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Digital control of Parallel Buck Converter

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***Abstract* - In this paper, design for digital control of parallel buck converter was simulated in MATLAB/Simulink. Digital controls are becoming dominant in almost every power electronic application because of its advantages when compared to analog control. The main aim of the paper is to achieve the digital control of parallel buck converters. By using the parallel buck converters, increased reliability and flexibility have been improved. Digital control also provides immunity to noise. Digital controller has low component ageing, low cost, zero drift characteristic, high reliability and controllability than other controllers. Digital control in power electronics has been intensively used during the last decade. In this paper, digital control of parallel buck converter was carried out.**

***Keywords* – Parallel Buck Converter, Voltage Mode Control, Current Mode Control, Analog to Digital Converter, Zero order hold.**

I. INTRODUCTION

In the developed world today there exist many technologies which rely on DC-DC converters. These technologies range from the simple cell phone charger and desktop computer power supply to large electric vehicle chargers and DC power distribution stations. Within all of these DC-DC converters there exist known inefficiencies which waste power during the use of the converter. Each converter is designed with a specific load current range in mind, and the efficiency is optimized over this range.

With larger and larger DC-DC converters being designed and used in industry, the main components (inductors, capacitors, switches, diodes, etc.) become increasingly expensive and large. As these converters are becoming more wide-spread, they are required to perform continuously without failures or faults, sometimes in harsh environmental conditions. These shortcomings of the DC-DC converter are what led to the development of systems employing parallel-connected DC-DC converters.

Parallel converters have become an emerging technique in power supply design for improving power processing, reliability and flexibility. There exist several advantages to parallel connected DC-DC converters including improved efficiency, decreased stress on critical components

Digital controller has low component ageing, low cost, zero drift characteristic, high reliability and controllability than other controllers. Digital control in power electronics has been intensively used during the last decade. The improved performances and price reduction of digital controller has enable their application in power electronic control. The primary advantages of digital control over analog control are higher increased flexibility by changing the software, more advanced control techniques and reduced number of components. The implementation of complex control function with analog circuits is difficult but using a digital programmable device, the implementation becomes easier.

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Switch mode DC-DC converters efficiently convert an unregulated DC input voltage into a regulated DC output voltage. Compared to linear power supplies, switching power supplies provide much more efficiency and power density. Switching power supplies employ solid-state devices such as transistors and diodes to operate as a switch, either completely on or completely off. Energy storage elements, including capacitors and inductors, are used for energy transfer and work as a low-pass filter. [9] presented a brief outline on Electronic Devices and Circuits which forms the basis of the Clampers and Diodes.

Switch-mode DC-DC converters include buck converters, boost converters, buckboost converters, Cuk converters and full-bridge converters, etc. Among these converters, the buck converter and the boost converter are the basic topologies. Both the buck-boost and Cuk converters are combinations of the two basic topologies. The full-bridge converter is derived from the buck converter. There are usually two modes of operation for DC-DC converters: continuous and discontinuous. The current flowing through the inductor never falls to zero in the continuous mode. In the discontinuous mode, the inductor current falls to zero during the time the switch is turned off. The major advantages of digital control over analog control are higher immunity to environmental changes such as temperature and aging of components, increased flexibility by changing the software, more advanced control techniques and shorter design cycles.

II. DESIGN OF DIGITAL CONTROL OF PARALLEL BUCK CONVERTER

A. Reason for Using Buck Converter

The name Buck Converter itself indicates that the input voltage is bucked or attenuated and low voltage appears at the output. A buck converter or step down voltage regulator provides non isolated, switch mode dc-dc conversion with the advantage of simplicity and low cost. It shows a simplified dc-dc buck converter that accepts a dc input and uses pulse width modulation of switching frequency to control the output voltage. The buck converter consists of Source Voltage, Diode, Inductor, Inductor Resistance, Capacitor, and Capacitive Resistance all connected to a Load.

