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Grid-Connected Full-Bridge Inverter Based on a Novel ZVS SPWM Scheme

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Abstract:

A Zero-Voltage Switching (ZVS) grid-connected full-bridge inverter and its modulation schemes are investigated. A novel space vector pulse width modulation scheme for the ZVS full-bridge inverter (ZVS SVPWM) is proposed in this paper. The ZVS SVPWM is evolved from the double-frequency (DF) SVPWM by adding gate drive to the auxiliary switch. The ZVS condition is analyzed and the circulation loss of the resonant branch is optimized by adjusting the energy storage in the resonant inductor. The reverse recovery of the body-diode of MOSFET is relieved and ZVS is realized for both main and auxiliary switches. The filter inductors are significantly reduced with higher switching frequency. The design guideline of resonant parameters and the implementation of ZVS SVPWM in DSP controller are introduced. The ZVS SVPWM scheme is verified on a 3kW inverter prototype.

Introduction

The full-bridge inverter is widely used in residential PV generation systems and uninterrupted power supply systems [1]. To reduce the filter size, the inverter is expected to operate with higher frequency whereas the switching frequency is usually limited by switching loss of the power devices. The high di/dt and dv/dt during the reverse recovery process may also damage the device. IGBT with fast antiparallel diode is used more often than MOSFET in the hard-switching full-bridge inverter. However, IGBT's switching is relatively slower. For these reasons the switching frequency of hard-switching full-bridge inverter is usually restricted below 20kHz, which leads to larger filters and lower power density [2].

To relieve the reverse recovery problem of MOSFET, topologies have been proposed by predecessors. Compared to the full-bridge inverter, two extra transistors and two diodes are added in the H6 inverter [3] to deactivate the body-diodes of MOSFETs. The dual buck inverters [4]-[6] use four phase legs which consist of one MOSFET in series with one external diode. Totally four filter inductors are needed. The body-diodes of MOSFETs are bypassed by the external circuit and the reverse recovery loss is reduced in these topologies.

However, the switching devices in these topologies still work in hard-switching mode and the switching frequency is still limited by the switching loss.

Another solution to reduce the switching loss and suppress the reverse recovery is the soft-switching technique, which has been investigated by predecessors.

The resonant DC link three-phase inverter (RDCL) in [7] and active-clamping resonant DC link three-phase inverter (ACRDCL) in [8] achieve zero-voltage switching for all switching devices. The reverse recovery of the antiparallel diodes is suppressed successfully and the power quality is improved. A number of soft-switching single-phase inverters are also proposed in recent years [10]-[19]. Active-clamping technique and classical bipolar PWM scheme are applied to the resonant DC-link full-bridge inverter [10]. The voltage stress is the same as the DC bus voltage whereas two auxiliary switches are needed. The maximum efficiency is 98.2%, but its auxiliary circuit is complex. Some key parameters of these soft-switching full-bridge inverters are listed in Table I.

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TABLE I
KEY PARAMETERS OF SOFT-SWITCHING FULL-BRIDGE INVERTERS

Topology	Auxiliary switches	P_o	f_s	Maximum efficiency
Active-clamping DC link [10]	1	7kW	20kHz	90.2%
ZVS DC link [11]	1	0.3kW	50kHz	96.0%
ZVS PWM commutation cell [12]	2	3kW	32kHz	94.6%
ZVS PWM coupled magnetics [13]	4	3kW	20kHz	98.2%

According to the predecessors' research, the DC side ZVS full-bridge inverters [10] [11] have the simplest structure. With this principal advantage, this paper mainly focuses on improving the efficiency and power density of DC side ZVS full-bridge inverter. The ZVS full-bridge inverter is based on the topology proposed in [10]. For the purpose of realizing the ZVS condition, an adjustable short-circuit stage controlled by the short-circuit pulse in every switching cycle is designed to reset the energy in the auxiliary resonant branch. The duration of the short-circuit stage varies according to the different load condition for optimizing the efficiency in both light and heavy load cases.

A.INVERTERS (INTRODUCTION)

A device that converts DC power into AC power at desired output voltage and frequency is called an Inverter. Phase controlled converters when operated in the inverter mode are called line commutated inverters. But line commutated inverters require at the output terminals an existing AC supply which is used for their commutation. This means that line commutated inverters can't function as isolated AC voltage sources or as variable frequency generators with DC power at the input. Therefore, voltage level, frequency and waveform on the AC side of the line commutated inverters can't be changed. On the other hand, force commutated inverters provide an independent AC output voltage of adjustable voltage and adjustable frequency and have therefore much wider application.[13] Inverters can be broadly classified into two types based on their operation

- Voltage Source Inverters(VSI)
- Current Source Inverters(CSI)

