Bidirectional AC– DC Converter for A DC Distribution System

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Abstract: A bidirectional ac–dc con- verter is proposed for a 380-V dc power distribution system to control bidirectional power flows and to improve its power con- version efficiency. To reduce the switches' losses of the proposed non isolated full-bridge ac–dc rectifier using a unipolar switching method, switching devices employ insulated-gate bipolar transistors, MOSFETs, and silicon carbide diodes. Using the analysis of the rectifier's operating modes; each switching device can be selected by considering switch stresses. A simple and intuitive frequency detection method for a single-phase synchronous reference frame-phase-locked loop (SRF-PLL) is also proposed using a filter compensator, a fast period detector, and a finite impulse response filter to improve the robustness and accuracy of PLL performance under fundamental frequency variations. In addition, design and control methodology of the bidirectional full-bridge *CLLC* resonant converter is suggested for the galvanic isolation of the dc distribu- tion system. A dead-band control algorithm for the bidirectional dc–dc converter is developed to smoothly change power conversion directions only using output voltage information. Experimental results will verify the performance of the proposed methods using a 5-kW prototype converter.

IndexTerms- AC–DC boost rectifier, bidirectional isolated con- verter, CLLC resonant converter dc distribution system.

1. INTRODUCTION

DC Distribution system is one of important future power systems to save energy and to reduce CO2 emission because it can improve the efficiency of systems due to the reduction of the number of power conversion stages. Especially, the dc distribution system for a residential house using dc home appliances can allow the flexibility of merging many renewable energy sources because most of the output of renewable energy sources is dc. The overall system configuration of the proposed 380-V dc distribution system is shown in Fig. 1. In order to balance the power flow and to regulate the dc-bus voltage, the dc distribution system requires an isolated bidirectional ac–dc converter to interface between dc bus and ac grid. It usually consists of a non isolated bidirectional ac–dc rectifier for grid-connected operation and an isolated bidirectional dc–dc converter to interface dc bus and dc link of the rectifier

1.1 EXISTING SYSTEM

The conventional SRF-PLL has a weak point of frequency tracking performance because it uses the constant angular frequency of a fundamental component. It can cause a tracking error in the PLL operation when the fundamental frequency changes to the different value of the constant angular frequency.

1.2 PROPOSED SYSTEM

AIM:

This paper presents A high-efficiency isolated bidirectional ac–dc converter is proposed for a 380-V dc power distribution system to control bidirectional power flows and to improve its power conversion efficiency. The single-phase non isolated bidirectional rectifier typically consists of a conventional full-bridge structure. It has two sinusoidal pulse width modulation (SPWM) methods such as the bipolar and the unipolar switching modes. One of the disadvantages of the bipolar switching mode is the need of a large inductor to reduce the input current ripple because the peak to- peak voltage of the inductor is more than twice the unipolar switching mode. If the full-bridge rectifier operates in the unipolar switching mode, inductance for a continuous current mode (CCM) power factor correction (PFC) operationcan reduced. One of full-bridge rectifier legs in the unipolar switching mode is operated at a line frequency while the other one is modulated at a switching frequency. However, the unipolar switching mode rectifier using conventional switching devices including a normal anti parallel diode causes high reverse recovery current and turn-on switching noise. The switching and the conduction losses in the bidirectional rectifier are the main cause of decreasing power conversion efficiency.

The phase estimation, so-called phase-locked loop (PLL), is required to control the bidirectional ac–dc rectifier; especially, the phase information of supply voltage is mandatory to generate a current reference. One of the popular PLL methods is synchronous reference frame (SRF-PLL) which uses a rotating reference frame for tracking a phase angle. However, the conventional SRF-PLL has a weak point of frequency tracking performance because it uses the constant angular frequency of a fundamental component. It can cause a tracking error in the PLL operation when the fundamental frequency changes to the different value of the constant angular frequency. Therefore, a more simple, faster, and more intuitive frequency detection method should be upgraded for improving the performance of the single-phase bidirectional rectifier.

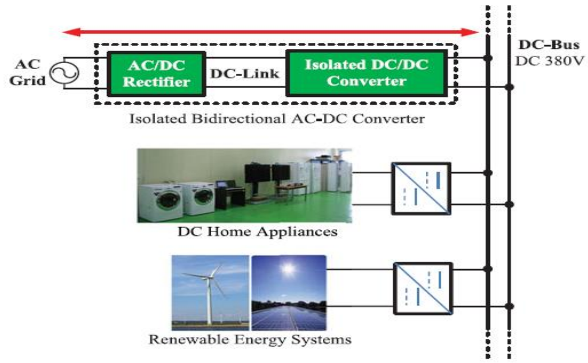
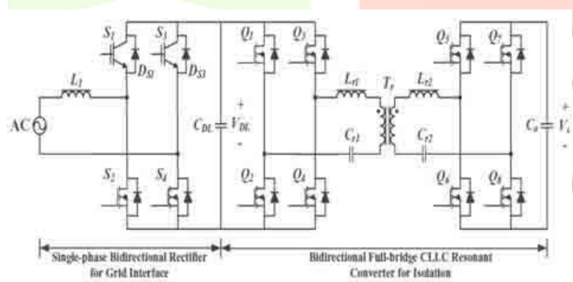


