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DESIGN AND IMPLEMENTATION OF BIDIRECTIONAL DC-DC CONVERTER WITH FIFTH ORDER RESONANT CONTROL

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Abstract:**Bidirectional DC-DC converter (BDC) has received lot of attention due to increase in need of system with capability of bidirectional energy transfer between two DC buses. Apart from the traditional applications such as DC motor drives, new application of BDC includes energy storage in renewable energy systems.The fluctuating nature of most renewable energy resources makes them suitable for standalone operation as a sole source of power. A common solution to overcome this problem is to use an energy storage device. The implementation of fifth order resonant converter provides flexibility and advantages compared to conventionally used circuits.The topology is used half bridge converter on both primary and secondary side of high frequency transformer. The provision of phase shift between the two input converters eliminates triplen harmonics and the usage of fifth order resonant filter results in the elimination of negative sequence harmonics**

Keywords- Half bridge converter, Fifth order resonant converter, Harmonic distortion, Isolated DC-DC Converter

I. INTRODUCTION

Power electronic circuits primarily process the energy supplied by a source to match the form required by the load by means of using semiconductor devices to control the voltage and current. The energy is usually available from the utility grid or from a bank of batteries with the applications ranging from high-power conversion equipment processing megawatts to everyday low power equipment with requirements of a few milliwatts.

The majority of power converters are unidirectional with the power being supplied from the source to the load. But, a number of applications like motor drives, uninterruptible power supplies, alternate energy systems, battery charger dischargers, telecommunication and space systems, require the additional exchange of energy from the load to the source. These applications utilize power converters with bi-directional transfer properties.

Applications that require exchange of power from the source to the load and viceversa have conventionally been implemented with two uni-directional converters; each processing the power in one direction. The escalating cost of energy in recent years has resulted in growing emphasis on energy management due to the drain on natural resources and environmental pollution, and energy saving techniques are becoming more important. The demand for the development of sophisticated, compact and efficient power systems has prompted research in bi-directional converters providing the desired bilateral power flow and capable of replacing the two unidirectional converters.

A Bi-directional DC-DC converter, capable of bilateral power flow, provides the functionality of two uni-directional converters in a single converter unit. The implementation of this converter topology demonstrates its feasibility and advantages when compared to the conventionally used circuits. The topology is based on a half-bridge on the primary and secondary side of a high frequency isolation transformer. Achieving bi-directional flow of power using the same power components provides a simple, efficient and galvanically isolated topology for a low power bi-directional dc-dc converter.

II. ISOLATED BIDIRECTIONAL DC-DC CONVERTER

The block diagram of the Isolated Bidirectional DC-DC (BDC) converter with the fifth order resonant filter is shown in the Fig. 1. It consists of a primary DC source, half bridge converter, high frequency transformer, resonant filter, a pulse generator and load. During Boost mode the source side converter acts as inverter and load side converter acts as rectifier and it is vice versa for Buck mode.

