Novel Hybrid Control Technique with Constant On/Off Time Control for DC/DC Converter to Reduce the Switching Losses

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Abstract—It has been shown that the resolution of DPWM can be dramatically increased by either constant on-time modulation or constant off-time modulation as compared to that for constant frequency modulation. However, the switching frequency increases dramatically for constant on/off-time modulation method under heavy/light load conditions. The objective of this paper is to propose a hybrid control technique with constant on/off-time control for DC/DC converter in order to reduce the switching frequency and switching losses. It will be shown that the proposed technique can significantly reduce the switching frequency of converter and thereby improving the efficiency up to 2%.

Keywords—hybrid control; constant on-time control; constant off-time control

I. INTRODUCTION

It is well known that digital power control provides less component aging, programmable platform, and robustness to noise. Furthermore, it is also with the advantages of short time-to-market and easy implementation of multi-loop control. Therefore, digital power control has been widely investigated recently [1-6]. However, the limit cycle issue caused by the resolution of Digital Pulse-Width Modulator (DPWM) and quantization error of A/D converter in digital control application [7] results in the oscillation of output voltage of converter even under steady state condition. Several techniques have been proposed to increase the effective modulation resolution [7-11]. It has been shown in [11] that the resolution of DPWM can be dramatically increased by either constant on-time modulation or constant off-time modulation as compared to that for constant frequency modulation.

Constant on/off-time control has been discussed in several applications [12]-[15]. However, as shown in Fig. 1, under constant on-time operation, the switching frequency and the accompanied switching losses significantly increase as the load increases. The increase of switching frequency is contributed by both load and the non-ideal characteristics of components, including turn-on resistor of power devices and resistor of passive components. This paper proposes a novel digital pulse-width modulation technique in order to reduce switching frequency and switching losses for constant on-time and off-time modulation. The basic idea of the proposed technique is to control the converter using constant on-time modulation under light load condition in order to reduce the switching frequency. In contrast, under heavy load condition, the converter is operated in constant off-time to reduce the switching frequency as shown in Fig.1.

This paper is organized as follows. The proposed hybrid modulation and switching control method is revealed in section II. Modeling and controller design of converter using the proposed hybrid modulation technique will be discussed in section III. Experimental results are presented in section IV.

II. NOVEL HYBRID CONTROL TECHNIQUE

A. Proposed hybrid control technique

Fig.2 shows the block diagram of buck converter with proposed modulation method. In this block diagram, constant on-time control and constant off-time control are included in digital control unit as shown in Fig.3. When the switch is connected to “0”, converter will be operated by constant on-time controller. When the switch is connected to ”1”, converter will be operated by constant off-time controller. The status of switch, “1” or “0”, is determined by output current such that the switching frequency keeps in a lower manner under any load condition. The threshold value of load current for the change of switching status will be determined by the upper bound of switching frequency. The relationship between switching frequency and load current will be discussed in Sub-section C.
As shown in Fig. 3, when error between reference and the output voltage is positive (output is smaller than its reference), increase of duty is required. For constant on-time control, off-time should be reduced to reflect this request of duty increase. However, for constant off-time control, on-time should be increased in order to increase the duty under this circumstance.

In contrast, when error between reference and the output voltage is negative (output is greater than its reference), off-time for constant on-time control should be increased while on-time for constant off-time control should be decreased. Therefore, as shown in Fig. 3, an 180-degree phase shifter of error voltage (error voltage is multiplied by -1) is required between constant on-time and constant off-time control in order to reflect these facts.

Moreover, in order to give a smooth transition, in the vicinity of transition point, two controllers are in operation simultaneously while one of the outputs is used for control.

