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Stabilizing Control of DC/DC Buck Converters with Constant Power Loads in Continuous Conduction and Discontinuous Conduction Modes Using Digital Power Alignment Technique

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Abstract - The purpose of this paper is to address the negative impedance instability in DC/DC converters. We present the negative impedance instability of PWM DC/DC converters loaded by constant power loads (CPLs). An approach to design digital controllers for DC/DC converters is presented. The proposed method, called Power Alignment control technique, is applied to DC/DC step-down choppers operating in continuous conduction or discontinuous conduction modes with CPLs. This approach uses two predefined state variables instead of conventional pulse width modulation (PWM) to regulate the output voltage. A comparator compares actual output voltage with the reference and then switches between the appropriate states. It needs few logic gates and comparators to be implemented, thus, making it extremely simple and easy to develop using a low-cost application specific integrated circuit (ASIC) for converters with CPLs. Furthermore, stability of the proposed controllers using the small signal analysis as well as the second theorem of Lyapunov is verified. Finally, simulation and analytical results are presented to describe and verify the proposed technique.

Keywords: Constant power loads, control, modeling, modeling and analysis, motor drives, negative impedance instability, power alignment, power converters, stability.

1. Introduction

Recently, power electronics based power systems have attracted more attention for applications such as electric/hybrid electric vehicles, air and space vehicles, industrial systems, communication systems, and many more due to their advantages in weight, size, efficiency, and capability to being tightly regulated. Conventional systems in vehicular applications are mechanical, hydraulic, or pneumatic in nature. The current trend is to replace these conventional mechanical systems with electric or electrically-assisted systems, which demand the use of advanced power electronics and motor drives. These advanced power systems include usage of tightly regulated DC/DC converters, DC/AC inverters, and motor drives. However, disadvantage of these systems is that they tend to be naturally unstable [1-4].

In fact, the unstable nature of the operation originates from the fact that the power processing DC/DC and DC/AC converters and motor drives in these applications need to be regulated rigorously to have a system with better performance. These power electronic based systems, when tightly regulated, act as constant power loads (CPLs) [1, 2, 5].

An example of a CPL is a DC/DC converter, which drives an electric load and tightly regulates the output voltage when the load has a one-to-one current-voltage characteristic. In constant power loads, although the instantaneous value of the impedance is positive ($V/I>0$), the incremental impedance is always negative ($dV/dI<0$). In fact, in a CPL, input current decreases/increases when the input voltage increases/decreases. As a result, CPLs have negative impedance characteristics. This is a destabilizing effect known as negative impedance instability [1-11]. Basic PWM DC-DC converters, such as buck, boost, buck-boost, Cuk, and flyback converters with constant power loads are unstable. Feeding CPLs may impact the stability and dynamics of the power electronic converters/systems in electrical distribution systems. Due to this unstable operational behavior of CPLs, classical linear control methods, which are often used to design controllers for DC/DC converters, have stability limitations Moreover, these control techniques are either overly sensitive to system parameters or extremely expensive to implement [1].

Behavior of DC/DC converters loaded by CPLs has been analyzed in [6] and [7] assuming that the converter operates around the operation point. In [6], a dynamic

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model of a buck converter feeding a CPL is presented. The results show that, by using voltage-mode control, the open-loop is unstable in continuous-conduction mode (CCM) and stable in discontinuous-conduction mode (DCM) and, by using current-mode control, the system is unstable in both conduction modes. The familiar linear control compensation techniques can be used for both buck and boost converters with current-mode control. However, using directly the single units, which were modeled in [6], in a large scale system, will not necessarily produce satisfactory results.

In [7], employing the existing models for DC/DC converters and the negative-resistance approximation for the load impedance, the paper systematically analyzes the dynamics of the converters. Analysis shows that a buck converter has one right-hand pole in the control-to-output transfer function with the current-loop closed. Furthermore, a boost converter has a low-frequency pole in the control-to-output transfer function with the current loop closed. Due to this low-frequency pole, even a moderate integrator gain could push the closed-loop poles into the right hand making the system unstable.

The effects of CPLs in an induction motor based electric propulsion system as well as a small distribution system consisting of a generation system; a transmission line, a DC/DC converter load, and a motor drive load are studied in [8] and [9]. Both systems are unstable due to the negative impedance characteristics. In [10] and [11], for driving constant power telecom loads, which are in parallel with batteries, it has been shown that the use of rectifiers with constant power output characteristics results in power supply systems which are better than those with the constant current output characteristics. A PID controller is designed and simulated to stabilize a telecom power supply with constant power loads and backup batteries in [12].

