A STEP-UP CONVERTER FOR GRID CONNECTED RENEWABLE ENERGY SOURCES

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ABSTRACT

This project presents a Step-up Converter for Grid Connected Renewable Energy Sources. With the rapid developments of large-scale renewable energy sources and HVDC grid, it is a promising option to connect the renewable energy sources to the HVDC grid with a pure DC system in which high-power high-voltage step-up dc–dc converters are the key equipment to transmit the electrical energy. This paper proposes a resonant converter which is suitable for grid-connected renewable energy sources. The converter can achieve high voltage gain using an LC parallel resonant tank. It is characterized by zero-voltage-switching (ZVS) turn-on and nearly ZVS turn-off of main switches as well as zero-current-switching turn-off of rectifier diodes; moreover, the equivalent voltage stress of the semiconductor devices is lower than other resonant step-up converters. The operational principle of the converter and its resonant parameter selection is presented in this paper. The principle of the proposed converter has been successfully verified by simulation results.

Keywords: The converter can achieve high voltage gain using an LC parallel resonant tank, zero-voltage-switching (ZVS) turn-on and zero-current-switching (ZVS) turn-off of rectifier diode.

1. INTRODUCTION

The development of renewable energy sources is crucial to relieve the pressures of exhaustion of the fossil fuel and environmental pollution. At present, most of the renewable energy sources are utilized in the form of AC power. The generation equipments of the renewable energy sources and energy storage devices usually contain DC conversion stages and the produced electrical energy is delivered to the power grid through DC/AC stages, resulting in additional energy loss. Moreover, the common problem of the renewable energy sources, such as wind and solar, is the large variations of output power. The connection of large scale of the renewable sources to the power grid is a huge challenge for the traditional electrical equipment, grid structure and operation. DC grid, as one of the solutions to the aforementioned issues, is an emerging and promising approach which has drawn much attention recently.

At present, the voltages over the DC stages in the generation equipments of the renewable energy sources are relatively low, in the range of few hundred volts to thousand volts; hence, high-power high-voltage step-up DC–DC converters are required to deliver the produced electrical energy to the HVDC grid. Furthermore, as the connectors between the renewable energy sources and HVDC grid, the step-up DC–DC converters not only transmit electrical energy, but also isolate or buff kinds of fault conditions; they are one of the key equipments in the DC grid.

Recently, several soft-switching topologies for high power high-voltage applications have been proposed. The converter topologies based on resonant switched capacitor are proposed with reduced switching loss and modular structure. Thyristors have large voltage and current ratings. However, the use of thyristor limits the switching frequency of the converter, resulting in bulky passive components and slow dynamic response. Moreover, the resonant inductors of the converters are unidirectional magnetized, leading to lower utilization of the magnetic core, which means that a great volume of core is required. In this project, a novel resonant step-up DC–DC converter with high output voltage is proposed. The converter utilizes a LC parallel tank.

Therefore, a transformer is not needed to obtain the high output voltage. To sum up, the converter is able to achieve
1) High output voltages in the absence of transformer
2) Simple structure
3) Positive output voltage
4) High conversion efficiency due to part of input power is processed once
5) Input surge current protection because of series connection of input source and switch.

1.1 OPERATING PRINCIPLE

The proposed converter, which consists of the merging of a buck PFC cell ($L1$, $S1$, $D1$, Co , and CB) and a buck–boost dc/dc cell ($L2$, $S1$, $D2$, $D3$, Co , and CB). Although $L2$ is on the return path of the buck PFC cell, it will be shown later in Section III-A that it does not contribute to the cell electrically. Thus, $L2$ is not considered as in the PFC cell. Moreover, both cells are operated in discontinuous conduction mode (DCM) so there are no currents in both inductors $L1$ and $L2$ at the beginning of each switching cycle $t0$. Due to the characteristic of buck PFC cell, there are two operating modes in the circuit. Mode A ($V\text{in}(\theta) \leq VB + Vo$): When the input voltage $v\text{in}(\theta)$ is smaller than the sum of intermediate bus voltage VB , and output voltage Vo , the buck PFC cell becomes inactive and does not shape the line current around zero-crossing line voltage [20], owing to the reverse biased of the bridge rectifier. Only the buck–boost dc/dc cell sustains all the output power to the load. Therefore, two dead-angle zones are present in a half-line period and no input current is drawn. The circuit operation within a switching period can be divided into three stages.

