

THE DEVELOPMENT OF MULTI LEVEL BUCK CONVERTER

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## ABSTRACT

A DC/DC converter generally needs to work under high switching frequency when used as an adjustable power supply to reduce the size of magnetic elements such as inductors, transformers and capacitors, but with the rising of the switch frequency, the switch losses will increase and the efficiency will reduce. To solve these problems, research is actively being done on a soft switching method that can be applied under high frequency and on a PWM converter that can be applied under low frequency such as a multi level topology. In this project, a DC-DC conversion method for reducing the ripple of output voltage is proposed. In this proposed converter, buck converters are connected in series to generate the output voltage. By using this method, the ripple of output voltage can be reducing compared to a conventional buck converter. Particularly when output voltage is low, the number of acting switching elements is less and the result of ripple reduction is more obvious, it is expected that the converter proposed in this project could be very useful in the case of wide-range output voltage.

## ABSTRAK

Penukar DC / DC umumnya diperlukan untuk bekerja di bawah frekuensi pensuisan yang tinggi apabila digunakan sebagai bekalan kuasa boleh laras bagi mengurangkan saiz unsur-unsur magnet seperti indukter, transformer dan kapasitor, tetapi dengan peningkatan kekerapan suis, kerugian suis akan meningkat dan kecekapan akan berkurang. Bagi menyelesaikan masalah-masalah ini, penyelidikan sedang giat dilakukan pada kaedah pensuisan yang lembut bagi membolehkan ia diguna pakai di bawah frekuensi tinggi dan pada penukar PWM yang boleh digunakan di bawah frekuensi rendah seperti topologi tahap yang berbilang. Dalam projek ini, satu kaedah DC-DC penukar untuk mengurangkan riak voltan keluaran adalah dicadangkan. Dalam penukar yang dicadangkan ini, penukar buck disambung secara siri untuk menjana voltan keluaran. Dengan menggunakan kaedah ini, riak voltan keluaran boleh dikurangkan berbanding dengan penukar buck konvensional. Terutamanya apabila voltan keluaran adalah rendah, bilangan yang bertindak menukar unsur-unsur kurang dan hasil pengurangan riak lebih jelas, ia dijangka bahawa penukar yang dicadangkan dalam projek ini menjadi sangat berguna dalam kes voltan keluaran jarak lebar.

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**LIST OF ABBREVIATIONS**

DC	Direct Current
CCM	Continues Conduction Mode
VMC	Voltage Mode Control
PWM	Pulse Width Modulation
MOSFET	Metal Oxide silicon Field Effect Transistor
BJT	Bipolar Junction Transistor
$R_{DS(on)}$	Static Drain-Source on Resistor
$V_{DSS}$	Drain to Source Voltage
ESR	Equivalent Series Resistor
IC	Integrated Circuit

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## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background of the Project**

The DC-DC converter is a type of power converter in power electronic is the circuits that convert the voltage from one DC to another DC level. Power electronics are become importance device in the world, which is widely used to control and conversion electrical power. In general, DC to DC converters are widely used at home and industries to produce the desired output power. The converter devices are uses in a variety applications for the power ranging from watt (mobiles phones), kilowatts (dc motor drives) to megawatts (vehicles). There are many types of dc-dc converter like buck converter, boost converter, buck-boost converter and etc in power electronics. With these converters, they can perform different types of applications: step-down of voltage, step-up, inversion of polarity, and conversion of dc to dc or vice versa.

A DC to DC converter usually works under high frequency to reduce the size of inductors, transformers, capacitors and so on. However, the higher the switching frequency, the more losses suffered, which result in a new problem of efficiency reduction. Recent studies mainly focus on two fields: one is on software switching methods to reduce the losses of switching under high working frequency conditions and the other is on the structure of multi-level converter under low frequency working conditions.

In this project, a multi-level DC to DC conversion method is presented to reduce the output voltage ripple of DC-DC converters. The proposed converter producing multi-voltage is made of buck converter in series, which reduces the ripple of output voltage compared to traditional buck converters. Furthermore, the number of acting switch elements will be reduced when the output voltage is lower, so that the multi-level DC/DC conversion method has a special advantage under lower output voltage. The proposed converter is especially for application to wide range output.

