Integration of Storage Device using Full-Bridge Forward Dc-Dc Converter for a Residential Microgrid Application

U. V. Suresh Prasad[1], K. N. S. Durga Prakash[2]

[1]PG Scholar, Department of Electrical & Electronics Engineering, Vishnu Institute of Technology; A.P, India

[2]Assistant Professor Department of Electrical & Electronics Engineering, Vishnu Institute of Technology; A.P, India

Abstract: ***The incorporation of renewable energy is limited in many ways by the variable and intermittent nature of its output. Hence, energy storage systems have to be used to buffer the source variations. A bidirectional dc-dc converter is generally needed to actively control the power flow between energy storage and the dc bus in residential microgrid applications. In this paper a new dc-dc converter topology has been proposed for residential microgrid. The proposed dc-dc converter has low number of switches compared to the converters usually applied to similar applications, high power operation, high usage of super capacitor stored energy, long battery life time, low input and output current ripple, high voltage ratio. These converter performances in microgrid are also approached in this paper. The simulations are carried out in Matlab/Simulink environment using simpower systems tool box.***

Keywords: Dc-Dc converter; storage system; distributed generation (DG); microgrid.

1. Introduction

During recent years, the utilization of renewable energy sources has been promoted quickly to fulfil increasing energy demand and deal with global climate change. Since the distributed power generation by renewable energy has different characteristics with conventional power generation by fossil fuels, novel configurations, topologies and control techniques are employed to integrate renewable energysources with utility grid. As the cost decreases continuously, photovoltaic (PV) generation has become one of the most important renewable energy sources and has been widely used. In olden days the PV systems are grid-connected and are usually without energy storage systems. Massive penetration of PV systems with the capability of exporting electric power into the grid, but without energy storage systems, can affect the grid due to their intermittent nature. To overcome this problem storage unit is used in microgrid. The storage unit mainly consists of two units one is battery bank and the other is supercapacitor bank. The battery bank acts as a backup device due to its high energy density [2], providing energy under the steadystate condition when the other sources are not capable. The supercapacitor bank acts as a quick discharge

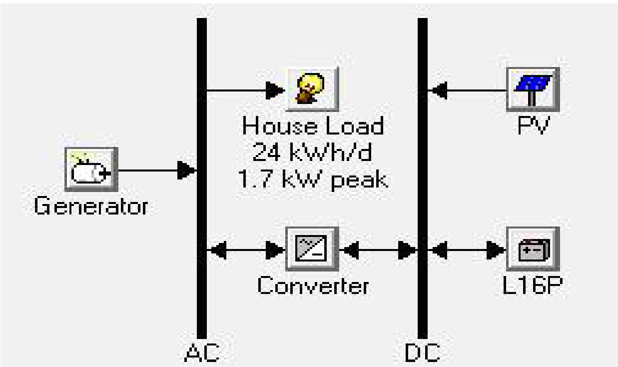

Figure 1: Residential microgrid system under study

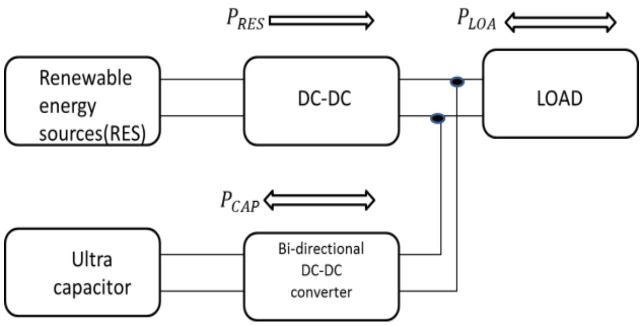

Figure 2: Block diagram of energy storage augmented renewable source system

device due to its high power density [3], providing energy to the microgrid during transitory periods, mainly during the biofuel generator start-up time.

Considering the local generation of distributed sources, residential microgrids are being proposed as an intersting solution for increasing renewable energy production and system reliability for household appliances. The residential microgrid under study here, as shown in Fig.1 [1], comprises DG source photovoltaic panel(PV), an energy storage system(L1GP), converter, generator, house load. The energy storage system contains battery bank and supercapacitor bank.

