Modelling Of Single Phase Off - Grid Inverter For Small Standalone System Applications

A THESIS SUBMITTED IN PARTIAL FULLFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

This paper presents the detail circuitry modeling of single phase off-grid inverter for small standalone system applications. The entire model is developed in MATLAB/Simulink platform using circuitry model. This off grid inverter consists of a high frequency DC-DC step up converter cascaded with a full bridge PI control voltage source inverter using SPWM modulation with LC filter to produce sine wave output. This is a common design used in many small commercial off-grid inverter. This off-grid inverter model is capable to produce AC sine wave output voltage at 230 V 50 Hz up to 1 kW power from a 48 V DC lead acid battery source. The AC sine wave output waveform achieved a voltage Total Harmonic Distortion (THD) of less than 1 % which is almost a pure sine wave. The conversion efficiency performance of the off-grid inverter achieved more than 94 %. The performance of the model is validated by real commercial off-grid inverter. The performance validation experiment shows that the off-grid inverter Simulink model conversion efficiency and THD performance are comparable to the commercial off-grid inverter. This model contributes to assist small to medium standalone system load and battery sizing design with greater accuracy.

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ABBREVATIONS USED

THD	TOTAL HARMONIC DISTORTION
PI CONTROLLER	PROPORTIONAL INTEGRAL CONTROLLER
PD CONTROLLER	PROPORTIONAL DERIVATIVE CONTROLLER
PID CONTROLLER	PROPORTIONAL INTEGRAL DIFFERENTIAL CONTROLLER
SPWM	SINUSOIDAL PULSE WIDTH MODULATION
MOSFET	METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTER

CHAPTER 1

INTRODUCTION

1.INTRODUCTION

Solar photovoltaic renewable energy has gained an exponential growth around the globe The is because the ease of installation and less maintenance due to no moving part involves in the photovoltaic system, besides that, the cost of the photovoltaic system has been reduced significantly throughout the years are that major factors that favour photovoltaic system as popular choices in the renewable energy industry.Power inverter is a power electronics converter that converts DC input voltage to AC output voltage with controlled output voltage magnitude and frequency. The inverter plays an important role in the renewable energy chain, it is an indispensable parts of solar photovoltaic and battery energy storage system.
Inverter has basically divided into three distinct categories, there are grid connected inverter, **off-grid inverter** and On/Off Grid Tie Inverter. Each inverter has there are own challenges.
The off-grid inverter basically uses in **standalone system**, the main challenges are to step up low DC battery voltage to AC supply voltage level in either single or three phase. It must be capable to maintain the AC output voltage magnitude and frequency under various load conditions within it rated power capacity.
Power inverter is a power electronics converter that converts DC input voltage to AC output voltage with controlled output voltage magnitude and frequency.
-->From the paper written by E.L.Owen, David Prince coined the term inverter. He explained that an inverter is used to convert direct current into single phase or poly phase alternating current.

Off-grid inverter basically consists of 2 stages of converter :
1) DC to DC voltage step up converter and DC to AC inverter with voltage PI control
2) LC filter to produce sine wave output.

<u>Each stage has its own challenges</u>
For the **first stage**, the DC to DC voltage step up conversion is carryout using the push-pull converter topology through a high frequency step up transformer and rectification. The high frequency push-pull converter topology has been commonly used as the first stages for many small to medium commercial off-grid inverter design.
The challenges are :

To step up the low battery DC voltage level with minimum losses, low footprint and weight of the components. There are literature proposed an interleaving push-pull converter which can produce high output voltage from a very low battery voltage input. The interleaved push-pull converter is a combination of multiple push-pull converters with transformer secondary rectifier connected in series for achieving the desired output voltage level.
-->According to the paper written by Wang J, it was mentioned about high efficiency interleaving push-pull converter with very low input voltage and high output voltage. The characteristics are high turns ratio, all transformers primaries in parallel and secondary output rectifiers in series.
The interleaved push-pull converter is a combination of multiple push-pull converters with transformer secondary rectifiers connected in series for achieving desired output voltage.
Another literature proposed to simplify the entire off-grid inverter by using only one stage of push-pull inverter to step up the voltage at switching frequency of 50 or 60 Hz. This significantly increases the size and weight of the transformer, and the AC output waveform is highly distorted and no longer sine wave
-->Shema S.S Daut presented a circuit design of push-pull topology inverter for photovoltaic applications. The inverter is a critical component responsible for control of the flow of electricity between the modules, battery and loads in any PV system.
There are other approaches by utilizing single or dual DC-DC boost converter topology to step the battery voltage to the desired voltage level in place of push-pull topology.
-->The other approaches are designed by Mao L. Chen, J. Deng, Thandar Aung, who proposed current fed half bridge front-end isolated dc/dc converter based inverter for PV applications. Zero current switching or natural communication of primary devices and zero voltage switching of secondary devices are achieved. This is a true isolated boost converter and has a higher voltage conversion ratio compared to the conventional active-clamped converter.
This approach reduces the use of step-up transformer and rectifier stage. However, it suffers from low efficiency and voltage magnitude stability to step up battery 12 V to 350 V and above.

The **second stage** is the DC to AC inverter where H-Bridge topology with either MOSFET or IGBT switching devices is commonly utilized. A Sinusoidal Pulse Width Modulation (SPWM) is use to switch the H-Bridge with LC filter to produce sine wave AC output waveform.
--> B.Ismail implemented a single phase sinusoidal pulse width modulation micro-controller based inverter for off-grid standalone system applications. The 200W designed prototype of the inverter was tested with the resistive load and was found that THD is less than 4% for voltage and 8% for current.
A PI feedback control is utilized for voltage or current control. There is literature proposed to have a very high switching frequency of 100 kHz for the push-pull inverter to step up the voltage followed by a 20 kHz SPWM switching frequency to switch the H-Bridge.
--> Nasrudin Abd, presented the design and implementation of low power stand-alone inverter for single PV module and 24V batteries input. The SPWM signals drive the full bridge single phase inverter through an onto counter gate. It is said that a very high switching frequency of 100 K Hz for the push-pull inverter to step up the voltage followed by 20 K Hz SPWM switching frequency to switch the H-Bridge.
--> Neil brown study demonstrates a high quality power of standalone inverter where by comparison between the power quality of standalone inverter with battery storage (off-grid) and power quality of the utility network. The outcome of the control scheme of the numerical model of standalone inverter has dynamic performance but also robustness under load variations.
It is assumed a constant voltage source and multi-level DC link is supply to the H-Bridge which does not reflect the actual inverter operation with battery.
--> R.Ramaprabha designed a 500W standalone PV system with reduced switch count multilevel inverter which a highly compatible standalone PV system with reduced switch count multi-level inverter to feed 500W AC Load with better power quality.

In summary the above introduction and literature's lack of performance analysis including conversion efficiency, total harmonic distortion and validation with reference to commercial off-grid inverter. The modeling details are not provided to make simulation reproducible. This paper intended to present the modeling of a complete single phase off-grid inverter commonly implements in commercial inverter. It consist of a

DC-DC 20 kHz high frequency step up converter and a H-Bridge inverter with 500 Hz SPWM and voltage PI feedback control.

1.1 OBJECTIVES OF WORK DONE

The overall objectives to be achieved in this study are:

1. It has to produce AC sine wave output voltage at 230V,50Hz up to 1Kw power from a 48V DC lead acid battery source.

2. The Total Harmonic Distortion for AC Sine Wave Output waveform should be achieved such that, it has to be less than 4%.

3. To maintain an efficiency of greater than 94% within a less period of time.

4. To show that the off-grid inverter Simulink model conversion efficiency and Total Harmonic Distortion performance are comparable to the commercial off-grid inverter.

5. It is ideal that this model contributes to assist small to medium standalone system load and battery sizing design with greater accuracy.

1.2 ORGANIZATION OF THE THESIS

The organization of the thesis as follows :

Chapter 2 : In this chapter, the major components used used in the circuit are discussed.

Chapter 3 : This chapter presets the mathematical modelling of a single phase or three phase off-grid inverter.

Chapter 4 : The various types of loads and various control structures are presented in this chapter

Chapter 5 : The final chapter gives the general conclusion and simulation results.

CHAPTER 2

CIRCUIT COMPONENTS

CHAPTER 2 : CIRCUIT COMPONENTS

The components that are used In the circuit are :

2.1 PI CONTROLLER :

A variation of Proportional Integral Derivative (PID) control is to use only the proportional and integral terms as PI control. The PI controller is the most popular variation, even more than full PID controllers. The value of the controller output.A P.I Controller is a feedback control loop that calculates an error signal by taking the difference between the output of a system, which in this case is the power being drawn from the battery, and the set point. The set point is the level at which we'd like to have our system running, ideally we'd like our system to be running near max power (990W) without causing the limiter to engage.