## **1.2 Problems Statement**

There are a lot of procedures in designing and implementing the multi level DC-DC buck converter. These involved a procedure from specification of converter, circuit topology selection, simulation to validate the design, components selection and lastly hardware implementation. Although the simulation gives a desired result, there are still gaps between theoretical principle and practical accomplishment. This happens because in theory, the calculation is done by making assumptions which can simplify or make the analysis. However, the hardware will be designed by observing the previous projects or research. The entire problem from the previous problem can be solved.

## **1.3 Objective**

There are three objectives in this project. Firstly, is to analyze the performance of multi level buck converter in wide ranges. For the structure of multi-level buck converter, the output parts of buck converter are connected in series which ensure the output isolation of all converters. Besides, to reduce the ripple of output voltage by using buck converter that connected in series. Lastly, to develop a prototype of multi-level buck converter using printed circuit board.

## **1.4 Scope of project**

There are many prototypes of dc-dc converters were being design and developed in recent years to meet the specific applications and purposes. So this project, it will focus on the fundamental use of dc-dc buck converter. It is to avoid the non-minimum phase problem that associated while using other converter such as boost and buck-boost converter.

Even there is several control modes like current control mode (CCM) and also sliding mode control, this project only use voltage mode control (VMC). VMC is useful when it comes if the sensitivity to the current loop is not desired and when there is a wide input variation or when multiple outputs are needed.

## **CHAPTER 2**

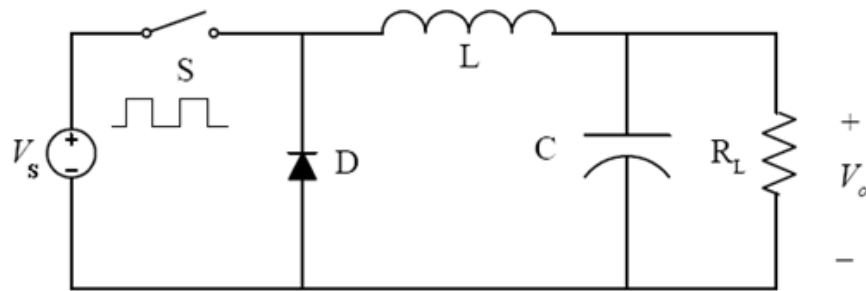
### **LITERATURE REVIEW**

#### **2.1 Introduction**

In the implementation of power conversion electronics circuits, one or more of the three basic configuration are usually employed. Other circuit topologies are usually gained from one or more of these configurations. The three basic configurations are the buck converter, the boost converter and the buck – boost converter. They are called basic means that only one switch is used and that there is no isolation from the output circuits.

#### **2.2 Buck converter**

Buck converter is a simplest power stage topology that converts a higher input voltage to a lower output voltage. The basic buck converter circuit or step-down switch mode power supply can also be called a switch mode regulator. The structure of a conventional non-isolated buck converter is shown as Figure 2.1.

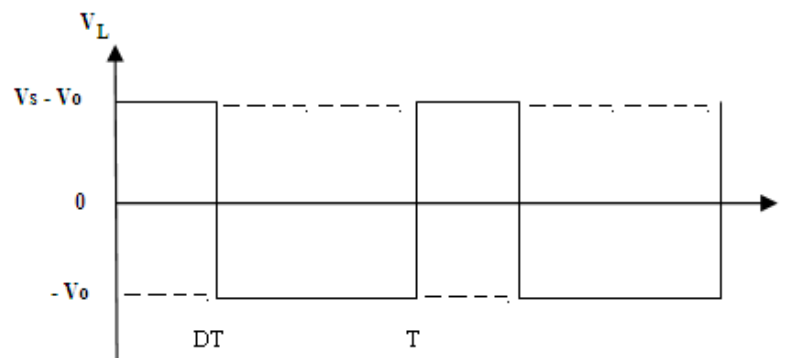


**Figure 2.1** Buck converter

Analysis of the buck converter begins by making these assumptions of Figure 2.1[1]:

- i) The circuit is operating in the steady state.
- ii) The inductor current,  $i_L$  is in continuous condition.
- iii) The output voltage is held constant at voltage,  $V_o$  and the capacitor is very large.
- iv) The switching period is  $T$ ; meanwhile the switch's closed time is  $DT$  and open time is  $(1-T)DT$ .