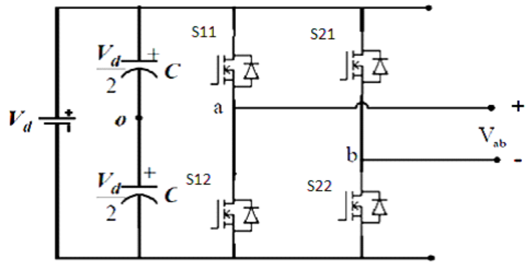
A current source inverter is fed with adjustable current from a DC source of high impedance, i.e; from a stiff DC current source. In a CSI fed with stiff current source, output current waves are not affected by the load. From view point of connections of semiconductor devices, inverters are classified as under [1],[2]

- Bridge Inverters
- Series Inverters
- Parallel Inverter

Bridge Inverters are classified as

- Half bridge
- Full bridge

B. Single Phase Full-Bridge Inverter



A single-phase inverter in the full bridge topology is as shown in Fig. 1 which consists of four switching devices, two of them on each leg. The full-bridge inverter can produce an output power twice that of the half-bridge inverter with the same input voltage. The S PWM switching schemes are discussed in this section, which improve the characteristics of the inverter.

$$\frac{Vd}{2}\,(S11\text{-}S12) = Van + Vno = Vao$$

$$\frac{Vd}{2}\,(S21\text{-}S22) = Vbn + Vno = Vbo$$

$$Vab = Van\text{-}Vbn$$

NOVEL ZVS SPWM SCHEME FOR ZVS FULL-BRIDGE INVERTER

The reverse recovery of the body-diode is a severe trouble in the MOSFET full-bridge inverter, which occurs during the commutation from the body-diode to the MOSFET.

Fig. 3, an auxiliary branch is installed between the DC bus and the inverter. It is composed of an auxiliary MOSFET *Sa*, clamping capacitor *Cc*, resonant inductor *Lr* and resonant capacitor *Cra*. The capacitors *Cr*1 ~ *Cr*4 are paralleled capacitors to the main switches. Before the commutation from body-diode to MOSFET in Fig. 3, the auxiliary switch *Sa* is turned off and the DC voltage *Vdc* across the phase leg can be resonated to zero by the resonant process. Therefore the main switches achieve ZVS turn-on.

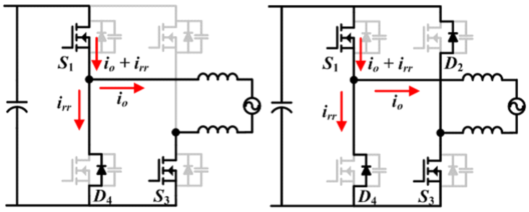
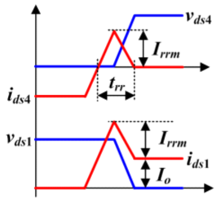


Fig. 1. (a) Commutation at one phase leg (b) Commutations at both phase legs



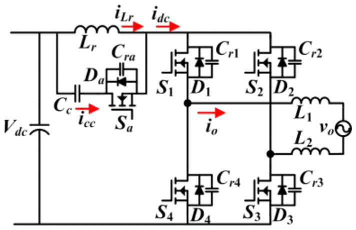


Fig. 2. Hard-switching turn-on Fig. 3. ZVS full-bridge inverter waveform

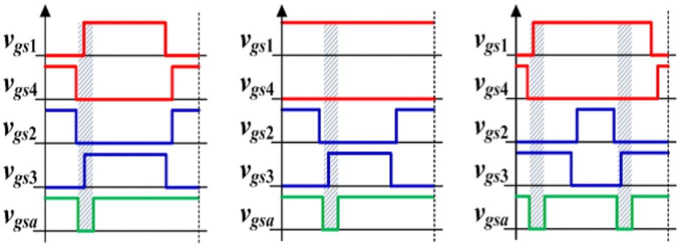


Fig. 4. *vgsa* with (a) bipolar SPWM (b) unipolar SPWM (c) DF SPWM

Equation (2) is derived from (1) with consideration of their actual directions. It shows that the current in the resonant inductor *Lr* not only discharges the parallel capacitors but also provides the load current.

