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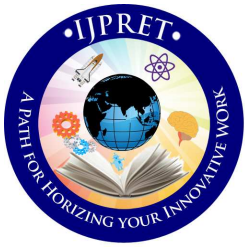

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A HIGH EFFICIENT WIDE WORK LOAD RANGE DOTM BASED DC-DC CONVERTER BASED ON ASYNCHRONOUS POWER SAVING TECHNIQUE

KUMAR KESHAMONI[1], B DEVRAJ[2], ML RAVI CHANDRA[3]

1. M. Tech- Student, Department of Electronics & Communication Engineering, Netaji Institute of Engineering &Technology.
2. Asst. Professor, Department of Electronics & Communication Engineering, Netaji Institute of Engineering &Technology.
3. Professor & HOD, Department of Electronics & Communication Engineering, Netaji Institute of Engineering &Technology.

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Abstract: DOTM is a commonly used technique for controlling power to internal electrical devices. DOTM technique based cascaded multilevel inverters have received increasing research attention in the past few years. These power converters provide advantages of high power quality waveforms, low switching losses, and high-voltage capability. The main advantage of DOTM is that power loss in the switching devices is very low. DOTM or Digital off time Modulation refers to the concept of rapidly pulsing the digital signal of a wire to simulate a varying voltage on the wire. This method is commonly used for driving motors, heaters, or lights in varying intensities or speeds. DOTM is a powerful way of controlling analog circuits and systems, using the digital outputs of microprocessors. In this project we propose a novel FPGA based control algorithm for conventional and cascaded multilevel FPGA controller algorithm has high output power quality, low output switching frequency, high conversion efficiency and one field embedded design chip. Conventionally for wide workload range applications, to keep good stability and high efficiency, a switching converter with multi-mode operation is necessary. With the advanced dig- ital signal processing, this work presents an asynchronous digital controller with dynamic power saving technique to achieve high power efficiency. The regulation is based on the off-time modulation, in which an adaptive resolution adjustment is proposed for the extension toward light-loaded range. The overall System Architecture will be designed using HDL language and simulation, synthesis and FPGA implementation (Translation, Mapping, Placing and Routing) will be done using various FPGA based EDA Tools.

Keywords: Window ADC, ARC, DOTM, Comparator, Switch Control, Off time Delay, On time Delay, Off time Generator, On time Generator, PWM, PFM, APSC, DPWM, Buck, Boost

Corresponding Author: Mr. KUMAR KESHAMONI

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1. INTRODUCTION: DC-DC converters are electronic devices used whenever we want to change DC electrical power efficiently from one voltage level to another. They're needed because unlike AC, DC can't simply be stepped up or down using a transformer. In many ways, a DC-DC converter is the DC equivalent of a transformer. There are many different types of DC-DC converter, each of which tends to be more suitable for some types of application than for others. For convenience they can be classified into various groups, however. For example some converters are only suitable for stepping down the voltage, while others are only suitable for stepping it up; a third group can be used for either. Another important distinction is between converters which offer full dielectric isolation between their input and output circuits, and those which don't. Needless to say this can be very important for some applications, although it may not be important in many others.

The wide-loaded and highly-efficient switching mode power supply (SMPS) has gained increased attention in the field of power management. It is worth noting that the switching loss dominates the conduction loss as load demand is sufficiently low, which propels the development of dual-mode control scheme for the past decade. However, a drawback of dual-mode converter is that without explicit monitoring of output current, performance deterioration is located between pulse-width modulation (PWM) and pulse-frequency modulation (PFM) as shown by the shadow area in Fig. Consequently, a tri-mode converter is configured subsequently to operate over the wide workload range of interest with efficient power conversion. To achieve the previous goal, the dithering skip modulation (DSM) is introduced to randomly reduce the switching activity based on the load current, depicted as the curve III in Fig. However, either dual-mode or tri-mode converter inevitably adopts additional sensor and monitor in response to the load demand, limiting the efficacy of multi-mode controller in switching regulator applications.