### Modulation method for the proposed control method

It is well known that the carrier is with fixed peak while the modulating signal is determined by the controller. For constant on-time and constant off-time control, the peak value is not fixed in order to retain constant on-time or constant off-time. Fig. 4 shows modulation process for constant on-time and constant off-time modulation control. As shown in Fig. 4 (A) for constant on-time modulation control, on-time

$$t_{on} + t_{off} = T_d$$

and the duty ratio is derived as:

$$d = \frac{T_{on}}{T_{on} + T_{off}}$$

According to Fig. 4 (B) for constant off-time modulation control, the duty ratio of constant off-time modulation is determined by:

$$d = \frac{t_{on}}{t_{on} + T_{off}}$$

### Analysis of switching frequency

In this section, switching frequency for constant on-time modulation and constant off-time modulation are analyzed. Fig. 2 illustrates the system configuration of the proposed technique using a buck converter as an example. Considering the non-ideal characteristics of power devices and passive component, the duty of converter varies with load [16]. The non-ideal characteristics of power devices and passive component include turn-on resistor of MOSFET, $R_{on}$, and DC resistor of inductor, $R_d$. As shown in Fig. 2, the duty ratio of buck converter can be derived and shown as:

$$D = \frac{V_{out}}{V_{in}} \left( R_d + \frac{I_L + V_{out}}{V_{in}} \right)$$

Fig. 4 Modulation process

(A) Constant on-time modulation, $d = \frac{T_{on}}{T_{on} + T_{off}}$

(B) Constant off-time modulation, $d = \frac{t_{on}}{t_{on} + T_{off}}$

C. Analysis of switching frequency

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Fig. 4 Modulation process

(A) Constant on-time modulation, $d = \frac{T_{on}}{T_{on} + T_{off}}$

(B) Constant off-time modulation, $d = \frac{t_{on}}{t_{on} + T_{off}}$
Under steady state, the average inductor current is equal to output current. Then (3) can be rewritten as:

\[ D = \frac{V_{\text{out}}}{V_{\text{in}}} + \frac{I_{\text{on}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \]  

When converter is operated in constant on-time control, \( T_{\text{on}} \) is constant and \( T_{\text{off}} \) is variable. The switching frequency of constant on-time control can be shown by:

\[ f_{\text{sw, CONT}} = \frac{1}{T_{\text{on}} + T_{\text{off}}} = \frac{1}{T_{\text{on}}} \left[ \frac{V_{\text{out}}}{V_{\text{in}}} + \frac{I_{\text{on}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \right] \]  

As converter is operated in constant off-time modulation, \( T_{\text{on}} \) is variable and \( T_{\text{off}} \) is constant. The switching frequency of constant off-time modulation can be determined by:

\[ f_{\text{sw, COFFT}} = \frac{1}{T_{\text{off}}} \left[ \frac{V_{\text{out}}}{V_{\text{in}}} + \frac{I_{\text{off}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \right] \]  

By (5) and (6), it is obviously that the switching frequency variation is contributed by the non-ideal characteristics of power devices and passive component inductor which include turn-on resistor of MOSFET, \( R_{\text{on}} \), and DC resistor of inductor, \( R_{\text{L}} \). As the load increases, the switching frequency increases for constant on-time modulation. In contrast, the switching frequency decreases for constant off-time modulation.

For the converter with a given maximum switching frequency the transition point indicated by the related load current, \( I_{\text{t, out, min}} \), can be derived by (5) and (6). When \( f_{\text{sw, off}} \) equals to \( f_{\text{sw, on}} \), the output current is defined as \( I_{\text{t, out, max}} \). And by (5) and (6), the following equation can be derived:

\[ \frac{1}{T_{\text{on}}} \left[ \frac{V_{\text{out}}}{V_{\text{in}}} + \frac{I_{\text{out}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \right] = \frac{1}{T_{\text{off}}} \left( 1 - \frac{V_{\text{out}}}{V_{\text{in}}} - \frac{I_{\text{out}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \right) \]  

The (7) can be rewritten as:

\[ I_{\text{out}} = \left[ \frac{T_{\text{on}}}{T_{\text{off}}} - \frac{V_{\text{out}}}{V_{\text{in}}} \right] \left( 1 + \frac{T_{\text{on}}}{T_{\text{off}}} \right) \left( R_{\text{on}} + R_{\text{L}} \right) + \frac{V_{\text{out}}}{V_{\text{in}}} \]  