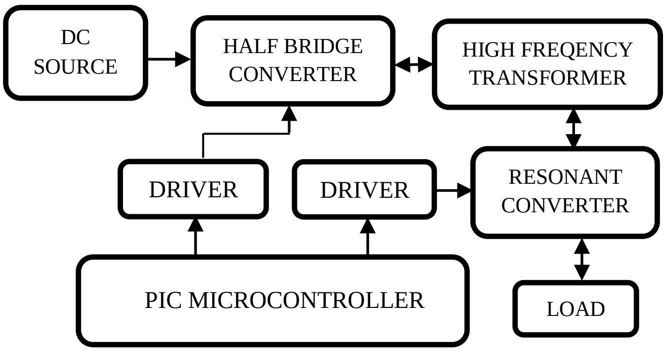

Fig. 1 Block diagram of Isolated Bidirectional DC-DC converter

A. Resonant converter

Resonant converters are widely used in different applications where soft switching is of great importance. Especially in high-voltage applications, resonant converters are suitable topologies since they can effectively absorb and take advantage of parasitic components, which are considerable due to the high-voltage transformers used to provide the voltage gain and galvanic isolation. In high-voltage applications, due to the structure of the transformer, a very large turn’s ratio is inevitable. This leads to a high value of the equivalent secondary capacitance. Furthermore, the primary winding and the secondary winding are not perfectly coupled due to the distance imposed by the required high-voltage insulation. The weak coupling leads to a large leakage inductance that must be modelled on both sides of the transformer. In order to analyse the converter, this transformer is usually modelled by an equivalent circuit based on the operating frequency of the converter and transformer configuration.

The proposed converter is a fifth-order resonant converter, which fully incorporates the transformer parasitic components into the resonant circuit. This topology uses a purely capacitive filter at the output side. This is a great advantage in high-voltage applications, due to the fact that there are so many issues with the fabrication of the inductor at high-voltage output in terms of insulation.

There are two main control techniques used to regulate the output voltage of the resonant converters.

- variable-frequency (VF) control method
- fixed-frequency phase-shift control method

In high-voltage applications, the VF technique is not preferable since the breakdown voltage of the insulation materials used in the converter significantly degrades with the increase in the frequency .Therefore the fixed-frequency phase-shift control technique is well suited for this application. In addition, since the range of load variations is very wide in this application (from absolutely no load to full load), the converter should be able to maintain ZVS for the entire range. Thus, the converter requires the circulating current even at light loads in order to have ZVS. This imposes a little extra conduction losses imposed by the reactive current, which is more pronounced in light loads. However, maintaining ZVS for light loads is essential in order to have a reliable operation and a noise-free control/drive circuitry. Also, since the voltage is pretty high in the primary side, the current is pretty low, and the extra conduction losses are negligible.

Inallequations,thetransformersecondary-sidevariablesaretransferredtotheprimaryside.TheprocedureinthisanalysisistofindtheequivalentimpedanceviewedfromdifferentpointsoftheresonanttankthroughtheFHAofthecurrentsandvoltages.TheFHAof$i_{LS1}(t)$,$i_{Lp}(t)$,and$i_{LS2}(t)$ aregivenby

$i_{LS1}(\mathrm{t})=I_{LS1}\sin(\omega_S \mathrm{t}-\phi)$ (1)

$i_{Lp}(\mathrm{t})=I_{Lp}\sin(\omega_S \mathrm{t}-\varphi)$ (2)

$i_{LS2}(\mathrm{t})=i_{LS1}-i_{Lp}=I_{Ls2}\sin(\omega_S \mathrm{t}+\delta)$.(3)

B. High frequency transformer

The high frequency transformer is the backbone of modern switched mode power supplies. The physical size is dependent on the power to be transferred as well as the operating frequency. Thehigher the frequency smaller will be physical size. Frequencies are usually between 20 and 100 kHz. Ferrite is mainly used as the core material.

C. Driver

Driver is an electrical circuit which is used to control another circuit or other components. They are usually used to regulate current flowing through a circuit or control the other factors such as prevent high voltages or rapidly changing voltages from damaging components or distorting other components.

