Bi-directional Converter for Interfacing Appliances with HFAC Enabled Power Distribution Systems in Critical Applications

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***Abstract* -- A new topology for a robust HFAC enabled bi-directional AC-AC converter is presented in this paper. HFAC PDSs are gaining traction in critical applications within outer space, aerospace and ground transportation PDSs as well as in renewable energy systems due to their advantages of being light deadweight, high power density, smaller capacitors and low arc-flash fault risk etc.**

Due to prominent adverse factors such as high impedance due to skin effect etc., the grid parameters (frequency, voltage etc.) selected for HFAC PDSs vary depending on the PDS length and power rating. Many of the electrical appliances available today cannot be cross matched and used in PDSs with other parameters, therefore the use of power converters as interfacing devices has been recommended. Currently there are only a few types of HFAC converters available in the market; out of which a majority uses resonant filters for sinewave generation whereas the remainder generates non-sinusoidal waveforms requiring complex controllers for voltage and frequency regulation along the PDS.

The proposed two-stage symmetrical topology converter with low-pass filters provide the operation flexibility within a band of voltages and frequencies. The stage-1 H-bridge is PWM switched to boost the DC link voltage, whereas the stage-2 H-bridge is SPWM switched followed by the lowpass filter to generate sinewave output. The two separate PWM controllers used are implemented on a single microcontroller board and swapped for bidirectional operation. Therefore, the new bi-directional converter could be used in multiple applications; thus, supports mass production leading to availability in abundance at low cost.

***Index Terms*— Bidirectional converter, High Frequency AC (HFAC), transportation power distribution systems, high speed switching.**

I. INTRODUCTION

The advantages of HFAC, such as high-power density, high efficiency, smaller capacitors and low arc-flash fault risk etc. has been well documented in many recent publications [1][2][3][4][5]. The HFAC grid parameters are selected depending on the PDS's length and power rating. A typical application that could harness the advantages of HFAC is an aircraft cabin power distribution, with LED lighting, passenger laptop/phone charging (enabled with contact-less sockets), gully-kitchen appliances etc., is depicted in Figure 1. HFAC grid parameters 120V 30 kHz sinusoidal wave could bring the less weight advantage for direct connecting appliances such as fluorescent/led lighting, motor drives, induction heating etc. The other appliances with front-end converters will benefit from comparatively fewer component count,

