Early Oscillation Detection for Hybrid DC/DC Converter Fault Diagnosis

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This paper describes a novel fault detection technique for hybrid DC/DC converter oscillation diagnosis. The technique is based on principles of feedback control loop oscillation and RF signal modulations, and is realized by using signal spectral analysis. Real-circuit simulation and analytical study reveal critical factors of the oscillation and indicate significant correlations between the spectral analysis method and the gain/phase margin method. A stability diagnosis index (SDI) is developed as a quantitative measure to accurately assign a degree of stability to the DC/DC converter. This technique is capable of detecting oscillation at an early stage without interfering with DC/DC converter's normal operation and without limitations of probing to the converter.

Nomenclature

- \( A_{cp} \) = Channel power amplitude and channel power frequency of oscillation
- \( CP_{c}(m) \) = Measured channel power at oscillation characteristic frequency
- \( CP_{c}(n) \) = Normal channel power at oscillation characteristic frequency
- \( CP_{sw}(m) \) = Measured channel power at switching frequency
- \( CP_{sw}(n) \) = Normal channel power at switch frequency
- \( f_{c} \) = Characteristic frequency of oscillation
- \( f_{og} \) = Unit gain crossover frequencies
- \( f_{osc} \) = Oscillation frequency showing in a time-domain waveform
- \( f_{s} \) = Side frequencies of FM type oscillation
- \( f_{sw} \) = DC/DC converter switching frequency
- \( f_{z} \) = Conner frequency at zero gain
- \( f_{ep} \) = Zero-phase frequency, a frequency when phase is 0° in Bode plot of frequency response analysis

I. Introduction

The electrical power system of a spacecraft plays a very critical role for space mission success. Such a modern power system may contain numerous hybrid DC/DC converters both inside the power system electronics (PSE) units and onboard most of the flight electronics modules. One of the failure modes for a DC/DC converter that poses a serious threat to mission safety is the random occurrence of system oscillation related to the inherent instability characteristic of DC/DC converters and design deficiencies of power systems.\(^1\) According to NASA studies, this type of failure occurred several times between 1995 and 2007, during flight system testing and, in one case, a critical flight mission.\(^2\) To ensure the highest reliability of the power system, oscillations in any form shall be promptly detected during part-level testing, system integrations testing, flight health monitoring, and on-board fault diagnosis. However, there are significant difficulties to determine the oscillation occurrence because the magnitude of oscillation at an early stage is very small to detect and the development of oscillation in most cases is so fast that once the oscillation starts the DC/DC converter may be catastrophically damaged in just seconds. When the DC/DC converter operates onboard a flight system, it may oscillate any time during input voltage and load transients or other large signal interferences. Therefore, monitoring or diagnosing the fault of the DC/DC converter in a system requires a real-time measurement technique and it becomes more difficult in practice.\(^1\)

Using gain-phase margin of feedback control loop to determine potential stability problems of DC/DC converters has been a practical method for years. This method provides an efficient tool for design verification of the converter.

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stability by using a frequency response analyzer (FRA) to measure control loop gain and phase angle at an appropriate loop-breaking point, and comparing the gain and phase with stability criteria so that the degree of the stability can be determined. However, the gain-phase margin method exhibits significant limitations for testing military and space hybrid DC/DC converters. Such limitations include: 1) Inaccessibility of the loop-breaking test point. Although voltage-remote-sense terminals can be used to probe a FRA, the majority of DC/DC converters are not equipped with the remote-sense terminals. 2) Indirect judgment for DC/DC converter stability. The generally designed gain-phase margins for the converter may not predict the stability when the converter operates in a system, because input filters and loads could change the margins. 3) Reduced sensitivity due to the alternative ways to connect loop-breaking point. The gain-phase margins may not indicate a low-level instability that may break the converter into serious oscillation under dynamic and transient power conditions; and 4) the gain-phase margin method injects noise signals into the control loop circuitry, forces the converter to oscillate over a wide range of frequency, and thus, interrupts the DC/DC converter's normal operation. This increases the risks of degrading and overstressing the space flight unit, which has not been studied adequately.