To overcome the instability problem, an approach to the design of stabilizing controllers for PWM DC/DC converters with constant power loads using sliding-mode control is presented in [5]. Advanced methods such as feedback linearization technique and sliding-mode control allow designers to avoid some of the problems; however, multi-connectivity and multi-dimensionality are still unavoidable issues [13], which make them very complicated to deal with. Most of the previous work done in the analysis and control of power electronic converters driving CPLs employ nonlinear methods, which either do not offer straight forward methods to find control algorithms or they are sensitive to the system parameters or expensive to implement or their responses are not fast.

This paper introduces a new digital Power Alignment control method in order to regulate the output voltage of tightly regulated DC/DC converters loaded by CPLs. This controller adjusts the output voltage based on different duty ratios instead of conventional pulse width modulation techniques. This control technique is extremely simple, fast, and highly robust. Furthermore, due to its inherent digital nature, it can be easily implemented within integrated circuits (ICs), digital signal processors (DSPs), and field programmable gate arrays (FPGAs). In addition, the overall dynamic response of the proposed controller is exceptionally fast, as will be discussed in detail in this paper.

This paper has been organized as follow. Negative impedance instability in the single PWM DC/DC converters is presented in Section II. Power Alignment, the new digital technique to control DC/DC converters with constant power loads, is introduced in Section III. Furthermore, Section IV presents the stability analysis of DC/DC step-down choppers controlled by the Power Alignment technique in discontinuous and continuous conduction modes. Moreover, simulation analyses of applying the proposed technique to the buck converters are depicted in Section V. Finally, Section VI presents the conclusion remarks.

2. Negative Impedance Instability in Pwm Dc/Dc Converters

In this section the negative impedance instability of a PWM buck converter is presented. The DC/DC PWM buck converter of Fig. 1, which is operating with the switching period T and duty cycle d with a constant power load is considered.

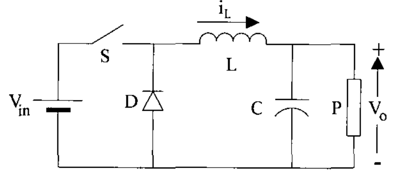


Fig. 1 Circuit diagram of a buck converter.

During continuous conduction mode of operation, the state space equations when the switch is ON are given by:

$$\frac{di_L}{dt} = \frac{1}{L}\left[v_{in} - v_o\right] \qquad \frac{dv_o}{dt} = \frac{1}{C}\left[i_L - \frac{P}{v_o}\right] \tag{1}$$

and when the switch is OFF are represented by:

$$\frac{di_L}{dt} = \frac{1}{L}\left[- v_o\right] \qquad \frac{dv_o}{dt} = \frac{1}{C}\left[i_L - \frac{P}{v_o}\right] \tag{2}$$

Using the state space averaging method [14], [15] these sets of equations can be shown by:

$$\begin{aligned}\frac{di_L}{dt} &= \frac{1}{L}\left[dv_{in} - v_o\right]\\ \frac{dv_o}{dt} &= \frac{1}{C}\left[i_L - \frac{P}{v_o}\right]\end{aligned} \tag{3}$$

Equations (3) are non-linear. For studying the small-signal stability of the buck converter of Fig. 1, small perturbations in the state variables due to the small disturbances in the input voltage and duty cycle are assumed. $\tilde{v}_{in}$ and $\tilde{d}$ are the small-signal variations of inputs, $\tilde{v}_o$ is the small-signal variations of the output, and $\tilde{i}_L$ and $\tilde{v}_o$ are the small-signal variations of the state variables of the small-signal model of the buck converter. The stability of this small-signal model can be determined by calculating the transfer functions and their pole locations.

$$\tilde{v}_o(s) = H_1(s)*\tilde{d}(s) + H_2(s)*\tilde{v}_{in}(s) \tag{4}$$

$$H_1(s) = \frac{\tilde{v}_o(s)}{\tilde{d}(s)} = \frac{\dfrac{V_{in}}{LC}}{s^2 - \left(\dfrac{P}{CV_o^2}\right)s + \left(\dfrac{1}{LC}\right)} \tag{5}$$

$$H_2(s) = \frac{\tilde{v}_o(s)}{\tilde{v}_{in}(s)} = \frac{\dfrac{D}{LC}}{s^2 - \left(\dfrac{P}{CV_o^2}\right)s + \left(\dfrac{1}{LC}\right)} \tag{6}$$

The poles of the transfer functions $H_1(s)$ and $H_2(s)$ have positive real parts. Therefore, the system is unstable as the effect of the constant power load.

3. Power Alignment Digital Control Technique

The objective of the Power Alignment digital control technique is to control the output power of converter based on generating high and low power pulses, rather than employing pulse width modulation (PWM) control technique. If the output power is lower than the desired power level, the controller chooses D_H as the switching duty ratio and, hence, high-power pulses are generated sequentially until getting the desired output power level. On the other hand, if the output power is higher than the desired power level, instead of generating high-power pulses, the controller chooses D_L $(D_L<D_H)$ as the duty ratio and therefore low-power pulses are generated to descend the level of the output power to its reference value. Fig. 2 shows the block diagram of the proposed control technique Since the on-time of the switch in a high-power switch is more than that of a low-power switch, more power will be delivered to the load during a high-power cycle. In this controlling method, switching frequency is constant and high-power and low-power duty cycles can be chosen in a way that converter operates either in continuous or discontinuous conduction modes.