PI controller IS the controller gain, which is a multiplier on the proportional error and integral term and a higher value makes the controller more aggressive at responding to errors away from the set point. The set point (SP) is the target value and process variable (PV) is the measured value that may deviate from the desired value. The error from the set point is the difference between the SP and PV and is defined as overview of PI Control.

PI control is needed for non-integrating processes, meaning any process that eventually returns to the same output given the same set of inputs and disturbances. A P-only controller is best suited to integrating processes. Integral action is used to remove offset and can be thought of as an adjustable

2.2 H bridge circuit

A H-bridge is an electronic circuit that switches the polarity of a voltage applied to a load. These circuits are often used in robotics and other applications to allow DC motors to run forwards or backwards.

Most DC-to-AC converters (power inverters), most AC/AC converters, the DC-to-DC push–pull converter, isolated DC-to-DC converter[2] most motor controllers, and many other kinds of power electronics use H bridges. In particular, a bipolar stepper motor is almost always driven by a motor controller containing two H bridges.

2.3 LC FILTER :

An LC circuit, also called a resonant circuit, tank circuit, or tuned circuit, is an electric circuit consisting of an inductor, represented by the letter L, and a capacitor, represented by the letter C, connected together. The circuit can act as an electrical resonator, an electrical analogue of a tuning fork, storing energy oscillating at the circuit's resonant frequency.

LC circuit (left) consisting of ferrite coil and capacitor used as a tuned circuit in the receiver for a radio clock
LC circuits are used either for generating signals at a particular frequency, or picking out a signal at a particular frequency from a more complex signal; this function is called a bandpass filter. They are key components in many electronic circuits.

2.4 FULL BRIDGE INVERTER WITH PI CONTROLLER :

The full bridge inverter converts the DC output voltage from the full bridge rectifier to AC sine wave output. The full bridge inverter with voltage PI control in Simulink bridge inverter is implemented using the universal bridge block from the Simulink Simscape Electrical blockset library. In the universal bridge block, the number of the bridge is set to 2 and the power electronic device is set to MOSFET so that the universal block will configure as four MOSFETs H-Bridge circuit. The
H-Bridge is switch and driven by Sinusoidal Pulse Width Modulation (SPWM). The SPWM modulator carrier frequency is set to 500 Hz. The output of the H-Bridge is then filtered through a LC loW PASS FILTER.

2.5 DC TO DC STEP UP TRANSFORMER :-

DC – DC Converter Transformers are used in step-up or step-down converters. These transformers can be used in self-saturated or square wave driven applications and have input voltage ranges of 5V, 12V, 24V, and 48V and output Voltage up to 300 VDC.
When a d.c voltage source is applied across the primary of the transformer, the current in the primary coil remains constant. Hence there is no change in the magnetic flux linked with the secondary. ... Thus a transformer can't step up dc voltage.

The transformer itself is designed for one basic task, and that is to convert high and low voltages. A transformer is built to transfer the energy from one circuit into another circuit by way of magnetic coupling. It can convert high and low voltages, it cannot convert AC to DC.
A DC-DC charger is effectively a smart-charger for your 12V system. It isolates the house battery system from the alternator, so that the vehicle's computer management system sees it as something like a set of lights.
The basic DC-DC converter will take the current and pass it through a "switching element". This turns the signal into a square wave, which is actually AC. The wave then passes through another filter, which turns it back into a DC signal of the appropriate voltage necessary.
The buck converter is a very simple type of DC-DC converter that produces an output voltage that is less than its input. The voltage drop across an inductor is proportional to changes in electric current flowing through the device.

<u>2.6 FULL BRIDGE RECTIFER</u> :-

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The reverse operation is performed by the inverter. The process is known as rectification, since it "straightens" the direction of current.
Bridge Rectifiers use four diodes that are arranged cleverly to convert the AC supply voltage to a DC supply voltage. ... At the same time, the diodes D1 and D4 will be reverse biased and will not conduct. The current will flow through the load resistor via the two forward-biased diodes.
Full Wave Bridge Rectifier is used to detect the amplitude of the modulating radio signal. Bridge rectifier circuits are also used to supply steady and polarized Dc voltage in electric welding.
In Full Wave Bridge Rectifier, an ordinary transformer is used in place of a center-tapped transformer. The circuit forms a bridge connecting the four diodes D_1, D_2, D_3, and D_4.
This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop “bridge” configuration to produce the desired output.
One significant application of diodes is to convert AC power to DC power. In the bridge rectifier, four diodes are used to design the circuit

which will allow the full-wave rectification without using a center-tapped transformer. File:Three-phase bridge rectifier.
A bridge rectifier has a higher efficiency than a half-wave rectifier. But in some cases, the efficiency of the center-tapped full-wave rectifier and the bridge rectifier is the same. A smooth output is obtained from a bridge rectifier than the half-wave rectifier.

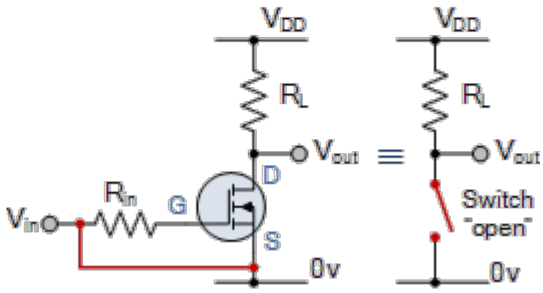
2.7 CAPACITIVE FILTER :

A capacitor-input filter is a filter circuit in which the first element is a capacitor connected in parallel with the output of the rectifier in a linear power supply. The capacitor is often followed by other alternating series and parallel filter elements to further reduce ripple voltage, or adjust DC output voltage.
A capacitor that is used to filter out a certain frequency otherwise series of frequencies from an electronic circuit is known as the filter capacitor. Generally, a capacitor filters out the signals which have a low frequency. The frequency value of these signals is near to 0Hz, these are also known as DC signals.
The types of capacitors that are commonly used for filtering applications in SMPSs include aluminum electrolytic capacitors, tantalum capacitors, film capacitors, and ceramic capacitors.
Using the simple capacitive filter in conjunction with a full-wave or bridge rectifier provides improved filtering because the increased ripple frequency decreases the capacitive reactance of the filter capacitor.
In the same way that capacitors can act as high-pass filters, to pass high frequencies and block DC, they can act as low-pass filters, to pass DC signals and block AC.
In a filter circuit the capacitor is charged to the peak of the rectified input voltage during the positive portion of the input. When the input goes negative, the capacitor begins to discharge into the load. The rate of discharge is determined by the RC time constant formed by the capacitor and the load's resistance..
When we connect a charged capacitor across a small load, it starts to supply the voltage (Stored energy) to that load until the capacitor fully discharges. Capacitor comes in different shapes and their value is measured in farad (F). Capacitors are used in both AC and DC systems.
A filter circuit is a device to remove the A.C components of the rectified output, but allows the D.C components to reach the load. ... A filter circuit is in general a combination of inductor (L) and Capacitor (C) called

LC filter circuit. A capacitor allows A.C only and inductor allows D.C only to pass.

<u>2.8 MOSFET SWITCH</u> :

MOSFET’s make very good electronic switches for controlling loads and in CMOS digital circuits as they operate between their cut-off and saturation regions.



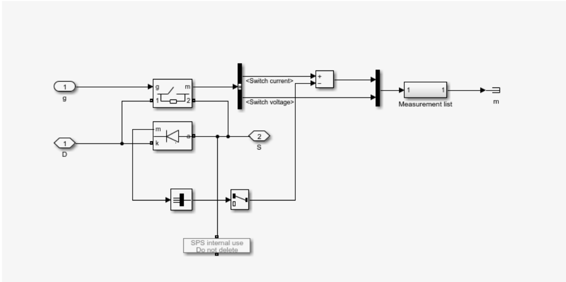
We saw previously, that the N-channel, Enhancement-mode MOSFET (e-MOSFET) operates using a positive input voltage and has an extremely high input resistance (almost infinite) making it possible to interface with nearly any logic gate or driver capable of producing a positive output.

We also saw that due to this very high input (Gate) resistance we can safely parallel together many different MOSFETS until we achieve the current handling capacity that we required.We now know that there are two main differences between field effect transistors, depletion-mode only for JFET’s and both enhancement-mode and depletion-mode for MOSFETs. In this tutorial we will look at using the *Enhancement-mode MOSFET as a Switch* as these transistors require a positive gate voltage to turn “ON” and a zero voltage to turn “OFF” making them easily understood as switches and also easy to interface with logic gates.The operation of the enhancement-mode MOSFET, or e-MOSFET, can best be described using its I-V characteristics curves shown below. When the input voltage, (V_{IN}) to the gate of the transistor is zero, the MOSFET conducts virtually no current and the output voltage (V_{OUT}) is equal to the supply voltage V_{DD}. So the MOSFET is “OFF” operating within its “cut-off” region.

