

Multiple Sets of Pulse Adjustment Control Technique Based on Input Voltage Feed-forward Compensation for DC-DC Converters

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Abstract. In order to increase the applicable input voltage scope of Pulse Adjustment (PA) controlled converter, a new control technique for DC-DC converters, Multiple Sets of Pulse Adjustment Based on Input Voltage Feed-forward Compensation (IVF-MSPA), is proposed in this paper. By introducing input voltage feed-forward compensation, at the beginning of each switching period IVF-MSPA controller senses the input voltage of the DC-DC converter and selects one among multiple sets of control pulses. Each set of control pulses is composed of high-power pulse and low-power pulse. The high-power pulse or low-power pulse is selected to drive the power switch by sensing the output voltage of the DC-DC converter at the beginning of each switching period. The principle and operational process of IVF-MSPA control technique are introduced in the paper. The control regulation and steady-state performance of IVF-MSPA controlled Boost converter operating in discontinuous conduction mode (DCM) are studied. The proportions of IVF-MSPA and PA control pulses as the function of input voltage within one repetition cycle are analyzed. Simulation and experimental results are presented to verify the feasibility and advantages of IVF-MSPA control technique as well as the correctness of the theoretical analysis. Research results show that the IVF-MSPA controlled converter enjoys excellent steady and transient state performance as well as the wider input voltage scope.

1. Introduction

In recent years, the countries around the world are facing such outstanding problems as the energy crisis and environmental degradation. It is crucial to use all kinds of energy comprehensively and efficiently for future sustainable energy supply. Our country per-capital share of oil resources is far lower than the world average, there is an obvious oil energy gap. At the same time, such as fog and water pollution environment problems also affect the national economy and people's livelihood which need to be solved in urgent. Therefore, further studying a series of technology problems of new energy is the key to sustainable development and solving energy shortage. Clean fuels such as solar and wind energy is concerned, clean energy power generation technology is developing rapidly and has a clear future. Compared with the traditional thermal power, clean energy power generation system has the advantages of renewable, no pollution, high degree of automation, but due to the influence of natural environment, its output characteristic is more complex, the power quality is difficult to guarantee, not directly provide electricity equipment. So specific power transformation technology is usually used, DC-DC switching technology (that is DC-DC switching converter) is one important part of it. Due to the nonlinear characteristics of photovoltaic array, the output voltage of photovoltaic array is affected by light intensity, environmental temperature and load conditions^[1-7]. Therefore, it is necessary to study a DC switching converter technique which can adapts to changes in wide range input source voltage.

In recent decades, Pulse Width Modulation (PWM) technique based on the classical linear control theory is widely used in the field of switch converter technology, but its performance in transient characteristics and stability is poor, thus some scholars put forward a kind of new control technique which is based on nonlinear control regulation called Pulse Adjustment (PA). Compared with the conventional PWM, PA control technique has more excellent transient performance and stability, but the PA controlled converter by a combination of two different control pulses has the

drawback of relatively narrow range of input voltage which limits its application in photovoltaic field^[8-12]. Then some modified pulse adjusting control technique mainly focus on the features of optimizing the output characteristic of the controlled converter which also does not apply to the occasions required wide range input voltage^[13-15]. In order to solve this problem, the paper puts forward and studies a new control technique named 'IVF-MSPA' for switching converters.

First, the paper will introduce the basic principle of the IVF-MSPA control technique, then study the work characteristics and controlling regulation of Boost converter operating in DCM as an example, finally verify the feasibility and advantages of IVF-MSPA control technique through the simulation and experimental results.

2. Principle of IVF-MSPA Control Technique

Unlike original pulse adjustment (PA) control technique realized by a combination of two different control pulses, IVF-MSPA control technique extends these two different pulses to multiple sets of control pulses. The principle of IVF-MSPA control technique is introduced as follows:

At the beginning of each switching period, the IVF-MSPA controller senses the input voltage and output voltage of DC-DC converter. The input voltage V_{in} is compared with the pre-defined voltage boundary σ_{n-1} ($n=2, 3$) to determine which one set of P_1^H and P_1^L , P_2^H and P_2^L , P_3^H and P_3^L will be selected as the control pulses. At the same time, the output voltage V_o is compared with desired voltage V_{ref} to determine corresponding level pulse between P_j^H and P_j^L ($j = 1, 2, 3$). When the output voltage is higher than the desired level, low-power pulse P_j^L with shorter turn-on time is employed. On the contrary, when the output voltage is lower than the desired voltage, high-power pulse P_j^H with longer turn-on time is used to drive the power switch. The longer the turn-on time, the more power is delivered to the load. As shown in Fig. 1, this is a IVF-MSPA controlled DC-DC converter operating in DCM, with IVF-MSPA consisting of three sets different control pulses P_1^H and P_1^L , P_2^H and P_2^L , P_3^H and P_3^L as an example.