A bidirectional dc-dc converter is necessary to connect the energy storage system (ultra-capacitor) to the microgrid dc bus or dc load. Once the super capacitor bank voltage is low and not controlled, the bidirectional dc-dc converter must have a high voltage ratio between the input and output stages. Moreover, it must be able to operate under a wide output power range. The block diagram of energy storage augmented renewable source system is as shown in Fig. 2.

2. Literature Survey

Previously, a buck boost converter has been implemented and used in applications where the desirable voltage ratio is not high. For the high voltage ratio application, transformer-coupled bidirectional converters have been proposed such as dual active bridge (DAB), dual active half bridge, full-bridge current fed, full-bridge voltage fed, and their derivatives. The dual active bridge (DAB) or modified DAB converters are approached in [4]-[8]. Among them, the DAB converter shown in Fig. 3 [11], it is formed by two full-bridge converters connected through a transformer. It needs more number of active devices there by resulting in high cost.

It also presents a high input and output current ripple as shown in Fig.4, the soft swithching occurs on specific range, and its operating range is between 28 and 45V. The load power demand varies between P_{min} =200 W and P_{max} =1200 W, and the phaseshift between the two modules should not be higher than 50^0 in order to limit the circulating reactive power [9]. However, it is not economical to operate the converter at zero output poower continually during steady state. Hence, a low-power 200 W is selected as the minimum operation power for the DAB system. This converter is appropriate for situations in which both charging and discharging processes demand high power levels [4]. Which is not the case regarding the desired application, as present hereinafter.

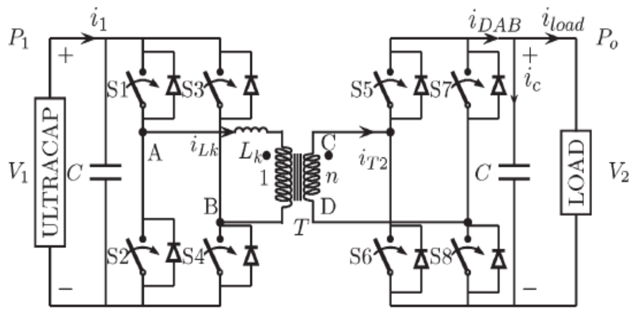

Figure 3: Dual active bridge(DAB) converter.

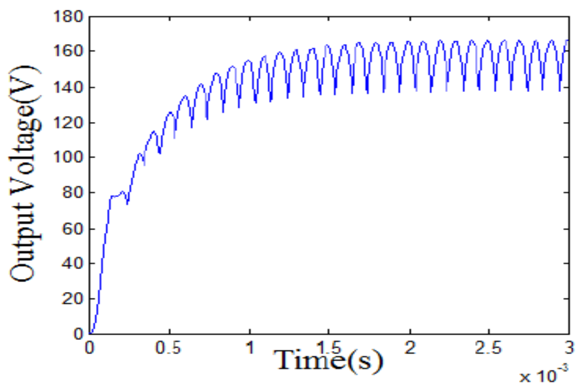

Figure 4: Output voltage of DAB converter

In case of residential microgrid charging and discharging need not to be done for same power levels because once the low supply interruptions the storage system of residential microgrid is not needed, there is a long period available for charging, it can be performed with lower power levels. This can not be achieved using DAB converter, to over come above problems the integrated full-bridge forward dc-dc converter has been proposed.

3. Construction of Proposed Integrated Full-Bridge-Forward Converter

The proposed converter is the combination of Full-bridge and forward converter. Full-bridge converter is responsible for the energy storage system discharing stage, while the forward cconverter is responsile for energy storage system charging stage. The full-bridge and forward converters are as shown in figures 5,6 resectively.

The maximum designed power for the microgrid energy storage system discharging process is equal to 1.4 KW, which is supplied by the super capacitor bank. The isolated static power converter traditionally use in applications with this power level (aboe 1 KW) is the full-bridge converter, shown in Fig.5. Due to the presence of the full-bridge converter for the discharging proces, it is possible to utilize the respective active switches to rectify the converter output voltage during the charging process. This way, it is necessary to add only the input stage of the respective converter for the charging procrss. One of th simplest converters for this aplication is the forward converter, as shown in Fig.6, which demands only one active swithch and is appropriate for the related power levels. Therefore, the proposed dc-dc converter, shown in Fig. 7, is the integration of full-bridge and a forward converter.