<u>CHAPTER 3</u>

<u>Mathematical Modelling of 1- phase off grid inverter</u>

<u>CHAPTER 3 :</u> Mathematical Modelling off 1 phase or 3 phase OFF-GRID Inverter



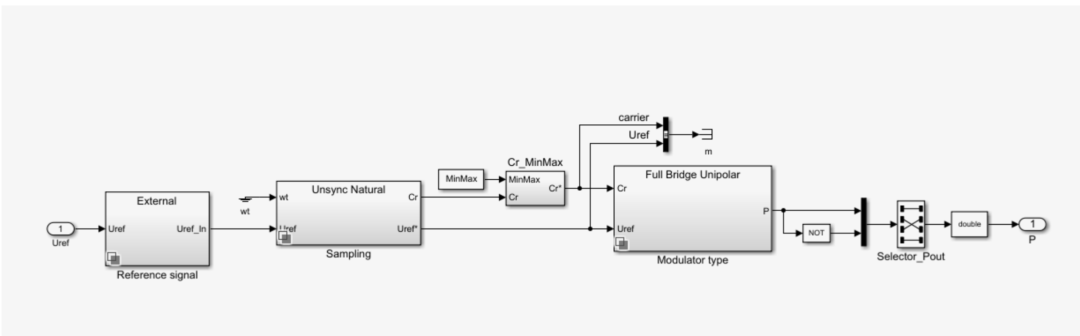
The metal-oxide semiconductor field-effect transistor (MOSFET) is a semiconductor device controllable by the gate signal (g > 0). The MOSFET device is co0nnected in parallel with an internal diode that turns on when the MOSFET device is reverse biased (Vds < 0) and no gate signal is applied (g=0). The model is simulated by an ideal switch controlled by a logical signal (g > 0 or g =0), with a diode connected in parallel.The MOSFET device turns on when a positive signal is applied at the gate input (g > 0) whether the drain-source voltage is positive or negative. If no signal is applied at the gate input (g=0), only the internal diode conducts when voltage exceeds its forward voltage Vf.
With a positive or negative current flowing through the device, the MOSFET turns off when the gate input becomes 0. If the current I is negative and flowing in the internal diode (no gate signal or g = 0), the switch turns off when the current I becomes 0.

The on state voltage Vds varies:

- Vds = Ron*I when a positive signal is applied at the gate input.
- Vds = Rd*I-Vf +Lon*dI/dt when the antiparallel diode is conducting (no gate signal).

The Lon diode inductance is available only with the continuous model. For most applications, Lon should be set to zero for both continuous and discrete models.

The MOSFET block also contains a series Rs-Cs snubber circuit that can be connected in parallel with the MOSFET (between nodes d and s)



Description

The Controlled PWM Voltage block represents a pulse-width modulated (PWM) voltage source. The block has two modeling variants, accessible by right-clicking the block in your block diagram and then selecting the appropriate option from the context menu, under **Simscape** > **Block choices**:

- **Electrical input ports** — The block calculates the duty cycle based on the reference voltage across its **ref+** and **ref-** ports. This modeling variant is the default.
- **PS input** — Specify the duty cycle value directly by using an input physical signal port.

For the **Electrical in0put ports** variant of the block, the demanded duty cycle is

$$100 * \frac{V_{ref} - V_{min}}{V_{max} - V_{min}} \textit{ percent}$$

where:

- V_{ref} is the reference voltage across the **ref+** and **ref-** ports.
- V_{min} is the minimum reference voltage.
- V_{max} is the maximum reference voltage.

The value of the **Output voltage amplitude** parameter determines amplitude of the output voltage.

At time zero, the pulse is initialized as high, unless the **Pulse delay time** parameter is greater than zero, or the demanded duty cycle is zero.

You can use parameters **Pulse delay time** and **Pulse width offset** to add a small turn-on delay and a small turn-off advance. This can be useful when fine-tuning switching times so as to minimize switching losses.

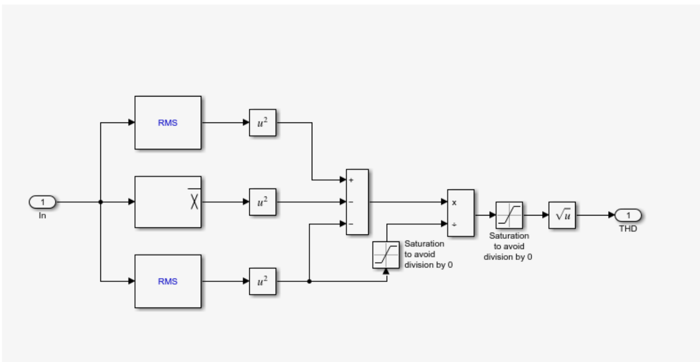
In PWM mode, the block has two options for the type of switching event when moving between output high and output low states:

- Asynchronous – Best for variable-step solvers — Asynchronous events are better suited to variable step solvers, because they require fewer simulation steps for the same level of accuracy. In asynchronous mode the PWM switching events generate zero crossings, and therefore switching times are always determined accurately, regardless of the simulation maximum step size.

- Discrete—time – Best for fixed-step solvers — Discrete-time events are better suited to fixed-step operation, because then the switching events are always synchronized with the simulation step. Using an asynchronous implementation with fixed-step solvers may sometimes result in events being up to one simulation step late.

If you use a fixed-step or local solver and the discrete-time switching event type, the following restrictions apply to the **Sample time** parameter value:

- The sample time must be a multiple of the simulation step size.
- The sample time must be small compared to the PWM period, to ensure sufficient resolution.



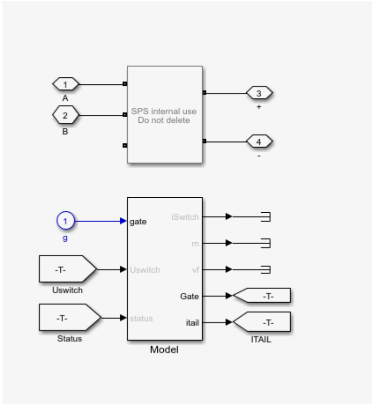
The THD block computes the total harmonic distortion (THD) of a periodic distorted signal. The signal can be a measured voltage or current.

The THD is defined as the root mean square (RMS) value of the total harmonics of the signal, divided by the RMS value of its fundamental signal. For example, for currents, the THD is defined as

$$\text{total harmonic distortion (THD)} = \frac{I(H)}{I(F)}$$

I_H=GI_{22}+I_{23}+…+I_{2n} I_n:RMS value of the harmonic nI_F:RMS value o f the fundamental current

The THD has a null value for a pure sinusoidal voltage or current.



The block has the following two **Simulation mode** options:

- PWM — The H-Bridge block output is a controlled voltage that depends on the input signal at the **PWM** port. If the input signal has a value greater than the **Enable threshold voltage** parameter value, the H-Bridge block output is on and has a value equal to the value of the **Output voltage amplitude** parameter. If it has a value less than the **Enable threshold voltage** parameter value, the block maintains the load circuit using one of the following three **Freewheeling mode** options:
    - Via one semiconductor switch and one freewheeling diode
    - Via two freewheeling diodes
    - Via two semiconductor switches and one freewheeling diode

  The first and third options are sometimes referred to as synchronous operation.

  The signal at the **REV** port determines the polarity of the output. If the value of the signal at the **REV** port is less than the value of the **Reverse threshold voltage** parameter, the output has positive polarity; otherwise, it has negative polarity.
- Averaged — This mode has two **Load current characteristics** options:
    - Smoothed
    - Unsmoothed or discontinuous

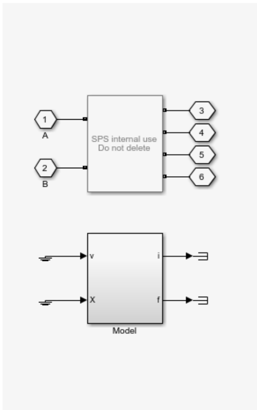
  The Smoothed option assumes that the current is practically continuous due to load inductance. In this case, the H-Bridge block output is:

  $$V_O V_{PWM} A_{PWM} - I_{OUT} R_{ON}$$

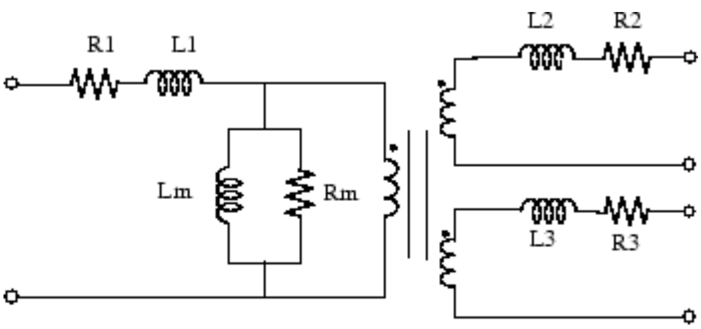
  where:

- V_O is the value of the **Output voltage amplitude** parameter.
- V_{PWM} is the value of the voltage at the **PWM** port.
- A_{PWM} is the value of the **PWM signal amplitude** parameter.
- I_{OUT} is the value of the output current.
- R_{ON} is the **Bridge on resistance** parameter.

