MULTI-MODE CONTROL BASED CURRENT-FED FULL-BRIDGE DC-DC CONVERTER FOR ELECTRIC VEHICLES

A Major project report submitted

in partial fulfillment of requirements for the award of degree

BACHELOR OF TECHNOLOGY

in

ELECTRICAL AND ELECTRONICS ENGINEERING

by

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CERTIFICATE

This is certify that this project entitled **"Multi-mode Control-fed Full-Bridge DC-DC Converter for Electric Vehicles"** is the bonafide work carried out by **AYESHA SIDDIKA, THALLAPALLY RAMYA SRI, CHERUPELLI ANVESH** bearing roll numbers **(180171244L), (17017T1235), (17017T1210)** during the Academic year 2020-2021 in partial fulfill,ment of the award of the degree **BACHELOR OF TECHNOLOGY in ELECTRICAL AND ELECTRONICS ENGINEERING** from **UCE KU Kothagudem** under the supervison guidence of

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ABSTRACT

In order to achieve high efficiency across wide load range, this project develops a multi-mode control strategy for DC-DC converter in electric vehicle on-board charger. The control strategy consists of three individual specific operation mode and one of them is implemented to obtain local high efficiency according to real-time load situation. Current-fed full-bridge is used as the topology to demonstrate the strength of this multi-mode control strategy. The performance of multi-mode based current-fed full-bridge converter will be observed in terms of peak efficiency.

CHAPTER 1

INTRODUCTION

1.1 General

In recent years, fast developments appear in the technology of motor drive and battery management for electric vehicles. As the main propulsion source for electric vehicles, battery needs to be repeat charged with highly reliable and efficient charging devices after it runs out of power. For now, the charging devices for electric vehicles can be classified as AC charger and DC charger, also known as slow charger and fast charger [1-2]. AC charger is normally AC-DC converter with power rating below 15kW and usually used in commercial and residential applications. As for the DC charger with power rating below 250kW, it suits fast charging applications more, like highway charging station and some other applications. Commonly speaking, the architectures of AC chargers are AC-DC converters with power factor correction functions and galvanic isolated DC-DC converter. As the main propulsion source of electric vehicles, charging characteristics of Li-ion battery consist of three stages which are trickle charring, constant current charging and constant voltage charging.

In order to improve the overall energy efficiency, the DC-DC part in AC charger needs to keep high efficiency in pretty wide load range. Literature [3-4] discuss the high efficiency PWM full-bridge converter based on phase shift method. Soft-switching is achieved by resonance between external inductor or leakage inductor and parasitic capacitance of power device. But, the oscillation of secondary side diodes is severe, also duty cycle loss issue exists. Literature [5-10] make some improvements against issues mentioned above and efficiency of full-bridge converter is further enhanced. Literature[11-13] address the so-called current-fed full-bridge converter with capacitive output filter. The dissipation and oscillation of secondary side diodes are tremondously reduced due to the effective serial connection of leakage inductance from transformer and external inductance. Literature[14-15] address the limited soft-switching range issue and provide several solutions to improve this issue. Most of the above research work focus on hardware architecture

refinement to improve conversion efficiency, which performs well at a single point of load or a section of load range. However, wide load range high efficiency can not be guaranteed. This paper investigates a multi-mode control strategy which implements different control approach at different section of load range. These individual control approaches are inherently highly efficient for certain load range, which contributes to high overall conversion efficiency for wide load range.

1.2 CURRENT-FED FULL-BRIDGE CONVERTER

As a vital part of on-board AC charger for electrical vehicles, it is quite necessary to achieve high efficiency across wide load range for DC-DC stage. Fig.1 shows the topology of proposed current-fed full-bridge converter with capacitive output filter and related waveforms of this converter. S1-S4 are power MOSFET, D1-D4 are corresponding anti-parallel body-diode, while C1-C4 are parasitic output capacitance. D5and D6 are ultra-fast recovery diodes. The external resonant inductor of primary side is used to creat conditions for soft-switching of primary switching devices. The converter works properly by modulating duty cycle of S1, S2 with 50% complementary drive of S3, S4. Meanwhile, voltage of secondary diodes is clamped at the level of output voltage, reducing oscillation a lot.

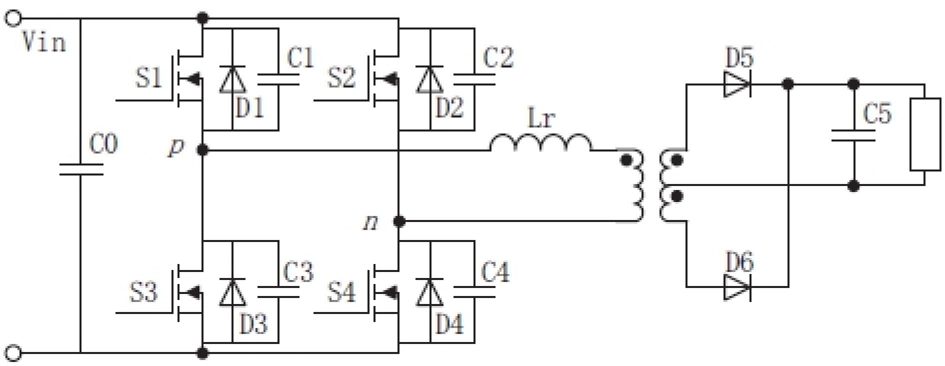


Fig 1.2.1 Circuit Diagram

In this paper, proposed converter is designed to operate under BCM (Boundary Conduction Mode) at full load in order to achieve soft-switching and relatively small RMS value of inductor current. When the load reduces, the converter goes to DCM (Discontinuous Conduction Mode). In this mode, switching frequency is lowered to reduce switching loss and improve efficiency. Fig.1.2.2 describes operation modes of BCM for the converter.

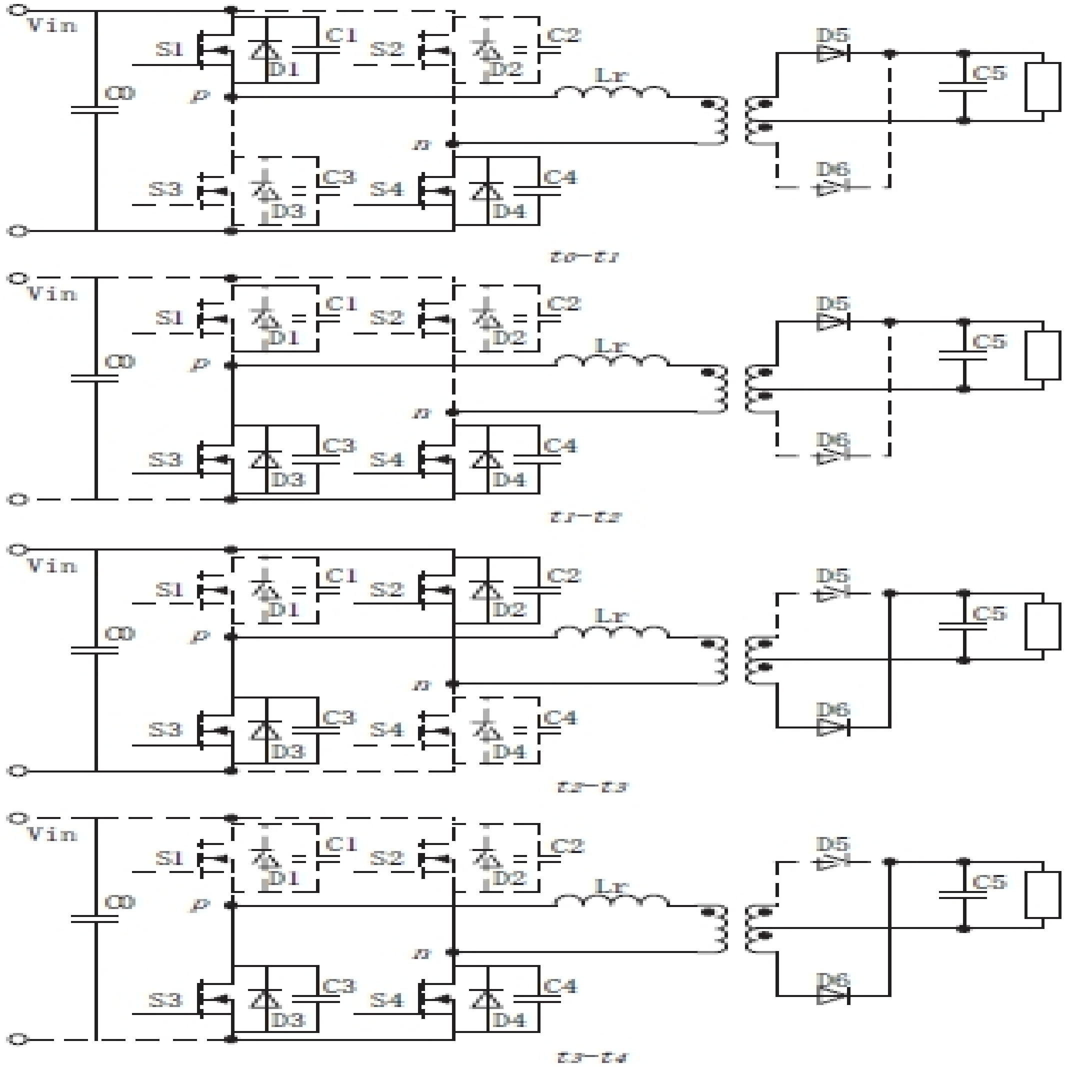


Fig. 1.2.2 Converter operation modes under BCM

Due to the similarity of DCM and BCM, except for one idle section (zero for inductor current), the operation modes of DCM will not be given here.

t0-t1 section:

S1, S4, D5 are on, the current of primary side and secondary side rise linearly.

t1-t2 section:

S1 is off, D5 is on, Lr resonates with C3. The voltage of C3 falls to zero, D3 transits to conduction and catches Lr current. Simultaneouly, the soft-switching condition is created for S3. Current of primary and secondary side fall linearly.

t2-t3 section:

S1, S4 are off, S2 is turned on with zero current, S3 is turned on with zero voltage, D6 is on. Primary side current rises negatively and secondary side current rises linearly.

t3-t4 section:

S2 is off, D6 is on, Lr resonates with C4, the voltage of C4 falls to zero, D4 transits to conduction and catches Lr current. Simultaneously, the soft-switching condition is created for S4. Primary side current rises negatively and secondary side current falls.

t4-t5 section:

S1, S4, D5 are on, current of primary and secondary side rise linearly.

III. MULTI-MODE CONTROL STRATEGY

For power electronics converter at different power level, implementation of different control methods give different performance. In this paper, according to the real situation of loading, the Type equation here.proposed converter is controlled by 3 different operation modes which are MCM, DCM, BCM so that high efficiency can be obtained for wide load range, as explained in Fig.3. In the control idea diagram, Vc stands for output control signal from error amplifier and d is duty cycle, fs means switching frequency while fsmax is maximum switching frequency.

MCM (Multi Cycle Mode) is also named pulse skipping mode. When the converter operates at light load, the control system first generates a series of pulses with fixed duty cycle by the function block of Ton Generator, and then all the switching devices are shut down. After the output voltage falls to certain pre-defined threshold, the pulse series will be generated again. By using this approach, switching frequency is dramatically reduced and light load efficiency is well improved. DCM (Discontinous Conduction Mode) regulates the switching frequency according to load. The conduction loss is fair enough with consideration that the load is smaller even though the peak current is relatively large. As for the switching loss, power devices of primary and secondary side can achieve soft-switching. So, the switching loss is further reduced on the basis of frequency lowering. The converter gain of DCM is given as:

$$G_{DCM} = \frac{TR}{1+\sqrt{1+\frac{4k}{D^2}}} \qquad (1)$$

In which, D stands for duty cycle, TR means turns ratio of transformer, k is system constant of converter as below:

$$k = \frac{4(TR)^2 L_r}{R T_s} \qquad (2)$$

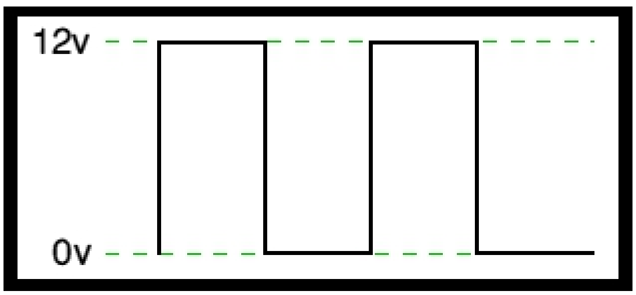
In which, R is load resistance, Ts is switching period of certain operation conditions. BCM (Boundary Conduction Mode) is operation mode when converter reaches full load point. The soft-switching ofprimary and secondary side power devices is achieved while keeps fairly small RMS value of inductor current. Furthermore, converter compactness is improved due to small inductance requirement in BCM design. The converter gain of BCM is given as following:

$G_{BCM} = D.(TR)$ (3)

1.3 Pulse width Modulation

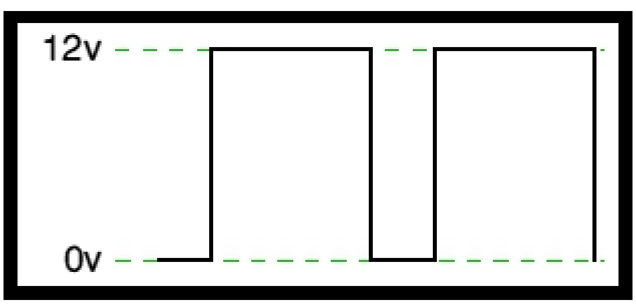
What is PWM?

