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역률개선을 위한 자기에너지 궤환기법의 간단한 삼상 단일전력단 AC/DC 컨버터

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A Simple Three-Phase Single-Stage AC/DC Converter with Magnetic Energy Feedback Technique for Power Factor Correction

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ABSTRACT

A simple three-phase single-stage AC/DC forward converter with transformer magnetic energy feedback technique for power factor correction is proposed. The operational principle of the proposed converter is presented. The proposed converter gives the good power factor correction, low line current harmonic distortions, and tight output voltage regulation. The prototype shows high power power factor with low line current harmonics.

1. Introduction

The most common three phase AC/DC converter requires six active switches. It is therefore natural to search for simple methods to perform AC/DC conversion without introducing undesired harmonic distortion to the input current. Several solution to this problem have been presented. One of the preferred topologies is the boost derived three-phase power factor correction circuit operating in discontinuous conduction mode (DCM) [1-2].

There is a need to look for a converter which can do harmonics rectification, power factor correction, isolated dc-dc conversion, and tight output voltage regulation to meets the adoption of standards IEC 1000 [3-5]. Such a converter needs to meet the IEC 1000 requirements without adding many components, especially in a low power level three phase system such as computer power supplies. Recently, several power conversion topologies have been suggested for the power factor correction. These converters include the single-ended primary inductance converter(SEPIC) and the flyback converter which performs power factor correction and isolated output voltage regulation in a single-stage at the expense of increased high frequency line current distortion [6-9]. Furthermore, the output voltage regulation have a low bandwidth in order to minimize the distortions in the input current. Above problems can be overcome with Integrated High Quality Rectifier/ dc Regulator(IHQRR) and the Boost Integrated Flyback Rectifier Energy Dc-dc converter(BIFRED) [3-5]. These converter offer a low cost alternative to the more conventional methods of power factor correction while providing a well regulated output voltage and isolated power conversion. Thus, these converters are one of the most suitable power supply especially in a low power level one. However, a drawback to the use of these converters is the relatively high current and voltage stress suffered by its switching component and dc-link capacitor due to operation of discontinuous current mode and load dependent characteristics, respectively. Futhermore, these configurations show a significant voltage ripple at twice the line frequency in the output voltage.

In this paper, a new converter based on a

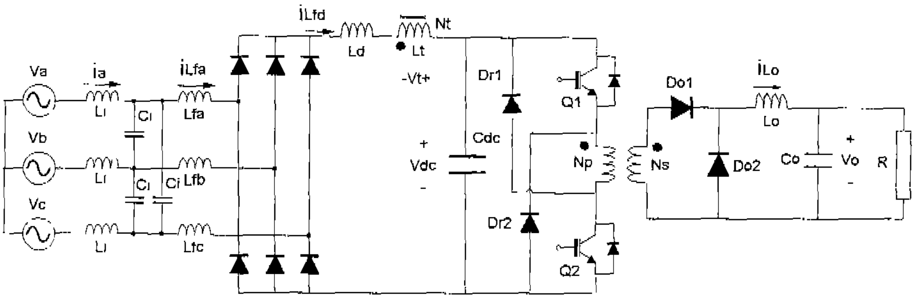

Fig. 1 Circuit diagram of proposed three-phase AC/DC converter

two-switch forward dc-dc converter is introduced. The proposed converter is capable of drawing high quality current waveforms from the ac power source by using a magnetic energy feedback technique while producing a regulated dc output with fast transient response in a single-stage. Thus, although this converter shows the high magnetizing current stress due to the use of the transformer magnetic energy to improve the quality of line current, the proposed converter is very suitable for low power level three-phase power supplies. The operational principle and analysis of the proposed converter is presented.

And simulated results which show the feasibility of the magnetic energy feedback technique for power factor correction are also given.

2. Operational principles of the proposed AC/DC converter

Fig. 1 shows the proposed three-phase single-stage AC/DC converter with a magnetic energy feedback winding. The proposed three-phase AC/DC converter consisting of an input filter, a boost inductor Lf, a three-phase diode rectifier, a magnetic energy feedback stage, and a two switches forward DC/DC converter. The proposed converter shown in Fig. 1 resembles the two-switch forward converter. The most obvious difference is the magnetic energy feedback winding in input stage which is wound on the transformer core. This magnetic energy feedback winding generates a switching frequency modulated voltage V_t which is the reflected voltage from the primary side of transformer during turn off time. This high frequency content of V_t, is filtered by the inductor L_d. The dc link capacitor, Cdc, is the high capacitance energy storage capacitor required to store the 360Hz ripple energy needed in a three-phase high power factor converter.

