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Review of Digital Control Techniques for Automotive DC-DC Converters

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***Abstract*—Electric and hybrid electric vehicles need a power plant that includes dc-dc converters. While using these converters, their control plays an important role in the overall performance of the vehicle. Due to their several drawbacks including poor communications, analog control schemes are not suitable for the automotive industry, whereas digital control methods successfully meet the demands. Various types of digital control techniques for dc-dc converters are studied and classified in this paper. The drawbacks and advantages of each method are described.**

I. INTRODUCTION

The conversion of automotive systems from 14V to 42V is inevitable in the future automobile industry. This transition to use 42V systems indicates the use of dc-dc converters. The electric vehicles and hybrid electric vehicles (EVs/HEVs) require dc-dc converters in addition to ac-dc/dc-ac converters. The control of these converters plays an important role in the overall performance of the HEV. Hence optimization of the efficiency and performance of various converters used in the HEV as well as the entire system level integration is the present major concern in the automotive industry. Control of dc-dc converters is racing towards complete digitalization so as to improve their performance. Even though digital control techniques are in the early stages they are proving to be the emerging technology of future.

Analog control has several disadvantages such as sensitivity to noise and temperature, which are a major problem in vehicles. Also poor communication between the system components makes the system level control harder. Even though analog control offers advantages such as higher bandwidth and being cheaply available, the advantages of using digital control dominates against the use of analog control. The digital controllers are gaining popularity due to their accuracy, flexibility and robustness. Digital control is a wide area and has applications in the control of dc-dc converters, power factor correction (PFC) circuits, etc. Due to the recent developments in the digital signal processor (DSP) technology and microprocessors digital control has become advantageous for high frequency low to medium-power switching converters [1]. Also the decreasing cost of the microprocessors over years has made digital control a more viable option as compared to analog control.

Digital control offers potential advantages such as lower sensitivity to parameter variations, programmability and possibilities to improve performance using more advanced schemes. The reaction time is very fast for any load changes and the control circuitry reacts quickly to make the changes as required to bring back the dc-dc converter to stable operating point. The digital circuits used for the digital control are less susceptible to aging, environmental variations, possess high noise immunity and are easier to implement [1-6]. Also in case the controller is changed then only the software needs to be changed and the hardware remains the same. Presently digital controller is preferred over its analog counterpart due to its reliability, high-level system integration and possibility of automatic tuning. Also more and more complicated algorithms can be implemented using the former one. Ease of programming, adaptability, low part count, etc., make digital control more advantageous [1-2].

In this paper, different digital control techniques are reviewed and summarized, including predictive control and dead-beat control techniques [1-6]. Advantages and disadvantages of each method are analyzed and their benefits to EVs/HEVs are investigated. Fixed and variable frequency topologies have been studied in this paper. Also a predictive digital control method that works well in both continuous and discontinuous mode is discussed. Finally predictive dead-beat current control technique has been studied.

II. DIGITAL CONTROL METHODS

A. Current Control Method for DC-DC converters operating in DCM:

This method is basically an estimative current control technique [2]. A converter with discontinuous current conduction is chosen as it provides zero-current switching of the active devices. The new proposed digital control technique can be easily implemented through a DSP chip and is interfaced to the dc-dc converter. As depicted in Fig. 1, in discontinuous conduction mode (DCM), there are three duty cycles d_1, d_2, and d_3 and we have

$$d_1+d_2+d_3 = T_s \qquad (1)$$

The typical waveforms of the inductor and diode are obtained by assuming that the variation in the input voltage is negligible compared to the switching frequency of the converter, and also that the output filter is large enough to filter the output voltage variations. From the diode current waveform in Fig. 1(b) we can obtain

$$I_{max} = d_1 T_s m_1 \quad (2)$$

$$d_2 T_s = I_{max} / m_2 \quad (3)$$

where, in a boost converter $m_1 = V_{in}/L$, $m_2 = (V_o\text{-}V_{in})/L$ and T_s is the switching period.

