Grid Connected Renewable Energy Sources Based on Soft Switching Technique

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Abstract-With the rapid development 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 pure DC system, in which high-power high-voltage step-up DC-DC converters are the key equipment to transmit the electrical energy. A resonant converter which is suitable for grid-connected renewable energy sources is proposed. The input for the proposed resonant converter is taken from the PV panel. The converter can achieve high voltage-gain using 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 (ZCS) turn-off of rectifier diodes, moreover, the equivalent voltage stress of the semiconductor devices is lower than other resonant step up converters. The operation principle of the converter and its resonant parameter selection is presented. The operation principle of the proposed converter has been successfully verified by simulation and experiment results.

***KeyTerms* : Resonant converter, voltage step-up, renewable energy, soft switching, voltage stress**

1 INTRODUCTION

1.1 General

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 with the form of AC power. The generation equipment 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, and 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 been drawn much attention recently.

Solar energy is a primary and renewable source of energy. As the cost of photovoltaic (PV) panels is seen to reduce continuously, PV-based power generation is gaining in popularity for both grid-connected and stand-alone systems. Solar panels harness the sun's energy in the form of light and convert the energy into electricity. Although the average consumer might associate solar panels with residential rooftop assemblies, solar panels are available for a wide range of applications, including powering individual gadgets, electronic devices and vehicle batteries. The smallest unit of a solar panel is the solar cell, also called a photovoltaic, or PV cell; it's the individual PV cell that turns sunlight into electricity. Individual cells arranged in a group are called a "module" or panel; a collection of two or more panels is called an array.

1.2 Power Electronics

Power electronics is the application of solid-state electronics to the control and conversion of electric power. It also refers to a subject of research in electronic and electrical engineering which deals with the design, control, computation and integration of nonlinear, time-varying energy-processing electronic systems with fast dynamics. The first high power electronic devices were mercury-arc valves. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors and transistors, pioneered by R. D. Middle brook and others beginning in the 1950s. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed.

An AC/DC converter (rectifier) is the most typical power electronics device found in many consumer electronic devices, e.g. television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. In industry a common application is the variable speed drive (VSD) that is used to control an induction motor. The power range of VSDs starts from a few hundred watts and end at tens of megawatts. The power conversion systems can be classified according to the type of the input and output power,

1. AC to DC (rectifier)
2. DC to AC (inverter)
3. DC to DC(Chopper)
4. AC to AC (Cycloconverter)

1.2.1 Devices

The capabilities and economy of power electronics system are determined by the active devices that are available. Their characteristics and limitations are a key element in the design of power electronics systems. Formerly, the mercury arc valve, the high-vacuum and gas-filled diode thermionic rectifiers, and triggered devices such as the thyratron and ignitron were widely used in power electronics. As the ratings of solid-state devices improved in both voltage and current-handling capacity, vacuum devices have been nearly entirely replaced by solid-state devices.

Power electronic devices may be used as switches, or as amplifiers. An ideal switch is either open or closed and so dissipates no power; it withstands an applied voltage and passes no current, or passes any amount of current with no voltage drop. Semiconductor devices used as switches can approximate this ideal property and so most power electronic applications rely on switching devices on and off, which makes systems very efficient as very little power is wasted in the switch.

1.3 DC-to-DC Converter

A DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. It is a class of power converter. DC to DC converters are important in portable electronic devices such as cellular phones and laptop computers, which are supplied with power from batteries primarily. Such electronic devices often contain several sub-circuits, each with its own voltage level requirement different from that supplied by the battery or an external supply (sometimes higher or lower than the supply voltage).

Additionally, the battery voltage declines as its stored energy is drained. Switched DC to DC converters offer a method to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing.

1.4 Application of Power Electronics

Applications of power electronics range in size from a switched mode power supply in an AC adapter, battery chargers, fluorescent lamp ballasts, through variable frequency drives and DC motor drives used to operate pumps, fans, and manufacturing machinery, up to giga watt-scale high voltage direct current power transmission systems used to interconnect electrical grids. Power electronic systems are found in virtually every electronic device. For example:

- DC/DC converters are used in most mobile devices (mobile phones, PDA etc.) to maintain the voltage at a fixed value whatever the voltage level of the battery is. These converters are also used for electronic isolation and power factor correction. A power optimizer is a type of DC/DC converter developed to maximize the energy harvest from solar photovoltaic or wind turbine system.

- AC/DC converters (rectifiers) are used every time an electronic device is connected to the mains (computer, television etc.). These may simply change AC to DC or can also change the voltage level as part of their operation.

- AC/AC converters are used to change either the voltage level or the frequency (international power adapters, light dimmer). In power distribution networks AC/AC converters may be used to exchange power between utility frequency50 Hz and 60 Hz power grids.

1.5 Resonant Converter

Resonant converters are becoming more and more popular these days due to their ability to achieve high efficiency through softly commutating the switching devices. Soft-switching techniques, such as Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS) can be implemented which provides better EMI performance along with higher efficiency. Resonant Converters are capable of achieving higher power density meaning the overall converter size can be reduced as the converter can operate at higher switching frequencies due to soft-switching.

A resonant converter can be divided into four main block sets: the full/half Bridge Converter, a Resonant Tank, a Rectifier, and a low-pass filter. Starting on the input side the full/half bridge converter is typically configured in complementary mode with a fixed duty cycle (~50%) and with some dead-time. The bridge converter is typically operated by adjusting the duty cycle but in the case of the resonant converter the bridge converter is frequency controlled. This means that by changing the frequency of the converter we change the impedance of the resonant tank.