To simplify the analysis, it is assumed that all semiconductor components are ideal. According to this assumption, the primary switch and the rectifiers do not have parasitic capacitances and represent ideal short and open circuits in their on and off states, respectively. Also, it is further assumed that the power transformer does not have the leakage inductances because of the ideal coupling, but possesses a finite magnetizing inductance L_m. The balanced three-phase coltage source is described by:

$$\begin{aligned} V_a &= V_m \cos(\omega t) \\ V_a &= V_m \cos(\omega t - \tfrac{2}{3}\pi) \qquad (1) \\ V_a &= V_m \cos(\omega t + \tfrac{2}{3}\pi) \end{aligned}$$

The switching frequency is much higher than line frequency. The DC link voltage Vdc is constant over a switching cycle. Finally, it is assumed that the inductance of boost inductor $L_{f,abc}$ operates in DCM and the output filter inductor L_o operates in CCM, respectively. The operation of a three-phase DCM AC/DC converter has 60 degree symmetry. It repeats a pattern every 60 degrees. Looking at the interval [-30°, 30°], we can find another symmetry. Interval [-30°, 30°] is a mirror image of interval [0°, 30°] reflected about 0° line. Thus, it will be adequate to look at a 30° interval. We consider interval [0°, 30°], where Va>0Vb>Vc. Fig. 2 and 3 shows the topological states of the converter during a switching cycle and its key waveforms with their

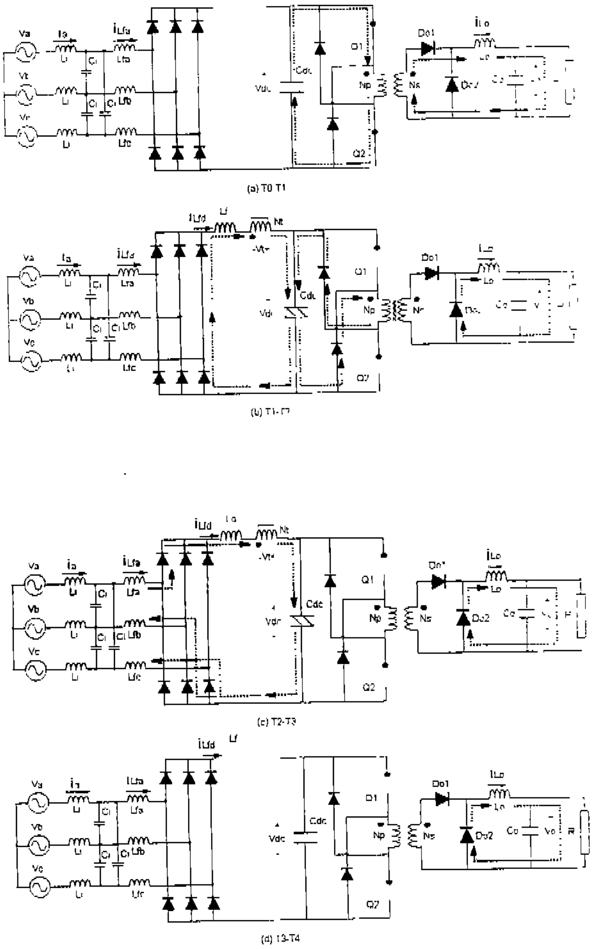

Fig. 2 Equivalent circuit for different operation stages of the proposed AC/DC converter

slopes, respectively. In view of phase current, four subtopologies can be identified within switch off time. This is shown in Fig. 4 with phase currents. The operation of the proposed converter can be divided into four mode.

During the on time, [T_0 - T_1: M_1], as seen in Fig. 2 and 3, the currents in the primary winding and the output inductor L_o rise linearly which is the same as that of on-time in a conventional forward converter. At T_1, the current flowing through L_m, i_{Lm}, can be written as

$$i_{Lm}(T_1) = i_{Lm,pk} = \frac{V_{dc}}{L_m} DT_s. \tag{2}$$

And its current slope is

$$S_{iLm}(M_1) = \frac{V_{dc}}{L_m}. \tag{3}$$

On the other hand, the current flowing through the inductor L_d is zero because the undotted end of the magnetic energy feedback winding is negative with respect to dotted end.

