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De-stability problem in DC-DC Buck Converter operating with CPL

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ABSTRACT

As the NAVY moves forward with plans to become less dependent on fossil fuels and more dependent on hybrid electric drives and all-electric ships, being aware of the stability issues associated with direct current (DC)-DC and DC-alternating current (AC) power converters and understanding how to solve the issues that come with using them, are very important. The negative input impedance that is observed when using a buck converter servicing a constant power load (CPL) is one of the issues that needs to be understood. Understanding the stability issue caused by the negative input impedance and mitigating this instability by implementing the adaptive controller is focus of this work.

Keywords: Model Reference Adaptive controller, Pulse width modulator, Direct current, Metal Oxide Semi conductor field effect transistor, Energy factor.

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I. INTRODUCTION TO CPL

A buck converter is a step down converter: it takes the input voltage and reduces the voltage so that the output is lower than the input. A buck converter is a simple circuit consisting of a source, two switches (usually a MOSFET and a diode), an inductor, a capacitor, and a load. Figure 1 is an example of a simple buck converter circuit. Power converters such as a buck converter are used because of their tight output voltage control capability, which enables them to respond almost immediately to system changes. This advantage of the buck converter is a disadvantage when it acts as a CPL. The buck has an input voltage range between 30V and output 5V DC. A buck converter regulates the output capacitor voltage by controlling the duty cycle ratio. This is accomplished by closing a control loop from the output voltage to the MOSFET base. Typically the output voltage is held constant independent of the input voltage. This causes the power consumed by R_{load} to be constant, and therefore, the buck converter looks like a CPL.

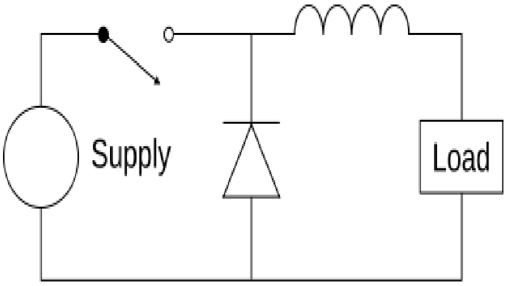

Figure 1. Circuit Diagram of Buck converter

In a CPL, the load maintains a constant power level by drawing more or less current as required by the situation. For example, if the input voltage decreases, the input current increases; or if the input voltage increases, the input current decreases in order to maintain a constant power level. This trait of a CPL is a "destabilizing effect known as negative impedance instability". A buck converter acts as a CPL at the input terminals because of the way the load appears across the output terminals. A couple of basic equations are necessary to mathematically explain the way the load appears.

From Ohm's Law, V =IR where V is voltage, I is current and R is resistance. Power P is given by P=IV and measured in Watts (W). Substituting Ohm's Law into the power equation, we get $p=V^2/R$ which was used to measure the load. Because of the tight output voltage regulation of the power converter, the output voltage is held constant at 5V DC. When the load V^2/R increases because R decreases, the power converter requires more input current in order to maintain the constant output voltage. A load is generally thought of as a resistance, and when resistors are added in parallel, the total resistance decreases because of: the $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$ where R_n is the nth resistor. Because the voltage output of the buck converter is not going to change–in other words, it maintains a constant 5 V DC at the output terminals – the only way to change the load or power level is to change the resistor value. As the load changes, the power level changes, and the stability at the input terminal of the buck converter is affected. Again, a CPL is a characteristic that is created when using power electronics, and the almost perfect regulation of the power electronics is the cause for the negative instability effect. Closing a control loop on V_o makes the buck converter act like a CPL.

Constant power loads create a destabilizing effect in the circuits they are connected to because of negative impedance instability. This negative impedance comes from the way the input voltage and current respond when a load change occurs in a CPL. When voltage decreases and current increases, or vice versa, this change in voltage or current is the destabilizing effect of a CPL. One possible fix is to not control them as tightly; doing so, however, can cause other issues because the control is tightly regulated so that a constant voltage or current is maintained at some point of interest. Another fix is to implement the proposed adaptive controller in the buck converter circuit mitigating its instability to bring the system a stability.