III. CONVERTER TOPOLOGY

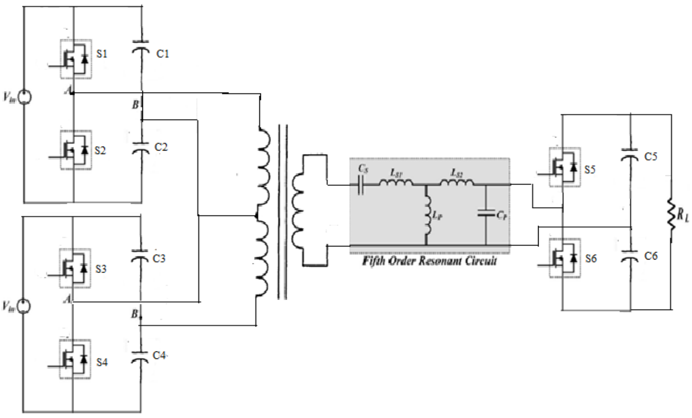

Fig. 2Isolated Bidirectional DC-DC converter circuit

Most of the existing Bidirectional DC-DC converters fall into the generic circuit structure which is fed by a current fed or voltage fed on one side. Based on the placement of the auxiliary energy storage, the Bidirectional DC-DC converter can be categorized into Buck and Boost type. The Buck type is to have energy storage placed on the high voltage side, and the Boost type is to have it placed on the low voltage side. To realize the double sided power flow in Bidirectional DC-DC converters, the switch cell should carry the current on both directions. The circuit diagram of proposed system is shown in Fig 2. It is usually implemented with a unidirectional semiconductor power switch such as power MOSFET (Metal-Oxide-Semiconductor-Field-Effect-Transistor) or IGBT (Insulated Gate Bipolar Transistor) in parallel with a diode, because the double sided current flow power switch is not available. For the Buck and Boost DC-DC type converters, the bidirectional power flow is realized by replacing the switch and diode with the double sided current switch cell.

In the Bidirectional DC-DC converters, isolation is normally provided by a transformer. The added transformer implies additional cost and losses. However, since transformer can isolate the two voltage sources and provide the impedance matching between them, it is an alternative in those kinds of applications. As a current source, inductance is normally needed in between. Advantages of this proposed converter topology include galvanic isolation between the two dc sources using a single transformer, low parts count with the use of same power components for power flow in either direction

By incorporating an appropriate value of phase shift between two converters at the input side with respect to each other to reduce or cancel the triplen harmonics and to control power flow from one DC source to another In summary, for the isolated bidirectional DC-DC converter, the operation of the circuit involves the utilization of the leakage inductance of the transformer as the main energy storing and transferring element deliver bidirectional flow power.

IV.OPERATING PRINCIPLE

The proposed converter is supplied by a hybrid system consisting of a primary DC source and a battery for emergency applications. Theproposedconverter circuit consistsof two half bridge converters at the source side with 60° phase shift connected to the primary side of the high frequency transformer. This is done to cancel the triplen harmonics. The load side half bridge converter is connected to the secondary side of the transformer through fifth order resonant filter. The proposed circuit is shown in Fig. 3. The modes of operation are as follows:

A.Boost mode

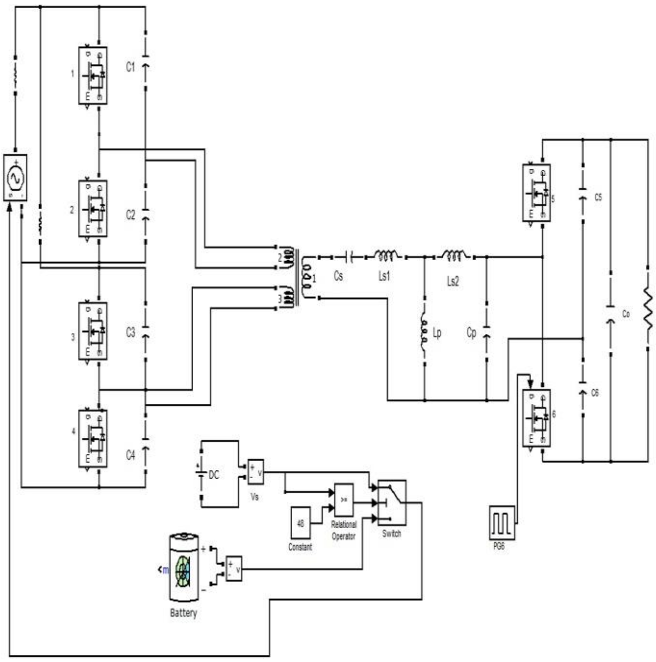

Fig. 3Boost mode

Fourier analysis waveforms of two source side converters V_1 and V_2 gives

$$V_1=\frac{4v_s}{\pi}\left[\sin\omega t+\frac{1}{3}\sin 3\omega t+\frac{1}{5}\sin 5\omega t+\frac{1}{7}\sin 7\omega t+\ldots\ldots\right] \quad (4)$$

