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SINGLE-PHASE HIGH GAIN GAMMA H-BRIDGE BASED AC-AC-DC CONVERTER FOR RENEWABLE ENERGY APPLICATIONS

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Abstract- This work proposes a single-phase AC-AC-DC converter with increased voltage gain. The suggested converter is developed from the Gamma AC-AC topology and the classical H-bridge rectifier circuit. The proposed single-phase rectifier is suitable for electric vehicle charging, wind, and microgrid applications. The high voltage gain of the Gamma AC-AC converter is achieved by utilising a coupled transformer where the gain is regulated by tuning the turns ratio of the transformer. The input and output voltage of the Gamma AC-AC converter share a common ground, the converter is controlled with safe commutation without utilising a snubber circuit thereby avoiding current and voltage spikes on the switches. The output of the Gamma AC-AC converter is fed to the H-bridge rectifier which contains an LC filter to minimise ripples of the output DC voltage. The proposed single-phase rectifier converter is analysed by building and simulating the power circuit in PSCAD-EMTDC software. Theoretical analysis of the proposed topology is validated by the results of the simulation. The peak input voltage of 57V is boosted by a factor 6 thus the AC-AC load voltage is 351V which rectified to a DC magnitude of 200V.

Keywords: AC-AC Converter, Gamma, H-bridge Rectifier, Single-Phase Rectifier.

1. INTRODUCTION

Impedance networks (Z-Source) or Z-Source-Inverters (ZSI) have enabled conventional converters to have voltage-boosting capabilities which is a requisite characteristic of modern power electronic converters. Until the introduction of the first impedance network by Fang in 2003, most power conversions were achieved with multi-stage conversions or single-stage conversions with only buck capabilities. Matrix converters, indirect AC-AC, and direct AC-AC converters are the commonly used converters for AC-AC power conversion. In the indirect AC-AC power conversion, the transmission line gets polluted by the diode rectifier, and matrix converters even though they provide output voltage with controllable frequency, however, they commonly have a low voltage transfer ratio of 86.6%. Direct AC-AC converters on the contrary have the following advantages reduced converter size, minimised line harmonics, simple topology, one-stage conversion, higher efficiency, and simple control techniques [1-3].

Also, direct AC-AC converters are better suited for SST (solid state transformers) [4] and DVR (dynamic voltage restorers) [5] applications because they provide flexible voltage amplitude regulation and higher efficiency [6]. Impedance networks popularly known as Z-Source are one of the latest developments in voltage conversion using power electronic converters. By design, ZSI comprises 2 capacitors and 2 inductors placed between the input and switches section of the converter; these energy-saving components are arranged in an X shape. ZSI allows concurrent gating of switches on the same leg; this feature provides the boosting factor because the inductors and capacitors are energized during this period which is the shoot-through. ZSI are single-stage converters with step-up/step-down voltage regulation, they have reduced weight, size, and cost juxtaposed to the classical boosting topologies. The improved ZSI, high performance, quasi ZSI, and T-Source were the next generation of impedance topologies after ZSI, they had features like high boosting factor, bidirectional current flow, continuous source current flow, etc which were not present in ZSI. After these topologies, the Trans/T-Source, various combinations of inductor-capacitor-transformer commonly known as LCCT ZS/QLCCT ZS were introduced. Next was the introduction of the family of Gamma networks comprising flipped and asymmetric networks. The delta, Y-source, L-source, sigma, and A-source networks followed the previous sets of networks. They have merits like achieving high voltage gain with reduced components, suitable for current source converter applications, and better voltage gain. One interesting characteristic of impedance networks is that they can be applied in any of the four power electronic converters. Some recent applications of AC-AC converters with impedance networks can be found in other impedance networks that have been introduced for various applications in power systems. Some application areas of the impedance-based converters are energy storage, DVR, UPS, variable speed drives, renewable energy systems such as fuel cells, wind, solar, hydro, etc, electric vehicles, DC circuit breakers, and electronic loads [7-13].

