Non-invasive Prognostication of Switch Mode Power Supplies with Feedback Loop Having Gain

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Abstract— Switch mode power supplies (SMPSs) provide one or more levels of direct output voltages from a single input direct voltage. Regulation of the output voltage is often achieved by sampling the output voltage and/or the current through a filtering inductor, passing the sampled voltage through a feedback circuit to control the frequency and/or the width of the pulses used to generate direct output voltages. Often one or more opto-isolators are used to provide both gain and isolation in the feedback loop. The authors present a novel method for non-invasive prognostic health monitoring of such SMPSs. The method employs a non-invasive method of causing an abrupt change in the SMPS current load and a non-invasive method to sample and process the damped ringing response to produce prognostic health signals that are correlated to degradation in the Current Transfer Ratio (CTR) of opto-isolators used in the feedback loop(s) of a SMPS. By sampling the ringing response, it is possible to detect the onset of degradation of the isolator before performance is adversely affected. The methods presented in this paper (1) are simple to implement, (2) support condition-based maintenance paradigms, (3) are applicable to a wide-range of SMPS feedback topologies, (4) reduce the occurrence of No Trouble Found (NTF) codes, and (5) reduce costs and reliability issues related to intermittent operational failures to maintain voltage regulation.[1][2]

TABLE OF CONTENTS

1——————————

[1] 1-4244-1488-1/08/$25.00 ©2008 IEEE.
[2] IEEEAC paper #1148, Version 1, Updated Aug. 14, 2007.

1. INTRODUCTION

One common type of electronic power supply (EPS) used in mil-aero applications is a switch mode power supply (SMPS) to provide one or more levels of direct output voltages from a single input direct voltage. A typical topology is one which has a Pulse Width Modulator stage, an Isolation/Transformer stage, an Output Filter stage and a Feedback Loop stage, as shown in Figure 1 and Figure 2. Regulation of the output voltage is often achieved by sampling the output voltage and/or the current through a filtering inductor, passing the sampled voltage through a feedback circuit to create an output that is used to control the frequency and/or the width of the pulses produced by the Pulse Width Modulator. This paper presents a novel method for non-invasive prognostic health monitoring of such a SMPS.

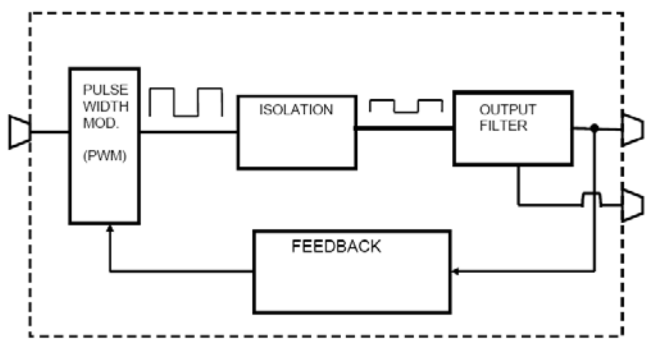

Figure 1: SMPS Block Diagram.

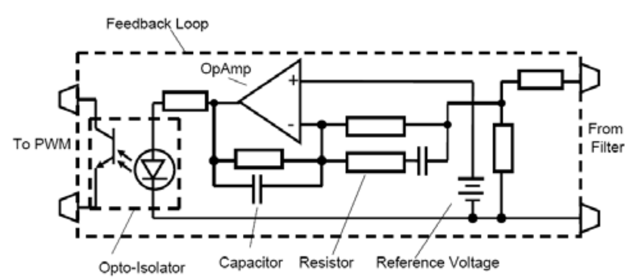

Figure 2: Typical SMPS Feedback Topology.

Opto-isolators are often used to provide both gain and isolation in the feedback loop, but they are also subject to damage with resultant loss of voltage regulation; the failure modes are varied and there are detectors and monitors for failed package connections, degraded capacitors, broken bars in squirrel cages, and degraded network servers **Error! Reference source not found.**-7.[4].