The current will be smooth if the PWM frequency is large enough. Synchronous operation where freewheeling is via a bridge arm back to the supply also helps smooth the current. For cases where the current is not smooth, or possibly discontinuous (that is, it goes to zero between PWM cycles), use the Unsmoothed or discontinuous option. For this option, you must also provide values for the **Total load series resistance**, **Total load series inductance**, and **PWM frequency**. During simulation, the block uses these values to calculate a more accurate value for H-bridge output voltage that achieves the same average current as would be present if simulating in PWM mode.



The Linear Transformer block model shown consists of three coupled windings wound on the same core.



The model takes into account the winding resistances (R1 R2 R3) and the leakage inductances (L1 L2 L3), as well as the magnetizing characteristics of the core, which is modeled by a linear (Rm Lm) branch.

The Per Unit Conversion

In order to comply with industry, the block allows you to specify the resistance and inductance of the windings in per unit (pu). The values are based on the transformer rated power Pn, in VA, nominal frequency fn, in Hz, and nominal voltage Vn, in Vrms, of the corresponding winding. For each winding, the per unit resistance and inductance are defined as

$$R(pu)=\frac{R(\Omega)}{R_{base}}$$

$$L(pu)=\frac{L(H)}{L_{base}}$$

The base impedance, base resistance, base reactance, and base inductance used for each winding are

$$Z_{base}=R_{base}=X_{base}=\frac{(Vn)^2}{Pn}$$

$$L_{base}=\frac{X_{base}}{2\pi fn}$$

For the magnetization resistance Rm and inductance Lm, the pu values are based on the transformer rated power and on the nominal voltage of winding 1.

Equations

For the lead-acid battery type, the model uses these equations.

- Discharge Model (i* > 0)
- $f_1(it,i*,i,Exp)=E_0-K\cdot\frac{Q}{Q-it}\cdot i*-K\cdot\frac{Q}{Q-it}\cdot it+\text{Laplace}^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot 0\right)$
- Charge Model (i* < 0)

$$f_2(it,i*,i,Exp)=E_0-K\cdot\frac{Q}{it+0.1\cdot Q}\cdot i*-K\cdot\frac{Q}{Q-it}\cdot it+\text{Laplace}^{-1}\left(\frac{Exp(s)}{Sel(s)}\cdot\frac{1}{s}\right)$$

For the lithium-ion battery type, the model uses these equations.

- Discharge Model (i* > 0)

$$f_1(it,i*,i)=E_0-K\cdot\frac{Q}{Q-it}\cdot i*-K\cdot\frac{Q}{Q-it}\cdot it+A\cdot\exp(-B\cdot it)$$

- Charge Model (i* < 0)

$$f_2(it,i*,i)=E_0-K\cdot{}_{Qit+0.1\cdot Q}\cdot i*-K\cdot{}_{QQ-it}\cdot it+A\cdot\exp(-B\cdot it)$$

For the nickel-cadmium and nickel-metal-hydride battery types, the model uses these equations.

- Discharge Model (i* > 0)

$$f_1(it,i*,i,Exp)=E_0-K\cdot{}_{QQ-it}\cdot i*-K\cdot{}_{QQ-it}\cdot it+\text{Laplace}^{-1}\left({}_{Exp(s)Sel(s)}\right)\cdot 0$$

- Charge Model (i* < 0)

$$f_2(it,i*,i,Exp)=E_0-K\cdot{}_{Q\downarrow it\downarrow+0.1\cdot Q}\cdot i*-K\cdot{}_{QQ-it}\cdot it+\text{Laplace}^{-1}\left({}_{Exp(s)Sel(s)}\cdot{}_{1s}\right)\cdot$$

In the equations:

- E_{Batt} is the nonlinear voltage, in V.
- E_0 is the constant voltage, in V.
- *Exp(s)* is the exponential zone dynamics, in V.
- *Sel(s)* represents the battery mode. *Sel(s)* = 0 during battery discharge, *Sel(s)* = 1 during battery charging.
- *K* is the polarization constant, in V/Ah, or polarization resistance, in Ohms.
- *i** is the low-frequency current dynamics, in A.
- *i* is the battery current, in A.
- *it* is the extracted capacity, in Ah.
- *Q* is the maximum battery capacity, in Ah.
- *A* is the exponential voltage, in V.
- *B* is the exponential capacity, in Ah^{-1}

Temperature Effect Equations

For the lithium-ion battery type, the impact of temperature on the model parameters is represented by these equations.

- Discharge Model (i* > 0)

$$f_1(it,i*,i,T,T_a)=E_0(T)-K(T)\cdot{}_{Q(T^a)Q(T^a)-it}\cdot(i*+it)+A\cdot\exp(-B\cdot it)-C\cdot it$$

$$V_{batt}(T)=f_1(it,i*,i,T,T_a)-R(T)\cdot i$$

- Charge Model (i* < 0)

$$f_1(it,i*,i,T,T_a)=E_0(T)-K(T)\cdot{}_{Q(T^a)it+0.1\cdot Q(T^a)}\cdot i*-K(T)\cdot{}_{Q(T^a)Q(T^a)-it}\cdot it+A\cdot\exp(-B\cdot it)-C\cdot it$$

$$V_{batt}(T)=f_1(it,i*,i,T,T_a)-R(T)\cdot i,$$

with

$$E_0(T) = E_0\big|_{T_{ref}} + \frac{\partial E}{\partial T}(T - T_{ref})$$

$$K(T) = K\big|_{T_{ref}} \cdot \exp\left(\alpha\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$

$$Q(T_a) = Q\big|_{T_a} + \frac{\Delta Q}{\Delta T} \cdot (T_a - T_{ref})$$

$$R(T) = R\big|_{T_{ref}} \cdot \exp\left(\beta\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right),$$

where:

- T_{ref} is the nominal ambient temperature, in K.
- T is the cell or internal temperature, in K.
- T_a is ambient temperature, in K.
- E/T is the reversible voltage temperature coefficient, in V/K.
- α is the Arrhenius rate constant for the polarization resistance.
- β is the Arrhenius rate constant for the internal resistance.
- $\Delta Q/\Delta T$ is the maximum capacity temperature coefficient, in Ah/K.
- C is the nominal discharge curve slope, in V/Ah. For lithium-ion batteries with less pronounced discharge curves (such as lithium iron phosphate batteries), this parameter is set to zero.

The cell or internal temperature, T, at any given time, t, is expressed as:

$$T(t) = \mathcal{L}^{-1}\left(\frac{P_{loss}R_{th} + T_a}{1 + s \cdot t_c}\right),$$

where:

- R_{th} is thermal resistance, cell to ambient (°C/W).
- t_c is thermal time constant, cell to ambient (s).
- P_{loss} is the overall heat generated (W) during the charge or discharge process and is given by

$$P_{loss} = (E_0(T) - V_{batt}(T)) \cdot i + \frac{\partial E}{\partial T} \cdot i \cdot T.$$

Aging Effect Equations

For the lithium-ion battery type, the impact of aging (due to cycling) on the battery capacity and internal resistance is represented by these equations:

$$Q(n)=Q_{BOL}-\varepsilon(n)\cdot(Q_{BOL}-Q_{EOL})\ if\ k/2\neq 0\quad Q(n-1)\ otherwise$$

$$R(n)=R_{BOL}+\varepsilon(n)\cdot(R_{EOL}-R_{BOL})\ if\ k/2\neq 0\quad R(n-1)\ otherwise,$$ with

$$n=kT_h\ (k=1,2,3,\ldots\infty)$$

where:

- T_h is the half-cycle duration, in s. A complete cycle is obtained when the battery is discharged and charged or conversely.
- Q_{BOL} is the battery's maximum capacity, in Ah, at the beginning of life (BOL) and at nominal ambient temperature.
- Q_{EOL} is the battery's maximum capacity, in Ah, at the end of life (EOL) and at nominal ambient temperature.
- R_{BOL} is the battery's internal resistance, in ohms, at the BOL and at nominal ambient temperature.
- R_{EOL} is the battery's internal resistance, in ohms, at the EOL and at nominal ambient temperature.
- ε is the battery aging factor. The aging factor is equal to zero and unity at the BOL and EOL.

The battery aging factor, ξ, is expressed as

$$\varepsilon(n)=\begin{cases}\varepsilon(n-1)+\dfrac{0.5}{N(n-1)}\left(2-\dfrac{DOD(n-2)+DOD(n)}{DOD(n-1)}\right) & if\ k/2\neq 0\\ \varepsilon(n-1) & otherwise,\end{cases}$$

where:

- *DD* is the battery DOD (%) after a half-cycle duration.
- *N* is maximum number of cycles and is given by

$$N(n)=H\left(\frac{DOD(n)}{100}\right)^{-\xi}\cdot\exp\left(-\psi\left(\frac{1}{T_{ref}}-\frac{1}{T_a(n)}\right)\right)\cdot(I_{dis\_ave}(n))^{-\gamma_1}\cdot(I_{ch\_ave}(n))^{-\gamma_2},$$

where:

  - *H* is the cycle number constant (cycles).
  - ξ is the exponent factor for the DOD.
  - ψ is the Arrhenius rate constant for the cycle number.