II. ENERGY FACTOR AND MATHEMATICAL MODELLING

All power DC/DC converters have a pumping circuit to transfer the energy from source to some passive energy storage elements, e.g, inductors and capacitors. The Energy Factor (EF) and its associated parameters comprising the pumping energy (PE), stored energy (SE), capacitor/inductor stored energy ratio (CIR) and energy losses (EL), can illustrate the unit step response which may be helpful for system design and in anticipating DC/DC converter characteristics. The DC/DC Buck converters are analyzed to demonstrate the application of EF, PE, SE and CIR. For convenience, the input voltage and current are defined as V_1 and I_1 respectively, and the output voltage and current are defined as V_2 and I_2 respectively. The switching frequency, switching time period and duty cycle ratios are defined as f, T and k respectively.The energy quantization is measured by the PE, which is used to count the input energy in the switching period (V_1 is usually constant). Its calculation formula is PE= V_1 I_1 The stored energy in an inductor is $W_L = \frac{1}{2} L\, I_L^2$The stored energy across a capacitor is $W_C = \frac{1}{2} C\, V_C^2$

Therefore, if there are n_L inductors and n_C capacitors, the total stored energy in a DC/DC converter is

$$SE = \sum_{j=1}^{n_L} W_{Lj} + \sum_{j=1}^{n_c} W_{cj}$$

The capacitor/inductor stored energy ratio (CIR) is

$$CIR = \frac{\sum_{j=1}^{n_c} W_{cj}}{\sum_{j=1}^{n_L} W_{Lj}}$$

Another factor is the EL in period T, which are proportional to the power losses. EL $= P_{loss} * T$
The Energy Factor is the ratio of stored energy and pumping energy.

$$\text{Therefore, } EF = \frac{SE}{PE}$$

The EF is used to describe the characteristics of power DC/DC converters. Usually, most DC/DC converter analysis assumes that input power is equal to output power, $P_{in} = P_o$ (or $V_1 I_1 = V_2 I_2$), so that pumping energy is equal to output energy in a period: PE = $V_1I_1T=V_2I_2T$. It corresponds that the efficiency (η) = V_2I_2T/P.E= 100%. If the load is purely resistive (R), $V_2 = I_2R$, and the Voltage transfer gain (M) of a DC/DC converter is $M = \frac{V2}{V1} = \frac{I2\,R}{V1}$

And, $P_{in} = P_o + P_{loss}$

The power transfer efficiency is $\eta = \frac{Po}{Pin}$

The time constant of a DC/DC converter is defined as

$$\tau = \frac{2T * EF}{1 + CIR}(1 + CIR\frac{1-\eta}{\eta})$$

The time constant τ is used to estimate the converter transient operation. It is proportional to the process settling time. Since a converter usually consist of multiple passive energy storage elements, for this investigation, the converter response should usually involve an oscillation component. The damping time constant τ_d of a DC/DC converter is defined as

$$\tau_d = \frac{2T * EF * CIR}{1 + CIR\eta + CIR(1-\eta)}$$

τ_d is used to estimate the converter response with oscillation. Both τ and τ_d are independent from the switching frequency f and conduction duty cycle ratio k and also available to form the transfer function of the DC/DC converter in S-domain. The transfer function of the DC/DC converter can be written as mathematical model

$$G(S) = \frac{M}{1 + s\tau}$$

To verify the theoretical analysis and the design of previous section, the parameters and specifications of DC/DC Buck converter are taken and are shown in table.1.

Table.1. The Specifications and parameters of Buck converter

Specification	value	Circuit Parameters	Value
Input Voltage	30V	Inductor, L1	100μH
Output Voltage	5V	Capacitor,C1	200μF

When the converter changes from one steady state to another, the corresponding stored energy changes. Therefore, there must be a transient process from one steady to the new state. The Energy Factor, its relevant application parameters, voltage transfer gain (M) and time constant (τ) of Buck converter are determined at the operating voltage 5V and for the switching frequency 25kHz and the values are listed in table.2.