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller’s power devices. When in PWM regulation, the current from the solar array tapers according to the battery’s condition and recharging needs Consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.

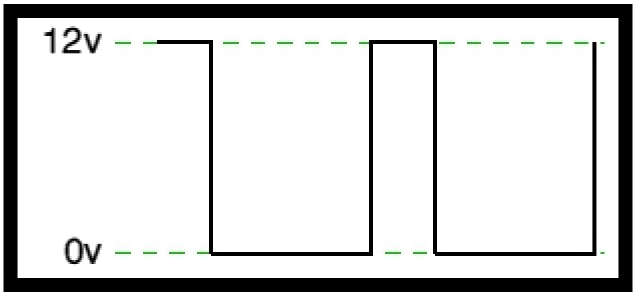


Pwm Signal

Similarly, if the switches keep the voltage at 12 for 3 times as long as at 0v, the average will be 3/4 of 12v - or 9v, as shown below.



and if the output pulse of 12v lasts only 25% of the overall time, then the average is



By varying - or 'modulating' - the time that the output is at 12v (i.e. the width of the positive pulse) we can alter the average voltage. So we are doing 'pulse width modulation'. I said earlier that the output had to feed 'a suitable device'. A radio would not work from this: the radio would see 12v then 0v, and would probably not work properly. However, a device such as a motor will respond to the average, so PWM is a natural for motor control.

1.3.1 Pulse Width modulator

So, how do we generate a PWM waveform? It's actually very easy, there are circuits available in the TEC site. First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the 'demand' voltage, the output goes high. When the triangle is below the demand voltage, the

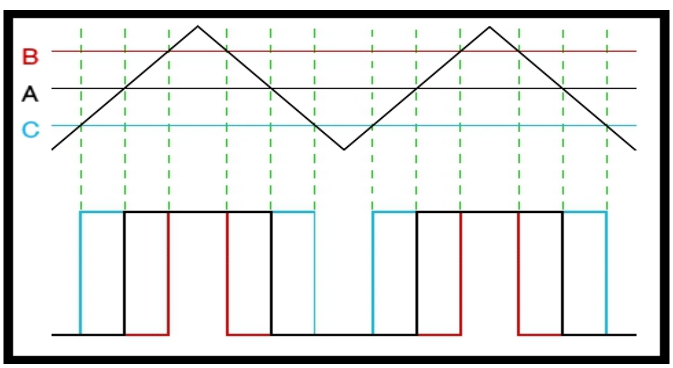


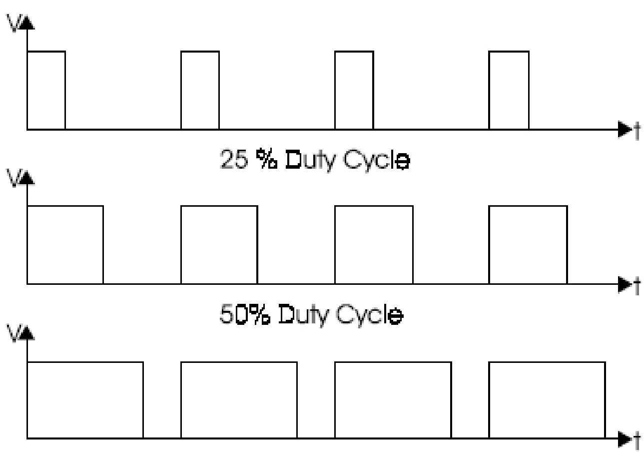
Fig 1.3.1 Pulse Width Modulator

When the demand speed it in the middle (A) you get a 50:50 output, as in black. Half the time the output is high and half the time it is low. Fortunately, there is an IC (Integrated circuit) called a comparator: these come usually 4 sections in a single package. One can be used as the oscillator to produce the triangular waveform and another to do the comparing, so a complete oscillator and modulator can be done with half an IC and maybe 7 other bits.

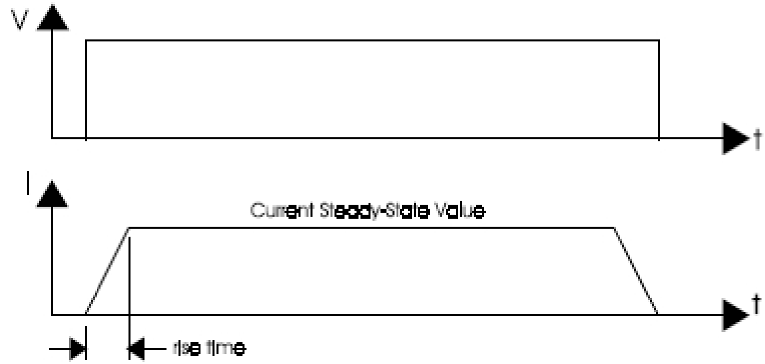
The triangle waveform, which has approximately equal rise and fall slopes, is one of the commonest used, but you can use a saw tooth (where the voltage falls quickly and rinses slowly). You could use other waveforms and the exact linearity (how good the rise and fall are) is not too important.

Traditional solenoid driver electronics rely on linear control, which is the application of a constant voltage across a resistance to produce an output current that is directly proportional to the voltage. Feedback can be used to achieve an output that matches exactly the control signal. However, this scheme dissipates a lot of power as heat, and it is therefore very inefficient.

A more efficient technique employs **pulse width modulation** (PWM) to produce the constant current through the coil. A PWM signal is not constant. Rather, the signal is on for part of its period, and off for the rest. The **duty cycle**, D, refers to the percentage of the period for which the signal is on. The duty cycle can be anywhere from 0, the signal is always off, to 1, where the signal is constantly on. A 50% D results in a perfect square wave. (Figure 1)



A solenoid is a length of wire wound in a coil. Because of this configuration, the solenoid has, in addition to its resistance, R, a certain **inductance**, L. When a voltage, V, is applied across an inductive element, the current, I, produced in that element does not jump up to its constant value, but gradually rises to its maximum over a period of time called the **rise time** (Figure 2). Conversely, I does not disappear instantaneously, even if V is removed abruptly, but decreases back to zero in the same amount of time as
the rise time.



Therefore, when a low frequency PWM voltage is applied across a solenoid, the current through it will be increasing and decreasing as V turns on and off. If D is shorter than the rise time, I will never achieve its maximum value, and will be discontinuous since it will go back to zero during V's off period (Figure 3).* In contrast, if D is larger than the rise time, I will never fall back to zero, so it will be continuous, and have a DC average value. The current will not be constant, however, but will have a ripple (Figure 4).

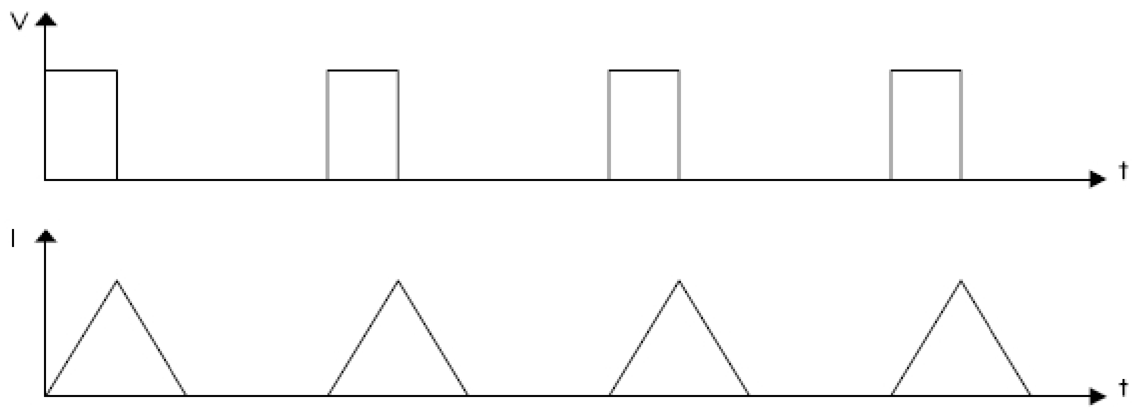
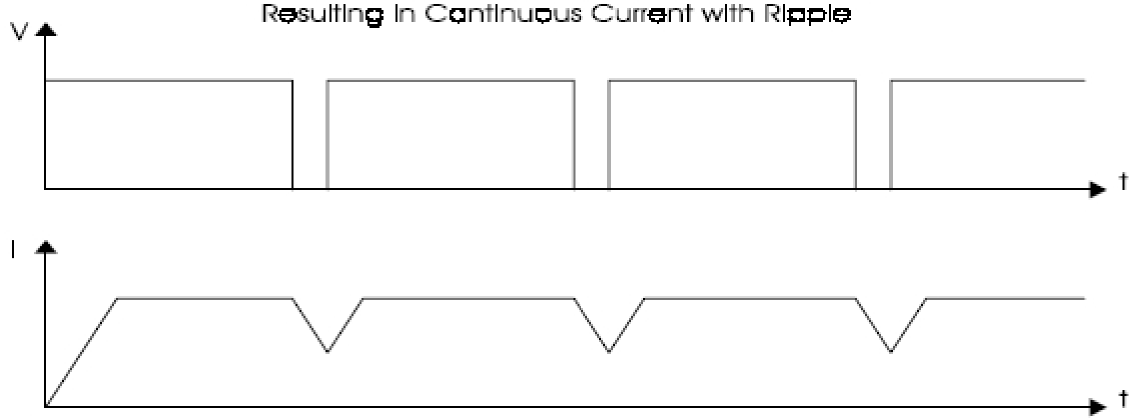
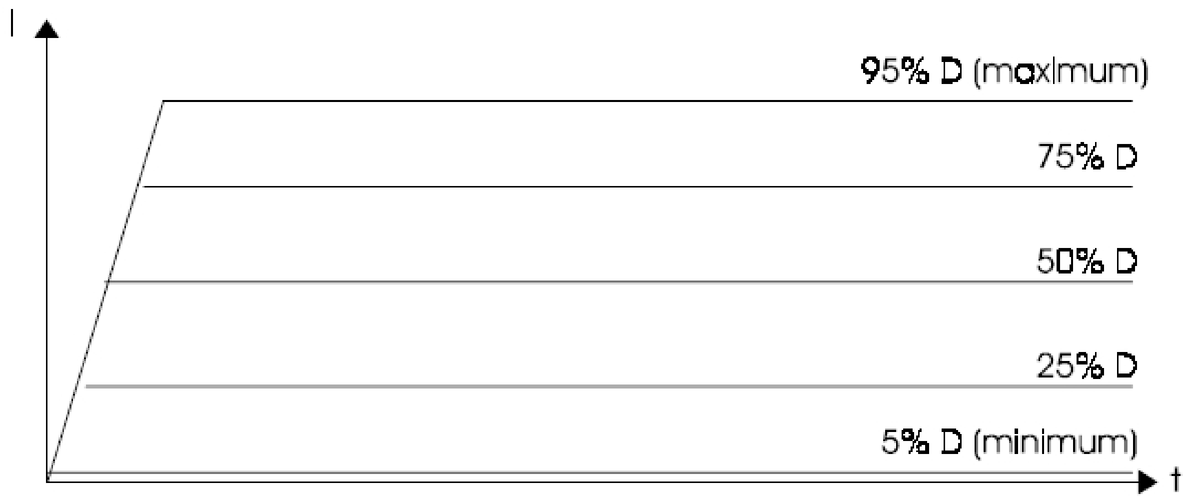


Figure 4 - Low Frequency PWM with D>rise time
Resulting in Continuous Current with Ripple



At high frequencies, V turns on and off very quickly, regardless of D, such that the current does not have time to decrease very far before the voltage is turned back on. The resulting current through the solenoid is therefore considered to be constant. By adjusting the D, the amount of output current can be controlled. With a small D, the current will not have much time to rise before the high frequency PWM voltage takes effect and the current stays constant. With a large D, the current will be able to rise higher before it becomes constant. (Figure 5)



Dither

Static friction, stiction, and hysteresis can cause the control of a hydraulic valve to be erratic and unpredictable. Stiction can prevent the valve spool from moving with small input changes, and hysteresis can cause the shift to be different for the same input signal. In order to counteract the effects of stiction and hysteresis, small vibrations about the desired position are created in the spool. This constantly breaks the static friction ensuring that it will move even with small input changes, and the effects of hysteresis are average out.