The essential to the analysis for determining the output  $V_o$  is to examine the inductor voltage first for the switch closed and then for the switch open. Figure 2.2 shows the inductor voltage waveforms for the switch closed and open [1].



**Figure 2.2** Inductor's Voltage Waveform

When the switch closed:

$$(\Delta i_L)_{closed} = \left( \frac{V_i - V_o}{L} \right) DT_s \quad (2-1)$$

When the switch open:

$$(\Delta i_L)_{opened} = - \left( \frac{V_o}{L} \right) (1-D)T_s \quad (2-2)$$

The net change in inductor current over one period is zero,

$$(\Delta i_L)_{opened} + (\Delta i_L)_{closed} = 0 \quad (2-3)$$

Solving for Equation 2-3,

$$V_o = V_s D \quad (2-4)$$

The average inductor current must be the same as the average current in the load resistor, since the average capacitor current must be zero for steady-state operation:

$$I_L = I_R = \frac{V_o}{R} \quad (2-5)$$

The value  $\Delta i_L$  is referred to the  $(\Delta i_L)_{opened}$  and the maximum value of the inductor current is

$$I_{max} = I_L + \frac{\Delta i_L}{2} = V_o \frac{1}{R} - \frac{(1-D)}{2LF} \quad (2-6)$$



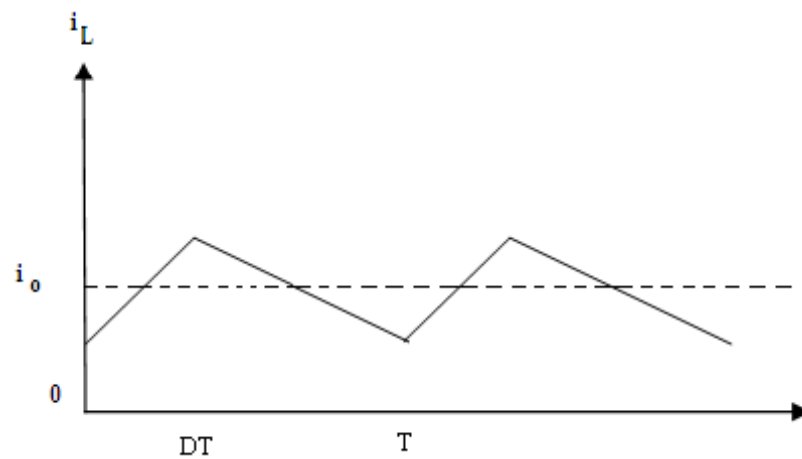
The minimum inductor current is,

$$I_{min} = I_L - \frac{\Delta i_L}{2} = V_o \left[ \frac{1}{R} - \frac{(1-D)}{2LF} \right] \quad (2-7)$$

The voltage ripple is determined by,

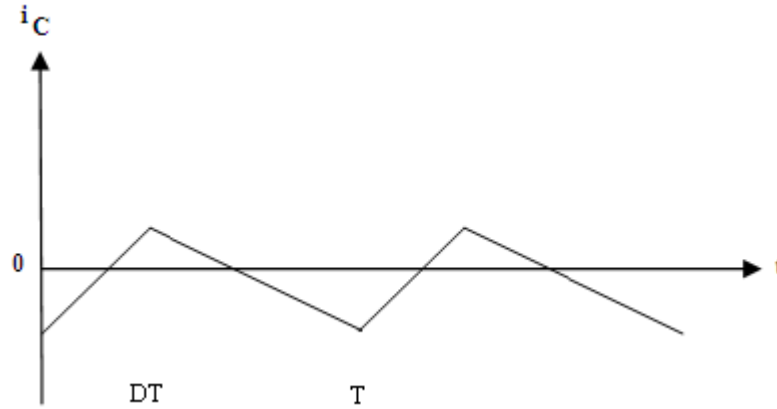
$$\frac{\Delta i_L}{2} = \frac{(1-D)}{8CLf^2} \quad (2-8)$$

The inductor current waveform for the Buck converter which is in continuous current mode is shown in Figure 2.3. The value is always positive and greater than zero.