Mode 2 begins when the switching MOSFET Q1 and Q2 switches off at T_1. The drain-to-source voltage of switch Q1 and Q2 rises steeply to $(1+N_{t/p})V_{dc}/2$ at switch turn off time and remains there throughout the mode 2. Since the voltage across the primary side of transformer is clamped at $Np/r\ V_{DC}$ by reset diodes Dr1 and dr2 during this mode, the magnetizing current i_{Lm} decreases linearly and its slope is

$$S_{iLm}(M_2) = -\frac{V_{dc}}{L_m}. \tag{4}$$

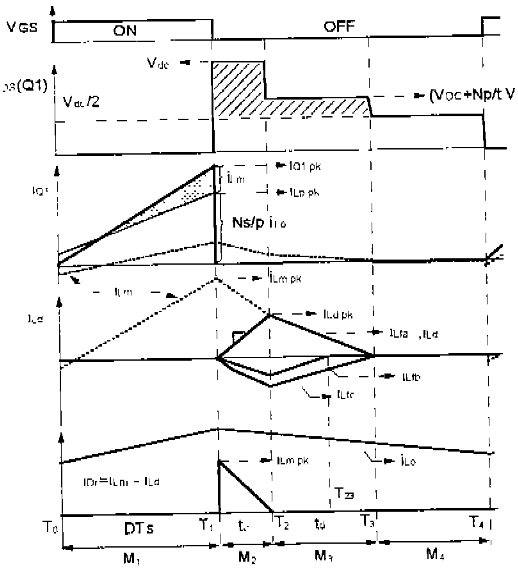

Fig. 3 Staedy-state waveforms of the proposed converter

Since L_m and L_t are wound on the same core as shown in Fig. 1, the undotted end in L_t is positive with respect to the dotted end. This voltage ($V_t = V_{dc}$) forces to increase the current $i_{Lf,abc}$ and i_{Ld} linearly as shown in Fig. 3. This current has the positive slope as

$$S_{iLfa}(M_2) = S_{iLd}(M_2) = \frac{V_a + Nt/p\ V_{dc} - V_{dc}}{L_f + L_d}$$

$$S_{iLfb}(M_2) = \frac{V_b + Nt/p\ V_{dc} - V_{dc}}{L_f} \tag{5}$$

$$S_{iLfc}(M_2) = \frac{V_c + Nt/p\ V_{dc} - V_{dc}}{L_f}$$

As can be seen in Fig. 2 and 3, the current flowing through the reset diode D_{r1} and D_{r2} are

$$i_{Dr} = Np/r\ i_{Lm} - Nt/r\ i_{Lf} \tag{6}$$

and its current slope is

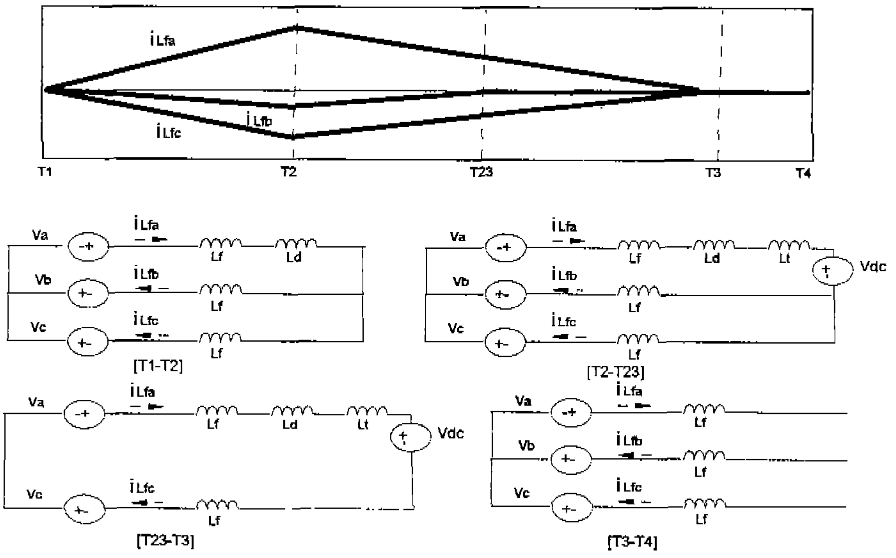

Fig. 4 Input current waveforms and equivalent circuits

$$S_{iDr1}(M_2) = -\frac{V_{DC}}{L_m} - \frac{V_a + Nt/p\ V_{dc} - V_{dc}}{L_f + L_d}. \qquad (7)$$

As can be seen in equations (6) and (7), the energy of magnetizing inductance L_m is transferred to the magnetic energy feedback winding and the voltage ($V_a + Nt/p\ V_{dc} - V_{dc}$) must be positive value to increase the current i_{Lfa} and i_{Lfd} linearly.