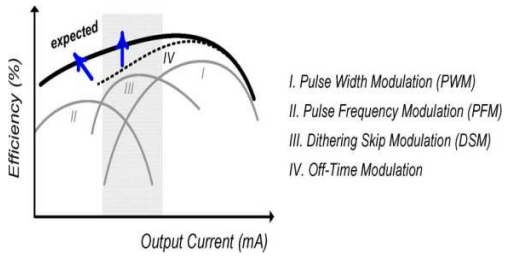


Fig. 1.1 Comparison of conversion efficiency among four modulation schemes

Taking into account the specified requirements discussed above, another technique named as off-time modulation is used by varying the clock frequency according to the computation load (curve IV). The amount of energy consumption only needs to be as high as required to satisfy the desired circuit performance. To further enhance the power efficiency, we propose two adaptive techniques based on the off-time modulation

scheme in this work. The feasibility of digital off-time modulation (DOTM) with the proposed asynchronous power saving controller (APSC) and the adaptive resolution controller (ARC) has been demonstrated whose power conversion efficiency is comparable to or higher than standard PFM operation over light-loaded range.

Several methods exist to achieve DC-DC voltage conversion. Each of these methods has its specific benefits and disadvantages, depending on a number of operating conditions and specifications. Examples of such specifications are the voltage conversion ratio range, the maximal output power, power conversion efficiency, number of components, power density, galvanic separation of in- and output, etc. When designing fully-integrated DC-DC converters these specifications generally remain relevant, nevertheless some of them will gain weight, as more restrictions emerge. For instance the used IC technology, the IC technology options and the available chip area will be dominant for the production cost, limiting the value and quality factor of the passive components. These limited values will in-turn have a significant impact upon the choice of the conversion method.

1.1. Voltage Conversion Ratio (VCR): Conventional switched mode converters use magnetic as their principal energy storage components. The sizes of the inductor and transformer are relatively large compared to the size of the whole converter. This approach has a number of problems such as loss in the magnetic components, difficulty in magnetic design lack of complete IC solution. Some research works have proposed esonant converters which can operate at very high frequencies. The sizes of inductors or transformers can be reduced considerably. However, the inductors still cannot be eliminated. Another concept of power converters is to use capacitor only for the energy storage. This is the so-called Switched-capacitor converter. This approach uses capacitors and switches only. The capacitors are charged and discharged by routing the switching appropriately. A number of topologies for different voltage conversion ratios can be achieved by various combinations of the switches and capacitors. The drawback of this approach is that the switching currents at the source, capacitor and transistor are very high and the EM1 is a main concern.

1.1.1. Maximal Output Power (MOP): The maximum power in voltage converter circuit we can represent the basic power flow in a converter by using this equation.

$$P_{out}=P_{in} - P_{losses}$$

Where Pin is the power fed in to the converter and Pout is the power coming of the converter and P losses are power wasted inside the converter.

1.1.2. Power Conversion Efficiency (PCE): There are no perfect converters for voltage conversion. The efficiency of the voltage converters are decided by the power conversion efficiency of the converter circuit.

Efficiency (%) = P_{out} / P_{in}

1.1.3. Power Density: Power density (or volume power density or volume specific power) is the amount of power (time rate of energy transfer) per unit volume.

1.2. Non-isolating converters: The non-isolating type of converter is generally used where the voltage needs to be stepped up or down by a relatively small ratio (say less than 4:1), and there is no problem with the output and input having no dielectric isolation. Examples are 24V/12V voltage reducers, 5V/3V reducers and 1.5V/5V step-up converters.

There are five main types of converter in this non-isolating group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step-down/reduction, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either step-down or step-up, but are essentially voltage polarity reversers or 'inverters' as well. (The Cuk converter is named after its originator, Slobodan Cuk of Cal Tech University in California.) The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

1.3. Isolating converters: All of the converters we've looked at so far have virtually no electrical isolation between the input and output circuits; in fact they share a common connection. This is fine for many applications, but it can make these converters quite unsuitable for other applications where the output needs to be completely isolated from the input. Here's where a different type of inverter tends to be used the isolating type.

There are two main types of isolating converters are available, the 'fly back' type and the 'forward' type. Like most of the non-isolating converters, both types depend for their operation on energy stored in the magnetic field of an inductor or in this case, a transformer. But in any type of DC-DC converter circuit the operation is depend on the control circuit inside it. Basically the various controller circuits are used based on the type of the conversion circuit. In this research work we carried out BUCK type DC-DC converter circuit. The BUCK type converter circuit designed by using DOTM based asynchronous power saving circuit has been designed for number of pulses to control number of circuits. The control pulses of this type design we can extend up to any number of pulses based on requirement. The entire design is carried out using Verilog HDL and simulation, synthesis, and implementation is performed on the Xilinx ISE suit bases on the Xilinx Spartan 3e FPGA.