**Figure 2.3** Inductor's Current Waveform

The average inductor current must be the same as the average current in the load resistor [2]. The capacitor current waveform was shown in Figure 2.4.



**Figure 2.4** Capacitor's current waveform

### 2.3 Multi-level Conversion Method

In Figure 2.1, it is shows the structure of a conventional non-isolated buck converter. In this type of converter, by adjusting the duty ratio (D) of the switch output voltage, the filter input voltage is

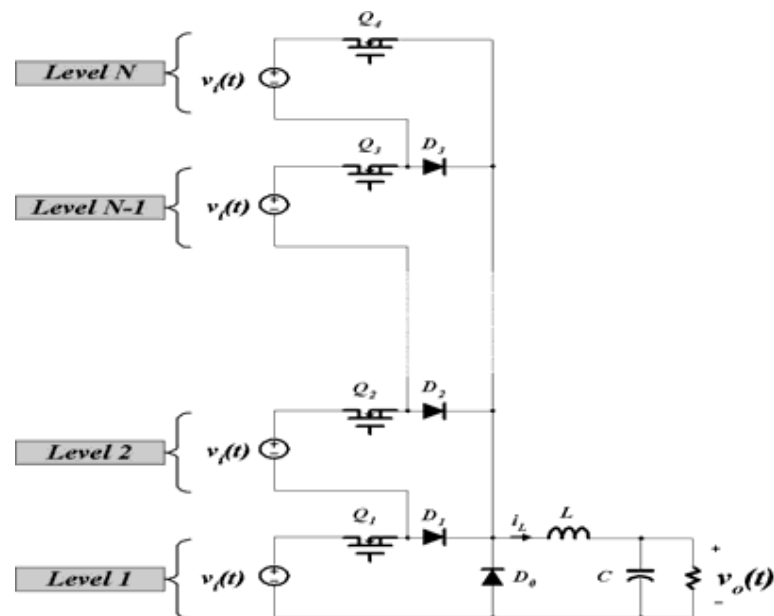
$$V_f = DV_i + \frac{2V_i}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin(n\pi D) e^{j(2\pi f n)t} \quad (2-9)$$

From formula above, it can be determined that the input voltage of the filter is composed of DC composition and the harmonics which is integral times the fundamental frequency. If the harmonics can be filtrated through the filter, the output voltage will only be related to DC [2].

The output voltage ripple of the DC/DC converter is determined by the collective effect of the switching frequency, inductance, capacitor, duty ratio and input voltage, etc. Therefore, the output voltage ripple can be reduced in many ways such as by improving the frequency of switching, increasing filter inductance or capacitance, or reducing the output voltage. [2]

However, increasing the switch frequency will increase the switch loss and reduce the efficiency, and increasing the filter inductance or capacitance will cause an increase of volume and system cost.

In this project, to reduce the output voltage ripple, a method of reducing the input voltage is proposed. This new multi-level DC/DC converter structure is presented in Figure 2.5. It consists of traditional DC/DC converters in series. The output parts of Buck converters are connected with diode in series which ensures the output isolation of all converters. In each level the middle diode and switching element are connected to the negative point of the up buck converter.



