Paper

A Low Harmonic High Power Factor Half Bridge Resonant AC/DC Converter

Chandan Chakraborty, Student Member and Muneaki Ishida, Member
Mie University, Mie 514-8507, Japan

A new resonant rectifier is introduced in this paper. Due to the suitability of operation in the lagging power factor mode, the series parallel CLL topology is utilized. The converter has been analyzed and simulation results have been obtained by using MATLAB. Control requirements have been identified and two new control schemes have been developed. The first scheme does not require any current sensor to improve the current drawn from the supply. The technique is to use a PI controller to maintain the output voltage constant, with an additional gain proportional to the rectified AC input voltage to create a fixed frequency modulation to improve the input current waveform. The second scheme uses a current sensor and forces both the output voltage and the input current to follow the corresponding desired references using two PI controllers. A laboratory prototype has been fabricated to realize the proposed converter topology along with the control schemes and satisfactory results have been found.

Keywords: Resonant Rectifier, CLL Topology, Half-Bridge Inverter, Frequency Control

1. Introduction

AC/DC converters are extensively used in Computers, wide variety of home appliances, medical instruments, DC drives etc.. Also in many of the DC/DC converters, AC/DC converters interface the available grid power to the unregulated DC input. In circumstances, where ohmic isolation is a mandatory requirement, transformers are used and to reduce the overall size of the converter (including the size of the transformer), operating frequency of the converter is stepped up. For hard-switched converters, increased losses with the increase in frequency set a limit of the operating frequency. However, due to Zero Voltage Switching (ZVS) and/or Zero Current Switching (ZCS), resonant converters [1-16] can be designed to operate at very high frequency and therefore are being proposed for use in such applications [11-16].

The additional requirement of AC/DC converters is to have minimum harmonic distortion of the input current, drawn from the available grid. With the imposition of strict regulations to lessen harmonic burden on to the system, the conventional and widely used uncontrolled rectifier as well as phase controlled thyristors are being replaced by improved performance AC/DC converter or an additional filter is put to operation. As the filter size used in power frequency is quite big and expensive, therefore major attentions are being paid to develop a small size, improved performance and low cost AC/DC converter.

The use of resonant converters in AC/DC converter has already been reported. Sulistyono and Enjeti [11] proposed the use of series resonant topology. The input AC is directly converted to high frequency AC, which is then fed to the resonant network, followed by rectifier and filter. No control strategies to improve the converter input current is proposed, instead a bigger size filter is used, which increases converter size and cost. Also the scheme requires four active switches. Hong et al [12] reported a system utilizing Parallel Resonant Converter (PRC). A full bridge topology increases device count and in addition PRC has it's own drawbacks as reported earlier [2]. As it has been well explained that a proper series-parallel topology can offer the good features of both series and parallel network [2,5], so a few publications followed which use series-parallel type network. So far, Belaguli and Bhat [13], Pinheiro et al [14], Durgesh et al [15] and Mollov and Forsyth [16] presented the performance of LCC type series-parallel resonant converter. While different controllers are proposed but the present authors are of the opinion that LCC topology is not very suitable to operate in the lagging power factor mode. In a recent publication [8], the present authors have presented a CLL topology with excellent performance. Therefore, this paper uses a CLL type network. The system is explained first and then the analysis and simulation have been carried out followed by controller details, experimental results and conclusion.

2. System Description

Fig.1 shows the proposed system. The topology may be interpreted as a diode bridge rectifier fed resonant DC/DC converter. The input AC supply is rectified and the unfiltered DC is used as the input to the resonant DC/DC converter. A half bridge series parallel CLL resonant topology is used in the resonant converter. For sinusoidal rectification with high power factor, the power drawn from the input is a double power frequency sinusoid with peak value twice the average output power. Therefore the output filter capacitor should be designed to store sufficient energy to be able to supply steady DC power to the load. Whereas the input filter is only to filter out high frequency current components generated due to high frequency switching in the CLL inverter, hence of small size. As the transformer is connected in series with one of the inductors (L_2), therefore the transformer leakage may properly be designed to replace the inductor. Particularly for low power output, using an inductor-transformer to operate