1.4. Advantages and Application of DC-DC converter circuit: Typical applications of DC-DC converters are where 24V DC from a truck batter y must be stepped down to 12V DC to operate a car radio, CB transceiver or mobile phone; where 12V DC from a car battery must be stepped down to 3V DC, to run a personal CD player ; where 5V DC on a personal computer motherboard must be stepped down to 3V, 2V or less for one of the latest CPU chips; where the 340V DC obtained by rectifying 240V AC power must be stepped down to 5V, 12V and other DC voltages as part of a PC power supply; where 1.5V from a single cell must be stepped up to 5V or more, to operate electronic circuitry; where 6V or 9V DC must be stepped up to 500V DC or more, to provide an insulation testing voltage; where 12V DC must be stepped up to +/- 40V or so, to run a car hifi amplifier's circuitry; or where 12V DC must be stepped up to 650V DC or so, as part of a DC-AC sine wave inverter. In all of these applications, we want to change the DC energy from one voltage level to another, while wasting as little as possible in the process. In other words, we want to perform the conversion with the highest possible efficiency. An important point to remember about all DC-DC converters is that like a transformer, they essentially just change the input energy into a different impedance level. So whatever the output voltage level, the output power all comes from the input; there's no energy manufactured inside the converter. Quite the contrary, in fact some is inevitably used up by the converter circuitry and components, in doing their job.

2. Buck converter: The basic circuit configuration used in the buck converter is shown in Fig.1. As you can see there are only four main components: switching power MOSFET Q1, flywheel diode D1, inductor L and output filter capacitor C1. A control circuit (often a single IC) monitors the output voltage, and maintains it at the desired level by switching Q1 on and off at a fixed rate (the converter's operating frequency), but with a varying duty cycle (the proportion of each switching period that Q1 is turned on). When Q1 is turned on, current begins flowing from the input source through Q1 and L, and then into C1 and the load. The magnetic field in L therefore builds up, storing energy in the inductor with the voltage drop across L opposing or 'bucking' part of the input voltage. Then when Q1 is turned off, the inductor opposes any drop in current by suddenly reversing its EMF, and now supplies current to the load itself via D1.

Digital control for high-frequency (e.g. hundreds of kilohertz to megahertz) switched-mode power supplies has gained increased attentions recent years due to a number of potential advantages [1-3]. A digital controller has lower sensitivity to parameter variations compared to its analog counterpart; therefore digital solution is a better option when the controller demands high precision such as

in controlling multiphase converters. Digital control can be configured flexibly to meet the requirements of different applications, and the digital interface makes it easy to communicate with a power management system. Furthermore, through advanced digital control algorithms, it is possible to improve system performance in terms of efficiency and speed.

However, there are still some critical challenges when applying digital control to high-frequency switched-mode power supplies. Among them, the limit cycle oscillation caused by quantization process (such as due to an A/D converter) in the feedback loop is the major problem. Unlike analog control, the resolution in a digital control loop has a finite value resulting from the quantizing elements in the system -- the A/D converter and the DPWM (which serves as a D/A converter). Duty cycle modulated by DPWM can only be discrete values and the resolution of DPWM ultimately determines the resolution of output voltage. Therefore if there is no DPWM level based on which the system can drive the output voltage to A/D converter's zero-error bin, the system will bounce up and down around the desired value. The amplitude and frequency of this limit cycle oscillation is hard to predict and confine. Reduction of the limit cycle oscillation requires high resolution DPWM. Several techniques have been proposed to increase modulation resolution, such as dithering technique, delay-line-based DPWM and hybrid DPWM (which is a combination of counter-based structure and delay-line structure). Besides the traditional constant frequency control, Li et al. proposed voltage-mode digital constant on-time modulation method and constant off- time method, which achieve significant improvement on the resolution of DPWM. Recently, a digital current-mode constant on-time control through V2 control architecture has been proposed, which limits the influence of the limit cycle oscillation. Additional digital ramp is added to further lower down oscillation amplitude, but the dynamic performance suffers because the modulation gain is decreased due to the additional ramp.