**Figure 2.5** Proposed multi-level DC/DC converter.

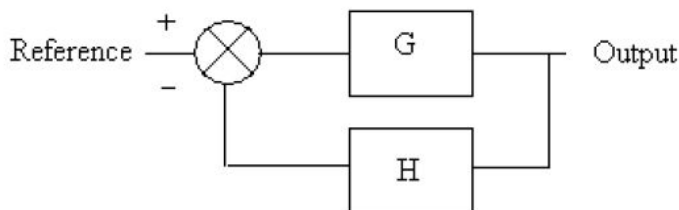
As to the conventional multi-level inverter, with the increase of levels and the number of switch elements, diodes and capacitors have to be added rapidly. However, the number of switch elements and the number of diodes will be reduced by  $N$  separately in the proposed  $N$ -level DC/DC converter. The power loss can be reduced by minimizing the acting levels according to the level of generating voltage.

## 2.4 Control scheme

There is several control schemes have been applied in the buck converters such as sliding-mode control, voltage-mode control and current-mode control. The external control is required to provide perfect regulation. Without the external control, the output is dependent on the input voltage and lack of line regulation. Every control schemes has their own advantages and disadvantages. [3]

The output voltage of DC-DC converter must be a regulated output voltage under varying load and input voltage condition. The converter component values are also changing with temperature, pressure, time and so forth. Controlling the output voltage is needed in a closed loop manner by using voltage feedback. The external control is required to provide perfect regulation. Without the external control, the output is dependent on the input voltage and lack of line regulation for every type of control schemes; they have their own advantages and disadvantages. [4]

Figure 2.6 below is show the block diagram of feedback control. The objective of the feedback control is used to ensure the output follow the reference value and reduce the disturbances to an acceptable level. The feedback network or control circuitry consists of error amplifier and pulse width modulator (PWM) to determine the required duty ratio of the power switch to maintain the output at desired level with fixed value for power converters. There are several forms of PWM control, but the most popular form is the frequency operation is fixed due to electromagnetic interference and noise considerations.



**Figure 2.6** Block diagram for feedback control

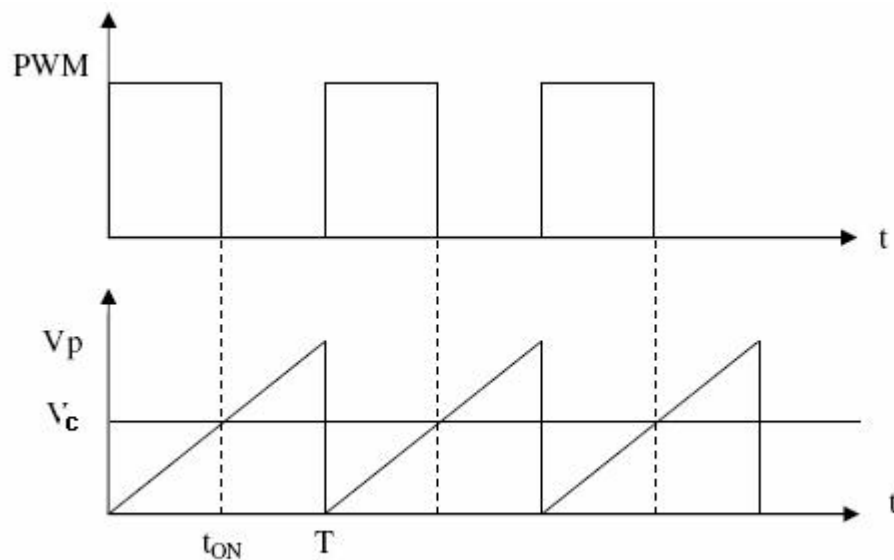
### 2.4.1 Voltage Mode Control (VMC)

The key feature of this control is the existence of a feedback loop which keeps track of the output voltage variation and adjusts the duty cycle. Furthermore, in this control scheme, the difference between the output voltage  $V_c$ , and a reference signal,  $V_{ref}$ , is processed by a compensation network which generates a control signal,  $V_{con}$ . This control signal tells how the duty cycle has to be changed in order to give the best transient dynamics for the desired output. This control signal is compared with a periodic ramp signal,  $V_{ramp}(t)$ , to generate a pulse width modulated signal which drives the switch [5].