Dither is a small ripple in the solenoid current that causes the desired vibration and there by increases the linearity of the valve. The amplitude and frequency of the dither must be carefully chosen. The amplitude must be large enough and the frequency slow enough that the spool will respond, yet they must also be small and fast enough not to result in a pulsating output.

The optimum dither must be chosen such that the problems of stiction and hysteresis are overcome without new problems being created. Dither in the output current is a byproduct of low frequency PWM, as seen above. However, the frequency and amplitude of the dither will be a function of the duty cycle, which is also used to set the output current level. This means that low frequency dither is not independent of current magnitude. The advantage of using high frequency PWM is that dither can be generated separately, and then superimposed on top of the output current.

This allows the user to independently set the current magnitude (by adjusting the D), as well as the dither frequency and amplitude. The optimum dither, as set by the user, will therefore be constant at all current levels.

1.4 Why the PWM frequency is important:

The PWM is a large amplitude digital signal that swings from one voltage extreme to the other. And, this wide voltage swing takes a lot of filtering to smooth out. When the PWM frequency is close to the frequency of the waveform that you are generating, then any PWM filter will also smooth out your generated waveform and drastically reduce its amplitude. So, a good rule of thumb is to keep the PWM frequency much higher than the frequency of any waveform you generate.

Finally, filtering pulses is not just about the pulse frequency but about the duty cycle and how much energy is in the pulse. The same filter will do better on a low or high duty cycle pulse compared to a 50% duty cycle pulse. Because the wider pulse has more time to integrate to a stable filter voltage and the smaller pulse has less time to disturb it the inspiration was a request to control the speed of a large positive displacement fuel pump. The pump was sized to allow full power of a boosted engine in excess of 600 Hp.

At idle or highway cruise, this same engine needs far less fuel yet the pump still normally supplies the same amount of fuel. As a result the fuel gets recycled back to the fuel tank, unnecessarily heating the fuel. This PWM controller circuit is intended to run the pump at a low speed setting during low power and allow full pump speed when needed at high engine power levels.

1.5 PWM Controller Features:

This controller offers a basic “Hi Speed” and “Low Speed” setting and has the option to use a “Progressive” increase between Low and Hi speed. Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor. Normally the controller keeps the motor at this Lo Speed except when Progressive is used and when Hi Speed is commanded (see below). Low Speed can vary anywhere from 0% PWM to 100%.

Progressive control is commanded by a 0-5 volt input signal. This starts to increase PWM% from the low speed setting as the 0-5 volt signal climbs. This signal can be generated from a throttle position sensor, a Mass Air

Flow sensor, a Manifold Absolute Pressure sensor or any other way the user wants to create a 0-5 volt signal. This function could be set to increase fuel pump power as turbo boost starts to climb (MAP sensor). Or, if controlling a water injection pump, Low Speed could be set at zero PWM% and as the TPS signal climbs it could increase PWM%, effectively increasing water flow to the engine as engine load increases. This controller could even be used as a secondary injector driver (several injectors could be driven in a batch mode, hi impedance only), with Progressive control (0-100%) you could control their output for fuel or water with the 0-5 volt signal.

Progressive control adds enormous flexibility to the use of this controller. Hi Speed is that same as hard wiring the motor to a steady 12 volt DC source. The controller is providing 100% PWM, steady 12 volt DC power. Hi Speed is selected three different ways on this controller: 1) Hi Speed is automatically selected for about one second when power goes on. This gives the motor full torque at the start. If needed this time can be increased (the value of C1 would need to be increased). 2) High Speed can also be selected by applying 12 volts to the High Speed signal wire. This gives Hi Speed regardless of the Progressive signal.
When the Progressive signal gets to approximately 4.5 volts, the circuit achieves 100% PWM – Hi Speed.

How does this technology help?
The benefits noted above are technology driven. The more important question is how the PWM
technology Jumping from a 1970's technology into the new millennium offers:

• **Longer battery life:**
– reducing the costs of the solar system
– reducing battery disposal problems

• **More battery reserve capacity:**
– increasing the reliability of the solar system
– reducing load disconnects
– opportunity to reduce battery size to lower
the system cost

• **Greater user satisfaction:**
– get more power when you need it for lessmoney!!

CHAPTER-II

DC-DC CONVERTER

A DC-to-DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically, the output produced is at a different voltage level than the input. In addition, DC-to-DC converters are used to provide noise isolation, power bus regulation, etc. This is a summary of some of the popular DC-to-DC converter topologies.

2.1 BUCK CONVERTER STEP-DOWN CONVERTER

In this circuit the transistor turning ON will put voltage V_{in} on one end of the inductor. This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor but now flowing through the diode. We initially assume that the current through the inductor does not reach zero, thus the voltage at V_x will now be only the voltage across the conducting diode during the full OFF time. The average voltage at V_x will depend on the average ON time of the transistor provided the inductor current is continuous.

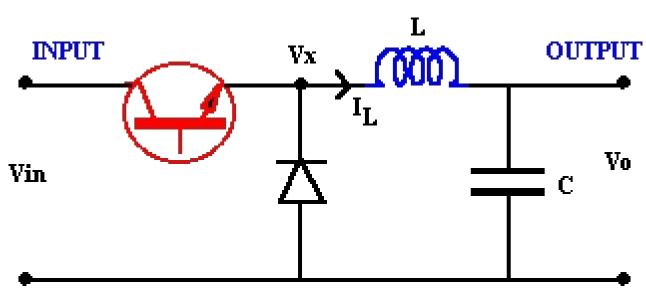
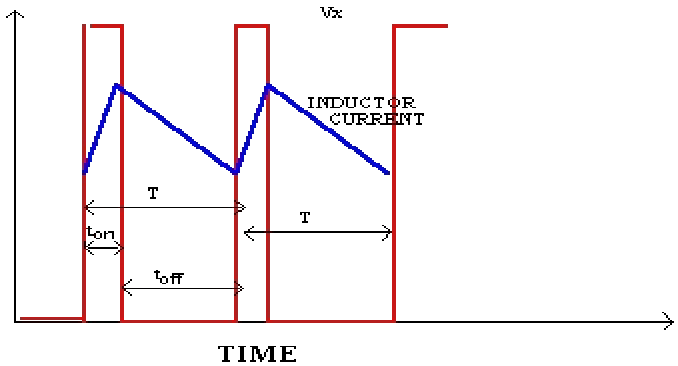


Fig 2.1 Buck Converter



Voltage and current changes

To analyze the voltages of this circuit let us consider the changes in the inductor current over one cycle. From the relation

$$\mathrm{V_x - V_o = L\frac{di}{dt}} \ldots\ldots\ldots\ldots\ldots (1)$$

the change of current satisfies

$$di = \int (V_x - V_o)\, dt + \int (V_x - V_o)\, dt \ldots\ldots\ldots (2)$$

For steady state operation the current at the start and end of a period T will not change. To get a simple relation between voltages we assume no voltage drop across transistor or diode while ON and a perfect switch change. Thus during the ON time V_x=V_{in} and in the OFF V_x=0. Thus

$$0 = di = \int_0^{t_{on}} (V_{in} - V_o)\, dt + \int_{t_{on}}^{t_{on}+t_{off}} (-V_o)\, dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This simplifies to

$$(V_{in} - V_o)t_{on} - V_o t_{off} = 0 \;\; \ldots\ldots\ldots\ldots\ldots (4)$$

or

$$\frac{V_O}{V_{in}} = \frac{t_{on}}{T} \ldots\ldots\ldots\ldots\ldots (5)$$

and defining "duty ratio" as

$$D = \frac{t_{on}}{T} \ldots\ldots\ldots (6)$$

The voltage relationship becomes Vo=D Vin Since the circuit is lossless and the input and output powers must match on the average $V_o * I_o = V_{in} * I_{in}$. Thus the average input and output current must satisfy $I_{in} = D\, I_o$ These relations are based on the assumption that the inductor current does not reach zero.

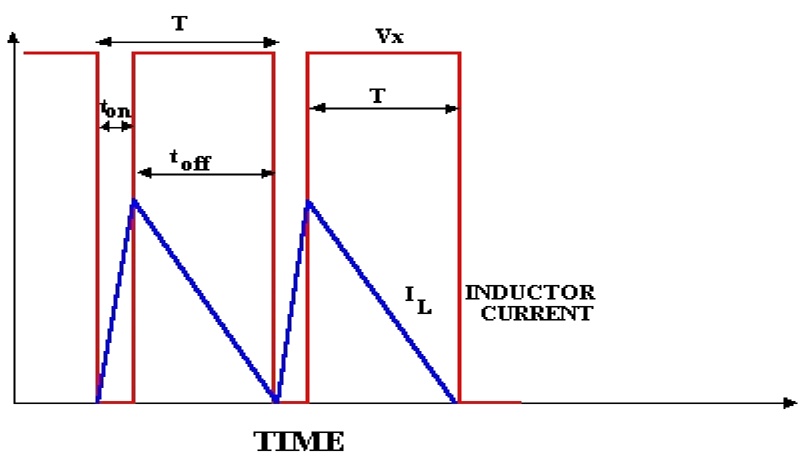
2.2 Transition between continuous and discontinuous

When the current in the inductor L remains always positive then either the transistor T1 or the diode D1 must be conducting. For continuous conduction the voltage V_x is either V_{in} or 0. If the inductor current ever goes to zero then the output voltage will not be forced to either of these conditions. At this transition point the current just reaches zero as seen in Figure (buck booster boundery). During the ON time V_{in}-V_{out} is across the inductor thus

$$I_L(peak) = (V_{in} - V_{out}).\frac{t_{ON}}{L} \qquad \textbf{(7)}$$

The average current which must match the output current satisfies

$$I_L(average\ at\ transition) = \frac{I_L(peak)}{2} = (V_{in} - V_{out})\frac{dT}{2L} = I_{out}(transition) \qquad (8)$$



Buck Converter at Boundary

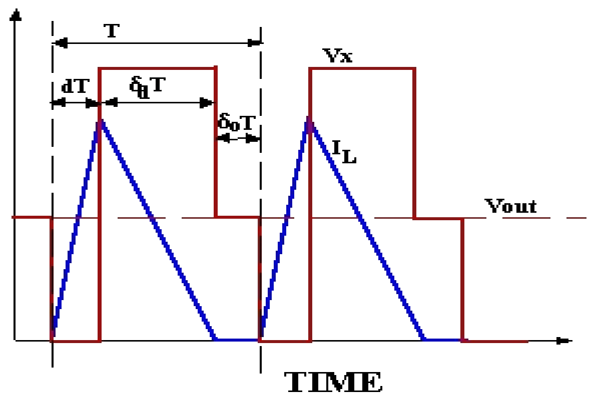
If the input voltage is constant the output current at the transition point satisfies

$$\mathrm{I_{out}(transition)} = \mathrm{V_{in}}\frac{(1-\mathrm{d})\mathrm{d}}{2\mathrm{L}}\mathrm{T} \qquad (9)$$