For constant on-time modulation control, the maximum switching frequency, \( f_{\text{sw, max, on}} \), can be derived by substituting (8) into (5) to give:

\[ f_{\text{sw, max, on}} = \frac{1}{T_{\text{on}}} \left[ \frac{V_{\text{out}}}{V_{\text{in}}} + \frac{T_{\text{on}} V_{\text{out}}}{T_{\text{off}} + T_{\text{on}}} \right] \]  

For constant off-time modulation control, the maximum switching frequency, \( f_{\text{sw, max, off}} \), can be derived by substituting (8) into (6) to give:

\[ f_{\text{sw, max, off}} = \frac{1}{T_{\text{off}}} \left[ \frac{1}{V_{\text{in}}} - \frac{T_{\text{off}} V_{\text{out}}}{T_{\text{off}} + T_{\text{on}}} \right] \]  

Moreover, \( T_{\text{on}} \) and \( T_{\text{off}} \) are defined as follows:

\[ T_{\text{on}} = T_{\text{on, 0}} \frac{V_{\text{out}}}{V_{\text{in}}} \]  

\[ T_{\text{off}} = T_{\text{off, max}} \frac{V_{\text{out}}}{V_{\text{in}}} T_{\text{on, 0}} \]  

where \( T_{\text{on, max}} = \sqrt{f_{\text{sw, max}}} \) \( T_{\text{on, 0}} = \) initial switching period

Substituting (11) and (12) into (8) gives \( I_{\text{out, t}} \) as shown in (13).

\[ I_{\text{out, t}} = \frac{V_{\text{out}}(T_{\text{on, 0}} - T_{\text{on, max}})}{(R_{\text{on}} + R_{\text{L}}) T_{\text{on, max}}} \]  

The (5) and (6) can be rewritten by (11) and (12) as:

\[ f_{\text{sw, CONT}} = \frac{1}{T_{\text{on, 0}}} \left[ \frac{V_{\text{out}}}{V_{\text{in}}} + \frac{I_{\text{on}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \right] \]  

\[ f_{\text{sw, COFFT}} = \frac{1}{T_{\text{off, max}} - T_{\text{off, min}}} \left[ \frac{V_{\text{out}}}{V_{\text{in}}} \right] \frac{I_{\text{out}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} \]  

According to (13)-(15), the switching frequency of the proposed modulation method can be obtained as:

\[ f_{\text{sw, proxid}} = \begin{cases} \frac{1}{T_{\text{on, 0}}} \frac{V_{\text{out}}}{V_{\text{in}}} \frac{I_{\text{on}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} & 0 < I_{\text{out, t}} \leq \frac{V_{\text{out}}(T_{\text{on, 0}} - T_{\text{on, max}})}{(R_{\text{on}} + R_{\text{L}}) T_{\text{on, max}}} \\ \frac{1}{T_{\text{off, max}} - T_{\text{off, min}}} \frac{V_{\text{out}}}{V_{\text{in}}} \frac{I_{\text{out}}(R_{\text{on}} + R_{\text{L}})}{V_{\text{in}}} & \frac{V_{\text{out}}(T_{\text{on, 0}} - T_{\text{on, max}})}{(R_{\text{on}} + R_{\text{L}}) T_{\text{on, max}}} < I_{\text{out, t}} < T_{\text{off, min}} \end{cases} \]  

As shown in (13), the variation of \( I_{\text{out, t}} \) is contributed by turn-on resistor of MOSFET, \( R_{\text{on}} \), and DC resistor of inductor, \( R_{\text{L}} \). Fig. 5 illustrates the relationship between load current and frequency in two kinds of \( R_{\text{L}} \) for proposed control method. Some of the remarks can be derived from Fig. 5.