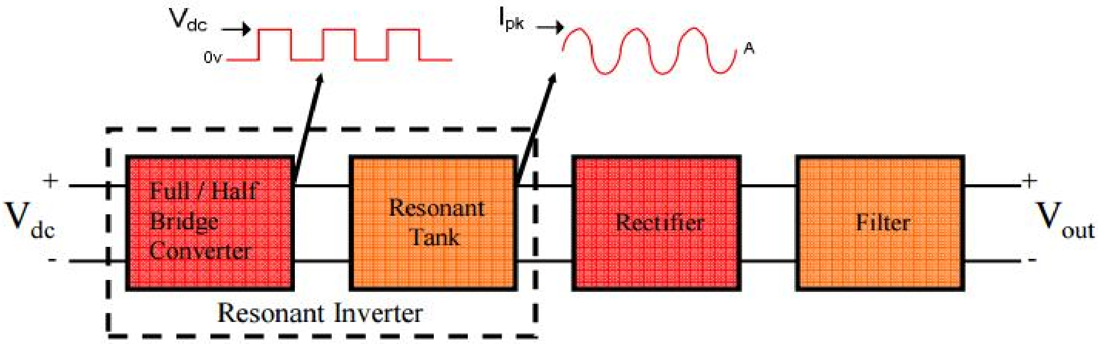


Figure 1.1: Architecture of resonant converter

The output of the bridge converter is a square wave with fixed duty cycle, with amplitude equal to Vdc and a DC offset of Vdc/2. The resonant tank is made up of reactive components (capacitors and inductors) and can have several different configurations. Depending on the tank configuration, the output will have either a sinusoidal current or voltage.

2 LITERATURE SURVEY

2.1Amir Parastar, Ali Gandomkar, MingGuo Jin and Jul-Ki Seok,"High Power Solid-State Step-up Resonant Marx Modulator with Continuous Output Current for Offshore Wind Energy Systems" this paper presents a new solid-state step-up resonant Marx modulator (SRM) with a continuous output current for offshore wind energy applications. The developed topology is based on the Marx generator concept, where magnetic switches are replaced by solid-state switching devices. The proposed converter is characterized by resonant switching transitions to achieve minimal switching losses and maximum system efficiency. Therefore, a higher switching frequency is conceivable to attain a higher power density.

2.2 Amir Parastar and Jul-Ki Seok, "High power step-up modular resonant DC/DC converter for offshore wind energy systems" this paper presents several multilevel modular DC/DC conversion systems based on the capacitor-clamped module concept for high power offshore wind energy applications. The interest in offshore wind farms has been increased significantly because of the stronger and more stable winds at sea, which will lead to a higher power production. DC/DC power conversion solutions are becoming more popular for fulfilling the growing challenges in the offshore wind power industry. Two types of the capacitor-clamped modules, the double-switch module and switchless module, are discussed.

2.3 S.Balakumar and B.Baskaran, "Design and modeling of wind fed resonant DC-DC converter through synchronous generator using MATLAB/Simulink" this paper presents the design, modeling and simulation of variable speed wind turbine through the LCL type DC-DC resonant converter for grid connected wind energy system using MATLAB/Simulink. Owing to enhancing the power demand and environmental issues, power generation from renewable energy is getting more consideration. The designed converter has main merits like reduced switching loss using soft switching methods, reduced transformer size, and filter size.

2.4 Caitríona E. Sheridan, Michael M.C. Merlin and Timothy C. Green, "Study of a Resonant DC/DC Converter in Alternate Discontinuous Mode"this paper looks at DC to DC conversion for high power applications. After having briefly reviewed the domain, a resonant bidirectional DC/DC converter already suggested in the literature is closely studied using a novel mode of operation, dubbed Alternate Discontinuous Mode. This operating mode alternates the two halves of the converter in such a way that the two DC grids are never connected. This alternative operating principle ensures the converters fault blocking capabilities and, by operating in discontinuous conduction mode, the switching losses are minimized..

2.5EloiAgostiniJr and Ivo Barbi, **"A novel three-phase three-level ZVS PWM dc-dc converter"** this paper presents a novel three-phase dc-dc converter based on the three-phase neutral point clamped (NPC) commutation cell. A static analysis is made for a particular mode of operation, allowing the development of a design procedure for the power stage. The small-signal analysis based on the phasor transformation is also proposed, providing fundamental knowledge for a satisfactory compensation in closed-loop operation. From the theoretical analysis carried out, a design procedure is elaborated, providing the values of all power stage components.

3 METHODOLOGY

3.1 Overview

A novel resonant step-up DC-DC converter is proposed, which not only can realize soft switching for main switches and diodes and large voltage-gain, but also has relatively lower equivalent voltage stress of the semiconductor devices and bidirectional magnetized resonant inductor. The operation principle of the converter and the design of the resonant parameters are presented. A 100V (±20%)/1000V, 1kW prototype is built in the lab to verify the effectiveness of the converter.

3.2 Proposed Converter Structure

The proposed resonant step-up converter is shown in Fig 3.1. The converter is composed of a full-bridge switch network, which is made up by Q_1 throughQ_4, a LC parallel resonant tank, a voltage doubler rectifier and two input blocking diodes, D_{b1} and D_{b2}. The steady-state operating waveforms are shown in Fig 3. 2 and detailed operation modes of the proposed converter are shown in Fig. 3.3-3.11.