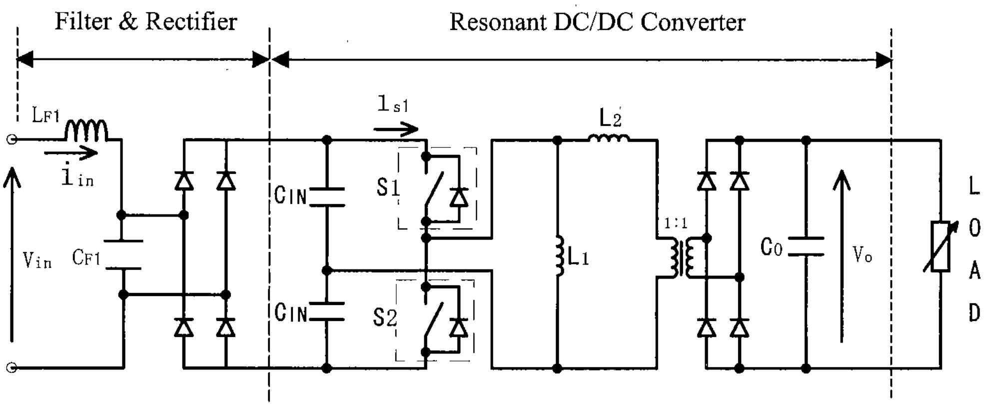

Fig.1. Proposed System.

both as inductor and transformer, both the inductors (L_l and L_2) may be replaced [9]. The capacitor C_{IN} is of very small size and used for voltage splitting purpose as required for the half bridge topology. The same capacitor is also used as the "C" ($C=2C_{IN}$) of the CLL topology. Although an IGBT based converter has been reported in this paper with operating frequency in the range of 25kHz to 30kHz, a MOSFET based converter may be developed to increase the operating frequency, thus reducing further the input side filter size as well as the size of the transformer and resonating components. The motivation of this paper is to realize sinusoidal rectification with a novel resonant topology.

3. Converter Analysis and Simulation

The resonant converter is operating at a frequency more than 25kHz. The power frequency being 60Hz, for each of the switching period the input voltage of the resonant DC/DC converter may be assumed to remain constant without much loss of accuracy. However from cycle to cycle the voltage level changes according to the rectified AC supply. The switching period being very small compared to that of the input AC voltage, for each of the switching cycles, the current through the switches and components may be treated on steady state basis. Now to understand the basic features of the CLL DC/DC converter, the input-output voltage gain (M) may be expressed as [10],

$$M = \frac{\left(\frac{\gamma_1}{a}\right)\left(\frac{\omega}{\omega_0}\right)^2}{\left[\left(\frac{\omega}{\omega_0}\right)^2 - \frac{1}{\gamma_2}\right]\sqrt{\left[1+\frac{\pi^4 Q^2}{64a^4}\left(\frac{\omega}{\omega_0}\right)^2\left\{\frac{\gamma_m(\gamma+\gamma_l-\delta)}{(\gamma+\gamma_l+\gamma_m-\delta)}\right\}^2\right]}} \quad \ldots\ldots(1)$$

Where,

$$Q = \frac{\omega_0 L_1}{R}, \qquad \delta = \frac{1}{\left[\left(\frac{\omega}{\omega_0}\right)^2 - 1\right]} \qquad \gamma = \frac{L_2}{L_1}$$

$$\gamma_1 = \frac{\gamma_m}{\gamma+\gamma_l+\gamma_m} \qquad \gamma_2 = \frac{\gamma+\gamma_l+\gamma_m}{1+\gamma+\gamma_l+\gamma_m} \qquad \gamma_l = \frac{L_l}{L_1} \qquad \gamma_m = \frac{L_m}{L_1}$$

L_l and L_m are the leakage and magnetizing inductances of the transformer as referred to primary side.

Fig.2 shows the gain (M) vs. frequency ratio (ω/ω_0) Characteristics for different values of load and inductance ratio ($\gamma=L_2/L_1$). Load is expressed in terms of Q factor ($Q=\omega_0 L_1/R$, where R is the load resistance). Ideal components and devices have been assumed for simplicity.

Operation in the lagging power factor mode does not require any device snubber and also offers higher efficiency compared to that of the leading power factor mode [2]. Therefore in the present study the converter is decided to operate always in the lagging power factor mode. In this regard the CLL converter is particularly suitable, because if the converter is designed to operate in the lagging power factor mode for a higher load current then with the decrease in load current the converter always remains in the same mode.

