DESIGN OF INTEGRATED ZVS SINGLE-INDUCTOR SYNCHRONOUS BUCK CONVERTER

Belsam Jeba Ananth. M, Vennila.M

Address for Correspondence
Professor, Associate Professor/EEE , DMI College of Engineering, Chennai, India

ABSTRACT
In order to suppress the cross regulation parameter which is the main problem faced by the single-inductor multi-output DC-DC converters, a new efficient converter is presented in this paper. The proposed converter includes two parameters, zero voltage switching (ZVS) and synchronization which makes the proposed converter to operate with less switching losses and switching frequency. Moreover the proposed converter reduces the coupling between the outputs obtained and the different outputs are controlled individually by using closed loop controller. This could reduce the cross regulation parameter effectively. This paper describes the theoretical aspects involved in the design procedure of the converter and the simulation results showed that this converter has better performance and highly efficient.

KEYWORDS- Buck converter, Proportional integral derivative (PID) controller, Synchronous buck converter, Zero voltage switching (ZVS).

I. INTRODUCTION
In recent scenario, DC-DC converters are in high demand. For portable applications buck converters are used in large extent. They require compact structure, light weight, low cost, high efficient, high performance. For the applications where multiple independent voltage levels are required, the single-inductor multiple-output (SIMO) DC-DC converters have gained increased attention. Though the SIMO converter has number of advantages, it has the main problem of cross regulation. In this paper a new integrated ZVS single inductor multi-output synchronous buck converter is presented which aims to increase the efficiency and to reduce the cross regulation problems [1]. This paper mainly based on three approaches as follows.

The first approach is to implement the soft-switching technique, zero voltage switching (ZVS) in the proposed buck converter operating in CCM. Zero voltage switching (ZVS) buck converter is more preferable over hard switched buck converter for low power, high frequency DC-DC conversion applications. In Zero voltage switching converter, turn on & turn off of a switch occurs at zero voltage that results in lower switching losses.

The second approach is to design the proposed converter to operate as the synchronous buck converter. Synchronization means two or more operations happen sequentially. This is done by adding a synchronous switch at the place of diode. By doing so, the proposed system will have less conduction loss and it also increases the efficiency of power conversion [2]. The third approach is to control the obtained multiple outputs individually by using PID controller. Closed loop control have been used thus the problems caused by cross regulation is minimized in the proposed converter.

The main overview is given above and this paper is formulated as follows. Section II presents the basics of the operation of the ZVS integrated single-inductor synchronous buck converter. Section III describes feature analysis. Section IV presents the design considerations. The experimental results are reported in Section V and Section VI concludes this paper.

II. INTEGRATED ZVS SINGLE-INDUCTOR SYNCHRONOUS BUCK CONVERTER

A. Conventional Sido Converter
The conventional converter does not contain soft-switching techniques and it works as an asynchronous converter where the events are not in a sequential form. The block diagram of the conventional SIDO converter is shown in Figure 1.

![Figure 1. Block diagram of the conventional converter.](image1)

The block diagram consists of three main parts: DC source, Single-Inductor Dual-Output buck converter, outputs, since it is a dual output converter two outputs are obtained and they are applied to two loads. Here the obtained two outputs are not controlled thus coupling between the outputs are occurred which leads to the cross regulation problem. Cross regulation is the main problem often faced by the systems which has multiple outputs, in which if one load voltage changes it automatically affects the another load connected to that system [6].

B. Circuit Description And Assumptions
The block diagram of the ZVS single-inductor multi-output synchronous buck converter is shown in Figure 2.

![Figure 2. Block diagram of integrated ZVS single-inductor synchronous buck converter.](image2)

The block diagram consists of four main blocks: Source, Proposed SIMO buck converter, multiple outputs and microcontroller unit with PID controller.

Since buck converter is a DC-DC converter, the input given to the SIMO buck converter is a DC supply from an appropriate DC source. The SIMO buck converter is proposed in this project in which it has been designed to operate as a synchronous buck converter and also it includes the soft-switching technique Zero Voltage Switching (ZVS), where the
above said two techniques are carried out in order to reduce the switching losses and make the converter to operate at low switching frequency.

The output part has three outputs which are obtained from a single inductor in the converter and those outputs are applied to three different loads. The microcontroller here it uses PID controller, controls the three outputs in a closed loop configuration by sensing the voltage levels of each output. This is done by a voltage sensing circuit. Gate driver is used to generate gate pulse to the MOSFET switch which is utilized as high side switch driven in full enhancement.