2.3 Voltage Ratio of Buck Converter (Discontinuous Mode)

As for the continuous conduction analysis we use the fact that the integral of voltage across the inductor is zero over a cycle of switching T. The transistor OFF time is now divided into segments of diode conduction d_dT and zero conduction d_oT. The inductor average voltage thus gives

$$(V_{in} - V_o)\ DT + (-V_o)\quad {}_dT = 0 \tag{10}$$



Buck Converter - Discontinuous Conduction

$$\frac{V_{out}}{V_{in}} = \frac{d}{d + \delta_d} \tag{11}$$

for the case $d + \delta_d < 1$ To resolve the value of δ_d consider the output current which is half the peak when averaged over the conduction times $d + \delta_d$

$$I_{out} = \frac{I_L(peak)}{2} d + \delta_d \tag{12}$$

Considering the change of current during the diode conduction time

$$\mathrm{I_L(peak)} = \frac{\mathrm{V_o(\delta_d T)}}{\mathrm{L}} \tag{13}$$

Thus from (6) and (7) we can get

$$I_{out} = \frac{V_o \delta_d T.(d + \delta_d)}{2L} \tag{14}$$

using the relationship in (5)

$$I_{out} = \frac{V_{in}\, d\, \delta_d T}{2L} \tag{15}$$

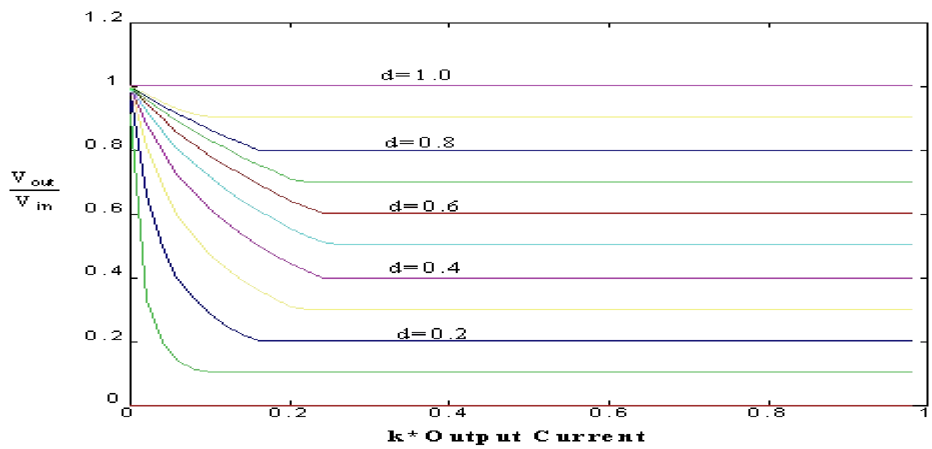
and solving for the diode conduction

$$\delta_d = \frac{2\, L\, I_{out}}{V_{in}\, d\, T} \tag{16}$$

The output voltage is thus given as

$$\frac{V_{out}}{V_{in}} = \frac{d^2}{d^2 + \left(\frac{2\, L\, I_{out}}{V_{in} T}\right)} \tag{17}$$

defining k* = 2L/(V_{in} T), we can see the effect of discontinuous current on the voltage ratio of the converter.



Output Voltage vs Current

As seen in the figure, once the output current is high enough, the voltage ratio depends only on the duty ratio "d". At low currents the discontinuous operation tends to increase the output voltage of the converter towards V_{in}.

2.4 BOOST CONVERTER STEP-UP CONVERTER

The schematic in Fig. 6 shows the basic boost converter. This circuit is used when a higher output voltage than input is required.

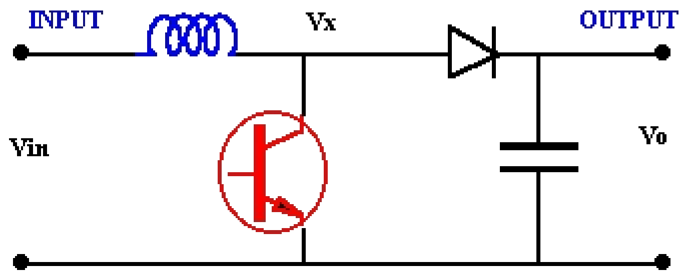


Fig 2.4 Boost Converter Circuit

While the transistor is ON $V_x = V_{in}$, and the OFF state the inductor current flows through the diode giving $V_x = V_o$. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in Fig. 7 and the average must be zero for the average current to remain in steady state

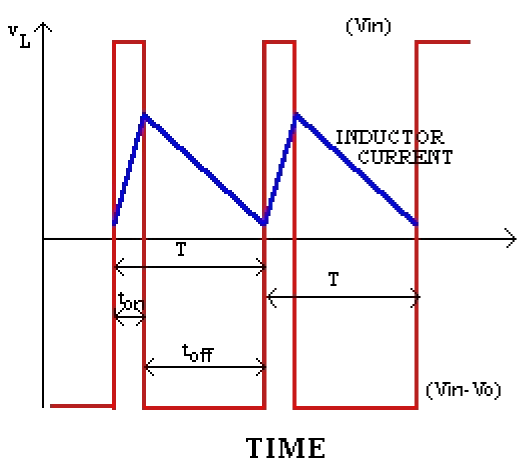
$$V_{in}t_{on} + (V_{in} - V_o)t_{off} = 0 \;\ldots\ldots\ldots\ldots (18)$$

This can be rearranged as

$$\frac{V_O}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{(1-D)} \;\ldots\ldots\ldots (19)$$

and for a lossless circuit the power balance ensures

$$\frac{I_O}{I_{in}} = (1 - D) \quad \ldots\ldots\ldots.. (20)$$



Voltage and current waveforms (Boost Converter)

Since the duty ratio "D" is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

2.5 BUCK-BOOST CONVERTER

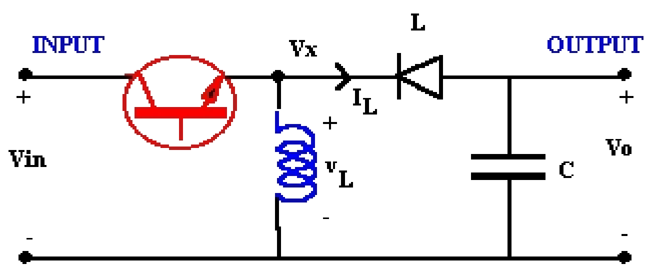


Fig 2.5 Buck-Boost Convertor

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

$V_{in}t_{ON} + V_o t_{OFF} = 0$ ………….. (21)

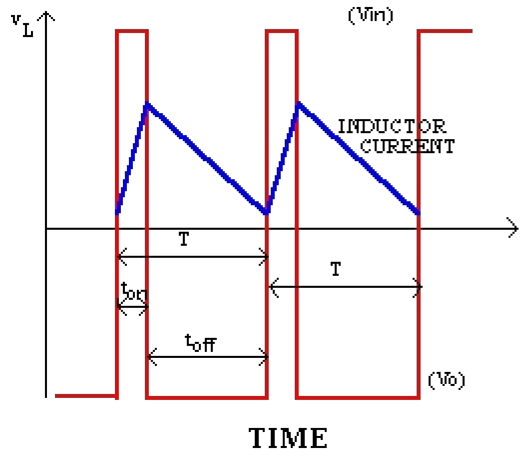
which gives the voltage ratio

$\frac{V_O}{V_{in}} = -\frac{D}{(1-D)}$ ………… (22)

and the corresponding current

$\frac{I_O}{I_{in}} = -\frac{(1-D)}{D}$ ……….. (23)

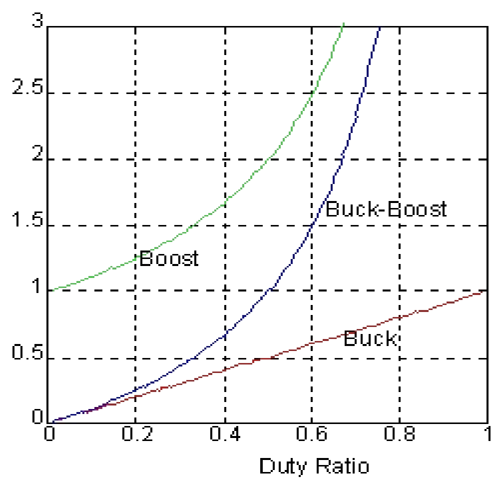
Since the duty ratio "D" is between 0 and 1 the output voltage can vary between lower or higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.



Waveforms for buck-boost converter

2.6 CONVERTER COMPARISON

The voltage ratios achievable by the DC-DC converters is summarized in Fig. 10. Notice that only the buck converter shows a linear relationship between the control (duty ratio) and output voltage. The buck-boost can reduce or increase the voltage ratio with unit gain for a duty ratio of 50%.



Comparison of Voltage ratio

2.7 CUK CONVERTER

The buck, boost and buck-boost converters all transferred energy between input and output using the inductor, analysis is based of voltage balance across the inductor. The CUK converter uses capacitive energy transfer and analysis is based on current balance of the capacitor. The circuit in Fig. below(CUK converter) is derived from DUALITY principle on the buck-boost converter.

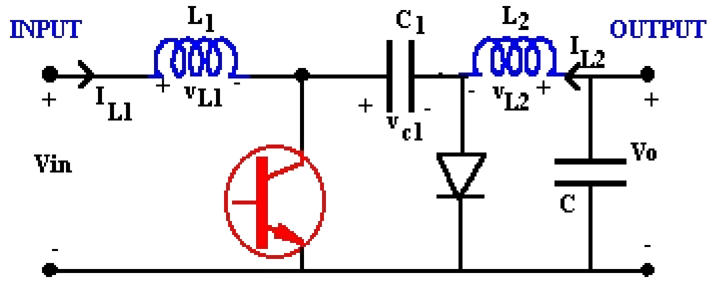


Fig 2.7 CUK Converter

If we assume that the current through the inductors is essentially ripple free we can examine the charge balance for the capacitor C1. For the transistor ON the circuit becomes

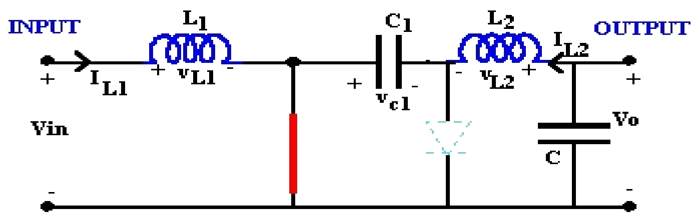


Fig 2.7.1 CUK "ON-STATE"

and the current in C1 is I_{L1}. When the transistor is OFF, the diode conducts and the current in C1 becomes I_{L2}.

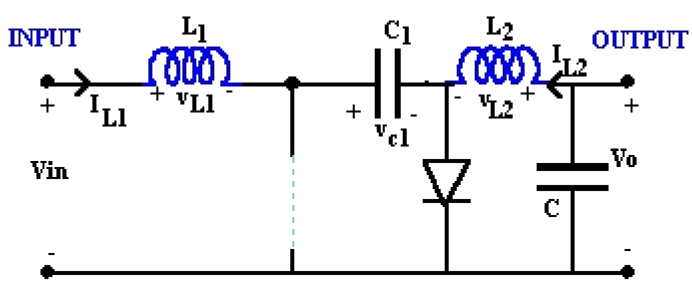


Fig 2.7.2 CUK "OFF-STATE"

Since the steady state assumes no net capacitor voltage rise ,the net current is zero

$$I_{L1}t_{ON} + (-I_{L2})t_{OFF} = 0 \text{ .... (24)}$$

which implies

$$\frac{I_{L2}}{I_{L1}} = \frac{(1-D)}{D} \quad \text{........ (25)}$$

The inductor currents match the input and output currents, thus using the power conservation rule

$$\frac{V_O}{V_{in}} = -\frac{D}{(1-D)} \quad \ldots\ldots\ldots\ldots (26)$$

Thus the voltage ratio is the same as the buck-boost converter. The advantage of the CUK converter is that the input and output inductors create a smooth current at both sides of the converter while the buck, boost and buck-boost have at least one side with pulsed current.

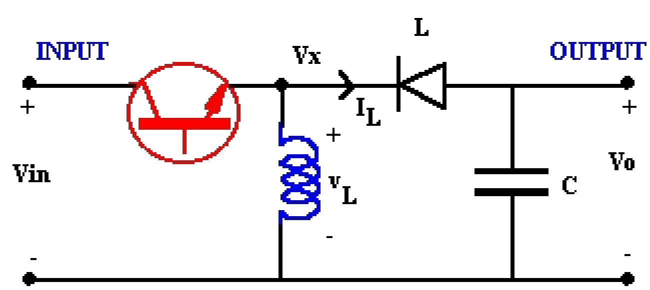
2.8 ISOLATED DC-DC CONVERTERS

In many DC-DC applications, multiple outputs are required and output isolation may need to be implemented depending on the application. In addition, input to output isolation may be required to meet safety standards and / or provide impedance matching. The above discussed DC-DC topologies can be adapted to provide isolation between input and output.

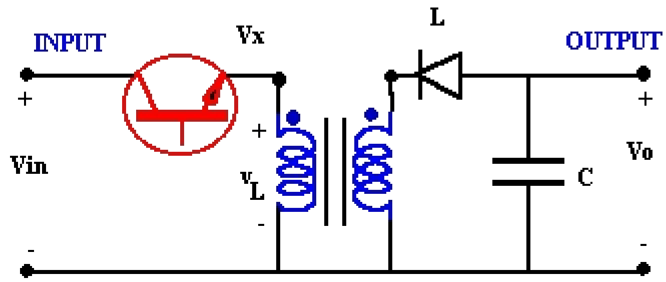
2.9 Flyback Converter

The flyback converter can be developed as an extension of the Buck-Boost converter. Fig (a) shows the basic converter; Fig (b)(replacing inductor by transformer) replaces the inductor by a transformer. The buck-boost converter works by storing energy in the inductor during the ON phase and releasing it to the output during the OFF phase. With the transformer the energy storage is in the magnetisation of the transformer core. To increase the stored energy a gapped core is often used.

