변압기 자화 에너지를 이용한 새로운 단일전력단 고역률 컨버터

New Single-Stage High Power Converter Using Transformer Magnetizing Energy

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Abstract : A new high power factor converter using transformer magnetizing energy for power factor correction with a single-switch/single-stage is proposed. The proposed converter gives the good power factor correction, low current harmonic distortions, and tight output voltage regulation. The prototype shows the IEC555-2 requirements are met satisfactorily with nearly unity power factor.

I. Introduction

With the adoption of standards such as IEC555-2, 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 [1-3]. Such a converter needs to meet the IEC555-2 requirements without adding many components, especially in a low power level system such as computer power supplies. The conventional PWM boost rectifier, operating in continuous current mode for power factor correction, is widely used because it has the continuous line current, smallest chock, minimum current distortion and lowest current stress than other methods [4-5]. However, the boost converter requires an additional DC-DC converter to provide mains to output isolation and to give output voltage lower than the peak input voltage. Therefore, this converter, with its reactive elements, power switches, controllers, and switch drivers, can add considerable expense, and hence it is not suitable for a low power level 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 [6-7]. 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)[1-2]. 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 forward dc-dc converter is introduced. Although this converter has a drawback such as the high current and voltage stress, the proposed converter is capable of drawing high quality current waveforms from the ac power source by using a magnetic coupled technique while producing a regulated dc output with fast transient response in a single-stage and a single-switch. Experimental results show the feasibility of the magnetic coupled technique for power factor correction in a low power level power supplies.

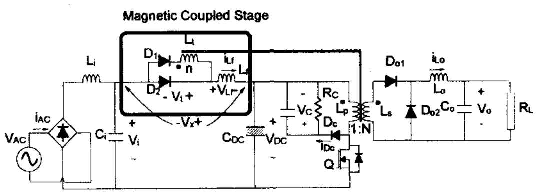

Fig. 1 Proposed high power factor converter with a magnetic coupled stage.

II. Operational principles of the proposed converter

Fig. 1 shows the proposed high power factor converter with a magnetic coupled stage. The proposed converter of Fig. 1 resembles the forward converter. The most obvious difference is the magnetic coupled stage in input side section which is wound on the transformer core. This magnetic coupled 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_f, to produce an output, V_x, which adds to V_i. The dc link capacitor, C_{DC}, is the high capacitance energy storage capacitor required to store the $120Hz$ ripple energy needed in a single-phase high power factor converter.

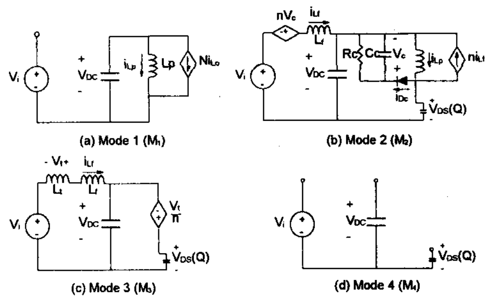

Fig. 2 Equivalent circuits for different operation stages of the proposed converter.

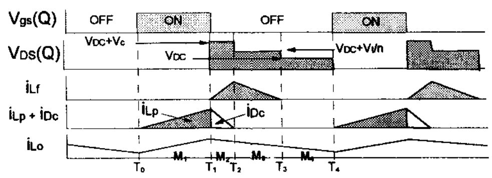

Fig. 3 Steady-state waveforms of the proposed converter

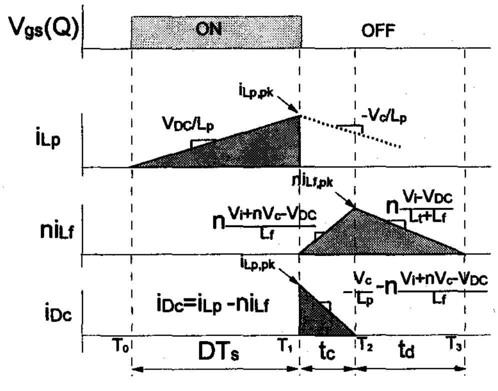

Fig. 4 Current waveforms with their slopes

Fig. 2 shows the topological states and Fig. 3 the key waveforms for the proposed converter in which the magnetic coupled stage operates discontinuously. For steady-state operation, assuming the transformer leakage inductance is much less than the transformer magnetizing inductance and $V_{DC} > V_t$, the operation of the proposed converter can be divided into four mode.