The dc-dc buck converter topology is most widely used in power management and microprocessor voltage-regulator applications. These applications require high frequency and transient response over a wide load current range. They can convert high voltage into low regulated voltage. Buck converter can be used in computers, where we need voltage to be stepped down. Buck converter provides long battery life for mobile phones which spend most of the time in stand-by state.

In general the simplest way to reduce the voltage of a DC supply is by using linear regulators. The source voltage is V_s which is to be step down to across the resistor which means the voltage across the resistor must be dropped which intern results in waste of power in the form of heat .This problem can be overcome by using Buck Converter as it uses switch (Diode) to operate in ON and OFF states.

B. Working principle of Buck Converter

The buck converter converts the unregulated source voltage V_{in} into a lower output voltage V_{out}. The mosfet works as a switch. The ratio of the ON time (T_{ON}) when the switch is closed to the entire switching period (T) is defined as the duty cycle D =Ton/T. The buck converter consists of main power switch, a diode, a low-pass filter (L and C) and a load.

The basic buck converter operates in ON and OFF states. In ON state, when the switch is closed the current to load is supplied from source voltage through inductor, where inductor gets charged to its peak level. In OFF state, when switch is open the inductor acts as source to the load. The timing of the switch operations are determined by the PWM control signal. During steady state, the ratio of output voltage over input voltage is D, which is given by, ——

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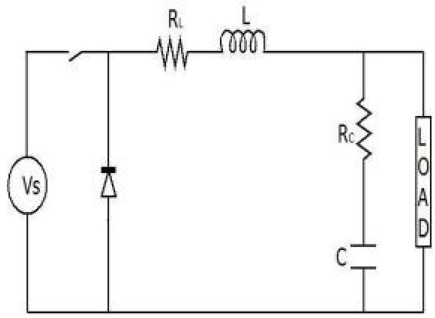

Fig.1 Buck Converter

During on state operation, the switch will be in closed state so that Vs will be the source voltage for the inductor as shown in fig.2. Obviously in this state the current through the diode flows from negative terminal to positive terminal which causes diode to be inactive. Hence there will be no backward current to the inductor. Inductor controls sudden changes in the current when the switch is on.

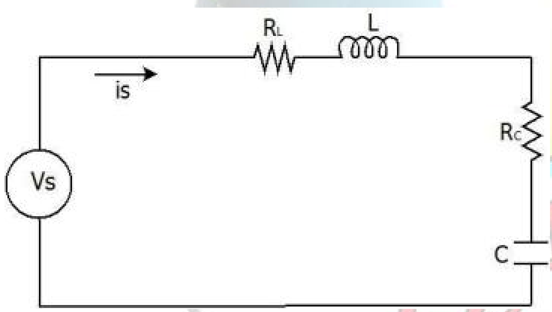

Fig. 2 Buck Converter in ON State

During off state operation, the switch will be in open state so that there will be no path to current to flow from source voltage Vs to inductor,shown in fig.3. In this state, inductor starts discharging, which causes current in diode to flow from positive to negative terminals. Hence there will be a backward current to the inductor. This acts as a low pass filter and removes harmonics in the output. It must be chosen large enough in accordance to control the voltage changes, overshoots, ripples during the time when the switch is changing on and off.

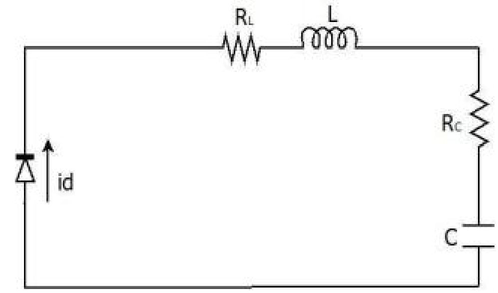

Fig 3 Buck Converter in OFF State

C. Design Values

Table1

CONVERTER SPECIFICATIONS

Input Voltage	12 V
Output Voltage	6 V
Duty Cycle	0.5
Inductor	4.1 mH
Capacitor	376 µF
Switching Frequency	100 KHz