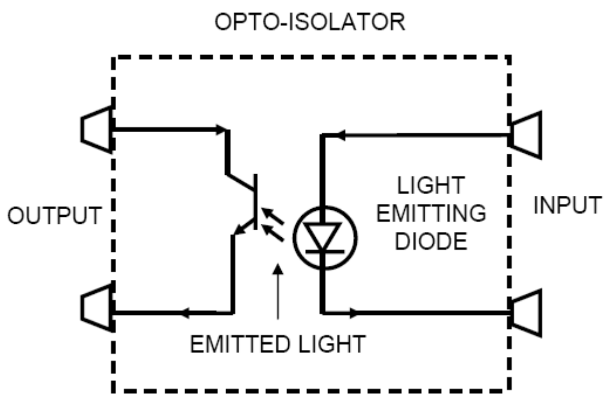

Figure 3: Topology of an Optoisolator Device.

By inducing an abrupt change in load current and sampling the resultant ringing response, it is possible to detect the onset of degradation of the isolator before performance is adversely affected. The methods presented in this paper (1) are simple to implement, (2) support condition-based maintenance paradigms, (3) are applicable to a wide-range of SMPS feedback topologies, (4) reduce the occurrence of No Trouble Found (NTF) codes, and (5) reduce costs and reliability issues related to intermittent operational failures to maintain voltage regulation.[3]

A prognostics health monitoring system was previously introduced where the crossover frequency is monitored through a voltage regulation feedback loop, and a fault-to-failure progression model is used to predict the health and remaining useful life (RUL) of an optical isolator in a SMPS 7.[5]-7.[6]. In this paper we extend previous experimental results and we introduce a new non-invasive prognostic sensor for the optical isolator in a SMPS: Ringdown™. Further, although this paper is presented in the context of an optoisolator, the results are valid for any feedback loop with amplification.

Mechanics of Failure

As previously discussed, common fault modes that are present in a SMPS are many and varied. For this paper, Ridgetop has focused on the degradation of an opto-isolator, as used in a feedback circuit; but the principals and the results apply to any amplifier in a feedback loop. The gain of an optoisolator is governed by its transfer characteristic expressed as a Current Transfer Ratio (CTR). When an opto-isolator is stressed, the crystal lattice of the light-emitting diode becomes damaged, the efficiency of the light emission is reduced, the CTR becomes smaller and the gain is reduced 7.[7]. A robust power supply should have a reasonable design margin built into the feedback gain so that as the isolator wears out, voltage will continue to regulate properly. As wear approaches a critical threshold, the SMPS will begin to fail much more rapidly. Moreover, there will be a greater tendency to display fault intermittency under stress and, in turn, NTF failure codes.

Fault-to-Failure Progression (FFP) Signature

An electronic power supply (EPS) has a response to an abrupt change in load current that will define its intrinsic natural frequencies, and thus its time constants and damping coefficients.. Ridgetop investigated three different SMPSes from C&D Technologies (now Murata): WPA50, CPCI325 and a VKA100; the VKA100 test bed is shown in Figure 4.

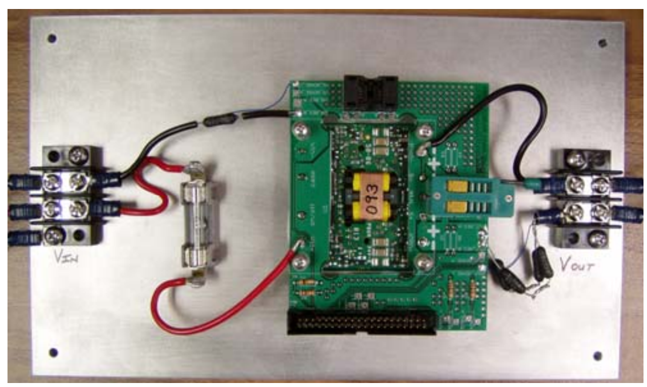

Figure 4: VKA 100 Test Bed w/Breakout Board on a Mounting Plate Assembly.

It was determined the response of an SMPS to an abrupt change in load current is a damped ringing response, an example is shown in Figure 5.

