A LOW COST SOFT-SWITCHED AC-TO-DC CONVERTER

Ju-Yeop Choi, Korea Institute of Science and Technology
Hyung-Soo Mok, Kon-Kuk Univ.
Taek-Yong Kim, Jeon-Sung Electric Co.

Abstract:

A highly efficient single-phase/three-phase compatible ac-to-dc converter is proposed and analyzed, which includes three identical single-phase both soft-switched dc-to-dc converter with boost converter as a pre-regulator for input power factor correction (PFC). The proposed converter structure provides a cost reduction and easy implementation of compatibility between single-phase 220v and three-phase 220v/380v with their inputs in delta or wye connections.

Keywords: 1-phase/3-phase compatible ac to dc converter, soft-switching, harmonics

INTRODUCTION

Three-phase ac-to-dc power converters are becoming popular for high voltage/high power applications such as telecommunications. They often require input/output transformer isolation for safety, a unity input power factor for minimum reactive power, free input harmonic currents fed back to the ac power distribution system, and, finally, high efficiency and high power density for minimum weight and volume. In recent years many researches have been focused on achieving the issues above mentioned and quite satisfactory improvements have been published so far [1,2,3,4,5]. However, in view point of commercial use, digital control implementation of three-phase switching power converters are still more complicated and expensive than analog control implementation in spite of their outstanding performance.

The proposed single-phase/three-phase compatible ac-to-dc converter has a similar topology to the novel Delco switch-mode-rectifier employing three separate identical single-phase ac-to-dc converters for each of a three-phase source with the dc output connected in parallel. Instead of a single-phase full-wave bridge rectifier followed by a resonant sine wave inverter in the dc-to-dc converter [6], a single-phase soft-switched ac-to-dc converter with input PFC circuit is adopted in this topology.

In the past, diode rectifiers are placed at the first converting stage to convert the ac input to dc with large capacitor connected as a filter on the dc side to reduce dc side ripple. However, this large size filter capacitor draws highly distorted current affecting the quality of the utility. But recently, harmonic pollution of the utility get much attention and strict standards such as IEEE, IEC, VDE and ANSI restrict the amount of current distortion to the specified limit depending on the capacity of the power electronics system. Therefore, simple diode rectifiers connected with large input filter capacitors are not favored and less used. To achieve a nearly sinusoidal current shaping at a unity power factor, proper circuits for PFC must be considered for a majority of power electronics applications such as switch-mode power supplies and power conditioners and uninterruptible power supplies.

Compared with an FET converter operating at 45 khz for a single-phase and three-phase [7], the proposed converter shows a fairly good improvements in efficiency and reducing harmonics due to the soft-switching effect in addition to providing active current shaping [8,9,10]. The advantages of the proposed scheme are simpler design, easier testing and higher reliability due to the three identical standardized modules. But disadvantages are higher component numbers and pulsating power flow compared with three-phase system, which are common to all Delco type of converters.

The increased total number of semiconductor components are six FETs and eight fast recovery diodes for each single-phase both soft-switched dc-to-dc converter with input PFC boost module. However, for the implementation of the zero-voltage-switched (ZVS) converter adopting space vector modulation PWM scheme [5] in Fig. 1, twelve active switches and four fast recovery diodes are required. Also, in the implementation of the single-stage configuration [11] in Fig. 2., ten active switches and fourteen fast recovery diodes are required. Even though there are less number of semiconductor devices in these topologies, the cost of total control circuitry for DSP implementation is still more expensive. Therefore, the system engineers are still hesitating in developing these sophisticated and advanced power electronics system in the real world.

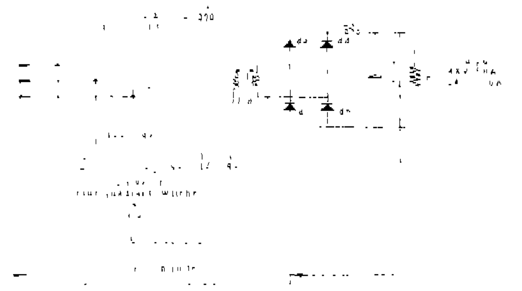


Fig 1 Circuit diagram of 3-phase ZVS PWM converter

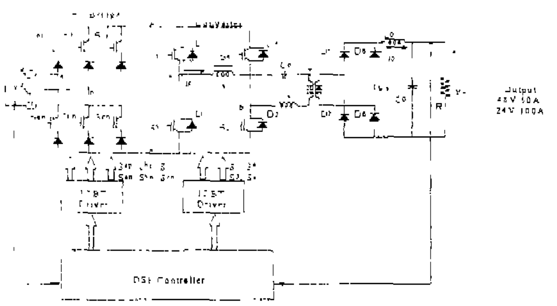


Fig. 2 Circuit diagram of 3-phase ZVZCS PWM converter

However, lower rated voltage and current switching devices can be used in each single-phase, which are cheaper than higher voltage and higher capacity ones in three-phase, a drastic cost reduction is achieved to offset the increased number of semiconductor components in the proposed topology.