- For the same maximum converter switching frequency limitation, as \( R_{\text{L}} \) decreases, the transition point will move toward greater current.

- The constant on-time modulation control range is extended, while decreasing the constant off-time modulation control range as \( R_{\text{L}} \) deceases.

![Fig. 5 The relationship between load current and frequency in three kinds of \( R_{\text{L}} \)](PEDS2009)
A. Converter Modeling

In order to design the controller, the converter model is derived first. Both DC resistor of inductor and ESR of capacitor are taken into account for more accurate modeling results. The transfer function between output voltage current and duty in s-domain, \( G_{a}(s) \), can be obtained by average state space method [16] as:

\[
G_{a}(s) = \frac{\dot{v}_{o}(s)}{d(s)} = \frac{V_{r}(s)R_{ESR} + 1}{RLC s^2 + [CR(R_c + R_a) + L + CR_{r}R] s + R_c + R_a + R}
\]

(17)

The related equation of (17) in z-domain can be derived by Tustin approximation [17] as:

\[
G_{a}(z) = \frac{\dot{v}_{o}(z)}{d(z)} = \left( \frac{V_{T}}{L} \right) \left[ \frac{2CR_{r} + T}{L} z^2 + 2T z + T - 2\frac{R_{r}C}{L} \right] \left[ 4 + \frac{2R_c + R_a}{L} \right] \left[ \frac{T}{L} z^2 + \frac{2T}{L} - 8z + \left( 4 + \frac{2R_c + R_a}{L} \right) \frac{T}{L} \right] \]

(18)

where

\( G_{a}(z) \): Transfer function between output voltage and duty in z-domain

B. Modeling of modulator

Fig. 6 shows modulation process and perturbation for constant on-time and constant off-time modulation control. As shown in Fig. 6 (A) for constant on-time modulation control, the perturbation indicates by the variable components of carrier which marked by dashed line. The response to the perturbation is indicated by (19).

\[
d = D + \dot{d}
\]

\[
t_{off} = T_{off} + \dot{t}_{off}
\]

Substituting (19) into (1) gives the DC and AC terms as shown in (20) and (21), respectively. Note that the non-linear terms are neglected.

\[(T_{on} + t_{off}) \cdot D = T_{on}
\]

\[
\dot{\dot{d}} = -\left( \frac{D + \dot{d}}{T_{on} + T_{off}} \right) = F_{\text{cor}}
\]

(20)

(21)

According to Fig. 6 (B) for constant off-time modulation control, DC and AC terms in response to the perturbation can be derived as shown in (22) and (23), respectively.

\[(t_{on} + t_{off}) \cdot (1 - D) = T_{off}
\]

\[
\dot{\dot{d}} = \frac{1 - D}{T_{on} + T_{off}} = F_{\text{con}}
\]

(22)

(23)

C. Controller design

The plant diagram can be further simplified as shown in Fig. 7. The loop-gain transfer function of constant on-time modulation excluding voltage controller can be derived as:

\[
T(z) = H \cdot G_{a}(z) \cdot F_{\text{cor}}
\]

\[
= \left( \frac{D}{T_{on} + T_{off}} \right) \left( \frac{V_{T}}{L} \right) \left[ \frac{2CR_{r} + T}{L} z^2 + 2T z + T - 2\frac{R_{r}C}{L} \right] \left[ 4 + \frac{2R_c + R_a}{L} \right] \left[ \frac{T}{L} z^2 + \frac{2T}{L} - 8z + \left( 4 + \frac{2R_c + R_a}{L} \right) \frac{T}{L} \right]
\]

(24)

Substituting the designed circuit parameters shown in Section IV into (24), the loop gain of buck converter under constant on-time modulation is obtained as:

\[
T(z) = \frac{-0.003277 z^2 - 0.001693 z + 0.001583}{z^2 - 1.851z + 0.8614}
\]

(25)