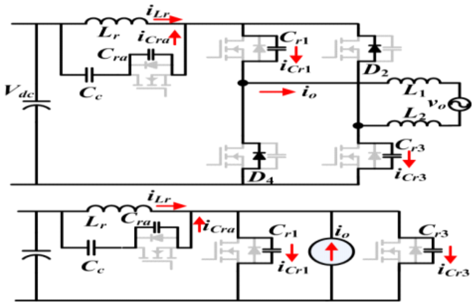


Fig. 5 Resonant circuit with bipolar SPWM in [10]

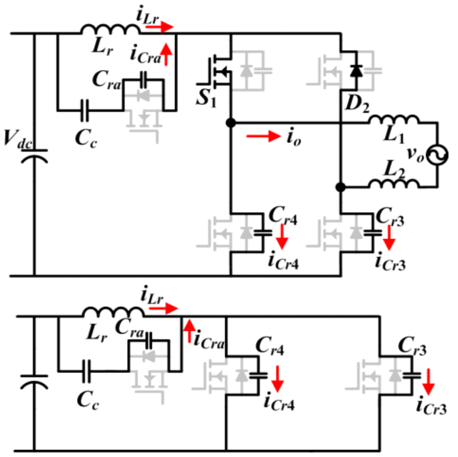


Fig. 6 Resonant circuit with unipolar and DF SPWM

$$i_{Lr} = -\left|i_{Cr1}\right| - \left|i_{Cr2}\right| - \left|i_{Cra}\right| - \left|i_o\right| = -\left|i_{Lr}\right|$$

Fig. 6 shows the resonant circuit with unipolar SPWM and DF SPWM. The current in the resonant inductor *Lr* discharges the parallel capacitors of main switches and charges the parallel capacitor of auxiliary switch. The load current is still freewheeling and does not participate in the resonant process. Their relationship can be obtained.

$$i_{Lr} + i_{Cra} = i_{Cr1} + i_{Cr2}$$

$$i_{Lr} = -\left|i_{Cr3}\right| - \left|i_{Cr4}\right| - \left|i_{Cra}\right| = -\left|i_{Lr}\right|$$

According to (2) and (4) it can be found that the amplitude of resonant current *iLr* is larger with bipolar SPWM, which may cause higher loss in the resonant inductor.

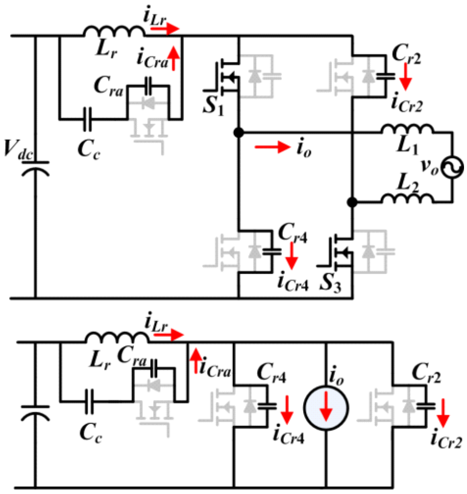


Fig. 7 Second resonant process for ZVS turn-on of auxiliary switch

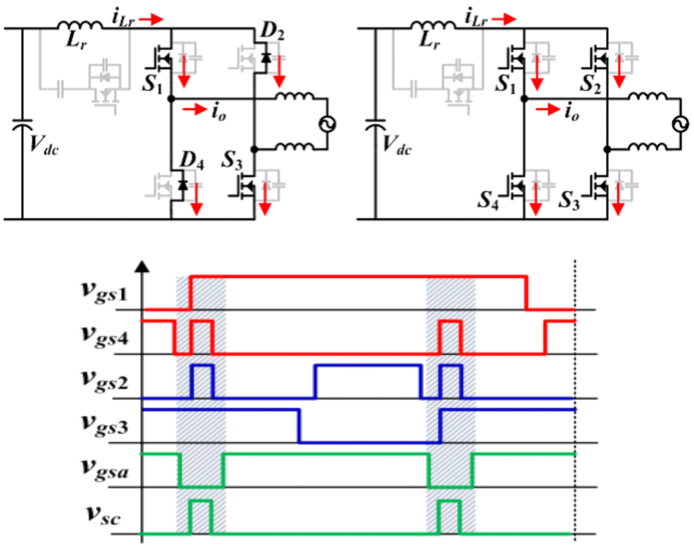


Fig. 8. (a) Charging circuit with bipolar SPWM (b) Charging circuit with proposed method (c) drive pulse of proposed method with DF SPWM

Equation (6) indicates that the actual direction of the resonant current iLr is reversed and its amplitude before the second resonant process must be charged larger than the sum of the load current and the resonant currents in the paralleled capacitors. A charging method with the reverse recovery current of diode is used in [10]. The main switches $S1$ and $S3$ are ZVS turned on after the resonant process in Fig. 6. The diodes $D2$ and $D4$ begin their reverse recovery stage and the resonant inductor is charged by the reverse recovery current.