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The conventional impedance network-based AC-AC converters had some inherent drawbacks such as complex commutation, discontinuous/inrush source current, required snubber circuit, and uncommon ground between the source and output. Nonetheless, some recently reported AC-AC converters provide improvements to the drawbacks of the previously reported topologies. The dead-time and shoot-through issues are resolved in [14] and controlled by a simple PWM technique, commutation problems are solved in [15-16], the discontinuous sources' current and uncommon ground drawbacks are fixed in [17] and the component count are reduced in [18]. From initial impedance networks of Z-Sources, Quasi Z-Source, and Modified Quasi Z-Source came the second generation of impedance networks based on Transformer with isolation and none-isolation features [19-20].

Diode rectifiers provide DC voltage from AC power sources utilising very simple circuit configurations. They contain less EMI and are highly reliable. Diode rectifiers provide coupling of power systems such as AC-DC microgrids, asynchronous power systems, and power devices [21-22]. Nonetheless, diode rectifiers do not meet harmonic standard requirements as they pollute power lines with harmonics especially high order-harmonics in three-phase diode rectifiers [23-24]. Several techniques have been proposed to minimise source current harmonics; increasing the diode pulses being the worthwhile technique, application of multiphase transformers [25-26], fixing (hybrid, active or passive) filters [27-28], and improving the rectifier circuit to minimise harmonic generation.

This work proposes a new method to generate high-gain rectified DC voltage by coupling a Gamma AC-AC converter with an H-bridge rectifier circuit.

The Gamma AC-AC converter is composed of two bidirectional switches and a coupled transformer, capacitor and LC filter the output. By tuning the turns ratio $\Gamma_r \frac{\omega_1}{\omega_2}$, the derived gained is regulated.

2. PROPOSED RECTIFIER TOPOLOGY

The power circuit of the proposed single-phase rectifier which is segmented into two parts is illustrated in Figure 1a. A flowchart showing the steps of deriving the proposed topology is illustrated in Figure 1b. The first part is the high-gain AC-AC converter composed of a coupled transformer, two bidirectional switches, a capacitor, and an LC filter. The output of the AC-AC converter is fed into the full bridge diode rectifier composed of four diodes and a resistive load. The turns ratio of the transformer Γ_r is expressed by Equation (1) where w_a, and w_b represent the number of turns on the first and second windings accordingly. Controlling the turns ratio within the margins expressed by $1 < \Gamma_r < 2$ provides a substantial boost factor juxtaposed with the traditional impedance AC-AC converter. The boost element B of the AC-AC converter is expressed by Equation (2) where D is the duty ratio. If boost element B is considered to be greater than zero, new duty cycle boundaries are established where the greater boost element value is produced because of the application of a smaller turns ratio.

$$\Gamma_r = \frac{w_a}{w_b} \tag{1}$$

$$B = \frac{1-D}{\left(1+\frac{1}{\Gamma_r - 1}\right)1-D} \tag{2}$$

As in the case of all impedance networks, the AC-AC section of the proposed single-phase rectifier operates in two modes i.e. non-shoot-through and shoot-through. These modes of operation are illustrated in Figures 2a, and 2b, accordingly. In the non-shoot-through mode, switch $S_{a,b}$ is turned on while switch $\mathrm{S}_{\mathrm{c,d}}$ is turned off. The location of the bidirectional switch developed from the common emitter layout makes it susceptible to current spikes caused by voltage fluctuations of the capacitor and voltage spikes caused by abrupt changes in the inductor current. These limitations are overcome by the application of safe commutation thus preventing switch damage. Modelling the coupled inductor as an ideal transformer with leakage inductor L_k and magnetizing inductor L_m yields turn ratio expressed by Equation (1) and transformer coupling coefficient (k) expressed by Equation (3) as:

$$k = \frac{L_m}{L_k + L_m} \tag{3}$$

In Figure 2a, switch $S_{a,b}$ is gated on while switch $\mathrm{S}_{\mathrm{c,d}}$ is gated off, therefore, the switches are in short-circuit and open-circuit states accordingly. Capacitor charges in this state. The following Equations are developed for this state when KVL is applied to the equivalent circuit of Figure 2a:

$$-v_i + v_{L2} + v_C = 0 \tag{4}$$

$$v_{Lm} - v_{L1} = 0 \tag{5}$$

$$-v_i + v_{L1} - v_{Lk} + v_{Lf} + v_o = 0 \tag{6}$$

The following equations are developed in this state when KCL is applied to the equivalent circuit of Figure 2a:

$$-i_{L1} + i_{Lm} + i_{Lk} = 0 \tag{7}$$

$$-i_{Lk} - i_{Lf} = 0 \tag{8}$$

$$-i_i + i_{L1} - i_{L2} - i_{Lm} = 0 \tag{9}$$

$$-i_{Lf} - i_{Cf} - \frac{v_o}{R} = 0 \tag{10}$$

Considering Equations (3) and (7), the leakage inductor voltage v_{Lk} is expressed by Equations (11) and (12) where Equation (12) is due to the ideal transformer characteristics.

$$v_{Lk} = L_k \frac{d}{dt}\left(i_{L1} - i_{Lm}\right) \tag{11}$$

$$v_{Lk} = \left(1 - \frac{1}{k}\right) v_{Lm} \tag{12}$$

Considering Equations (5) and (6), the source voltage and the magnetizing inductor voltage are computed as:

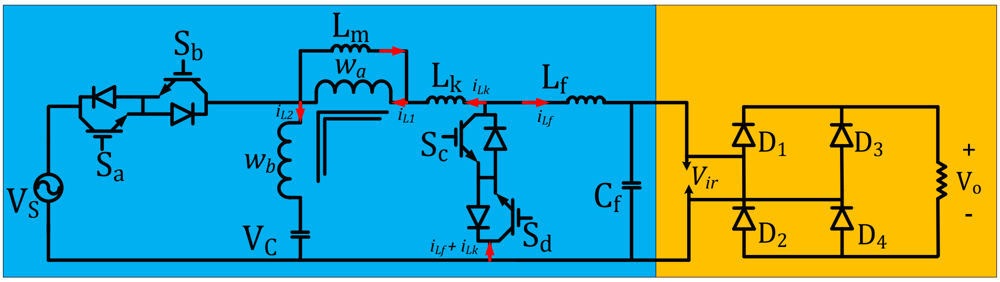

Figure 1a. Proposed single-phase rectifier

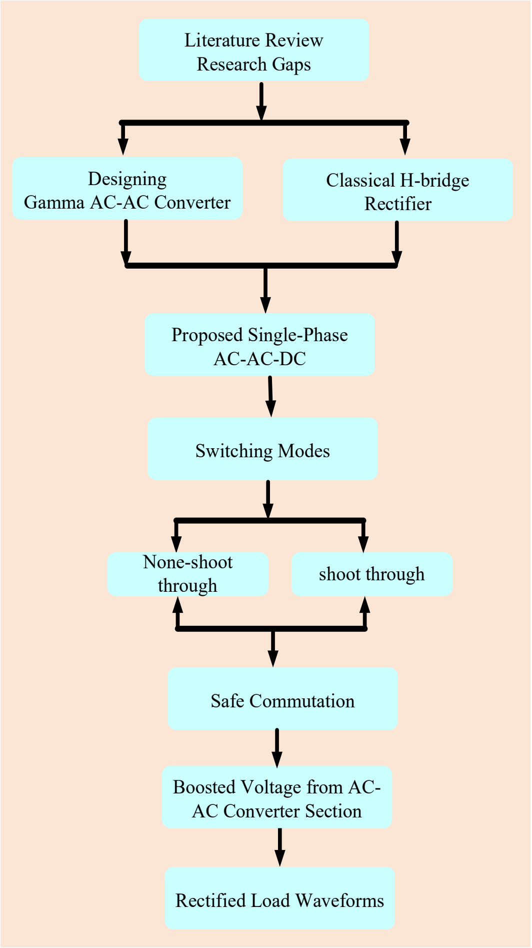

Figure 1b. Flowchart showing steps of deriving proposed topology

$$-v_i+\frac{v_{Lk}}{\Gamma_r}+v_C=0 \tag{13}$$

$$v_{Lm}=\Gamma_r\left(v_i-v_C\right) \tag{14}$$

Also, the source voltage and inductor filter voltage are computed by:

$$-v_i+\Gamma_r(v_i-v_c)-\Gamma_r\left(1-\frac{1}{k}\right)(v_i-v_c)+v_{Lf}+v_o=0 \tag{15}$$

$$v_{Lf}=\left(1-\frac{\Gamma_r}{k}\right)v_i+\frac{\Gamma_r}{k}v_C-v_o \tag{16}$$