In this paper, a novel technique to detect a small signal as a potential oscillation that may affect the stability of DC/DC converters is presented. This technique utilizes power spectral analysis method to detect early-stage oscillation signals buried in a wide range of input voltage noise and to identify the oscillation signal based on the principles of circuit oscillation, noise spectral analysis method, and RF signal amplitude/frequency modulation (AM/FM) theories. It provides a useful tool to diagnose real-time stability problems for spacecraft power system consisting of various DC/DC converters. To monitor and detect the oscillation, one can simply connect a spectral analyzer to the power input of an operating DC/DC converter. It is particularly useful for hybrid DC/DC converters without remote-sense pins. Furthermore, a stability diagnosis index (CDI) has been defined using channel power magnitudes at characteristic frequency ($f_{ch}$) and switching frequency ($f_{sw}$) that are unique to every type of DC/DC converters.

II. DC/DC Converter Instability and Determination

A. The Control Loop Transfer Functions

Switching-mode DC/DC converters, as used in all space flight electronic hardware, have potential instability issues due to the output voltage control concept of using negative feedback with loop compensation. Figure 1 shows the block diagram of a typical DC/DC converter with closed-loop negative feedback control. This model includes three key transfer functions within the converter: $G_1(s)$, the AC transfer function of the modulator including power transistors and transformer; $G_2(s)$, the transfer function of the output filter; and $H(s)$, the transfer function of the error amplifier with a compensation network. Similarly, $B(s) = H(s)C(s)$ represents output of the error amplifier, and $E_{o}(s)$ is a measure of the error of the closed-loop system and is equal to the error $E(s) = R(s) - C(s)$ when $H(s) = 1$. The output of the open-loop system, as $B_1$, $B_4$ opened, is

$$C(s) = G_1(s)G_2(s)R(s).$$  

The output of the closed-loop system, as $B_1$, $B_4$ closed, is

$$C(s) = G_1(s)G_2(s)E_{o}(s) = G_1(s)G_2(s)[R(s) - H(s)C(s)],$$  

and therefore

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It is clear that the $H(s)$ in the denominator of Eq. (3) plays a critical role in controlling the system output, but it is also the main source of causing the system to be unstable. Although the $H(s)$ can be designed with an adequate compensation means for a stable system, a practical verification method must be followed throughout the chains of design, manufacture, and user application for DC/DC converters to minimize the impact on stability from real-world variations within the chains.

### B. Effects of Control Loop Gain and Phase on Stability

According to the feedback control theory, each transfer function block shown in Fig. 1 has its associated gain and phase around the feedback loop when viewed over a range of frequencies. The total closed-loop gain of a DC/DC converter is designed to have a gain roll-off rate to a -1 slope, i.e., -20 dB per decade, when passed across the unity gain (0 dB) region. At this point, the phase shift is designed to be less than 360° (180° from the EA plus 90° from the compensation, and plus 90° from the -1 slope), a condition for a stable system. When the phase shift passes across 360° (or 0° in a Bode plot), the gain is designed to be more than -15 dB, another condition for a stable system. Obviously, the 90° from the compensation is an adjustable value at the design stage to force the total phase shift to be less than 360°. However, any one of the three phase shift elements around the loop can significantly cause the total shift to become close to 360°, the primary condition for DC/DC converter oscillation.

Frequency response of the control loop is an effective measure for study of the system performance, and it can be plotted into a Bode plot to illustrate the gain and phase-shift behaviors against frequencies. Figure 2 includes two pairs of the typical Bode plot obtained from two of the DC/DC converters under test. The plot A pair shows not only the gain and phase values that meet the stability requirement, but also indicates adequate gain/phase margins for stable operation of the converter at potential extreme transient conditions. As can be seen from the plot A pair, the -2 slope gain starts to roll off from 45 dB at 100 Hz and changes to -1 slope gain as a Zero at its corner frequency, $f_z(A)$. The -2 slope roll-off is mainly contributed by the output $L_o/C_o$ filter for forward-type converters, and is heavily dependent on the equivalent series resistance (ESR) of the output load ($R_L$) for the flyback-type converters. The roll-off corner frequencies can be calculated as $f_{zc} = 1/2\pi (L_o C_o)^{1/2}$ and $f_{zc} = 1/2\pi R_L C_o$, respectively. Similarly, the zero corner frequency, $f_z(A)$, is contributed by the equivalent series resistance (ESR) of the output capacitor and the capacitance value itself. It can be described as

\[
f_z(A) = 1/2\pi R_{ESR} C_o \tag{4}
\]

In the meantime, the phase shift governed by the R-C compensation network has achieved a 66° gain margin away from 0° (or 360°) at the unity gain (0 dB) and the gain crossover frequency $f_{cg}(A)$ of 1.0 kHz. The phase continues to boost to the largest value of 80° at about 5.5 kHz, and starts to roll across the 0° at about 47 kHz, which is called zero-phase frequency as $f_{zp}(A)$. At this point, there is still a -24 dB gain to guarantee the stability of the system.