Fig.1.1 380-V Dc Distribution System With An Isolated Bidirectional AC–DC Converter

Some isolated full-bridge bidirectional dc–dc converter topologies have been presented in recent years. A boost full bridge zero-voltage switching (ZVS) PWM dc–dc converter was developed for bidirectional high-power applications. However, it needs extra snubber circuits to suppress the voltage stress of the switches. A bidirectional phase-shift full-bridge converter was proposed with high-frequency galvanic isolation for energy storage systems. This converter can improve power conversion efficiency using a zero-voltage transition feature; however, it requires input voltage variations to regulate constant output voltage because this topology can only achieve the step-down operation. A bidirectional full-bridge *LLC* resonant converter was introduced for a UPS system without any snubber circuits. This topology can operate under soft-switching conditions of primary switches and secondary rectifier. In addition, the topology confines voltage stresses without any clamp circuits. However, application of this converter showed different operations between transformer's turn ratio and the difference of resonant networks. Therefore, the novel design guides suitable for a 380-V dc distribution system should be proposed.

In this paper, the high-efficiency isolated bidirectional ac–dc converter system with several improved techniques will be discussed to improve the performance of a 380-V dc distribution system. In order to increase the efficiency of the non isolated full-bridge ac–dc rectifier, the switching devices are designed by using insulated-gate bipolar transistors (IGBTs) without an anti parallel diode, MOSFETs, and silicon carbide (SiC) diodes. Through the analysis of operational modes, each switch is selected by considering switch stresses. The major novelty of the proposed PLL is the suggestion of a simple and intuitive frequency detection method for the single-phase SRF-PLL using an advanced filter compensator, a fast quad-cycle detector, and a finite impulse response (FIR) filter. Finally, design guides and gain characteristics of the bidirectional full-bridge *CLLC* resonant converter with the symmetric structure of the primary inverting stage and secondary rectifying stage will be discussed for a 380-V dc distribution system. Experimental results will verify the performance of the proposed methods using a 5-kW prototype converter.

1. CIRCUIT CONFIGURATION OF THE PROPOSED ISOLATED BIDIRECTIONAL AC–DC CONVERTER



PWM CONTROLLER

Fig. 2.1 shows the circuit configuration of the proposed isolated bidirectional ac–dc converter.
It consists of the single phase bidirectional rectifier for grid interface and the isolated bidirectional full-bridge *CLLC* resonant converter for galvanic isolation. To control the proposed converter, the power flow directions in the converter are defined as follows: rectification mode (forward direction of power flow) and generation mode (backward direction of power flow).The switching method of the proposed single-phase bidirectional rectifier is unipolar SPWM. In order to reduce the switching losses caused by the reverse recovery current in the rectification mode, the high-side switches of the proposed rectifier are composed of two IGBTs without anti parallel diodes ($S1$ and $S3$) and two SiC diodes ($DS1$ and $DS3$). The low side switches are composed of two MOSFETs ($S2$ and $S4$) for reducing conduction loss and for using ZVS operation in the generation mode. The detailed circuit operation of the proposed bidirectional rectifier and advanced PLL method will be discussed.

2. BIDIRECTIONAL AC-DC CONVERTER

High-power rectifiers do not have a wide choice of switching devices because there are not many kinds of the switching devices for high-power capacity. IGBT modules or intelligent power modules (IPMs) are chiefly used. A fast recovery diode (FRD) has a small reverse recovery time trr . On the other hand, a medium-power rectifier system around 5 kW for a residential house or building has a wide selection of switching devices such as discrete-type IGBTs and MOSFETs. In the bidirectional rectifier using the unipolar switching method, the turn-on period of low-side switches increases one and half times more than the turn-on period of the high-side switches. Therefore, the low-side switches should be chosen to consider low conduction losses for increasing the power conversion efficiency. Therefore, soft-switching techniques using additional passive or active snubber circuits have been proposed. Especially, commercial IGBTs without the antiparallel diode can be selected to replace antiparallel FRDs to SiC diodes. In theory, the SiC diode does not have *t*rr . Therefore, the combination of IGBTs without the antiparallel diode and the SiC diodes is another viable solution to reduce the reverse recovery problems.