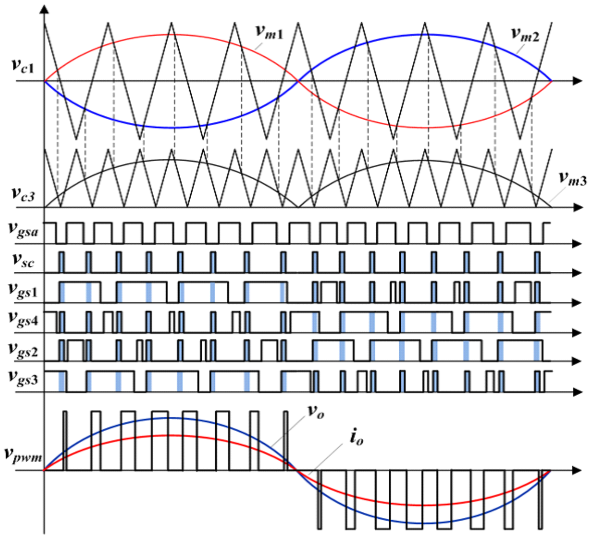


Fig. 9 Novel ZVS SPWM scheme

Comparing with the unipolar SPWM, DF SPWM has the advantage of lower current ripple and reduced harmonics [20], which is beneficial to reduce the filter. Hence the novel ZVS SPWM proposed in this paper is the combination of the DF SPWM and the short-circuit pulse. The switching sequence for unity power factor application is presented in Fig. 9.

RESEARCH METHODOLOGY (DIFFERENT PWM TECHNIQUES FOR SINGLE PHASE INVERTER)

A. Single pulse width modulation

In this control, there’s only one pulse per half cycle and the width of the pulse is varied to control the inverter output. The gating signals are generated by comparing a rectangular reference signal of the amplitude Ar with triangular carrier wave of amplitude Ac, the frequency of the carrier wave determines the fundamental frequency of output voltage. By varying Ar from 0 to Ac, the pulse width can be varied from 0 to 100 percent. The ratio of Ar to Ac is the control variable and defined as the modulation index.[1],[2],[5].

B. Multiple pulse width modulation

The harmonic content can be reduced by using several pulses in each half cycle of output voltage. The generation of gating signals for turning ON and OFF transistors by comparing a reference signal with a triangular carrier wave The frequency Fc, determines the number of pulses per half cycle. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation (UPWM).[1],[2].

C. Sinusoidal pulse width modulation (SPWM)

Instead of, maintaining the width of all pulses of same as in case of multiple pulse width modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The distortion factor and lower order harmonics are reduced significantly. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency Fc. The frequency of reference signal Fr ,determines the inverter output frequency and its peak amplitude Ar,controls the modulation index M,and Vrms output voltage VO.The number of pulses per half cycle depends on carrier frequency .[1],[13]. Inverters that use PWM switching techniques have a DC input voltage that is usually constant in magnitude. The inverters job is to take this input voltage and output ac where the magnitude and frequency can be controlled. There are many different ways that pulse-width modulation can be implemented to shape the output to be AC power. The duty cycle of the one of the inverter switches is called the amplitude modulation ratio, ma.

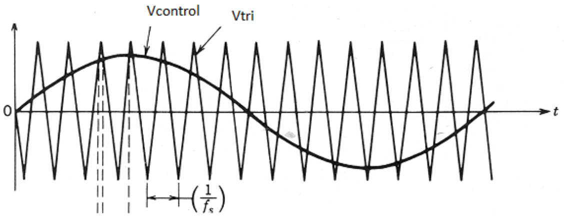
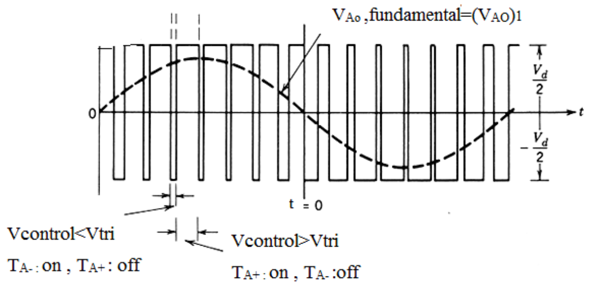


Fig. 2 – Desired frequency is compared with a triangular waveform



Pulse-width Modulation (PWM)

$$Ma = \frac{Vcontrol}{Vtri} \quad .... \ (1)$$

Where Vcontrol is the peak amplitude of control

$$M_f = \frac{fs}{f_1} \quad ....(2)$$

$$Vcontrol > Vtri\ Ta\_pos \text{ is on, } V_A = \frac{Vd}{2}$$
$$\ldots (3)$$
$$Vcontrol < Vtri\ Ta\_neg \text{ is on, } V_A = -\frac{Vd}{2}$$

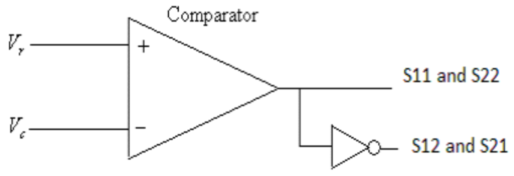
In fig. 3 the switches Ta+ and Ta- are controlled based on the comparison of v control and Vtri (See equation 3). The two switches are never off at the same time which results in the output voltage fluctuating between +/- Vd/2.[1],[7],[13].