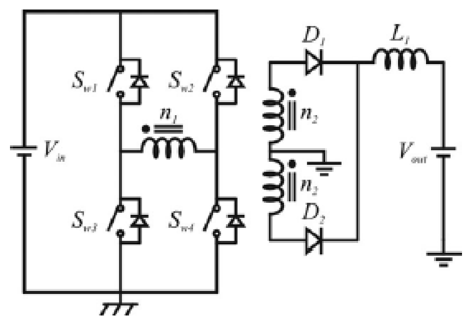

Figure 5: Full-bridge converter

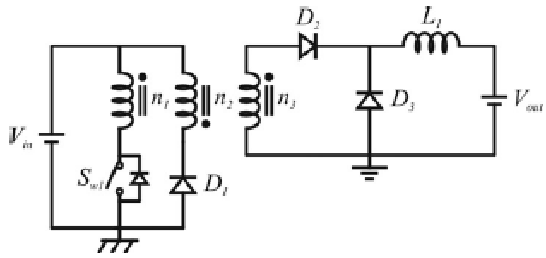

Figure 6: Forward converter

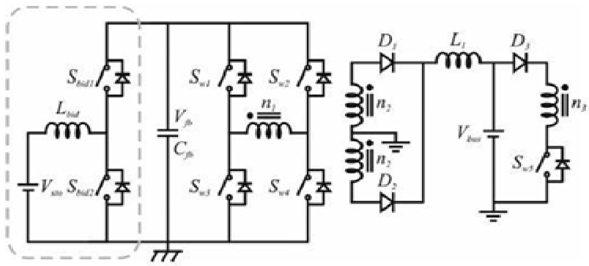

Figure 7: Proposed integrated full-bridge-forward dc–dc converter including a bidirectional converter

The energy storage system discharging stage is similar to traditional full-bridge converter operation. The charging stage, presents some differences compared to the traditional forward converter operation, namely, the transformer demagnetizing process is executed by the antiparallel diodes of the full-bridge converter switches and a clmping circuit, instead of the additional transformer winding; and the output inductor is eliminated. The output inductor of the forward converter must be eliminated because it would restrain proper full-bridge converte operation, due to the high imposed duty cycle loss [10]. Its function on the forward converter operation is performed by the primay winding transformer leakage inductance. A three-winding transformer is required in this topology. Windings 1 and 2 are used in the full-bridge operation, and windings 1 and 3 in the forward operation. One diode needs to be added in series with the transformer tertiary winding to avoid current circulatin through the antiparallel diode of the forward converter switch during full-bridge converter operation mode.

In order to avoid voltge spikes during the turn-off of the forward converter active switch due to the interruption of the current through the transformer leakage inductance, clamping circuit isfirst added in parallel to this switch. Depending upon type of clamping the proposed integrated full-bridge-forward dc-dc converters are two types:

A. Integrated Full-Bridge-Forward Converter Including Dissipative Passive Clamping Circuit

Integrated full-bridge-forward converter including dissipative clamping circuit has a small difference from the full-bridge-forward converter as shown in Fig. 7, that is a clamping circuit is added parallel to the forward converter switch. This clamping circuit is composed of one diode, one capacitor, and one resistor, as shown in Fig.8.

B. Integrated Full-Bridge-Forward Converter Including Regenerative Active Clamping Circuit

Regenerative active clamping circuit is used to reduce even more losses in clamping circuit. For proposed topology under study special attention should be taken, since the active clamping circuit cannot regenerate energy to the microgrid dc bus through the transformer tertiary winding due to the

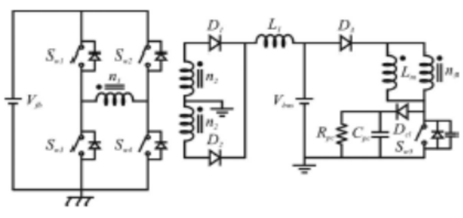

Figure 8: Integrated full-bridge-forward converter including dissipative passive clamping circuit