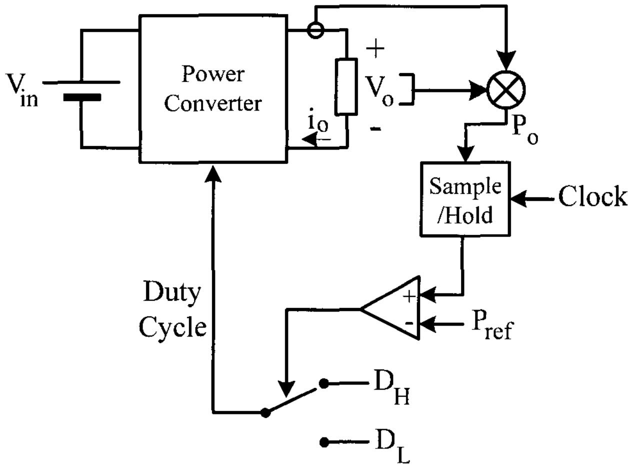
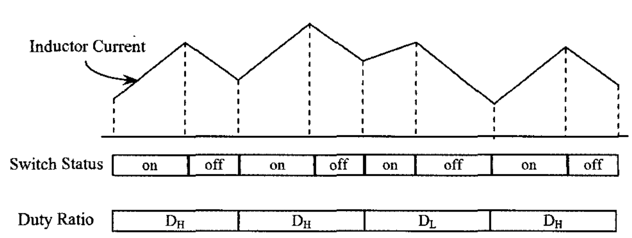
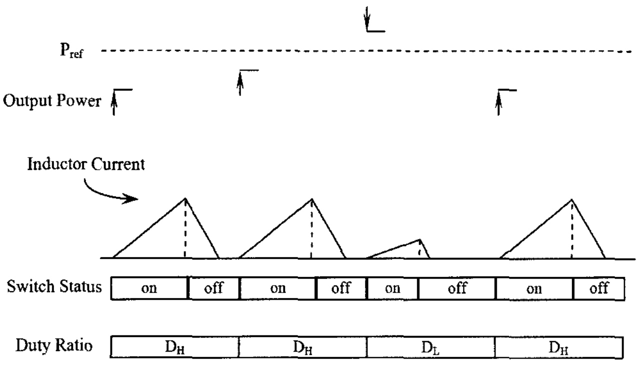


Fig. 2 Block diagram of the Power Alignment control technique.

Fig. 3 shows the current waveform of the inductor of a power converter after applying the proposed digital control technique. Fig. 3 (a) shows the operation of the converter in continuous conduction mode and Fig. 3 (b) depicts the operation in discontinuous conduction mode. At the beginning of each switching cycle, output power is being sampled and compared with its reference value. If the output power is less than the reference value, the controller decides to a apply high-power pulse to converter and, if it is higher than the reference value, the controller generates a low-power pulse to regulate the power.



(a)



(b)

Fig. 3 High and low power cycles, (a) operation in CCM, (b) operation in DCM.

Since the input current increases linearly with the on-time of the switch, the energy which is drawn from the input power source in a high-power cycle of a buck converter is equal to:

$$\Delta E_{in,HP} = \frac{(V_{in}D_H T)^2}{2L} + I_0 V_{in} D_H T \tag{7}$$

Similarly, the amount of energy drawn from the input source in a low-power cycle is equal to:

$$\begin{aligned} \Delta E_{in,LP} &= \frac{(V_{in}D_L T)^2}{2L} + I_0 V_{in} D_L T \\ &= \frac{(V_{in}D_H T)^2}{2k^2 L} + \frac{I_0 V_{in} D_H T}{k} = \frac{\Delta E_{in,HP}}{k^2} + \frac{(k-1) I_0 V_{in} D_H T}{k^2} \end{aligned} \tag{8}$$

Therefore in discontinuous conduction mode operation a low-power pulse transfers $1/k^2$ as much energy as a high-power pulse, and in continuous conduction mode the amount of energy which is being transferred to the inductor in a high-power switching cycle during the on-time of the switch is much more than k^2 times the amount of energy which is being transferred to the inductor in a low-power switching cycle. In this technique, the output power sampler and the driver of the switches are synchronized; hence, the switching frequency is constant and the output power is being sampled once in each switching period. Designing stabilizing controllers for other DC/DC converters such as boost, buck-boost, Cuk, flyback, and Weinberg converters with constant power loads follows the same procedure.