1.2 CONVERTER

As efficiency is at a premium in a power electronic converter, the losses that a power electronic device generates should be as low as possible. Devices vary in switching speed. Some diodes and thyristors are suited for relatively slow speed and are useful for power frequency switching and control; certain thyristors are useful at a few kilohertz. Devices such as MOSFETS and BJTs can switch at tens of kilohertz up to a few megahertz in power applications, but with decreasing power levels. Vacuum tube devices dominate high power (hundreds of kilowatts) at very high frequency (hundreds or thousands of megahertz) applications. Faster switching devices minimize energy lost in the transitions from on to off and back, but may create problems with radiated electromagnetic interference. Gate drive (or equivalent) circuits must be designed to supply sufficient drive current to achieve the full switching speed possible with a device. A device without sufficient drive to switch rapidly may be destroyed by excess heating.

1.3 BOOST CONVERTER

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple.

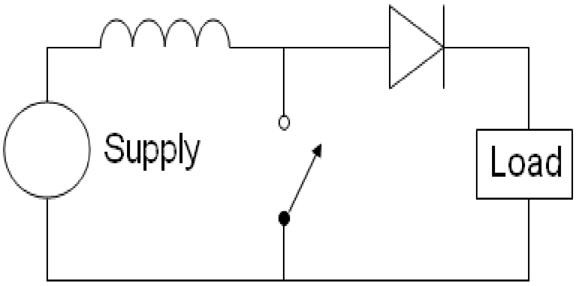

Fig 1.1 Boost converter

Power can also come from DC sources such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it “steps up” the source voltage. Since power ($P = VI$) must be conserved, the output current is lower than the source current.

A boost converter may also be referred to as a 'Joule thief'. This term is usually used only with very low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since a normal load wouldn't be able to handle the battery's low voltage. This energy would otherwise remain untapped because in most low-frequency applications, currents will not flow through a load without a significant difference of potential between the two poles of the source (voltage.)

1.4 BUCK-BOOST CONVERTER

In this circuit the transistor turning ON will put voltage V_{in} on one end of the inductor. This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor but now flowing through the diode.

We initially assume that the current through the inductor does not reach zero, thus the voltage at V_x will now be only the voltage across the conducting diode during the full OFF time. The average voltage at V_x will depend on the average ON time of the transistor provided the inductor current is continuous.

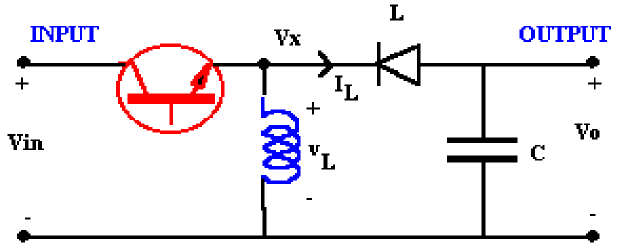

Fig 1.4.1(a) Schematic for buck-boost converter

With continuous conduction for the Buck-Boost converter $V_x = V_{in}$ when the transistor is ON and $V_x = V_o$ when the transistor is OFF. For zero net current change over a period the average voltage across the inductor is zero.

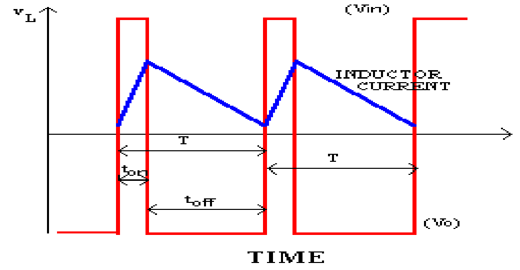

Fig 1.4.5(b) Waveforms for buck-boost converter

2. CIRCUIT DIAGRAM

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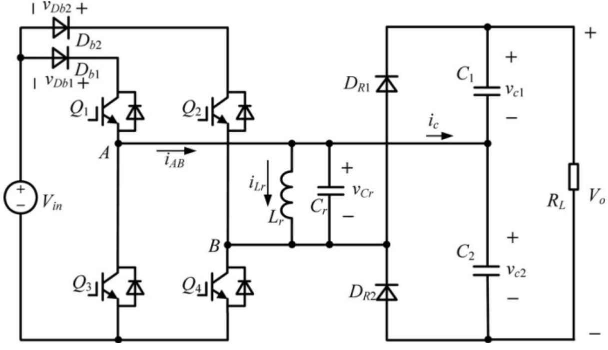


2.1 CONVERTER

In general, inverters are utilized in applications requiring direct conversion of electrical energy from AC to DC or indirect conversion from AC to AC. DC to AC conversion is useful for many fields, including power conditioning, harmonic compensation, motor drives, and renewable energy grid-integration.