D. Parallel Buck Converter

The parallel connection of switch mode converter is a well known strategy. It involves phase shifting of two or more buck converters connected in parallel and operating at the same switching frequency. Two buck converters are connected in parallel feeding a common resistive load,shown in fig 4. Converters are connected in parallel to equalize the load currents in the individual converters. The two converters are working at the same switching frequency so as to reduce the current ripple, conduction losses, Lower switching frequency for each phase to fast transient response. Using a parallel scheme, where switch S_1 and inductance L_1 are for converter1 while S_2 and L_2 for converter2. The switches and diodes conduct in complementary fashion. If switch S_1 conducts, then diode D_1 will not conduct and vice versa. The circuit operates as, the inductor current flows continuously over one switching period. The switch is either on or off according to the switching function and this results in two circuit states. The first sub-circuit state is

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when the switch is turned on, diode is reverse biased and inductor current flows through the switch, the second sub-circuit state is when the Switch is turned off and current freewheels through the diode.

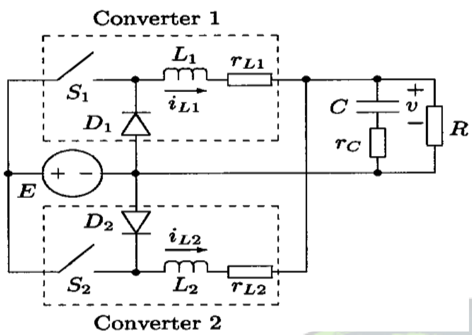

Fig. 4 Parallel Connected Buck Converter

E. Current Sharing Mechanisms

Parallel converters operate under closed-loop feedback control to regulate output voltage, equalize the currents in the individual converters. A parallel DC-DC converter provides smooth acceleration control, high efficiency and fast dynamic response. To achieve the above advantages, two current sharing mechanisms are used namely, voltage mode control, current mode control. The control concepts are proposed to provide sharing of load currents between parallel connected converters. To control the switch, Pulse width modulation (PWM) is the most frequently used control method. A saw-tooth signal is compared with a control signal to produce a series of pulses that control the states of the power electronic switches. The controlled system provides a more accurate and faster current limit under over load condition.

1.Voltage Mode Control

In Voltage mode control (VMC) the Output voltage of the Convertor is again fed back to an error amplifier and compared with a reference voltage fed externally. The difference in Voltage is passed through a Control Unit and fed to a comparator. The Ramp Signal and the voltage difference fed produce the Pulse to control the Switch. Since only the output voltage from the converter is used to produce the pulse this method is called voltage Mode Controller. The analog PWM feedback logic controls the switching action. This is achieved by obtaining a control voltage V_{con} as function of the output voltage Vo and a reference signal in the form, Where Kp is the gain of proportional controller .An externally generated saw-tooth voltage defined as V_{ramp} is used to determine the switching instants.

$$V_{ramp(t)} = V_L + (V_U - V_L) * F * (t/TS)$$

where Ts is the time period and V_U and V_L are upper and lower threshold voltages respectively. Here F(x)denotes the fractional part of (x),In voltage mode control, the controlled voltage V_{con} is then compared with the periodic saw-tooth wave V_{ramp}, to generate the switching signal q [1, 0] is described by,

If $V_{ramp} < V_{con}$, q=1

$V_{ramp} > V_{con}$, q=0

The inductor current increases while the switch is on, q=1 and falls while the switch S is off , q=0.

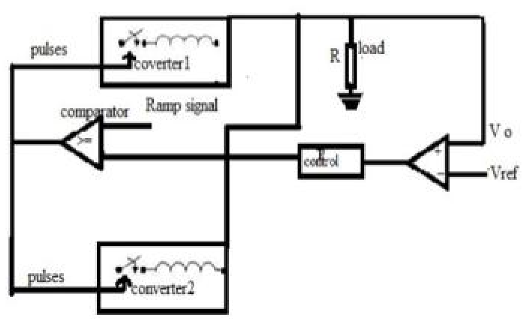

Fig.5Block Diagram of Voltage Mode Control

2. Current Mode Control

There are two feedback loops in the current-mode controlled dc-dc converter, a current feedback loop and a voltage feedback loop. The inductor current is used as a feedback states. Both the inductor currents and the output voltage controlled by this scheme. The control strategy is designed such that the inductor current I_{L1}, I_{L2} currents follows the sinusoidal line voltage. An analog multiplier