At the beginning of each switching period, if $V_{in} < \sigma_1$, which means the input voltage is much lower than the rated input voltage, the highest level of a set of control pulse is employed sequentially; if $\sigma_1 < V_{in} < \sigma_2$, which means the input voltage is close to the rated input voltage, the second higher level of a set of control pulse is employed sequentially; If $V_{in} > \sigma_2$, which means the input voltage is much higher than the rated input voltage, the lowest level of a set of control pulse is employed sequentially. According to the output voltage sensed, high-power pulse P_j^H or low-power pulse P_j^L is used, if $V_o < V_{ref}$, high-power pulse P_j^H is selected to drive the power switch; if $V_o > V_{ref}$, low-power pulse P_j^L is selected to drive the power switch.

Above all, the IVF-MSPA controller selects one among multiple sets of control pulse according to the amplitude of the converter input voltage and emits the high-power pulse P_j^H or low-power pulse P_j^L according to the relationship between the output voltage of DC-DC converter and the desired voltage. A IVF-MSPA repetition cycle is consisted of pulse sequence constructed by the combination of P_j^H and P_j^L . When the converter is operating in the steady-state, the IVF-MSPA controller emits the same pulse sequence repeatedly.

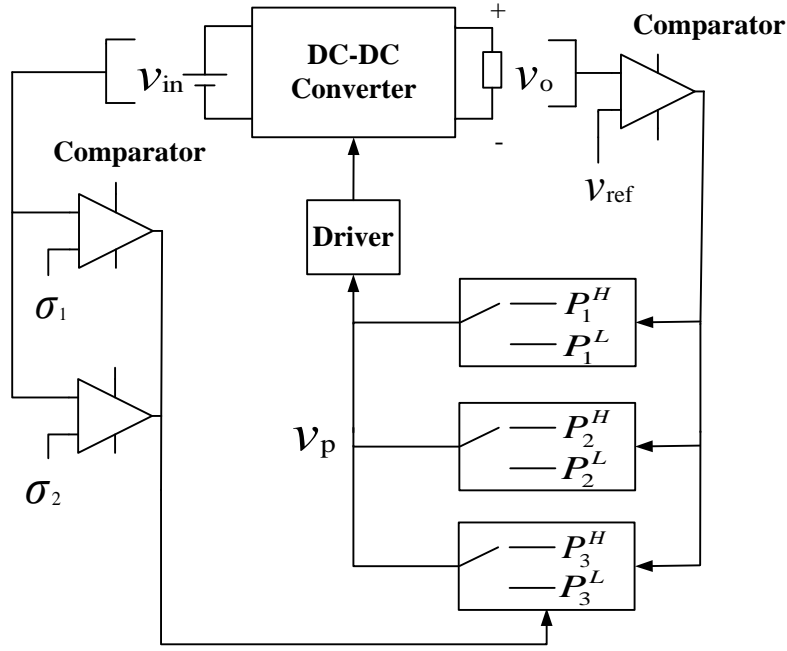


Fig.1 Block diagram of IVF-MSPA controller

3. Analysis of the IVF-MSPA Controlled Boost Converter Operating in DCM

3.1 Steady-state Characteristics Analysis.

As shown in Fig. 2, this is the Boost converter power circuit. Assuming that the Boost converter output voltage ripple can be ignored in each switching period, the analysis is introduced as follows.