A smart grid is a modernized electrical grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.

2.2 LC Parallel Tank

When a constant voltage but of varying frequency is applied to a circuit consisting of an inductor and capacitor the reactance of both the Capacitor and Inductor circuits is to change both the amplitude and the phase of the output signal as compared to the input signal due to the reactance of the components used. At high frequencies the reactance of a capacitor is very low acting as a short circuit while the reactance of the inductor is high acting as an open circuit. At low frequencies the reverse is true, the reactance of the capacitor acts as an open circuit and the reactance of the inductor acts as a short circuit. Between these two extremes the combination of the inductor and capacitor produces a “Tuned” or “Resonant” circuit that has a Resonant Frequency, (fr) in which the capacitive and inductive reactance’s are equal and cancel out each other, leaving only the resistance of the circuit to oppose the flow of current. This means that there is no phase shift as the current is in phase with the voltage. Consider the circuit below.

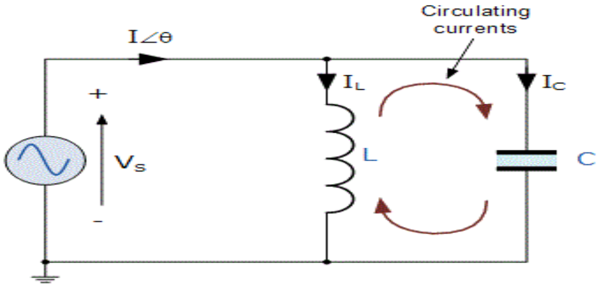


Fig 2.2 LC Parallel Tank

The circuit consists of an inductive coil, L and a capacitor, C. The capacitor stores energy in the form of an electrostatic field and which produces a potential (static voltage) across its plates, while the inductive coil stores its energy in the form of an electromagnetic field. The capacitor is charged up to the DC supply voltage, V by putting the switch in position. When the capacitor is fully charged the position of switch changes. The charged capacitor is now connected in parallel across the inductive coil so the capacitor begins to discharge itself through the coil. The voltage across C starts falling as the current through the coil begins to rise. This rising current sets up an electromagnetic field around the coil which resists this flow of current. When the capacitor, C is completely discharged the energy that was originally stored in the capacitor, C as an electrostatic field is now stored in the inductive coil, L as an electromagnetic field around the coils windings. However, things are not perfect and every time energy is transferred from the capacitor, C to inductor, L and back from L to C some energy losses occur which decay the oscillations to zero over time. This oscillatory action of passing energy back and forth between the capacitor, C to the inductor, L would continue indefinitely if it was not for energy losses within the circuit.

2.3 VOLTAGE DOUBLER

Although it is usual in Electrical or Electronic Circuits to use a voltage transformer to increase a voltage, sometimes a suitable step-up transformer or a specially insulated transformer required for high voltage applications may not always be available. One alternative approach is to use a diode voltage multiplier circuit which increases or “steps up” the voltage without the use of a transformer. Voltage multipliers are similar in many ways to rectifiers in that they convert AC-to-DC voltages for use in many electrical and electronic circuit applications such as in microwave ovens, strong electric field coils for cathode-ray tubes, electrostatic and high voltage test equipment, etc, where it is necessary to have a very high DC voltage generated from a relatively low AC supply.