Table.2 Energy Factor, relevant parameters, voltage transfer gain and time constant of buck converter

Pumping Energy, PE	6.949e-5
Stored Energy, SE	0.006625
Capacitor/Inductor stored Energy, CIR	273.4
Energy Losses, EL	0.002548
Energy Factor, EF	95.33
Power Efficiency, η	0.7599
Voltage transfer gain, M	1.013
Time constant, τ	0.0006087

The transfer function of the buck converter in S-domain is found to be $G(S) = \dfrac{1.013}{1+0.0006087s}$

From the above obtained transfer function model, the controller tunings for the PID controller are found to be Kp=1.987, Ki=3265 and Kd=0. Finally, based on Lyapunov's stability theorem, the proposed controller containing adjustable parameters are implemented for Buck converter by choosing adaptation gain, γ=0.7. This proposed controller guarantees closed-loop system stability and a tracking performance for the output voltage for the variations in the line voltage, reference voltage and the load.

III. SYSTEMATIC CONTROLLER DESIGN

This section constructs a Lyapunov's stability based MRAC for controlling the PWM width of buck converter. The MRAS control system for Buck converter is shown in Figure.2.

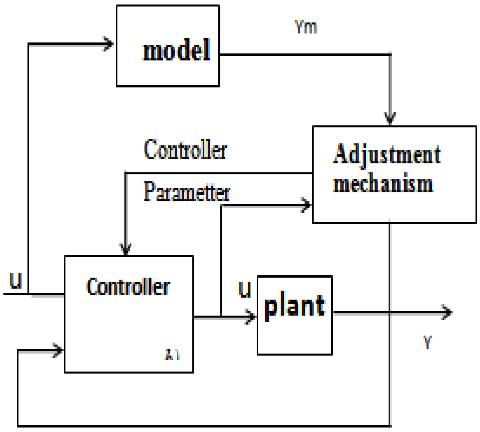

Figure 2. Block Diagram of MRAC

For time-varying systems, the following stability theorem can now be stated. Let x = 0 be an equilibrium point for the time-variable differential function of the type

$$\frac{dx}{dt} = f\,(x,t) \text{ and } D = \left\{ x \in R^n \mid \ \| x \| < r \right\}$$

Let V be a continuously differential function such that $\alpha_1 (\|x\|) \le V(x,t) \le \alpha_2 (\|x\|)$

$$\frac{dv}{dt} = \frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} + f(x,t) \le -\alpha_3 (\| x \|) \quad \text{For } \forall\ t$$

≥ 0, where α_1, α_2 and α_3 are class k functions. Then x = 0 is uniformly asymptotically stable.

While using Lyapunov theory for adaptive system, we find that $\frac{dv}{dt}$ is usually negative semi definite where V is a Lyapunov function. The procedure is to determine the error equation and a Lyapunov function with a bounded second derivative.

For a first order system, the system is described by the plant as $\frac{dy}{dt} = -ay + bu$; Where 'u' is the control variable (i.e., the plant input), 'y' is the measured output (i.e., the plant output), 'a' and 'b' are the plant parameters. The desired response is given by the equation

$\frac{dy_m}{dt} = -a_m y_m + b_m u_c$ Where 'u_c' is the model input, 'y_m' is the model output, 'a' and 'b' are the model parameters. Let the controller be given by $u(t) = \theta_1 u_c(t) - \theta_2\ y(t)$. The controller has two parameters

$\theta_1$and θ_2. If they are chosen to be $\theta_1 = \theta_1^0 = \frac{b_m}{b}$;

$$\theta_2 = \theta_2^0 = \frac{a_m - a}{b}$$

The input–output relations of the system and model are the same. This is called perfect model following. To apply Lyapunov stability theory, introduce the error as e = y– y_m. since we are trying to make the error small it is natural to derive a differential equation for error,

$$\frac{de}{dt} = -a_m e - (b\theta_2 - a_m + a)\, y + (b\theta_1 - b_m)\, u_c$$

It is now to construct a parameter adjustment mechanism that will derive the parameters $\theta_1$and θ_2 to their desired values. For this purpose, assume $b\gamma > 0$ and introduce the following quadratic function.