The capacitor current and filter capacitor current are computed as:

$$i_C=\gamma_\Gamma(i_{Lm}-i_{Lf}) \tag{17}$$

$$i_{Cf}=i_{Lf}-\frac{v_o}{R} \tag{18}$$

In Figure 2b, switch $S_{c,d}$ is gated on while switch $S_{a,b}$ is gated off, therefore, the switches are in short-circuit and open-circuit states accordingly. The capacitor discharges and feeds the load in this state. The following Equations are developed for this state when KVL is applied to the equivalent circuit of Figure 2b:

$$-v_C-v_{wb}+v_{wa}-v_{Lk}=0 \tag{19}$$

$$v_{Lf}+v_o=0 \tag{20}$$

The following equations are developed in this state when KCL is applied to the equivalent circuit of Figure 2b:

$$i_{Lf}-i_{Cf}-\frac{v_o}{R}=0 \tag{21}$$

$$-i_C-i_{Lm}+i_{L1}=0 \tag{22}$$

Considering Equations (11) and (19), the capacitor voltage, leakage inductor voltage, and magnetising inductor voltage are expressed by Equation (23). Magnetising inductor voltage, turns ratio and capacitor voltage are expressed by Equation (24).

$$-v_C-\frac{v_{L_m}}{\gamma_\Gamma}+v_{L_m}-\left(1-\frac{1}{k}\right)v_{L_m}=0 \tag{23}$$

$$v_{L_m}=\left(\frac{\gamma_\Gamma k}{\gamma_\Gamma-k}\right)v_C \tag{24}$$

The output voltage and filter inductor voltage are related by:

$$v_{Lf}=-v_o \tag{25}$$

Considering Equation (22), the capacitor current is computed by:

$$-i_C-i_{Lm}+\frac{i_C}{\gamma_\Gamma}=0 \tag{26}$$

$$i_C=\left(\frac{\gamma_\Gamma}{1-\gamma_\Gamma}\right)i_{Lm} \tag{27}$$

The filter currents are related by:

$$i_{Cf}=i_{Lf}-\frac{v_o}{R} \tag{28}$$

Considering the above equations derived by analysing Figures 2a and 2b, the voltage gain i.e. ratio of the output-input voltage and the duty cycle is computed as:

$$\frac{v_o}{v_i}=\frac{(1-D)}{1-D\left(1+\dfrac{k}{\gamma_\Gamma-k}\right)} \tag{29}$$