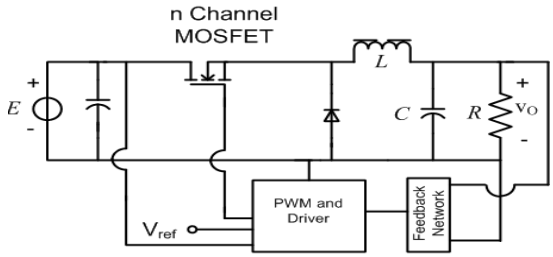


Fig.2.1. Buck converter circuit

Without going too deeply into its operation, the DC output voltage which appears across the load is a fraction of the input voltage, and this fraction turns out to be equal to the duty cycle. So we can write

Vout / Vin = D, or Vout = Vin x D

Where D is the duty cycle, and equal to Ton/T, where T is the inverse of the operating frequency. So by varying the

switching duty cycle, the buck converter's output voltage can be varied as a fraction of the input voltage. A duty cycle of 50% gives a step-down ratio of 2:1, for example, as needed for a 24/12V step-down converter. How about the current ratio between output and input? Well, not surprisingly that turns out to be the reciprocal of the voltage ratio — ignoring losses for a moment, and assuming our converter is perfectly efficient. So a quick rule of thumb is:

Iout / In = Vin / Vout

So when we're stepping down the voltage by 2:1, the input current is only half the value of the output current. Or it would be, if it were not for the converter's losses. Because real-world converters aren't perfect the input current is typically at least 10% higher than this.

3. ARCHITECTURE: The switch control block is the integration of window adc and DOTM blocks. This block will accept the signals as Vo and Vref and produces the output signals of pulses to the MOSFETS. The Vo and Vref signals are used by the window adc block and the window adc block will produce Ton and Toff signals to the DOTM block. The DOTM block will receive the signals of Ton and Toff to the On time and Off time generator blocks. The On time and Off time blocks will produce the on pulse and off pulse signals including the on and off enable signals to the ARC block. The ARC block will produce the pulses to the MOSFETS. The entire operation of the DC-Dc converter is controlled by the switch ctrl circuit block

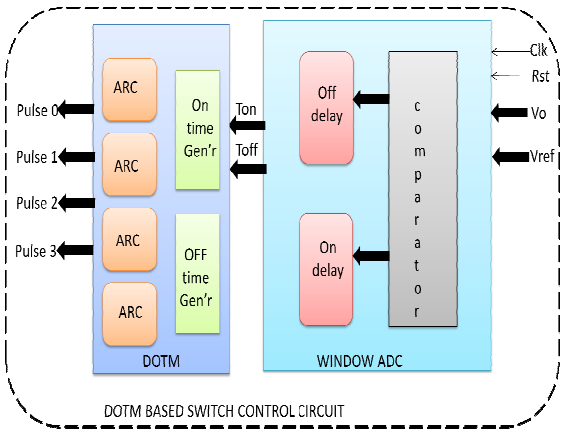


Fig. 3. DOTM Based Switch control circuit

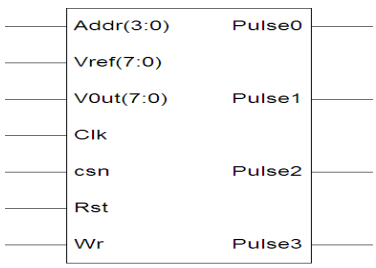
3.1. WINDOW ADC: ADC is the first block in the digitally-controlled DC-DC buck converter proceeding with the regulated output. The regulated output is in the vicinity of reference voltage when the system is in the steady state. Therefore, an effective windowed ADC with the characterization of self-sampling, as depicted in Fig, is developed in order to reduce the hardware cost and increase reliability. Is used to control the propagation delay of measurement delay-line after comparing the regulated output with the reference voltage by passing through a stage. Mean- while, conducts the reference delay-line to generate the sampling clock. The sampling clock will trigger the data registers to collect the difference information between regulated output and reference voltage in a digital stream of thermometer code, as shown in Fig. Meanwhile, the sampling clock informs the APSC whether the evaluation is done or not. Once the digital error

stream is produced by the self-sampling delay line, all the delay units switches into sleep mode instead, reducing the standby current consumption significantly. Simulation result shows that the current dissipation is about 10 A when the operating switching frequency is 44 kHz.