Fig.2 shows the characteristic for the DC/DC converter with flat input and output voltages. However, in the present case the input voltage is a rectified sine wave. The output voltage remaining constant, variation of the input voltage implies a change in the converter gain. Also if the converter is operated at constant frequency, then the output DC voltage being constant, more current will be drawn at the peak of the

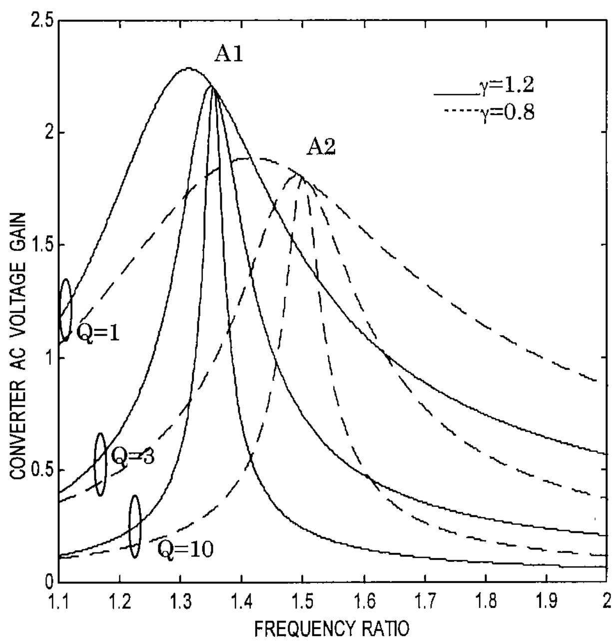

Fig.2. M vs. ω/ω_0 Characteristics.

input voltage whereas current intake will be reduced when the input voltage is small. The converter input current may be expressed as,

$$i_{in} = \frac{\sqrt{2}V_m \sin(2\pi f t)}{\pi Z}\sin(2\pi f_s t - \phi) \quad ....(2)$$

where,

$$Z = \sqrt{\upsilon^2 + \zeta^2} \qquad \phi = \tan^{-1}(\zeta / \upsilon)$$

$$\upsilon = \frac{\alpha'\gamma' + \beta'\delta'}{\gamma'^2 + \delta'^2} \qquad \zeta = \frac{\beta'\gamma' - \alpha'\delta'}{\gamma'^2 + \delta'^2}$$

$$\alpha' = \left(\frac{\omega}{\omega_0}\right)\left\{(1+\gamma) - \gamma\left(\frac{\omega}{\omega_0}\right)^2\right\}Q^2 R \qquad \beta' = \frac{8}{\pi^2}\left\{\left(\frac{\omega}{\omega_0}\right)^2 - 1\right\}QR$$

$$\gamma' = \frac{8}{\pi^2}\left(\frac{\omega}{\omega_0}\right) \qquad \delta' = \left(\frac{\omega}{\omega_0}\right)^2 (1+\gamma)Q$$

V_m is the peak magnitude of input AC voltage, f and f_s are the power frequency and switching frequency respectively.

The variation of Q is plotted in Fig.3. and the corresponding input current (unfiltered version) is shown in Fig.4.

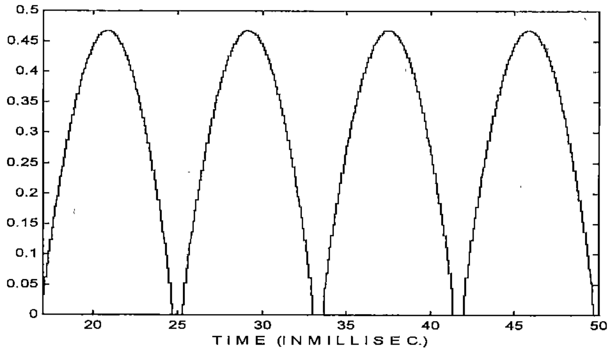

Fig.3. Q vs. Time Characteristic

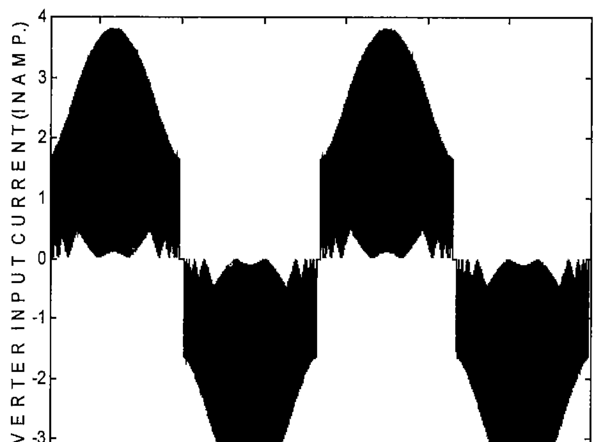

Fig.4. Converter Input Current (unfiltered).

4. Control Aspects

Two new control schemes are proposed. The schemes differ in terms of complexity and performance and called as Scheme-1 and Scheme-2. Simplified block diagrams are shown in Fig.5 and 6 respectively. The function of the controller is (i) to keep output voltage constant despite change in input voltage and/or output load and (ii) to shape the converter input current as close to sine wave as possible.