The circuit diagram of the proposed converter is shown in Figure 3.

![Figure 3. Circuit diagram of integrated ZVS single-inductor synchronous buck converter.](image)

The above shown circuit diagram consists of the components as follows;

- S1, S2, S3, S4 - MOSFET switches
- C1, C2, C3 - Capacitors
- C_p - Bypass Capacitor
- L - Inductor
- D - Diode
- M - Motor load
- B - Battery
- R - Resistive load

The proposed Integrated ZVS Single-Inductor Synchronous Buck Converter contains four MOSFET switches namely S1, S2, S3 and S4 in which the switch S1 does the normal operation as in a buck converter, the switch S2 is responsible for the synchronous operation which is added by replacing a diode from the existing system. The other two switches S3 and S4 are operated manually to switch ON and OFF the loads, where the third load depends upon either to switch S1 or switch S2 according to the mode of operation.

The bypass capacitor C_p is connected across the switch S1 which is capable of introducing ZVS technique in the system. The inductor L does its work as in buck converter which induces voltage and also stores some energy for the upcoming modes. Finally three outputs are obtained from a single inductor and those outputs are applied to three loads such that used for different applications as DC motor which regards the water pump application, a battery which used for storing the energies and used for later use, a resistive load here it is shown as a lamp load respectively. The inductor fully discharges (on state), the voltage at the load will always be greater than zero and the Figure 4. For simplicity the circuit diagram is shown with only the motor load.

![Figure 4. Equivalent diagram of mode 1.](image)

When the switch is first closed (ON state), the current will begin to increase, and the inductor will produce an opposing voltage across its terminals in response to the changing current. This voltage drop counteracts the voltage of the source and therefore reduces the net voltage across the load. Over time, the rate of change of current decreases, and the voltage across the inductor also then decreases, increasing the voltage at the load. During this time, the inductor stores energy in the form of a magnetic field. If the switch is opened while the current is still changing, then there will always be a voltage drop across the inductor, so the net voltage at the load will always be less than the input voltage source.

B. Mode 2

In second mode the switch S1 will be in OFF condition and the switch S2 will be in ON condition. The equivalent diagram is shown below in the Figure 5. For simplicity the circuit diagram is shown with only the motor load.

![Figure 5. Equivalent diagram of mode 2.](image)

When the switch is opened again (off state), the voltage source will be removed from the circuit, and the current will decrease. The changing current will produce a change in voltage across the inductor, now aiding the source voltage. The stored energy in the inductor's magnetic field supports current flow through the load. During this time, the inductor is discharging its stored energy into the rest of the circuit. If the switch is closed again before the inductor fully discharges (on state), the voltage at the load will always be greater than zero.

### IV. Feature Analysis

This paper mainly presents three approaches and their features are discussed below as follows.

a. Synchronous Buck Converter

A buck converter is a voltage step down and current step up converter. The simplest way to reduce the voltage of a DC supply is to use a linear regulator (such as a 7805), but linear regulators waste energy as they operate by dissipating excess power as heat. Buck converters, on the other hand, can be remarkably efficient (95% or higher for integrated circuits), making them useful for tasks such as...
converting the main voltage in a computer (12V in a desktop, 12-24V in a laptop) down to the 0.8-1.8V needed by the processor.

The basic operation of the buck converter has the current in an inductor controlled by two switches. In the idealized converter, all the components are considered to be perfect. Specifically, the switch and the diode have zero voltage drop when on and zero current flow when off and the inductor has zero series resistance [5], [7].

A synchronous buck converter is a modified version of the basic buck converter circuit topology in which the diode, D, is replaced by a second switch, S₂.