$$V_2=\frac{4v_s}{\pi}\left[\sin\left(\omega t-\frac{\pi}{3}\right)+\frac{1}{3}\sin3\left(\omega t-\frac{\pi}{3}\right)+\frac{1}{5}\sin5\left(\omega t-\frac{\pi}{3}\right)+\frac{1}{7}\sin 7\left(\omega t-\frac{\pi}{3}\right)+\cdots\right] \quad (5)$$

The resultant voltage applied to the transformer primary is

$$\mathrm{Vp}=V_1+V_2$$

$$\mathrm{Vp}=\frac{4v_s}{\pi}\sqrt{3}\left[\sin\left(\omega t-\frac{\pi}{6}\right)+\frac{1}{5}\sin\left(5\omega t+\frac{\pi}{6}\right)+\frac{1}{7}\sin\left(7\omega t-\frac{\pi}{6}\right)+\ldots.\right] \quad (6)$$

Inboost mode of operation the source side converter acts as inverter this square wave is applied to the resonant converter though isolation transformer which provides a low impedance to the square wave and smoothens it into a sine wave and the right side converter acts as a rectifier. The output capacitor provides smooth DC output as ripple free. The operation of source side half bridge converter consists of two modes of operation

Mode 1:S_1 ON, S_2OFF; $V_O = V_S/2$

During mode I the switch S_1 starts to conduct and capacitor C_2 charges form –Vc to Vc and capacitor C_1 discharges to –Vc.So the output voltage across C_2 is Vin+Vc$_1$. The current flows through S_1, resonant converter,C_2 then back to source. Therefore the output voltage of the source side converter is

$$V_o=\left(\frac{2}{T_o}\int_0^{\frac{T_0}{2}}\frac{Vs^2}{4}\,dt\right)^{\frac{1}{2}}=\frac{Vs}{2} \quad (7)$$

In the secondary side switch S_5 starts to conduct and the current flows through S_5 and C_5 and it is charges to Vs output voltage applied across the load. Similarly for second converter at the same side but the switch S_3 is turned on in a phase delay of 60° with respect to S_1 and the mode I operation are remains same as convertor I.

Mode 2:S_1 ON, S_2OFF; $V_O = -V_S/2$

During mode 2 switch S_1 is turned off and S_2 is turned on then capacitor C_1 starts to charge form –Vc to Vc and C_2 discharge to –Vc. So the output voltage across the C_1 is Vin+Vc$_2$. The current flows through S_2,C_1 then back to source. Similarly for second converter at the same side but the switch S_4 is turned on in a phase delay of 60° with respect to S_2 and the mode II operation are remains same as convertor I. In the secondary side switch S_5 is turned off and S_6 starts to conduct and the output voltage applied across the load as 2Vs.