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generates the current programming signal by multiplying the rectified line voltage with the output of the voltage error amplifier. This modulation makes the current programming signal follow the shape of input voltage. The signal acts as a reference current. It is compared with the switch current in a PWM comparator. The resulting pulses drive a mosfet. The control input signal is proportional to reference current i_{ref}. The reference current i_{ref} is a function of output of the controller to regulate the output voltage. The control voltage can be defined as,

$$V_{con}=V_{offset}- K_v(V_o- V_{ref}) - K_i(i_1-m\ i_2)$$

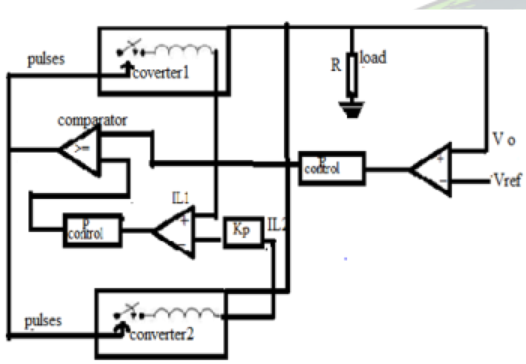

Fig.6 Block Diagram of Current Mode Control

F. Digital Control

Digital controls are increasingly used in power converters because of their advantage when compared to analog controllers. The main advantages of using digital controls over analog are the ability to perform more advanced and sophisticated functions that potentially result in improving power conversion efficiency and dynamic performance of the power converter, the ease of digital control function and loop upgradeability and reduced sensitivity to component variations compared to analog controllers.

1.Block Diagram of Digital Buck Converter

A digital controller for switching mode power supplies is one of the fields that is recently emerging. The reason for digital control becoming more popular in power electronics is its advantages over analog control, such as immunity to component variations and the ability to implement functions that improve the whole system performance. The digital controller consists mainly of three components. They are the analog to digital converter, digital compensation unit and digital pulse width modulator unit. The output voltage is sensed from the buck converter. The sampled output voltage is compared to a reference voltage to result to the error voltage. The voltage error signal is then digitized using the Analog to Digital converter, which is realized in simulink using the ADC blocks. Based on the value of the error signal, the compensator computes for the digital pulse width modulator, which outputs the pulsating switch control waveforms.

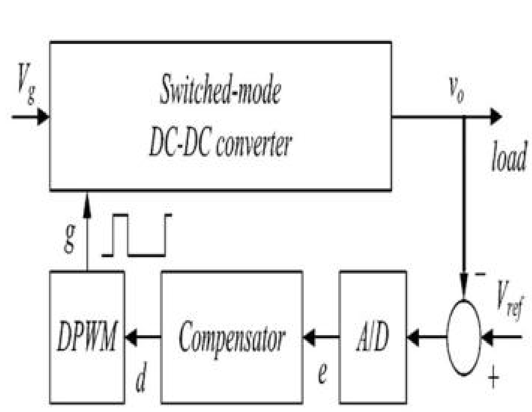

Fig.7 Block Diagram of Digital Buck Converter

The DPWM is the output of the quantized PWM. Ideally, the desired error voltage is zero, but this would always have a small value that is represented digitally using the A/D block. The Zero Order will sample the error voltage that is it will convert the signal from continuous time to discrete time. Relationship of the input and output of the zero order block is given, where T is the sampling period and1/T is the sampling frequency. The Quantizer block sets the number of bit representation or resolution of the signal. Analog to digital conversion was performed whenever analog signals are sampled that is reference voltage, Sampled

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output voltage, and inductor current. Quantization was performed after analog to digital conversion, inside the compensators, and in the PWM circuit. The saturation block models the conversion range of the A/D converter.