Mode 1 ($T_0 - T_1 : M_1$**)** : As can be seen in Fig. 3, the operation of mode 1, M_1, is the same as that of on-time in a conventional forward converter. Thus, the currents in the primary winding and the output inductor L_o rise linearly. At T_1, the current flowing through L_p, i_{Lp}, can be written as

$$i_{Lp}(T_1) = i_{Lp,pk} = \frac{V_{DC}}{L_p} DT_s. \tag{1}$$

On the other hand, the diode D_1 and D_2 in the megnetic coupled stage are reverse biased because the undotted end of the magnetic coupled stage is negative with respect to dotted end. Thus, the current flowing through the inductor L_f is zero.

Mode 2 ($T_1 - T_2 : M_2$**)** : Mode 2 begins when the switching MOSFET Q switches off at T_1. The drain-to-source voltage of switch Q rises steeply to ($V_{DC} + V_c$) at switch turn off time and remains there throughout the mode 2. Since the voltage across the primary side of transformer is clamped at V_c by RCD clamp circuit during this mode, the primary current i_{Lp} decreases linearly with slope of $-V_c/L_p$. Since L_p and L_f are wound on the same core as shown in Fig. 1, the undotted end in L_f is positive with respect to the

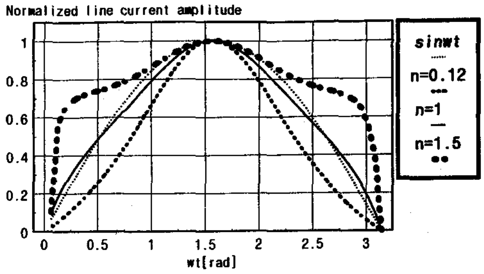

Fig. 6 Input current waveform distortions respect to n

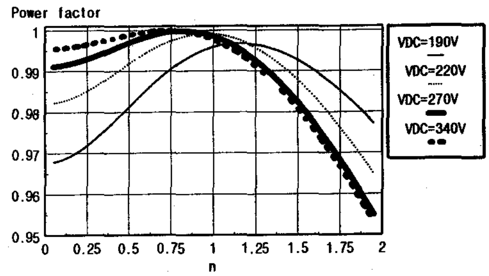

Fig. 7 Power factor of various dc link voltage respect to n

dotted end. This voltage ($V_t = nV_c$) forces to increase the current i_{Lf} linearly as shown in Fig. 3. This current has the positive slope of ($V_i + nV_c - V_{DC})/L_f$. To explain the mode 2 and 3, the switching waveforms of various currents with their slopes are depitched in Fig. 4. As can be seen in Fig. 2 and 4, the current flowing through the clamp diode D_c is

$$i_{Dc} = i_{Lp} - n \cdot i_{Lf}. \tag{2}$$

At T_2, the current i_{Lf} can be written as

$$i_{Lf}(T_2) = i_{Lf,pk} = \frac{V_i + nV_c - V_{DC}}{L_f} t_c. \tag{3}$$

Using the equation (3) and current slopes shown in Fig. 4, the duration of mode 2, t_c, can be easily obtained as follows

$$t_c = \frac{L_f DT_s V_{DC}}{L_f V_c + nL_p(V_i + nV_c - V_{DC})}. \tag{4}$$

From Fig. 4, the current slope of i_{Dc} during mode 2 can be obtained as

$$slope\ of\ i_{Dc}|_{mode\,2} = -\left(\frac{V_c}{L_p} + n\frac{V_i + nV_c - V_{DC}}{L_f}\right) \tag{5}$$