- I_{dis_ave} is the average discharge current in A during a half cycle duration.
- I_{ch_ave} is the average charge current in A during a half cycle duration.
- γ_1 is the exponent factor for the discharge current.
- γ_2 is the exponent factor for the charge current.

CHAPTER 4

TYPES OF LOADS & CONTROLLERS

CHAPTER 4 : TYPES OF LOADS & CONTROL STRUCTURES

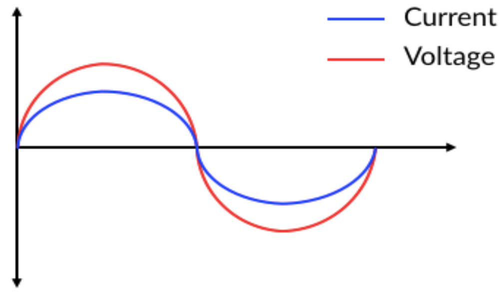
According To Load Nature :

- Resistive Electrical Loads.
- Capacitive Electrical Loads.
- Inductive Electrical Loads.

- Combination Electrical Loads

RESISTIVE LOAD

Load which consumes only active power is called as resistive load. And if you look at the voltage and current waveforms of such load, you'll find that, the voltage & current are perfectly in phase with each other.



Now when I say they are perfectly in phase, that means, both the waveforms reaches their peak value at the same time. They also reaches the zero value at the same time. One example is shown above.

As such type of load only consumes active power, power flows from Source to load only. There will be no power flowing from Load to source. Yes, in few cases power also flows from load to source.

As such loads only consumes active power, power factor of such loads is Unity! And which is a very good sign.

Example of Resistive load

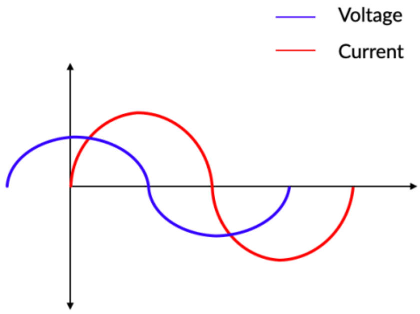
Example of resistive load are : Lights,Heaters Or any other loads that consist of only heating elements. Those are the examples of resistive load.

Properties of Resistive Load

1. This loads consumes only active power
2. Voltage & current waveform of such loads are perfectly in phase with each other.
3. Power factor of such load is unity
4. Power always flow from source to load

Inductive Load

Load which consumes only reactive power is called as inductive load. And if you look at the voltage and current waveforms of such load, you'll find that, the voltage & current are out of phase with each other by 90 degrees.



Now, when I say they out of phase, that means, both the waveforms reaches their peak value at different times. They also reaches the zero value at different times. If you look at the waveform you'll find that voltage has head start then the current. We can also say current is lagging behind the voltage. As such type of load only consumes reactive power, power can flow from Source to load or even load to source. Further, power factor of such loads is not Unity! Power factor of such loads is lagging in nature. And which is not a very good sign.

Example of Inductive Load

Few examples of inductive load are : Electric Motor, Fans, Washing machine, or anything that has a motor inside it. Also, Reactors used in power system is an example of inductive load.

Properties of Inductive loads

- This loads consumes only reactive power
- Voltage & current waveform of such loads are out of phase with each other by 90 deg.
- Power factor of such load is lagging
- Power flows from source to load and load to source

This type of loads are not easy loads as the resistive loads. They creates lot of problem in the system. But of course they are equally important. Since, current lags behind the voltage by 90 deg in such type of loads, that makes switching of such load difficult. As we know, circuit breaker opens at current zero condition. If you look at the current & voltage waveforms of such load you'll find that, when current is zero, voltage is maximum.And hence, when circuit breaker opens at current zero, voltage across the breaker contact is maximum. Whereas, in case of resistive load both current & voltage becomes zero at same time.

Therefore, switching such type of inductive loads is critical.Such type of load also affects the power factor of system heavily. And hence, electricity bill goes up.

Capacitive Load

Capacitive load is similar to that of inductive load. In capacitive loads also, current & voltage are out of phase with each other. The only difference is that, in capacitive load current leads the voltage by 90 deg. Whereas, in inductive load current lags behind the voltage by 90 deg.

VARIOUS CONTROLLERS

Controllers

A controller is a mechanism that minimize the difference between the actual value of a system (i.e. the process variable) and the desired value of the system (i.e. the setpoint).
Uses of controllers:

1. Controllers improve the steady-state accuracy by decreasing the steady state error which improves the stability
2. They reduces the unwanted offsets produced by the system and also control the maximum overshoot of the system.
3. They reduces the noise signals and can also help to speed up the slow response of an overdamped system.

The various types of controllers are used to improve the performance of control systems

Types of Controllers

1. Proportional controllers.
2. Integral controllers.
3. Derivative controllers

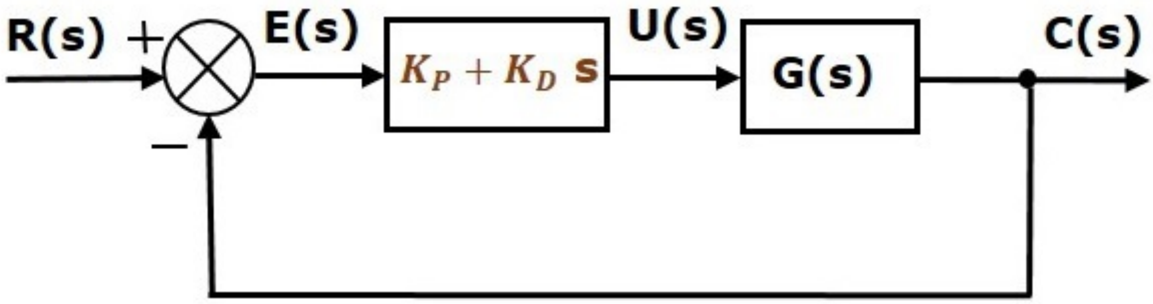
As there are some disadvantages using these controllers alone like they increase maximum overshoot of the system,instability,slow response etc . so combination of these modes are used to control the system
There are three types of controllers can be combined into new controllers they are:

1. Proportional and integral controllers (PI Controller)

2. Proportional and derivative controllers (PD Controller)
3. Proportional integral derivative control (PID Controller)

PD Controller

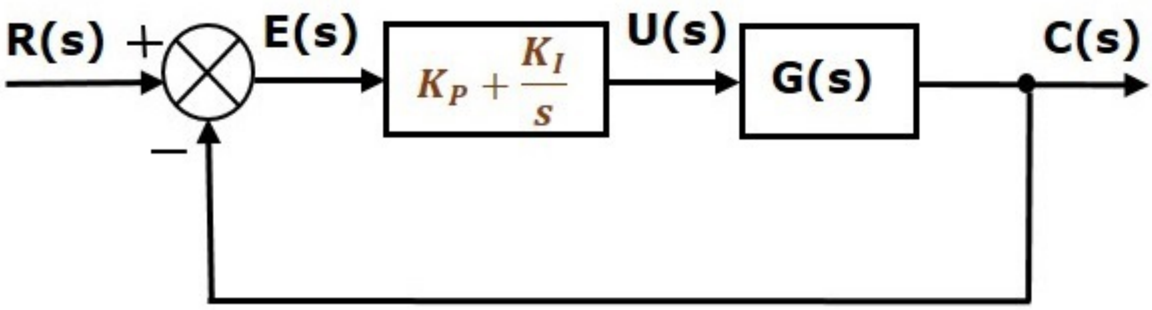
PI controller is combination of propotional derivative controller



The transfer function of the proportional derivative controller is KP+KDS
PD controller thus adds a single zero to the loop transfer function.
PD-control correlates the **controller** output to the error and the derivative of the error
To control the steady-state error, the derivative gain Kd must be high. This decreases the response times of the **system** and can make it susceptible to noise. Improves damping and maximum overshoot. Reduces rise time & settling time.

PI controller

PI controller is combination of propotional integral controller.



The transfer function of proportional integral controller is KP+KI/S
PI control is a form of feedback control**,** It provides a faster response, stops the system from fluctuating, and it is also able to return the system to its set point.