On the contrary, the plot B pairs reveal an extremely unstable response of a DC/DC converter, in which the R-C compensation network has been intentionally altered to place a zero, $f_z(B)$, as shown in gain plot B in Fig. 2. The gain rolls off in a -1 slope manner and changes to 0 dB/decade just before the unit gain crossover frequency $f_{cg}(B)$, and remains flat for the next 50-kHz range before it rolls off again. But it becomes too late for the gain to keep a larger margin when the phase shift rolls across the 0° (or 360°) point. Despite the phase shifting 122° away from the 0° (or 360°) at gain crossover, it goes down sharply as the frequency increases because there is no longer an adequate gain to boost the phase shift. In this particular situation, some noise signals generated from the entire loop of the converter with 8kHz to 60kHz frequencies (see point M in Fig. 2) began to travel through $B_fB_rB_3$ and feed back to $B_3$ (see Fig. 1) with exactly the same amplitude as at $B_f$ to cause the converter to become very unstable. This converter may not oscillate at this point, because the phases within the frequency range are still large enough to keep...
the converter stable. However, there must be some noise signals at \( f_p \) that could appear on the input of the control loop and become in phase with the output of feedback signals of the same frequency. It could make the converter break into oscillation even though this frequency still has a small gain of -8.6 dB. It has been proved that a DC/DC converter will become very unstable or oscillate if the feedback loop gain is close to unity (0 dB) which means the same signal amplitude appears at its input and output, and if the phase shift rolls to 0° (or 360°) which means the signal at input and output are in phase.  

III. The Approach of Detecting Early Oscillation Using Spectral Analysis

The early oscillation within hybrid DC/DC converters behaves as a conditionally stable situation, in which the converter may remain within normal operation but shows some signs of potential oscillation that could occur at some worst-case conditions such as turn-on line-input transient and sudden load changes. The early signs of the oscillation typically are small-amplitude signals related to an oscillation as well as some unusual gain/phase margins of a Bode plot. They are normally obscured in a large amount of background noise. The approach of the early oscillation detection technique is to effectively identify the weak oscillation signal at \( f_p \).

A. Determining the Characteristic Frequency of the Oscillation

When a DC/DC converter oscillates, it runs at a specific frequency or a certain frequency range. Thus, the oscillation frequency can be one of the critical characteristics for identifying the oscillation. As described in Fig. 1, if there is a moment in which a noise signal within the control loop starts from the \( B_t \) with 0° phase lag, and then travels through \( B_{1}-B_{2}-B_{3} \) reaching \( B_f \) with a 360° phase delay, the initial signal at \( B_{3} \) and the final signal at \( B_f \) are now in phase. The loop will oscillate if, at the same moment, the noise gain within the loop becomes close to 0 dB, which means the signal amplitudes at \( B_{3} \) and \( B_f \) are equal. The specific frequency at which the phase is 0 degree can be defined as a characteristic frequency \( f_c \) of the oscillation.

To determine the oscillation frequency, an open-frame DC/DC converter was modified for its feedback loop compensation R-C network as an oscillation simulator, in which a 3,900 pF capacitor was replaced by a 560 pF capacitor, and the resistor was adjusted incrementally from its original 1.0 kΩ to 6.8 kΩ. Two Bode plots were obtained for the normal condition with \( R=1.1 \) kΩ and for the 5.6 kΩ condition that was just before the start of the oscillation. As seen in Fig. 3a, the plot for the normal condition shows adequate gain and phase margins, but the plot of pre-oscillation condition shows that the gain is very close to 0 dB while the phase lag reaches 0° (or 360°), an absolutely necessary condition for a feedback loop oscillation. By continuously increasing the resistor value to 6.8