Damped Ringing Response

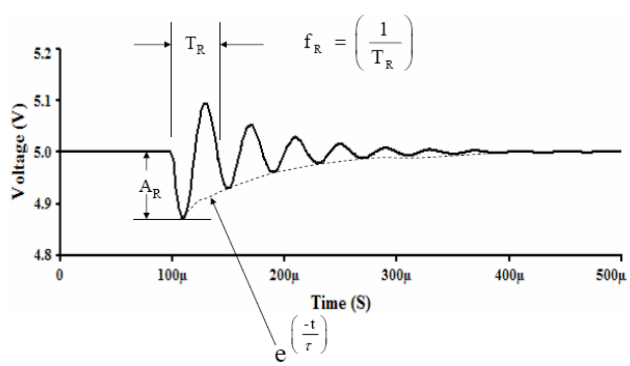

Figure 5: Dampened Ringing Response

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[3] Patent pending.

Mathematical Modeling

The SMPS output, due to a step or impulse load change, can be modeled by the following expressions (refer to Figure 5):

EQ.1: $V_O = V_{DC} + A_R \left\{ \exp\left({-t}/{\tau} \right) \right\} \left\{ \cos\left(\omega t + \phi \right) \right\}$

V_{DC} = the direct voltage output of the SMPS; A_R is the peak amplitude of the dampened ringing response; t is time; and τ is the dampening time constant.

EQ. 2: $\omega = 2\pi f_R$

f_R = the resonant frequency of the dampened ringing response; and ϕ is the phase shift of the resonant frequency.

The terms A_R, τ and ω are complex expressions dependent primarily upon the exact topology of the SMPS, especially the feedback loop; the current mode of the SMPS (continuous current flow or discontinuous current flow); and the type of the abrupt current change (impulse or step). For continuous current mode and an impulse type of current change, the terms become the following:

EQ. 3: $A_R = -Z_{out} \Delta I \dfrac{A}{A+1} \left(\dfrac{1}{\omega_0 \sqrt{1 - {1}/{4Q^2}}} \right)$,

EQ. 4: $\tau = \left(\dfrac{2Q}{\omega_0} \right)$,

EQ. 5: $\omega = \omega_0 \sqrt{1 - {1}/{4Q^2}}$,

EQ. 6: $\omega_0 = \sqrt{A+1} \left(\dfrac{1}{\sqrt{LC}} \right)$ and

EQ. 7: $Q = \sqrt{A+1} \left(\dfrac{1}{R} \sqrt{\dfrac{C}{L}} \right)$.

These expressions show the amplitude, the duration of the ringing and the frequency of the ringing response are related to and dependent upon the gain (A), resistance (R), capacitance (C) and inductance (L) of the feedback loop of the SMPS. Of the three variables that change in response to an abrupt stimulus such as an abrupt change in load current, the dampening time and the ring frequency are particularly amenable to prognostication methods.

Gain and Phase

Figure 6 is a line plot of the loop gain (A) in dB and the phase (B) in degrees of an exemplary SMPS versus frequency. The crossover frequency (f_C) is the frequency at which the loop gain is 0 dB. For the SMPS to be stable, the phase margin (180 degrees minus the absolute value of the phase) must be positive and greater than some design margin (for instance, 45 degrees). The SMPS represented by Figure 6 is stable. The SMPS has a resonant frequency, f_R, as indicated in the phase plot, and it is the frequency at which the phase is minus 180 degrees (0 degree phase margin). The SMPS does not oscillate because the gain margin at the resonant frequency is less than 0 dB: gain margin is defined as the loop gain at the frequency in which the phase is -180 degrees. An abrupt change, such as that induced by an abrupt change in the load current, introduces disruptions that cause the SMPS to begin to oscillate at the resonant frequency, but the oscillations are damped because the gain is less than one (negative value in dB) at that frequency.

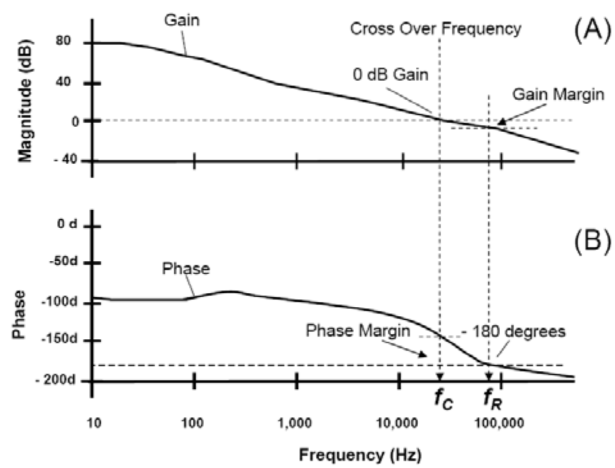

Figure 6: Gain and Phase Line Plots – Typical SMPS with Feedback.