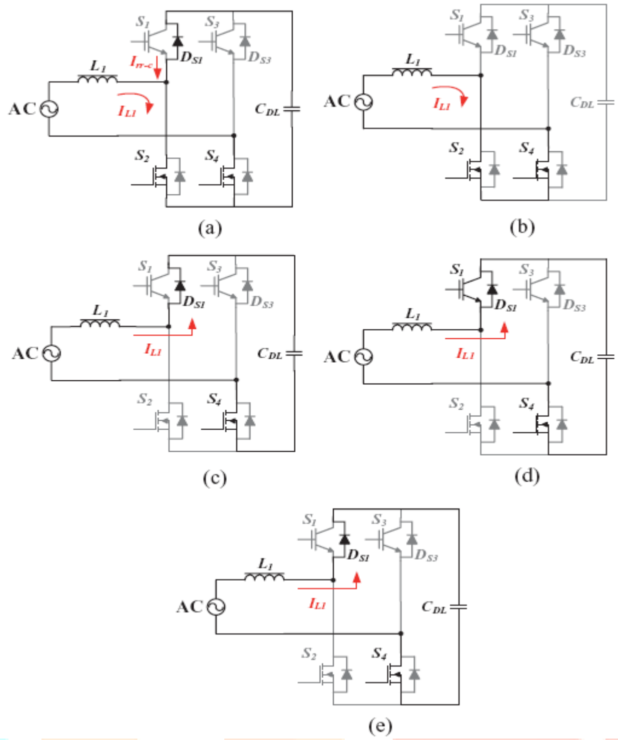


Fig.3.1 Operating modes of the proposed bidirectional ac–dc rectifier in the rectification mode: (a) *Mode* 1, (b) *Mode* 2, (c) *Mode* 3, (d) *Mode* 4, and (e) *Mode*

IGBTs in the view point of the conduction loss when the same current flows into the switching devices. Therefore, MOSFETs are suitable for the low-side switches in the unipolar switching method.

3.1 Consideration for Reverse Recovery Losses in a Rectification Mode

In the rectification mode, the bidirectional rectifier has five operating modes in a single switching cycle. The circuit operations in the positive half period of the input voltage. The dark lines denote conducting paths for each state. The theoretical waveforms of the proposed rectifier. At time *t*0 , the low-side switch *S*2 turns ON. At this time, if *DS*1 is FRD, *DS*1 cannot immediately turn OFF because of its reverse recovery process. This simultaneous high reverse recovery current causes an additional switching loss on *S*2. The reverse recovery current increases the current stress on the lowside switches and decreases the EMI performance of the rectifier.

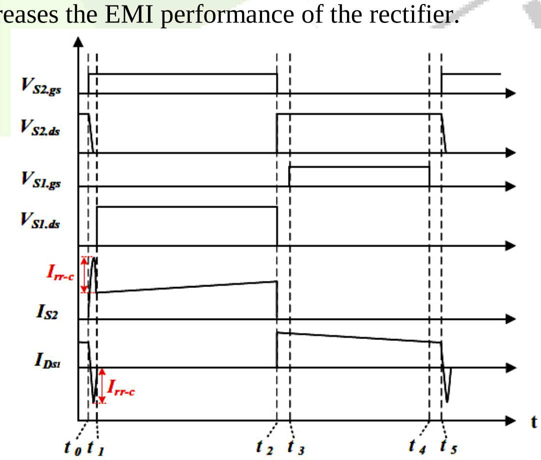


Fig.3.2. Theoretical operating waveforms of the proposed bidirectional ac–dc rectifier in the rectification mode.

At *t*3 , the gate signal *VS*1.gs turns ON. Since the IGBTs cannot conduct in the reverse direction, the energy in the input voltage source and the inductor *L*1 is still discharged through SiC diode *DS*1 . In the rectification mode, the high-side SiC diodes instead of the IGBTs are fully operated during entire rectification modes. Therefore, the conduction loss of the high-side switches depends on the forward voltage drop of the SiC diodes.

3.2. Consideration for Switching Losses in a Generation Mode

In the generation mode using the same switching pattern as the rectification mode,the antiparallel diode including the low-side switch *S*2 will be conducted by freewheeling operation using inductor's energy as shown in *Mode* 2. During this period, the energy stored in the output capacitance of *S*2 can be fully discharged. In *Mode* 3, *S*2 turns ON under the ZVS condition. Through these operation modes, the turn-on losses in the low-side switches can be reduced. When the high-side switch *S*1 turns ON in *Mode* 5, the antiparallel diode