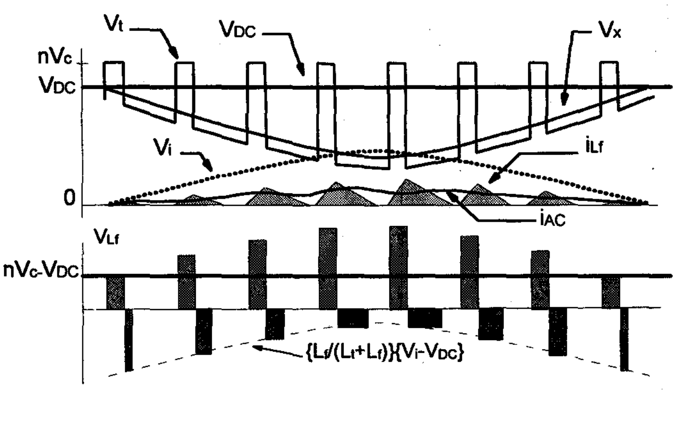

Fig. 5 Idealized dc link waveforms of power factor correction operation.

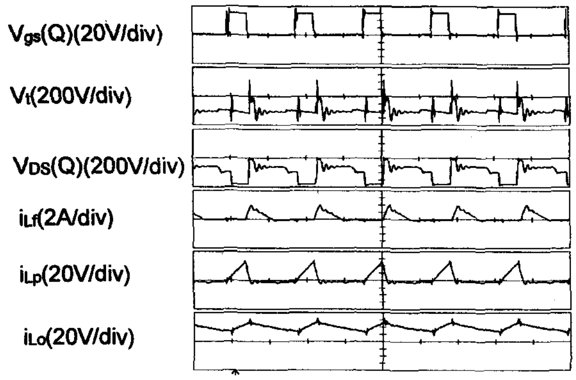

Fig. 8 Experimental waveforms of the proposed converter operating at 60V dc input.

During this mode, the magnetizing energy of L_p is transferred to the magnetic coupled stage and the voltage ($V_i + nV_c - V_{DC}$) must be positve value to increase the current i_{Lf} linearly.

Mode 3 ($T_2 - T_3$:M_3) : After the current i_{Dc} is reduced to zero, the voltage V_t can not force i_{Lf} increase since the clamp voltage V_c is not reflected to the magnetic coupled stage. Thus i_{Lf} ramps down to zero during mode 3. This current has the negative slope of $(V_i - V_{DC})/(L_t + L_f)$. Using the current slopes shown in Fig. 4, the duration of mode 3, t_d, can be easily obtained as follows

$$t_d = \frac{L_t + L_f}{L_f} \cdot \frac{V_i}{V_{DC} - V_i} \cdot t_c. \quad (6)$$

Mode 4 ($T_3 - T_4$:M_4) : After the mode 3, the discontinuous current mode is occured.

It is noted that the output current influences only during mode 1 and the PFC by using magnetic coupled stage is achieved only during mode 2 and 3. During mode 2, 3, and 4, the output stage is not influenced by rectified input voltage because the freewheeling diode D_{o2} is forward biased. Hence, the proposed converter has an independence of output voltage regulation and power factor correction which is not possible in a BIFRED. As a results, the output voltage ripple at twice the line frequency which appeared in a BIFRED can be eliminated in the proposed converter. Fig. 5 shows the idealized dc-link waveforms of power factor correction operation. The magnetic coupled inductor L_t generates the narrow pulses whose amplitude is nV_c. The pulse widths are identical and determined by the equation (4). This voltage V_t makes the magnetic coupled stage operate in a discontinuous conduction mode. The peak values of i_{Lf} will follow the high frequency voltage pulses V_{Lf} (= $V_i + V_t - V_{DC}$) whose amplitude is modulated by a line voltage with dc offset ($nV_c - V_{DC}$). If the value of nV_c equal to that of V_{DC}, the only rectified input voltage V_i is applied across the inductor L_f. Thus the peak values of i_{Lf} follow the rectified input voltage V_i. Thus in this proposed converter, the value of nV_c can be designed to has the value of V_{DC}, which results in a sinusoidal line current.