Fault-to-Failure Progression (FFP) Signature

The investigations led to the identification of a Fault-to-Failure Progression (FFP) Signature: As the gain of the feedback loop degrades, the number of detectable negative excursions of the sinusoidal waves in the damped ringing response of the SMPS to an abrupt change in load current is reduced. This is predicted by the expressions in the mathematical modeling of the damped ringing response and by the Bode gain and phase diagrams (Figure 6): as the gain degrades, the initial amplitude (EQ,s 3, 6 and 7) tends to become smaller; the exponential time constant (EQ.s 4, 6 and 7) tends to become smaller; and the cross-over frequency becomes lower. One or more of these, depending on the exact feedback topology and circuit values, will dominate. More importantly, the result is a reduction in the number of detectable sinusoids in the damped ringing response.

FFP Signature Variations

There are two significant types of response, as shown in Figure 7: (A) shows fixed frequency responses in which the dampening time is reduced as the gain degrades; (B) shows variable frequency responses in which the frequency is reduced as the gain degrades. The (A) type of response was noted and investigated in the recent NASA SBIR CEV NNX07CA29P, effective date 2/14/2007; the (B) type of response was noted and investigated in a previous NASA SBIR CEV NNA06AA22C, effective date 1/20/2006. Both types of response are amenable to prognostication.

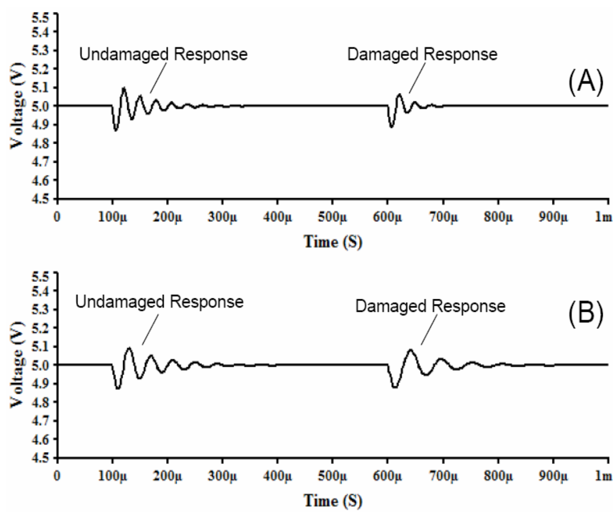

Figure 7: Damped Ringing Frequency Response – (A) Fixed Frequency and (B) Variable Frequency.

Figure 8 shows the damped response when a good optoisolator with a CTR of 138% was used in the VKA 100 test bed shown in Figure 4.

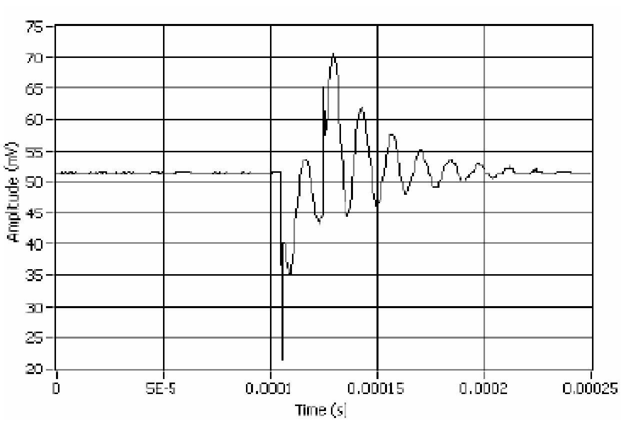

Figure 8: Damped Response, Opto CTR = 138%.