B. Buck mode

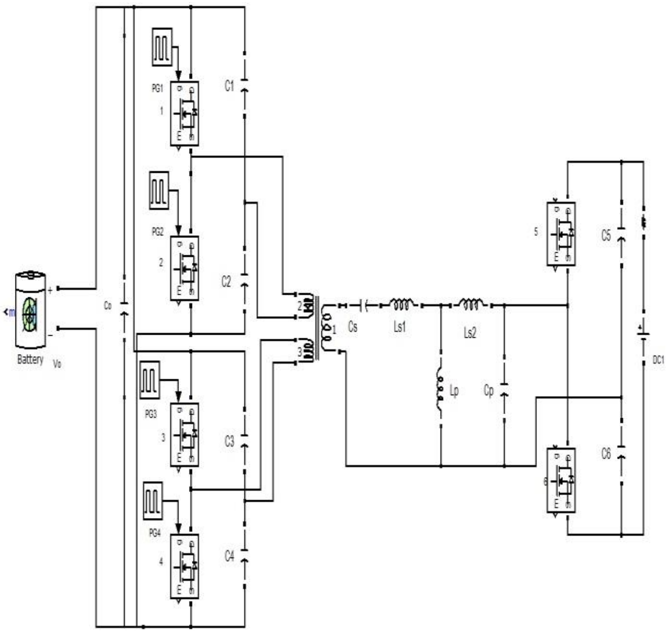

Fig. 4Buck mode

Similarly inBuck mode the load side converter acts as inverter and the power flows from load to source. The source side converter which acts just like a diode rectifiers through the coupling transformer as same as in boost mode. The output voltage from the source side converters is stored in to a battery for emergency applications. The output voltage appears across the output is 56.64V but the nominal output voltage of the battery is 48V. So the battery gets charged by giving input voltage to the battery greater than the nominal value.

V. DESIGN CONSIDERATIONS

Turns ratio

$$E_1 = 4.44 \times N_1 \times \emptyset \times f$$

$$48 = 4.44\times N_1 \times 10 \times 10^{-6} \times 40 \times 10^3$$

$$N_1 = 28$$

$$E_2 = 4.44 \times N_2 \times \emptyset \times f$$

$$100 = 4.44\times N_2 \times 10 \times 10^{-6} \times 40 \times 10^3$$

$$N_2 = 57$$

TABLE 1 TRANSFORMER PARAMETERS

Parameters	Values
Nominal input voltage	48v
Nominal output voltage	100v
Magnetizing inductance	500H
Primary and secondary leakage inductance L_{lkp},L_{lks}	0.08H

Resonant circuit parameters

The resonant filter is designed by using the resonant frequency, which can be written as,

$$F_r=\frac{1}{2\pi\sqrt{LC}} \quad (8)$$

Let, Cs=44nF

Cp=140nf

Lp=500uH

$$F_r=\frac{1}{2\pi\sqrt{L_{s1}C_s}}=\frac{1}{2\pi\sqrt{L_{s1}\times 44\times 10^{-9}}}$$

So that L_{s1} can be calculated as 315μH

Similarly F_5= 5× F_s

ThereforeL_5= 705 μH

Where

$$L_5 = L_{s2} + L_p$$

LetL_p=500 μH then

L_{s2}= 205 μH

TABLE 2 RESONANT FILTER PARAMETERS

Resonant filter parameters	values
Series capacitance C_s	44nF
Series inductance1 L_{s1}	315μH
Series inductance2 L_{s2}	205μH
Parallel inductance L_p	500μH
Parallel capacitance C_p	140nF

Capacitor specification for half bridge converter

$$c_1 = c_2 = \frac{0.876p_o(1-0.636M_g)}{{V_o}^2 f} \quad (9)$$

Where, M_g=$\frac{V_o}{V_{in}}$(10)

$$c_1 = c_2 = 1e^{-6}$$

Simulation circuit parameters

TABLE 3 VALUES FOR SIMULATION SETUP

Simulation setup parameters	Ratings
Nominal input voltage	48 V
Output voltage	210 V
Switching frequency	40 KHz
Transformer turns ratio	28:57

VI. OUTPUT WAVEFORMS AND RESULTS

A.Boost mode

The output waveforms and results of the simulated circuit for an Isolated BDC using MATLAB software are shown below. The output waveforms and results obtained can be used so that it is easier to design the prototype model. The waveform of the output voltage is shown below in Fig.5.