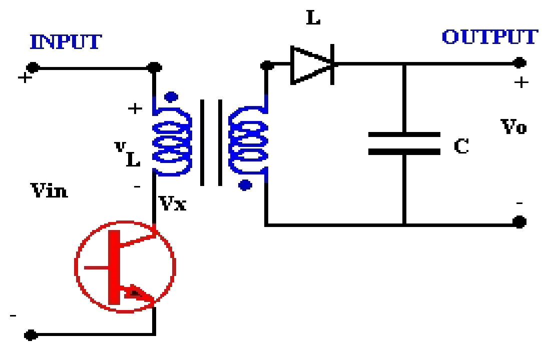
In Fig (c) the isolated output is clarified by removal of the common reference of the input and output circuits.



(a) Fig 2.9 Buck-Boost Converter



(b) Fig 2.9.1 Replacing inductor by transformer



(c) Fig 2.9.2 Flyback converter re-configured

2.10Forward Converter

The concept behind the forward converter is that of the ideal transformer converting the input AC voltage to an isolated secondary output voltage. For the circuit in Fig. (forward converter), when the transistor is ON, Vin appears across the primary and then generates

$$V_x = \frac{N_1}{N_2} V_{in} \ldots\ldots\ldots\ldots (27)$$

The diode D1 on the secondary ensures that only positive voltages are applied to the output circuit while D2 provides a circulating path for inductor current if the transformer voltage is zero or negative.

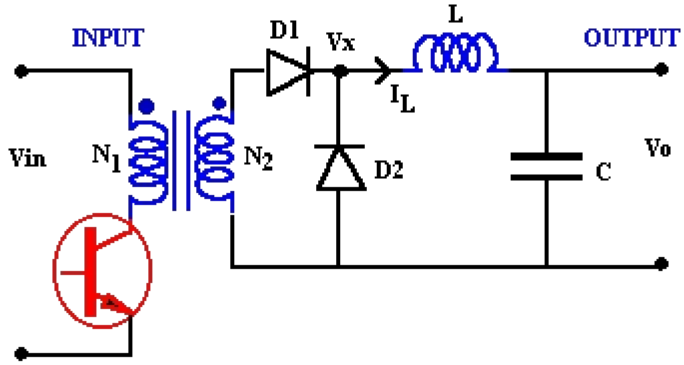


Fig 2.10 Forward Converter

2.11 Forward Converter

The problem with the operation of the circuit in Fig above(forward converter) is that only positive voltage is applied across the core, thus flux can only increase with the application of the supply. The flux will increase until the core saturates when the magnetising current increases significantly and circuit failure occurs. The transformer can only sustain operation when there is no significant DC component to the input voltage. While the switch is ON there is positive voltage across the core and the flux increases. When the switch turns OFF we need to supply negative voltage to rset the core flux. The circuit in Fig. below shows a tertiary winding with a diode connection to permit reverse current. Note that the "dot" convention for the tertiary winding is opposite those of the other windings. When the switch turns OFF current was flowing in a "dot" terminal. The core inductance act to continue current in a dotted terminal.

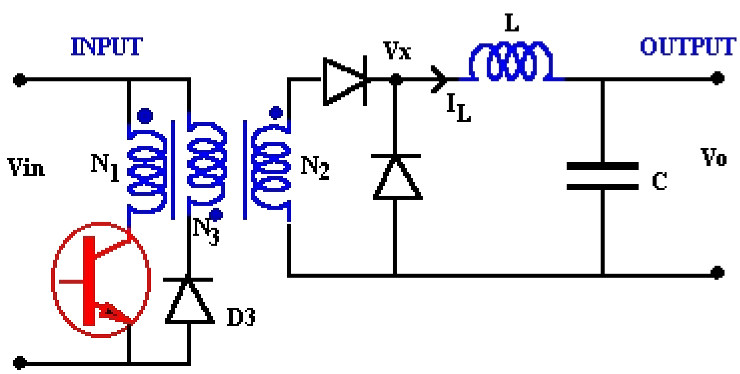


Fig 2.10.1 Forward converter with tertiary windi

CHAPTER-III

SIMULATION THEORY

3.1 GENERAL

MATLAB (**mat**rix **lab**oratory) is a numerical computing environment and fourth-generation programming language. Developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran. Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPADsymbolic engine, allowing access to symbolic computing capabilities. An additional package, Simulink, adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems.

In 2004, MATLAB had around one million users across industry and academia. MATLAB users come from various backgrounds of engineering, science, and economics. MATLAB is widely used in academic and research institutions as well as industrial enterprises.

3.2 MATLAB HISTORY

Cleve Moler, the chairman of the computer-science department at the University of New Mexico, started developing MATLAB in the late 1970s. He designed it to give his students access to LINPACK and EISPACK without them having to learn Fortran. It soon spread to other universities and found a strong audience within the applied mathematics community. Jack Little, an engineer, was exposed to it during a visit Moler made to Stanford University in 1983. Recognizing its commercial potential, he joined with Moler and Steve Bangert. They rewrote MATLAB in C and founded MathWorks in 1984 to continue its development. These rewritten libraries were known as JACKPAC. In 2000, MATLAB was rewritten to use a newer set of libraries for matrix manipulation, LAPACK.

MATLAB was first adopted by researchers and practitioners in control engineering, Little's specialty, but quickly spread to many other domains. It is now also used in education, in particular the teaching of linear algebra and numerical analysis, and is popular amongst scientists involved in image processing.

3.3 SIMULINK

Simulink, developed by MathWorks, is a commercial tool for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi-domain simulation and Model-Based Design

Simulink is a block diagram environment for multi-domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems.Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

3.4 Building the Model

Simulinkprovides a set of predefined blocks that you can combine to create a detailed block diagram of your system. Tools for hierarchical modeling, data management, and subsystem customization enable you to represent even the most complex system concisely and accurately.

3.4.1 Selecting Blocks

The Simulink Library Browser contains a library of blocks commonly used to model a system. As shown in **Fig.3.4.2**, these include:

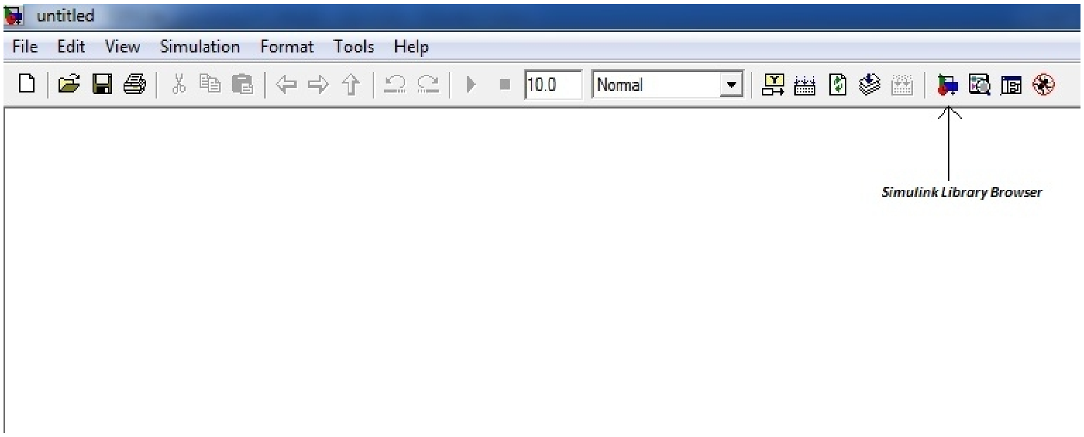


Fig.3.4.1. Building a new model

- Continuous and discrete dynamics blocks, such as Integration and Unit Delay
- Algorithmic blocks, such as Sum, Product, and Lookup Table
- Structural blocks, such as Mux, Switch, and Bus Selector

We can build customized functions by using these blocks or by incorporating hand-written MATLAB, C, Fortran, or Ada code into the model.The custom blocks can be stored in their own libraries within the Simulink Library Browser.

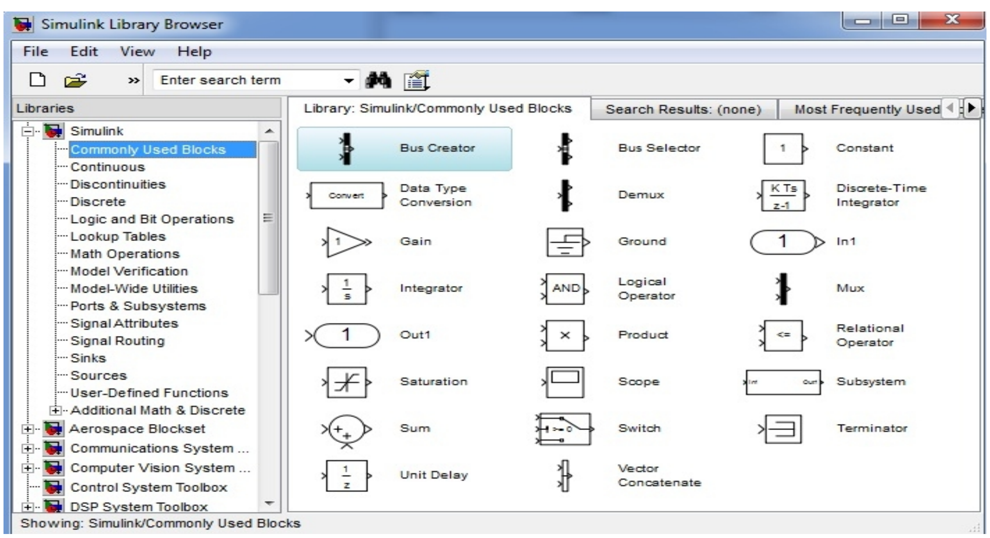


Fig.3.4.2. Commonly used blocks

Simulink add-on products let you incorporate specialized components for aerospace, communications, PID control, control logic, signal processing, video and image processing, and other applications. Add-on products are also available for modeling physical systems with mechanical, electrical, and hydraulic components.

To build a model as shown in **Fig.3.4.1** by dragging blocks from the Simulink Library Browser into the Simulink Editor, we then connect these blocks with signal lines to establish mathematical relationships between system components. Graphical formatting tools, such as smart guides and smart signal routing, help we control the appearance of the model as webuild it. We can add hierarchy by encapsulating a group of blocks and signals as a subsystem in a single block.

The Simulink Editor gives a complete control over what we see and use within the model. For example, we can add commands and submenus to the editor and context menus. We can also add a custom interface to a subsystem or model by using a mask that hides the subsystem's contents and provides the subsystem with its own icon and parameter dialog box.

3.4.2 Navigating Through the Model Hierarchy

The Explorer bar and Model Browser in Simulink helpsto navigate the model. The Explorer bar indicates the level of hierarchy that we are currently viewing and lets we can move up and down the hierarchy. The Model Browser provides a complete hierarchical tree view of your model, and like the Explorer bar, can be used to move through the levels of hierarchy.

3.4.3 Managing Signals and Parameters

Simulink models contain both signals and parameters. Signals are time-varying data represented by the lines connecting blocks. Parameters are coefficients that define system dynamics and behavior.Simulink helps to determine the following signal and parameter attributes as shown in **Fig.3.3**:

- Data type—single, double, signed, or unsigned 8-, 16- or 32-bit integers; Boolean; enumeration; or fixed point
- Dimensions—scalar, vector, matrix, N-D, or variable-sized arrays
- Complexity—real or complex values
- Minimum and maximum range, initial value, and engineering units

If we choose not to specify data attributes, Simulink determines them automatically via propagation algorithms, and conducts consistency checking to ensure data integrity.These signal and parameter attributes can be specified either within the model or in a separate data dictionary. We can then use the Model Explorer to organize, view, modify, and add data without navigating through the entire model as shown in **Fig.3.4.4**.