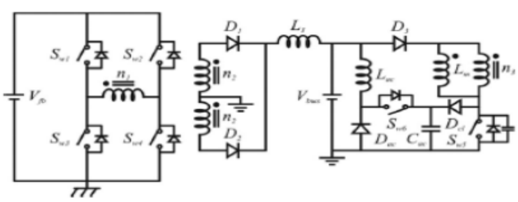

Figure 9: Proposed converter with regenerative active clamping circuit

Presence of the series diode, thus eliminating the possibility of use of some traditional active clamping circuits. On considering this fact, the proposed forward converter with an active clamping topology is shown in Fig.9. Basically, the clamping resistor is replaced by an active switch, a diode and an inductor. The active clamping circuit switch can be turned ON during any forward converter operation stage. The switch on time (duty cycle) is an important factor to determine the voltage level across the clamping circuit. The lower the switch on time, the higher the clamping circuit voltage and, consequently, a lower portion of energy is deviated toward the clamping circuit, reducing the switching and conduction losses on this circuit, and increasing the converter efficiency. The comparisons of various converters are shown in table 1.

4. Operation Stages of Integrated Full-Bridge-Forward Converter Including Dissipative Passive Clamping Circuit

The energy storage system discharging process is identical to the traditional full-bridge converter [10], so it is not explained. Special attention is focused on the energy storage system charging process (double-ended forward converter) due to its particularities. The operation of proposed converter is explained below.

First stage: This stage shown in Fig. (a), starts when the forward converter switch S_{w5} is turned ON. The antiparallel diodes of the S_{w1} and S_{w4} switches also turn ON once they are forward biased. Positive voltages are applied to the transformer magnetizing (1) and primary (2) and tertiary (3) leakage inductances. Therefore, the currents through these elements increase.

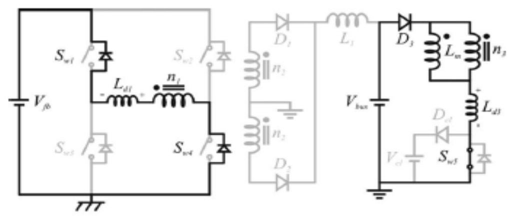

Figure (a)

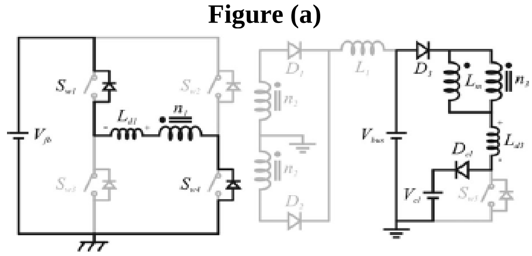

Figure (b)

$$v_{L_{m\_1}}(t) = \frac{L_m(n^2 L_{d1}(V_{bus})+nV_{fb}L_{d3})}{n^2 L_{d1}(L_m+L_{d3})+L_m L_{d3}} \quad (1)$$

$$v_{L_{d1\_1}}(t) = \frac{v_{L_{m\_1}}(t)}{n} - V_{fb} \quad (2)$$

$$v_{L_{d3\_1}}(t) = V_{bus} - v_{L_{m\_1}}(t) \quad (3)$$

Second stage: This stage, shown in Fig. (b), starts when the forward converter switch turns OFF. Therefore, the clamping diode D_{c1} turns ON, assume the current that circulated through the forward converter switch. This current decreases because a negative voltage (4) is applied to the tertiary winding leakage inductance. The currents through the antiparallel diodes of the S_{w1} and S_{w4} switches also decrease because the voltage applied to the primary winding leakage inductance (5) becomes negative. In this subinterval, the magnetizing current is deviated to the clamping circuit, resulting in losses for the topology. The clamping circuit voltage causes overvoltage on the forward converter switch; however, a high value reduces the duration of this and the next stages, reducing the clamping circuit losses. The voltage across the magnetizing inductance is given by (6)

$$v_{L_{d3\_2}}(t) = V_{bus} - V_{c1} - v_{L_{m\_2}}(t) \quad (4)$$

$$v_{L_{d1\_2}}(t) = \frac{v_{L_{m\_2}}(t)}{n} - V_{fb} \quad (5)$$

$$v_{L_{m\_2}}(t) = \frac{L_m(n^2L_{d1}(V_{bus}-V_{c1})+nV_{fb}L_{d3})}{n^2L_{d1}(L_m+L_{d3})+L_mL_{d3}} \quad (6)$$