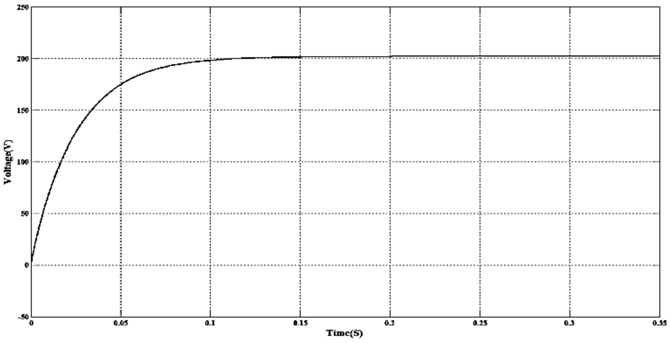

Fig. 5 Output voltage waveform of BDC in Boost mode

The waveform of the source side converters with phase shift is shown below in Fig.6.

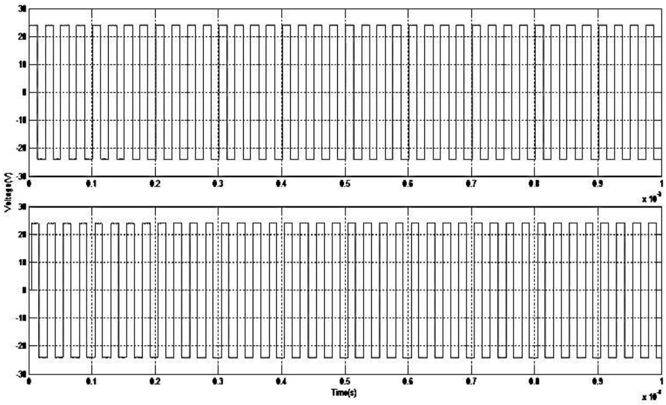

Fig. 6 Output voltage waveform of source side converters

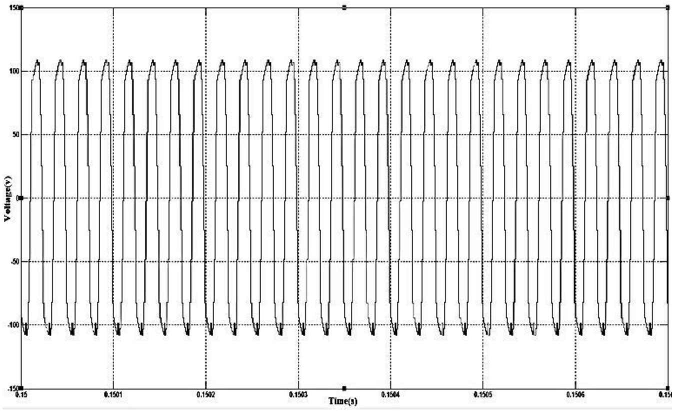

Fig. 7 Voltage waveform at the secondary side of the transformer.

FFT analysis for Boost mode

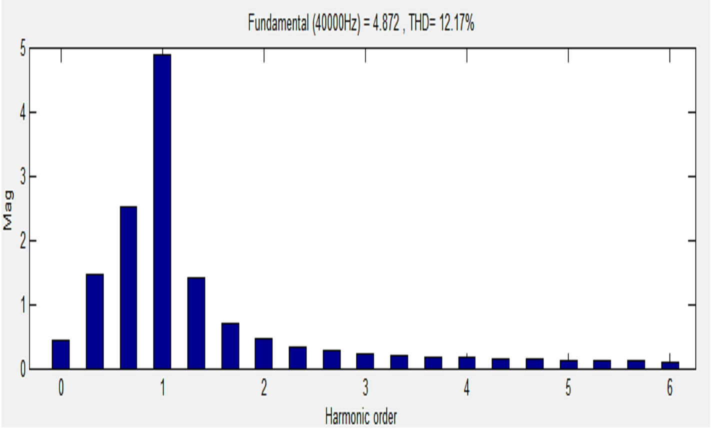

Fig. 8 FFT Analysis of BDC in Boost mode

B.Buck mode

The output waveforms and results of the simulated circuit for an Isolated BDC in Buck mode are shown below