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

2) Output filter capacitors C_1 and $C_2$are equal and large enough so that the output voltageV_0 is consideredconstant in a switching period T_s.

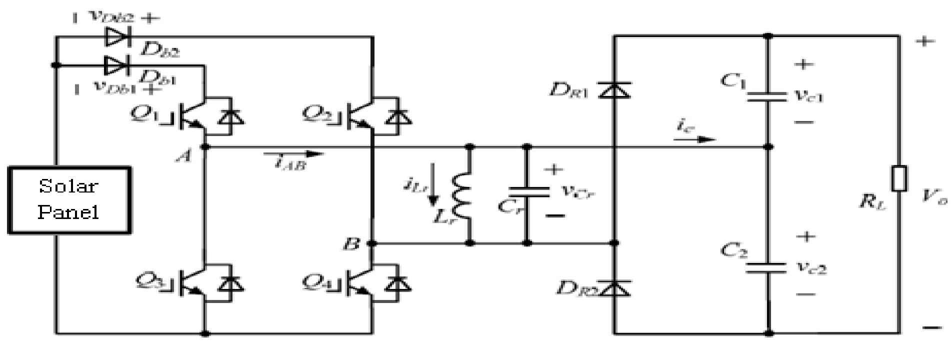


Figure 3.1: Topology of resonant step up converter

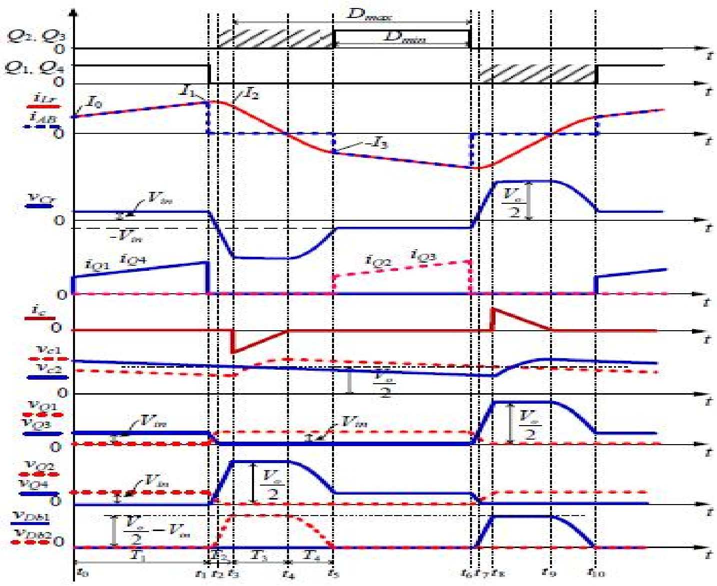


Figure 3.2 : Operating waveforms of the proposed converter

3.3 Solar Panel

Solar panel refers to a panel designed to absorb the sun's rays as a source of energy for generating electricity or heating. A photovoltaic (in short PV) module is a packaged, connected assembly of typically 6×10 solar cells. Solar Photovoltaic panels constitute the solar array of a photovoltaic system that generates and supplies solar electricity in commercial and residential applications. Each module is rated by its DC output power under standard test conditions, and typically ranges from 100 to 365 watts.

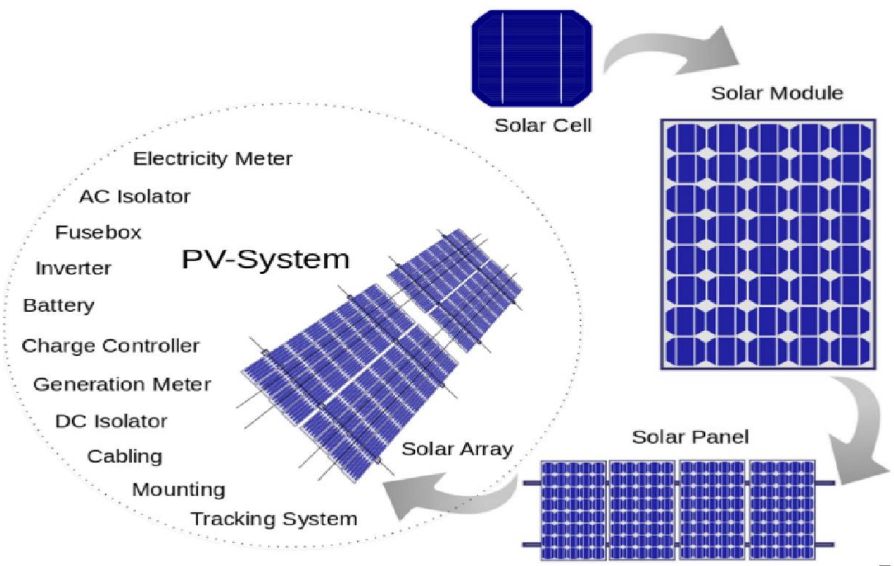


Figure 3.3 : From a solar cell to a PV system

A photovoltaic system typically includes a panel or an array of solar modules, a solar inverter, and sometimes a battery and/or solar tracker and interconnection wiring.The price of solar power, together with batteries for storage, has continued to fall so that in many countries it is cheaper than ordinary fossil fuel electricity from the grid. Solar modules use light energy (photons) from the sun to generate electricity through the photovoltaic effect.