4. Stability Analysis

In this section stability of the buck converters with constant power loads and controlled by the Power Alignment digital technique is studied. First, we analyze the small-signal stability of the buck converters with CPLs in discontinuous conduction mode; then, we address the stability of the buck converters with CPLs in continuous conduction mode using the second theorem of Lyapunov.

4.1 Operation in Discontinuous Conduction Mode

In this section stability of the buck converter with constant power loads and controlled by the Power Alignment digital technique is studied. Considering a general switching period consisting of α high-power switching cycles and β low-power switching cycles, state space averaging (SSA) model of the buck converter in DCM is:

$$\begin{aligned} &\frac{d\bar{i}_L}{dt} = \frac{1}{(\alpha+\beta)T_s} \\ &\left[\alpha\left(\frac{\bar{v}_{in}-\bar{v}_o}{L} d_H T_s - \frac{\bar{v}_o}{L} t_{D_H}\right) + \beta\left(\frac{\bar{v}_{in}-\bar{v}_o}{L} d_L T_s - \frac{\bar{v}_o}{L} t_{D_L}\right)\right] = 0 \\ &\frac{d\bar{v}_o}{dt} = -\frac{\bar{v}_o}{RC} + \frac{1}{C}.\frac{1}{\alpha+\beta} \\ &\left[\alpha \frac{d_H T_s + t_{D_H}}{d_H T_s + t_{D_H}} \bar{i}_{L_H} + \beta \frac{d_L T_s + t_{D_L}}{d_L T_s + t_{D_L}} \bar{i}_{L_L}\right] \end{aligned} \tag{9}$$

where:

$$\bar{i}_{L_H} = \frac{1}{2} I_{Lpeak_H}.(d_H + \frac{t_{D_H}}{T}) = \frac{v_{in} T_s d_H^2 (v_{in} - \bar{v}_o)}{2\bar{v}_o L} \tag{10}$$

and

$$\bar{i}_{L_L} = \frac{1}{2} I_{Lpeak_L}.(d_L + \frac{t_{D_L}}{T}) = \frac{v_{in} T_s d_L^2 (v_{in} - \bar{v}_o)}{2\bar{v}_o L} \tag{11}$$

SSA model of the buck converter after being simplified can be written as:

$$\frac{d\bar{v}_o}{dt} = -\frac{\bar{v}_o}{RC} + \frac{v_{in}(v_{in} - \bar{v}_o)T_s}{2LC(\alpha+\beta)\bar{v}_o}(\alpha d_H^2 + \beta d_L^2) \tag{12}$$

This is a nonlinear equation. Linearizing it around its operating point results in:

$$\begin{aligned} \frac{d\tilde{v}_o}{dt} &= [-\frac{P_{ref}}{C} - \frac{T_s V_{in}^2}{2LC(\alpha+\beta)P_{ref}}(\alpha D_H^2 + \beta D_L^2)].\tilde{v}_o \\ &+ \frac{T_s V_{in}(V_{in} - V_{ref})}{LC(\alpha+\beta)V_{ref}}(\alpha D_H \tilde{d}_H + \beta D_L \tilde{d}_L) \end{aligned} \tag{13}$$

where $P_{ref} = V_{ref}^2 / R$

$$\tilde{v}_o(s)=\frac{\frac{T_sV_{in}(V_{in}-V_{ref})}{LC(\alpha+\beta)V_{ref}}\alpha D_H}{s+\frac{P_{ref}}{C}+\frac{T_sV_{in}^2}{2LC(x+y)P_{ref}}(\alpha D_H^2+\beta D_L^2)}\tilde{d}_H(s)+\frac{\frac{T_sV_{in}(V_{in}-V_{ref})}{LC(\alpha+\beta)V_{ref}}\beta D_L}{s+\frac{P_{ref}}{C}+\frac{T_sV_{in}^2}{2LC(x+y)P_{ref}}(\alpha D_H^2+\beta D_L^2)}\tilde{d}_L(s) \qquad (14)$$

To have a stable system the transfer functions $\frac{\tilde{v}_o(s)}{\tilde{d}_H(s)}$ and $\frac{\tilde{v}_o(s)}{\tilde{d}_L(s)}$ need to be stable. In other words, their poles must be in the left hand side of the s-plane. Since the effective poles of the system are in the left hand side of the s-plane, system is asymptotically stable.

$$s=-\left(\frac{P_{ref}}{C}+\frac{T_sV_{in}^2}{2LC(\alpha+\beta)P_{ref}}(\alpha D_H^2+\beta D_L^2)\right)<0 \qquad (15)$$

4.2 Operation in Continuous Conduction Mode

Small-signal stability of the buck converter in continuous conduction mode can be shown in a similar way as its operation in discontinuous conduction mode. In this section, in order to have a different method to prove the stability, we use the second theorem of Lyapunov.