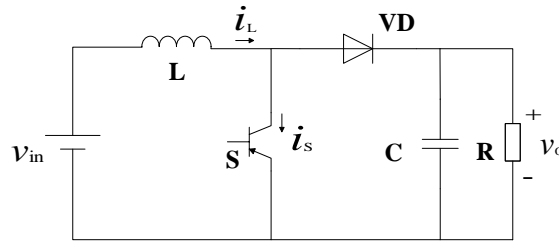


Fig.2 Diagram of Boost converter

Within P_j^H and P_j^L ($j = 1, 2, 3$) control pulse cycle, the averaged current flowing from V_{in} is respectively

$$I_{in,Hj} = \frac{V_o V_{in}}{2L(V_o - V_{in})} D_{Hj}^2 T, \quad j = 1, 2, 3 \quad (1a)$$

$$I_{in,Lj} = \frac{V_o V_{in}}{2L(V_o - V_{in})} D_{Lj}^2 T \quad (1b)$$

Where the duty ratio of the P_j^H and P_j^L control pulse are D_{Hj} and D_{Lj} , respectively.

The delivered energy from input during P_j^H and P_j^L control pulse cycle is respectively

$$E_{in,Hj} = \frac{V_o V_{in}^2}{2L(V_o - V_{in})} D_{Hj}^2 T^2 \quad (2a)$$

$$E_{in,Lj} = \frac{V_o V_{in}^2}{2L(V_o - V_{in})} D_{Lj}^2 T^2 \quad (2b)$$

We assumes that the numbers of control pulses P_j^H and P_j^L within one IVF-MSPA repetition cycle are μ_j^H and μ_j^L , respectively. Therefore the energy delivered from input during the IVF-MSPA repetition cycle is

$$\Sigma E_{in} = \mu_j^H E_{in,Hj} + \mu_j^L E_{in,Lj} \quad (3)$$

During one IVF-MSPA repetition cycle, we have

$$(\mu_j^H + \mu_j^L)PT = \eta \Sigma E_{in} \quad (4)$$

Where η is the power conversion efficiency of the Boost converter and $P = V_o^2/R$ is the power consumed by the load. Then by combining (2)–(4), we have

$$P = \frac{\eta TV_o V_{in}^2 (k_j D_{Hj}^2 + D_{Lj}^2)}{2L(V_o - V_{in})(k_j + 1)} \quad (5)$$

Where the proportion of control pulses P_j^H and P_j^L within one IVF-MSPA repetition cycle is $k_j = \mu_j^H / \mu_j^L$.

From (5), we come to the conclusion that the parameters of k_j , D_{Hj} and D_{Lj} need to be changed to adapt to the changes in the input voltage of the Boost converter. An illustrative example, if the input voltage changes in the first amplitude range ($V_{in} < \sigma_1$), by adjusting the pulse number ratio k_1 , the IVF-MSPA controlled Boost converter is adapted to the variation of the input voltage, D_{H1} and D_{L1} are employed.

3.2 The Design of the Control Parameters

The IVF-MSPA control parameters are vitally important to achieve the control strategy and good control characteristics or not, the design of the IVF-MSPA control parameters is described in detail as follows.

The parameters of the Boost converter are given in Table 1.

Table 1 The parameters of the Boost converter

Parameters	Signification	Value
V_{in} / V	Rated input voltage	6
V_o / V	Output voltage	12
P / W	Output power	4.5
$L / \mu H$	Inductor	33
$C / \mu F$	Filter capacitor	2000
$T / \mu s$	Switching cycle	50

The critical condition of the Boost converter operating in DCM is

$$I_o \geq I_D \quad (6)$$

Where I_o is the current flowing from the load and I_D is the averaged current flowing from the diode VD in one switching cycle. From (6), we have

$$\frac{L}{RT} < \frac{D(1-D)^2}{2} \quad (7)$$

Then according to the data in Table 1, we deduce that any control pulse duty ratio D must be less than 0.76 if the Boost converter operating in DCM.

Within only single control pulse cycle, analogizing from (5), we have

$$P = \frac{\eta TV_o V_{in}^2 D^2}{2L(V_o - V_{in})} \quad (8)$$

Then by assuming $\alpha = PL$, $\beta = \eta T$, we deduce

$$V_{in} = \frac{\sqrt{\alpha^2 + 2\alpha\beta V_o^2 D^2} - \alpha}{\beta V_o D^2} \quad (9)$$

From (9), the Boost converter operating in 4V input voltage, the duty ratio D of the single control pulse is 0.47. Analogously, the weighted average of the duty ratio of control pulses P_1^H and P_1^L within one IVF-MSPA repetition cycle is $(k_1 D_{H1} + D_{L1}) / (k_1 + 1) = 0.47$. In order to obtain lesser output voltage ripple, the difference between D_{H1} and D_{L1} should not be set too much,

with $k_1=1$. Finally, we determine that the duty ratio D_{H1} and D_{L1} are 0.68 and 0.26, respectively. According to the method described above, D_{H2} and D_{L2} , D_{H3} and D_{L3} are determined respectively (listed in Table 2).