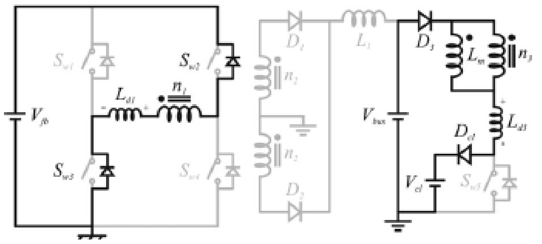

Figure (C)

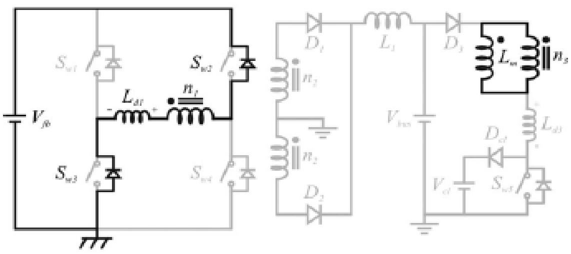

Figure (d)

Third stage: This stage, shown in Fig. (c), starts when the antiparallel diodes of the S_{w1} and S_{w4} switches turn OFF, since the current through them reaches zero, and the antiparallel, diodes of the S_{w2} and S_{w3} switches turn ON. The current through these diodes increases because the voltage applied to the primary winding leakage inductance (7) continues negative. Therefore, the current through the primary winding is inverted. The current through the clamping circuit diode continues to decrease once the voltage applied to the tertiary winding leakage inductance (8) keeps negative, but with a lower rate. Therefore, in this subinterval, the magnetizing current is gradually transferred from the clamping circuit to the converter output. The voltage across the magnetizing inductance is given by (9)

$$v_{L_{d1\_3}}(t) = \frac{v_{L_{m\_3}}(t)}{n} + V_{fb} \quad (7)$$

$$v_{L_{d3\_3}}(t) = V_{bus} - V_{c1} - v_{L_{m\_3}}(t) \quad (8)$$

$$v_{L_{m\_3}}(t) = \frac{L_m(n^2L_{d1}(V_{bus}-V_{c1})-nV_{fb}L_{d3})}{n^2L_{d1}(L_m+L_{d3})+L_mL_{d3}} \quad (9)$$

Fourth stage: This stage, shown in Fig. (d), starts when the current through the clamping circuit diode D_{c1} reaches zero and it turns OFF. The currents through the antiparallel diodes of the S_{w2} and S_{w3} switches decrease once the voltage applied to the primary winding leakage inductance (10) becomes positive. The voltage applied to the tertiary winding leakage inductance (11) is equal to zero and applied to the magnetizing inductance is given by (12)

$$v_{L_{d1\_4}}(t) = \frac{n^2L_{d1}V_{fb}}{n^2L_{d1}+L_m} \quad (10)$$

$$v_{L_{d3\_4}}(t) = 0 \quad (11)$$

$$v_{L_{m\_4}}(t) = \frac{nL_mV_{fb}}{n^2L_{d1}+L_m} \quad (12)$$

Fifth stage: This stage starts when the antiparallel diodes of the S_{w2} and S_{w3} switches turn OFF once the current through them reaches zero. The voltages applied to the primary and tertiary windings leakage inductances, and converter current are equal to zero. This stage ends when the forward converter switch S_{w5} is turned ON, starting the next operation period.

The above topology solves the voltage spike problems, during the clamping circuit on state; the magnetizing current is deviated toward the passive elements.

Table 1: Comparison of Converters

Parameters	*DAB*	*DAB+ bidirectional*	*Full-bridge-forward + bidirectional*
Active switches	8	10	7 or 8 (with active clamping)
Input current ripple (A)	63.89	3.93	3.82
Output current ripple (A)	16.61	7.40	0.45
Transformer leakage inductance (μH)	4	6.67	1
Inductors	0	1	2
Diodes	0	0	4
RMS input (storage) current (A)	32.71	29.53	29.31

5. Photovoltaic Cell and Boost Converter Module

Photovoltaics (PV) is a method of generating electrical power by converting sunlight into direct current electricity using semiconducting materials that exhibit the photovoltaic effect. A photovoltaic system employs solar panels composed of a number of solar cells to supply usable solar power. The power generated by these PV cell is very small. To increase the output power the PV cells are connected in series or parallel to form PV module. The equivalent circuit of the PV cell is shown in Fig. 10.