![Figure 6. Synchronous buck converter.](image)

This modification is a trade-off between increased cost and improved efficiency. Figure 6 shows the synchronous buck converter topology. In a standard buck converter, the fly-back diode turns on, on its own, shortly after the switch turns OFF, as a result of rising voltage across the diode results in a power loss which is equal to,

\[ P_D = V_D (1 - D) I_D \]  

(1)

Where;

- \( V_D \) - Voltage drop across the diode
- \( D \) - Duty cycle
- \( I_D \) - Load current

The comparison or difference between synchronous and asynchronous operation have been summarized below in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1. DIFFERENCE BETWEEN SYNCHRONOUS AND ASYNCHRONOUS OPERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SYNCHRONOUS</strong></td>
</tr>
<tr>
<td>All the events will occur at a certain time order and each</td>
</tr>
<tr>
<td>operations are predicted</td>
</tr>
<tr>
<td>Two or more operations can happen sequentially.</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>There is no coupling between the events, which means the</td>
</tr>
<tr>
<td>operations are not interchanged.</td>
</tr>
<tr>
<td>It supports high data transfer rate.</td>
</tr>
</tbody>
</table>

**B. Zero Voltage Switching**

A soft-switching technique means that the switching transitions occur under the favorable conditions – device voltage or current is zero. This will reduce the switching losses, switching stress, possibly low EMI, easier thermal management. Thus the soft-switching technique must be used in very high frequency operations. For the most part, it can be considered as square wave power utilizing a constant off-time control which varies the conversion frequency, or on-time to maintain regulation of the output voltage.

Regulation of the output voltage is accomplished by adjusting the effective duty cycle, performed by varying the conversion frequency. This changes the effective on-time in a ZVS design. The foundation of this conversion is simply the volt-second product equating of the input and output. It is virtually identical to that of square wave power conversion, and vastly. The difference between conventional square wave and zero voltage switching is shown in Figure 7.

![Figure 7. ZVS vs. Conventional Square Wave.](image)

Unlike the energy transfer system of its electrical dual, the zero current switched converter. During the ZVS switch off-time, the L-C tank circuit resonates. This traverses the voltage across the switch from zero to its peak, and back down again to zero. At this point the switch can be reactivated, and lossless zero voltage switching facilitated. Therefore, the MOSFET transition losses go to zero - regardless of operating frequency and input voltage. This could represent a significant savings in power, and result in a substantial improvement in efficiency. Obviously, this attribute makes zero voltage switching a suitable candidate for high frequency, high voltage converter designs [5], [8].

Additionally, the gate drive requirements are somewhat reduced in a ZVS design due to the lack of the gate to drain (Miller) charge, which is deleted when \( V & I \) equals zero. The technique of zero voltage switching is applicable to all switching topologies; the buck regulator and its derivatives (forward, half and full bridge), the fly-back, and boost converters, to name a few. This presentation will focus on the continuous output current, buck derived topologies.

Some of the advantages of zero voltage switching are as follows:

2. Reduced EMI / RFI at transitions.
3. No power loss due to discharging Goss.
4. No higher peak currents, (i.e. ZCS) same as square wave systems.
5. High efficiency with high voltage inputs at any frequency. Can incorporate parasitic circuit and component L & C

**C. Zero Voltage Switching**

A microcontroller is a small computer on a single integrated circuit containing a processor core, memory, and programmable input peripherals. Program memory in the form of Ferroelectric RAM, NOR flash or OTP ROM is also often included on chip, as well as a typically small amount of RAM. Microcontrollers are designed for embedded applications, in contrast to the microprocessors used in personal computers or other general purpose applications. Microcontrollers are used in automatically controlled products and devices, such as automobile engine control systems, implantable medical devices, remote controls, office machines, appliances, power tools, toys and other embedded systems.

By reducing the size and cost compared to a design that uses a separate microprocessor, memory, and input/output devices, make it economical to digitally control even more devices and processes [2] - [4]. A proportional integral derivative controller (PID controller) is a
control loop feedback mechanism commonly used in industrial control system.

A PID controller continuously calculates an "error value" as the difference between a measured process variable and a desired set point. The simple schematic diagram PID controller is shown in Figure 8.

![Figure 8. PID Controller.](image)

PID controller has all the necessary dynamics: fast reaction on change of the controller input (D mode), increase in control signal to lead error towards zero (I mode) and suitable action inside control error area to eliminate oscillations (P mode). Derivative mode improves stability of the system and enables increase in gain K and decrease integral time constant Ti, which increases speeds of the controller response. PID controller is used when dealing with higher order capacitive processes when their dynamic is not similar to the dynamics of an integrator. PID controller is often used in industry, but also in the control of mobile objects when stability and precise reference following are required.