From the above two equations we can find the average diode current in one complete cycle which happens to be the average load current. We can also obtain d_1 as

$$d_1 = \sqrt{\frac{2L}{T}} * \frac{1}{V_{in}} * \sqrt{i_{D(av)}(V_o - V_{in})} \quad (4)$$

It can be clearly seen that d_1 depends on V_o, V_{in} and $I_{d(avg)}$ for a given converter. Here, it is assumed that the time period is constant and the value of inductor do not change appreciably.

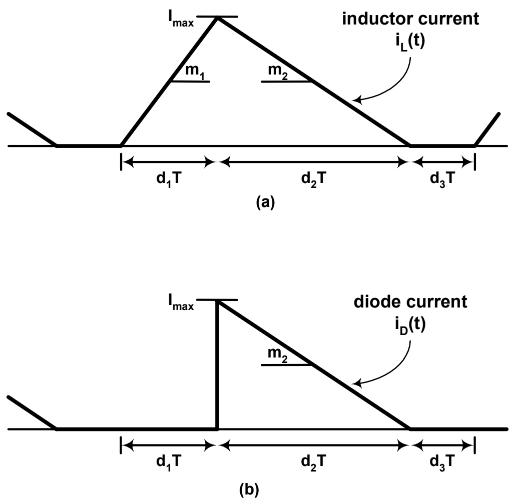

Figure 1. Typical current waveforms of (a) inductor and (b) diode of a boost converter operating in DCM.

Hence (4) can be used as a new approach to find out the on-time of the switch in order that the average current of the diode follows the desired reference signal, which might be the output of the voltage compensator circuit. This methods works well in the discontinuous conduction mode, easy to be implemented and is insensitive to the parameter variations.

B. Predictive Digital Current Programmed Control:

The predictive digital current programmed control algorithm works on the principle of predicting the duty cycle of the next switching cycle based on the values obtained from the previous cycles [1-2]. Also the input and output voltage values are to be sampled to calculate the next duty cycle. Predictive valley control, predictive peak control, and predictive average control are all achievable using this method.

Trailing edge modulation works well for a predicted valley current control as the switching cycle starts from t=0 and also the sampling of the valley point is done at t=0 (i.e. at the start of a new cycle). But for predicted peak and predicted average control the sampling and the starting of a switching cycles do not coincide and this causes oscillation problems such as period doubling.

The objective of the control method is that the valley inductor current follows the reference signal i_c. The sampled inductor current $i(n)$ can be written as the function of previous sampled current $i(n\text{-}1)$ and the duty ratio $d(n)$. It is assumed that the input and output voltage, inductance and the switching period are known. As shown in Fig. 2, we can write

$$i(n) = i(n-1) + \frac{V_{in} d(n) T_s}{L} - \frac{(V_{in} - V_o) d'(n) T_s}{L} \quad (5)$$

where $d' = 1\text{-}d$. Rewriting equation (5),

$$i(n) = i(n-1) + \frac{V_{in} T_s}{L} - \frac{V_o d'(n) T_s}{L} \quad (6)$$

Extending equation (6) for another switching cycle and from Fig. 2,

$$i(n+1) = i(n-1) + \frac{2V_{in} T_s}{L} - \frac{V_o d'(n) T_s}{L} - \frac{V_o d'(n+1) T_s}{L} \quad (7)$$

Solving equation (7) for predicted duty cycle $d(n+1)$, we obtain the equation

$$d[n+1] = 2 - d[n] - \frac{L}{V_o T_s}[i_s[n] - i_c] - 2\frac{V_{in}}{V_o} \quad (8)$$

$i_s[n]$ is the sampled current $i(n\text{-}1)$ and i_c is the current signal to be achieved (equal to $i(n+1)$).

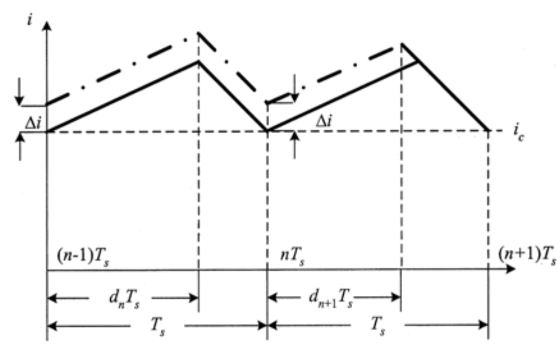

Figure 2. Valley current control under trailing edge modulation.