G. Block Diagram Description

1. Analog To Digital Converter

Analog to Digital (A/D) is the process of converting a continuous range of analog to digital codes. Such Conversion processes are necessary to interface real-world systems, which typically monitor continuously varying analog signals, with digital systems that process, store, interpret and manipulate the analog values. Analog signals are directly measurable quantities. When signals are in digital form they less susceptible to the deterious effects of additive noise. Analog to digital converter provides a link between the analog world and the digital world. Analog to digital converter are used virtually everywhere, where an analog signal has to be processed, stored, or transported in digital form. There are two ways to best improve the accuracy of A/D conversion. By increasing the resolution which improves the accuracy in measuring the amplitude of the analog signal. By increasing the sampling rate which increases the maximum frequency that can be measured.

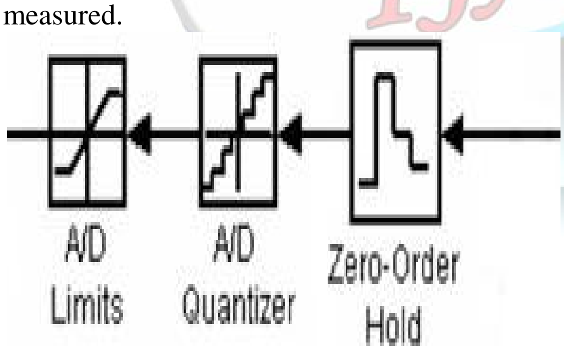

Fig.8 Analog to Digital Converter

2. Zero-Order Hold

The Zero-Order Hold block samples and holds its input for the specified sample period. The block accepts one input and generates one output, both of which can be scalar or vector. If the input is a vector, all elements of the vector are held for the same sample period. The Zero-Order Hold block implements a sample-and-hold function operating at the specified sampling rate. The block accepts one input and generates one output, both of which can be scalar or vector. This block provides a mechanism for discretizing one or more signals or resampling the signal at a different rate. You can use it in instances where you need to model sampling without requiring one of the other more complex discrete function blocks. For example, it could be used in conjunction with a quantizer block to model an A/D converter with an input amplifier. The Zero-Order Hold block is a bus-capable block. The input can be a virtual or nonvirtual bus signal. No block-specific restrictions exist. All signals in a nonvirtual bus input to a Zero-Order Hold block must have the same sample time, even if the elements of the associated bus object specify inherited sample times.

3. A/D Quantizer

The quantizer block passes its input signal through a stair-step function so that many neighboring points on the input axis are mapped to one point on the output axis. The effect is to quantize a smooth signal into a stair-step output. The output is compared using the round-to-nearest method, which produces an output that is symmetric about zero. $y=q*\text{round}(u/q)$ Where y is the output, u is the input, and q is the quantization interval parameter. The quantizer block accepts and outputs real or complex signals of type single or double.

4. A/D Limits

The saturation block imposes upper and lower limits on an input signal. The Saturation dynamic block bounds the range of an input signal to upper and lower saturation values. When the input signal is within the range specified by the lower limit and upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. An input signal

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outside of these limits saturates to one of the bounds where, the input below the lower limit is set to the lower limit. The input above the upper limit is set to the upper limit. The input for the upper limit is the up port, and the input for the lower limit is the low port. A Saturation block accepts and outputs real signals of any data type.

5. Compensator

A first-order lag compensator C(s) can be designed using the root locus. A lag compensator in root locus form is given by the following, This has a similar form to a lead compensator, except now the magnitude of z0 is greater than the magnitude of p0 (and the additional gain Kc is omitted). A phase-lag compensator tends to shift the root locus to the right in the complex s-plane, which is undesirable. For this reason, the pole and zero of a lag compensator are often placed close together (usually near the origin) so that they do not appreciably change the transient response or stability characteristics of the system.