It has been shown in Section II that, by employing the state space averaging techniques, the operation of a buck converter in continuous conduction mode can be expressed as (3). Considering a general switching period consisting of α high-power switching cycles and β low-power switching cycles, state space averaging (SSA) model of buck converter controlled by the Power Alignment digital technique is:

$$\frac{dx_1}{dt}=\frac{-x_2}{L}+\frac{(\alpha d_H+\beta d_L)}{L(\alpha+\beta)}V_{in} \qquad (16)$$
$$\frac{dx_2}{dt}=\frac{1}{C}(x_1-\frac{x_2}{R})$$

where x_1 and x_2 are the moving averages of i_L and v_o, respectively.

The objective of the control system in our DC/DC converters with constant power loads is to control the output power. P_{out} is the output power and P_{ref} is the output reference power. To design this type of controllers, the moving averages of their state variables are used. This will significantly simplify the design.

The Power Alignment controller needs to keep the variables along their reference value; therefore,

$$P_{out}=P_{ref}, \qquad \dot{P}_{out}=0 \qquad (17)$$

The above condition results in the following state space equations:

$$\frac{dx_1}{dt}=\frac{-x_2}{L}+\frac{(\alpha d_H+\beta d_L)}{L(\alpha+\beta)}V_{in} \qquad (18)$$
$$0=\frac{1}{C}(x_1-\frac{x_2}{R})$$

In order to prove the stability of the system, a continuously differentiable positive definite function, $V(x)$, needs to be defined. Let $V(x)$ to be presented by the following quadratic function,

$$V(x)=\frac{1}{2}(x-x_e)^T I(x-x_e) \qquad (19)$$

where x is the vector representation of the state variables given by,

$$x=[x_1 \quad x_2]^T \qquad (20)$$

and x_e is the state variable equilibrium point shown by ,

$$x_e=[x_{1e} \quad x_{2e}]^T \qquad (21)$$

and I is a two by two identity matrix.

At the state variable equilibrium point, we have:

$$0=\frac{-x_2}{L}+\frac{(\alpha d_H+\beta d_L)}{L(\alpha+\beta)}V_{in} \qquad (22)$$
$$0=\frac{1}{C}(x_1-\frac{x_2}{R})$$

Therefore, the equilibrium point can be expressed as:

$$x_{2e}=\frac{(\alpha d_H+\beta d_L)}{(\alpha+\beta)}V_{in} \qquad (23)$$
$$x_{1e}=\frac{(\alpha d_H+\beta d_L)}{(\alpha+\beta)}\frac{V_{in}}{R}$$

Using the above definitions, $V(x)$ can be written as:

$$V(x)=\frac{1}{2}[x_1-x_{1e} \quad x_2-x_{2e}]\begin{bmatrix}1&0\\0&1\end{bmatrix}\begin{bmatrix}x_1-x_{1e}\\x_2-x_{2e}\end{bmatrix} \qquad (24)$$

After algebraic multiplications, $V(x)$ can be expressed as (25).

$$V(x)=\frac{1}{2}[(x_1-x_{1e})^2+(x_2-x_{2e})^2] \qquad (25)$$

Equation (25) shows that $V(x)$ is a continuously differentiable positive definite function. Its derivative is:

$$\dot{V}(x)=\dot{x}_1(x_1-x_{1e})+\dot{x}_2(x_2-x_{2e}) \qquad (26)$$

Substituting the parametric equivalents of equilibrium points in above equation results in (27).

$$\dot{V}(x)=\frac{-R}{L}(x_1-\frac{(\alpha d_H+\beta d_L)}{R(\alpha+\beta)}V_{in})(x_1-x_{1e}) \qquad (27)$$

Therefore, derivation of (19) results as the following:

$$\dot{V}(x)=-\frac{R}{L}(x_1-x_{1e})^2 \qquad (28)$$

$V(x)$ is a negative definite function and, consequently, $V(x)$ is a Lyapunov function. Therefore, the closed-loop system is uniformly asymptotically stable in the large [16] and the arbitrary operating point x_e is a stable equilibrium point. The stability analysis of other types of DC/DC converters such as boost, buck-boost, Cuk, flyback, and Weinberg converters with the proposed stabilizing controller follows the same procedure.

5. Simulation Results Of Applying Proposed Technique To The Buck Converter with Constant Power Loads

5.1 Operation in Discontinuous Conduction Mode

Using the derived formulations, a DC/DC buck converter operating in discontinuous conduction mode (converter 1), with parameters given in Table 1, has been chosen to be controlled by the Power Alignment digital technique.

Table 1 Circuit parameters of the buck converter (converter 1) with CPL operating in DCM.