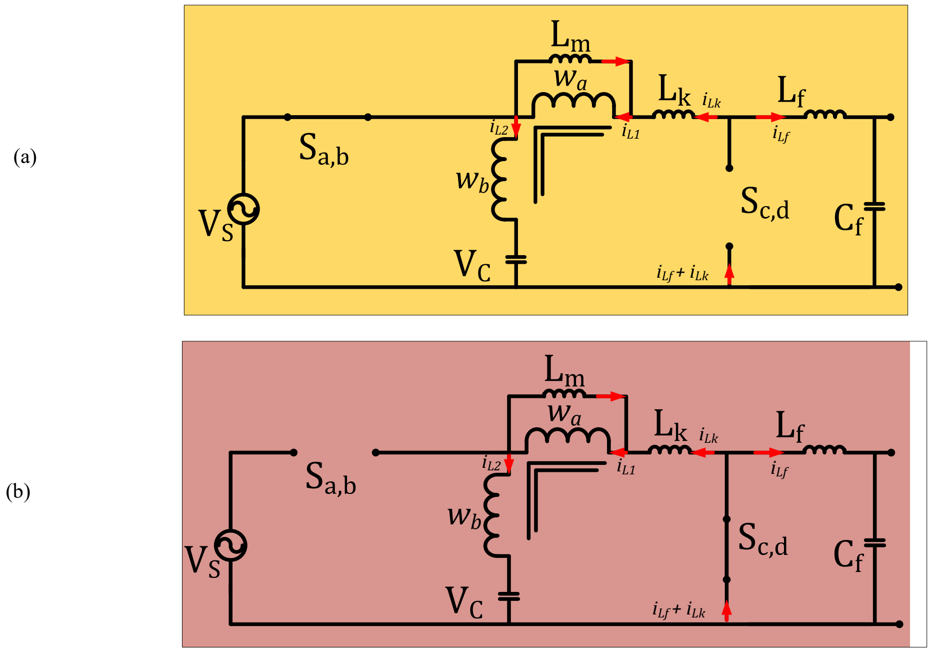

Figure 2. a) Non-shoot-through mode, b) shoot-through mode

The boost element, input voltage and capacitor voltage are computed as

$$\begin{cases} B = \dfrac{v_C}{v_i} \\ B = \dfrac{v_C}{v_i} = \dfrac{(1-D)}{1-D\left(1+\dfrac{1}{\gamma_\Gamma - 1}\right)} \end{cases} \tag{30}$$

The H-bridge rectifier part of the proposed single-phase converter is illustrated by Figure 3 and the corresponding theoretical output waveforms are illustrated by Figure 4. The input voltage of the H-bridge rectifier is fed by the load voltage of the boost AC-AC converter. This voltage is expressed by Equation (30). Analysis of the rectifier circuit is provided below.

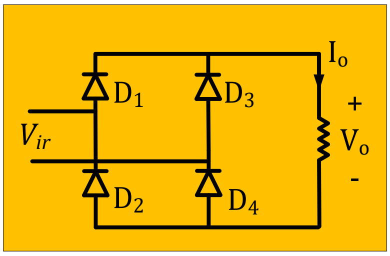

Figure 3. H-bridge rectifier

Equation (31) represents the input voltage of the rectifier section of the topology and the average component of the output voltage, current, and power is expressed by Equation (32) to Equation (35):

$$V_{i_r} = v_m \sin\omega t \tag{31}$$

$$V_{o_{dc}} = \frac{1}{2\pi}\int_0^{2\pi} V_o d\left(\omega t\right) \tag{32}$$

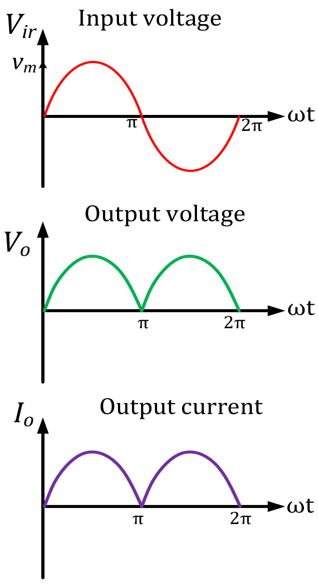

Figure 4. Theoretical input/output waveform

$$V_{o_{dc}} = \frac{2v_m}{\pi} = 0.637v_m \tag{33}$$

$$i_{o_{dc}} = \frac{V_{o_{dc}}}{R} \tag{34}$$

$$P_{o_{dc}} = \frac{V_{o_{dc}}^2}{R} = \frac{0.405V_m^2}{R} \tag{35}$$

3. SIMULATION RESULTS

The proposed high-gain AC-AC H-bridge coupled rectifier is presented in this section. The power circuit of the proposed topology is built and simulated in PSCAD/ EMTDC software using the input values indicated in Table 1. The corresponding output waveforms produced after simulation are illustrated in Figure 5 to Figure 13. The peak input voltage of the proposed converter of $57V$ magnitude is illustrated in Figure 5, the corresponding V_{rms} component of the source voltage is $40V$. The average peak output voltage of the AC-AC section of the proposed converter illustrated by Figure 6 is 350V, therefore, the V_{rms} component is approximately 247V. The ratio of the V_{rms} component of the input voltage and output voltage gives a boost factor of 6.2.