![Figure 3. a) Bode plots showing zero-phase frequencies \( f_p \) at normal and pre-oscillation conditions, and b) switching/output noise waveforms showing the \( f_{osc} \). The \( f_p \) indicated in a Bode plot c) can be measured in a power spectrum d) as a characteristic frequency \( f_c \).](image-url)
.kΩ, the gain dropped to 0 dB and the control loop became completely unstable. Some noise signals with the zero-phase frequency \( f_{zp} = 52.2 \text{ kHz} \), at this moment, appeared at the input of the loop and were in phase with the signals at output of the loop. During power on, the converter ran into serious oscillation at \( f_{osc} = 51.5 \text{ kHz} \) (19.4 \mu s period) as shown in Fig. 3b. Based on this assumption of existence for the oscillation frequency, a power spectrum was taken from a hybrid DC/DC converter as shown in Fig. 3d at the same condition when a Bode plot as in Fig. 3c was obtained. The \( f_{zp} \) of 98.9 kHz measured in the Bode plot was detected in a power spectrum as about 94.6 kHz. Note that the \( f_{zp} \) of the Bode plot and characteristic frequency \( f_c \) in the power spectrum, at this condition, agreed perfectly with each other.

To further investigate the correlation between frequencies of the two measurement methods, 18 of the \( f_{zp} \) and 18 corresponding \( f_c \) were measured simultaneously when adjusting the simulator to create 18 incremental oscillation noise levels. The test results in Fig. 4a show that the two frequencies had a strong relationship with a correlation coefficient of \( r = 0.9453 \) and with the fact that 89.4% of power spectrum readings were accounted for by the Bode plot readings. Fig. 4b represents correlation of the frequencies for a MFL2812S DC/DC converter, which indicates even stronger correlation for the two measurement methods. In general, the feedback loop oscillation frequency detected by using a spectral analysis method was found to be in a range of high frequencies, being unique for every individual type of converter, and in strong-linear correlation with the zero-phase frequency presented in a Bode plot of the gain/phase margin measurement method.

B. Amplitude and Frequency Modulations of the Oscillation

Referring to radio frequency (RF) theory, modulation is a process of using specific circuits to impose information contained in a lower frequency electronic signal onto a higher frequency signal. In the case of DC/DC converter oscillation, a process that is very similar to the RF modulation occurs around every circuit fraction of the converter feedback loop. The switching signal \( V_{os} \) (in higher frequency) as a carrier is modulated by the feedback-loop oscillating signal \( V_o \) (in lower frequency). If the \( V_o \) causes amplitude of the \( V_{os} \) to vary, the amplitude modulation (AM) occurs. In a different aspect, a frequency modulation (FM) occurs if the \( V_o \) causes the switching frequency \( f_{sw} \) to vary. For DC/DC converter oscillations, the AM and FM may occur at the same time and may be mixed together. The equation describing the voltage of the AM wave \( (v_{AM}) \) may be written as

\[
v_{AM} = V_{os} \sin^2 2\pi f_{sw} t + \frac{1}{2} V_o \cos 2\pi (f_{sw} - f_c) t - \frac{1}{2} V_o \cos 2\pi (f_{sw} + f_c) t\]

and the frequency of the FM wave \( (f_{FM}) \) may be described in an equation as

\[
f_{FM} = f_{sw} + \Delta f \sin 2\pi f_c t
\]

where \( \Delta f \) is the frequency deviation, the maximum change in frequency that the modulated wave undergoes.

As can be seen from Eq. (5), the AM-type oscillation generally contains three frequency components: the switching frequency \( f_{sw} \), the lower-sideband frequency \( f_{sw} - f_c \) and upper-sideband frequency \( f_{sw} + f_c \). Since the waves of the oscillation have a rather complex wave shape and can be considered as a sum of a set of pure sine waves, each of the sine waves that make up the complex oscillation wave will have the both sideband frequencies. Waveforms in Fig. 5 illustrate the amplitude modulation observed during one of the tests in this study. Figure 5a is a time-domain switching waveform that is AM modulated and thus has an amplitude swing of 59.9 kHz. The spectrum of Fourier analysis in Fig. 5b indicates the oscillation frequency of 59.1 kHz and a switching frequency of 565.2 kHz, as well as two sideband frequencies about 59 kHz apart from both sides of the switching frequency. This is a typical AM modulation because there is only one pair of sideband frequencies appearing in the spectrum.
significant periodic signal other than the early oscillation signal has been found. Therefore, the evidence of using
examine the early oscillation signal. With the gain of the noise signal being closer to 0 dB at \( f_{zp} \), the must-oscillating
condition, the amplitude of the EOS increased and the sideband signals emerged as shown in Fig 6c. Note that there
oscillation characteristic frequency
gains very close to 0 dB. By carefully analyzing all possible noise sources within the entire converter circuit, no
oscillation strongly
the frequency response method seems obvious. Figure 6b is a closer-look spectrum with a 120-kHz narrow span to
small to affect performance of the DC/DC converter. In an extreme condition, however, the EOS may reach to a
zero dB-gain and in-phase situation, and therefore, makes the converter run into a fatal continuous oscillation.