Generally, in industrial applications where three-phase ac voltages are available, it is preferable to use three-phase system, because of their low frequency ripple content at the output and a higher power-handling capability along with constant instantaneous power flow. Therefore, usually, the three-phase, six-pulse, full-bridge diode rectifier is a commonly used circuit topology before strict standards are enforced recently.

Based on the previous researches the use of single-phase diode rectifiers in three-phase, four-wire systems draws a quite amount of currents in the neutral which may increase the size of the neutral conductor to carry as much as current as the line conductors. Therefore, it has been preferred to use a three-phase rectifier system over a single-phase rectifier system.

Nevertheless, the converters described in this paper can be used for either single-phase or three-phase with their inputs in delta and wye connections depending on the condition of ac source. The overall schematic diagram of the proposed converter is shown in Fig. 3, which includes a soft-switched 1 kw PFC stage using boost converter following full-bridge MOSFET converter stage operating at 100 khz.

The proposed each single-phase ac-to-dc converter consists of two main power conversion stages. The first stage is a single-phase ac-to-dc rectifier consisting of an input filter, a boost inductor, a single-phase diode rectifier, an active power correction stage, and a dc-link filter capacitor. The second stage is dc-to-dc converters with high frequency isolation. In each power module shown in Fig. 4, the PFC stage provides maximum achievable output dc voltage, and sinusoidal input currents in phase with their corresponding input voltages while zero-current zero-voltage switched dc-to-dc converter utilizes the parasitic capacitance of the switches and the transformer leakage inductance.

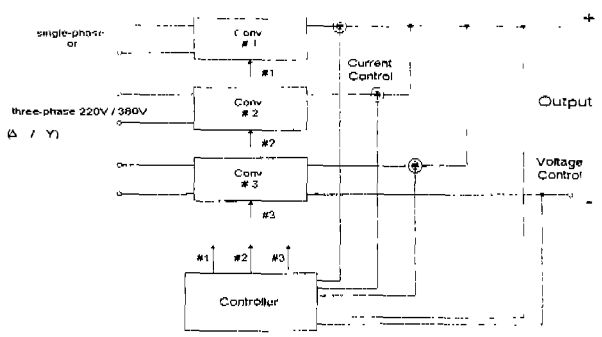


Fig. 3: Overall schematic diagram of the proposed converter

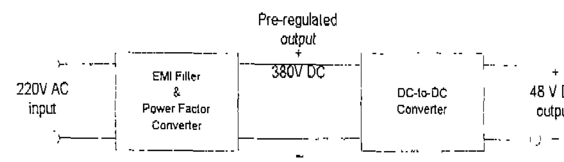


Fig. 4: A block diagram of each power module

The validity of this topology which provides a unity input power factor, low harmonic distortion and high efficiency along with reduced volume and weight is illustrated by simulation and experimental results.

2. SOFT-SWITCHED PFC BOOST CONVERTER AND DC-TO-DC FULL-BRIDGE CONVERTER

A. PFC converter

In all of power electronics applications, the power input is 60hz sine wave ac voltage to be converted desired dc output voltage. Since typical ac currents are far from a sinusoidal waveforms in single-phase and/or three-phase diode rectifier systems, the resulting power factor is not satisfactory to customers and also utility company due to the harmonic contents in the line current without PFC. Recently, in Korea, strict standards for harmonics of a poor line-current waveforms and the input power factor are enforced on most of power electronics systems. By selecting a conventional boost converter as a PFC pre-regulator for active current shaping, it is possible to shape the input current drawn by the rectifier bridge to be sinusoidal and in phase with the input voltage. In the proposed system, electrical isolation between the utility input and the output of the power electronic system is provided in the following dc-to-dc converter stage, which is common as in the switch-mode dc power supplies.