Figures 7 and 8 illustrate the DC output waveforms of the proposed rectifier circuit for the voltage and current respectively. The ripple component of these waveforms is greatly minimized because the filter components are properly selected for the ripple component. Figure 9 shows the current waveform of the filter inductor, the magnitude of this current validates Equations (21) and (27). The waveforms of the THD and FFT for the AC output section of the proposed topology are shown in Figure 10 to Figure 13. The magnitude of these waveforms is within industry-accepted standards hence the waveform distortions are minute. The voltage and current THDs are illustrated in Figures 10 and 11 accordingly while the voltage and current FFT waveforms are illustrated in Figures 12 and 13, respectively. The even-order frequencies are naturally eliminated. The lower-order frequencies are a bit high but decrease along the line. As can be seen, the 9th, 11th, etc frequencies are almost zero in magnitude.

Table 1. Simulation variables

Variables	Magnitude
Switching Frequency f_s	30 kHz
Load frequency f_o	50 Hz
Input voltage V_i	V_{rms} = 40 V, $V_{\max}$ = 57 V
Filter Inductance L_f	50 mH
Filter Capacitance C_f	40 µF
Coupled Inductance	$\omega_a = \omega_b = 0.6$ mH
Load Resistance R	100 Ω

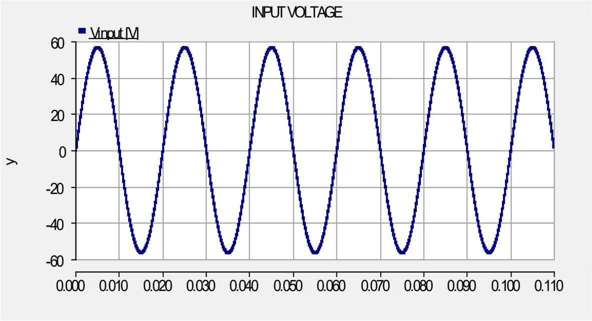

Figure 5. Input voltage waveform

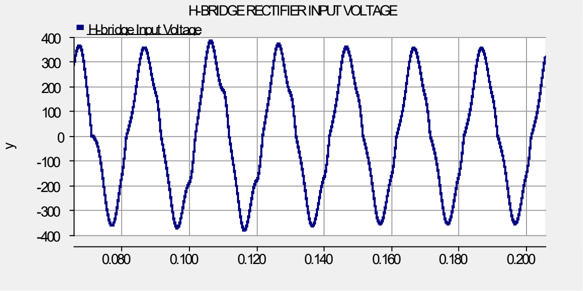

Figure 6. H-bridge rectifier input voltage

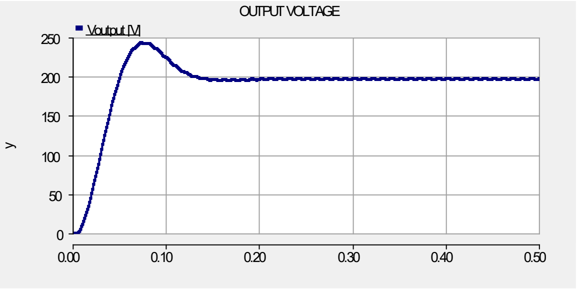

Figure 7. Output voltage waveform

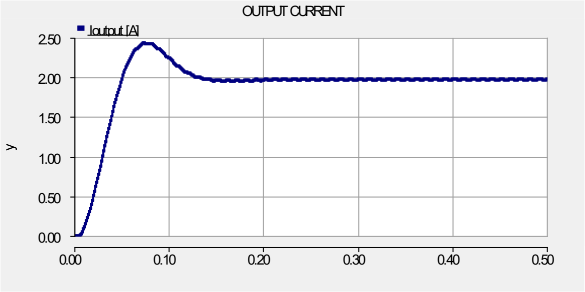

Figure 8. Output current waveform

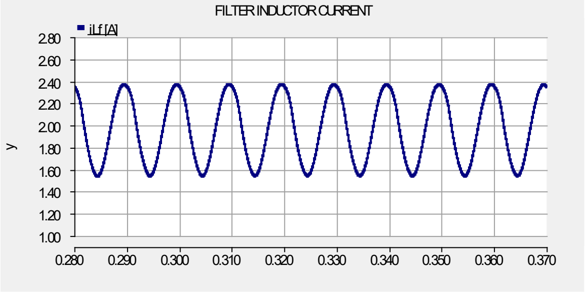

Figure 9. Current waveform of the filter inductor

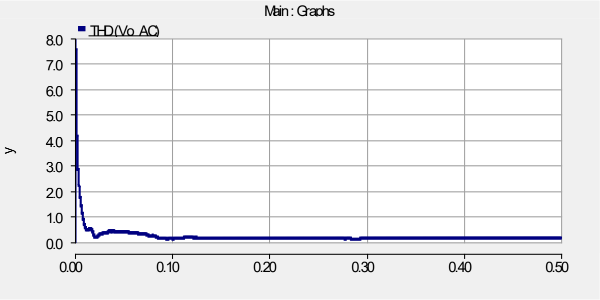

Figure 10. Voltage THD waveform

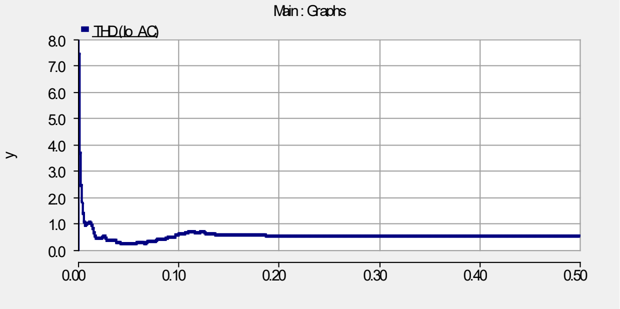