Table 2 The parameters of the IVF-MSPA control

Parameters	Signification	Value
D_{H1}	Duty ratio of control pulse P_{H1}	0.68
D_{L1}	Duty ratio of control pulse P_{L1}	0.26
D_{H2}	Duty ratio of control pulse P_{H2}	0.48
D_{L2}	Duty ratio of control pulse P_{L2}	0.16
D_{H3}	Duty ratio of control pulse P_{H3}	0.28
D_{L3}	Duty ratio of control pulse P_{L3}	0.12
σ_1 / V	Reference input voltage	5
σ_2 / V	Reference input voltage	7

3.3 Control Pulse Combination

From (5), we deduce that k_j as a function of V_{in} is

$$k_j = \frac{2PL(V_o - V_{in}) - \eta TV_o D_{Lj}^2 V_{in}^2}{\eta TV_o D_{Hj}^2 V_{in}^2 - 2PL(V_o - V_{in})} \quad (10)$$

Therefore, equation (10) and Figure 3a can be used to estimate the proportion of IVF-MSPA control pulses at any input voltage.

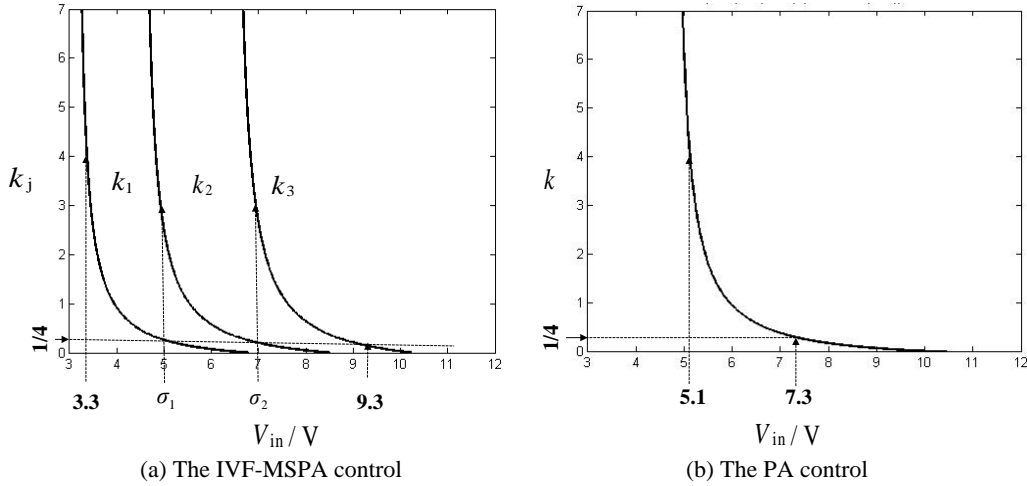


Fig.3 k_j or k as a function of input voltage V_{in}

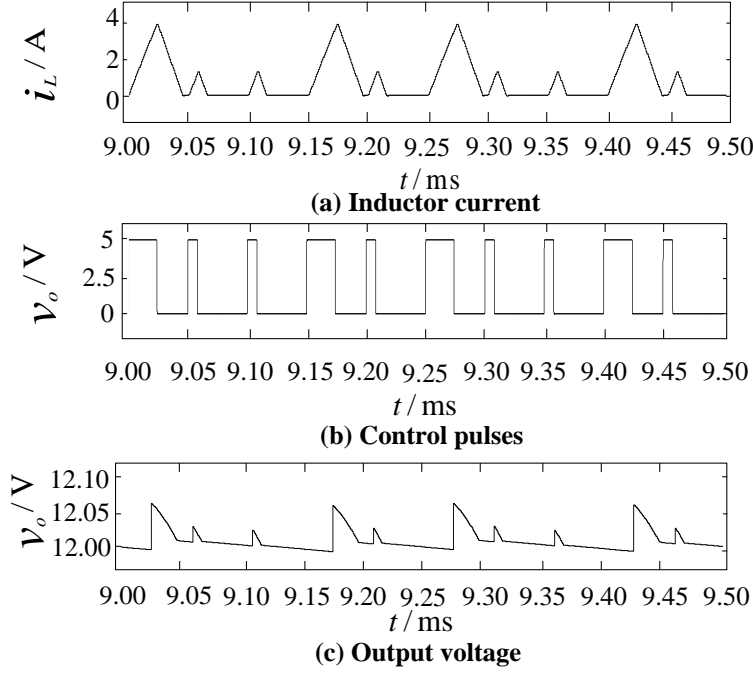
From Fig 3a, we know that the IVF-MSPA controlled Boost converter can normally operate under input voltage variations from 3.3V to 9.3V, k_j varying between 1/4 and 4. The larger k_j than 4 and the smaller k_j than 1/4, the larger the output voltage ripple. From Fig 3b, we deduce that the PA controlled Boost converter can normally operate under input voltage variations from 5.1V to 7.3V, k_j varying between 1/4 and 4.