It can be used to avoid large disturbances and noise presents during operation process

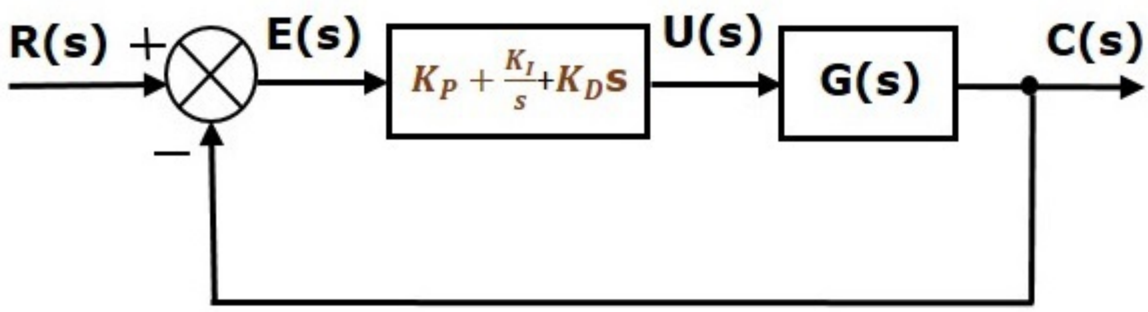
The proportional integral controller is used to decrease the steady state error without affecting the stability of the control system._

The most simple and often most effective controller

The controller maintains the output load voltage at the desired value to supply the power for a variety of loads with a minimum THD. The parameters of the PI controller were adjusted for the minimal total harmonic distortion (THD) .

PID Controller

PID is the combination of propotional integrated derivative controllers.



The transfer function of the proportional integral derivative controller is KP+KIs+KDsKP+KIs+KDs.

It is a control loop feedback mechanism generally used in industrial control applications to regulate temperature, flow, pressure, speed, and other process variables.

It is widely employed because it is very understandable and because it is quite effective.

PID controllers for plants with under-damped step response and provides the means for a systematic adjustment of the controller gain in order to meet transient performance specifications

It is used when dealing with higher order capacitive processes

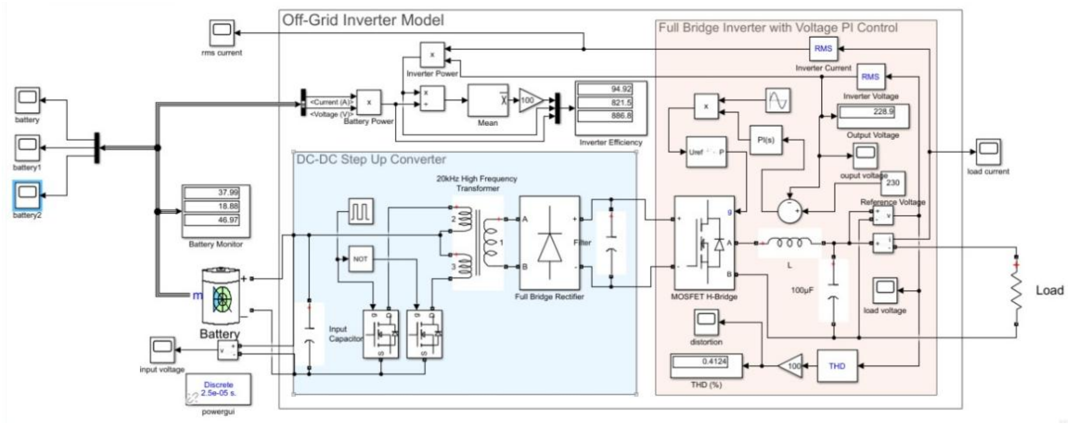
The PI and PID controllers are usually employed in the industrial micro-inverters . The popularity of these well-known controllers is determined by the easy implementation, efficiency, with min THD and well-developed tuning techniques of controller parameters.

CHAPTER 5

SIMULATION RESULTS

CHAPTER 5 : SIMULATION RESULTS

The entire off-grid inverter model is developed using MATLAB/Simulink platform with Simscape Electrical blocksets. The completed model is then tested and simulate under Simulink environment for performance analysis. The complete overview of the off-grid inverter model in Simulink is shown.



