Intermittent instability and its control in parallel converters

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Abstract. This paper studies intermittency instability and its control in parallel converters. By numerical simulation, the intermittent subharmonic and chaos are captured with coupled interference signal, their characteristics are described by bifurcation diagrams as parameter varies. Then the paper proposes control methods and it is proved effective by the comparison of power spectrums. The conclusion can help engineer to explain the inherent irregular motion in vehicle, and design more stable power electronic supplies.

1. Introduction
DC-DC converter is the core part of power supply\textsuperscript{[1]}. Its stability is very important for the performance of power system. Parallel converters are suitable for the needs of low voltage, large current and distributed modular power system\textsuperscript{[2-4]}. It is widely used in vehicle engineering to provide power to air condition and other auxiliary equipments. Intermittency is an abnormal working state in converters for its unpredictability, which will affect the stability of the vehicle. Intermittency is characterized by sporadic noise\textsuperscript{[5]}. Further study can help engineer to explain the inherent irregular motion in DC-DC converter, and design more stable power electronic supplies.

2. Parallel Buck converters with coupled interference signal

2.1 Overview of system operation
In practice, the system is often disturbed by external signals. Interference signals are transmitted or radiated into the circuit through the coupling channel, which affects the normal operation of converters. For that, we introduce interference signals (the circuit is often interfered by such periodic sinusoidal signals in the RF environment) and add them to the input voltage,

\[ E' = E + v_s \sin(2\pi f_0 t) = E[1 + \alpha_s(2\pi f_0 t)] \tag{1} \]

where \( E \) is input voltage, \( v_s \) is the voltage amplitude of the interference signal, \( f_0 \) is the frequency of interference signal. \( \alpha_s \) is the amplitude ratio of the interference voltage to the input voltage, represents the intensity of the interference source, is given by

\[ \alpha_s = \frac{v_s}{E} \tag{2} \]
Figure 1. shows parallel Buck converters with coupled interference signals.

The state equation of parallel bucks is listed as follows:

\[
\begin{align*}
\dot{v} &= \frac{v}{(R + r_C)C} + \frac{R}{(R+ r_C)C}i_1 + \frac{R}{(R+ r_C)C}i_2 \\
\dot{i}_1 &= -\frac{Rv}{(R + r_C)L_1} - \frac{1}{L_1}\left(\frac{Rr_C}{R + r_C} + r_{L1}\right)i_1 - \frac{Rr_C}{(R + r_C)L_1}i_2 + \frac{E^*u_1}{L_1} \\
\dot{i}_2 &= -\frac{Rv}{(R + r_C)L_2} - \frac{Rr_C}{(R + r_C)L_2}i_1 - \frac{1}{L_1}\left(\frac{Rr_C}{R + r_C}L_1 + r_{L2}\right)i_2 + \frac{E^*u_2}{L_2}
\end{align*}
\]  

(3)

2.2. Simulation results

According to the state equation, the simulation model is established by MATLAB, circuit parameters are chosen as follows:

| Table 1 Component values. | Value |
|---------------------------|-------|
| Capacitor $C$, ESR $r_C$ | $47\mu F$, 0.01 $\Omega$ |
| Inductor $L_1$, ESR $r_{L1}$ | $20mH$, 0.05 $\Omega$ |
| DC offset voltage | 5 $V$ |
| Input voltage $E$ | 22 $V$ |
| Current gain $K_i$ | 5 |
| Lower limit voltage $V_L$ | 3.8 $V$ |
| Switching period $T$ | 400$\mu S$ |
| Load resistor $R$ | 10 $\Omega$ |
| Inductor $L_2$, ESR $r_{L2}$ | $20mH$, 0.2 $\Omega$ |
| Reference voltage $V_{ref}$ | 11.3 $V$ |
| Voltage gain $K_{i1}$, $K_{i2}$ | $3.5, 3.5$ |
| Split ratio $m$ | 1 |
| Upper limit voltage $V_U$ | 8.2 $V$ |
The waveforms of the state variables as time varies can be observed directly. Without interference signal, inductor current and capacitor voltage are periodic in time domain as shown in figure 3, indicating that parallel converters present period-1, the system is in a stable state[6].

Coupling with intruding interference signal, the parallel converters present different operations due to different interference frequency.

![Figure 3. System state without interference signals](image)

(a) inductor current of time domain
(b) capacitor voltage of time domain

If the frequency of interference signal is n times of the switching frequency of the converters, n is a positive integer. Taking n=1 and n=2 as examples, the Poincare section of the system is observed and exhibited as figure 4(a) and (b). Poincare section describes the sample state at each switching point. It is a useful way to describe the operation of the system.

When \( f_0 = f_s \) and \( f_0 = 2f_s \), where \( f_0 \) is interference frequency, they are both characterized by only one intersection, showing the converters is in period-1, indicating that system is stable. If the frequency of interference signal is \( 1/n \) times of the switching frequency of the converters, Figure
4(c) and (d) show two examples with n=2 and n=4, parallel converters are in period-2 and period-4, characterized by 2 and 4 intersections on the Poincare sections.