III.SPWM Switching Techniques:

A. PWM with bipolar voltage switching
B. PWM with unipolar voltage switching

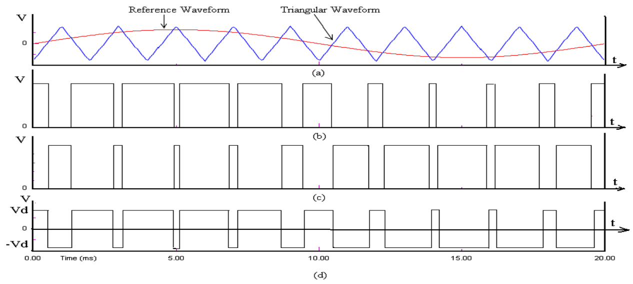
A.SPWM with Bipolar Switching:

The basic idea to produce PWM Bipolar voltage switching signal is shown in Fig. 4 . It comprises of a comparator used to compare between the reference voltage waveform V*r* with the triangular carrier signal Vc and produces the bipolar switching signal. If this scheme is applied to the full bridge single phase inverter as shown in Fig., all the switch S11, S21, S12 and S22 are turned on and off at the same time. The output of leg A is equal and opposite to the output of leg B.[3] The output voltage is determined by comparing the reference signal, Vr *and* the triangular carrier signal, Vc.



Bipolar PWM generator

In this scheme the diagonally opposite transistors S 11, S21, and S12 , S22 are turned on or turned off at the same time. The output of leg A is equal and opposite to the output of leg B. The output voltage is determined by comparing the control signal, Vr and the triangular signal, Vc as shown in Fig. 5 to get the switching pulses for the devices, and the switching pattern and output wave formis as follows.[2],[8].



SPWM with Bipolar voltage switching (a) Comparison between reference waveform and triangular waveform (b) Gating pulses for S1 and S4 (c) Gating pulses for S2 and S3 (d) Output waveform

Vr > Vc S11 is on === > Vao = Vd and

$$S_{22} \text{ is on} ==>>Vbo = -\frac{Vd}{2} \quad \text{... (4)}$$

$$Vr < Vc \quad S_{12} \text{ is on} ===>Vao = -\frac{Vd}{2} \text{ and}$$

$$S_{22} \text{ is on} ==>>Vbo = \frac{Vd}{2} \quad \text{.....(5)}$$

Hence,

$$Vbo\,(t) = Vao\,(t) \quad \text{.....(6)}$$

B. SPWM with Unipolar Switching:

In this scheme, the triangular carrier waveform is compared with two reference signals which are positive and negative signal. The basic idea to produce SPWM with unipolar voltage switching is shown in Fig. 6. The different between the Bipolar SPWM generators is that the generator uses another comparator to compare between the inverse reference waveform−Vr. The process of comparing these two signals to produce the unipolar voltage switching signal. The switching pattern and output waveform is as follows in Fig. 7

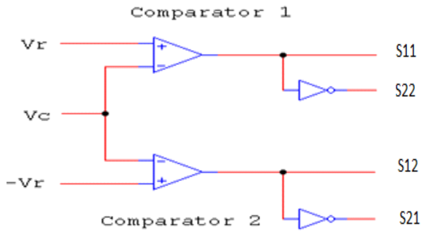


Fig. 6 Unipolar PWM generator

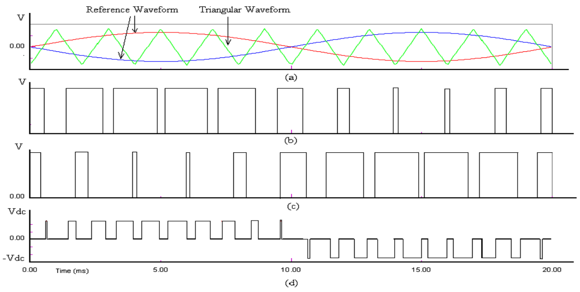


Fig. 7 Waveform for SPWM with Unipolar voltage switching (a) Comparison between reference waveform and triangular waveform (b) Gating pulses for S1 and S4 (c) Gating pulses for S2 and S3 (d) Output waveform

In this scheme, the devices in one leg are turned on or off based on the comparison of the modulation signal Vr with a high frequency triangular wave. The devices in the other leg are turned on or off by the comparison of the modulation signal – Vr with the same high frequency triangular wave.[2],[8]. The logic behind the switching of the devices in the leg connected to ‘a’ is given as,

$$Vr > Vc \quad S_{11} \text{ is on} ===>Van = \frac{Vd}{2} \text{ and}$$

$$Vr < Vc \quad S_{12} \text{ is on} ===>Van = -\frac{Vd}{2} \quad \text{... (7)}$$

and that in the leg connected to ‘b’ is given as

$$-Vr > Vc \quad S_{11} \text{ is on} ===>Vbn = \frac{Vd}{2}$$

$$-Vr > Vc \quad S_{11} \text{ is on} ===>Vbn = -\frac{Vd}{2} \quad \text{... (8)}$$