III. Analysis of waveform distortion and power factor

For simple analysis purpose, it will be assumed that the value of nV_c equal to V_{DC}. It is noted that the input current waveform is not purely sinusoidal. It contains harmonics distortions due to DCM operation. The harmonic distortions of input current can be represented by the function of the peak line voltage $V_{i,max}$, dc-link capacitor voltage V_{DC}, and turns ratio of magnetic coupled stage n. In steady state, the on time DT_s is almost constant over an ac line cycle. Using equation (3) and Fig. 4, the average inductor

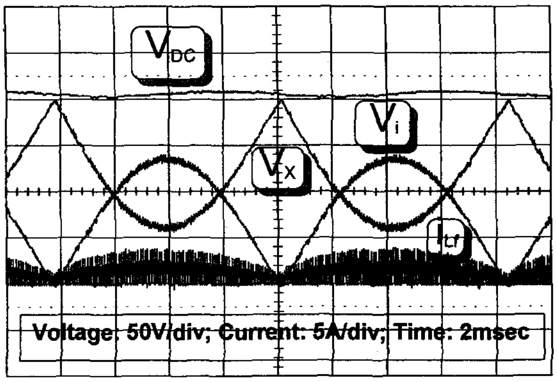

Fig. 9 Experimental dc link waveforms of power factor correction operation.

Table 1
Proposed converter parameters list

Rc	2k Ohm	Cc	4.7uF
Lp	1.2mH	Lt	1.2mH
Ls	1.2mH	Lf	500uH
CDC	220uF	Li	700uH
Ci	3uF	Lo	1mH
Co	47uF		

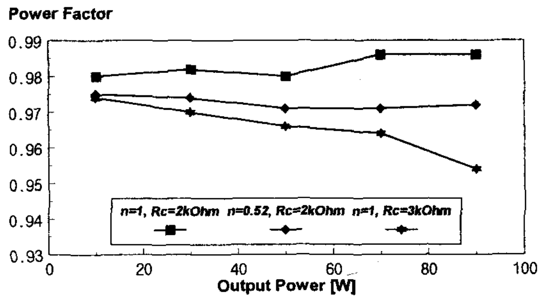

Fig. 10 Experimental plot of overall power factor as a function of output power with respect to the value of n and R_c

current $i_{Lf,c}$ during t_c time can be written as

$$I_{Lf,c} = \frac{T_s}{2} i_{Lf,pk} t_c. \quad (7)$$

While the average inductor current $i_{Lf,a}$ during t_a time can be written as

$$I_{Lf,d} = \frac{T_s}{2} i_{Lf,pk} t_a. \quad (8)$$

The average current $I_{Lf,av}$ can be found by summing of $I_{Lf,c}$ and $I_{Lf,a}$ over a switching period T_s as:

$$I_{Lf,av} = I_{Lf,c} + I_{Lf,d} = \left(\frac{t_c^2}{2T_sL_f}\right)\frac{V_{DC}V_i - (k_M - 1)V_i^2}{V_{DC} - V_i}. \quad (9)$$

From above equation, the waveform of average current $I_{Lf,av}$ depends on the turns ratio of the megnetic coupled power stage, n. A design with low line current harmonic distortions can be obtained by choosing n. Therefore, the average currents $I_{Lf,av}$ as a function of n are plotted in Fig. 6. As can be seen in Fig. 6, in case of n=1, the relatively low line current harmonic distortions can be obtained. This result can be conformed by calculating the power factor. Using the equation (9), the power factor(PF) can also be expressed as

$$PF = \frac{P_i}{(V_{i,rms} \cdot I_{i,rms})} \quad (10)$$

where

$$P_i = \frac{1}{\pi}\int_0^{\pi} V_{i,max} \cdot \sin\omega t \cdot I_{Lf,av} d\omega t$$

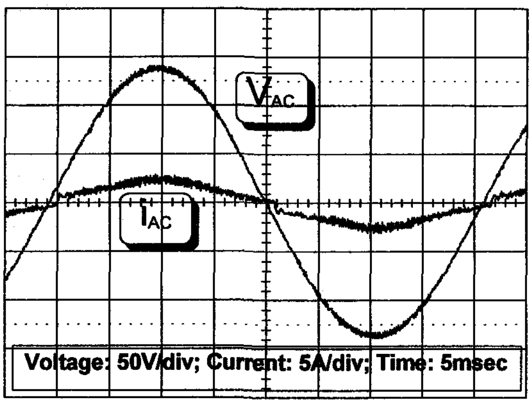

Fig. 11 Experimental waveforms of line current and voltage

$$= \frac{1}{\pi} \int_0^{\pi} V_{i,\max} \cdot \sin\omega t \cdot \left(\frac{t_c^2}{2T_s L_f} \right) \frac{V_{DC} V_i - (k_M - 1) V_i^2}{V_{DC} - V_i} \, d\omega t \quad (11)$$