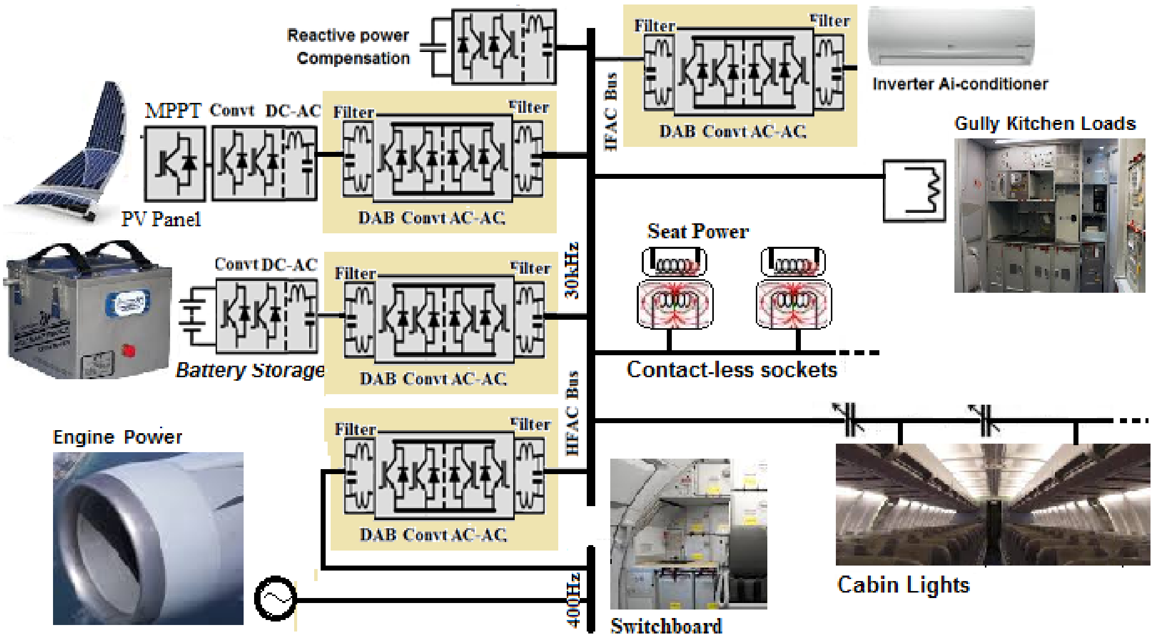

Fig. 1. Aircraft Cabin HFAC Enabled PDS

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simpler controls, smaller capacitors etc.; all leading to lower volume/deadweight, with lower arc-flash fault risk [4]. and higher durability.

However, the widespread utilizations of HFAC is hampered due to the inability of using 50/60Hz electrical appliances in HFAC enabled PDSs. Possibility of cross-matching with HFAC parameters and using had only a limited success. Therefore, the use of AC-AC power converters as interfacing devices has been recommended [3]. The recommended point of load converters has to be available in abundance at low cost for it to be effectively deployed in HFAC PDSs to connect 50/60 Hz appliances. Further, the converter could operate bi-directionally to capture any re-generative or distributed solar/battery power used for efficiency and reliability improvements within modern PDSs. [3].

Most of the AC-AC converters available today are designed for 50/60 Hz UPS systems where the focus is on the power supply stability. The available HFAC converters use resonant filtering [4] making them only suitable for fixed frequency applications; thus, not supporting the concept of low cost by mass production. There had been attempts to utilize square wave in HFAC. Cycloconverter with bidirectional power switches has been proposed as the interfacing converter for 50/60Hz appliances, as well as coupling converter for utility grid connections [5]. However, these laps in voltage control and the bidirectional switches need complex control/gate-driver arrangements for operation. Therefore, a novel converter that overcome these deficiencies and generate sinusoidal HFAC with simpler control/gate-driver circuitry is much needed and this paper presents a suitable circuitry.

This paper is organized as follows: Section II of this paper gives a description of the Proposed Converter Circuit Topology and the requirement for wideband operation. Section III provides a description of the Converter Operation Principle leading to a wide operation bandwidth and bidirectional operation. Section IV discusses about the Simulation Studies performed and the Results. Section V discusses about the hardware design of the converter, laboratory experiment setup and the results from the experiment. Section VI discuss about the Conclusion and Future work.

II. PROPOSED CONVERTER CIRCUIT TOPOLOGY

The proposed bidirectional converter has to be capable of operating in many HFAC PDSs with different gird parameters. The modular type circuitry selected has to be efficient, reliable and suitable for mass production. As depicted in Fig. 2, a two-stage double H-bridge voltage source converter with a DC link is selected as the circuit topology for the new converter. Contrasting to the conventional resonant filters used with HFAC converters, lowpass filters with cut-off set at above the highest from the operational frequency band is selected for both input and output side filters of the new converter. This makes the complete AC-AC converter circuitry being symmetrical and suitable for bidirectional operation. The input side H-bridge works as an uncontrolled diode bridge whereas the output side H-bridge is SPWM switched for generating output waveform. Reversed power flow is achieved by swapping the PWM controller supported by the identical components used in the symmetrical circuit topology. Details on how the new converter works within an operational band is described in section III bellow.