3.4 Converter Operation Principle

3.4.1Mode 1 [t_0, t_1]

During this mode, Q_1 and Q_2 are turned on resulting in the positive input voltage V_{in}across the LC parallel resonant tank, i.e.,v_{Lr}=v_{Cr}=V_{in}. The converter operates similar to a conventional Boost converter and the resonant inductor $L_r$acts as the Boost inductor with the current through it increasing linearly from I_0. The load is powered by C_1 and C_2. At t_1, the resonant inductor current i_{Lr}reaches I_r.

$$I_1=I_0+\frac{V_{in}T_1}{L_r}(3.1)$$

whereT_1 is the time interval of t_0 to t_1. In this mode the energy delivered from $V_{in}$to $L_r$is,

$$E_{in}=\frac{1}{2}L_r(I_1^2\text{-}I_0^2)(3.2)$$

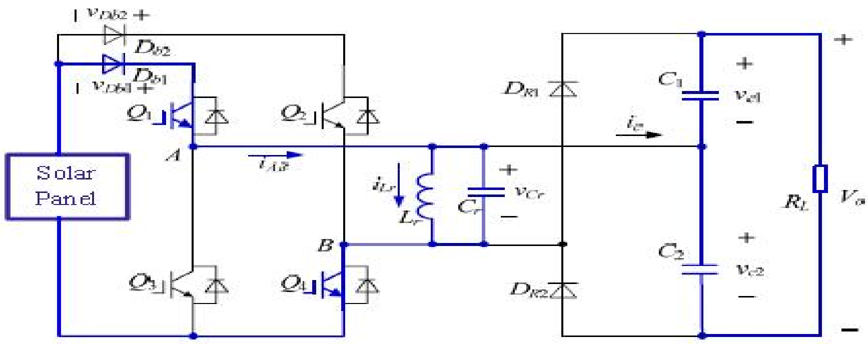


Figure 3.4: Equivalent circuit of operation stage [t_0, t_1]

3.4.2 Mode 2 [t_1, t_3]

Att_1, Q_1 and Q_4 are turned off and after that $L_r$resonates with C_r, v_{Cr}decreases from $V_{in}$and i_{Lr}increasesfrom I_1 in resonant form. Taking into account theparasitic output capacitors of Q_1through Q_4 and junctioncapacitor of D_{b2}, the equivalent circuit of the converterafter$t_1$is shown in Fig. 3.5(a), in which CD_{b2}, CQ_1 and CQ_4 are charged, CQ_2 and CQ_3 are discharged.

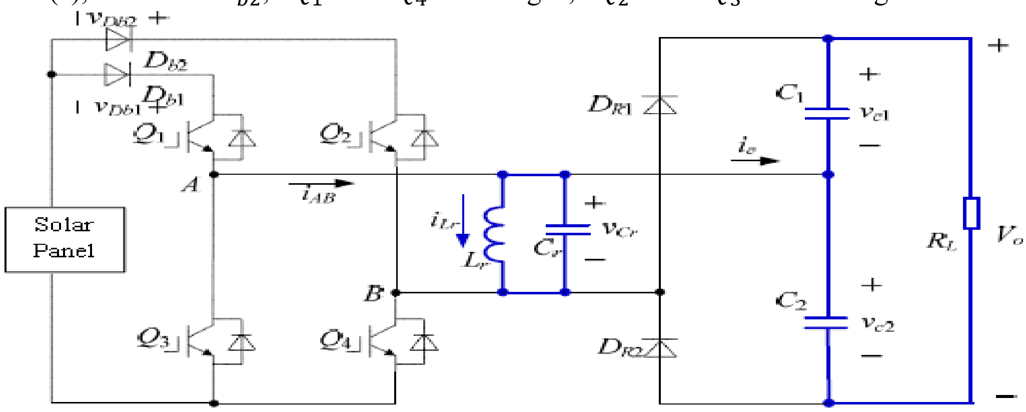
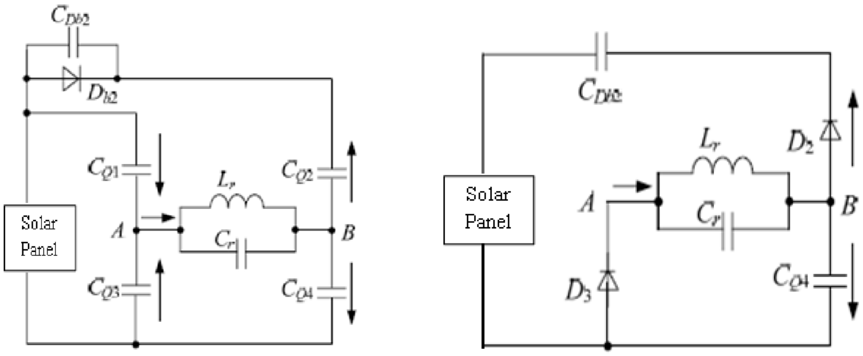


Figure 3.5 : Equivalent circuit of operation stage [t_1, t_3]

In order to realize zero-voltage-switching (ZVS) for $Q_2$and Q_3, an additional capacitor, whose magnitude is about 10 times with respect to CQ_2, is connected in parallel with D_{b2}. Hence, the voltage across D_{b2} is considered unchanged during the charging/discharging process and D_{b2} is equivalent to be shorted. Due to $C_r$be much larger than the parasitic capacitances, the voltages across Q_1 and Q_4 increase slowly. As a result, Q_1 and Q_4 are turned off at almost zero voltage in this mode.