Consider the basic circuit shown below Full Wave Voltage Multiplier

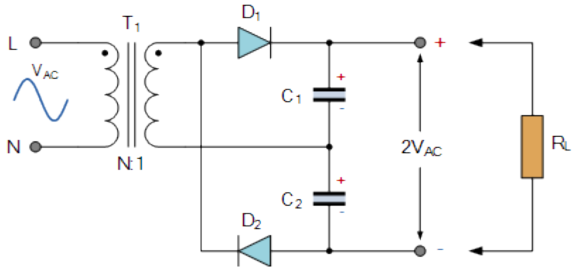


Fig 2.3 Full Wave Voltage Multiplier

The above circuit shows a basic symmetrical voltage multiplier circuit made up from two half-wave rectifier circuits. By adding a second diode and capacitor to the output of a standard half-wave rectifier, we can increase its output voltage by a set amount. This type of voltage multiplier configuration is known as a Full Wave Series Multiplier because one of the diodes is conducting in each half cycle, the same as for a full wave rectifier circuit. When the sinusoidal input voltage is positive, capacitor C1 charges up through diode D1 and when the sinusoidal voltage is negative, capacitor C2 charges up through diode, D2. The output voltage 2VP is taken across the two series connected capacitors. The voltage produced by a voltage multiplier circuit is in theory unlimited, but due to their relatively poor voltage regulation and low current capability there are generally designed to increase the voltage by a factor less than ten. As its name suggests, a Voltage Doubler is a voltage multiplier circuit which has a voltage multiplication factor of two. The circuit consists of only two diodes, two capacitors and an oscillating AC input voltage (a PWM waveform could also be used). This simple diode-capacitor pump circuit gives a DC output voltage equal to the peak-to-peak value of the sinusoidal input. In other words, double the peak voltage value because the diodes and the capacitors work together to effectively double the voltage.

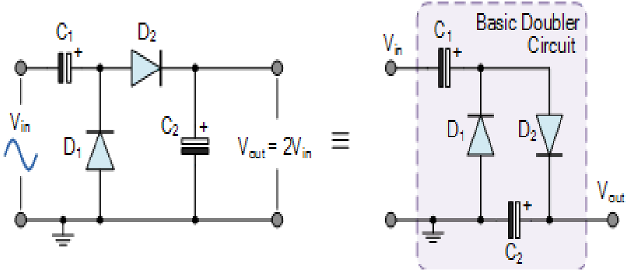


Fig 2.3 voltage doubler circuit

So how does it work. The circuit shows a half wave voltage doubler. During the negative half cycle of the sinusoidal input waveform, diode D1 is forward biased and conducts charging up the pump capacitor, C1 to the peak value of the input voltage, (Vp). Because there is no path for capacitor C1 to discharge into, it remains fully charged and acts as a storage device in series with the voltage supply. At the same time, diode D2 conducts via D1 charging up capacitor, C2. During the positive half cycle, diode D1 is reverse biased blocking the discharging of C1 while diode D2 is forward biased charging up capacitor C2. But because there is a voltage across capacitor C1 already equal to the peak input voltage, capacitor C2 charges to twice the peak voltage value of the input signal. In other words, V(positive peak) + V(negative peak) as on the negative half-cycle, D1 charges C1 to Vp and on the positive half-cycle D2 adds the AC peak voltage to Vp onC1 and transfers it all to C2. The voltage across capacitor, C2 discharges through the load ready for the next half cycle. Then the voltage across capacitor, C2 can be calculated as: Vout = 2Vp, (minus of course the voltage drops across the diodes used) where Vp is the peak value of the input voltage.

2.4 CONVERTER COMPARISON

The voltage ratios achievable by the DC-DC converters is summarized in Fig. Notice that only the buck converter shows a linear relationship between the control (duty ratio) and output voltage. The buck-boost can reduce or increase the voltage ratio with unit gain for a duty ratio of 50%.

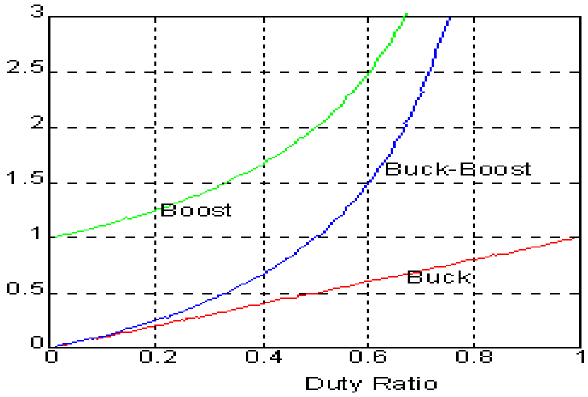


Fig 2.4.6 Comparison of Voltage ratio

3. OPERATING PRINCIPLE AND DESIGN CONSIDERATIONS

The proposed resonant step-up converter is shown in Fig. 1. The converter is composed of an FB switch network, which comprises Q 1 through Q, an LC parallel resonant tank, a voltage doublers rectifier, and two input blocking diodes, D 4. The steady-state operating waveforms are shown in Fig. 2 and detailed operation modes of the proposed converter are shown in Fig. 3. For the proposed converter, Q2 and Q are tuned on and off simultaneously; Q 1 and Q 43 are tuned on and off simultaneously.