III. CONVERTER OPERATION PRINCIPLE

To enable a full flexible AC-AC conversion the new converter should be capable of increasing or decreasing the output waveform amplitude and frequency. Similarly, the converter input also could be capable of working with a range than a fixed amplitude and frequency values. The input side H-bridge works as an uncontrolled rectifier with any parameters embedded on the input waveform. The output side H-bridge is operated as a SPWM converter having control over the output side waveform amplitude and frequency. Additionally, to achieve an overall voltage increase above the input side waveform amplitude, the

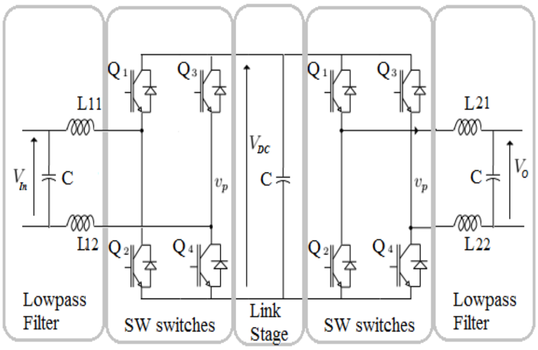
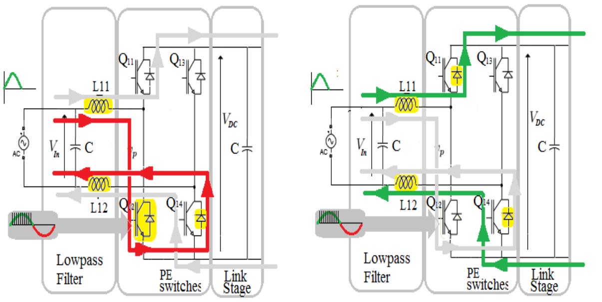
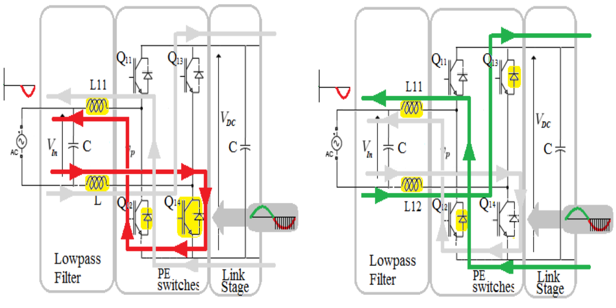


Fig. 2. Proposed Converter Topology



(a) Input Positive – Charging Inductor

(b) Input Positive – Discharging Inductor



(c) Input Negative – Charging Inductor

(d) Input Negative – Discharging Inductor

Fig. 3. Input side H-bridge Operation as a Boost Converter

input side H-bridge is operated as a DC boost converter to raise the DC link stage voltage that could support output waveform amplitude requirements. Details of each H-bridge operation is explained as follows;

A. *Input-side H-bridge DC Boost Converter*

As depicted in Fig. 3, the inductor L11 combined with the PWM operated Q2 and the body diode of Q1 acts as a boost converter during the positive half cycle of the input waveform. Similarly, during the negative half cycle of the input waveform, inductor L12 combined with PWM operated Q4 and body diode of Q3 act as a boost converter. Combination of the above two provide a continuous DC boost action superimposed on already active uncontrolled rectification performed by the body diodes of the H-bridge. Typically, 10kHz switching speed is used for the PWM switching and the input side low-pass filter is de-composes into a capacitor and two inductors during the forward power flow. This makes the inductors L1 and L2 available for DC boost [7] operation.

B. *Output side H-bridge SPWM converter*

Selection of a H-bridge at the output stage of the proposed converter provides the advantages of having low THD, capability of soft switching and low electrical stress on power switches of the converter. A H-bridge stage switched with constant pulsewidth PWM requires a tuned filter to form sinusoidal HFAC output. When the H-bridge stage is switches with PWM, generated following a reference sinewave with desired frequency, the converter output square wave generated would be of varying pulsewidth already following the reference sinewave (SPWM); thus, a lowpass filter would be sufficient to convert it to a sinusoidal waveform having reference wave frequency. This feature provides the SPWM operated H-bridge, followed by a lowpass filter, to be sufficient to generate the desired sinewave output and the capability of changing the operating frequency by changing the reference. The SPWM switching speed is set over at least 50 times the generated sinewave frequency [6] posing a limit on the maximum value at 20kHz for a converter operating with 1.0MHz SPWM switching speed.

Additionally, the SPWM generation could include control over the output waveform amplitude as a fraction of the input voltage (modulation index) providing the required flexibility in both amplitude and frequency of converter output waveform. Fig. 4 shows the circuit topology for the SPWM operated output stage.