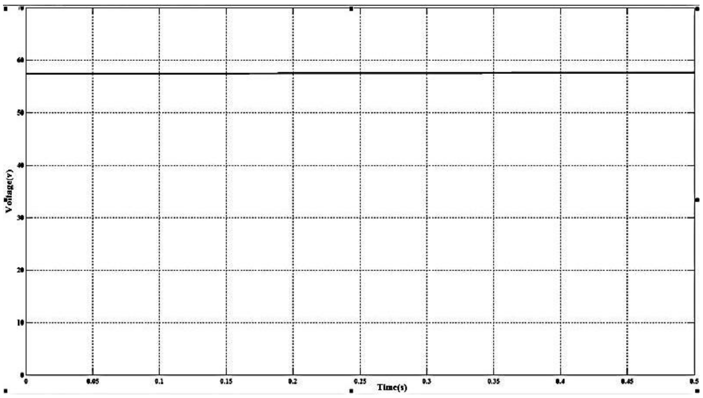

Fig. 9 Output voltagewaveform of BDC in Buck mode

The waveform of the output voltage obtained for the converter circuit is shown in Fig. 9.

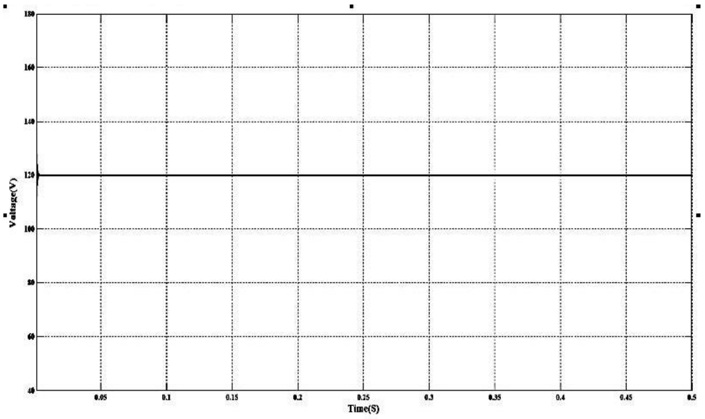

Fig. 10 Input voltage waveform of BDC in Buck mode

FFT analysis for Buck mode

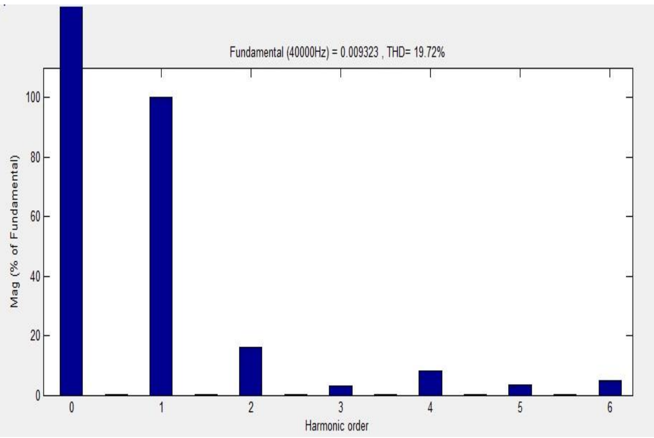

Fig. 11 FFT Analysis of BDC in Buck mode

VII. CONCLUSION

In this paper the operation of Bidirectional DC-DC converter was discussed for both buck and boost mode. The addition of two converter voltages with phase shift resulting the elimination of triplen harmonics and also the addition of fifth order resonant circuit gives the output with reduced fifth order harmonics i.e., negative sequence harmonics. These negative sequence harmonics produce opposing torque in a drive system. In this proposed model these negative sequence harmonics are highly reduced and provides better efficiency. The operation of Bidirectional DC-DC converter has been verified through simulations.

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