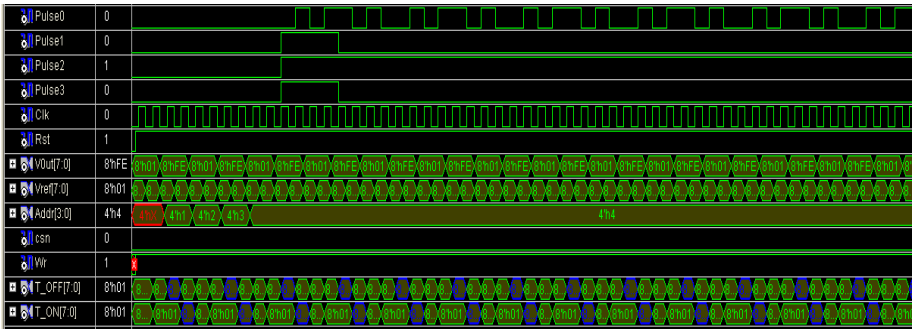
3.2. DOTM: In the system where a power converter and a digital controller form a feedback loop, the digital off-time modulator serves the purpose of a digital-to-analog converter (DAC). The discrete set of duty ratios and achievable output voltages correspondingly is dependent on the modulation resolution. Namely, there is an undesired oscillation occurs if the resolution is not sufficiently high. Fig depicts the 10-bit digital-input off-time modulator with a hybrid structure and an ARC. It is one of the solutions being targeted at constructing a complete, robust digital block capable of operating at a high switching frequency and a small silicon area, low power consumption and less complexity comparable to the counter based modulator. As opposed to counter-based modulator, only the first 6 bits, are segmented out of the to perform the comparison, while the remaining last 4 bits characterizes which delay cell is multiplexed. Only when 10 bits are all in a match will the off-time duration be determined and the pulse given to deliver to- ward the on-time generator. The on-time duration produced by a feed forward delay-line is preferable over the range in which the total losses are minimized, which will be analyzed later. The *system clock* is therefore generated and fed back into the analog power train, DSP, ADC, and APSC. Furthermore, the ARC is utilized for the increase of output workload range based on the code segmentation

3.3. Switch Control circuit: The switch control block is the integration of window adc and DOTM blocks. This block will accept the signals as Vo and Vref and produces the output signals of pulses to the MOSFETS. The Vo and Vref signals are used by the window adc block and the window adc block will produce Ton and Toff signals to the DOTM block. The DOTM block will receives the signals of Ton and Toff to the On time and Off time generator blocks. The On time and Off time blocks will produce the on pulse and off pulse signals including the on and off enable signals to the ARC block. The ARC block will produce the pulses to the MOSFETS. The entire operation of the DC-Dc converter is controlled by the switch ctrl circuit block.

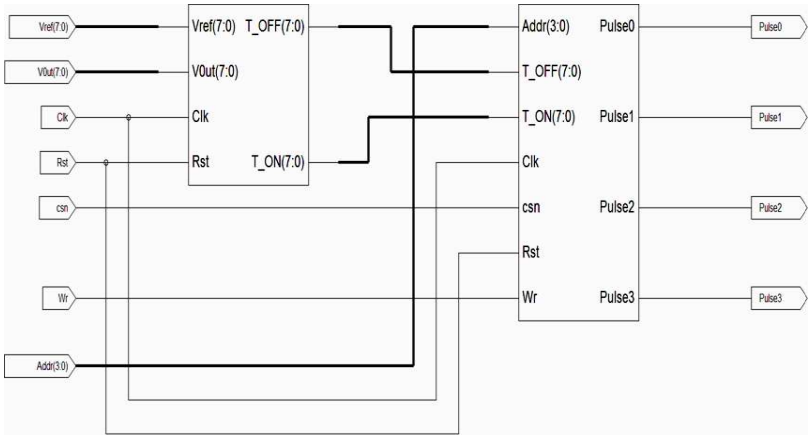
Block Diagram:



Simulation Results:



Implementation Results:



4. Conclusion: Various individual modules of DC-DC converter switch control circuit using DOTM have been designed, verified functionally using HDL-simulator, synthesized by the synthesis tool, and a final net list has been created. This design of the switch control circuit is capable of controlling more number of power MOSFET devices in DC-DC converter circuit.

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