$v(e,\theta_1,\theta_2)=$

$$\frac{1}{2}\left(e^2 + \frac{1}{b\gamma}(b\theta_2 + a - a_m)^2 + \frac{1}{b\gamma}(b\theta_1 - b_m)^2\right)$$

Where 'γ' is adaptation gain. This function is zero when e is zero and the controller parameters are equal to the correct values. For the function to qualify as a Lyapunov function the derivative $\frac{dv}{dt}$ must be negative. The derivative

$$\frac{dv}{dt} = \frac{1}{2}\left(2e\frac{de}{dt} + \frac{1}{b\gamma}2(b\theta_2 + a - a_m).b.\frac{d\theta_2}{dt} + \frac{1}{b\gamma}2(b\theta_1 - b_m).b.\frac{d\theta_1}{dt}\right)$$

The condition is that $\frac{dv}{dt}$ should be negative semi-definite. If the parameters are updated as

$$\frac{d\theta_1}{dt} = -\gamma u_c e \quad \text{and} \quad \frac{d\theta_2}{dt} = \gamma y e \text{, then}$$

We get $\frac{dv}{dt} = -a_m e^2$

The derivative of v with respect to time is thus negative semi definite but not negative definite. This implies that v(t) ≤ v(0) and thus that e, θ_1 and θ_2 must be bounded. This implies that y = e + y_m also is bounded.

IV.BIFURCATION ANALYSIS

In this work, a particular power electronics device called a buck converter was introduced and how it acts like a constant power load was discussed. The stability issues with CPLs were reviewed from bifurcation analysis for load change, and a few ideas were mentioned on how to help make a circuit with a CPL more stable. The methods used to analyze the system in simulation, are discussed in this work. A software package: MATLAB Simulink model is used for the simulations. The phase portrait (Capacitor Voltage Vs inductor current) and time domain waveform is taken for load change. The analysis has done for open loop condition, PID controller and proposed controller.