The voltage control part in both the schemes is carried out in the same way, sensing the output voltage, comparing with a voltage reference, thus generating an error. The error is processed by a Proportional-Integral (PI) Controller (PI Controller-1) and clamped before feeding to a Voltage to Frequency (i.e. V-to-F) Converter. AD537 is used as the V-to-F Converter. The $+V_S$ of AD537 being connected to 15V, the input is required to be clamped to 11 V (i.e. 4V below the $+V_S$ as specified for safe operation of the device [17]). Thus the highest operating frequency is decided by the R-C network around the AD537, considering input voltage to be 11V. Whereas, the lower limit of operating frequency is decided by the point "A" (i.e. A1, A2 etc.) in Fig.2, therefore depends on input-output voltage gain and converter components magnitudes. Thus "A" should be carefully selected corresponding to the minimum possible input voltage and maximum possible load current. Because with the increase in load current the controller automatically decreases the operating frequency to compensate for the voltage and if by any chance the operating point shifts to left beyond "A" then subsequent decrease in frequency will only decrease the output voltage more and more, thus giving rise to a stability problem, which should be avoided by properly selecting the operating point. To avoid the occurrence of such condition, a lower frequency limit corresponding to point "A" may also be set similar to higher frequency limit.

The control schemes differ in the way, the input current shaping is undertaken. In Scheme-1, the input AC voltage is stepped down, rectified and attenuated and then added to the output of the PI Controller-1 as shown in Fig.5. It has been experienced that this has a remarkable effect on the input current by greatly decreasing the 3rd harmonic component. While any change in the output voltage will be compensated by the PI Controller-1, but addition of the rectified sine component (proportional to $|V_{in}|$) will create a frequency modulation in similar way in each of the half cycles. The average operating frequency depends on voltage gain and output load, and due to the modulation, in each of the half cycles near zero crossing, the input to the V-to-F Converter being minimum, the operating frequency moves towards point "A", thus coming close to the resonance condition increasing current intake. On the other hand, when in each of the half cycles, the input voltage increases, the input to the V-to-F Converter also increases, thus moving away from the resonance condition, the corresponding impedance increases. It has been shown in the following section, that with a proper choice of the gain (i.e. attenuation factor), major improvement in the input current quality is achieved.

Scheme-2 uses a current feedback along with the voltage feedback as described above. The AC side current is sensed by LEM LA-55P. The current signal is converted to a proportional voltage signal and compared with a corresponding current reference to generate a voltage,

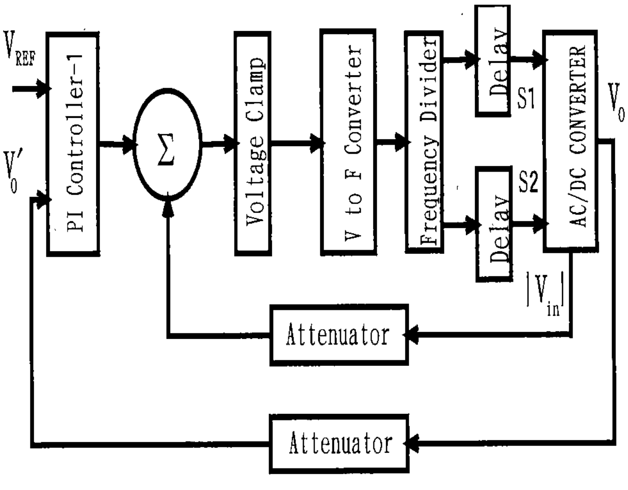

Fig.5. Control Scheme-1.

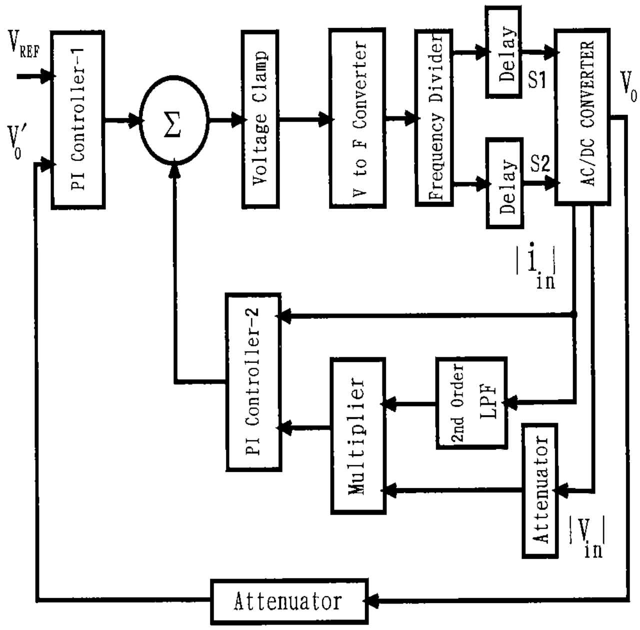

Fig.6. Control Scheme-2.