Predictive valley current control gives satisfactory results using the trailing edge modulation technique. In the same way leading edge modulation technique is found to give good results for predictive peak current control method. Also, the predictive average current control works well for both trailing triangle and leading triangle modulation techniques. The waveforms corresponding to the leading edge modulation for predictive peak method and triangle modulation techniques for average current control are shown in Fig. 3 and Fig. 4 respectively.

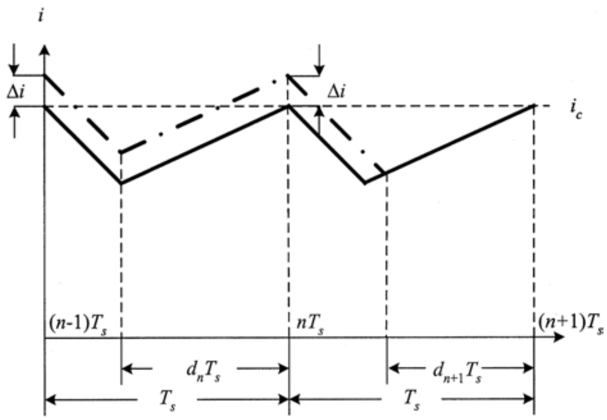

Figure 3. Peak current control under leading edge modulation.

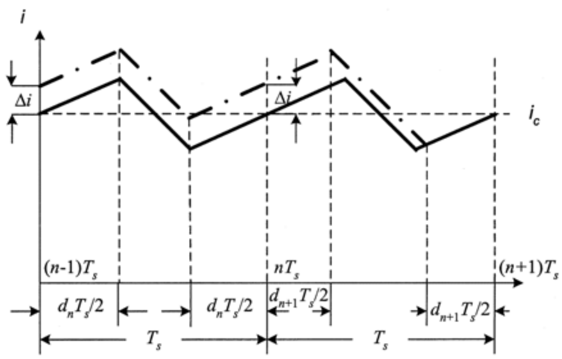

Figure 4. Average current control under triangle modulation.

The basic control law that was devised for $d[n+1]$ works well for all types of control methods and it is so programmed that for each control method a corresponding modulation method is chosen. The robustness of the designed controller depends on the value of inductance and changes in temperature, operating conditions and aging might make a difference in its performance. Also a constant reference value for the output voltage is used instead of the real time sampled output voltage value to simplify the control law. The principles developed in the predictive digital current programmed control algorithm can be easily applied to buck, boost and buck-boost converters.

C. Variable Frequency Predictive Control Method:

Till now, only the duty cycle was being predicted one cycle ahead and is calculated. In the second method, the proposed algorithm requires at least 2-3 cycles to achieve the target current and it can be applied only to converters operating in continuous conduction mode (CCM). Also in the first method, the evaluation of square root in order to predict the duty cycle consumes a lot of time. A new method was developed recently [3], which deals the variable frequency and constant on-time concept. This method deals with constant on-time and variable frequency concept. In this way only the t_{off} time has to be calculated in every cycle. One disadvantage is that the CCM/DCM boundary condition has to be checked for every cycle in addition to calculating t_{off}. In this method the transistor on-time will be kept constant by design and is selected such that it is in the range of switching frequency variation and the minimum computation time. As depicted in Fig. 5, we can derive the equation for

$i\,(n+1)$ as follows:

$$i[n]+m_1 t_{on}-m_2 t_{off}=i[n+1]=i_c \tag{9}$$

where $i[n]$ is the sampled current, i_c is the reference current, m_1 and m_2 are the slopes of the current waveform during t_{on} and t_{off} times.