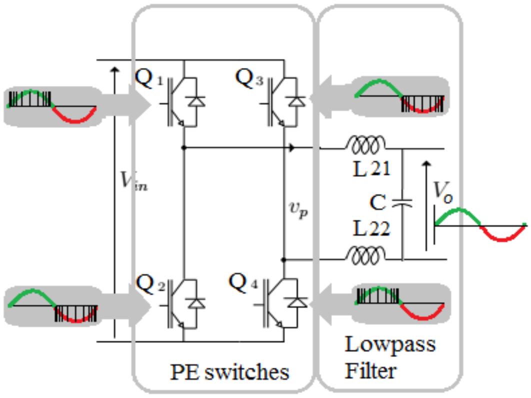


Fig. 4. Output side H-bridge Operating as a SPWM Converter

C. *Bi-directional operation capability*

The proposed converter is designed with a symmetrical topology with same circuitry appearing both at the input and output sides of the converter. Power flow direction is defined by the switching arrangement (Boost PWM or SPWM) in each H-bridge; thus, making the reverse direction power flow easily achievable by controller swapping as depicted in Fig. 5.

D. *Closed-loop Controllers*

Controllers designed with an inner current loop and an outer voltage loop are utilized for amplitude control of both the DC link stage and the output stage of the converter. Well established Power Factor Control (PFC) algorithm is utilized due to it's advantages of having low THD and high-power factor on feed-in power supply [8]. Use of closed loop techniques on the output sinewave frequency control as well as phase control (none unity power factor loads) is excluded; Further study is required to include load sharing control schemes that would satisfy both HFAC and 50/60Hz operation which could differ widely with the grid parameters used.

IV. SIMULATION STUDIES AND RESULTS

A. *Simulation Studies using MatLab/Simulink*

MatLab/Simulink and Simscape library blocks were used for building the model. PFC controller is built as a subsystem and the compensator parameters were tuned using the facility available within the Simulink software platform. As the electronic components used in the symmetrical circuit topology were unchanged, both the forward and reversed power flow were tested with the same tuned parameters for the compensator. Both, PWM and

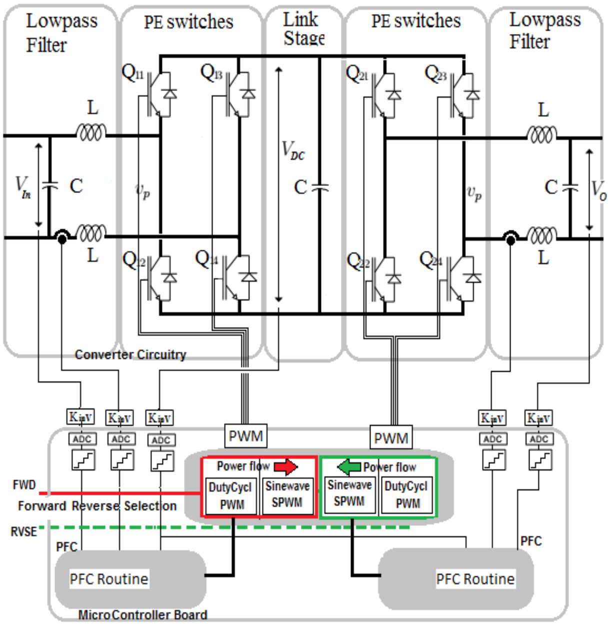


Fig. 5. AC-AC Converter with Bi-directional Power Flow

SPWM generators and open loop waveforms were tested using sections of the model before implementing them in the complete bidirectional AC-AC converter model (Simscape) with closed loop control.

B. Test Scenarios and Simulation Study Results

The model built was tested successfully with some forward and reversed power flow conditions. Table-I lists out four scenarios for testing using the developed Simulink model.