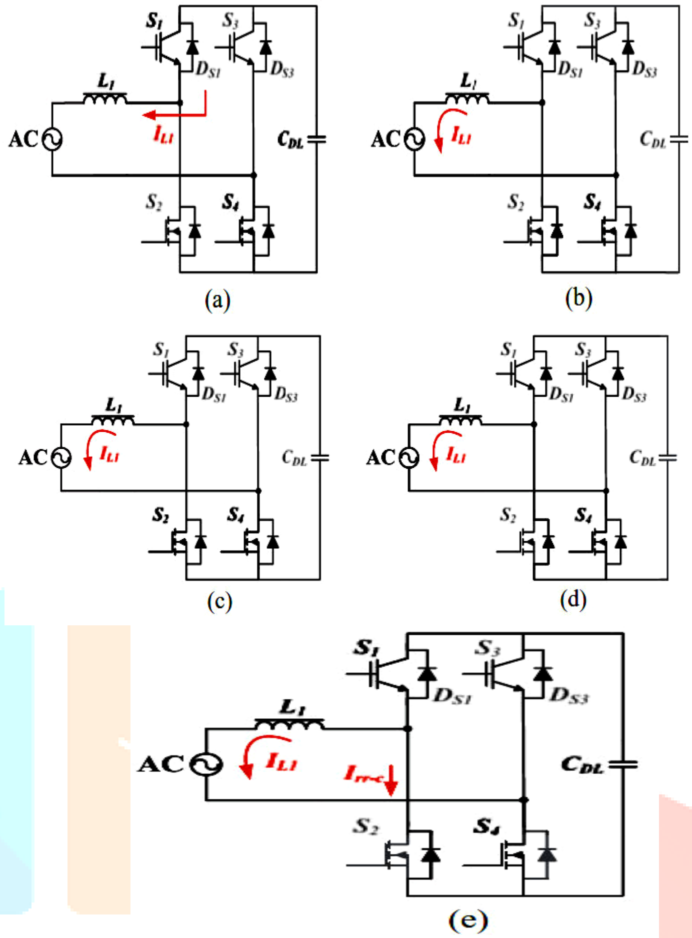


Fig. 5. Operating modes in the rectifier's generation mode using the same switching pattern as the rectification mode: (a) *Mode* 1, (b) *Mode* 2, (c) *Mode* 3, (d) *Mode* 4, and (e) *Mode* 5.

Of *S*2 cannot immediately turn OFF because of poor reverse recovery performance of the MOSFET's antiparallel diode. The MOSFET's losses in the generation mode depend on the MOSFET's *R*DS.on and the reverse recovery characteristics of the antiparallel diode. The selection of the MOSFET can determine the significant loss factor between switching and conduction losses. Using this switching pattern in the generation mode, there are no benefits of the ZVS operation. However, the reverse recovery losses can be significantly reduced as compared with the same switching pattern of the rectification mode. The modified switching pattern does not affect the power conversion and control performances of the ac–dc rectifier.

3.3. Consideration for Conduction Losses

In the unipolar switching method, the turn-on period of lowside switches is one and half times longer than the turn-on period of high-side switches. Generally, the conduction loss in MOSFETs can be calculated using the rms current passing through MOSFET's *R*DS.on. Since the turn-on period of the low-side switches is 75% of the fundamental period of the ac input current, the rms current of the low-side switches can be calculated using the following equation:

$$I_{\mathrm{rms.low}} = \sqrt{\frac{1}{2\pi}\int_{o}^{\frac{3}{2}\pi}(I_{\mathrm{in}.P}\sin\omega t)^2 d\omega t}. \qquad (1)$$

Through the aforementioned assumptions, the peak current *I*in.*P* and the average current *I*in.av of the ac input can be derived as follows:

$$I_{\mathrm{in}.P} = \sqrt{2}\frac{P_{\mathrm{out}}}{\eta V_{\mathrm{in.rms}}} \qquad (2)$$

$$I_{\mathrm{in.av}} = \frac{2}{\pi} I_{\mathrm{in}.P} \qquad (3)$$

where η is the power conversion efficiency.

4. BIDIRECTIONAL DC–DC CONVERTER

Future aircraft are likely to employ electrically powered actuators for adjusting flight control surfaces and other high power transient loads. Ultra capacitors are one possible form of energy storage device that may be used to meet transient power demands and smooth the load on the generators. A loss model was introduced for performance evaluation and design optimisation in. Reference validated the Performance of the DAB topology for next generation power conversion systems using ultra capacitor-based technologies. The dynamic performance of the DAB converter was modeled and analysed.

This project makes a contribution to the steady-state analysis of the DAB converter by presenting equations for the RMS and average device currents and the RMS and peak inductor/transformer currents. These equations are useful in predicting the losses that occur in the devices and passive components. The small number of passive components, the inherent soft switching property and galvanic isolation make the converter a candidate for high-power-density aerospace applications.

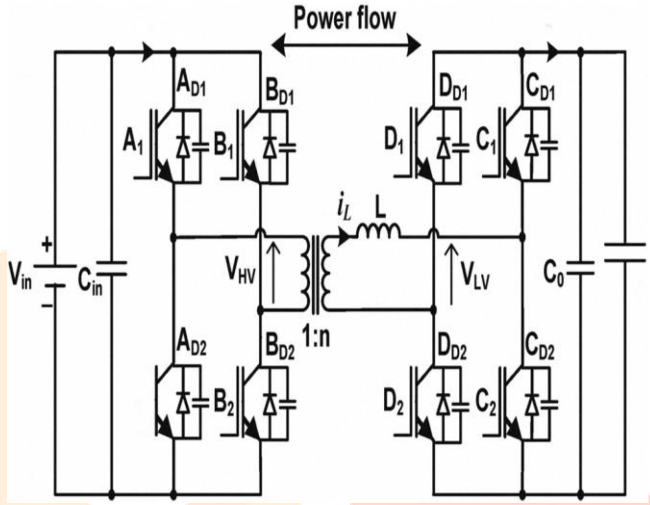


Fig 4.1 Schematic of the DAB DC-DC Converter

4.1 DC-DC CONVERTER

DC-DC converters are devices which change one level of direct current voltage to another (either higher or lower) level. They are primarily of use in battery-powered appliances and machines which possess numerous sub circuits, each requiring different levels of voltage. A DC-DC converter enables such equipment to be powered by batteries of a single level of voltage, preventing the need to use numerous batteries with varying voltages to power each individual component.

4.1.1 Why DC-DC Converters are Useful?

DC-DC converters are used to fill the gaps left by the limitations of direct and alternating currents. Direct current (DC) is a steady flow of electric energy in the same direction, while alternating current (AC) is a flow of energy which frequently changes in direction and intensity.