In Unipolar switching scheme the output voltage level changes between either 0 to –Vd or from 0 to +Vd. This scheme ‘effectively’ has the effect of doubling the switching frequency as far as the output harmonics are concerned, compared to the bipolar- switching scheme[1],[2],[,3],[12],.

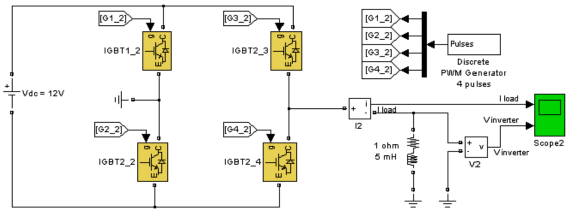


Fig.10 MATLAB Simulation model for ff unipolar voltage switching

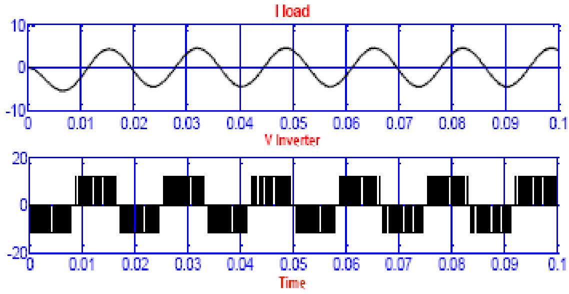


Fig.11Simulated result of unipolar voltage switching pulses

INTRODUCTION

Right by default Here you can give MATLAB commands typed at the prompt, >>. Unlike FORTRAN and other compiled computer languages, MATLAB is an **interpreted** environment—you give a command, and MATLAB tries to execute it right away before asking for another.

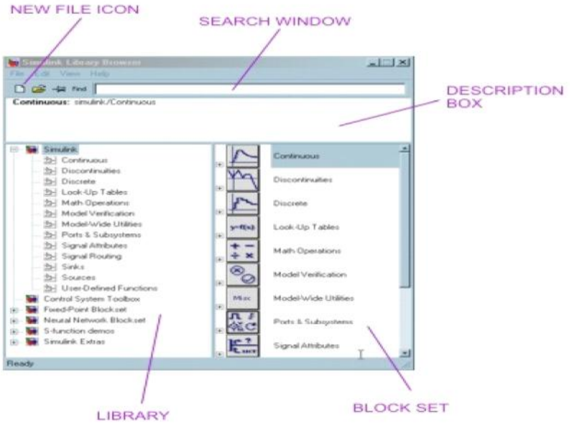
Graphical versus command-line usage

MATLAB was originally entirely a command-line environment, and it retains that orientation. But it is now possible to access a great deal of the functionality from graphical interfaces—menus, buttons, and so on. These interfaces are especially useful to beginners, because they lay out the available choices clearly.2 One does not always need to make a choice, though; for instance, it is possible to save a figure’s styles as a template that can be used with different data by pointing and clicking.

WHAT IS SIMULINK

Simulink (Simulation and Link) is an extension of MATLAB by Math works Inc. It works with MATLAB to offer modeling, simulating, and analyzing of dynamical systems under a graphical user interface (GUI) environment. The construction of a model is simplified with click-and-drag mouse operations. Simulink includes a comprehensive block library of toolboxes for both linear and nonlinear analyses. Models are hierarchical, which allow using both top-down and bottom-up approaches.

Getting Started

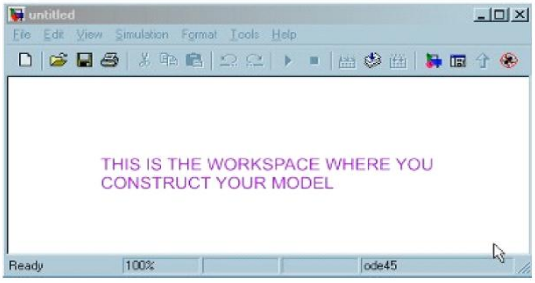


To see the content of the blockset, click on the "+" sign at the beginning of each toolbox.

To start a model click on the NEW FILE ICON as shown in the screenshot above.

Alternately, you may use keystrokes CTRL+N.