In conclusion, the applicable input voltage scope of the IVF-MSPA controlled Boost converter is much wider than the PA controlled Boost converter.

4. Simulation Results

Simulations are performed using the same parameters given in Table 1 and Table 2. Fig.4 shows the steady-state waveforms of the IVF-MSPA controlled Boost converter operating in the rated input voltage 6V.

Fig.4 Steady-state waveforms of IVF-MSPA converter for 6V input voltage



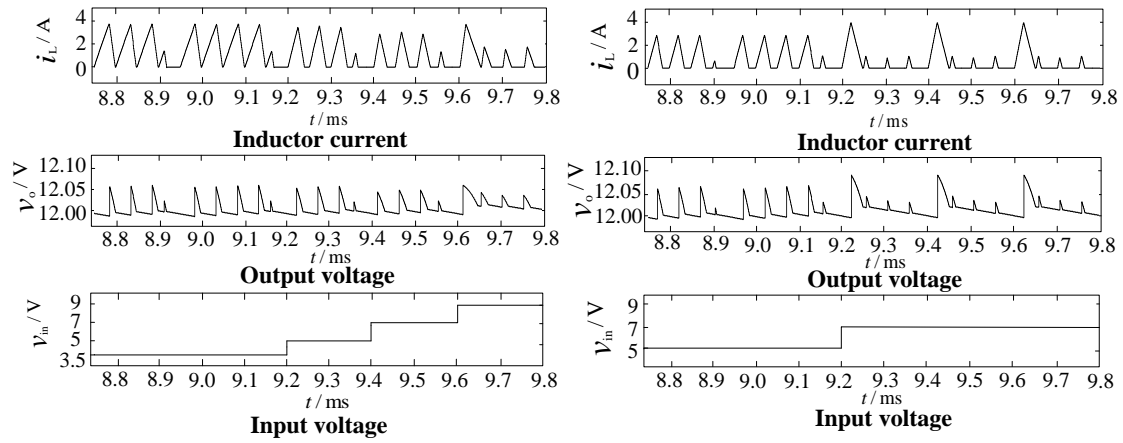
From Fig.4b, we can know that the control pulses within the IVF-MSPA repetition cycle are $P_2^H - 2P_2^L - P_2^H - P_2^L$, and the proportion k_2 of the IVF-MSPA control pulses is $2/3$.

From Fig.4c, we can deduce that the output voltage of the IVF-MSPA converter is 12V, and the voltage ripple is 65mV.

The waveforms of IVF-MSPA and PA controlled converter under input voltage variations are shown in Fig.5. From Fig.5, we can see the output voltage ripple of the IVF-MSPA control is 70mV, input voltage varying from 3.5V to 5V to 7V to 9V, while the output voltage ripple of the PA control is 100mV, input voltage varying from 5V to 7V.

From Fig.5a, we can know that there is no obvious rise for the output voltage of the IVF-MSPA controlled converter under input voltage varying from 5V to 7V; from Fig.5b, we can see that there is a little rise for the output voltage of the PA controlled converter under input voltage varying from 5V to 7V.

From the discussion above, we deduce that the output voltage ripple of the IVF-MSPA control is lower than the PA control under input voltage variations, and compared with the PA controlled converter, the IVF-MSPA controlled converter enjoys excellent steady and transient state performance and the wider input voltage scope.



