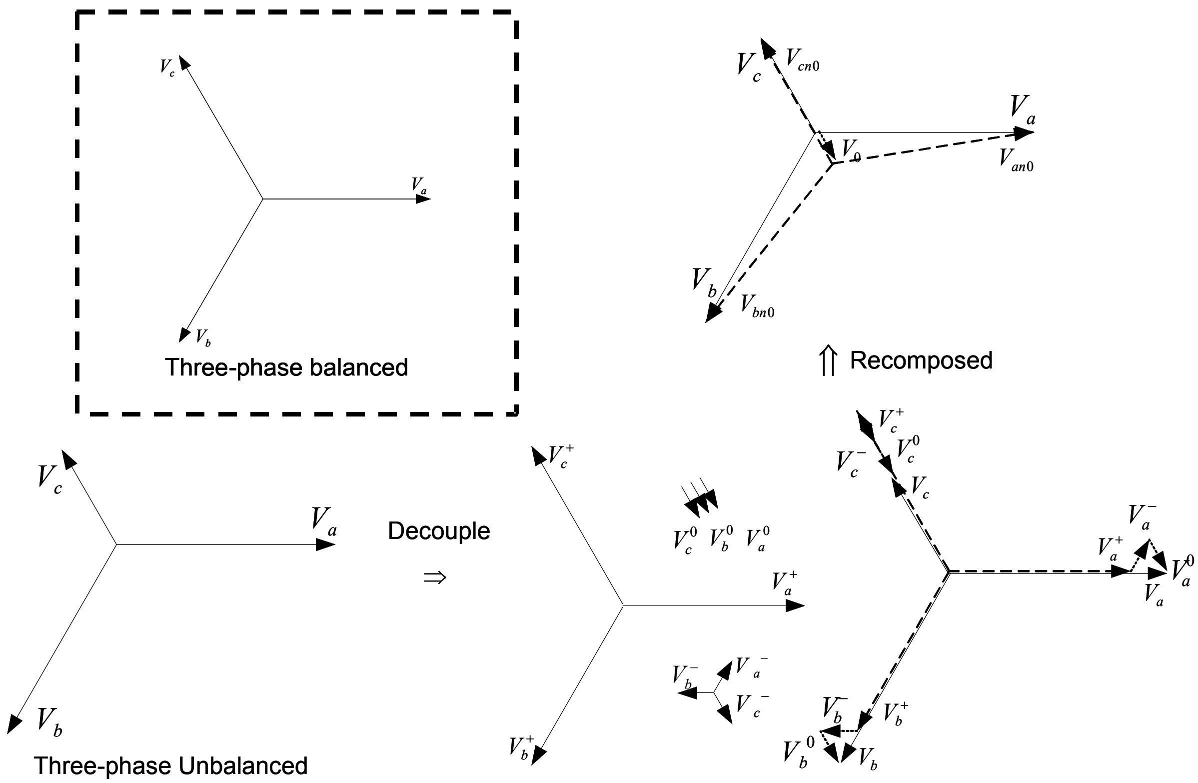


Fig.5 The vector diagram of three-phase input voltage in balanced and unbalanced power system.

and in the lower comparator it is compared with $R_s(i_p+2i_n)$ as depicted in Fig.1. When the two inputs of a comparator meet as depicted in Fig.4, the comparator changes its state, which resets the correspondent Flip-Flop. As a result, the correspondent switch is turned off. In this process, the duty ratios d is determined for the correspondent switch in each switching cycle. Implementation of equation (4) by one-cycle control results in the proposed controller.

## 3. OPERATION OF UCI CONTROLLED THREE-PHASE PFC IN UNBALANCED SYSTEMS

For three-phase unbalanced condition, Article [6] points out that unbalanced three-phase input voltages $v_a$, $v_b$, $v_c$ can be decoupled into positive $v_a^+$, $v_b^+$,$v_c^+$ , negative $v_a^-$, $v_b^-$,$v_c^-$, and zero sequence $v_a^0$, $v_b^0$, $v_c^0$, components as drawn in Fig.5, and since the vector sum of the positive and negative sequence components is zero, while the vector sum of the zero sequence components is non-zero, it will be convenient to decouple unbalanced three-phase voltages into two parts—non-zero sequence components and zero sequence components as in Fig.5.

As discussed in the previous section, equation (2) was derived under the assumption that $v_a+v_b+v_c=0$, however in an unbalanced three-phase system as shown in Fig.5, $v_a+v_b+v_c\neq0$, due to the presence of the zero sequence components. It is, therefore, the objective of this paper to examine the UCI controller under the unbalanced condition. With unbalanced three-phase voltages, the relationship established in equation (2) for the phase voltage $v_a$, $v_b$, $v_c$, and output voltage $E$ needs be reevaluated.