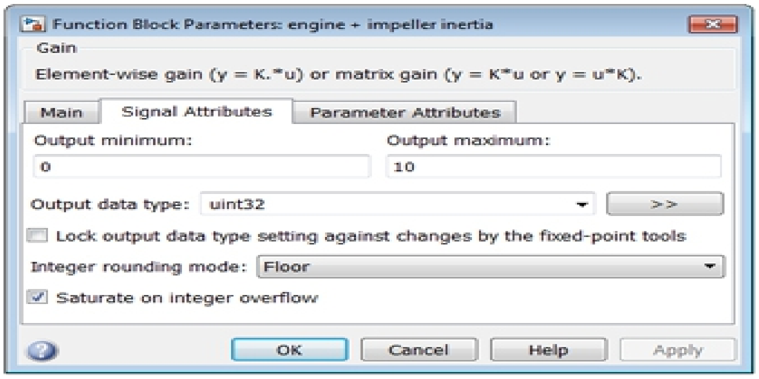


Fig.3.4.3 Signal Attributes tab

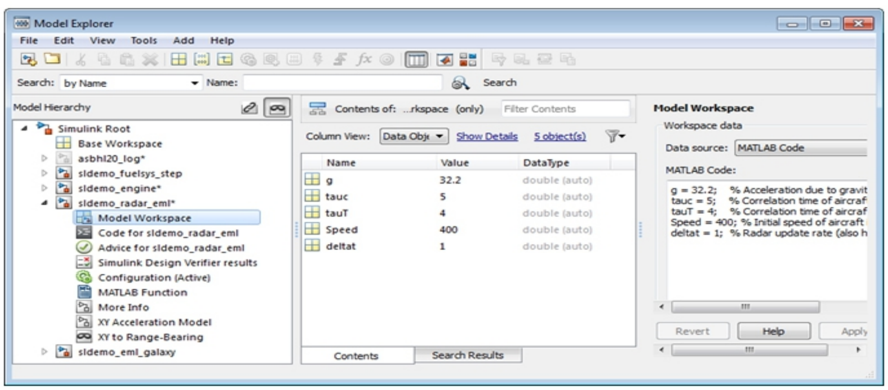


Fig.3.4.4 Model Explorer Window

3.4.4 Simulating the Model

We can simulate the dynamic behavior of the system and view the results as the simulation runs. To ensure simulation speed and accuracy, Simulink provides fixed-step and variable-step ODE solvers, a graphical debugger, and a model profiler.

3.4.5 Choosing a Solver

Solvers as shown in **Fig.3.4.5** are numerical integration algorithms that compute the system dynamics over time using information contained in the model. Simulink provides solvers to support the simulation of a broad range of systems, including continuous-time (analog), discrete-time (digital), hybrid (mixed-signal), and multirate systems of any size.

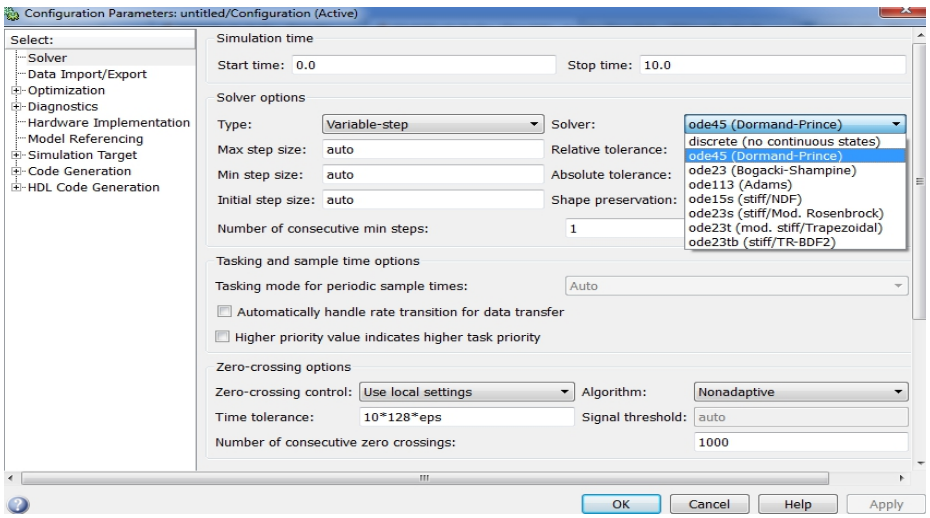


Fig.3.4.5. Configuration Parameters dialog box showing the Solver pane.

These solvers can simulate stiff systems and systems with discontinuities. We can specify simulation options, including the type and properties of the solver, simulation start and stop times, and whether to load or save simulation data. We can also set optimization and diagnostic information. Different combinations of options can be saved with the model.

3.4.6 Running the Simulation

We can run your simulation interactively from the Simulink Editor or systematically from the MATLAB command line. The following simulation modes are available:

- Normal (the default), which interpretively simulates the model
- Accelerator, which increases simulation performance by creating and executing compiled target code but still provides the flexibility to change model parameters during simulation
- Rapid Accelerator, which can simulate models faster than Accelerator mode by creating an executable that can run outside Simulink on a second processing core

To reduce the time required to run multiple simulations, we can run those simulations in parallel on a multi-core computer or computer cluster.

3.4.7 Analyzing Simulation Results

After running a simulation, we can analyze the simulation results in MATLAB and Simulink. Simulink includes debugging tools to help to understand the simulation behavior.

3.4.8 Viewing Simulation Results

We can visualize the simulation behavior by viewing signals with the displays and scopes provided in Simulink. We can also view simulation data within the Simulation Data Inspector, where we can compare multiple signals from different simulation runs. Scope is the block in Simulink by which we can measure and view the voltage, current, and power in electrical domain. **Fig.3.4.8.** shows the output of a multilevel converter through scope.

Alternatively, we can build custom HMI displays using MATLAB, or log signals to the MATLAB workspace to view and analyze the data using MATLAB algorithms and visualization tools.

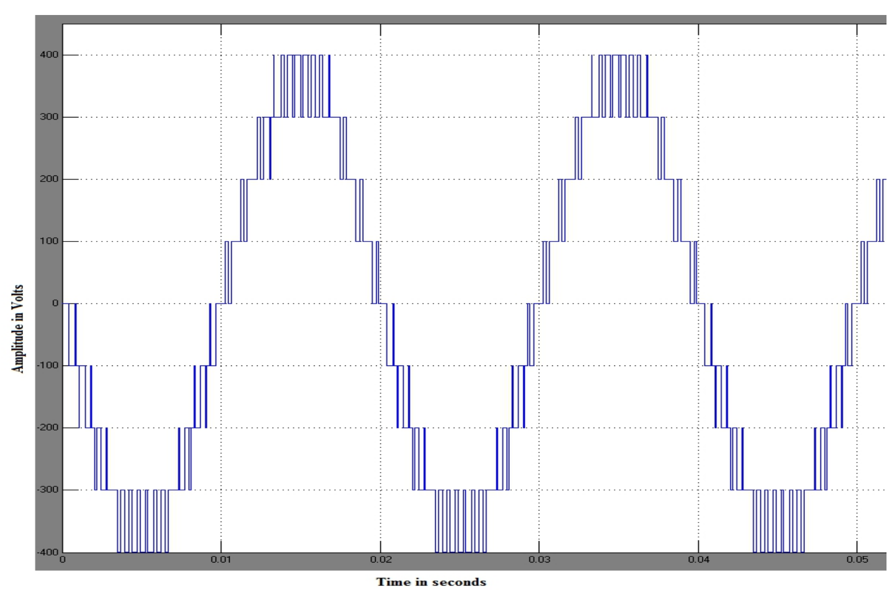


Fig.3.4.8. Multi-step waveform

3.4.9 Debugging the Simulation

Simulink supports debugging with the Simulation Stepper, which lets we step back and forth through your simulation viewing data on scopes or inspecting how and when the system changes states.With the Simulink debugger we can step through a simulation one method at a time and examine the results of executing that method. As the model simulates, you can display information on block states, block inputs and outputs, and block method execution within the Simulink Editor.

3.5 SIM POWER SYSTEMS

SimPowerSystems™ provides component libraries and analysis tools for modeling and simulating electricalpower systems. The libraries include models of electrical power components, including three-phase machines,electric drives, and components for applications such as flexible AC transmission systems (FACTS) andrenewable energy systems. Harmonic analysis, calculation of total harmonic distortion (THD), load flow, and
other key electrical power system analyses are automated. SimPowerSystems was developed by Hydro-Québec ofMontreal.

SimPowerSystems models as shown in **Fig.3.5**can be used to develop control systems and test system-level performance. We canparameterize the models using MATLAB® variables and expressions, and design control systems for theelectrical power system in Simulink®. We can add mechanical, hydraulic, pneumatic, and other components tothe model using Simscape™ and test them all in a single simulation environment. To deploy models to othersimulation environments, including hardware-in-the-loop (HIL) systems, SimPowerSystems supports C-code generation.

Starting with MathWorks Release 13, SimPowerSystems and SimMechanics ofthe Physical Modeling product family work together with Simulink® to modelelectrical, mechanical, and control systems.Electrical power systems are combinations of electrical circuits andelectromechanical devices like motors and generators. Engineers working inthis discipline are constantly improving the performance of the systems.Requirements for drastically increased efficiency have forced power systemdesigners to use power electronic devices and sophisticated control systemconcepts that tax traditional analysis tools and techniques. Furthercomplicating the analyst's role is the fact that the system is often so nonlinearthat the only way to understand it is through simulation.

Land-based power generation from hydroelectric, steam, or other devices is notthe only use of power systems. A common attribute of these systems is their useof power electronics and control systems to achieve their performanceobjectives.SimPowerSystems was designed to provide a modern design tool that allowsscientists and engineers to rapidly and easily build models that simulate powersystems.

SimPowerSystems uses the Simulink environment, allowing you tobuild a model using simple **click and drag**procedures. Not only can you drawthe circuit topology rapidly, but your analysis of the circuit can include itsinteractions with mechanical, thermal, control, and other disciplines. This ispossible because all the electrical parts of the simulation interact with theextensive Simulink modeling library. Since Simulink uses MATLAB® as itscomputational engine, designers can also use MATLAB toolboxes and Simulink blocksets. Sim Power Systems and SimMechanics share a specialPhysical Modeling block and connection line interface.
Users can rapidly put Sim Power Systems to work. The libraries contain models of typical power equipment such as transformers, lines, machines, and power electronics. These models are proven ones coming from textbooks, and theirvalidity is based on the experience of the Power Systems Testing andSimulation Laboratory of Hydro-Québec, a large North American utilitylocated in Canada. The capabilities of SimPowerSystems for modeling a typicalelectrical grid are illustrated in demonstration files. And for users who want torefresh their knowledge of power system theory, there are also self-learningcase studies.

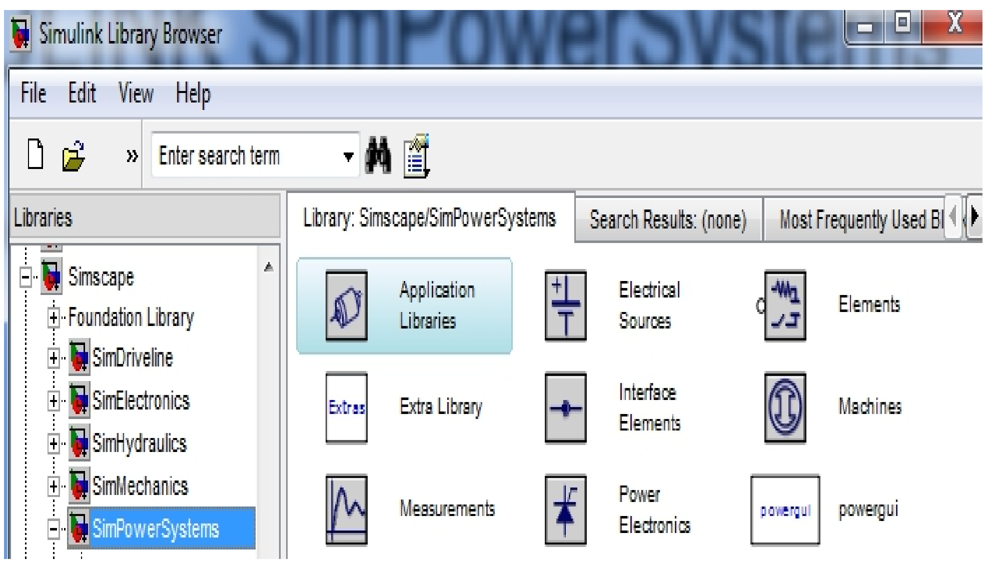


Fig.3.5. SimPowerSystems pane

3.6 Modeling Electrical Power Systems

With SimPowerSystems, we build a model of a system just as we would assemble a physical system. Thecomponents in the model are connected by physical connections that represent ideal conduction paths. Thisapproach describes the physical structure of the system rather than deriving and implementing theequations for the system. From the model, which closely resembles a schematic, SimPowerSystemsautomatically constructs the differential algebraic equations (DAEs) that characterize the behavior of the system.These equations are integrated with the rest of the Simulink model.