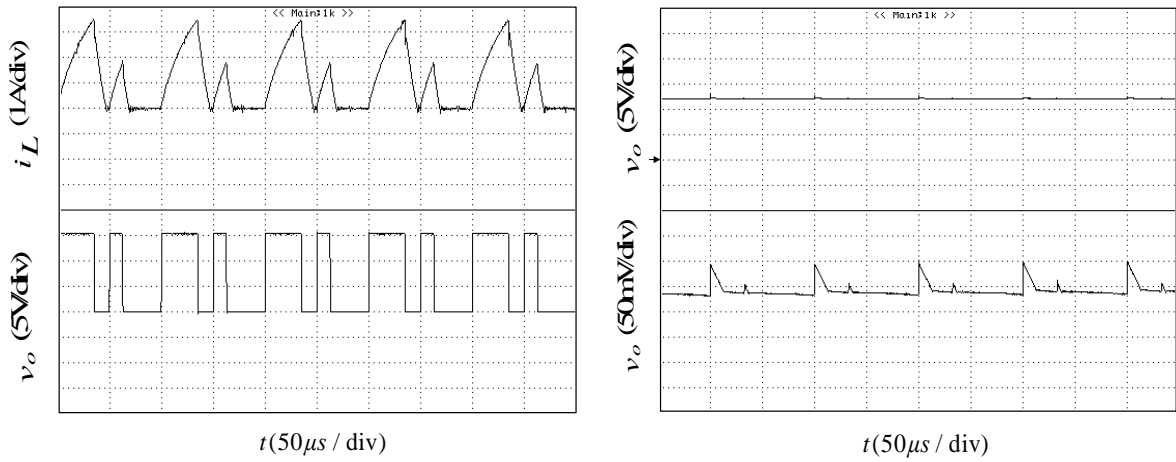
(a) IVF-MSPA control

(b) PA control

Fig.5 Waveforms of IVF-MSPA and PA controlled converter under input voltage variations

5. Experimental Results

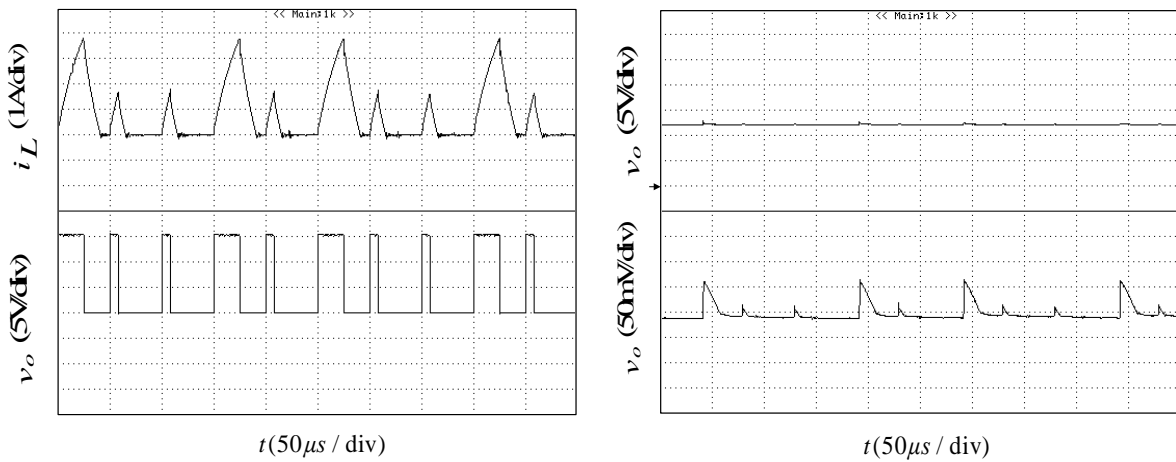
Experiments are also performed using the same parameters given in Table 1 and Table 2. The waveforms of the IVF-MSPA controlled converter under different input voltage (4V, 6V, 8V) are shown in Fig.6~fig.8.