SIMULINK MODEL OF AN OFF GRID INVERTER

<u>SIMULATION RESULTS DISPLAYING FOR VARIOUS LOADS :</u>

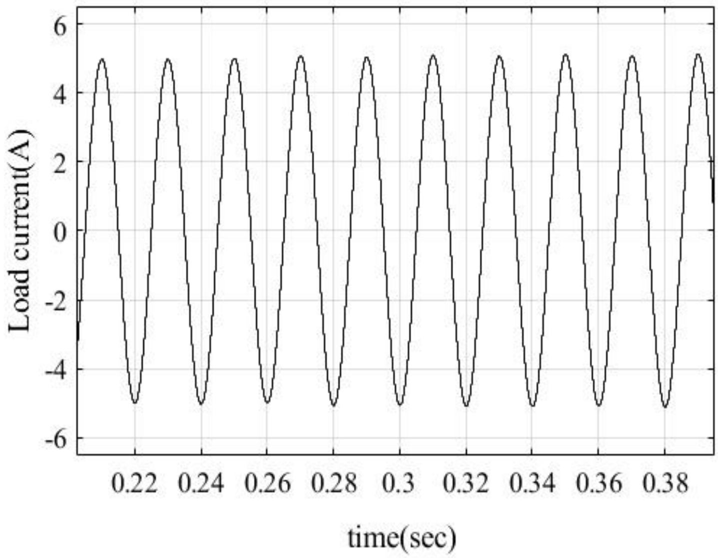
1) LOAD CURRENT FOR R LOAD,RL LOAD,RC LOAD,RLC LOAD

2) LOAD VOLTAGE FOR R LOAD,RL LOAD,RC LOAD,RLC LOAD

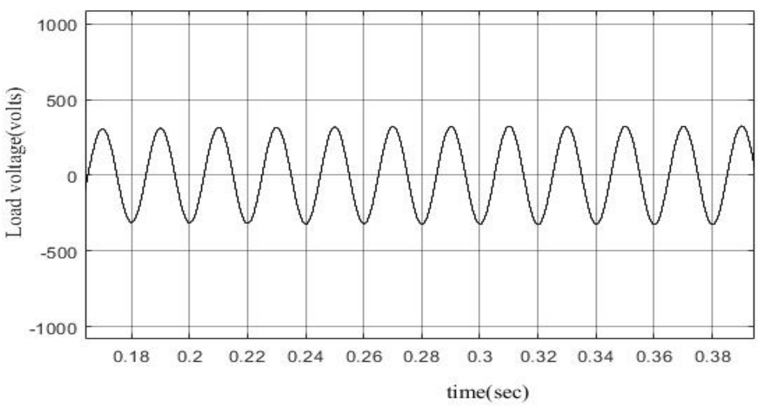
3) TOTAL HARMONIC DISTORTION FOR R LOAD, RL LOAD, RLC LOAD

<u>FOR R - LOAD</u>

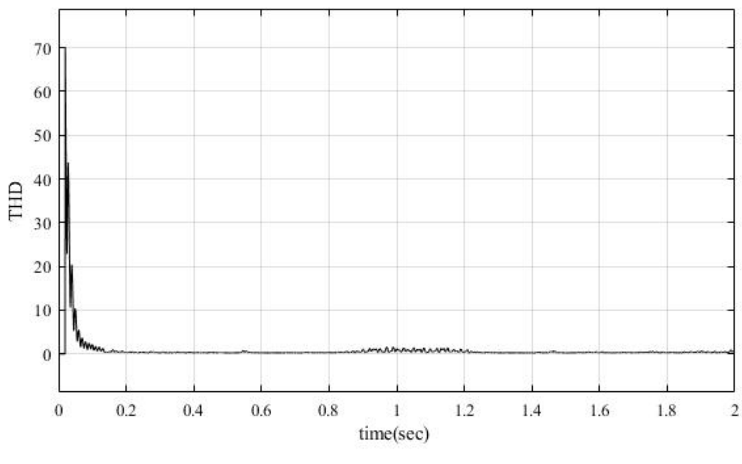
LOAD CURRENT AT R-LOAD



LOAD VOLTAGE AT R-LOAD

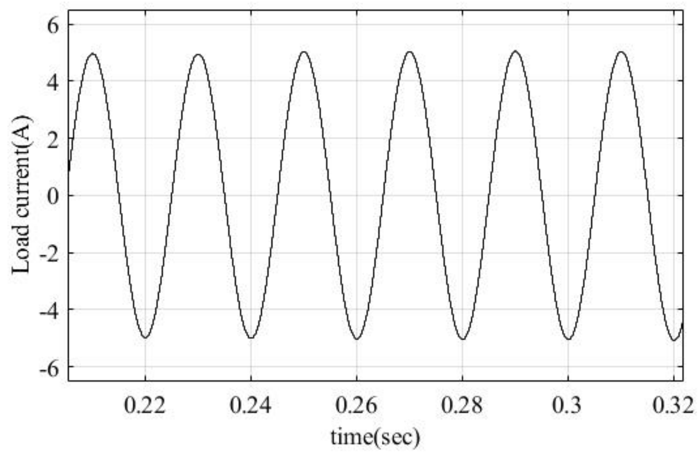


TOTAL HARMONIC DISTORTION AT R-LOAD

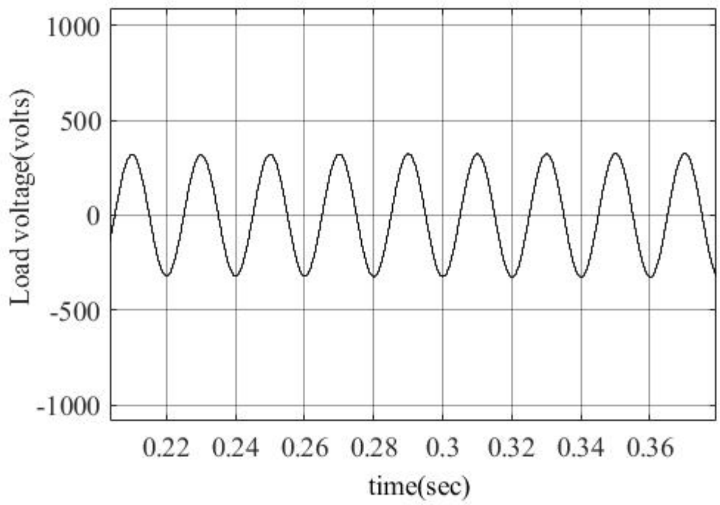


FOR RL-LOAD

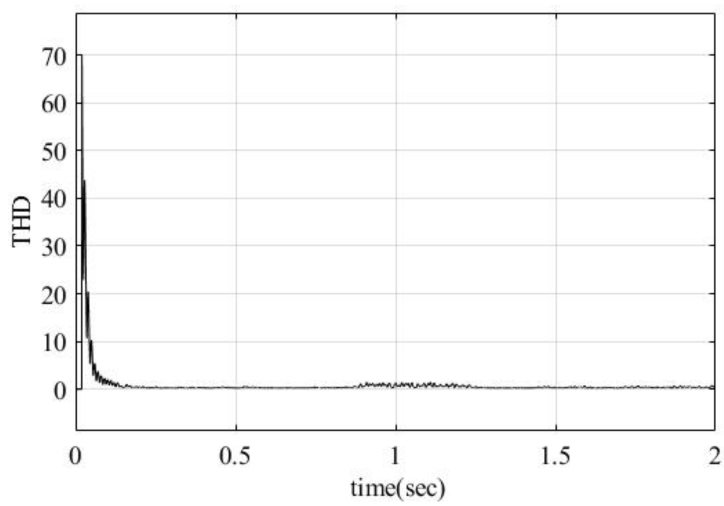
LOAD CURRRENT FOR RL-LOAD



LOAD VOLTAGE FOR RL-LOAD

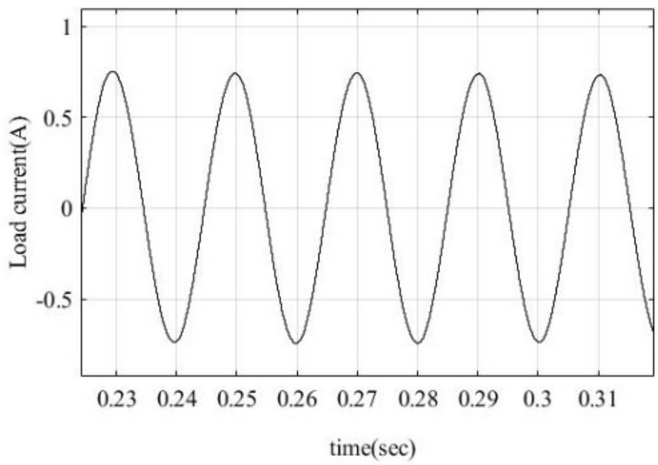


TOTAL HARMONIC DISTORTION AT RL-LOAD

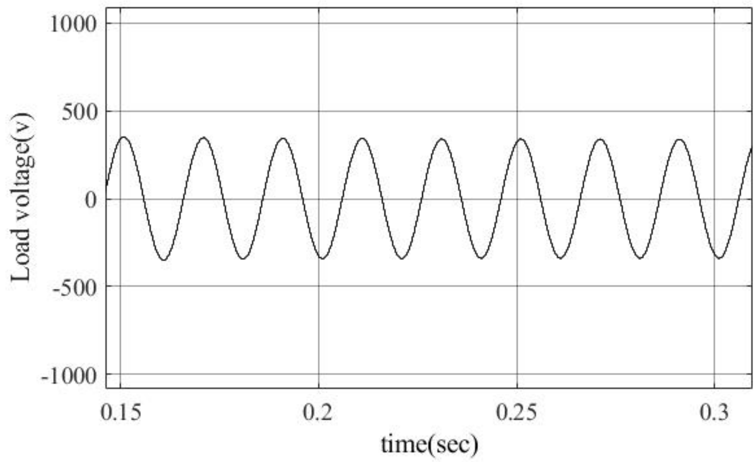


For RC-LOAD

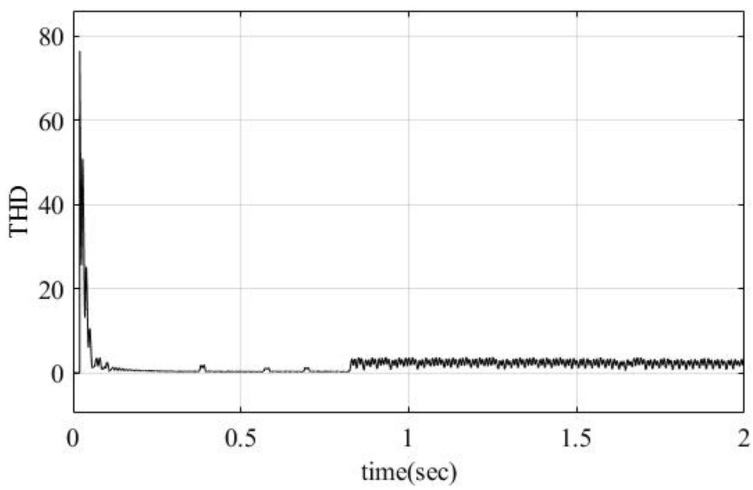
LOAD CURRENT AT RC-LOAD



LOAD VOLTAGE AT RC-LOAD

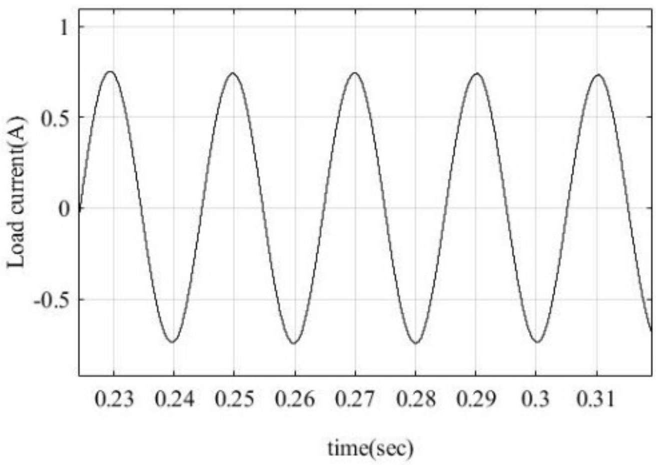


TOTAL HARMONIC DISTORTION AT RC-LOAD

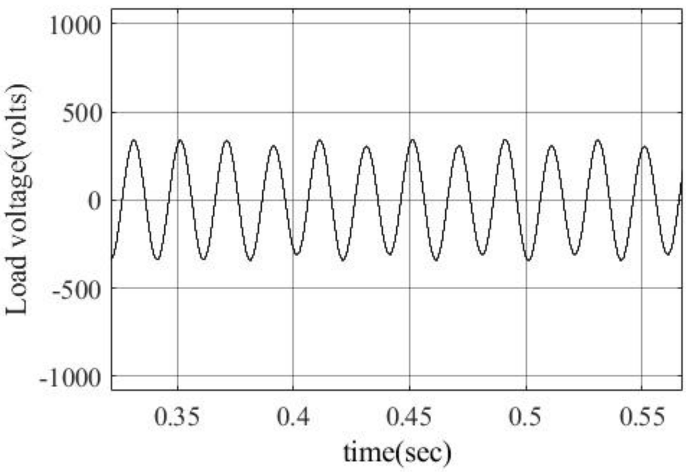


<u>For RLC LOAD</u>

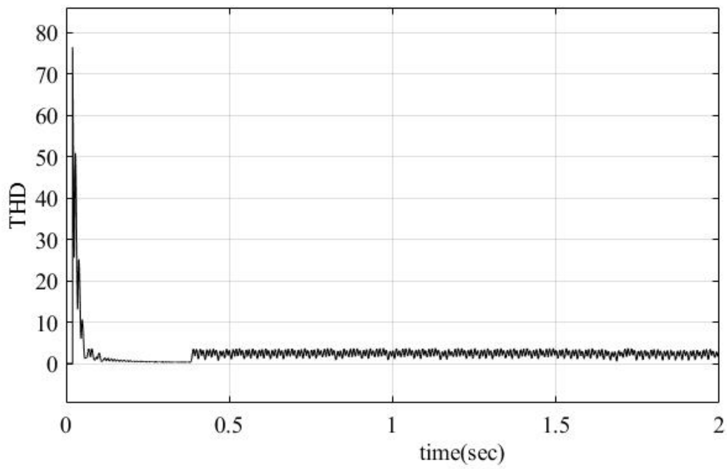
LOAD CURRENT FOR RLC LOAD



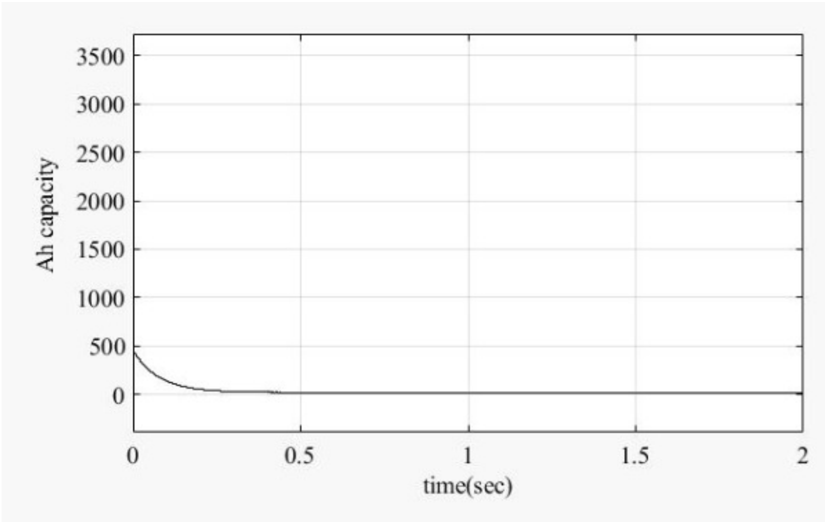
LOAD VOLTAGE FOR RLC LOAD



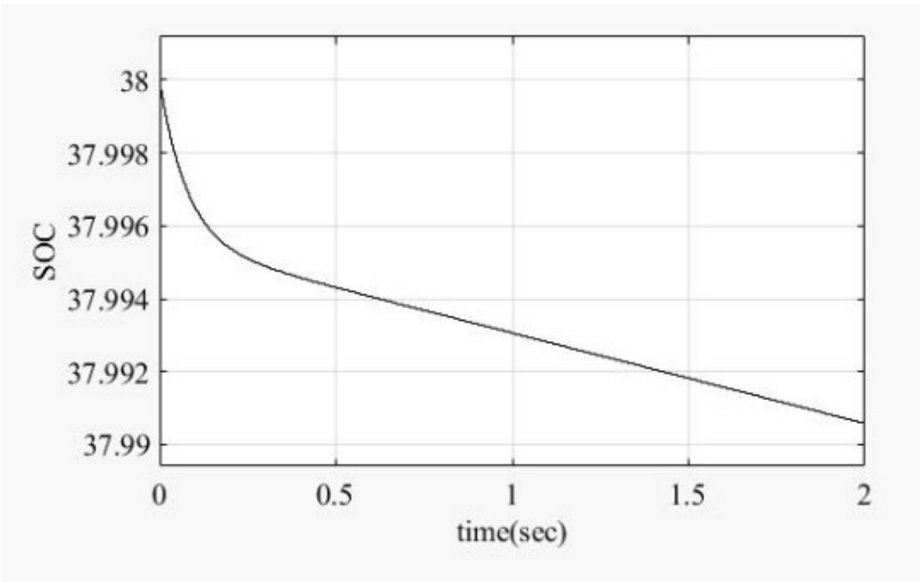
TOTAL HARMONIC DISTORTION FOR RLC LOAD



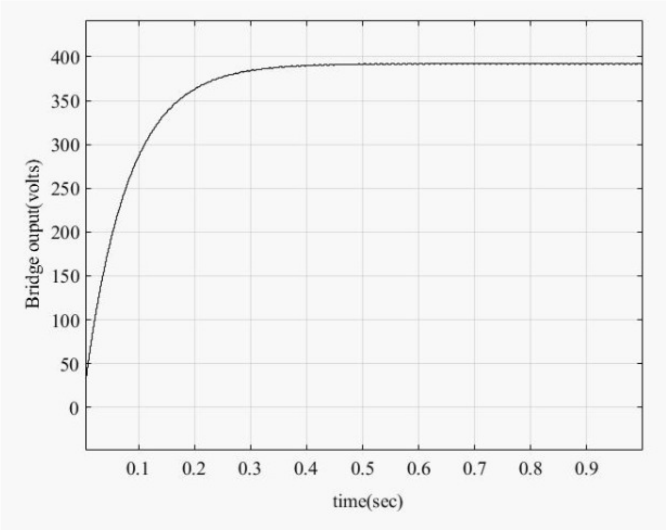
Amp - Hour capacity



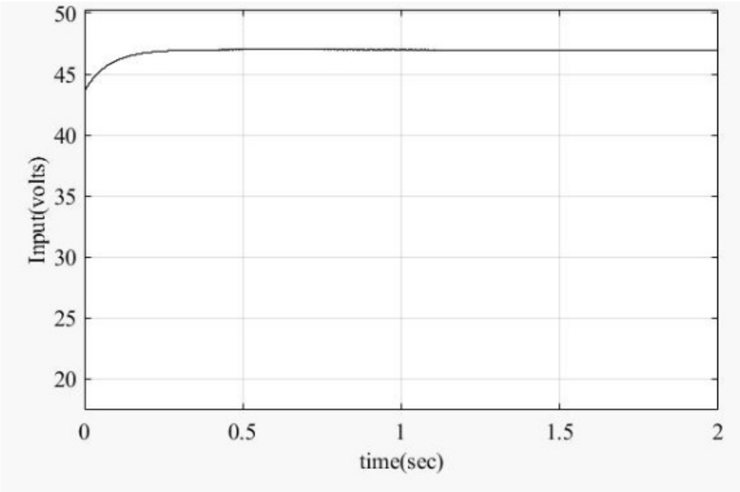
State of Charge



Bridge Output



Input Voltage



RESULTS

LEAD - ACID BATTERY

	R-LOAD	RL-LOAD
Load Voltage (V)	325	325
Load Current (A)	5	5
Total Harmonic Distrotion (THD)	0.412	0.2877
Inverter Efficiency	94.92	94.92
RMS Voltage	228.9	229.7

LITHIUM - ION BATTERY

	R-LOAD	RL-LOAD
Load Voltage (V)	325	325
Load Current (A)	5	5
Total Harmonic Distrotion (THD)	0.412	0.2877
Inverter Efficiency	94.92	94.92
RMS Voltage	228.9	229.7

LEAD - ACID BATTERY

	RC-LOAD	RLC-LOAD
Load Voltage (V)	314	314
Load Current (A)	1	1