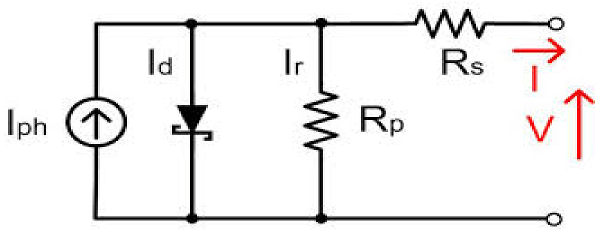

Figure 10: Equivalent circuit of PV cell.

Where,
I_d= Diode current;
R_p=Shunt resistance;
R_s=Series resistance;
I_{ph}= Light generated current;
I=Output current;
V=Output voltage.

Boost converters are essentially a step-up power converter that take in a low voltage input and provide an output at a much higher voltage. A block diagram of an ideal dc/dc boost converter is shown in the Fig. 11.

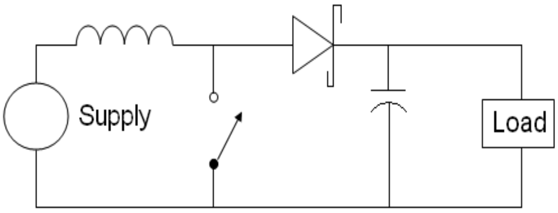

Figure 11: Boost converter

The input and output voltage relationship is controlled by the switch duty cycle, D, according to the equation below.

$$V_{out} = \frac{1}{1-D} * V_{in}$$

Where,
V_{out} =Output voltage;
V_{in} =Input voltage;
D=Duty cycle.

An ideal boost converter is lossless in terms of energy, so the input and output power are equal. In practice, there will be losses in the switch and passive elements, but efficiencies better than 90% are still possible through careful selection of system components and operating parameters such as the switch frequency.

6. Matlab Modeling and Simulation Results

A. Full-Bridge Converter

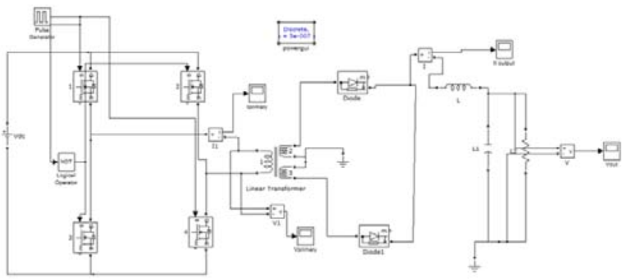

Figure 12: The Matlab/Simulink model of full-bridge Converter

The Matlab/Simulink model of the full-bridge converter is shown in Fig.12.

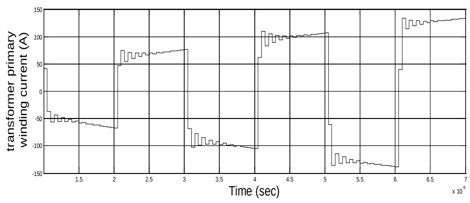

Figure 1.2.1: Transformer primary winding current

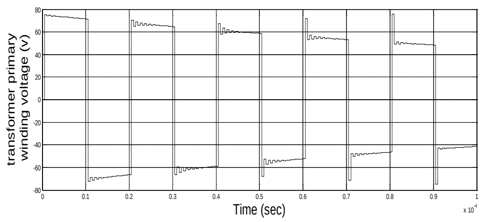

Figure 1.2.2: Transformer primary winding voltage

The transformer primary winding current, voltages of the full-bridge converters are as shown Fig.12.1 and Fig. 12.2 respectively.