In order to simplify the analysis of the converter, the following assumptions are made

1) All switches, diodes, inductor, and capacitor are ideal components

2) Output filter capacitors C1 and C2 b1 are equal and large enough so that the output voltage V is considered constant in a switching period Ts .o and Db2

3.1.1 OPERATINGMODE 1

Mode 1 [t0 , t1] [See Fig. 3(a)] During this mode, Q 1 and Q 4 are turned on resulting in the positive input voltage V ACross the LC parallel resonant tank,

i.e., $V_{Lr} = V_{Cr} =$ V in.(1)

The converter operates similar to a conventional boost converter and the resonant inductor Lr acts as the boost inductor with the current through it increasing linearly from I0 . The load is powered by C1 and C2. At t1, the resonant inductor current i_{Lr} reaches I_1.

$$I_1 = I_0 + \frac{V_{in} T_1}{L_r} \quad (2)$$

where T1 is the time interval of t0 to t1 .In this mode, the energy delivered from Vin to Lr is

$$E_{in} = \frac{1}{2} L_r\left(I_1{}^2 - I_0{}^2\right) \qquad (3)$$

3.1.2 OPERATINGMODE 2

At t1 , Q1 and Q4 are turned off and after that Lr resonates with Cr , V_{cr} decreases from Vin , and i_{Lr} increases from I_1 in resonant form. Taking into account the parasitic output capacitors of Q1 through Q4 and junction capacitor of D_{b2}, the equivalent circuit of the converter after t1 is shown in Fig.

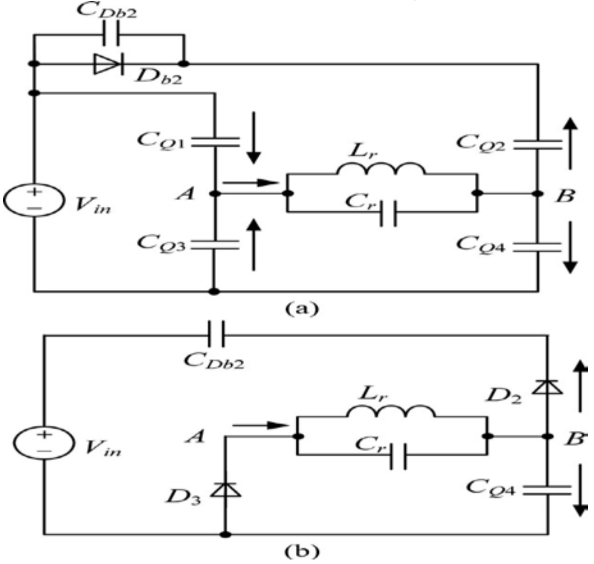


Fig 3.1 Circuit Diagram for Mode 2

in which CDb2 , CQ1 , and CQ4 are charged, CQ2 and CQ3 are discharged. In order to realize zero-voltage switching for Q2 and Q3, an additional capacitor, whose magnitude is about ten times with respect to CQ2 , is connected in parallel with Db2 . Hence, the voltage across Db2 is considered unchanged during the charging/discharging process and Db2 is equivalent to be shorted. Due to Cr is much larger than the parasitic capacitances, the voltages across Q1 and Q4 increase slowly. As a result, Q1 and Q4 are turned off at almost zero voltage in this mode. When V_{cr} drops to zero, I_{Lr} reaches its maximum magnitude. After that, V_{cr} increases in negative direction and I_{Lr} declines in resonant form. At t2,$V_{Cr}= -$Vin the voltages acrossQ1 and Q4 reach Vin , the voltages across Q2 and Q3 fall to zero and the two switches can be turned on under zero-voltage condition. It should be noted that although Q2 and Q3 could be turned on after t2 , there are no currents flowing through them. After t2 ,Lr continues to resonate with Cr, V_{Cr} increases in negative direction from $-$Vin, i_{Lr} declines in resonant form. D_{b2} will hold reversed-bias voltage and the voltage across Q4 continues to increase from Vin . The voltage across Q1 is kept at V_{in}. The equivalent circuit of the converter after t2 is shown in Fig, in which D2 and D3 are the antiparallel diodes of Q2 and Q3, respectively. This mode runs until V_{Cr} increases to $-V_{o/2}$ and i_{Lr} reduces to I_2, at t_3, the voltage across Q4 reaches $V_{o/2}$ and the voltage across D_{b2} reaches $V_{o/2}-V_{in}$. It can be seen that during t_1 to t_3 , no power is transferred from the input source or to the load, and the whole energy stored in the LC resonant tank is unchanged, i.e.