Variable	Parameter	Value
L	Inductance	$50\,\mu H$
C	Output filter capacitance	$200\,\mu F$
P_{ref}	Constant power load	$15W$
V_{in}	Input voltage	$40\ V$
R	Load	$10\,\Omega$
D_H	Duty cycle of a high-power pulse	0.28
D_L	Duty cycle of a low-power pulse	0.05
f	Switching frequency	$20kHz$

Fig. 4 presents the simulation results of applying the Power Alignment technique to the buck converter 1. Converter is operating in discontinuous conduction mode and the controller tries to select the pattern of applying high-power and low-power duty cycles in such away that output power stays as close as possible to its reference value Fig. 4 shows that, in this case, the controller chooses one high-power pulse followed by two low-power pulses to regulate the power.

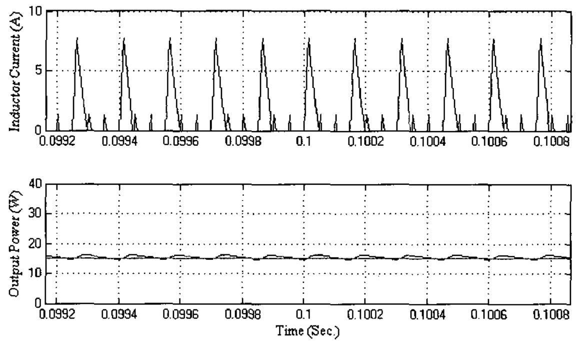


Fig. 4 Simulation results of applying the Power Alignment method to the converter 1 in DCM.

Fig. 5 depicts the dynamic response of the Power Alignment controlled buck converter to the output power reference step change from 15 W to 25 W at 0.1 Sec. As is shown in this figure, not only controller quickly follows the output power, but also there is no overshoot. Fig. 6 depicts the dynamic response of the Power Alignment controlled buck converter to the output power reference step change from 15 W to 20 W and load resistance step change from 10 Ω to 5 Ω at 0.1 Sec. As shown in Fig. 4, at the beginning, the controller chooses one high-power pulse followed by two low-power pulses to regulate the power. Then, as it can be seen in Fig. 6, at 0.1 second output power increases as a result of increasing the output voltage; therefore, the controller applies only low-power pulses to descend the power and voltage. Finally, after the initial transient, the controller applies a combination of high and low power pulses to keep tracking the output power.

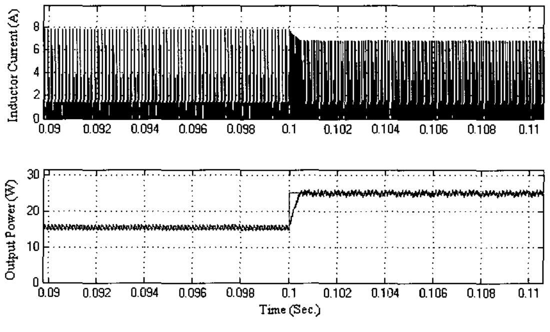


Fig. 5 Dynamic response of the Power Alignment controlled buck converter to output power reference step change from 15 W to 25 W at 0.1 Sec. in DCM.

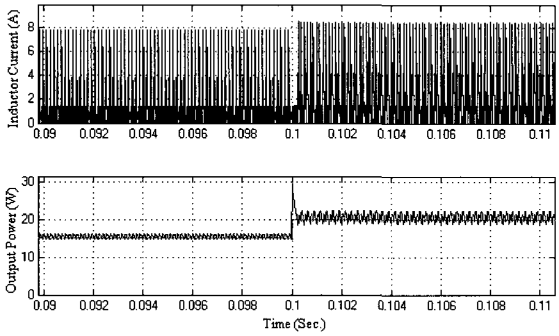


Fig. 6 Dynamic response of the Power Alignment controlled buck converter to output power reference step change from 15 W to 20 W and load resistance step change from 10 Ω to 5 Ω at 0.1 Sec. in DCM.

Fig. 7 presents the dynamic response of the Power Alignment controlled buck converter to an input voltage step change from 40 V to 50 V and output power reference step change from 15 W to 20 W at 0.1 Sec. Moreover, Fig. 8 shows the dynamic response of the Power Alignment controlled buck converter to an input voltage step change from 40 V to 50 V, load resistance step change from 10Ω to 5Ω, and output power reference step change from 15W to 30W at 0.1 Sec.

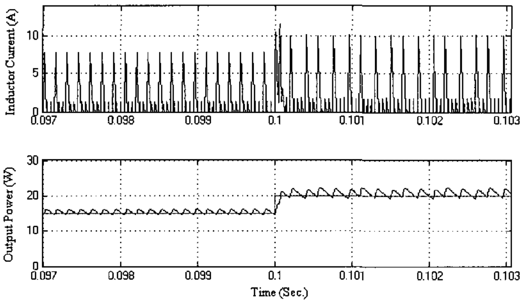


Fig. 7 Dynamic response of the Power Alignment controlled buck converter to input voltage step change from 40 V to 50 V and output power reference step change from 15 W to 20 W at 0.1 Sec. in DCM.