B. Full-Bridge-Forward Converter with Dissipative Passive Clamping Circuit

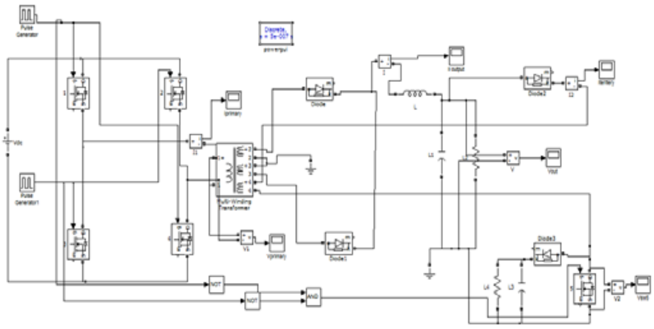

Figure 13: The Matlab/Simulink model of full-bridge forward converter with dissipative passive clamping circuit.

The design parameters of proposed full-bridge forward converters has been shown in table 2, the Matlab/Simulink model of full-bridge forward converter with dissipative passive clamping circuit is as shown in Fig.13.

Table 2: Proposed Converter Design Parameters

Parameters	*Symbol*	*Value*
Switching frequency	f_s	50 KHZ
Transformer turns ratio	n_1:n_2:n_3	1:6:7
Clamping circuit capacitor	C_{pc}	13 nF
Full-bridge converter output inductor	L_1	1350 μH
Active clamping circuit inductor	L_{ac}	5.4 mH
Output capacitor	C_{fb}	100μF

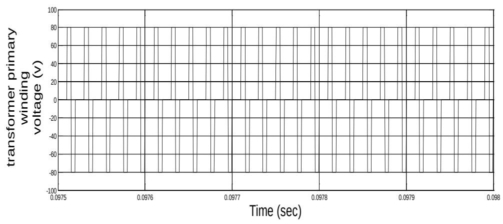

Figure 13.1: Transformer primary winding voltage

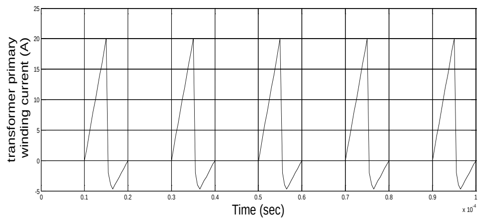

Figure 13.2: Transformer primary winding current

The transformer primary winding voltages, current of full-bridge–forward converter with dissipative passive clamping circuit are shown in Fig. 13.1 and Fig. 13.2 respectively.

C. Forward Converter with Regenerative Active Clamping Circuit

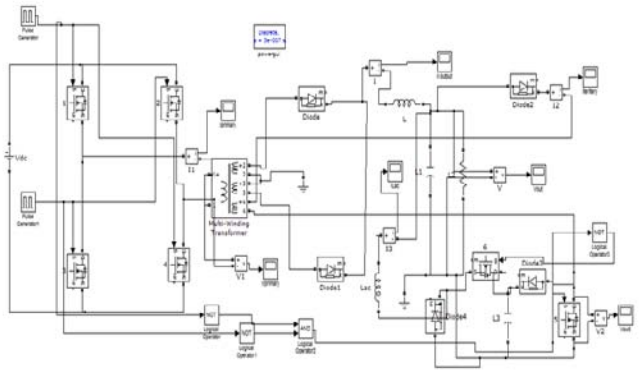

Figure 14: The Matlab/Simulink model of full-bridge forward converter with regenerative active clamping circuit.

The Matlab/Simulink model of full-bridge forward converter with regenerative active clamping circuit is as shown in Fig.14.

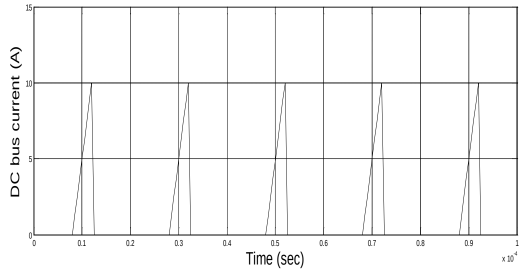

Figure 14.1: Dc bus current.

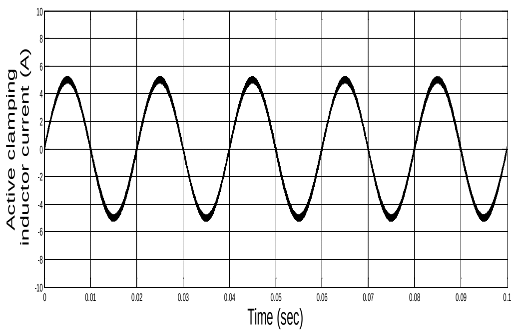

Figure 14.2: Active clamping circuit inductor current.