Inductor current and control pulses

Output voltage and voltage ripple

Fig.6 Experimental results of IVF-MSPA control for 4V input voltage



Inductor current and control pulses

Output voltage and voltage ripple

Fig.7 Experimental results of IVF-MSPA control for 6V input voltage

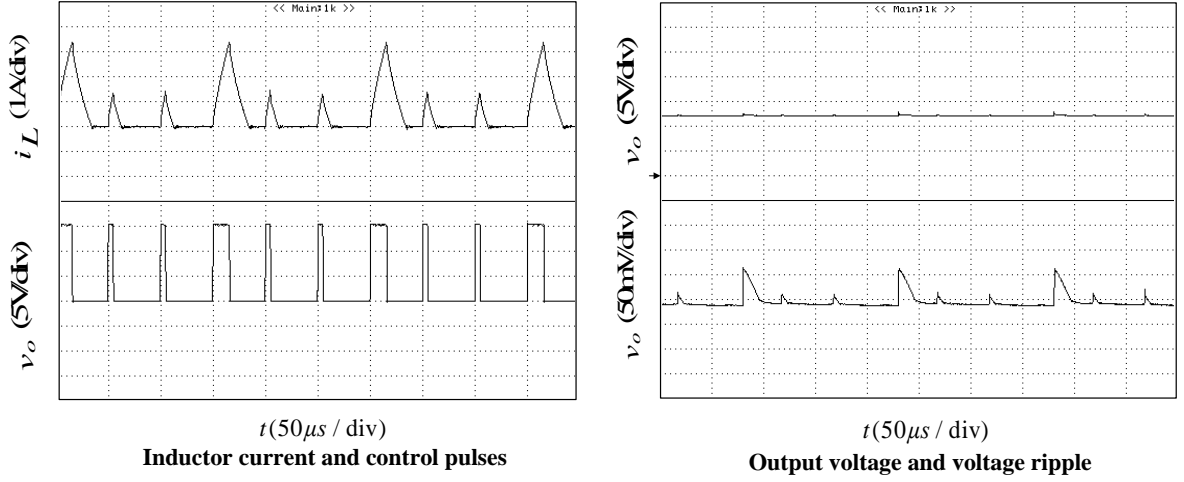
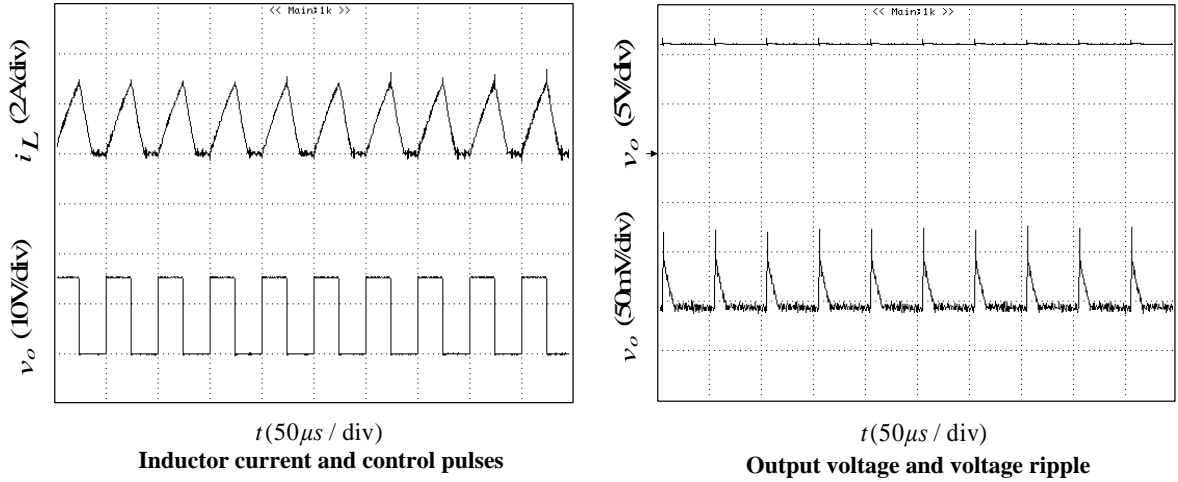


Fig.8 Experimental results of IVF-MSPA control for 8V input voltage

The waveforms of the PA controlled converter under 4V input voltage are given in Fig.9, from which is known that the PA converter can not normally operate in steady-state so that the output voltage 11V is much lower than the desired voltage 12V.



9 The waveforms of the PA control for 4V input voltage

Fig.

6. Summary

Multiple Sets of Pulse Adjustment Based on Input Voltage Feed-forward Compensation (IVF-MSPA), a new control technique for DC-DC converters is proposed and studied in the paper. Boost converter operating in DCM is taken as an example to illustrate the principle and control regulation of IVF-MSPA control scheme. Theory analysis, simulation results and experimental results show that the IVF-MSPA controlled converter enjoys good steady and transient state performance as well as the wider input voltage scope compared with the PA controlled converter.

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