In the voltage mode control scheme, the converter output voltage is sensed and subtracted from an external reference voltage in an error amplifier. Then the error amplifier produces a control voltage that is compared to a constant amplitude saw tooth waveform. After that the comparator produces a PWM signal that is fed to drives of controllable switches in the dc – dc converter. The duty ratio of the PWM signal depends on the value of the control voltage. Furthermore the frequency of the PWM signal is the same as the frequency of the saw tooth waveform. The advantage of this scheme is simple hardware implementation and flexibility.

The error amplifier reacts in a fast manner to changes in the converter output voltage. As a result, voltage mode control scheme provides good load regulation against variations in the load. However regulation against variations in the input

voltage is delayed because changes in the input voltage must first manifest themselves in the converter output before it can be corrected. The pulse width modulation circuit converts the output from the error amplifier into a duty ratio. The output from the converter then is compared with output voltage reference. The difference is then amplified by error amplifier and produced  $V_c$  or  $V_c$ . It's then compared with saw tooth waveform with amplitude  $V_p$  and the output from comparator is used at drive circuitry. It is shown at figure 2.7 where PWM is produced by comparing  $V_c$  with  $V_p$  [5].



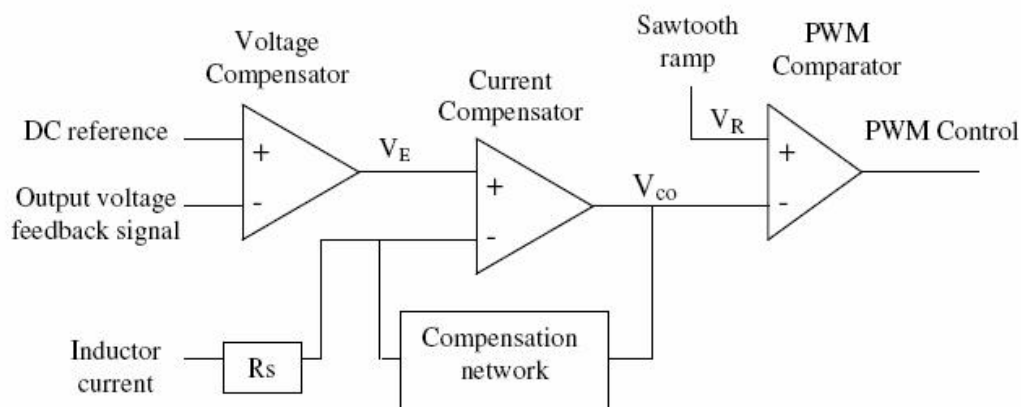
**Figure 2.7** Signal pulse width modulator (PWM)

#### 2.4.2 Current Mode Control (CMC)

An additional inner control loop feedback an inductor current signal and this signal are converted into its voltage analogue is compared to the control voltage. This modification of replacing the saw tooth waveform of the voltage mode control scheme by a converter current signal changes the dynamic behaviour. The result of

current mode control is a faster response and mainly applied to boost and buck-boost converters which suffer from an undesirable non-minimum phase response [6].

With the inductor current taken into account, of course current mode control performs better, however the application of current mode control to the buck converter does not gain much benefit over voltage mode control. This is because the inductor current information can be readily derived from the output voltage in the case of the buck converter. In addition, with the absence of the low frequency inductor current dynamics, the inheritances of non-minimum phase problem associated with the boost and buck-boost converters is automatically eliminated. High frequency instability in the form of sub harmonics and chaos is possible in current mode control. Figure 2.8 shows the block diagram for Current Mode Control.



**Figure 2.8** Current mode control block diagram

The voltage across the current sense resistor which represents the actual inductor current is fed into the current compensator and compared to the desired current program level. The difference or current error is then amplified and filtered. After that it is compared with a saw tooth ramp at PWM comparator input to generate the required duty ratio. This control scheme also provides excellent noise immunity to the spike sensed in the inductor current. When the clock pulse turns the

power switch on, the oscillator ramp ( $V_{co}$ ) immediately dives to its lowest level which means volts away from the corresponding current error level at the input of the PWM comparator [3].