$$\frac{1}{2}L_rI^2{}_1+\frac{1}{2}C_rV^2{}_{in} = \frac{1}{2}L_rI^2{}_2+\frac{1}{2}C_r(\frac{V_0}{2})^2 \qquad (4)$$

We have

$$i_{Lr}(t)=\frac{V_{in}}{Z_r}\sin[\omega_r(t-t_1) + I_1\cos[\omega_r(t-t_1)] \qquad (5)$$

$$i_{Lr}(t)=V_r\cos[\omega_r(t-t_1) - I_1\sin[\omega_r(t-t_1)] \qquad (6)$$

$$T_2 = \frac{1}{\omega_r}[\arcsin\left(\frac{V_{in}}{\sqrt{{V_{in}}^2+\frac{L_r{I_1}^2}{C_r}}}+\arcsin\left(\frac{V_{in}}{2\sqrt{{V_{in}}^2+\frac{L_r{I_1}^2}{C_r}}}\right)\right] \qquad (7)$$

Where $\omega_r=1/\sqrt{L_rC_r}$, $Z_r=\sqrt{L_r/C_r}$, and T2 is the time interval of ti to t3

3.1.3 OPERATINGMODE 3

Mode 2 [t3 , t4] [See Fig. 3(b)] At t3,$V_{Cr}=-V_{o/2}$,D_{R1} conducts naturally, C1 is charged by i_{Lr} through D_{R1}, V_{Cr} keeps unchanged, and i_{Lr} decreases linearly. At t4, i_{Lr}=0. The time interval of t3 to t4 is

$$T_3=\frac{2I_2L_r}{V_0} \qquad (8)$$

The energy delivered to load side in this mode is

$$E_{out}=\frac{V_0I_2L_r}{4} \qquad (9)$$

The energy consumed by the load in half-switching period is

$$E_R=\frac{V_0I_0T_3}{2} \qquad (10)$$

Assuming 100% conversion efficiency of the converter and according to the energy conversation rule, in half-switching period

$$E_{in}=E_{out}=E_r \qquad (11)$$

Combining (8), (9), (10), and (11), we have

$$I_2=V_0\sqrt{\frac{I_0T_s}{V_0L_r}} \qquad (12)$$

$$T_3=2\sqrt{\frac{T_SI_0L_r}{V_0}} \qquad (13)$$

3.1.4 OPERATINGMODE 4

Mode 4 [t5 , t6] [See Fig. 3(c)] If Q2 and Q3 are turned on before t5 , then after t5 , Lr is charged by Vin through Q2 and Q3 , iLr increases in negative direction, and the mode is similar to Mode 1. If Q2 and Q3 are not turned on before t5 , then after t5 , Lr will resonate with Cr , the voltage of node A V_A will increase from zero and the voltage of node B V_B will decay from Vin ; zero-voltage condition will be lost if Q2 and Q3 are turned on at the moment. Therefore, Q2 and Q3 must be turned on before t5 to reduce switching loss. The operation modes during [t6, t10] are similar to Modes 2–4, and the detailed equivalent circuits are shown in Fig. 3(f) – (h). During [t6, t10], Q2 and Q3 are turned off at almost zero voltage, Q1 and Q4 are turned on with ZVS, and DR2 is turned off with ZCS.