TABLE-I
BI-DIRECTIONAL POWER FLOW SIMULATION SCENARIOS

item	Scenario	Input HB1	Link Stage	Output HB2
1	Forward power flow	Amplitude=12V Freq=50Hz	Link=20Vdc	Amplitude=11V Freq=1000Hz
2	Forward power flow	Amplitude=11V Freq=1000Hz	Link=20Vdc	Amplitude=12V Freq=50Hz
3	Reversed power flow	Amplitude=12V Freq=50Hz	Link=20Vdc	Amplitude=11V Freq=1000Hz
4	Reversed power flow	Amplitude=11V Freq=1000Hz	Link=20Vdc	Amplitude=12V Freq=50Hz

Results from the study for the listed scenarios are shown in figure 7. These results are carried forward to the laboratory testing stage as the reference waveforms for testing using the prototype converter constructed in the laboratory. Both unipolar and bipolar SPWM switching was used during the study and the results shown are from unipolar switching.

C. Analysis from Simulation Study Results

The controller for the input side H-bridge was made to generate constant duty cycle PWM (typical 10kHz) to perform the boost operation on DC-link, whereas the controller for output side H-bridge was made to generate variable duty cycle SPWM (typical 1.0MHz) in the simulation studies performed. The model was developed with enebled blocks from Simulink library to facilitate easy swap over of controllers for reverse direction power flow. As automated code generation supported by Simulink was used for coding the microcontroller board, additional care was taken during building the model to use only the blocks that supported code generation.

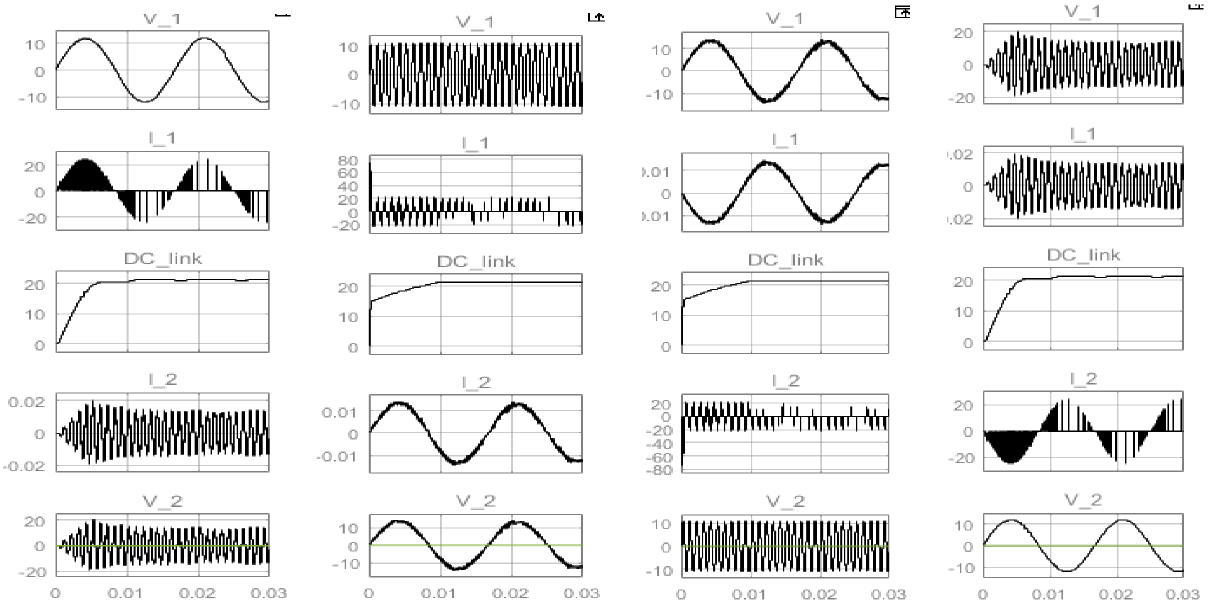
Simulation study results depicted in Fig. 6 show satisfactory performance with the generated sinewaves during both forwards and backward power flow. Further study is required to deal with start-up issue and add soft-switching feature to the operation.

V. LABORATORY TESTING AND RESULTS

A prototype of the AC-AC converter was constructed in the laboratory for testing. Highlights form the components selection, PCB design, microcontroller board selection and coding are given in the following sections.