In order to stabilize pre-regulated dc output voltage, Vd is chosen slightly in excess of the peak of the maximum of the ac voltage (for example, ac input 220v + 20% = 264v case, peak voltage = 1.4142 x 264 = 373v). However, the energy efficiency from input utility to dc output of PFC circuit is less than the conventional circuit. Therefore, the considerations should be given for an efficiency as high as possible. The implementation of the PFC circuit with dc output rectification has been popular recently and an attempt was made combining both PFC and soft-switching for better efficiency and reduced harmonic contents of the input currents. For an improved power density and higher switching frequency, soft-switching technique was applied to boost converter, shown in Fig. 5, where 380vdc output of the PFC stage is determined. This topology utilize the parasitic capacitance of the MOSFET switches and the necessary amount of inductance for resonant switching with soft-switching, and its expected key voltage and current waveforms are shown in Fig. 6.

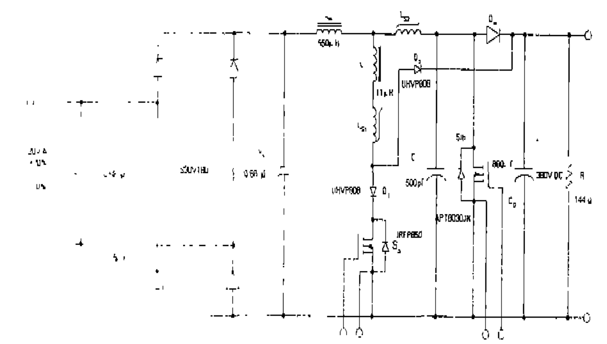


Fig. 5: A block diagram of PFC ckt. using the soft-switched boost converter

In the past the cost, slightly higher power losses, and complexity of active current shaping have prevented their widespread usage. However, recently, in addition to a strict enforcement of harmonic standards the increased device integration (special ICs and other components suitable for soft-switched PFC applications) lowers the cost of development and the components of the PFC circuit.

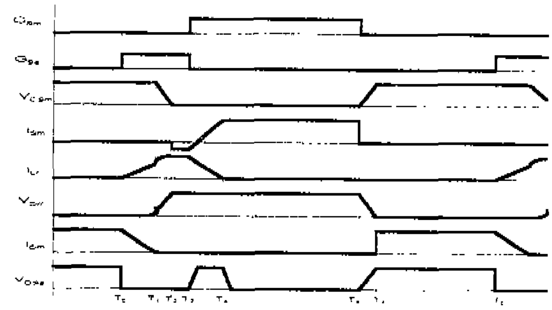


Fig. 6: Expected key waveforms of the boost converter

The Unitrode ML4812 is the one of resulting ICs, which is designed to optimally facilitate a "boost" type PFC controller using peak-current mode control. Since the ML4812 functions as a current regulator, the current which is necessary to terminate the cycle is a product of the sinusoidal line voltage times the output of the error amplifier which is regulating the output dc voltage. In order to provide stable operation in case duty cycle exceeds 50%, ramp compensation is programmable with an external resistor. Figure 7 shows a block diagram of the key functions of the ML4812 but its implementation using *Pspice* will be given for the future due to the limited space.

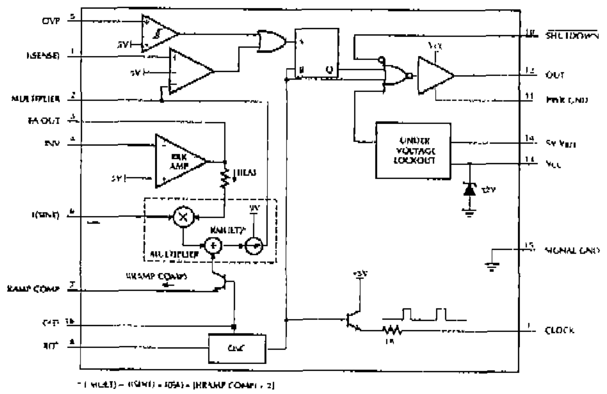
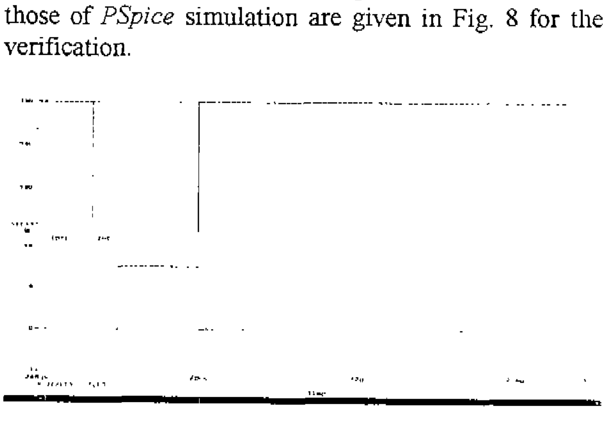
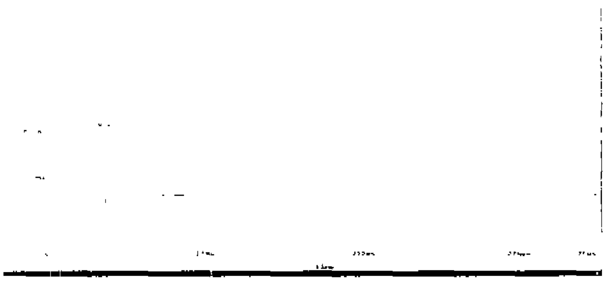