proportional to the current error. The error is fed to a PI Controller (PI Controller-2). The outputs of PI Controller-1 and PI Controller-2 are added to generate the voltage signal required to drive the AD537 to control the converter. An important aspect of this Scheme is to generate the reference current signal, which should be a sine wave, the magnitude being proportional to power drawn from the input. As the controller will try to follow the reference signal, therefore stability problem may arise and harmonic distortion may appear if the current reference is not properly selected. To generate a voltage signal corresponding to the current reference, the AC side voltage is stepped down and rectified. The voltage output proportional to the current from the current sensor is rectified and filtered by a 2nd order low pass filter. The filtered output is multiplied with the stepped down rectified AC signal (proportional to $|V_{in}|$) to generate the current reference signal. The details of the block schematics are shown in Fig.6.

5. Experimental Results

The AC/DC converter has been fabricated in the laboratory. The available inductances of 306μH, 240μH and capacitance of 0.11μF are used. Both the controllers have been implemented. For the time being, a 75V (rms) input and 100V, 1.5A output application, has been considered. The high frequency transformer has been produced using ferrite core and the parameters are measured. The leakage inductance and magnetizing inductance (both referred to primary) are found to be 72 μH and 4.14 mH respectively. It has been discussed that the magnetizing inductance is having negligible effect on the performance of the CLL converter, however, the leakage being effectively in series with L_2, have significant influence on the performance [10]. In fact, by loosely designing the transformer, the inductor L_2 in the CLL topology may be replaced by the transformer leakage inductance. Thus, including the effect of transformer leakage inductance, the resonating frequency at no-load is calculated to be 27.43kHz.

Figs.7 and 8 show the waveforms for full load and half load respectively, when only PI Controller-1 and associated circuitry are in operation to keep output voltage constant. No indirect (as in Scheme-1) or direct (as in Scheme-2) method of current control is applied. The corresponding harmonic spectra are also shown. A dominant 3rd harmonic component is noted for both the loading conditions. Subsequently the Total Harmonic Distortion (THD) for the two cases are calculated and found to be 17.92% and 20.91% respectively. The situations change radically when current control methods are applied. Figs.9 and 10 show the waveform, when controller of Scheme-1 is put into operation. The attenuator gain of the inner loop is adjusted to yield better input current waveform. The corresponding harmonic spectrum shows the harmonic contents of the waveform. The corresponding THDs are found to be 9.3% and 7.9% respectively.

It is obvious that until and unless the input current is sensed and forced to follow a sine wave, further improvement in input current waveform is not possible. For such purpose, Scheme-2 is realized and Figs.11 and 12 show the waveforms for full load and half load condition respectively. The THDs are calculated from harmonic spectrum shown in the same figures, and found to be 2.93% and 3.32% for the two cases. As the input side AC voltage waveform is not a perfect sine wave, having a THD of about 2%, therefore performance of both the schemes are very satisfactory. Further improvement is possible by selecting the reference current waveform from a sine wave source synchronized with the AC mains rather than directly from the AC mains as pursued in Scheme-1 and 2. However, this is only at the cost of increased components count and complexity in the control circuitry.

6. Conclusions

A novel resonant AC/DC converter with improved input current waveform has been presented in this paper. A CLL type series-parallel topology has been opted for, to operate in the lagging power factor mode, within the entire range of load and/or input voltage variation. Because of the half-bridge topology, only two switches are required. Also,