For this reason, the DC-DC converter has become an important electrical component, acting as the direct current equivalent of a transformer for battery-operated devices, enhancing or reducing intensity as needed.

4.1.2 How DC-DC Converters Work?

In its simplest form, a DC-DC converter simply uses resistors as needed to break up the flow of incoming energy – this is called linear conversion. However, linear conversion is a wasteful process which unnecessarily dissipates energy and can lead to overheating. A more complex, but more efficient, manner of DC-DC conversion is switched-mode conversion, which operates by storing power, switching off the flow of current, and restoring it as needed to provide a steadily modulated flow of electricity corresponding to the circuit's requirements. This is far less wasteful than linear conversion, saving up to 95% of otherwise wasted energy.

4.1.3 DC-DC Converters:

DC-DC converters can vary widely in size, usage, and the level of voltage processed. They are commonly used in car stereo equipment and radios (converting energy from the DC car battery to meet the lesser requirements of this equipment), cell phones, and laptop computer.

4.2 RECTIFIERS (AC / DC CONVERSION)

Rectifiers are basically used to convert Alternating current (AC) to Direct Current (DC). Half wave Rectifiers only converts either the positive or negative cycle of an AC to DC. A Full wave Rectifier converts both the positive and negative cycle of an AC to DC.

4.3 Classification of Rectifiers

Uncontrolled Rectifier
Phase-Controlled Rectifier
Single-Phase PFC AC/DC Converter
Single-Phase Single-Stage PFC AC/DC Converter
Single-Phase Bi-directional AC/DC Converter

PWM Synchronous Rectifier
Three-Phase PFC AC/DC Converter
Three-Phase Bi-directional AC/DC Converter

4.4 Basic Rectifier Concepts

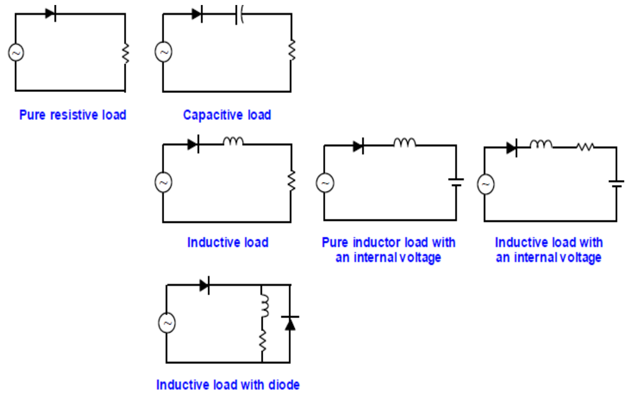


Fig 4.1 Basic Rectifier Concept

5. BIDIRECTIONAL CONVERTERs

The world now is going to exercise the power electronic applications device for complex systems when most difficulty face for human being in many stream of fields.. The energy can supplied from utility grid or bank of batteries; with the application ranging from high power conversion equipment of MW to the very low power equipment of a few watts. Most of power converter devices have common unidirectional application with power being supplied from the source to the load.

5.1 Bidirectional DC-DC Converters

Most bidirectional DC-DC converter topologies can be illustrated below and it also characteristics power flows in both directions[1-3]. Energy storages in general uses bidirectional DC-DC converter for charging and discharging applications may be either in half-bridge or full-bridge arrangement of semi-conductor switching devices. The buck type of converter has energy storage on the high voltage side, whereas boost type of converter has energy storage on the low voltage side.

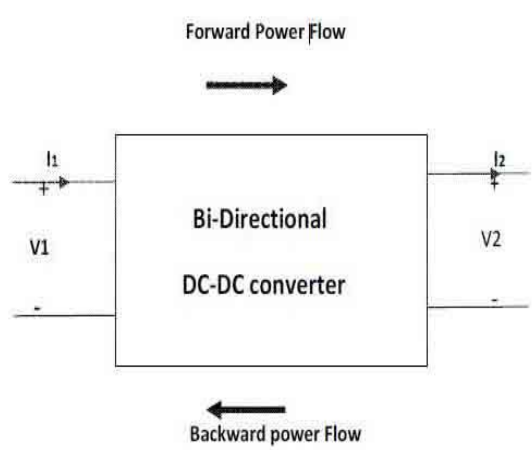


Fig.5- 1 Illustration of bidirectional power flow

5.2 Isolated Bidirectional AC-DC Converters

The transformer is used for isolating bridge converters which is on both sides of DC-DC converters or it isolates input and load. Generally bidirectional converters have a structure similar to the Fig. 1-3. The topology consists of two high switching frequencies DC-AC and AC-DC converters with similarly high frequency transformer which is primarily used to maintain the galvanic isolation between the sources. Therefore the topology consists both rectifier and inverter on either of its bridges. Since the transformer has a numbers of turns on both sides then it is essential for voltage matching between the two sources. As the term bi-directional indicates, there are basically two mode of operations where the of switches either turned-off or turned-on in order to control power flow from either direction. The two mode of operations are noted as charging/step-down and discha step-up detail will be discussed.