(a) (b)

Figure 3.6: Further equivalent circuits of Mode 2 (a) [t_1, t_2] (b) [t_2, t_3]

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. Att_2, v_{Cr}= -V_{in}, the voltages across Q_1 and Q_4 reach V_{in}, the voltages across Q_2 and Q_3 fall to zero and the two switches can be turned on under zero-voltage condition. It should be noted that although Q_2 and Q_3 could be turned on after t_2, there are no currents flowing through them.

$$\frac{1}{2}\mathrm{L_r I_1^2}+\frac{1}{2}\mathrm{C_r V_{in}^2} = \frac{1}{2}\mathrm{C_r}(\frac{\mathrm{V_0}}{2})^2 \quad (3.3)$$

We have,

$$i_{Lr}(t)=\frac{V_{in}}{Z_r}\sin[\omega_r(t-t_1)]+I_1\cos[\omega_r(t-t_1)] \quad (3.4)$$

$$v_{cr}(t) = V_{in}\cos[\omega_r(t-t_1)]-I_1 Z_r\sin[\omega_r(t-t_1)) \quad (3.5)$$

$$T_2=\frac{1}{\omega_r}\left[arcsin\left(\frac{V_{in}}{\sqrt{V_{in}^2+\frac{LrI_1^2}{C_r}}}\right)+arcsin\left(\frac{V_0}{2\sqrt{V_{in}^2+\frac{LrI_1^2}{C_r}}}\right)\right] \quad (3.6)$$

Where, $\omega_r = 1/\sqrt{L_r C_r}$,$Z_r = \sqrt{L_r/C_r}$ T_2 is the time interval of $t_1$to t_2.

3.4.3 Mode 3 [t_3, t_4]

At t3, v_{Cr} =-Vo/2, D_{R1} conducts naturally, $C_1$is charged byi_{Lr}through DR1, v_{Cr}keeps unchanged, i_{Lr} decreases linearly. At t_4, i_{Lr} =0. The time interval of t_3 to t_4 is,

$$T_3 = \frac{2I_2L_r}{V_0} \quad (3.7)$$

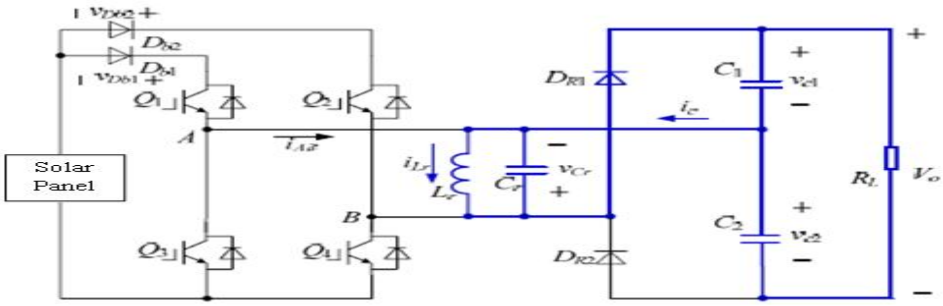


Figure 3.7: Equivalent circuit of operation stage [t_3, t_4]

The energy delivered to load side in this mode is,

$$E_{out} = \frac{V_0 I_2 T_3}{4} \quad (3.8)$$

The energy consumed by the load in half switching period is

$$E_R = \frac{V_0 I_0 T_3}{2} \quad (3.9)$$

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

$$E_{in} = E_{out} = E_R \quad (3.10)$$

Combining (3.7), (3.8), (3.9) and (3.10), we have

$$I_2 = V_0\sqrt{\frac{I_0 T_3}{V_0 L_r}} \quad (3.11)$$

$$T_3 = 2\sqrt{\frac{T_S I_0 L_r}{V_0}} \quad (3.12)$$

3.4.4 Mode 4 [t_4, t_5]

At t_4, i_{Lr}decreases to zero and the current flowing through D_{R1} also decreases to zero, and D_{R1} is turned off with zero-current-switching (ZCS), therefore, there is no reverse recovery. After t_4, $L_r$resonates with C_r, $C_r$is discharged through L_r, v_{Cr}increases from -$V_0/2$ in positive direction,i_{Lr}increases from zero in negative direction. Meanwhile, the voltage across Q_4 declines fromV_0/2. At *t*5, v_{Cr}= -V_{in}, i_{Lr}= -V_{in}.

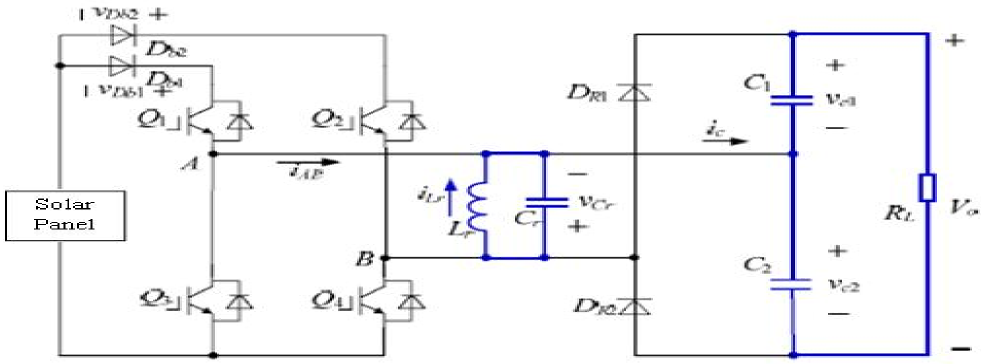


Figure 3.8 : Equivalent circuit of operation stage [t_4, t_5]