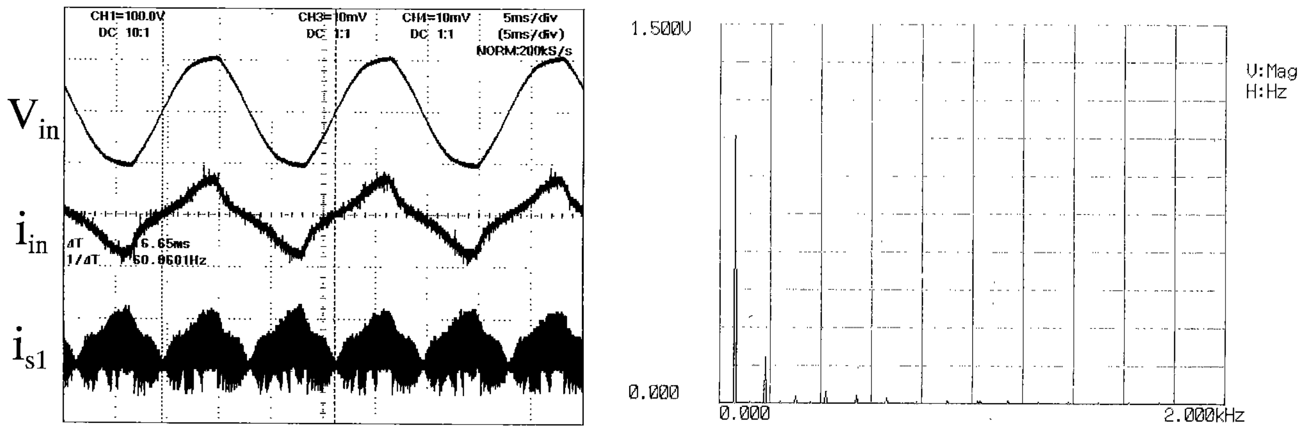

Fig.7. Experimental Waveforms and Harmonic Spectrum
(For Full Load With No Current Control)
Volt Scale: 100V/div. Amp Scale: For i_{in}->5A/div. For i_{s1}->10A/div.

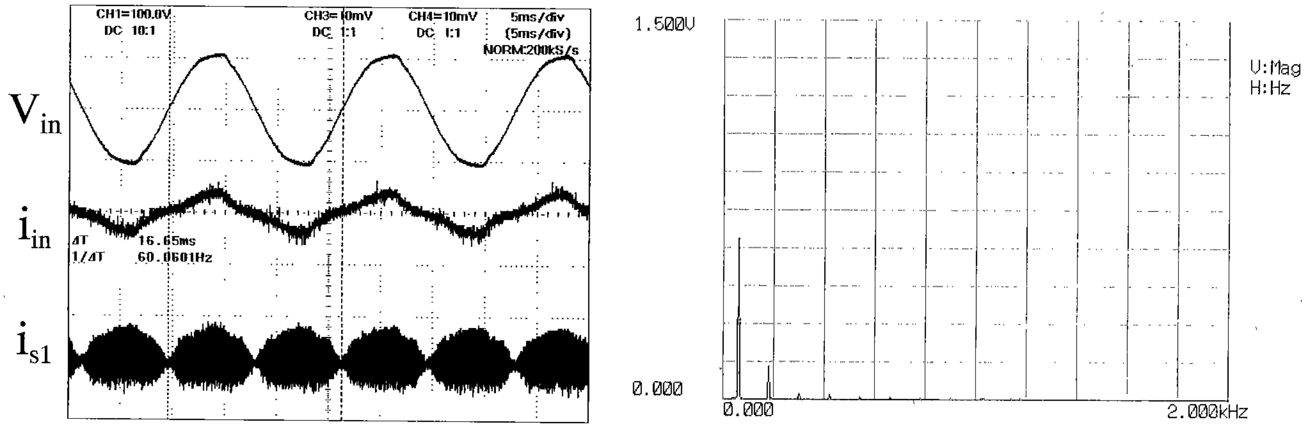

Fig.8. Experimental Waveforms and Harmonic Spectrum
(For Half Load With No Current Control)
Volt Scale: 100V/div. Amp Scale: For i_{in}->5A/div. For i_{s1}->10A/div.