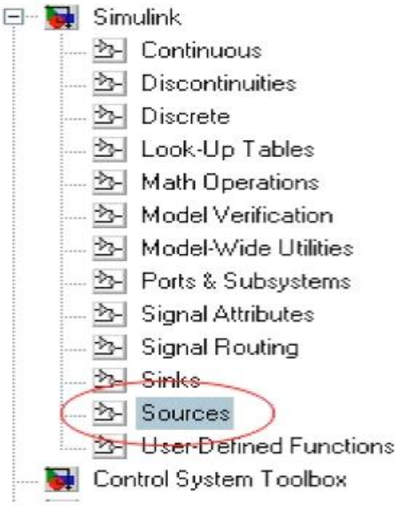
A new window will appear on the screen. You will be constructing your model in this window. A screenshot of a typical working (model) window that looks like one shown below:



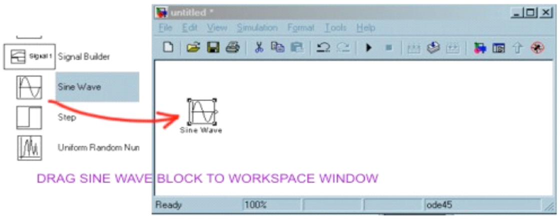
You may not know what they are all about but perhaps you could catch on the organization of these toolboxes according to the category. For instant, you may see Control System Toolbox to consist of the Linear Time Invariant (LTI) system library and the MATLAB functions can be found under Function and Tables of the Simulink main toolbox.

STEP 1: CREATING BLOCKS.

From BLOCK SET CATEGORIES section of the SIMULINK LIBRARY BROWSER window, click on the "+" sign next to the Simulink group to expand the tree and select (click on) Sources.



A set of blocks will appear in the BLOCKSET group. Click on the Sine Wave blockand drag it to the workspace window (also known as model window)



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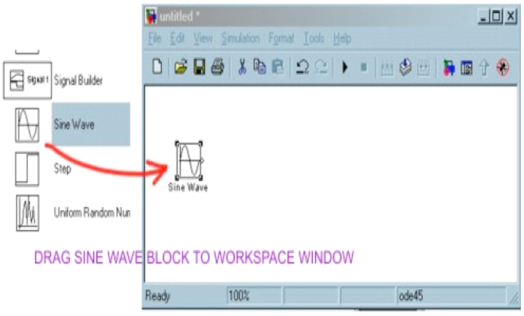
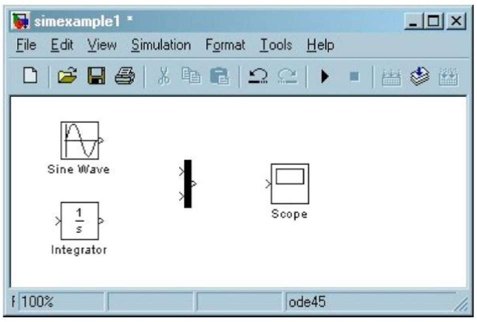


I am going to save this model under the filename: "simexample1". To save a model, you may click on the floppy diskette icon. Or from FILE menu, select Save or CTRL+S. All Simulink model file will have an extension ".mdl". Simulink recognizes file with .mdl extension as a simulation model (similar to how MATLAB recognizes files with the extension .m as an MFile).

Once all the blocks are dragged over to the work space should consist of the following components:



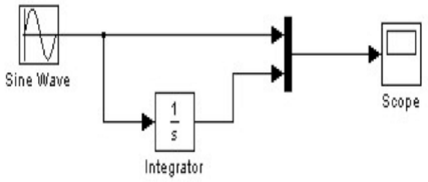
You may remove (delete) a block by simply clicking on it once to turn on the "select mode" (with four corner boxes) and use the DEL key or keys combination CTRL-X.

STEP 2: MAKING CONNECTIONS

To establish connections between the blocks, move the cursor to the output port represented by ">" sign on the block. Once placed at a port, the cursor will turn into a cross "+" enabling you to make connection between blocks.

To make a connection: left-click while holding down the control key (on your keyboard) and drag from source port to a destination port.

The connected model is shown below.

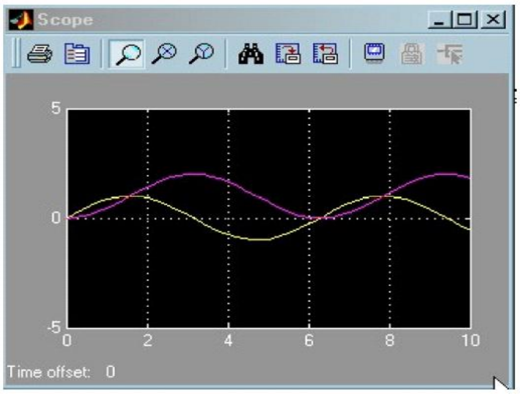


A sine signal is generated by the Sine Wave block (a source) and is displayed by the scope. The integrated sine signal is sent to scope for display along with the original signal from the source via the Mux, whose function is to multiplex signals in form of scalar, vector, or matrix into a bus.