In this mode, the whole energy stored in LC resonant tank is unchanged, i.e.,

$$\frac{1}{2}C_r\left(\frac{V_0}{2}\right)^2 = \frac{1}{2}L_r I_3^2 + \frac{1}{2}C_r V_{in}^2 \quad (3.15)$$

We have,

$$I_0 = I_3 = \frac{1}{2}\sqrt{\frac{C_r(V_0^2-4V_{in}^2)}{L_r}} \quad (3.16)$$

$$i_{L_r}(t) = \frac{V_0}{2\omega_r L_r}\sin[\omega_r(t - t_5)] \quad (3.17)$$

$$v_{C_r}(t) = \frac{-V_0 cos[\omega_r(t-t_5)]}{2} \quad (3.18)$$

$$T_4 = \frac{1}{\omega_r} arc\cos\left(\frac{2V_{in}}{V_0}\right) \quad (3.19)$$

where T_4 is the time interval of t_4 to t_5.

3.5 Matlab Tools and Usage

3.5.1 Introduction

MATLAB (Matrix Laboratory) is a multi-paradigm numerical computing environment and fourth generation programming language. Developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran and Python.

Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing capabilities. An additional package, Simulink, adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems.In 2004, MATLAB had around one million users across industry and academia. MATLAB users come from various backgrounds of engineering, science, and economics. MATLAB is widely used in academic and research institutions as well as industrial enterprises.

Typical uses include:

- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including Graphical User Interface building

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non interactive language such as C or Fortran.The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects, which together represent the state-of-the-art in software for matrix computation.

3.5.2 Key Features

- High-level language for numerical computation, visualization, and application development
- Interactive environment for iterative exploration, design, and problem solving.
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, numerical integration, and solving ordinary differential equations.

4 RESULTS AND DISCUSSION

The proposed model is developed using MATLAB/Simulink. The simulink diagram and their simulation results are shown below.