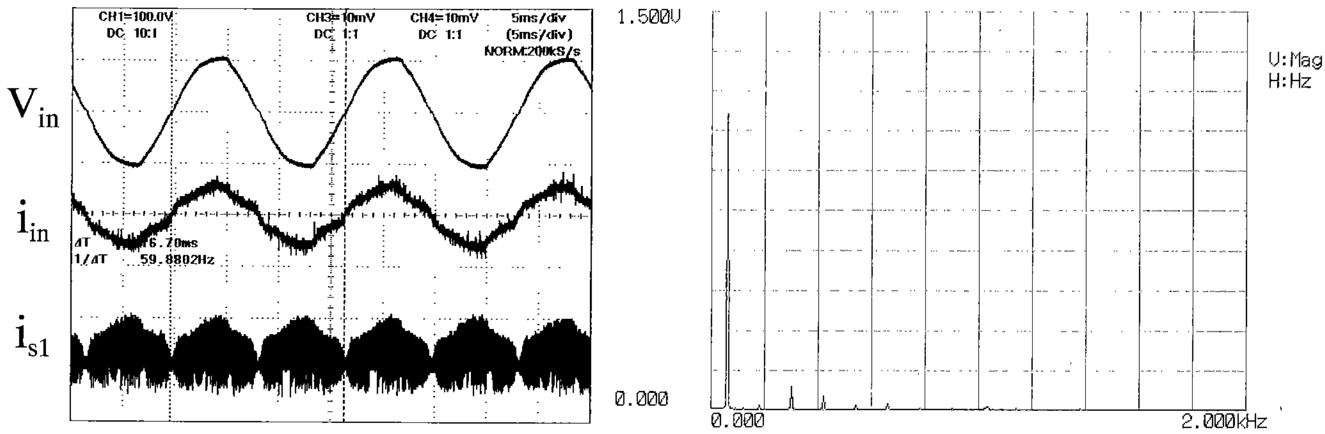

Fig.9. Experimental Waveforms and Harmonic Spectrum
(For Full Load With Controller of Scheme-1 in Operation)
Volt Scale: 100V/div. Amp Scale: For i_{in}->5A/div. For i_{s1}->10A/div.

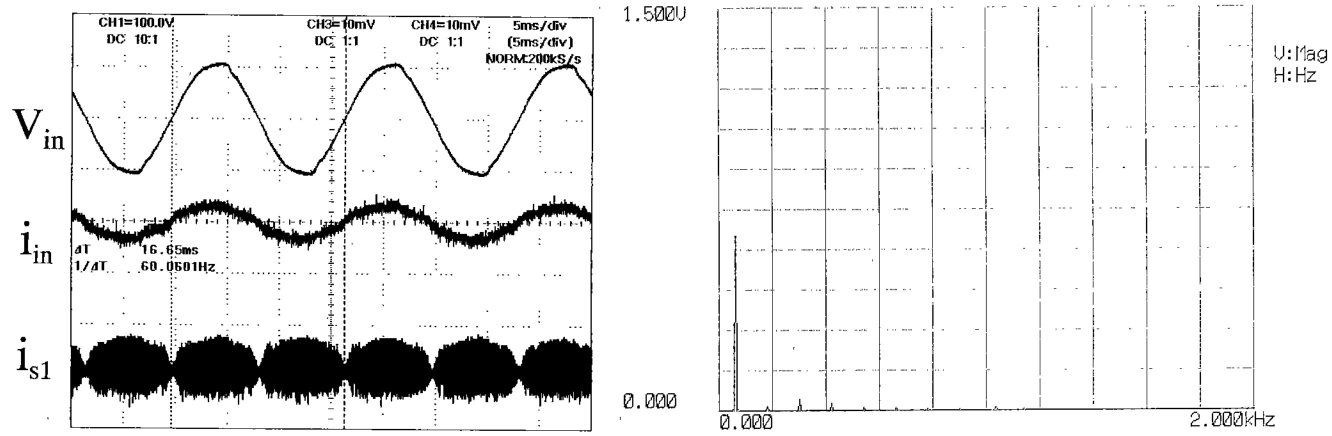

Fig.10. Experimental Waveforms and Harmonic Spectrum
(For Half Load With Controller of Scheme-1 in Operation)
Volt Scale: 100V/div. Amp Scale: For i_{in}->5A/div. For i_{s1}->10A/div.