When a lag compensator is added to a system, the value of this intersection will be a smaller negative number than it was before. The net number of zeros and poles will be the same (one zero and one pole are added), but the added pole is a smaller negative number than the added zero. Thus, the result of a lag compensator is that the asymptotes' intersection is moved to the right in the complex plane, and the entire root locus is shifted to the right as well. It was previously stated that a lag compensator is often designed to minimally change the transient response of system because it generally has a negative effect. At high frequencies, the lag compensator will have unity gain. At low frequencies, the gain will be z0 / p0which is greater than 1. This z0 / p0 factor will multiply the position, velocity, or acceleration constant (Kp, Kv, or Ka), and the steady-state error will thus decrease by the same factor.

6. Digital Pulse Width Modulator

The resolution of the Digital pulse width modulation depends on the number of ADC bits. The digital value is compensated and compared with the reference value which gives the duty cycle. Digital pulse width modulation (DPWM) provides a digital to time domain conversion. The time is quantized into number of discrete slots and is selected by a digital input instead of a carrier ramp signal. The duty cycle is compared with the time slots in order to generate the PWM signal. The Digital Pulse Width Modulator also serves as a D/A converter. The quantizer and saturation block combinely works as a digital to analog converter. The digital error signal e(n) at the A/D output is obtained by quantization of analog error voltage e(t), while the duty cycle d at the DPWM output is obtained by quantization of the duty cycle command k. The characteristic of a quantizer having a continuously varying input x and an output y = Q(x).

The range of x is divided into the binary of width q, where q is the quantization level, or the value of the quantizer's least significant bit . For x in the kth bin, the output y equals the kth discrete output value (y = kq). We choose the quantization interval (q) is 1/1024. The quantized signal is converted into an analog signal by the device of saturation. The gating signals are generated by an analog error corrected signal is compared with the high frequency carrier signal (400 KHz). The frequency of the carrier signal determines the fundamental frequency of the output voltage (d).

III. SIMULATION MODEL AND RESULTS

Using the MATLAB, parallel buck converter in open loop was simulated, shown in fig 9. In the parallel buck converter, input voltage is 12V and the output voltage is 6V.The duty cycle is 0.5.

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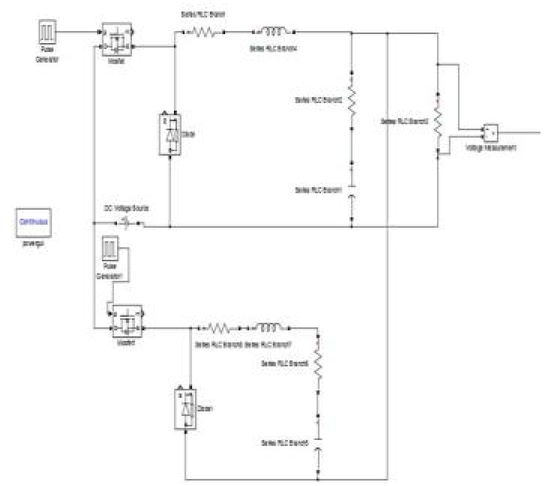

Fig.9 Simulation Model of Parallel buckConverter in Open Loop

Fig10 shows the simulink model of parallel buck converter in voltage mode control, was simulated using MATLAB. For regulating the output voltage and to equalize the load currents in individual converters, closed loop voltage mode control is needed.In voltage mode control, the measured output voltage is compared with the reference voltage and then difference in error is given to the controller and it is compared, then it will drive the switch.