4.1 Simulink Diagram

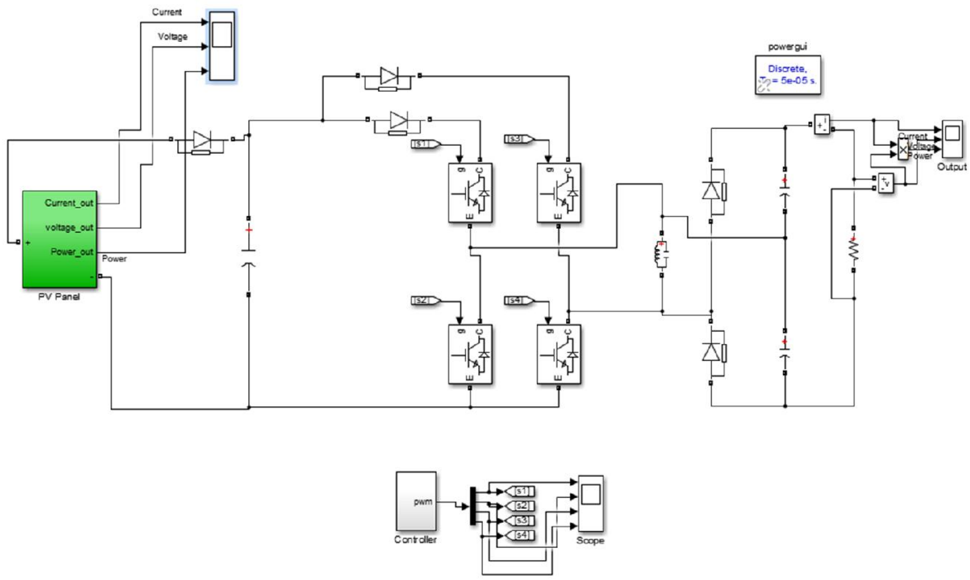


Figure 4.1: Simulink diagram of proposed method

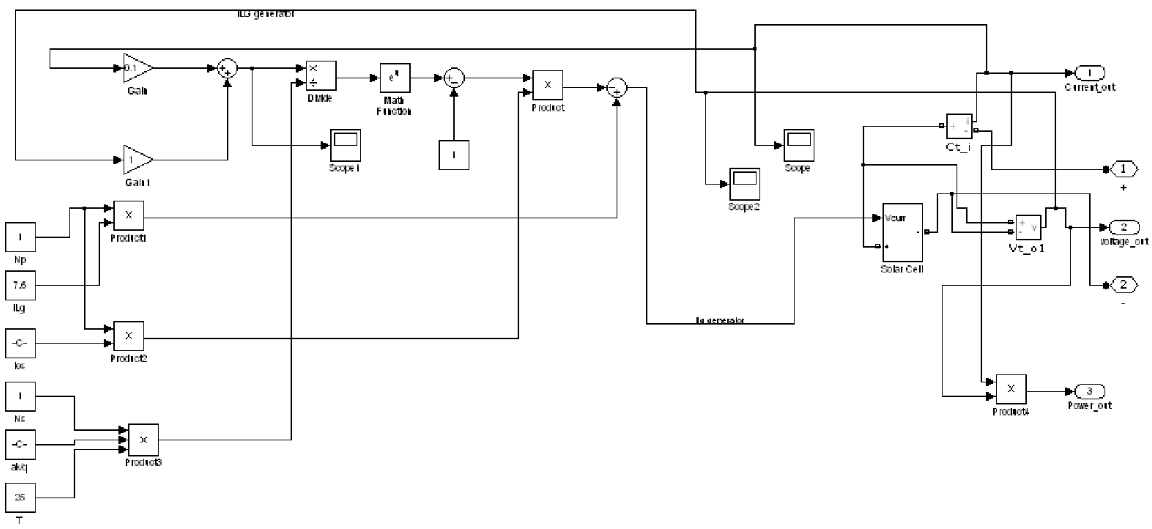


Figure 4.2: Simulink diagram of PV panel

4.2 Simulation Results

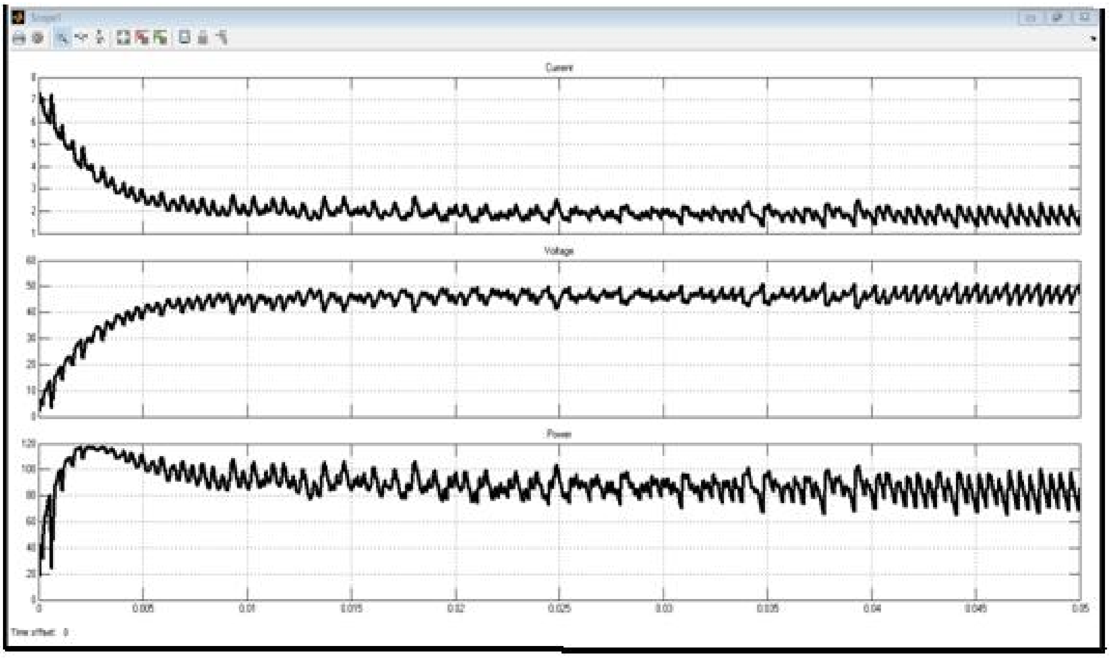


Figure 4.3: Input waveform of current, voltage and power

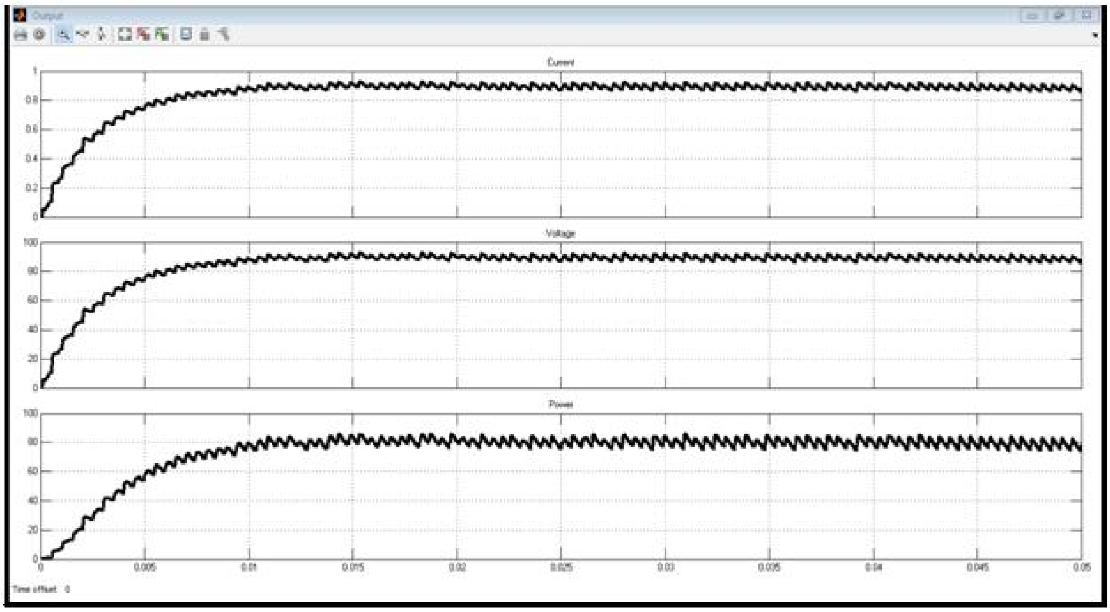


Figure 4.4: Output waveform of current, voltage and power

5 CONCLUSION

A novel resonant DC-DC converter is proposed, which can achieves very high step-up voltage gain and it is suitable for high-power high-voltage applications. In this project Photo Voltaic (PV) panel can be connected to grid in order to analyze the performance. The converter utilizes the resonant inductor to delivery power by charging from the input and discharging to 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.