Fig. 7: A block diagram of the ML4812

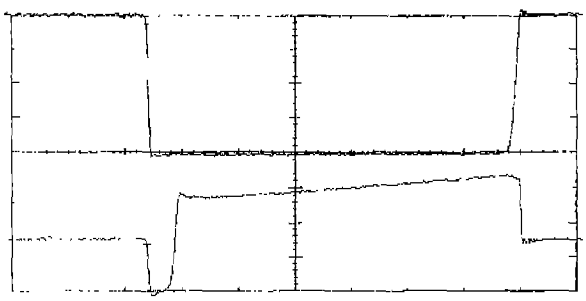
A single-phase 220vac input/380vdc 1kw output prototype is constructed and experimental results and those of *PSpice* simulation are given in Fig. 8 for the verification.



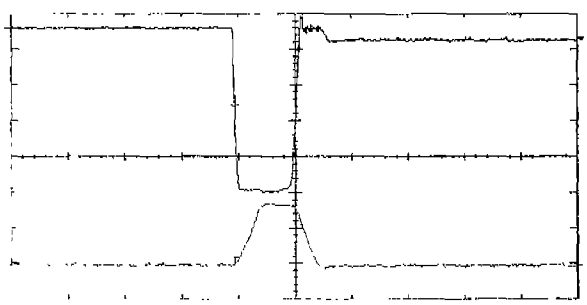
(a) upper: v_{Gsm} (solid), v_{Gsa} (dotted), sweep: 2μs/div
lower: v_{Gsm}, i_{Lr}, sweep: 2μs/div



(b) upper: i_{Sm}, v_{Csa}, sweep: 2μs/div
lower: $v_{Dm}/100$, i_{Dm}, sweep: 2μs/div



(c) upper: v_{sm}, lower: i_{sm}, sweep: 2μs/div



(d) upper: v_{sa}, lower: i_{sa}, sweep: 2μs/div

Fig. 8: (a), (b) simulated key waveforms (PSPICE) (c), (d) experimental voltage and current waveforms of main switch and of auxiliary switch

B. Soft-switched dc-to-dc full bridge (FB) converter

Basically, the soft-switched FB converter in this topology is the same as the one called as zero-voltage zero-current switched FB converter, which stems from mainly utilizing the advantage of the FB-ZVS converter incorporating a saturable resonant inductor. With a small modification, the resulting effect has been pronounced, which eliminates a most of shortcomings of well-known phase-shifted dc-to-dc FB converter.

The advantages and disadvantages with the causes are as following [10]:

Advantages:

- reduced conduction loss of the switches due to reduced circulating energy
- increased effective duty cycle resulting in the use of a larger transformer turns ratio to minimize the current in the primary circuit and the voltage in the secondary circuit
- improved output characteristics such as reduced secondary parasitic ringing and rectifier voltage stresses

Disadvantages:

- wider load range to be achieved with ZVS without increasing the circulating energy
  the limited switching frequency range of the converter due to a large flux change in the core
- limited choice of saturable inductor mainly determined by the thermal tolerance of the core material

In order to overcome a couple of shortcomings above mentioned, another way to implement the proposed scheme is to move the resonant inductor from the primary to the secondary by splitting two instead of one and also limiting switching frequency less than several hundred khz, which is more realistic above medium level output capacity. As a result, the core loss is significantly reduced due to the operation in the first quadrant instead of traveling from negative saturation to positive saturation.