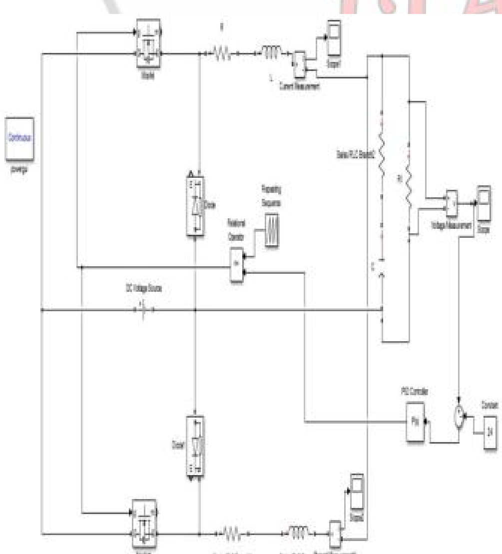

Fig10 Simulation Model of Parallel Buck Converter in Voltage Mode Control

Fig11 shows the simulink model of parallel buck converter in current mode control. In current mode control, there are two loops. They are voltage feedback loop and current feedback loop. In voltage feedback loop, the measured output voltage is compared with the reference voltage and it is given to the controller. In current feedback loop, the two inductor currents are measured. The control signal is produced to drive the switch.

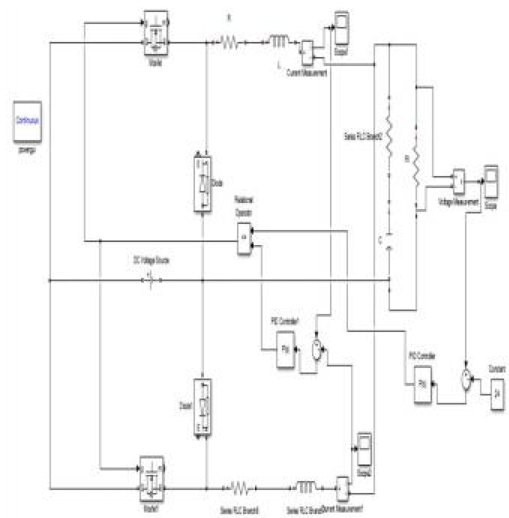

Fig 11Simulation Model of Parallel Buck Converter in Current Mode Control

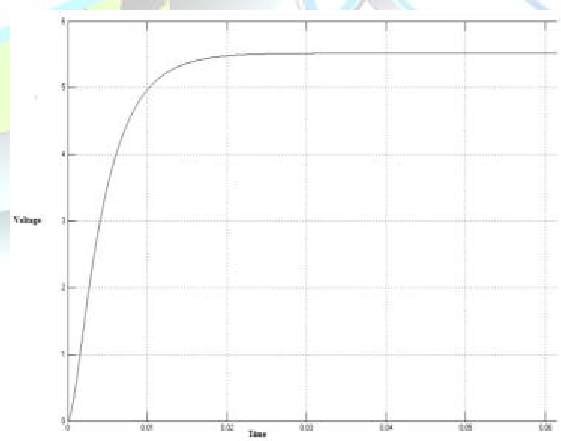

Fig. 12 Simulation Result in Open Loop

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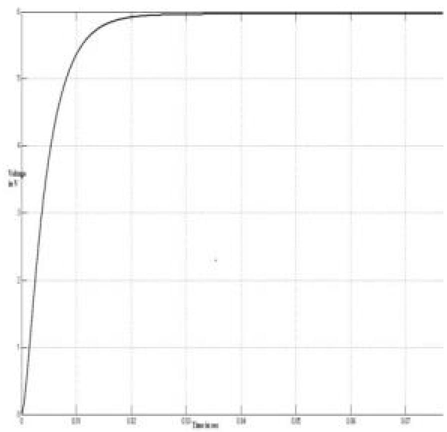

Fig13 Simulation Result in Closed Loop

Fig 12 shows the simulink result of parallel buck converter in open loop. The input voltage is 12V and the output voltage is 6V. In open loop, it is not possible to achieve the 6V.Using open loop exact voltage will not be obtained. For achieving 6 V, closed loop control was implemented. Fig 13 shows the simulink result of parallel buck converter in closed loop. In closed loop control, efficiency of the converter will be improved.

IV CONCULSION

The digital control of parallel buck converter was simulated in Matlab. The digital parallel buck converter offers more advantages such as reduced stress on critical components, flexibility and reliability. To share the load currents, current control mechanisms were designed. Digital controllers are often superior in performance and lower in price than their analog counterparts. Digital controllers offer more advantages than analog controller.

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