From (9), t_{off} can be calculated as follows:

$$t_{off}[n]=\frac{i[n]-i_c+m_1 t_{on}}{m_2} \tag{10}$$

This control method is applicable to both CCM and/or DCM operating modes, for example $t_{off}=[(i[n]-i_c)+\frac{v_g-v}{L}t_{on}]\frac{L}{v}$ for a buck converter operating in CCM and $t_{off}=\frac{1}{2}\frac{v_g}{v}\frac{(v+v_g)}{L}\frac{t_{on}^2}{i_C}-t_{on}$ for a boost converter operating in DCM. While operating at the boundary of CCM and DCM modes either (i) the CCM/DCM boundary condition is checked first and then the appropriate equation is used, or (ii) t_{off} can be computed for both DCM and CCM and then the larger of the two is picked.

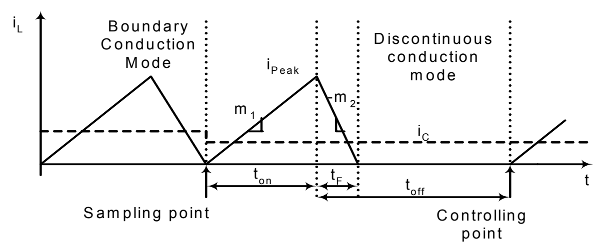

Figure 5. Variable frequency (constant on-time) predictive digital current mode control.

D. Sensorless Current Mode Control Method:

The authors of [4] have proposed a new control method according to which the controlling current signal is not sensed but estimated. This can still be considered as a current mode control loop even though it is only the output voltage that is being sampled/sensed. Current mode controllers are superior to voltage mode controllers due to their fast inner current loop and improved dynamics resulting in more robustness. But the need for current sensing increases cost and reliability. Hence a sensor less control of dc-dc converters has been proposed in [4]. The control scheme is a standard dual loop current mode controller. The major difference in this control method compared to other techniques is that the inductor current is estimated rather than measured. The current controller is of deadbeat type. The overall control structure is drawn in Fig. 6.

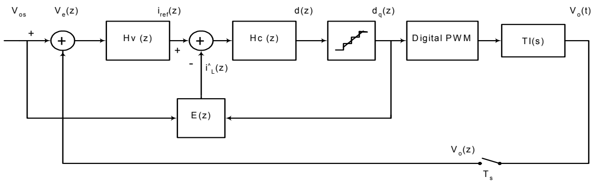

Figure 6. Sensor less current mode control scheme.

In Fig. 6, V_e(z) is the error voltage in discrete time domain, i_{ref}(z) is the reference current output from voltage controller in discrete time domain, *d*(*z*) is the duty cycle, $d_q(z)$ is the quantized duty cycle, $V_o(t)$ is the output voltage of the power stage, V_o(z) is the sampled output voltage, $i_L(z)$ represents the estimated inductor current values and TI(s) represents the current to voltage transfer function of the converter. As the resolution of the PWM is limited the duty cycle has to be quantized so that the PWM can resolve the value. Inductor current in n[th] cycle for a buck converter can be shown in Fig. 7.

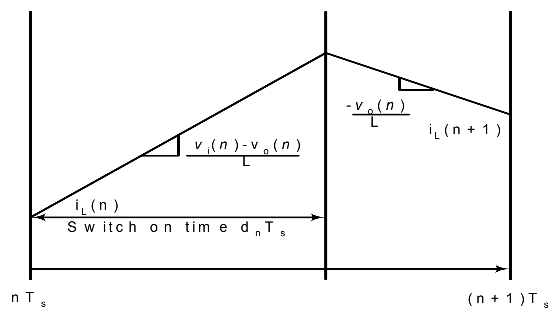

Figure 7. Inductor current in cycle n.