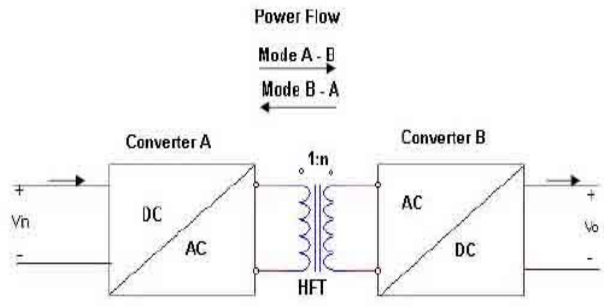


Fig. 5.2 Basic structure of isolated bidirectional AC-DC converter.

5.3 The Need For Galvanic Isolation

Transformer isolation needs for a system when there is no need of direct connection between source and load. If there is non isolation between the load and the source, a single circuit fault occurred on any circuit component of the system has high probability to damage the entire system. Fig.1.4 shows the above effects of either we have galvanic isolation or not, X indicates there is a fault on the short circuit is

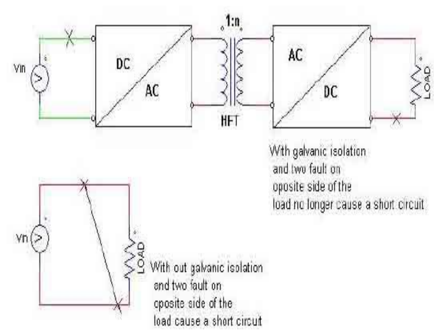


Fig.5.3 Effect of galvanic isolation in circuit.

The concept of power flow in both direction for bidirectional dc-dc converter is operation of switching devices realize current flow in each way. Bidirectional dc-dc converters are developed from two unidirectional semiconductor switching devices such as; MOSFET, Transistors and IGBT power switches constructed with parallel diodes. The topology consists of two high switching frequencies DC-AC and AC-DC converters with similarly high frequency transformer which is primarily used to maintain the galvanic isolation between the sources. Generally bidirectional converters have a structure similar to the. The topology consists of two high switching frequencies DC-AC and AC-DC converters with similarly high frequency transformer which is primarily used to maintain the galvanic isolation between the sources.

6. CLLC RESONANT CONVERTERS

High power, efficiency and density are the major core cause for the development of new resonant converter. These converters are called LLC resonant converters which solve the drawbacks of the previously known series and parallel resonant converters will discuss in detail in this chapter. Based on their fusibility, these resonant converters developed due to their ability of higher switching frequencies, higher efficiencies, simple and small packaging. These are also the paths considered for the development and manipulating of the LLC resonant converter.
Series Resonant Converter, Parallel Resonant Converter and Series Parallel Resonant are the three most popular topologies.

6.1. Three Most Common Resonant Topologies

In this case, the dual active full-bridge switch topology is connected to the series resonant converter on both sides of the transformer 1. The resonant inductor Lr and Resonant capacitors are series connected with active full-bridge MOSFETs switches . Therefore at the resonant switching frequency the voltage gain almost have unity value.

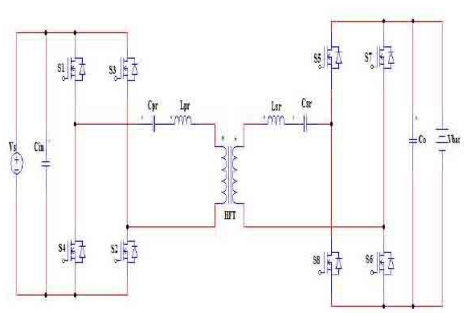


Fig 6.1 Full-bridge series resonant converter

The general code developed in appendix generates value for the parameter of the resonant tank(i.e. Lp, Cp, Ls, and Cs). The developed code interface with simulink developed plant output voltage and switching frequency. The generated values of the resonant tank parameter value are selected if they satisfy the required resonant frequency. From Fig.2-2 the parameter values are Lp = 335.8µH, Ls = 28.8µH, Cs = 392nF and Cp = 13.5µF. The parameters value for this series isolated bi-directional resonant converter is specified as follow:

Transformer turn ratio: 25:3, Input voltage: 400V, Rload : 0.8Ω, Resonant frequency: 100KHz. This is due to the law loss during zero voltage switching(ZVS) and MOSFETs application in DC-DC converter. If the region selected for the operation is on the left side; then the switching frequency is lower than the resonant frequency the converter will work under zero current switching(ZCS) condition.

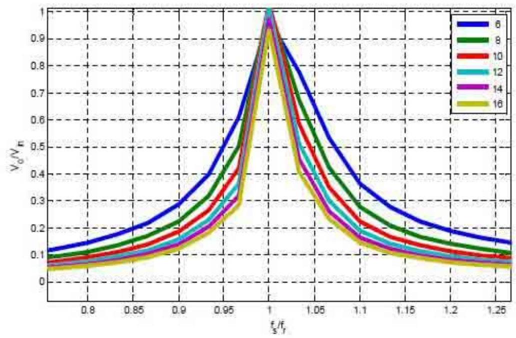


Fig. 6.2: Characteristics of SRC resonant converter

7.1. PI- CONTROLLERS

PI controller will eliminate forced oscillations and steady state error resulting in operation of on-off controller and P controller respectively. A control without D mode is used when:

a) Fast response of the system is not required
b) Large disturbances and noise are present during operation of the process
c) There is only one energy storage in process (capacitive or inductive)
d) There are large transport delays in the system

7.2 PID CONTROLLER:

PID controller has all the necessary dynamics: fast reaction on change of the controller input (D mode), increase in control signal to lead error towards zero (I mode) and suitable action inside control error area to eliminate oscillations (P mode). PID controller is often used in industry, but also in the control of mobile objects (course and trajectory following included) when stability and precise reference following are required. Conventional autopilot is for the most part PID type controllers.