In original phase-shifted dc-to-dc FB-ZVS converter, the ZVS range of lagging leg switches is quite limited unless the leakage inductance is very large and also the IGBTs cannot be used with large external capacitors, since the external capacitor reduces ZVS range. However, in the FB-ZVS converter incorporating a saturable resonant inductor, the primary current is reset since the saturable inductor blocks reverse current during the freewheeling mode.

In addition, in the phase-shifted dc-to-dc soft-switched FB converter, a dc blocking capacitor with fairly small capacitance is added to achieve zero-current switching for lagging leg switches. Due to lower conduction loss, higher power density and lower cost, it is desirable to use IGBTs instead of MOSFETs, especially for high-voltage applications. Circuit diagram of soft-switched FB converter is shown in Fig. 9 and its expected key voltage and current waveforms are shown in Fig. 10.

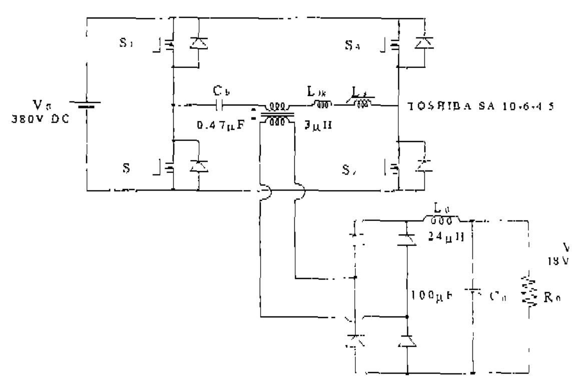


Fig. 9: Circuit diagram of soft-switched FB converter

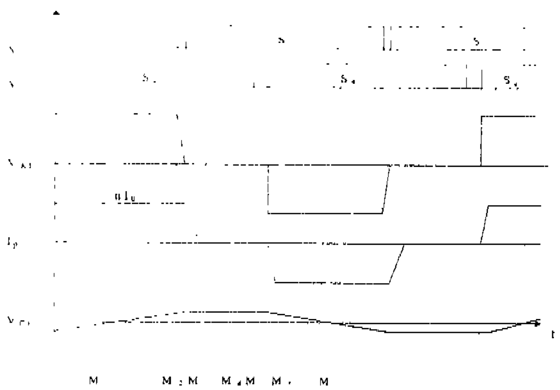
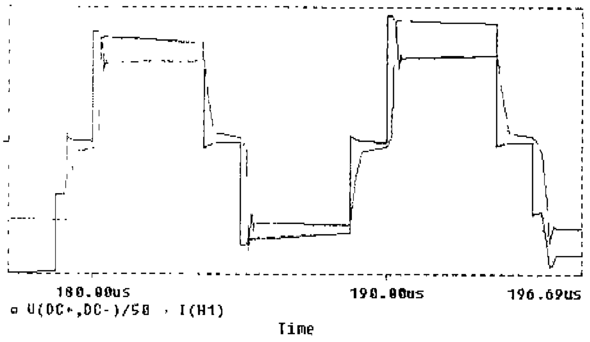
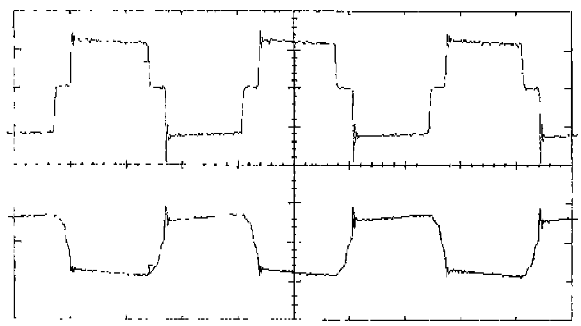


Fig. 10: Expected key voltage and current waveforms

In order to verify the above theory, experimental results of primary voltage and current and those of *PSpice* simulation are given in Fig. 11. A 380vdc input/48vdc 1kw output prototype was built and experimental results are presented to verify design.



(a) upper: v_{AB}, lower: i_{AB}, sweep: 2μs/div



(b) upper: v_{AB} lower: i_{AB}, sweep: 2μs/div

Fig. 11: (a) simulated key waveforms (PSPICE) (b) experimental primary voltage and current waveforms

3. 1-PHASE/3-PHASE COMPATIBLE AC-TO-DC CONVERTER IMPLEMENTATION

For the sake of stability in a single-phase soft-switched ac-to-dc converter with input PFC circuit, specific desgn considerations are given, where basic guidelines are suggested [12]. Based on the previous research of small-signal modeling and analysis for both boost converter and dc-to-dc converter, the interaction problems of both converters were investigated. The integrated system stability was analyzed and validated through investigation of PFC boost converter output impedance followed by dc-to-dc FB converter input impedance ratio at the integration. Furthermore, as long as the current-mode loop control is provided in dc-to-dc FB converter, harmonics of double line-frequency (120hz) can be reduced within the acceptable range without tuning a harmonic trap filter.