Since fig.5 depicted that:

$$\begin{cases} v_a = v_{an0} + v_{a0} \\ v_b = v_{bn0} + v_{b0} \\ v_c = v_{cn0} + v_{c0} \end{cases} \quad \cdots\cdots (6)$$

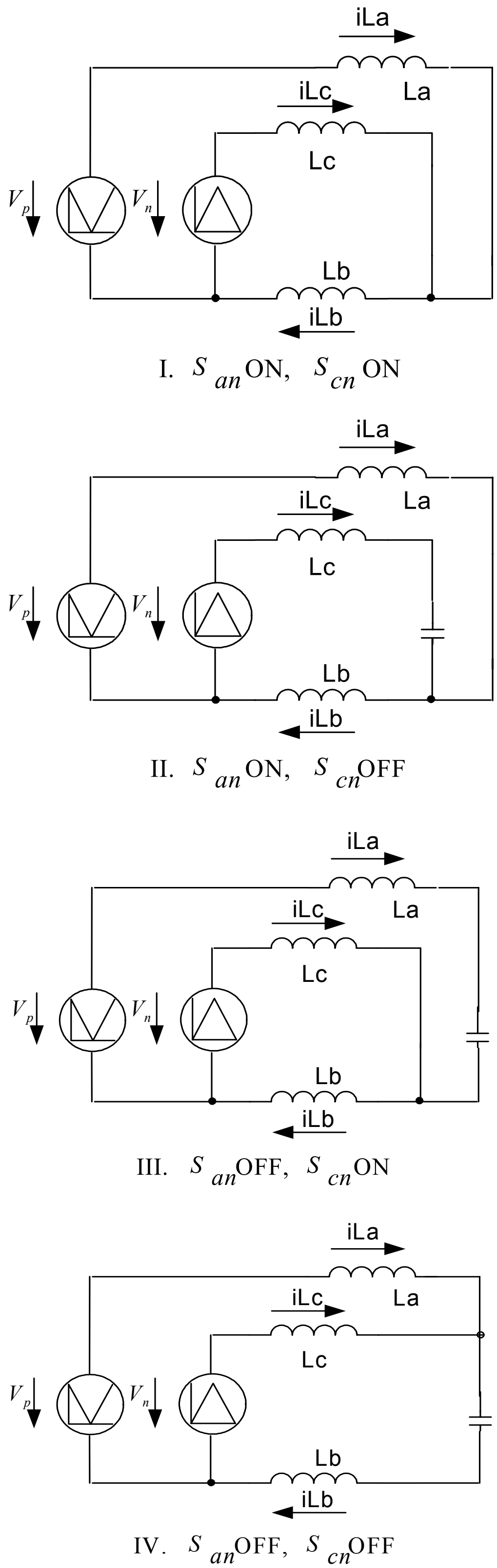


Fig.6 The equivalent circuits for the parallel-connected dual-boost topology in all four switching states

as well as $v_{ano}+v_{bno}+v_{cno}=0$, and $v_{ao}+v_{bo}+v_{co}\neq 0$, equation (1) can be rewritten as below:

$$\begin{bmatrix} V_p \\ V_n \end{bmatrix} = \begin{bmatrix} v_{ab} \\ v_{cb} \end{bmatrix} = \begin{bmatrix} v_{an0}-v_{bn0} \\ v_{cn0}-v_{bn0} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_{an0} \\ v_{bn0} \\ v_{cn0} \end{bmatrix} \quad (7)$$

**Table 1. Switching states and inductor voltages for the parallel-connected dual-boost topology**

| State | $S_{an}$ | $S_{cn}$ | $V_{La}$ | $V_{Lc}$ | $V_{Lb}$ |
|---|---|---|---|---|---|
| I | ON | ON | $V_p^*$ | $V_n^*$ | $V_t^*$ |
| II | ON | OFF | $V_p^*+\frac{1}{3}\cdot E$ | $V_n^*-\frac{2}{3}\cdot E$ | $V_t^*-\frac{1}{3}\cdot E$ |
| III | OFF | ON | $V_p^*-\frac{2}{3}\cdot E$ | $V_n^*+\frac{1}{3}\cdot E$ | $V_t^*-\frac{1}{3}\cdot E$ |
| IV | OFF | OFF | $V_p^*-\frac{1}{3}\cdot E$ | $V_n^*-\frac{1}{3}\cdot E$ | $V_t^*-\frac{2}{3}\cdot E$ |