STEP 3: RUNNING SIMULATION

You now can run the simulation of the simple system above by clicking on the play button (alternatively, you may use key sequence CTRL+T, or choose Start submenu under Simulation menu).

Double click on the Scope block to display of the scope.



The Role of simulation in design

Electrical power systems combine electrical circuits and electrical devices such as motors and generators. Engineers working on this discipline are constantly improving the performance of the systems.

Power requirements for power efficiency forced power system developers to use power electronic instruments and advanced control system concepts as tax conventional analysis tools and techniques. If the role of the analyst becomes more complicated, the system is often such a contradiction, the only way to understand is by simulation.

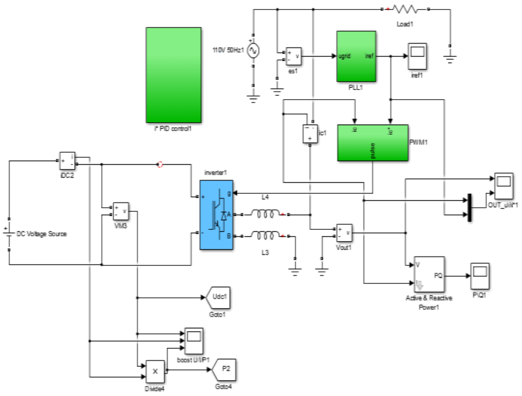
What is simpower system

SimPowerSystems is a modern design tool that allows scientists and engineers to build models that simulate electrical systems quickly and easily. SimPowerSystems uses the simulan environment, allowing you to create a model using simple clicks and drag systems. You can draw a faster circuit topology, but your analysis of the circuit has its interactions with mechanical, thermal, control and other components. This is possible because all electrical components of the simulation interact with an extensive simulation modeling library.

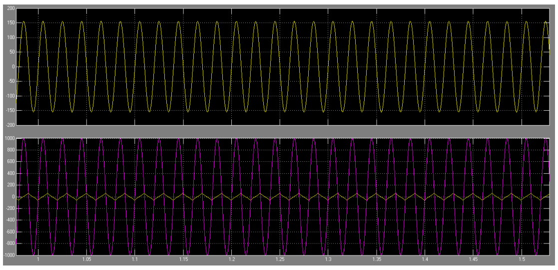
Nonlinear Simulink Blocks for Sim Power Systems Models

You must have the following products installed to use SimPowerSystems:

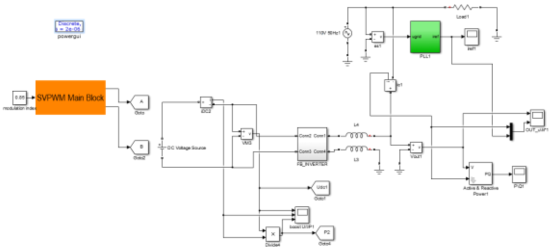
- MATLAB
- Simulink



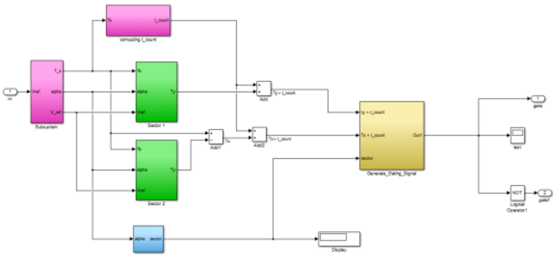
Simulation circuit of ZVS Full Bridge Inverter



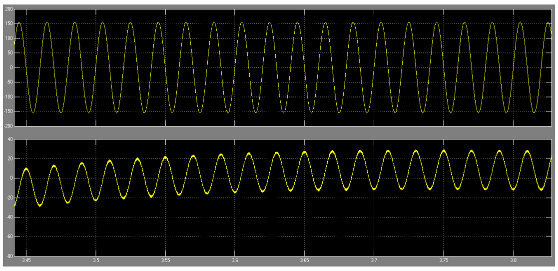
Grid side voltages and currents



Extension Simulation Circuit



Proposed SVPWM Scheme Simulation



Grid Voltages and Currents

CONCLUSION

A ZVS grid-connected full-bridge inverter with a novel ZVS SVPWM scheme is proposed in this paper. Both main switches and auxiliary switch can realize ZVS operation and the reverse recovery of the body-diode is relieved. Comparing with the existing ZVS full-bridge inverter, external parallel diodes are removed and smaller filter is used with higher switching frequency to save the cost and reduce the size. High efficiency from light load to heavy load is achieved by adjusting the resonant energy. The ZVS full-bridge inverter is attractive for high efficiency application such as residential PV systems.