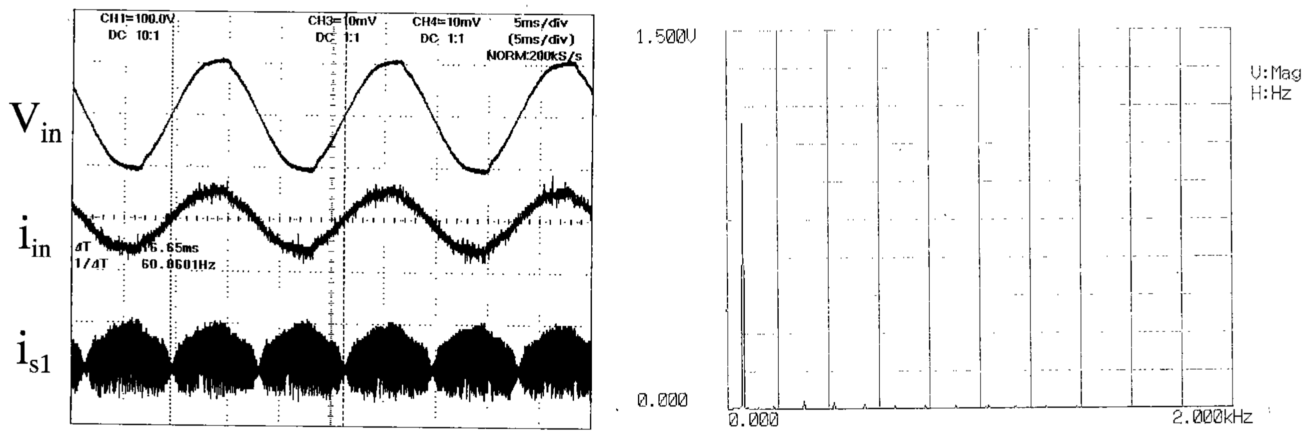

Fig.11. Experimental Waveforms and Harmonic Spectrum
(For Full Load With Controller of Scheme-2 in Operation)
Volt Scale: 100V/div. Amp Scale: For i_{in}->5A/div. For i_{s1}->10A/div.

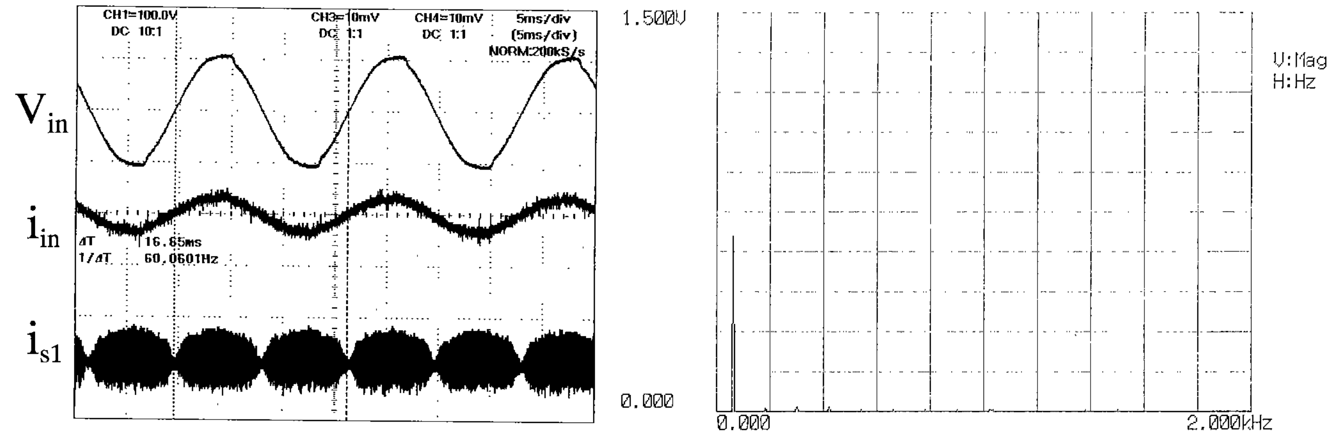

Fig.12. Experimental Waveforms and Harmonic Spectrum
(For Half Load With Controller of Scheme-2 in Operation)
Volt Scale: 100V/div. Amp Scale: For i_{in}->5A/div. For i_{s1}->10A/div.

the capacitors required to split the input DC voltage for the inverter are also used as the capacitor in the resonant network. The magnitude of the capacitors being very small, do not distort the rectified voltage of the input side rectifier bridge, however, absorbs any switching spikes due to the stray inductances and associated current switching. Two new current control methods are proposed and implemented. Excellent improvement in the input current waveform has been observed. Scheme-2 offers so far the best waveform quality for the proposed kind of AC/DC converter, which use a resonant stage in between the input side AC and the output side DC.

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Chandan Chakraborty was born on August 17, 1965 in Calcutta, India. He receivedB.E.E(Hons.) and M.E.E degrees from Jadavpur University, Calcutta in 1987 and 1989 respectively and Ph.D from Indian Institute of Technology, Kharagpur, in 1997. Since 1993, he is a Lecturer in Electrical Engineering Department at the Jadavpur University. Presently he is a Researcher at the Mie University. He is interested in Power Electronics, Electric Drives, Magnetics and Renewable Energy Systems.

Muneaki Ishida was born in Aichi, Japan on April 12, 1952. He received the B.S., M.S., and Ph.D degrees from Nagoya University in 1975, 1977 and 1980 respectively, all in Electrical and Electronic Engineering. He was with Nagoya University as a Research Associate in the Department of Electrical Engineering from 1980 to 1987. Since 1987, he has been with Mie University, initially as an Associate professor and from October, 1996 as a Professor. He is engaged in research on static power converters, AC motor drive systems and development of new type motors using piezo-electric devices. He has received two paper awards and chaired many technical sessions of national/international conferences.