DC/DC converters almost always have a lower level of early oscillation because of their superior design regarding
oscillation frequency
shows an early oscillation signal
oscillation strongly
Figure 6a reveals an early oscillation signal in a power spectrum for a QV24-5-25 converter, which corresponds
to the normal condition of the loop performance shown in Fig. 3a with a zero-phase frequency \( f_{zp} = 68.2 \) kHz. This is the only significant signal magnitude in this power spectrum besides the amplitude of the switching frequency. It represents an early oscillation at the \( f_{zp} \) due to some of the Fourier components of the noise within the loop having gains very close to 0 dB. By carefully analyzing all possible noise sources within the entire converter circuit, no significant periodic signal other than the early oscillation signal has been found. Therefore, the evidence of using oscillation characteristic frequency \( f_c \) for the spectrum analysis method to represent the zero-phase frequency \( f_{zp} \) in the frequency response method seems obvious. Figure 6b is a closer-look spectrum with a 120-kHz narrow span to examine the early oscillation signal. With the gain of the noise signal being closer to 0 dB at \( f_{zp} \), the must-oscillating condition, the amplitude of the EOS increased and the sideband signals emerged as shown in Fig 6c. Note that there

C. The Indicator of Early Oscillation
Early oscillation of hybrid DC/DC converters has been found to be periodic variations of a very low level noise signal presented within the feedback loop of the converter. It is a natural phenomenon when one or more of the Fourier components of the noise appear in phase and with close-to-zero gain at the loop input and output. The periodic variation means that the noise signal changes in amplitude, frequency, or both at the same time. The early oscillation exists in every type of power converter that has a negative feedback control scheme, but the degree of the oscillation strongly depends on the total noise level contained within the converter. In fact, space-grade hybrid DC/DC converters almost always have a lower level of early oscillation because of their superior design regarding noise-level reduction. The oscillation frequency is also unique for every type of converter, since the design of total loop performance for a specific type has defined exactly when the phase should come to zero degree and thus the oscillation frequency has been predetermined. An early oscillation signal (EOS) at normal conditions may be too small to affect performance of the DC/DC converter. In an extreme condition, however, the EOS may reach to a zero dB-gain and in-phase situation, and therefore, makes the converter run into a fatal continuous oscillation.
is only one pair of sideband signals, and the 58 kHz frequencies spaced apart on both sides of the switching frequency are equal roughly to the EOS frequency. Fig. 6d is a narrow-span power spectrum representing EOS in Fig. 6c. It can be seen that the signal increase in amplitude from -58.4 dBm in Fig. 6b to -51.1 dBm in Fig. 6d clearly implies the development of the oscillation from its early stage to the mature stage. Unfortunately, the signal change of -7.0 dBm (0.45 mV) in amplitude seems too small to be detected by an oscilloscope.

Based on detailed studies of the new approach described in previous sections, an early oscillation indicator for hybrid DC/DC converters can be established by efficiently detecting the early oscillation signal at its characteristic frequency \( f_a \) and the sideband signal amplitudes around the switching frequency \( f_s \). The high-sensitivity power spectra shown in Fig. 6 are capable of separating the EOS from its background noise, and therefore can provide a more effective tool to identify an oscillation at the early stage. Using channel power magnitude \( M_{CP} \) (in dBm/Hz) of the spectrum as a quantity measure for a signal level can be another advantage for identifying the low-level signal. The early oscillation signals are multi-frequency signals containing numerous harmonics, and the channel power works exactly to measure the total energy of the signal within the frequency range. Therefore, the channel power could provide high distinguishability when comparing among similar signals.