The dc bus current and active clamping circuit inductor current of full-bridge forward converter with regenerative active clamping circuit are as shown in Fig. 14.1 and Fig. 14.2 respectively.

D. Comparison result of Proposed Converter with Dual Active Bridge Converter (DAB)

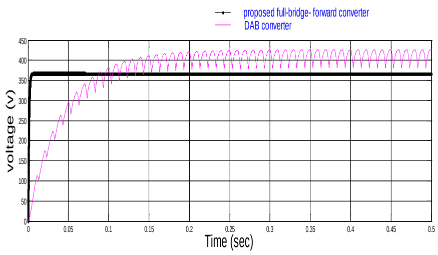

Figure 15: Comparison of proposed converter with dual active bridge converter (DAB).

The comparison of proposed converter output voltage with dual active bridge converter (DAB) output voltage is shown in fig.15, from that we can observe that the output voltage of DAB converter more ripples when compared to the proposed full-bridge forward dc-dc converter.

E. Integration of Storage Device using Proposed Dc-Dc Converter in Residential Microgrid System

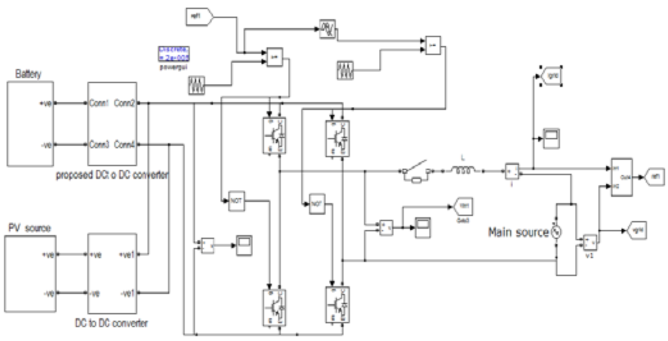

Fig. 16. The Matlab/Simulink model of integration of storage device using proposed converter in residential microgrid system.

In the above Fig.16, the Matlab/Simulink model of integration of storage device using proposed converter in residential microgrid system has been shown.

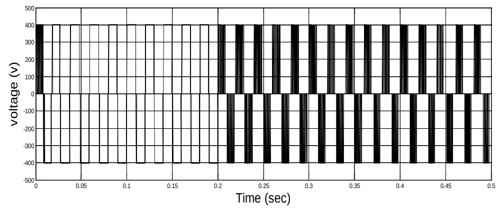

Figure 16.1: Grid connected voltage

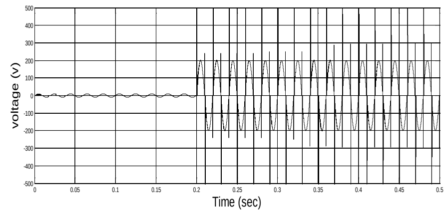

Figure 16.2: Island voltage

The grid connected and island conditions of the above circuit voltages are as shown in Fig 16.1 and Fig.16.2 respectively.

7. Conclusion

In this paper a new dc-dc converter has been proposed for residential microgrid application. This converter is used in microgrid in between storage device and dc bus, for connecting energy storage system to the dc bus. In this paper a special attention is focused on the microgrid energy storage system charging stage, the proposed integrated full-bridge-forward dc-dc converter has low number of switches, low input and output current ripple, high power operation, longer battery life time, high voltage ratio, high usage of super capacitor stored energy when compared to the DAB converter.

In this paper two different clamping circuits are connected for the proposed full-bridge-forward dc-dc converter, the operation of stages one of the proposed converter including clamping circuit (full-bridge-forward converter including dissipative clamping) is explained in this paper, a comparison table of proposed converter and the DAB converter in terms of number of devices, current , voltage levels, in several ways is placed in this paper. The Matlab/Simulink results of the proposed converters, the comparison graph of proposed converter and DAB in terms of output voltage, the grid connected and island voltages of microgrid using a proposed converter is placed in this paper.

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