and

$$V_{i,rms} \cdot I_{i,rms} = \sqrt{\left(\frac{1}{\pi} \int_0^{\pi} I_{Lf,av}^2 d\omega t \right)} \cdot \frac{V_{i,\max}}{\sqrt{2}}$$

$$= \sqrt{\left(\frac{1}{\pi} \int_0^{\pi} \left(\frac{t_c^2}{2T_s L_f} \frac{V_{DC} V_i - (k_M - 1) V_i^2}{V_{DC} - V_i} \right)^2 d\omega t \right)} \cdot \frac{V_{i,\max}}{\sqrt{2}} \quad (12)$$

Hence, the power factor as a function of V_{DC} with variations in the values of n can also be plotted in Fig. 7. This figure shows the high power factor better than 0.99 in the neighborhood of n=1 regardless of the dc link voltage. Therefore, based on this figure, the turns ratio n=1 is selected. As a results, the nearly optimal turns ratio of magnetic coupled stage can be obtained for high power factor and low line current harmonics distortions by theoretical analysis.

IV. Experimental results

To determine the feasibility of using the magnetic coupled technique in PFC application with a single-stage, a breadboard was constructed to the specifications listed below:

- o input voltage: 100 Vrms
- o output voltage: 48 Vdc
- o output power: 90W
- o switching frequency: 11kHz

The maximum output power is about 90W due to power dissipation limitation in the clamp resistor and transformer. The converter parameters are listed in Table 1. Fig. 8 shows the experimental waveforms of the breadboarded circuit operating at 60V dc input. It can be seen that all the waveforms are agree well with the theoretical analysis. Fig. 9 shows the dc-link waveforms of power factor correction operation. It is quite clear that the power factor correction has been achieved by the magnetic coupled stage. Fig. 10 shows the plot of the experimentally obtained overall power factor as a function of output power with variations in the values of n and Rc. In case of $n=1$ and $Rc=2k\Omega$, the power factor stays relatively high for the entire load range down to 10% of rated. Thus, the turns ratio of 1 for a magnetic coupled stage and the clamped resistor of $Rc=2k\Omega$ has been selected for near optimum performance. Fig. 11 shows the oscillogram of the line current, voltage. The line current shows the sinusoidal waveform keeping in phase with the line voltage. Thus high power factor can be obtained by using the proposed technique. Fig. 12 shows the measured line current harmonics superimposed on the specified IEC555-2 Class D limits. This clearly shows that the proposed converter meets the regulations with a considerable margin, and the measured power factor is 0.985.

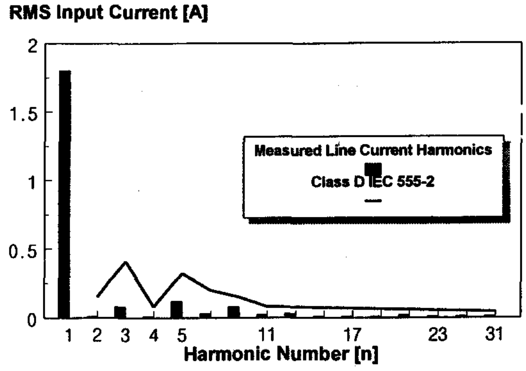

Fig. 12 Measured line current harmonics superimposed on the specified IEC555-2 Class D limits.

V. Conclusions

This paper has presented analysis and experimental results for a forward converter incorporating the magnetic coupled technique. The proposed new magnetic coupled 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 and single switch without significiant output voltage ripple at twice the line frequency. The analysis of the harmonic distortions and power factor are carried out. Based on this anaysis, the nearly optimal value of the turns ratio of magnetic coupled stage is selected for he high power factor. The prototype successfully meets the IEC555-2 requirements with a high power factor. Thus, the proposed converter is suitable for low power level power supplies.

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