To determine if the \( M_{CP} \) in the input noise power spectrum is truly reliable for DC/DC converter fault diagnosis of stability, correlations between the channel power method and gain-phase margin method were studied. Figure 7 illustrates strong correlations between the channel power and gain-phase margins, which were obtained by using the QV24-5-25 oscillation simulator under the same test conditions. Because the correlations appeared to be non-linear, Rank Order Correlation Coefficient \( r_s \) was utilized to describe how the channel power (in dBm) increased (or decreased) with changes of gain and phase margins. The test data curves indicated the clear trends that the \( M_{CP} \) decreased while the gain and phase margins increased (or decreased) accordingly with quite large \( r_s \) values equal to

\[
\text{Figure 6. a) Power spectrum in 540-kHz span showing the EOS and the switching signal, b) Amplitude and frequency of the EOS in 120-kHz span, c) The increased EOS and emerging sideband signals indicate a growing oscillation, and d) The increased EOS showing in a narrow span spectrum.}
\]

\[
\text{Figure 7. Correlations between channel power and gain-phase margins for the QV24-5-25 converter.}
\]
0.9608 for gain margin and 0.8989 for phase margin. In fact, the lower r value for Fig. 7b simply meant that there was a larger portion of negative relationship between the two parameters, compared to the positive relationship shown in Fig. 7a. The $M_{CP}$ contains total average noise energy of the oscillation within a specified frequency range, so that it makes the channel power reading more stable and more sensitive to oscillation in the early stage than the pulse amplitude in a Fourier spectrum as observed in this experiment.

D. The Stability Diagnosis Index

In order to accurately assign a degree of stability to a specified hybrid DC/DC converter for fault diagnosis, a quantitative measure to represent the stability condition should be well established. The stability diagnosis index (SDI) is proposed to evaluate the DC/DC converters’ stability performance based on measurement data of early oscillation signals from the power spectrum. As a comprehensive index, the data contains measured channel power at the oscillation characteristic frequency ($CP_{ef}(m)$) and measured channel power at $f_{oa}$ with all significant sideband frequencies ($CP_{rw}(m)$), both in dBm. The index can be considered as a ratio of $CP_{ef}(m)$ and $CP_{rw}(m)$ of the measured EOS to $CP_{ef}(n)$ and $CP_{rw}(n)$ of the normal EOS, so that the measured EOS can be evaluated against the normal EOS. Clearly, a normal EOS level of a specific DC/DC converter should be pre-determined by conducting experimental tests on the module or collecting the data from the manufacturers. The SDI then, can be defined as

$$SDI = 1/2 \left[ \frac{CP_{ef}(m) - CP_{ef}(n)}{CP_{ef}(m) + CP_{ef}(n)} \right]^{1/2} \left[ \frac{CP_{rw}(m) - CP_{rw}(n)}{CP_{rw}(m) + CP_{rw}(n)} \right]$$

(7)

The SDI in Eq. 7 is dimensionless, and has a value from 0 to 1. Thus, a SDI value of zero would indicate a normal stable situation, in which both measured $CP_{ef}$ and $CP_{rw}$ equal the normal $CP_{ef}$ and $CP_{rw}$. Note that the measured SDI value shall not be smaller than the normal SDI value in all circumstances, or a measurement error could be involved. As a guideline for applications, DC/DC converters with SDI values of 0 to 0.5 should be considered as acceptable.

IV. Conclusion

Based on this study, the DC/DC converter oscillation frequency has been proved to be the zero-phase frequency ($f_{oa}$) in a Bode plot of traditional gain-phase margin method, which is adopted as the fundamental of the early oscillation detection technique. The oscillation characteristic frequency ($f_c$) can be defined for the spectrum analysis method to represent the $f_{oa}$. Any amount of increase in channel power magnitude ($M_{CP}$) from their nominal levels at $f_c$ and at $f_{oa}$ could indicate an ongoing oscillation and can be utilized to determine the types, intensity, and change tendency of the oscillation. This technique shows significant advantages over the gain-phase margin method in terms of detection sensitivity, real-time monitoring capability, and test probing flexibility. By using the SDI scheme, it has potential as a powerful tool for flight DC/DC converter health monitoring and fault diagnosis.

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