The Effect of Pulse Width Modulation (PWM) Frequency on the Reliability of Thermoelectric Modules

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Abstract

Pulse-width-modulation (PWM) control has many benefits when used to control power to thermoelectric modules (TEM's). This scheme allows the use of smaller, lighter circuitry that dissipates less heat than a comparable linear controller. However, abruptly turning power on and off to a TEM has been known to cause thermal cycling which reduces the reliability of the module. This thermal cycling fatigues the solder junctions causing an increase in the module's electrical resistance. As a result, some system designers have been reluctant to use PWM controllers in their cooling apparatuses.

This paper quantifies the effect of PWM control on the reliability of TEM. TEM's are powered with PWM signals of various frequencies from 0.1 to 10K Hz. The electrical resistance of these modules is then tracked throughout the duration of the test. These changes in electrical resistances are used to directly correlate the frequency of PWM control with TEM reliability.

Introduction

PWM control schemes have been used in thermoelectric temperature controllers for many years. PWM temperature controllers deliver power to a TEM by switching power to the module either completely on or completely off. This is usually done via a transistor. The PWM output signal consists of a periodic square wave with a variable "on time" (T_{on}). This "on time", when expressed as a percentage of the period (P) of the square wave, is known as the duty cycle. Power to a TEM is adjusted by varying the duty cycle of the square wave. The frequency of the signal (F_s) is simply the frequency of the square wave, 1/P. An example of a PWM signal is shown in Figure 1 and an example of a PWM circuit is shown in Figure 2.

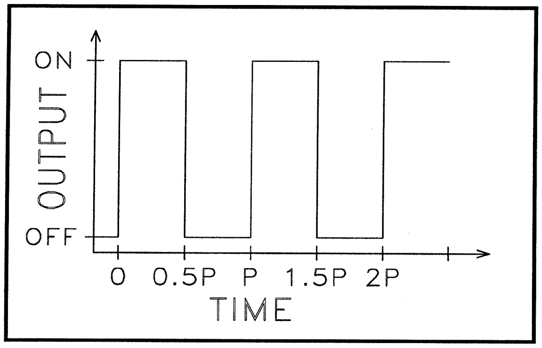

Figure 1. PWM signal, 50% duty cycle

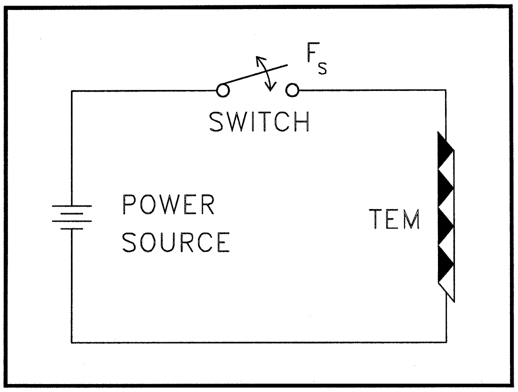

Figure 2. PWM circuit

The other common topology used in temperature controllers is called analog control. Analog controllers generally vary the power to a TEM by placing an energy dissipating element, such as a transistor, in series with the module. Adjusting the power passed through this dissipating element in turn varies power to the TEM. This method yields a linear signal to the TEM but can generate considerable amounts of waste heat in the dissipating element. Removing the heat from the power transistors generally requires large, heavy, heat sinks, fans, and large power transistors. PWM controllers can generally be made smaller, lighter, and for less money than their analog counterparts because smaller transistors can be used and little, if any, heat sinking is required.

There is, however, a potential drawback to using a PWM temperature controller. The very nature of the signal causes bursts of cooling which, in turn, causes thermal expansion and contraction in the TEM. This expansion and extraction is a well documented cause of degradation and failure and is the crux of reliability tests such as the Bell 40-90 test. Many system designers have been reluctant to use PWM controllers because of this. Other system designers who do use PWM controllers are in disagreement as to which PWM control frequencies are least damaging.

An ideal frequency for PWM controllers is not intuitively obvious. Lower frequency PWM signals cause larger temperature variations in the TEM. The temperatures in the TEM are simply given more time to equilibrate to their steady-state "full on" and "full off" temperatures during the "on" and "off" periods of the PWM signal. Higher frequency PWM signals yield a more constant TEM temperature but do so at the cost of introducing more potentially damaging pulses.

The purpose of this paper was to explore the use of PWM controllers of various frequencies in conjunction with thermoelectrics. This was done to determine if this type of signal is damaging to TEM's or if certain frequencies are more damaging than others.

Test Method

Six groups of three TEM's each were powered with various frequency signals. The frequencies of these PWM signals were 0.1, 1, 10, 100, 1K, and 10K Hz. The duty cycle was a constant 50%, and the "on" voltage was 15 volts for all cases.

The AC resistance (ACR) of each TEM, as measured on a TE Technology Inc. model TS-205 tester[1], was measured before the testing began and then periodically during testing. Changes in ACR were used to determine the damage to each TEM and allowed correlation's to be made between PWM frequency and TEM degradation.

The ACR of each TEM was measured three times at every test interval. The average of these three tests was recorded as the module's ACR for that test interval. The ACR of the three modules in each group was then averaged to yield the group's ACR for each test interval. The modules were not removed from the test apparatus for these measurements. This was to avoid possible damage during assembly and disassembly. Rather, the TEM's were unhooked from the PWM controller and the ACR was measured in situ.

Power was turned off to the TEM's and all fixtures were allowed to equilibrate to room temperature before ACR was measured. This was done so all of the modules would be near the same temperature during the measurements minimizing any temperature dependant effects of the TE material.