The compensator is designed based upon the well known proportional-integral controller. The related z-domain model of a PI-compensator is:

\[
C_{pi}(z) = \frac{(K_c + K_p z/2) - (K_c - K_p z/2)}{z - 1}
\]

(26)

The zero of PI-compensator is placed near the dominant pole of \( T(z) \) and the system bandwidth can therefore be determined.
by the DC gain of PI-compensator. For the specifications of bandwidth (BW) = 10 kHz \((F_{SW}/10)\) and phase margin (PM) > 45 degrees, the digital compensator can be derived by this method to give:

\[
C_{CV,\text{CONT}}(z) = \frac{30.297z - 30}{z - 1}
\]  

(27)

According to (24)-(27), the designed controller for constant off-time modulation can be obtained as:

\[
C_{CV,\text{COFF}}(z) = \frac{30.297z - 30}{z - 1}
\]  

(28)

\[
\hat{z}(s)\]

(29)

Fig. 7 z-domain model of constant on/off-time modulation buck converter

Table I design specification

<table>
<thead>
<tr>
<th>Controller, (K_p)</th>
<th>Controller, (K_i)</th>
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<tbody>
<tr>
<td>30.16</td>
<td>30.16</td>
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<tr>
<td>Command, (V_{\text{set}})</td>
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<tr>
<td>Bandwidth</td>
<td>11.2 kHz</td>
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<tr>
<td>Phase Margin</td>
<td>51.1 deg</td>
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IV. EXPERIMENTAL RESULTS

Fig. 8 shows the experimental setup which consists of a buck converter with synchronous rectification and an FPGA-based digital controller for proposed hybrid control technique. The details of converter specifications and components are shown in Table II.

Fig. 9 shows the switching frequency of conventional constant on-time, constant off-time and proposed techniques. As shown in Fig. 9 (A), the switching frequency for constant on-time control goes up under heavy load condition. The simulation results derived from (14) is confirmed by the experimental results and both agree with each other. Similar results can be derived for constant off-time control. The exception is the switching frequency becomes lower under light load condition. In contrast, as shown in Fig. 9 (B) for the proposed technique, the switching frequency is within a limited range despite of load changes and the proposed hybrid control technique can significantly reduce the switching frequency and switching losses. Fig. 10 shows the experimental results around the transition point. As shown in Fig. 10, the voltage ripple is less than 38 mV, 2.5% of output voltage under both conditions. Fig. 11 shows the dynamic response to load impact. As shown in Fig. 11, the voltage ripple is less than 106 mV, ±3.53% of output voltage. Fig. 12 shows the measured results of efficiency. As shown in Fig. 12, the efficiency improvement by the proposed technique is up to 2%.

<table>
<thead>
<tr>
<th>Table II Specifications</th>
<th>Value</th>
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<tr>
<td>Input voltage, (V_{\text{in}})</td>
<td>5V</td>
</tr>
<tr>
<td>Output voltage, (V_{\text{out}})</td>
<td>1.5V</td>
</tr>
<tr>
<td>Inductor, (L/\text{DCR})</td>
<td>1 (\mu\text{H}/23 \text{m}\Omega)</td>
</tr>
<tr>
<td>Capacitor, (C/\text{ESR})</td>
<td>2990 (\mu\text{F}/2.4 \text{m}\Omega)</td>
</tr>
<tr>
<td>Output current, (I_{\text{out}})</td>
<td>20A</td>
</tr>
<tr>
<td>Gain of ADC</td>
<td>76.6</td>
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</table>

Fig. 8 System of the experimental setup

(A) constant on/off time, experimental and simulation

(B) proposed, experimental

Fig. 9 Switching frequency vs. output load
This paper proposes a new hybrid control technique which provides constant on-time and off-time control. The effective of DPWM resolution is increased as compared to that for conventional constant frequency PWM method. Moreover, the switching frequency is significantly reduced comparing to either constant on-time or constant off-time control. Experimental results demonstrate the effectiveness of the proposed hybrid control technique and the efficiency improvement is up to 2%.

**REFERENCE**