For the dual-boost equivalent circuit shown in Fig.3, four switch states are available for the two switches San and Scn. The switching states and inductor voltages are shown in Table 1. The equivalent circuits of the dual-boost in all switching states are shown in Fig.6, where

$$\begin{bmatrix} V_p^* \\ V_n^* \\ V_t^* \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} \\ \frac{1}{3} & \frac{1}{3} \end{bmatrix} \cdot \begin{bmatrix} V_p \\ V_n \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} \\ \frac{1}{3} & \frac{1}{3} \end{bmatrix} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_{an0} \\ v_{bn0} \\ v_{cn0} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \\ \frac{1}{3} & -\frac{2}{3} & \frac{1}{3} \end{bmatrix} \cdot \begin{bmatrix} v_{an0} \\ v_{bn0} \\ v_{cn0} \end{bmatrix} \quad (8)$$

For a three-phase PFC with a constant switching frequency, only two switching sequences are possible, i.e. I, II, IV (when $d_a>d_c$) or I, III, IV (when $d_c<d_a$) during each switching cycle. Based on the assumption that switching frequency is much higher than the line frequency, the inductor voltage-second balance is used. When $d_a>d_c$, it can be expressed below:

$$\begin{cases} V_p^*\cdot d_c + (V_p^*+\frac{1}{3}\cdot E)\cdot(d_a-d_c) + (V_p^*-\frac{1}{3}\cdot E)\cdot(1-d_a) = 0 \\ V_n^*\cdot d_c + (V_n^*-\frac{2}{3}\cdot E)\cdot(d_a-d_c) + (V_n^*-\frac{1}{3}\cdot E)\cdot(1-d_a) = 0 \\ V_t^*\cdot d_c + (V_t^*-\frac{1}{3}\cdot E)\cdot(d_a-d_c) + (V_t^*-\frac{2}{3}\cdot E)\cdot(1-d_a) = 0 \end{cases} \quad (9)$$

From equation (9), the following equation is true:

$$V_p^* + V_n^* - V_t^* = 0 \quad (10)$$

Combination of the equation (9), (10) and further simplification yield

$$\begin{bmatrix} 1-d_a \\ 1-d_c \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} \frac{V_p^*}{E} \\ \frac{V_n^*}{E} \end{bmatrix} \quad \text{.............................(11)}$$

It can be verified that same equation can be achieved for the other switching sequence I, III, and IV ($d_a<d_c$ ) as well.

In the first 60° region, the relationship between $V_p^*$, $V_n^*$ and $v_a, v_b, v_c$ can be derived as below:

$$\begin{cases} V_p^* = \frac{2}{3}\cdot V_p - \frac{1}{3}\cdot V_n = \frac{2}{3}\cdot(v_{an0}-v_{bn0}) - \frac{1}{3}\cdot(v_{cn0}-v_{bn0}) = v_{an0} \\ V_n^* = \frac{2}{3}\cdot V_n - \frac{1}{3}\cdot V_p = \frac{2}{3}\cdot(v_{cn0}-v_{bn0}) - \frac{1}{3}\cdot(v_{an0}-v_{bn0}) = v_{cn0} \end{cases}$$

........................................................... (12)

With UCI controller the key equation depicted in equation (4) will not be changed, thus the relationship between input currents and voltages can be derived by the combination of equation (11), (12) and (4), which is expressed as below:

$$\begin{bmatrix} i_a \\ i_c \end{bmatrix} = \frac{V_m}{R_s \cdot E} \cdot \begin{bmatrix} v_{an0} \\ v_{cn0} \end{bmatrix} \quad \text{---------------------------------- (13)}$$

for three-phase three-wire system $i_a + i_b + i_c = 0$, the following relationship can be derived:

$$\begin{bmatrix} v_{an0} \\ v_{bn0} \\ v_{cn0} \end{bmatrix} = R_e \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \text{--------------------------------------- (14)}$$

which indicates that in an unbalanced system, the input currents will follow the non-zero sequence component of input voltages.

Although all above equations are derived on the assumption of working in the first 60° region, it can be verified those equations are valid for other five regions.

## 4. SIMULATION AND EXPERIMENT

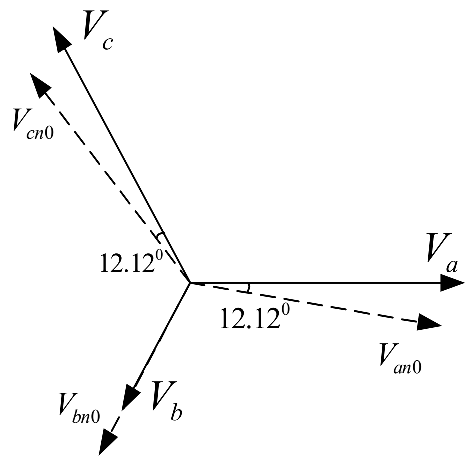


Fig.7 Vector relationship between input voltage V and its none zero sequence component $V_{no}$

Simulation and experiments were conducted with following conditions:

Input AC voltages: .