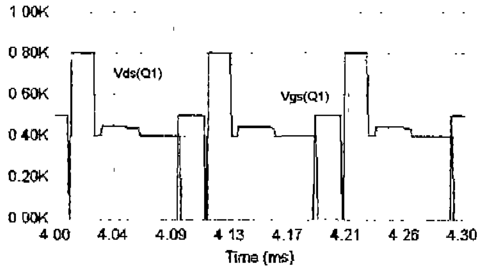

Fig. 5 Simulated key waveforms: Gate Signal and Voltage across switch Q1

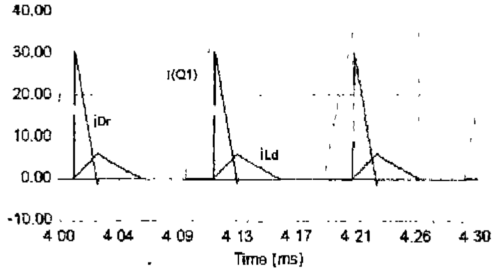

Fig. 6 Simulated key waveforms: iLfd, iDr1, i(Q1)

After the current i_{Dr1} is reduced to zero, the voltage V_t can not force $i_{Lf,a}$ increase since the dc link capacitor voltage V_{dc} is not reflected to the energy feedback winding. Thus i_{Lfa} ramps down to zero during the time interval [T2-T23]. These currents have the slope as

$$S_{iLfa}(T_2 - T_{23}) = S_{iLd}(T_2 - T_{23}) = \frac{-3V_b}{(L_f + L_d + L_t)} \cdot \cdot \frac{1}{(V_{dc} + 3V_b)} \cdot \left[V_a + \frac{(V_b - V_c)}{V_{dc} + 3V_b} V_{dc} \right]$$

$$S_{iLfb}(T_2 - T_{23}) = \frac{1}{L_f} \cdot \frac{-3V_b^2}{V_{dc} + 3V_b} \qquad (8)$$

$$S_{iLfc}(T_2 - T_{23}) = \frac{-3V_b}{L_f} \cdot \cdot \frac{1}{(V_{dc} + 3V_b)} \cdot \left[V_c - \frac{(V_b - V_c)}{V_{dc} + 3V_b} V_{dc} \right].$$

After the time T23, b-phase current is reduced to zero, thus, a-phase and c-phase currents are flow as shown in Fig. 4.

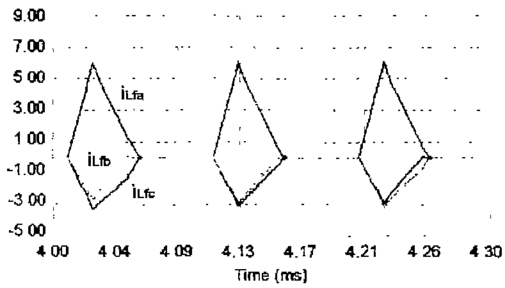

Fig. 7 Simulated key waveforms: iLfa, iLfb, iLfc

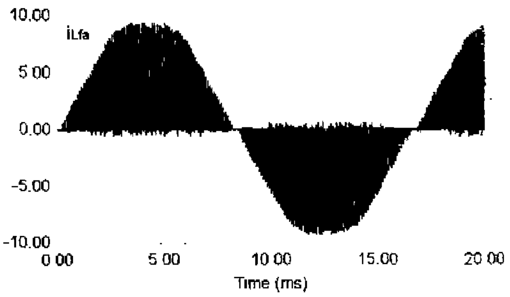

Fig. 8 Simulated input DCM a-phase current

During the time interval [T23-T3], a-phase and c-phase currents have the slope as

$$S_{iLfa}(T_{23}-T_3)=S_{iLd}(T_2-T_{23})=-\frac{1}{(L_f+L_d+L_f)}\cdot$$

$$\cdot\frac{(V_b-V_c)^2V_{dc}^2}{(V_{dc}+3V_b)^2(V_{dc}+V_c-V_a)} \qquad (9)$$

$$S_{iLfc}(T_{23}-T_3)=\frac{1}{L_f}\cdot\frac{-(V_b-V_c)^2V_{dc}^2}{(V_{dc}+3V_b)^2(V_{dc}+V_c-V_a)}.$$

After the mode 3, the discontinuous current mode is occurred.