The proposed cascaded converter topology can be used in a single-phase, or three of the single-phase converter modules may be used in a three-phase connection depending on the input source condition. The three-phase converter connections are shown in Fig. 12. The three phase converter modules were connected with their inputs in wye. In load balancing control circuit, the control signal from dc voltage control is used to set all three individual converters, but ac control loops are provided separately to all three PFC modules.

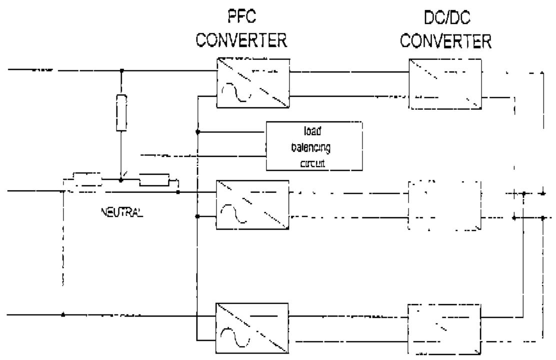


Fig. 12: Three-phase converter connections (wye)

Experiments were completed for both the single-phase and the three-phase case. Figure 13 shows the line-to neutral input voltage and current waveforms of a single-phase module. Nearly sinusoidal input current is shown providing high power factor. However, after zero crossing of the current waveform, a short period of instability is appeared, which needs to be corrected. In the three-phase connection case of Fig. 14, this effect has a detrimental impact on input power factor.

At full load, the total current harmonics of single-phase connection is 4.5%, which is somewhat larger than those of simulated case, 2%. In case of three-phase connections, the measured THD is 10.5%, which is larger than expected. As was mentioned, the instability around zero crossing might be the cause of this high THD and, in addition, this could be due to variations of power circuits and control parameters of each individual module. Nevertheless, the resulting power factor is 0.98 for single-phase and 0.95 for three-phase, showing the advantages of the proposed topology.

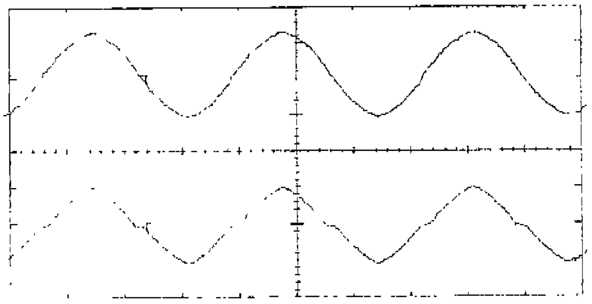


Fig. 13: Single-phase connection
upper. v_{in}. lower: i_{in}. sweep: 5ms/div

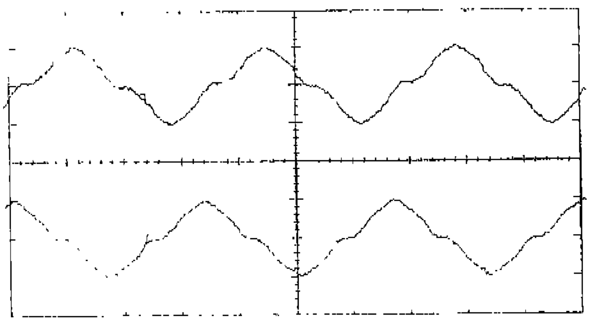


Fig. 14: Three-phase connection
upper. i_{an}. lower: i_{bn}, sweep: 5ms/div

4. CONCLUSIONS

This paper addresses the analysis and design of three single-phase ac-to-dc converter which draws high quality input current waveforms from the ac source along with single-phase/three-phase compatibility. The experimental results of the proposed converter provides an excellent power factor along with high efficiency due to soft-switching. Three individual single-phase soft-switched 1 kw PFC stage using boost converter followed by full-bridge MOSFET converter operating at 100 khz are constructed for telecommunication applications. Compared with a hard-switching FET converter operating at 100 kHz, the proposed converter shows a fairly good improvement in efficiency and in reducing harmonics.

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