A. Selection of circuit components

Power MOSFETs are used in both the H-bridges. As hard switching is inevitable in both DC boost converter and SPWM converter operations, MOSFETs with low gate charge and low switching losses were selected. Further, MOSFETs and bypass diodes capable of operating at 1.0MHz switching frequency are selected for the H-bridges. In order to minimize trace inductance and stray capacitance effects, GanFET Power Stage IC LMG5200 from TI was selected for building the power stage. This Power Stage IC combines a half H-bridge consisting of two GaN MOSFETs (WBG type) and high/low side gate drivers for operating the same. Highlights from the Power Stage IC are the 80V_{max} link stage, 6V_{max} driver stages with a 2.0V switching threshold, continuous output current of 10A and a 30ns propagation delay during switching.



a). Item No.1 b). Item No.2 c). Item No.3 d). Item No.4

Fig. 6. Simulation Study Results

The lowpass filter stages were designed with a cut-off frequency at 10kHz. As the prototype was planned to be operated around 15V and 100mA, 4.0uF 100V and 2.2uH 5A were selected as the filter circuit elements.

The DC link capacitor will have to suppress the double input waveform frequency ripple from upstream as well as the SPWM switching current ripple from downstream. 50Hz was selected as the minimum operating frequency and 10kHz as the maximum value for the design. Similarly, DC link was planned to be operated below 25V, therefore 470uF 63V was considered as the rating for the link capacitor.

Signal pre-conditioning is used to convert all current and voltage feedback signals to a 2V $\pm 1.0V_{max}$ signal that could be connected to the onboard ADCs used from the microcontroller board. An OpAMP based amplify and level shift circuitry was selected to perform the required pre-conditioning. Feedback signals with 100mA AC currents, 15V AC voltages and 25V DC voltages were converter to 2.0V ± variable values with a common ground reference for feeding into the microcontroller board.

B. *Selection of the microcontroller board and coding*

Microcontroller based implementation facilitates the easy swapping of controller routines for bi-directional operation. However, the microcontroller board used has to be fast enough to produce 8 of PWM outputs, 5 of ADC inputs, serial communication with the host PC, 2 of PFC subroutines and other calculations at 1.0MHz speed as required for SPWM switching. Texas Instruments (TI) microcontroller board Delfino LaunchXL with a 32-bit TMS320F28377S processor operating at 200MHz, 10 Nos. of 12bit onboard ADC inputs, 9 of onboard PWM outputs and a 5.0Mbps UART was selected for the experiment.

Simulink supports automated code generation for the TI Delfino LanchPad; therefore, this facility was used for coding the controller board. This process enabled testing all modules by simulation before being implemented on the LaunchPad as well as on the actual converter (plant).

C. *Test Scenarios and Results from Laboratory Testing*

The prototype circuitry constructed and assembled for testing is depicted in Fig. 9. Laboratory testing was performed for the same scenarios listed under simulation studies. Forward and reversed power flow was tested by swapping connections (physical) to the input sinewave generator and output resistive load together with the controller swapping (software). Results from Simulink model testing was used as the reference waveforms for laboratory testing.

The DC stage boost was performed with 10kHz PWM switching, whereas the output sinewave was generated with SPWM at 1.0MHz. Results from the laboratory tests performed showed a close resemblance to reference (simulation) waveforms. DC boost from $10V_{peak}$ 50Hz to 15V dc is shown in Fig.7. The sinusoidal output waveforms generated at 50 and 400Hz are shown in Fig.8. The 1000Hz waveform showed significant common mode noise making the overall shape to deviate from the desired. The observed noise could be generated due to high-speed switching which has to be eliminated by following advanced PCB design techniques recommended for high frequency switching applications. Additionally, advanced coding techniques also could be explored to minimize any noise generated from the microcontrollers delivering output in the MHz range.