In order to simplify the analysis of the converter, the following assumptions are made:

1) All switches, diodes, inductor, and capacitor are ideal components;

2) Output filter capacitors C1 and C2 b1 are equal and large enough so that the output voltage V is considered constant in a switching period Ts .o and Db2

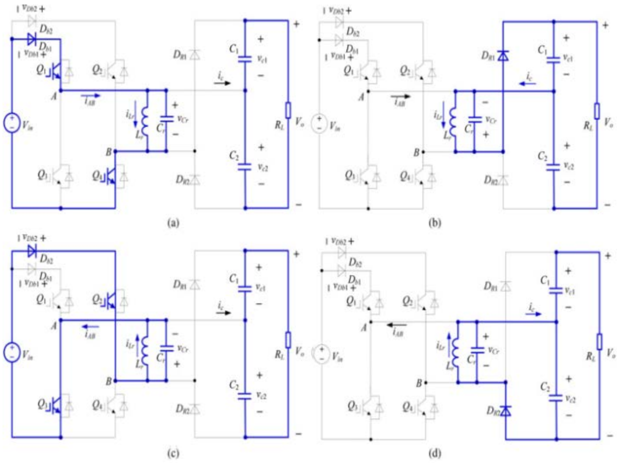


Fig 3.1 Circuit operation stages of the proposed converter.

3.2 DESIGN CONSIDERATIONS:

To simplify the circuit analysis, some assumptions are made as follows

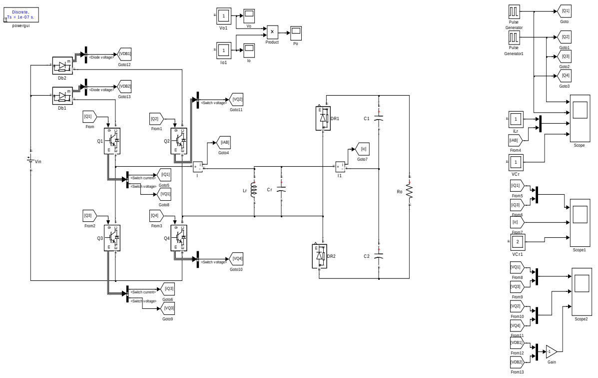
1) All components are ideal

2) Line input source is pure DC

3) Both capacitors *C1*and *C2*are sufficiently large such that they can be treated as constant DC voltage sources without any ripples

4) The switching frequency *fs* is equal or higher than the resonating frequency of he LC parallel tank.

4. SIMULATION DIAGRAM AND RESULTS



Parameters:

Input voltage (Vin)	3.6 – 4.5 kV
Output voltage (Vo)	77 - 80 kV
Inductance (L)	600 µH
Capacitance (C)	1.68 µF
Filter capacitance (C1, C2)	22 µF

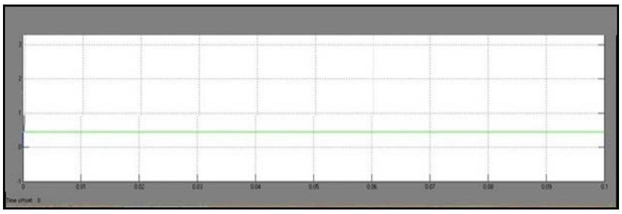


Fig 5.1 Input voltage

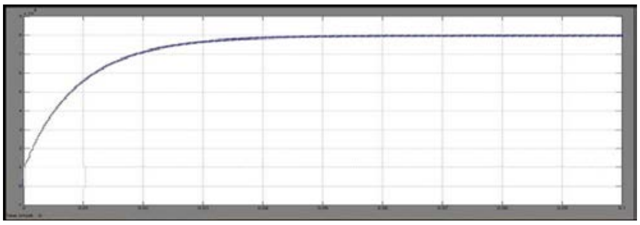


Fig 5.2 Output waveform

6. CONCLUSION

A novel resonant DC–DC converter is proposed in this paper, which can achieve very high step-up voltage gain and it is suitable for high-power high-voltage applications. The converter utilizes the resonant inductor to deliver power by charging from the input and discharging at the output. The resonant capacitor is employed to achieve zero-voltage turn-on and turn-off for the active switches and ZCS for the rectifier diodes. The analysis demonstrates that the converter can operate at any gain value (> 2) with proper control; however, the parameters of the resonant tank determine the maximum switching frequency, the range of switching frequency, and current ratings of active switches and diodes. The converter is controlled by the variable switching frequency. Simulation and experimental results verify the operation principle of the converter and parameters selection of the resonant tank.

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