Figure 11. Current THD waveform

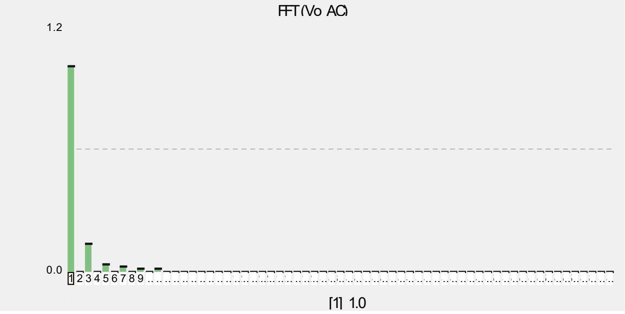

Figure 12. Voltage FFT waveform

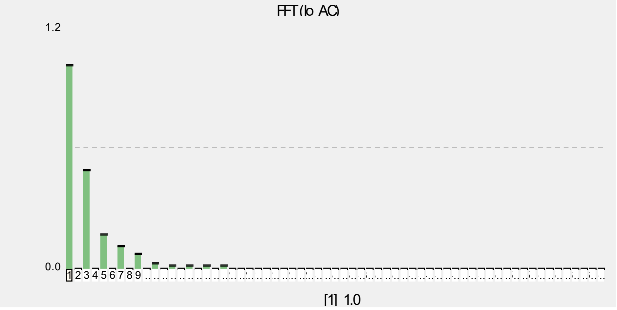

Figure 13. Current FFT waveform

6. CONCLUSIONS

This paper proposed a new technique of generating higher gain rectified DC voltage by coupling a Gamma AC-AC converter with the classical H-bridge rectifier circuit. The proposed single-phase rectifier converter is suitable for electric vehicle charging, renewable energy, and microgrid applications. Theoretical analysis of the proposed converter in shoot-through where the boosting feature is enabled and non-shoot-through (switching sequences) modes is extensively analyzed. Switching of the switches is safely commutated thus avoiding current and voltage spikes of the switches even though snubber circuits are not employed.

Simulation waveforms of the proposed topology affirm theoretical analysis and show optimal working conditions of the propound rectifier. The source voltage is boosted by a boost factor of more than 6 and the ripple content of the output DC voltage is less because of the selection of a suitable output filter. Practically, the proposed topology is suitable for double and/or single stage voltage conditioning such as AC-AC-DC and AC-DC voltage conditioning respectively. Suitable applicable areas are wind generation, AC and DC bus bars in microgrids, and distributed generation systems.

Reducing the double-stage voltage conditioning feature of the proposed topology to a single-stage voltage conditioning while improving the boost factor with reduced component count provides future research opportunities.

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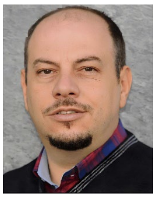

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