However, in most case, the interference signal is random, and its frequency is not just the rational multiples of the switching frequency exactly. Generally, the frequency of the interference signal is close to the switching frequency. Therefore, assuming $f_0 = 2501Hz$, taking the interference intensity of intruding interference signal as the parameter. Figure 5. shows the time-bifurcation diagram of inductance current under different interference intensities.

![Time-bifurcation diagrams with varied intensity of the interference signal.](image)

(a) $\alpha_r = 0.1$  (b) $\alpha_r = 0.35$  
(c) $\alpha_r = 0.62$  (d) $\alpha_r = 0.67$.

From these four figures, we have the following observations:

- When the interference signal intensity is weak, as shown in Figure 5. (a), the converters are still in period-1 although the sampled inductance current fluctuates around 0.5A, indicating that the interference signal has little impact on the converters.
- As the intensity of the interference signal increases gradually, intermittency can be captured intermittency in the converters. The converter alternates between stable period-n and subharmonic states regularly. When $\alpha_r = 0.35$, converters experiences period-1 and period-2 subharmonic alternately, and when $\alpha_r = 0.62$ the converter experiences period-1 and period-2 subharmonic alternately. Figure 5 (b) and (c) give the corresponding time-bifurcation diagrams.
- Further increase the intensity of the coupling interference signal can cause the converter experiences period-1 and 2i subharmonic alternately. Until the intensity of the coupling interference signal reaches a critical value, intermittent chaos appears in converters, period 1 and chaos present alternately. Figure 5(d) gives the corresponding time bifurcation diagrams as $\alpha_r = 0.67$.
- Intermittency is periodic. Intermittent period is defined as $T_{in} = 1/|f_0 - f_i|$ after summary and analysis. When the frequency of the interference signal is close to the switching frequency of the converter, converters take a long time to finish an intermittent process. In this example, there is 1Hz between two frequencies, so the intermittent period $T_{in} = 1s$. 


3. Suppression of Intermittent instability by Resonant Parametric Perturbation

In actual systems, chaos is destructive and should be avoided. But structure and parameters of designed systems are determined, and they cannot be changed. Resonance parameter perturbation is an effective method to transform converters from chaos to regular state or cause the system to move away from its original periodic orbit by perturbing the frequency or amplitude of appropriate parameters. It is one of non-feedback chaotic control methods.

There are many parameters in parallel converters. The choice of parameters is related to the control effect. After careful comparison, we choose the reference voltage which has great influence on converters and is easily disturbed as the resonance perturbation parameter\(^7\). When \(\alpha = 0.67\), we replace \(V_{ref} [1 + \alpha \sin(2\pi f_s t + \psi)]\) with \(V_{ref}\), where \(\alpha\) is the amplitude of the perturbing signal, \(\psi\) is the phase shift between the perturbing signal and the switching frequency of converters. The perturbing frequency is as same as the frequency of converters.

Setting \(\psi = 0\), \(\alpha\) varies from 0 to 0.02. Lots of simulation show when the system is stable at period 1, the minimum effective perturbing amplitude is 0.017. Figure 6(a) gives the bifurcation diagram of the state variable of with different perturbing signal amplitude. Furthermore, the operation with phase shift as parameter can be observed when the perturbing amplitude is 0.017. Figure 6 (b) clearly illustrates the period-1 region of converters is centered at around \(\psi = 1.5\). Finally the operation with phase shift as parameter can be observed when the \(\psi = 1.5\). It is concluded that \(\alpha = 0.01\) and \(\psi = 1.5\) are the optimal amplitude and phase in parallel converters.

![Figure 6. Parameter bifurcation diagrams](image)

(a) \(\alpha\) as parameter \((\psi = 0)\) (b) \(\psi\) as parameter \((\alpha = 0.017)\) (c) \(\alpha\) as parameter \((\psi = 1.5)\)

To illustrate the effect of perturbation, we observe the phase portraits of system by experiments. The phase portrait without perturbation contains countless orbits as shown in Figure 7 (a), indicating the system is unstable. But the phase portrait with perturbation is depicted by a closed orbit, as shown in Figure 7 (b), indicating the system is in a stable period-1. By comparing the phase portraits, resonance parameters perturbation transforms converters to the regular state effectively.

![Figure 7. Phase portraits](image)

(a) \(\alpha = 0, \psi = 0\) (b) \(\alpha = 0.017, \psi = 1.5\)

4. Conclusions

In this paper, parallel Buck converters with coupled interference signal are constructed and investigated. It is found that the intermittent instability of converters is characterized by intermittent harmonics or intermittent chaos. The research results show that when the system is disturbed by
coupled parasitic signals, the intermittent harmonics and intermittent chaos can be captured. The specific mode of operation relates to the intensity of the interference. Coupling circuit conduction and radiation interference are the source of intermittency. The resonant parameter perturbation method can control the system in a stable state.

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