It is noted that the output current i_{L_o} is linearly increased only during mode 1 and the current $i_{Lf,abc}$ exists only during modes 2 and 3. During modes 2, 3, and 4, the output stage is not influenced by the rectified line voltage because the freewheeling diode D_{o2} is forward biased. Hence, the proposed converter is independent of the output voltage regulation and power factor correction which are not possible in a BIFRED. As a results, the output voltage ripple at twice the line frequency appeared in a BIFRED can be eliminated in the proposed converter.

3. Simulation results

To determine the feasibility of using the magnetic energy feedback technique in three-phase PFC application with single-stage, computer simulation is carried out using Spice program.
The converter parameters are listed in Table 1. The controller is based on the integrated PWM chip UC3823 from Unitrode, which is the same as that of the conventional dc/dc converter. Fig. 5-7 shows the simulated key waveforms of the proposed

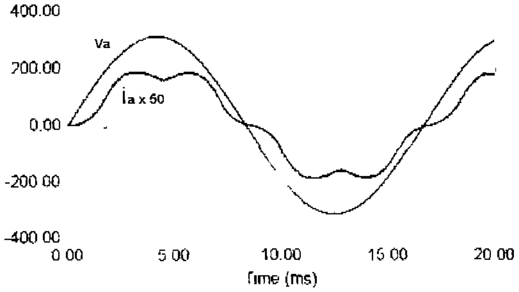

Fig. 9 Simulated a-phase voltage and current

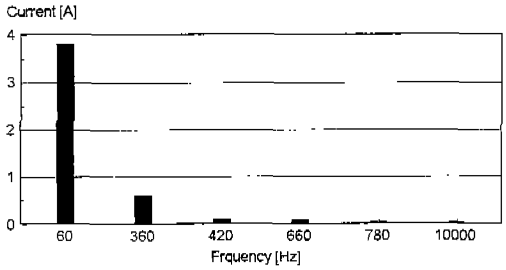

Fig. 10 FFT results of a-phase current

AC/DC converter. It can be seen that all the waveforms are agree well with the theoretical analysis. Fig. 8 shows the DCM a-phase current. Fig. 9 and 10 show a-phase current and voltage and FFT results of current. Althought the a-phase current shows some distortions, a-phase current shows the sinusoidal waveform keeping in-phase with the voltage. Thus the high power factor can be obtained by using the proposed magnetic coupled technique.

4. Conclusions

This paper presents an operational principles and simulated results for two-switch forward converter incorporating the magnetic energy feedback technique. The proposed magnetic energy feedback power factor correction technique gives the good power factor correction and low line current harmonic distortions. Furthermore, the proposed converter is capable of producing an isolated output voltage regulation in a single-stage without the significant output voltage ripple at several times the line frequency. The simulation results shows the high power factor. Thus, the proposed three-phase AC/DC converter is suitable for low power level

Table 1 : Proposed converter parameters list

Lm	0.5mH	Lt	0.5mH
Ls	0.1mH	Ld	100uH
Lf,abc	800uH	Cdc	1000uF
Co	1000uF	Li	0.1mH
Ci	2uF	fsw	10kHz

three-phase power supplies.

Nomenclature

Va, Vb, Vc : abc phase voltages
ia, ib, ic : abc phase currents
Cdc : dc-link capacitor
Vdc : dc-link capacitor voltage
$L_{f,abc}$: boost inductor in input stage
$i_{Lf,abc}$: DCM abc pahse currents flowing through boost inductors
Lm : Magnetizing inductance
Np, Ns : turns of primary winding and secondary winding of transformer
Nt : turns of magnetic energy feedback winding
Np/s : Np / Ns
Nt/p : Nt / Np
Ci : Input filter capacitor
Li : Input filter inductor
fsw : Switching frequency
S_{iLm} : magnetizing current slope
S_{iLm} : boost inductor current slope
i_{Dr} : current flowing through the reset diode D_r

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