$v_a = 120V, v_b = 40V, v_c = 120V$ (RMS value)

DC rail voltage: $E = 440V$

Input inductance: $L = 1.97mH$

Switch frequency: $50kHz$

Resistance of the load: $R = 250\Omega$

Assuming input current only follows the non-zero component of input voltage, according to vector diagram

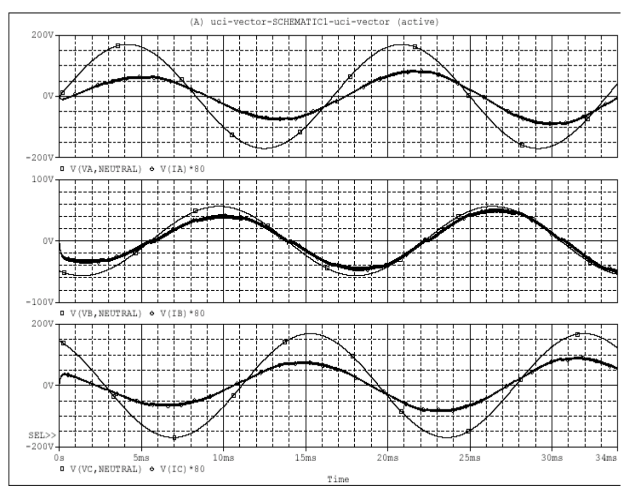


Fig.8 Simulation input three-phase voltage and current waveforms of APF with unbalanced input voltage—from top to bottom the voltage & current of Phase A, B, and C respectively

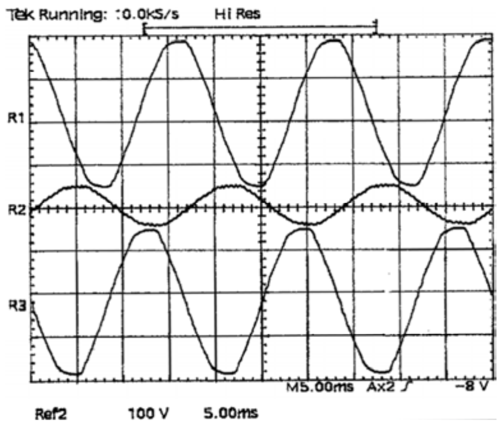


Fig.9 Experiment waveforms of PFC with unbalanced input voltage—three-phase voltage (100volts/div)

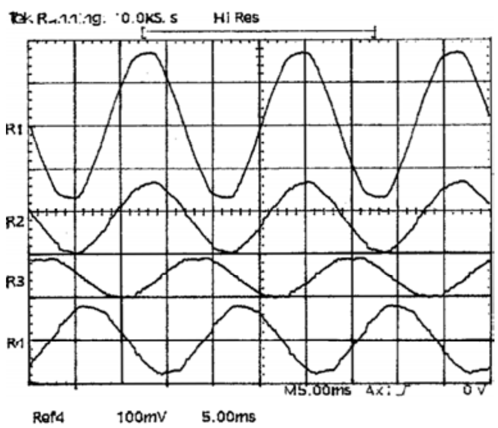


Fig.10 Experiment waveforms of PFC with unbalanced input voltage—the voltage of phase A and three-phase current (100volts/div for voltage; 2amps/div for current)

analysis in Fig.5, the phase difference between $v_a$ and $i_a$, $v_b$ and $i_b$, $v_c$ and $i_c$, should be $-12.12^0$, $0^0$, $12.12^0$ respectively, the amplitude of the non-zero component in $v_a, v_b, v_c$ should be 109.13v, 66.67v and 109.13v (RMS value), which is verified by PSPICE simulation results shown in Fig.7. The input current will follow the non-zero component of input voltage $v_{an0}, v_{bn0}, v_{cn0}$. The phase shift between voltage and current in Fig. 8 verify the theory analysis.

Experiments were carried out under same condition. The results of the experiment are depicted in Fig. 9 and Fig.10.

In Fig.9 the voltage waveforms of phase A, B, and C are listed from top to bottom respectively, the scale of voltages is 100volts/div; In Fig.10 R1 is the voltage waveform of phase A, R2, R3, and R4 are the current waveform of phase A, B, and C respectively the scale of currents is 2amps/div.

The waveforms in Fig.9 and Fig.10 show that the proposed control method performs normally in either balanced or unbalanced AC system.

## 5. CONCLUSION

In this paper, the UCI controlled three-phase PFC operating under the three-phase unbalanced condition is studied. Theory analysis shows that under the unbalanced condition the input currents of the three-phase system will still be sinusoidal and they will follow the non-zero sequence component of input voltage. A pspice simulation model and a 1kVA experiment equipment were built, all simulation and experiment results indicate that with UCI controller PFC can generate sinusoidal current in either balanced or unbalanced situation.

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