A control module was also tested at every interval. The purpose of the control module was to establish the repeatability of the test equipment. The ACR of the control module was measured three times and averaged to yield the average ACR of the control module for each test interval.

Module Selection

The modules chosen for this test were 40 mm square, 127 couple devices. The geometry of the pellets was 1.4 mm square at the base and 1.05 mm tall. This pellet geometry was chosen to yield the fastest thermal time constant and, therefore, worst case results with respect to temperature cycling. The 40 mm square module was chosen because it is the most common size used in the thermoelectric industry

Test Apparatus

Six individual test fixtures were constructed for the tests. Each fixture was used to test one group of modules. The fixtures consisted of a power supply, a PWM controller, and a heat sink onto which the TEM's were clamped. A removable gasket was placed over the TEM's and clamping mechanism to prevent condensation from forming on the TEM's and damaging them.

The clamping mechanism was constructed to add minimal thermal loading on the TEM's. It consisted of an aluminum bar and screws that compressed the TEM's to the heat sink. A strip of rubber was placed between the TEM's and the bar to act as a thermal insulator and to prevent the bar from damaging the TEM's. Thermally conductive grease was placed between the TEM's and the heat sink. A picture of the heat sink, TEM's, and the clamping mechanism is shown in Figure 3.

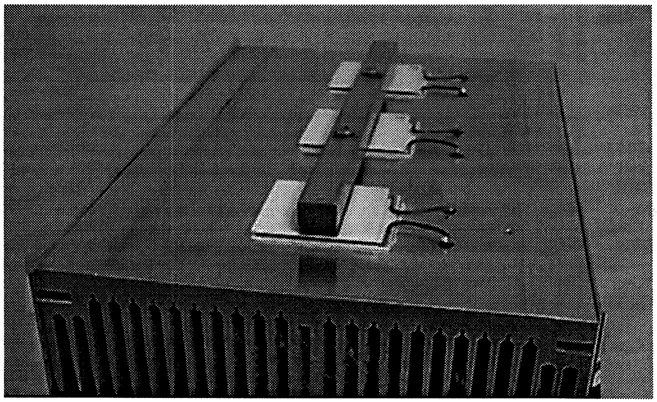

Figure 3. Test apparatus

Results

The temperatures at the cold side of the TEM's in the 0.1 Hz fixture varied from -9°C to 15°C. These temperatures varied between 1°C and 4°C in the 1 Hz fixture. The temperature variations were either too small or changing too rapidly to measure in all other cases. The typical operating ambient temperature for these fixtures was 27°C, and the typical operating temperature of the heat sink was 35°C. The results of the test are shown in Figures 4a and 4b.

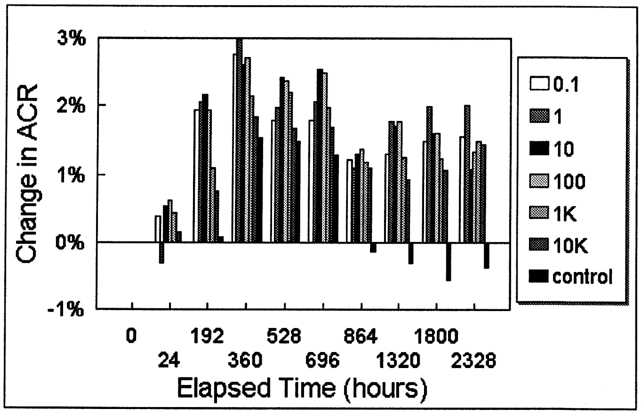

Figure 4a. Change in average ACR as a function of time and frequency

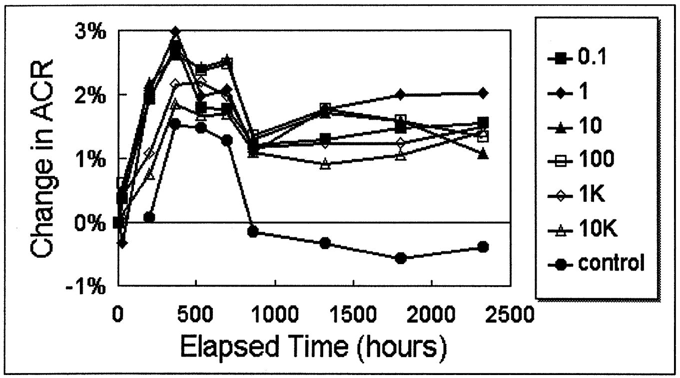

Figure 4b. Change in average ACR as a function of time and frequency

Discussion

There is a slight increase in ACR in all groups of the thermoelectric modules. This increase remained relatively constant once the 192 hour test interval was reached. The amount of increase is small, especially in comparison with the control module. It is not enough to substantially affect the performance of the TEM's.

There is no statistically significant data or emerging patterns to suggest that any of the test frequencies are more damaging than others. The test period may not be long enough, however, to sufficiently uncover subtle shifts in ACR. An extended test period would allow reasonable reliability projections over a TEM's typical service life of 50,000 to 100,000 hours.

Conclusions

There was only a slight degradation in the ACR of all of the TEM's tested. It can be concluded that all of the PWM frequencies tested so far have had little impact on the ACR to cause concerns regarding reliability.

The changes in ACR with respect to frequency are still too small to make any determination of an optimal frequency for a PWM controller since all patterns regarding this are statistically insignificant. Testing should be extended to determine if any statistically significant patterns will emerge.

References

1. Buist, R. J., Methodology for Testing Thermoelectric Materials and Devices, CRC Handbook of thermoelectrics, CRC Press, Inc., 1995.