Total Harmonic Distrotion (THD)	2.631	3.372
Inverter Efficiency	88.41	87.62
RMS Voltage	222.3	227.9

LITHIUM-ION BATTERY

	RC-LOAD	RLC-LOAD
Load Voltage (V)	314	314
Load Current (A)	1	1
Total Harmonic Distrotion (THD)	2.631	3.372
Inverter Efficiency	88.41	87.62
RMS Voltage	222.3	227.9

COMPARISION BETWEEN LEAD-ACID & LITHIUM ION BATTERIES

	LEAD - ACID	LITHIUM - ION
Load Voltage (V)	325	325
Load Current (A)	5	5
Total Harmonic Distrotion (THD)	0.412	0.412
Inverter Efficiency	94.92	94.92
Input Voltage	48	48

CONCLUSION

A detail circuitry modeling of an off-grid inverter model in Simulink is presented. Each stage of the off-grid inverter modeling are clearly illustrated and are fully reproducible. The off-grid inverter uses a 20 kHz high frequency transformer push-pull inverter to step up the battery 48 VDC to 400 VAC and convert back to DC through a full bridge rectifier. The 400 VDC is then converted to 230 VAC 50 Hz sinewave through H-bridge inverter with Sinusoidal Pulse Width Modulation and LC filter. The output voltage is control and maintains by PI feedback control. The off-grid inverter model is capable of converting a 48 V from a lead acid battery source to 230 V 50Hz up to a power rating of 1000 W. It achieved an average conversion efficiency of ≥94 % and produces sinewave output waveform with THD of less than 1 %.
Single PI Controller can be applicable for various loads.
An off-grid inverter is majorly designed for single load alone as per the researchers, but we designed for multiple loads with a single controller.

The performance of the Simulink model is also validated with the commercial off-grid inverter. The Simulink model presented can be flexibly changed to meet the commercial inverter with similar topology. This model contributes to assist small to medium standalone system load and battery sizing design with greater accuracy.

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