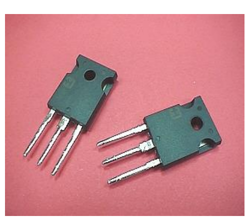
8. PHASE LOCKED LOOP

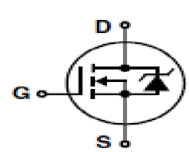
A PLL is a feedback control system that automatically adjusts the phase of a locally generated signal to match the phase of an input signal. PLLs operate by producing an oscillator frequency to match the frequency of an input signal. In this locked condition, any slight change in the input signal first appears as a change in phase between the input signal and the oscillator frequency.

Pulse Width Modulations Controller

Pulse-width modulation (PWM), as it applies to motor control, is a way of delivering energy through a succession of pulses rather than a continuously varying (analog) signal. By increasing or decreasing pulse width, the controller regulates energy flow to the motor shaft. The motor's own inductance acts like a filter, storing energy during the "on" cycle while releasing it at a rate corresponding to the input or reference signal. In other words, energy flows into the load not so much the switching frequency, but at the reference frequency.

9. MOSFET SWITCH-IRFP250N





(**M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor). The most popular and widely used type of field effect transistor (see FET). MOSFETs are either NMOS (n-channel).

Values

Input AC Supply 220v
Capacitor value 0.1f
Capacitor Voltage 220v
Transformer primary voltage 200v

Primary Inductor value1e-3
Capacitor value 1e-6
Secondary inductor value 1e-3
Capacitor value 1e-6
Resistant value 5000e3
Output voltage 140v.

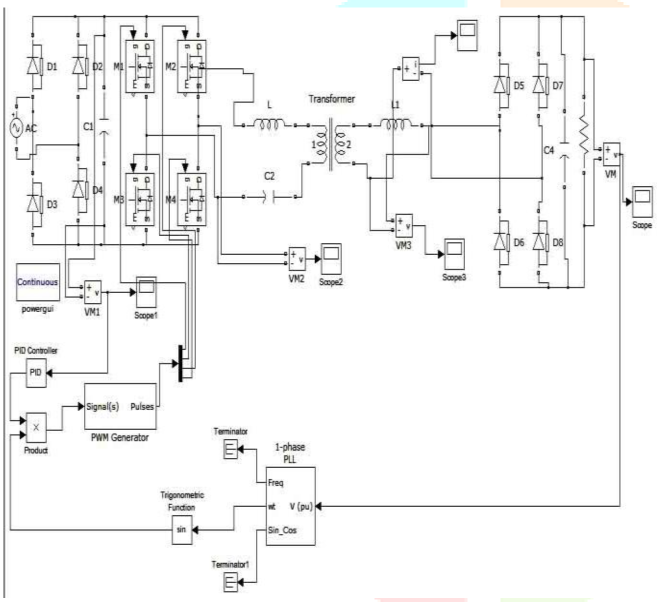
Values

Input DC voltage 500v
Resistance 1e-3
Capacitor value 1e-6
Transformer Primary Winding
Capacitor value 470e-6
Inductor value 2.11e-6
Secondary Winding
Capacitor value 470e-6
Inductor value 2.11e-6
AC Output voltage 60v

This forward power flow represents for the to control power flows and reducing the switching loss and improve power conversion efficiency.