We can use the sensor blocks in SimPowerSystems to measure current and voltage in your power network, andthen pass these signals into standard Simulink blocks. Source blocks enable Simulink signals to assignvalues to the electrical variables current and voltage. Sensor and source blocks connect a control algorithmdeveloped in Simulink to a SimPowerSystems network.

3.7 Modeling Custom Components

SimPowerSystems enables to model custom components by using the fundamental elements included in itslibraries and by combining these elements with Simulink blocks.

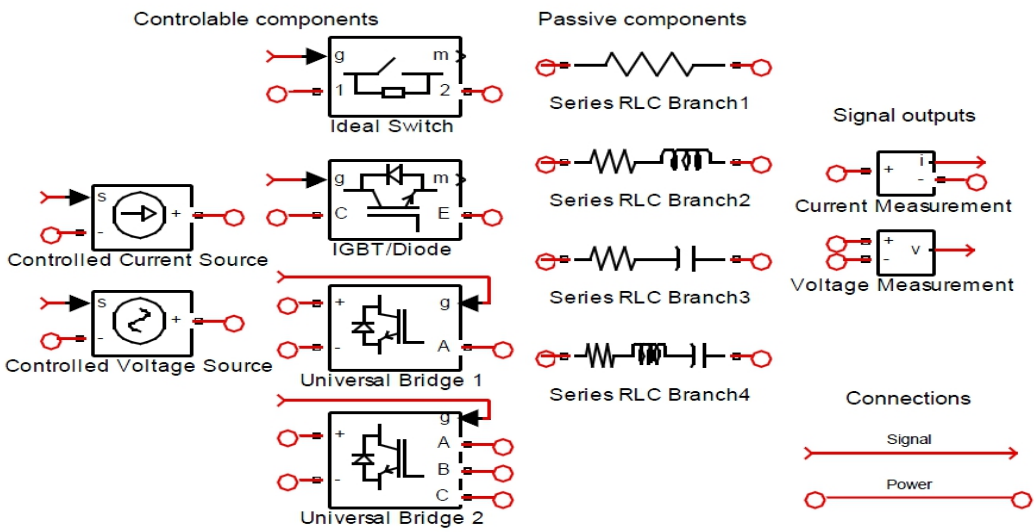


Fig.3.7.1. Simpower system Libraries

Components provided in SimPowerSystems as shown in **Fig.3.7.1** include:

Electrical elements: Linear and saturable transformers; arrestors and breakers; and transmission line models.

Electric machinery: Models of synchronous, permanent magnet synchronous, and DC machines; excitationsystems; and models of hydraulic and steam turbine-governor systems

Power electronics: Diodes, simplified and complex thyristors, GTOs, switches, IGBT models, and universalbridges that allow selection of standard bridge topologies

Control and measurement: Voltage, current, and impedance measurements; RMS measurements; active andreactive power calculations; timers, multimeters, and Fourier analysis; HVDC control; total harmonic distortion;and abc-to-dq0 and dq0-to-abc transformations

Electrical sources: To implement sinusoidal current source, sinusoidal voltage source, generic battery model, Controlled AC Current and Voltage sources, DC Voltage Source. To implement three-phase voltage source with programmable time variation of amplitude, phase, frequency, and harmonics, and to implement three-phase source with internal R-L impedance. The entire blocksets is shown in **Fig.3.7.2**

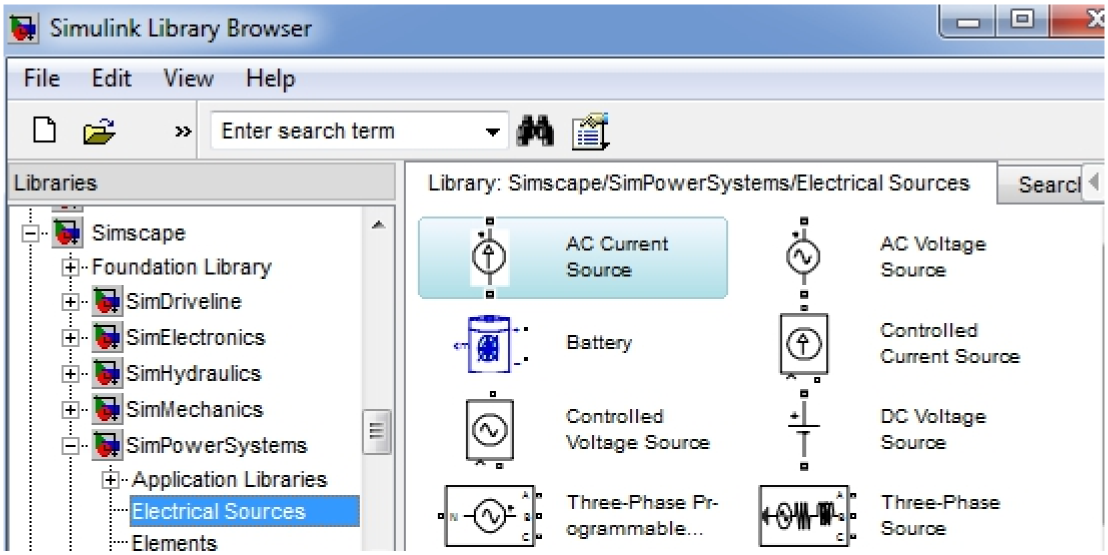


Fig.3.7.2. Blocksets of electrical sources used in SimPowerSystems

Three-phase components: RLC loads and branches; breakers and faults; *pi*-section lines; voltage sources;transformers; synchronous and asynchronous generators; and motors, analyzers, and measurements

Electric Drives and Other Application Libraries

SimPowerSystems provides the following specialized application libraries:

Flexible AC Transmission Systems (FACTS): Phasor models of flexible AC transmission systems

Distributed Resources: Phasor models of wind turbines

Electric Drives: Editable models of electric drives that include detailed descriptions of the motor, converter, andcontroller for each drive. The Electric Drives library includes permanent magnet, synchronous, and asynchronous (induction) motors. The converters and controllers implement the most common strategies for controlling the speed and torque for these motors, such as direct-torque control and field-oriented control.

SimPowerSystems supports the development of complex, self-contained power systems, such as those in automobiles, aircraft, manufacturing plants, and power utility applications. You can combine SimPowerSystems with other MathWorks physical modeling products to model complex interactions in multi-domain physical systems. The block libraries and simulation methods in SimPowerSystems were developed by Hydro-Québec of Montreal.

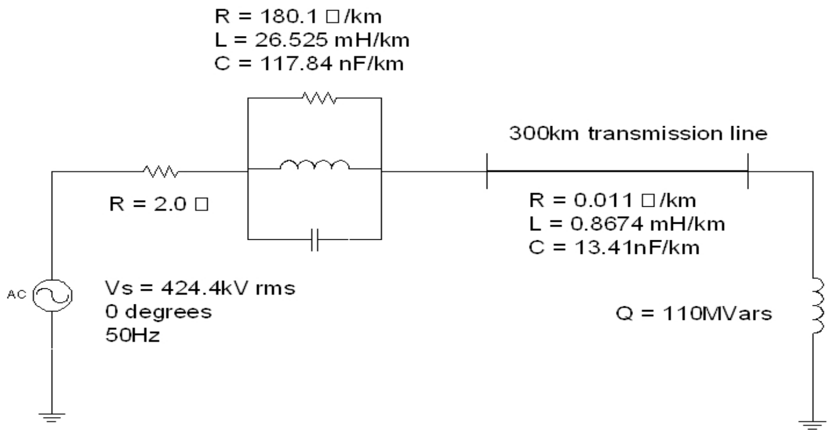


Fig.3.7.3. Circuit of a transmission line

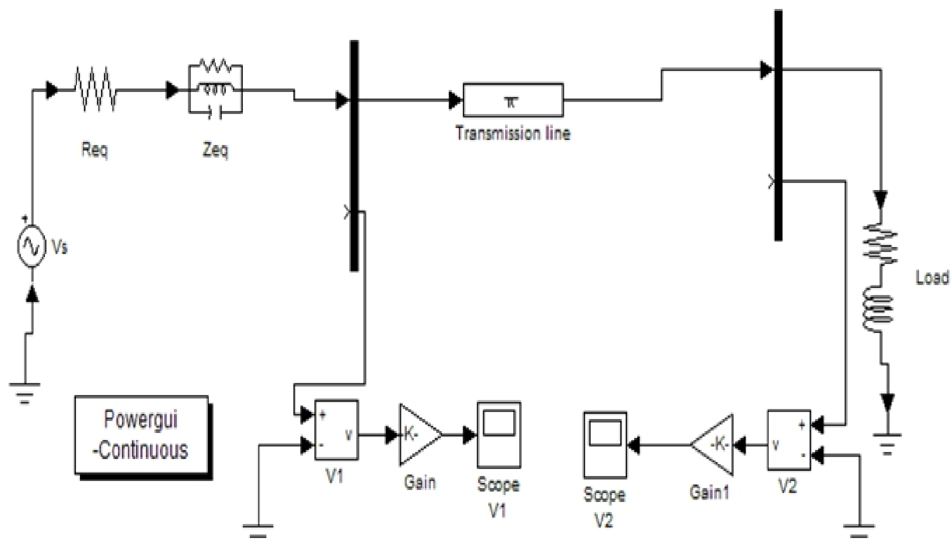


Fig.3.7.4. Same circuit designed in Simulink window

Thus users can rapidly put SimPowerSystems to work. The libraries that containing modelsof typical power equipment such as transformers, lines, machines, and powerelectronics are used to construct a electrical circuit shown in **Fig.3.7.3** and the completely designed circuit of the same in Simulink window as shown in **Fig.3.7.**4

3.8 Connecting to Hardware

We can connect the Simulink model to hardware for rapid prototyping, hardware-in the-loop (HIL) simulation, and deployment on an embedded system.

3.8.1 Running Simulations on Hardware

Simulink provides built-in support for prototyping, testing, and running models on low-cost target hardware, including Arduino®, LEGO® MINDSTORMS® NXT, PandaBoard, and BeagleBoard. We can design algorithms in Simulink for control systems, robotics, audio processing, and computer vision applications and see them perform in real time.

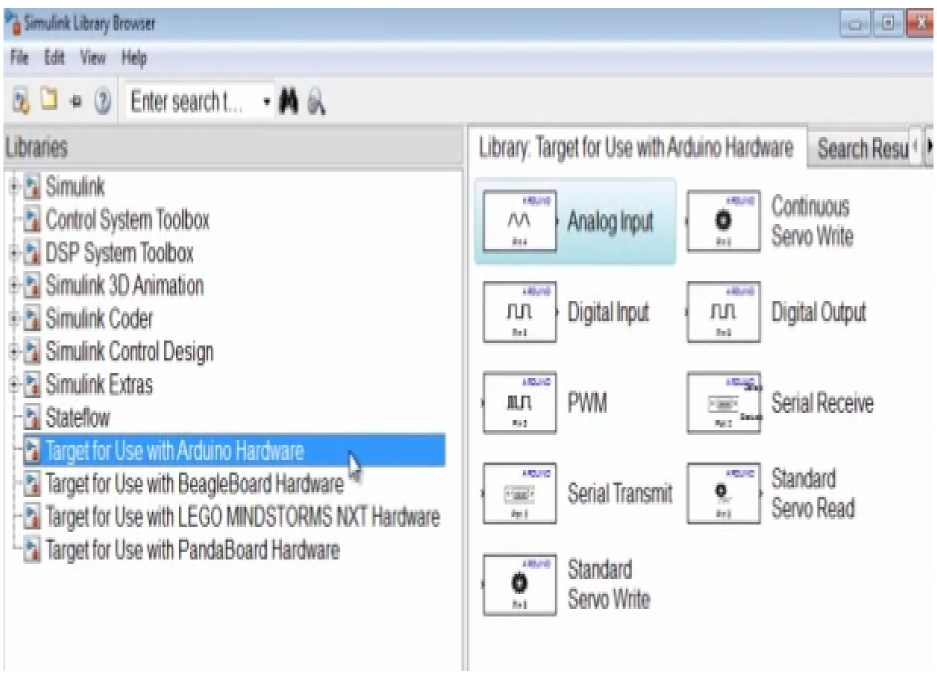


Fig.3.8.1. Hardware Interface to simulink

Simulink provides built-in support for prototyping, testing, and running models on low-cost target hardware, including Arduino®, LEGO® MINDSTORMS® NXT, and BeagleBoard as shown in Fig.3.8.2.