REFERENCE

[1] CIGRE B4-52 Working Group, “HVDC grid feasibility study,” Melbourne: International Council on Large Electric Systems, 2011.
[2] A. S. Abdel-Khalik, A. M. Massoud, A. A. Elserougi, and S. Ahmed, “Optimum power transmission-based droop control design for multi-terminal HVDC of offshore wind farms,” IEEE Trans. Power Syst., vol. 28, no. 3, pp. 3401–3409, 2013.
[3] F. Deng and Z. Chen, “Design of protective inductors for HVDC transmission line within DC grid offshore wind farms,” IEEE Trans. Power Del., vol. 28, no. 1, pp. 75–83, 2013.
[4] F. Deng and Zhe Chen, “Operation and control of a DCgrid offshore wind farm under DC transmission system faults,” IEEE Trans. Power Del., vol. 28, no. 1, pp. 1356– 1363, 2013.
[5] C. Meyer, “Key components for future offshore DC grids,” PhD Thesis, RWTH Aachen University, 2007.
[6] W. Chen, A. Huang, S. Lukic, et al, “A comparison of medium voltage high power DC/DC converters with high step-up conversion ratio for offshore wind energy systems,” in Proc. IEEE ECCE, 2011, pp. 584–589.
[7] L. Max, “Design and control of a DC collection grid for a wind farm,” PhD Thesis, Chalmers University of Technology, 2009.
[8] Y. Zhou, D. Macpherson, W. Blewitt, and D. Jovcic, “Comparison of DC-DC converter topologies for offshore wind-farm application,” in Proc. Conf. PEMD, 2012, pp. 1–6.
[9] S. Fan, W. Ma, T. C. Lim, et al, “Design and control of a wind energy conversion system based on a resonant dc/dc converter,” IET Renew. Power Gener., vol. 7, no. 3, pp. 265–274, 2013.
[10] F. Deng and Z. Chen, “Control of improved full-bridge three-level DC/DC converter for wind turbines in a DC grid,” IEEE Trans. Power Electron., vol. 28, no. 1, pp. 314–324, 2013.
[11] C. Meyer, M. Höing, A. Peterson, and R. W. De Doncker, “Control and design of DC grids for offshore wind farms,” IEEE Trans. Ind. Appl., vol. 43, no. 6, pp. 1475–1482,2007.
[12] C. Meyer and R. W. De Doncker, “Design of a threephaseseries resonant converter for offshore DC grids,” in Proc. IEEE Ind. Appl. Soc. Conf., 2007, pp. 216–223.
[13] S. P. Engel, N. Soltau, H. Stagge, and R. W. De Doncker, “Dynamic and balanced control of three-phase highpowerdual-active bridge DC–DC converters in DC-grid applications,” IEEE Trans. Power Electron., vol. 28, no. 4, pp. 1880–1889, 2013.
[14] K. Stephan, “Modular DC/DC converter for DC distribution and collection networks,” PhD thesis, EPFL, Switzerland, 2012.
[15] T. Luth, M. Merlin, T.Green, F. Hassan, and C. Barker, “High frequency operation of a DC/AC/DC system for HVDC applications,” IEEE Trans. Power Electron., vol. 29, no. 8, pp. 4107–4115, 2014.
[16] Y. Zhou, D. Jiang, P. Hu, et al “A prototype of modular multilevel converters,” IEEE Trans. Power Electron., vol. 29, no. 7, pp. 3267–3278, 2014.

[17] W. Chen, X. Ruan, H. Yan, and C. K. Tse, “DC/DC conversion systems consisting of multiple converter modules: stability, control and experimental verifications,” IEEE Trans. on Power Electron., vol. 24, no. 6, pp. 1463– 1474, 2009.
[18] K. Park and Z. Chen, “Analysis and design of a parallel connected single active bridge DC-DC converter for highpowerwind farm applications,” IEEE Power Electronicsand Applications (EPE), 2013, pp.1–10.
[19] C. Zhan, A. Bullock, C. Smith, and A. Crane, “Power collection and transmission systems,” European PatentApplication, EP2341594A1, 2011.
[20] P. Monjean, J. Delanoe, J. Auguste, C. Saudemont, J. Sprooten , A. Mirzaian, and B. Robyns, “Topologies comparison of multi-cell medium frequency transformer for offshore farms,” in Proc. IET AC and DC Power Transmission, 2010, pp. 1–5.
[21] A. A. Hagar, “A new family of transformerless modular DC-DC converters for high power applications,” Ph.D. dissertation, Dept. Elect. Eng., Univ. of Toronto, Toronto, ON, Canada, 2011.
[22] C. Zhan, C. Smith, A. Crane, et al, “DC transmission and distribution system for a large offshore wind farm,” in Proc. IET AC and DC Power Transmission, 2010, pp. 1–5.
[23] N. Denniston, A. Massoud, S. Ahmed, et al, “Multiple module high gain high voltage DC-DC transformers for offshore wind energy systems,” IEEE Trans. Ind.Electron., vol. 58, no. 5, pp. 1877– 1886, 2011.
[24] W. Chen, A. Huang, C. Li, et al, “Analysis and comparison of medium voltage high power DC/DCconverters for offshore wind energy systems,” IEEETrans. Power Electron., vol. 28, no. 4, pp. 2014–2023, 2013.
[25] A. Parastar, A. Gandomkar, M. Jin, and J. Seok, “High power solid-state step-up resonant Marx modulator with continuous output current for offshore wind energy systems,” in Proc. IEEE ECCE, 2013, pp. 1709–1716.