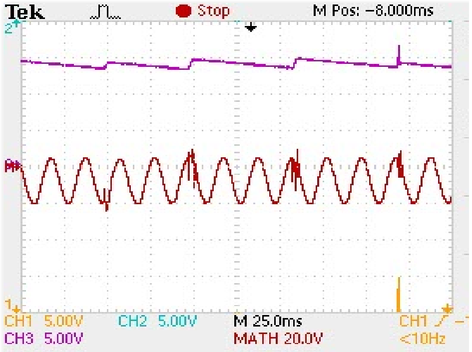
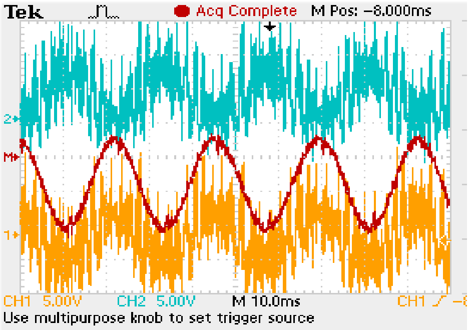
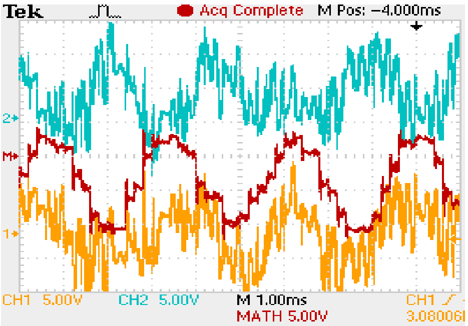


Fig. 7. Experiment results - DC Link Boost



(b) Output Sinewave 50Hz



(c) Output Sinewave 400Hz

Fig. 8. Experiment results

VI. CONCLUSION AND FUTURE WORK

A new circuit topology for a bi-directional HFAC enebled AC-AC converter is presented in this paper. The two symmetrical H-bridge stages of the converter are switched differently; the input side with constant duty cycle PWM to boost DC link voltage and the output side with varying duty cycle SPWM for generating sinusoidal output waveform. Digital control is utilized for generating PWM for each H-bridge, which is swapped for bi-directional operation. Successful operation of the converter is demonstrated through simulation studies as well as by laboratory testing. It is noted that at least a factor of 100 is desired between the frequency of the output waveform and