10. SIMULINKMODELS AND SIMULATION RESULTS FOR BIDIRECTIONAL AC-DC CONVERTER

Forward Power Flow



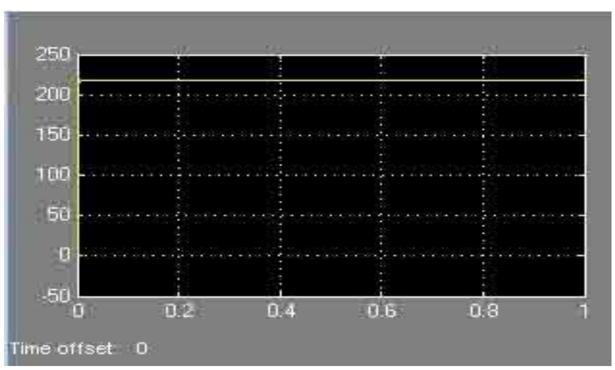
Circuit Diagram in Simulation

Forward Power Flow

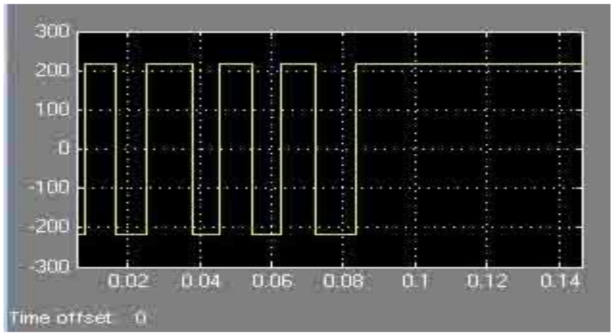
Definition of Forward Power Flow

If DC bus side power demand increases than power flow AC bus to DC bus side that is called forward power flow Input voltage-220V AC input is given to Diode bridge rectifier, which converters AC to DC This is filtered out using a capacitor and given to full bridge inverter circuit which produces AC square wave output. Through an isolation Transformer it is fed to secondary side through a diode bridge rectifier to get the regulated DC and through filters. Isolation T/F is used to provide isolation b/w high PW circuit. Accordingly, a number of methods are specially designed for the solution of the power flow problem on radial distribution systems, most of which are based on the forward/backward sweep method. AC Input supply 220v and Output voltage 140v resonant converter we obtain high magnitude voltage and less sleeting. Distribution systems were designed to operate under radial (unique path from any given bus to the source) and unidirectional power flow conditions, but with dispersed generation in the network the power flow is no longer unidirectional. An existence of DG units the system results with new tasks for the distribution.

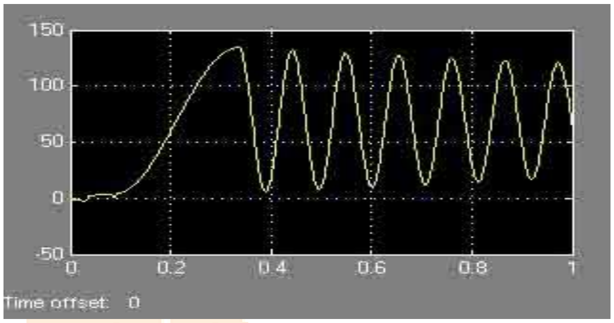
Capacitor Voltage



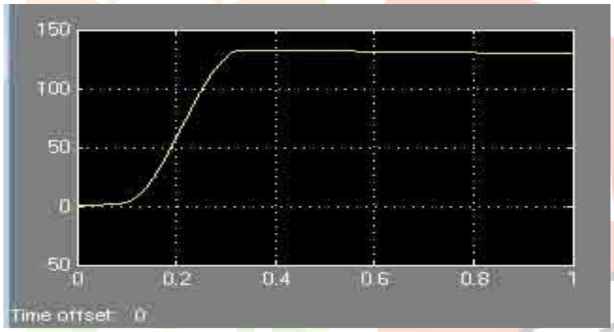
Transformer Primary Winding Voltage



Transformer Secondary Winding Voltage



Output Voltage



Backward Power Flow

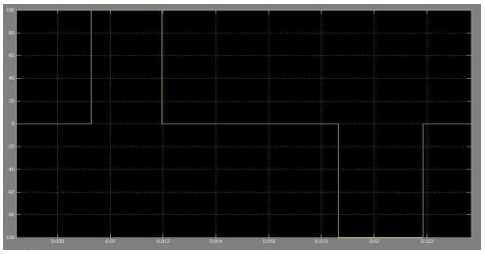
Definition of Backward Power Flow

If AC bus side powers demand increases than power flow DC bus to AC bus side that is called backward power flow This DC Source is connected to the load through two stages. This is a high frequency T/F- to reduce its core size. Then the output of it is given to diode bridge rectifier, which converters this AC to DC and finally given to charge the battery. Charging current and battery voltage can be seen in the output scope.

Circuit Diagram in Simulation.

For the analysis of radial or weakly meshed distribution systems supplying voltage dependent loads is here developed.

Transformer Primary Winding Voltage



Output Voltage

CONCLUSION

The isolated bidirectional ac–dc converter is proposed for the 380-V dc power distribution system to control the bidirectional power flow and to improve its power conversion efficiency. In order to improve the reverse recovery problem, the high-side switches of the ac–dc rectifier employ IGBTs without antiparallel diodes and SiC diodes. In addition, the low-side switches are composed of two MOSFETs to reduce the conduction loss in the rectification mode. For comparison with the conventional IGBT switches, the total conduction losses of the rectifier's switches are calculated in the rectification mode. The simple and intuitive frequency detection method for the single-phase SRF-PLL is also proposed using the filter compensator, fast QD, and FIR filter to improve the robustness and accuracy of the PLL performance under fundamental frequency variations. The proposed PLL system shows lower detection fluctuation and faster transient response than the conventional techniques. Finally, the proposed *CLLC* resonant converter can operate under the ZVS for the primary switches and the soft commutation for the output rectifiers. The soft-switching condition of the converter is derived to obtain the design methodology of the resonant network. Gain properties are also analyzed to avoid gain reduction and non monotonic gain curve under high-load conditions. In addition, the dead-band and switch transition control algorithms are proposed to smoothly change the power flow direction in the converter. From light to full load, the overall power conversion efficiency of the 5-kW prototype converter was measured to almost 96% at 2.5 kW and 94.5% at the full load of 5 kW.

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