Figure 9 shows the damped response when a badly degraded optoisolator with a CTR of 17% was used in the VKA 100 test bed. As degraded optoisolators were used, the number of negative excursions of the damped response became smaller.

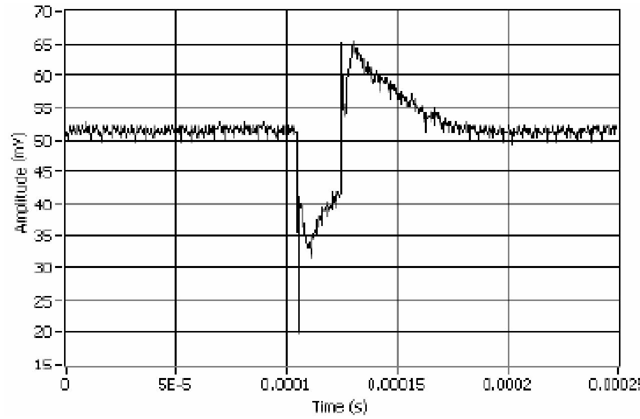

Figure 9: Damped Response, Opto CTR = 17%

2. RINGDOWN™ SENSOR

A block diagram of a RINGDOWN sensor design is shown in Figure 10.

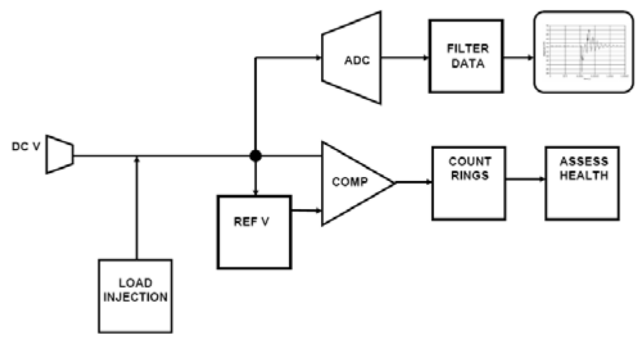

Figure 10: Block Diagram of a RINGDOWN Sensor.

A control program in, for example, a micro-controller causes an abrupt load change; the damped ringing response is displayed (top right) and a health assessment is made (bottom right). At the top right of the block diagram, the damped ringing response is converted to digital data, filtered and displayed. At the bottom right of the block diagram, the damped ringing response is converted to a train of pulses, each pulse corresponding to a sinusoid in the damped response. The pulses are counted and the count is used to assess the health of the SMPS.

3. CONDITION-BASED MAINTENANCE

A SMPS with a degraded (loss of amplification) feedback loop produces a damped ringing response with fewer detectable sinusoids compared to an non-degraded SMPs. The ability to detect degradation, before noticeable loss of regulation of the output DC voltage, provides a basis for preventative maintenance based on condition. Maintenance can be scheduled and mission-outage and downtime prevented.

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4. MITIGATION OF INTERMITTENCIES

We have noticed that a degraded SMPS tends to recover after it is powered-off, but a degraded SMPS, when returned to use, soon exhibits signs of degraded performance. This is a source of intermittent, anomalous operation: degraded performance, diagnosis, removal, test okay, return to service, degraded performance … This type of intermittent okay, fail, okay can be broken by the ability to detect degradation and produce a health assessment of other than 100%: regardless of a subsequent test result, the SMPS is known to be degraded. Removal for repair rather than test okay, is mitigation of intermittency.

5. ACTIVITIES

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6. SUMMARY AND CONCLUSION

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8. BIOGRAPHY

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James Hofmeister *is a senior principal engineer and engineering manager. He has been a software* *developer, designer and architect for IBM and represented IBM as a member of the board of directors of the Southern Arizona Center for Software Excellence. At Ridgetop Group, he is a principal investigator and lead design engineer, specializing in analog and digital circuit designs for electronic prognostics. He is a co-author on six patents (5 IBM and 1 Ridgetop) and five other pending Ridgetop patents. He retired from IBM in 1998 after a 30-year career and joined Ridgetop Group in 2003. He received a BS in electrical engineering from the University of Hawai'i, Manoa Campus, and a MS in electrical and computer engineering from the University of Arizona.*