Tuning is adjustment of control parameters to the optimum values for the desired control response. Stability is a basic requirement. However, different systems have different behavior, different applications have different requirements, and requirements may conflict with one another. PID tuning is the difficult problem, even though there are only three parameters and in principle is simple to describe, because it must satisfy complex criteria within the limitations of PID control. There are accordingly various methods for loop tuning, some of them:

2. Ziegler–Nichols tuning method.
3. PID tuning software methods.

V. SIMULATION RESULTS

The simulation process in this paper is carried out in two ways as follows;

1. Without Controller.
2. With Controller

The input given to the system is DC supply of 24V shown in Figure 9.

![Figure 9. Input Voltage.](image)

The zero voltage switching of the existing system and the proposed system is shown in Figure 10. From the graph it is seen that the switch will be turned ON only after the voltage reaches zero, so that the system would operate with less switching losses.

![Figure 10. Switching Technique. (a) Conventional System. (b) Proposed buck converter.](image)

The output current and output voltage of the three different loads in the system without controller is shown in Figure 11 and Figure 12 respectively.

![Figure 11. Output Current.](image)

From the above graph it is seen that the current obtained from the first load was 0.076A, from the second load was 0.077A, from the third load was 0.188A.

![Figure 12. Output Voltage](image)
The voltage obtained from the three different loads are, from the first load it was 7.68V, from the second load it was 7.7V from the third load it was 18.8V. The average buck output obtained is 11V. However these outputs are not stable they would alter for each buck operation due to the cross regulation and coupling between the outputs. The graph which shows the output and input power of the system is shown in Figure 13. The output power obtained from the system was 4.73W and the input power was 5W.

![Figure 13. Output and Input Power.](image)

The output current and output voltage of the three different loads in the system without controller is shown in Figure 14.

![Figure 14. Results of the System with Controller.](image)

(a) Output Current. (b) Output Voltage

From the above graph it is seen that the current obtained from the three outputs are very low values due to the loads used. The voltage obtained from the three different loads are, from the first load it was 12V, from the second load it was 12V from the third load it was 18V. The average buck output obtained is 14V. Here the obtained outputs are stable and hence they won’t alter for each buck operation thus the cross regulation and coupling between the outputs were eliminated. The speed of the motor load in rps is shown in Figure 15.

![Figure 15. Motor Speed in rps.](image)

The efficiency of the existing system and the proposed system is compared and it shown in Figure 16.

![Figure 16. Efficiency](image)

The overall efficiency of the proposed system is increased about 10% than the existing system. The overall results were analyzed detailly and the whole performance of the proposed Buck Converter was summarized in the Table 2.

**TABLE 2. OVERALL COMPARISON TABLE**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>EXISTING SYSTEM</th>
<th>PROPOSED SYSTEM (WITHOUT CONTROLLER)</th>
<th>PROPOSED SYSTEM (WITH CONTROLLER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT VOLTAGE</td>
<td>Cross Regulation occurred</td>
<td>Cross Regulation occurred</td>
<td>No Cross Regulation</td>
</tr>
<tr>
<td>ZVS</td>
<td>Not achieved</td>
<td>Achieved</td>
<td>Achieved</td>
</tr>
<tr>
<td>TYPE OF OPERATION</td>
<td>Asynchronous</td>
<td>Synchronous</td>
<td>Synchronous</td>
</tr>
<tr>
<td>NO. OF OUTPUTS</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>CONTROLLER</td>
<td>Not Used</td>
<td>Not Used</td>
<td>PID Controller</td>
</tr>
<tr>
<td>BUCK</td>
<td>18V</td>
<td>18V</td>
<td>18V</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>77%</td>
<td>95%</td>
<td>95%</td>
</tr>
</tbody>
</table>

**VI. CONCLUSION**

This paper proposes the design methodology of a new DC-DC converter called Integrated ZVS Single-Inductor Multi-Output Synchronous Buck Converter in CCM operation. The proposed converter has included two main approaches such as zero voltage switching (ZVS) and synchronization. The proposed converter present a simple structure and lower cost converter compared to other soft-switching converters. The synchronous topology makes the proposed system to operate sequentially. Moreover, the multiple outputs are controlled individually in a closed loop using PID controller, so that the coupling between the outputs are eliminated and thus the cross regulation problem is suppressed effectively. Thus the proposed converter can yield high step-down voltage ratio and the efficiency is bought to about 95%.

**REFERENCES**

Interleaved ZVS Buck Converter with Coupled-Inductors,” IEEE Conference on Power Electronics, 978-18756-1/11.