Fig.3.8.2.low-cost target hardware

With Real-Time Windows Target™, we can run Simulink models in real time on Microsoft® Windows® PCs and connect to a range of I/O boards to create and control a real-time system as shown in **Fig.3.8.1** To run the model in real time on a target computer, we can use xPC Target™ for HIL simulation, rapid control prototyping, and other real-time testing applications. See xPC Target Turnkey for available target computer hardware.Simulink models can be configured and made ready for code generation. By using Simulink with add-on code generation products, you can generate C and C++, HDL, or PLC code directly from your model.

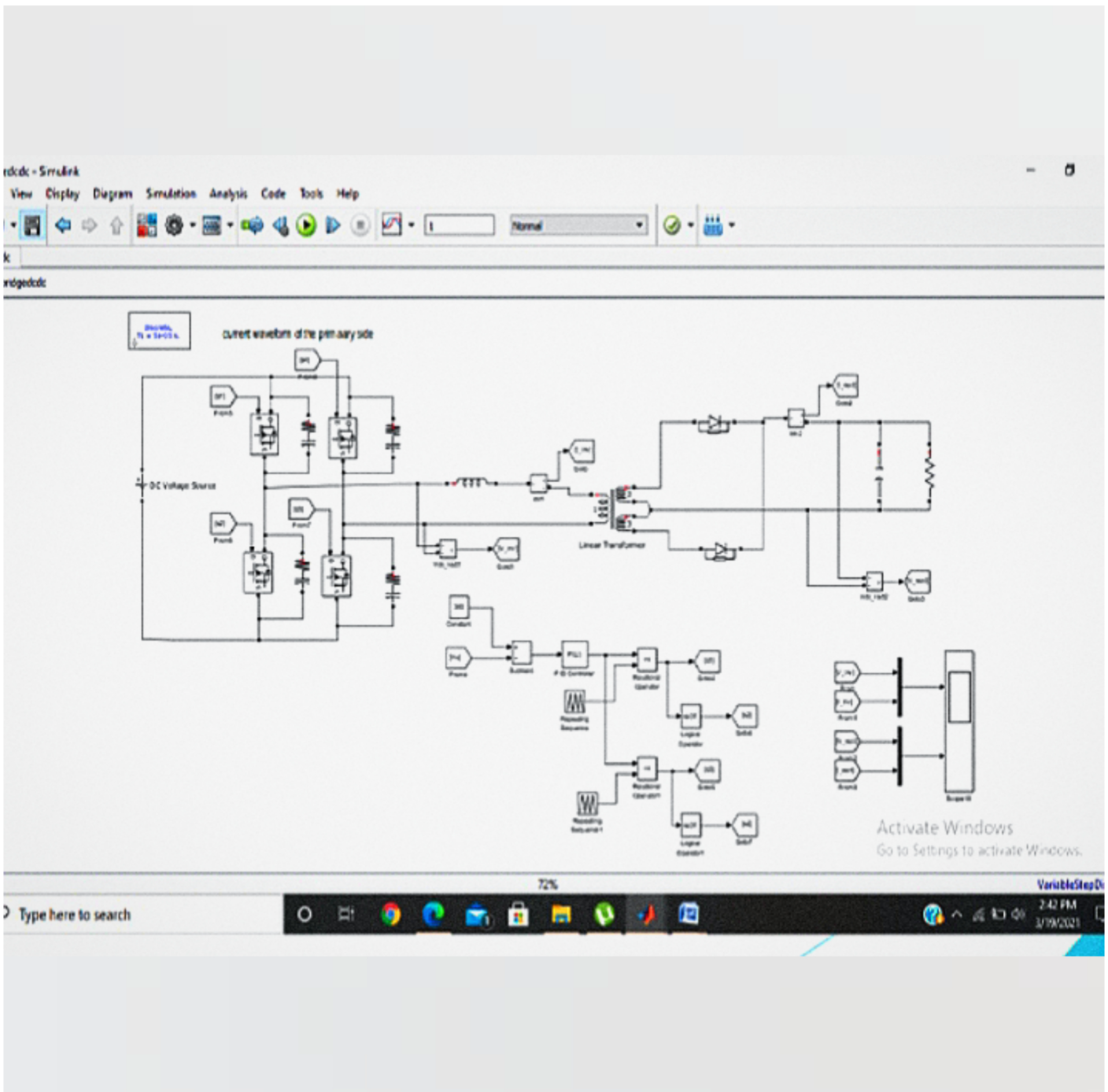
3.9 APPLICATIONS

A number of MathWorks and third-party hardware and software products are available for use with Simulink. For example, Stateflow extends Simulink with a design environment for developing state machines and flow charts.Coupled with Simulink Coder, another product from MathWorks, Simulink can automatically generate C source code for real-time implementation of systems. As the efficiency and flexibility of the code improves, this is becoming more widely adopted for production systems, in addition to being a popular tool for embedded system design work because of its flexibility and capacity for quick iteration. Embedded Coder creates code efficient enough for use in embedded systems.

xPC Target together with x86-based real-time systems provides an environment to simulate and test Simulink and Stateflow models in real-time on the physical system. Embedded Coder also supports specific embedded targets, including Infineon C166, Motorola68HC12, Motorola MPC 555, TI C2000, TI C6000, RenesasV850 and RenesasSuperH.With HDL Coder, also from MathWorks, Simulink and Stateflow can automatically generate synthesizableVHDL and Verilog.

Simulink Verification and Validation enables systematic verification and validation of models through modeling style checking, requirements traceability and model coverage analysis. Simulink Design Verifier uses formal methods to identify design errors like integer overflow, division by zero and dead logic, and generates test case scenarios for model checking within the Simulink environment.The systematic testing tool TPT offers one way to perform formal test- verification and validation process to stimulate Simulink models but also during the development phase where the developer generates inputs to test the system. By the substitution of the Constant and Signal generator blocks of Simulink the stimulation becomes reproducible.

SimEvents adds a library of graphical building blocks for modeling queuing systems to the Simulink environment. It also adds an event-based simulation engine to the time-based simulation engine in Simulink.



CHAPTER-IV

MATLAB RESULTS

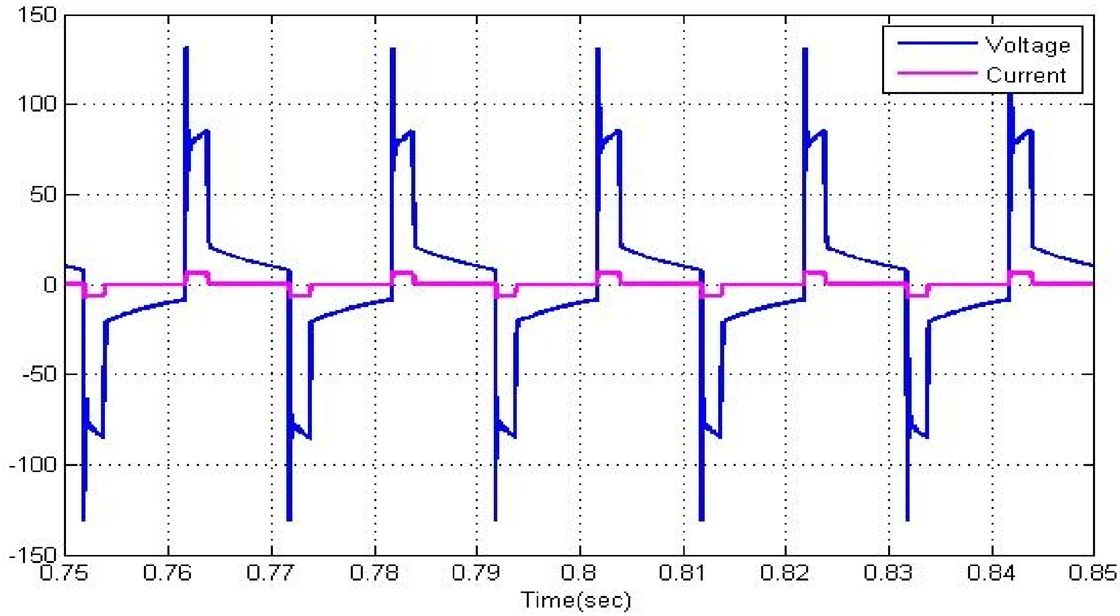


Fig.4.1. Voltage difference of bridge leg middle points and resonant inductor current

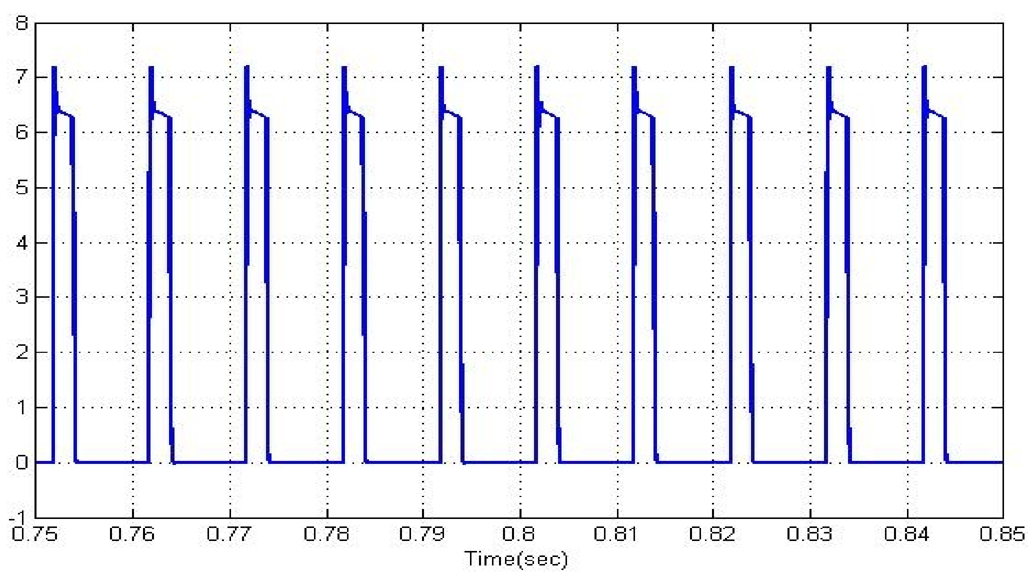


Fig 4.2. Voltage and current waveforms of secondary side rectifier diode

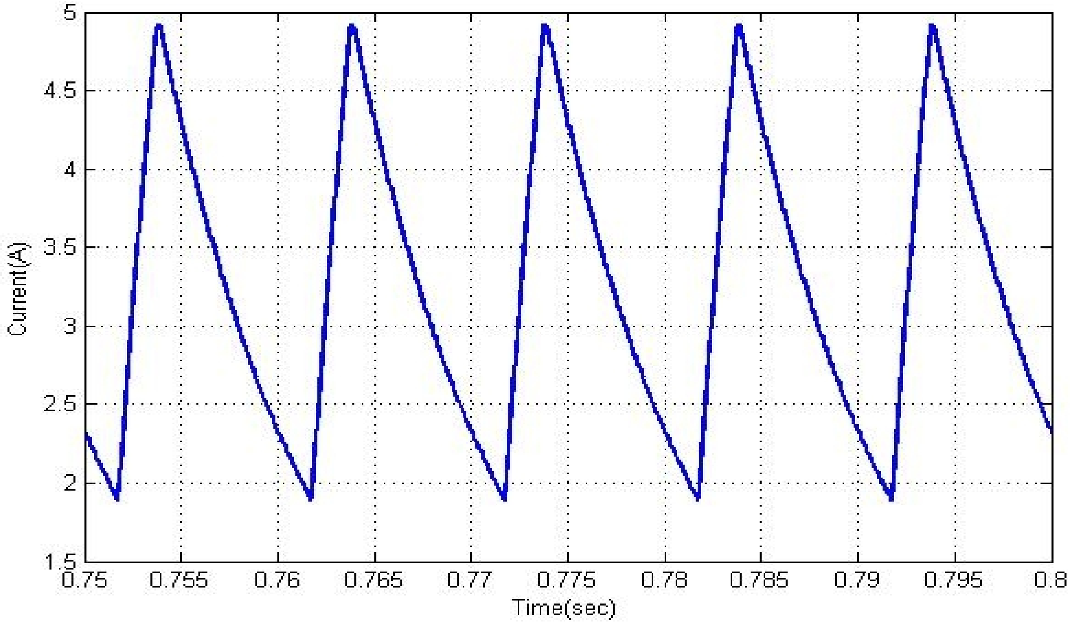


Fig 4.3 Current waveform of primary side resonant inductor

CHAPTER-V

CONCLUSION

This project investigates a multi-mode control strategy for current-fed full-bridge converter used in electric vehicles. According to the load condition, the strategy combines BCM,DCM, MCM together to achieve high efficiency across wide load range. The peak efficiency of established prototype is 96.2% at the point of about 75% load. Efficiency is kept higher than 95% for most of the load range.

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