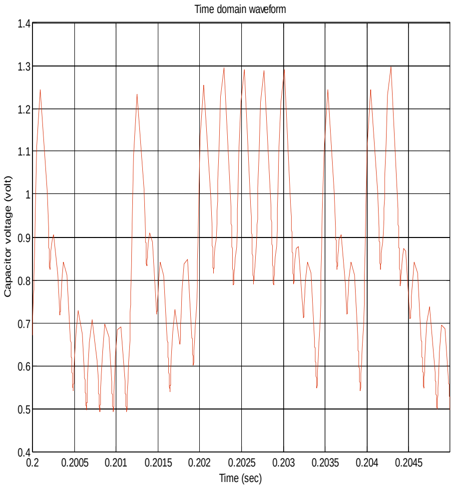

Figure 3. Time domain waveform for open loop

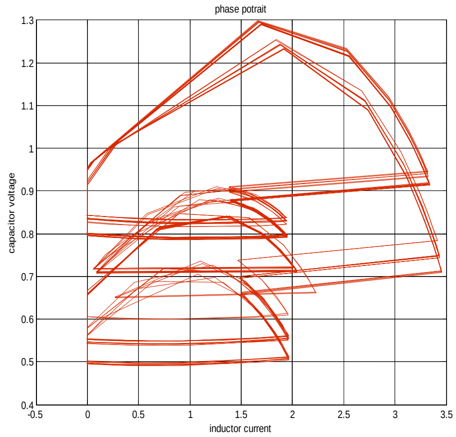

Figure 4. Phase-potrait for open loop

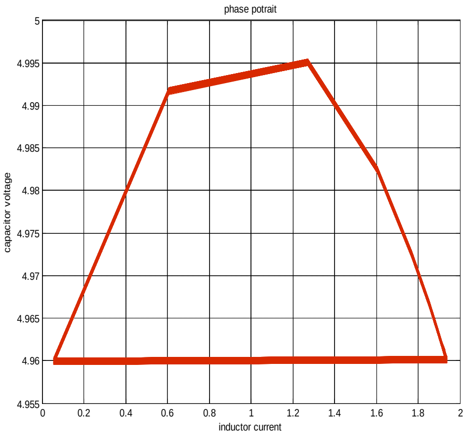

Figure 5. Phase-potrait for PID Controller

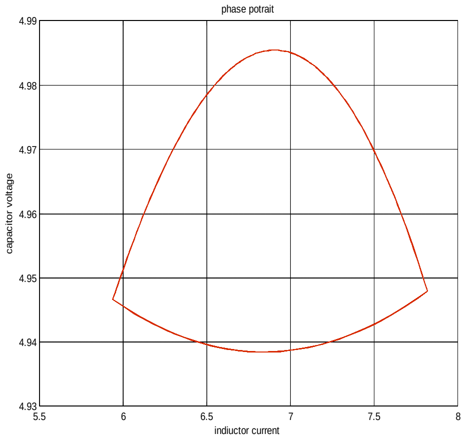

Figure 6. Phase-potrait for Proposed Controller

Simulations have been carried out to verify the chaos controlling idea. The chaos coming due to the load variation under open loop is successfully controlled by implementing PID controller and proposed controller respectively. Also, the phase portrait given above shows the stable result.

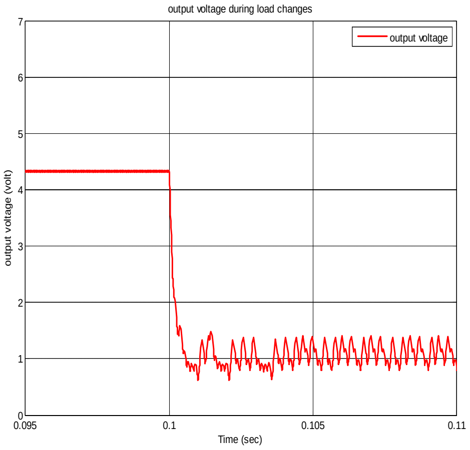

Figure 7. Regulatory response of buck converter under open loop

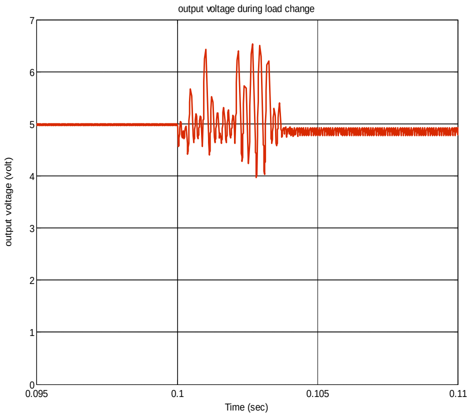

Figure 8. Regulatory response of buck converter for PID controller

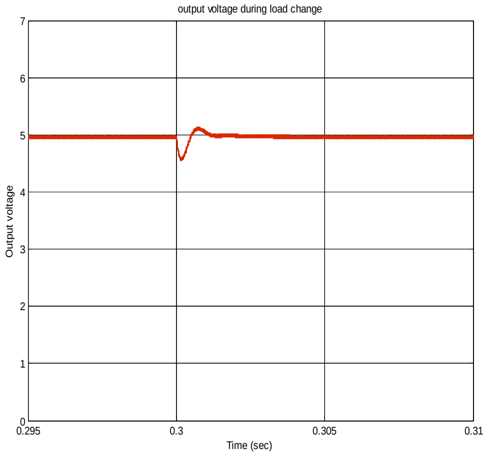

Figure 9. Regulatory response of buck converter for Proposed controller

The regulatory response given above shows the stable result when the load value drops from 5Ω to 1Ω for the operating voltage 5V. The proposed method also shows the chaos coming due to line variation is successfully controlled. The proposed scheme also provide good dynamical responses and guarantees closed-loop system stability, a tracking performance and also robustness to the load disturbances. The simulation result demonstrates the efficiencies of the approach.

IV. CONCLUSIONS

The voltage controlled buck converter is used for the analysis of bifurcation and chaos. The simulated results have been shown for load change. To control such spurious effects in voltage controlled buck converter, an adaptive method through energy factor modeling has been considered. It is proved that stable operation is possible for load variation.

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