The equation for the inductor current in the n[th] cycle is given as follows (from Fig. 7)

$$i_L(n+1) = i_L(n) + \frac{v_i(n) - v_o(n)}{L} d(n) T_s - \frac{v_o(n)}{L} T_s (1 - d(n)) \qquad (11)$$

$v_i(n)$ and $v_o(n)$ are the output and input voltages of the dc-dc converter respectively and the duty cycle for the nth cycle is given as d (n). From (14) the equation for d (n) can be calculated as follows:

$$d(n) = \frac{L}{v_i(n) T_s} [i_L(n+1) - i_L(n)] + \frac{v_o(n)}{v_i(n)} \qquad (12)$$

The advantage of the dead-beat control is that the inductor current value is made to follow the reference current $i_{ref}(n)$ in one cycle such that $i_L(n+1)$ is equal to $i_{ref}(n)$. Hence the above equation becomes

$$d(n) = \frac{L}{v_i(n) T_s} [i_{ref}(n+1) - i_L(n)] + \frac{v_o(n)}{v_i(n)} \qquad (13)$$

It is taken care of that the period doubling oscillation is avoided by choosing an appropriate PWM modulation strategy, for a particular inductor current control strategy.

E. Predictive digital dead-beat controller for dc-dc converters:

In this method, a dead-beat controller is studied for dc-dc converters operating in continuous conduction mode [5]. The inner loop is based on the dead beat concept and the outer voltage loop is based on the digitized proportional-integral (PI) controller. The resulting two-loop controller is far superior to that of the analog controller and also the design of such a controller is simple and reliable. In addition, the load does not need to be considered in the controller design due to the dead-beat characteristics of the inner current loop.

Assuming that the sampling time is equal to the switching time and the output voltage is constant during the switching cycle, in a buck converter the inductor current at the end of n[th] cycle can be written as follows:

$$i_{L,n+1|d_n} = i_{L,n} + \frac{v_{o,n}}{L} T_{sw} - \frac{V_i}{L}(1 - d_n) \qquad (14)$$

where , $i_{L,n+1|d_n}$ is the value of inductor at time t_{n+1}, when the duty ratio is d_n.

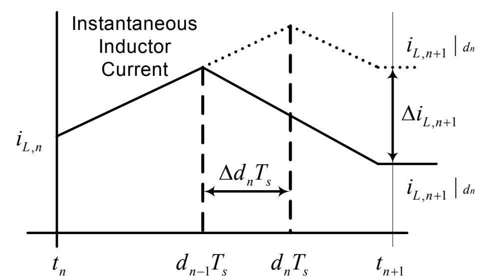

Figure 8. Inductor current during one switching period.

As suggested in Fig. 8, we can write the change in inductor current $i_{L,n+1}$ as:

$$\Delta i_{L,n+1} = \frac{V_i}{L} T_{sw} \Delta d_n \qquad (15)$$

Where $\Delta i_{L,n+1} = i_{L,n+1}|_{dn} - i_{L,n+1}|_{d(n-1)}$ and $\Delta d_n = d_n - d_{n-1}$.

A dead-beat control law is thus formulated as follows:

$$d_n = d_{n-1} + \frac{L}{V_i T_{sw}} \varepsilon_{n+1}$$
$$\varepsilon_{n+1} = i_{Lref,n+1} - i_{L,n+1|d_{n-1}} \qquad (16)$$

Where ε_{n+1} is the difference between desired current and the value of current if the duty ratio is unchanged, at t_{n+1}.

By calculating the duty cycle using the above control law, the inductor current will reach its reference value $i_{L\,ref,n+1}$ at t_{n+1}.

A major difficulty in using equation (16) is that the error ε_{n+1} has to be predicted. Supposing that i_{Lref} is constant $i_{L,n+1}\big|_{d_{n-1}}$ can be calculated using the simplified predictor method [6]. The equation can be written as follows:

$$\hat{i}_{L,n+1|d_{n-1}} = 2.i_{L,n|d_{n-1}} - i_{L,n-1|d_{n-2}} \tag{17}$$

In this method the duty cycle is updated only once in every two switching cycles. This control method can be used in EVs/HEVs due to its inherent time delay compensation so that the reaction time is very fast for frequent load changes.

III. CONCLUSION

Various digital control methods have been studied in this paper. Due to their digital nature, these control methods can successfully be implemented in the dc-dc converters that are used in the automotive industry to improve the overall performance of the vehicles. The discussed digital techniques are suitable for DCM or CCM operating modes or both and are applicable to the entire family of dc-dc converters.

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