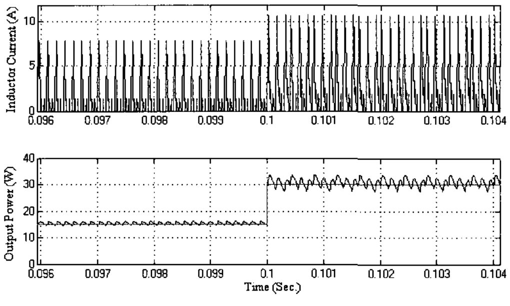


Fig. 8 Dynamic response of the Power Alignment controlled buck converter to input voltage step change from 40V to 50V, load resistance step change from 10Ω to 5Ω, and output power reference step change from 15W to 30W at 0.1 Sec. in DCM.

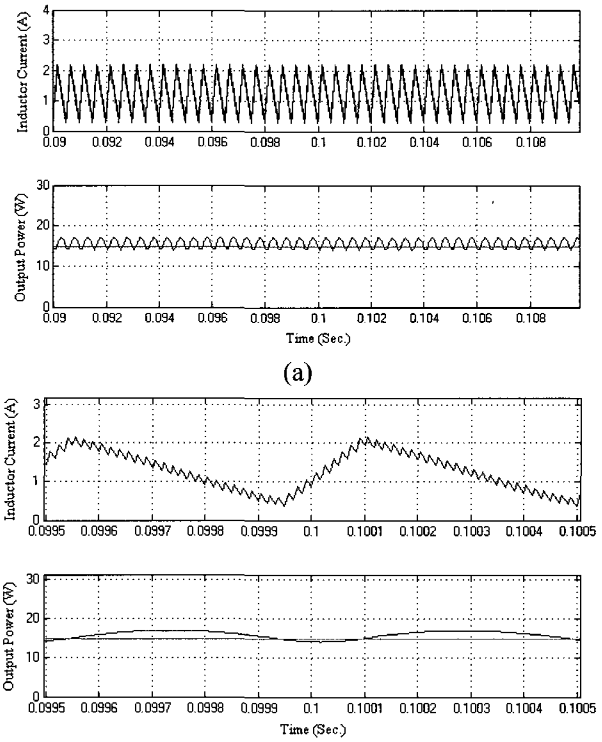
5.2 Operation in Continuous Conduction Mode

In this section, a conventional DC/DC buck converter operating in continuous conduction mode (converter 2) with parameters given in Table 2 has been chosen.

Table 2 Circuit parameters of the buck converter (converter 2) with CPL operating in CCM.

Variable	Parameter	Value
L	Inductance	600 μH
C	Output filter capacitance	100 μF
P_{ref}	Constant power load	15W
V_{in}	Input voltage	40 V
R	Load	10 Ω
D_H	Duty cycle of a high-power pulse	0.46
D_L	Duty cycle of a low-power pulse	0.26
f	Switching frequency	60kHz

Fig. 9 (a) presents the simulation results of applying Power Alignment technique to the proposed buck converter. Fig. 9 (b) shows a detailed graph of the inductor current and output power of the proposed buck converter around 0.1 sec. Converter is operating in continuous conduction mode and the controller tries to select the pattern of applying high-power and low-power duty cycles in such away that the output power stays as close as possible to its reference value.



(a)

(b)

Fig. 9 Simulation results of applying the Power Alignment method to the proposed buck converter in CCM.

Fig. 10 depicts the dynamic response of the Power Alignment controlled buck converter to an output power reference step change from 15 W to 25 W at 0.1 Sec. As is shown in this figure, not only the controller quickly follows the output power, but also the overshoot of the response is not high. Fig. 11 depicts the dynamic response of the Power Alignment controlled buck converter to an output power reference step change from 15 W to 20 W and load resistance step change from 10 Ω to 5 Ω at 0.1 Sec.

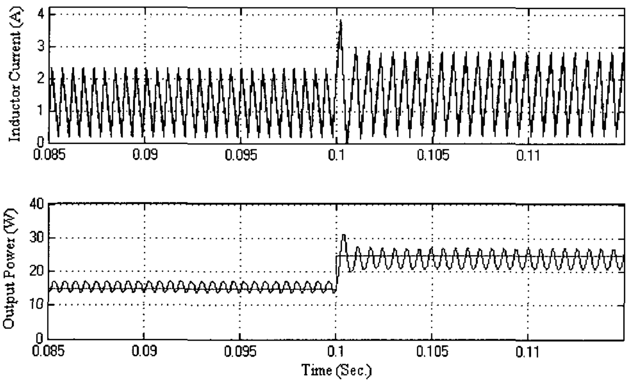


Fig. 10 Dynamic response of the Power Alignment controlled buck converter to output power reference step change from 15 W to 25 W at 0.1 Sec. in CCM.