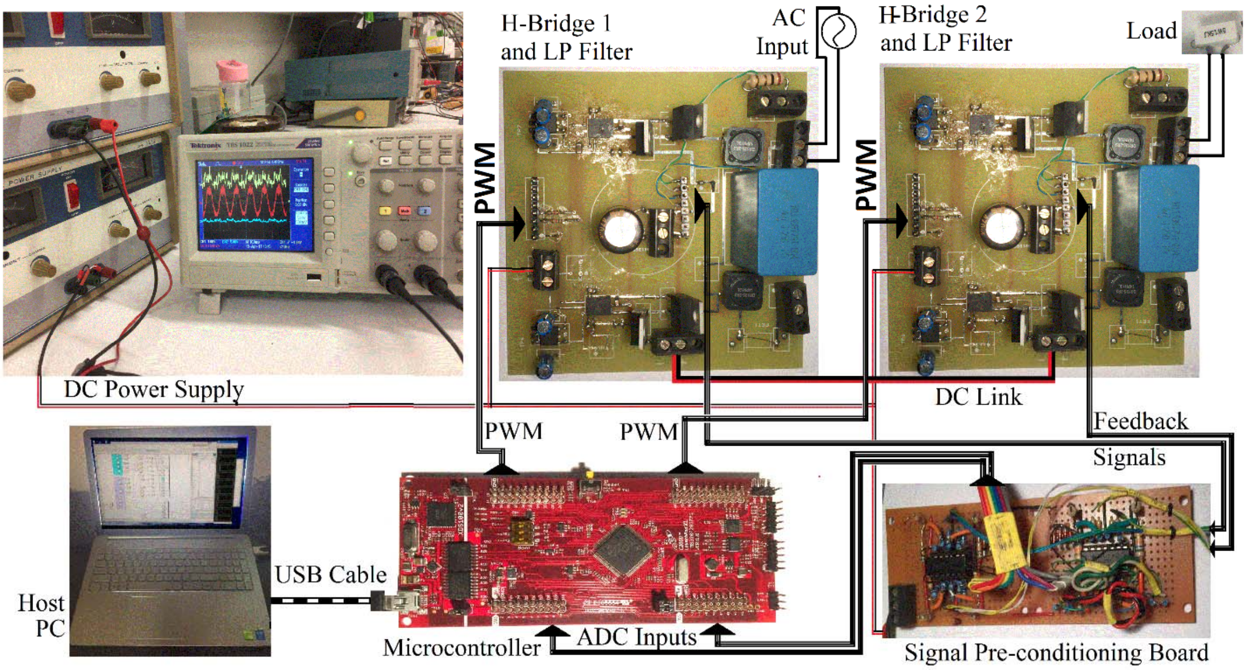


Fig. 9. Laboratory Testing Setup

the H-bridge MOSFET switching speed, posing a limit on the maximum frequency of generated HFAC. Therefore, both modern microcontrollers with higher operating speeds with advanced coding techniques and MOSFETs capable of operating at high switching speeds are essential for increasing the frequency of the HFAC output generated. The proposed AC-AC converter is capable of generating sinusoidal output waveform with both voltage and frequency regulation supporting parallel load and generation connections along the PDS. Possibility of using one converter for a range of voltages and frequencies (50 to 1000Hz) supports mass production leading to availability in abundance at low cost.

The output H-bridge SPWM controller works aligned with the reference sinewave generated, thus the simple PFC controller utilized could be replaced with a suitable complex controller for reactive power support to enable use with active loads.

In this paper, a stand-alone application where output sinewave frequency and voltage are set as reference parameter is considered. The output H-bridge SPWM controller works aligned with a reference sinewave generated and could be connected to a Phase Locked Loop (PLL) subroutine for grid connected parallel operation. Additionally, already established parallel generation techniques well established with both 50/60Hz and HFAC converters could be used with the output stage SPWM controller for upgrading the converter to a grid connected parallel operation mode.

REFERENCES

[1] P. Jain, S. Pan, J. Drobnik, "A Review of High-Frequency Power Distribution Systems: For Space, Telecommunication, and Computer Applications", *IEEE Transactions on Power Electronics*. Vol: 29, Issue 8, pp 3852 - 3863 (2014).

[2] M. Wang, Q. Huang, W. Yu, "High-frequency AC Distributed Power Delivery System", *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp: 3648 – 3654, year 2016.

[3] Zhongming Ye, John C. W. Lam and Praveen K. Jain, "A Robust One-Cycle Controlled Full-Bridge Series-Parallel Resonant Inverter for a High-Frequency AC (HFAC) Distribution System", *IEEE Transactions on Power Electronics*, pp 2331–2343, Vol 22, Issue:6, year 2007.

[4] Mengqi Wang, Qingyun Huang, Wensong Yu and Alex Q. Huang, "High-frequency AC Distributed Power Delivery System", *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, year 2016.

[5] W. Anand Fernando; Dylan Dah-Chuan Lu, "Feasibility study of existing 50/60Hz electrical appliances for HFAC power distribution systems", *2016 IEEE International Telecommunications Energy Conference (INTELEC)*, pp 1-8, year 2016

[6] M. F. N. Tajuddin, N. H. Ghazali, I. Daut and B. Ismail, "Implementation of DSP Based SPWM for Single Phase Inverter", *IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion,* pp 1129–1134, year 2010.

[7] Montie A. Vitorino, Alu´ısio A. M. Bento, Darlan A. Fernandes, Maur´ıcio B. R. Correa, "Design of Boost Converter Operating in CRM Controlled by OCC", *IEEE 2013 Brazilian Power Electronics Conference*, pp 440-447 Year 2013.

[8] S. Y. Hui; Henry Shu-Hung Chung; Siu-Chung Yip, "A Bidirectional AC-DC Power Converter With Power Factor Correction", *IEEE Transactions on Power Electronics*, Volume: 15 Issue:5 Pages:942-948 Year 2000.