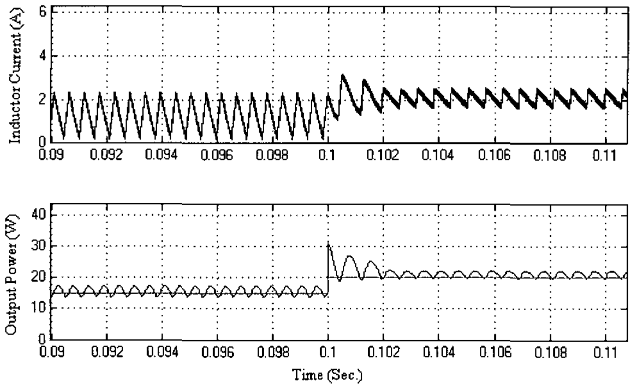


Fig. 11 Dynamic response of the Power Alignment controlled buck converter to output power reference step change from 15 W to 20 W and load resistance step change from 10 Ω to 5 Ω at 0.1 Sec. in CCM.

Fig. 12 presents the dynamic response of the Power Alignment controlled buck converter to an input voltage step change from 40 V to 50 V and output power reference step change from 15 W to 20 W at 0.1 Sec. Moreover, Fig. 13 shows the dynamic response of the Power Alignment controlled buck converter to an input voltage step change from 40 V to 50 V, load resistance from 10Ω to 5Ω, and output power reference step change from 15W to 30W at 0.1 Sec.

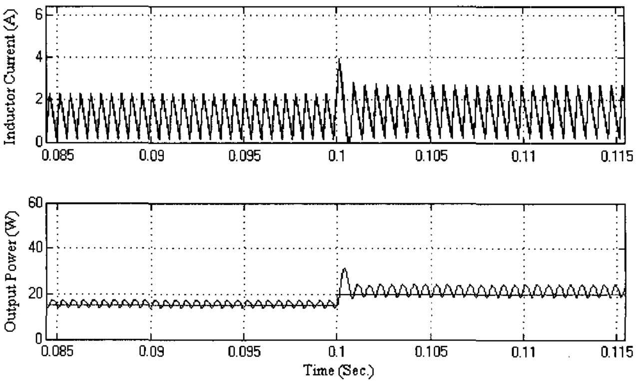


Fig. 12 Dynamic response of the Power Alignment controlled buck converter to input voltage step change from 40 V to 50 V and output power reference step change from 15 W to 20 W at 0.1 Sec. in CCM.

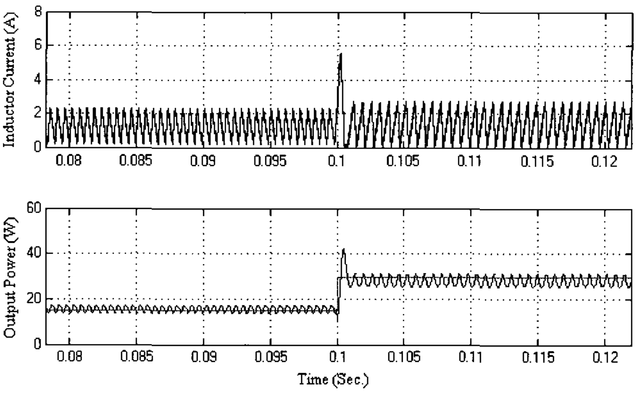


Fig. 13 Dynamic response of the Power Alignment controlled buck converter to input voltage step change from 40V to 50V, load resistance step change from 10Ω to 5Ω, and output power reference step change from 15W to 30W at 0.1 Sec. in CCM.

6. Conclusion

In this paper, the negative impedance instability behavior of PWM DC/DC converters with constant power loads is presented. Power Alignment as a new digital control technique is introduced. By applying the models from the state space averaging approach for DC/DC converters with constant power loads, power alignment controllers are designed and applied to DC/DC buck converters operating in either continuous conduction or discontinuous conduction modes. Small-signal state space averaging technique as well as Lyapunov theorem are employed to prove the stability of the buck converter with CPL and controlled by Power Alignment technique.

The responses of the controllers under different operations and in the presence of significant variations in load, input voltage, and reference output power are also studied. Large-signal control, simplicity of construction, and high reliability are described as the main advantages. Simulation results show that the proposed method offers a very fast dynamic response and it is robust against the variations of the parameters of the power converter. This method is applicable to other power electronic converters as well.

The proposed method is simple and does not require a detailed small or large signal model of the power converter. Since there are no state variables in the control system, there is no need to feedback from state variables. This makes the controller design simple and low-cost. Due to its simplicity, the proposed method can easily be implemented using a general-purpose DSP, or FPGA or a specifically designed integrated circuit.

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