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Operational Characteristics of a 200°C LC Parallel Resonant Circuit

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Abstract

Research efforts are currently underway at the NASA Lewis Research Center to design and demonstrate an inverter capable of operating with a baseplate temperature of 200°C. In support of this project, various electrical components including capacitors, inductors, transformers, cables, and semiconductor switches are being developed or evaluated for integration into the inverter. In this work, a parallel LC resonant circuit was constructed and evaluated under simultaneous electrical and thermal stressing. The tests were performed in the temperature range of 25°C to 200°C with an applied voltage of up to 90V, 20kHz. The individual components were comprised of high temperature film capacitors and powder core inductors developed in-house. The circuit was characterized in terms of the component currents and case temperatures as well as frequency of resonance as a function of applied bias and temperature. The results obtained, which have indicated good functional stability up to 200°C, are presented and discussed.

Introduction

The design requirements for many future power systems emphasize compactness, lightweight, reliability, and highly efficient operation. In addition, exposure of the power systems to high temperatures is anticipated in a wide span of environments ranging from space exploration missions to terrestrial applications. The development of electrical components and systems capable of high temperature operation represents, therefore, a key element to meeting these technological challenges and to fulfilling the requirements of advanced space power systems. For example, by operating the spacecraft radiator and power electronics at a higher temperature, the radiator becomes more efficient allowing its size to be reduced. This, in turn, would result in simplified and better thermal management of the power system and would decrease the spacecraft weight, thereby reducing launch costs or increasing payload capability. The high temperature components could also be used in the control electronics for turbine and automotive engines. The operating temperatures of these engines constrain circuit and system designers to locate the electronics in relatively cool areas or compartments away from the engine. This leads to the use of wiring harnesses and other hardware which add weight to the vehicle and increase fuel costs. Additionally, the successful and efficient drilling of wells for geothermal energy extraction necessitates the use of electronic sensors which can withstand prolonged exposure to high temperatures encountered in down-hole drilling operation. These sensors collect information about the nature of the underlying rock and soil formations which provide clues about the presence of oil or natural gas.

State-of-the-art power components are limited to maximum operating temperatures of 105°C with some devices functioning at temperatures up to 150°C. Some signal-level devices are capable of withstanding temperatures up to 200°C, but they only operate at low currents and voltages; typically only a few milliamperes at voltages less than 125V and are unsuitable for use in high power applications. The major barriers to operating components continuously at 200°C and high power levels are, to name a few, the dielectric and magnetic materials, metallization techniques, and the thermal and electrical packaging design. Identification of new materials and components capable of providing reliable and efficient operation at high temperature, and improvement in current designs and processes thus play an important role for meeting the future needs and requirements of advanced space and other power systems.

Research efforts to develop lightweight, reliable 200°C power inverter for space-based applications are being performed at the NASA Lewis Research Center. As part of this program, an LC parallel resonant circuit was designed and built using film capacitors and powder core inductors especially designed for high temperature operation. The performance of the tank circuit was evaluated while being subjected to simultaneous electrical and thermal stressing. The experimental setup and the results obtained are presented and discussed.

Experimental Procedures

A combined research effort, utilizing contracts and in-house testing facilities at the NASA Lewis Research Center, has led to the development of power components capable of continuous operation at 200°C. The resonant circuit characterized in this work utilized film capacitors and powder core inductors. The foil-film capacitors, which employed a proprietary 3M Company polymer film, were jointly developed with the Westinghouse Research Center [1-2]. Each capacitor has a rating of 0.8μF and is capable of operating at 125VAC, 20kHz, and 8A. The inductors, which were developed in-house, utilized molypermalloy powder cores in their construction. The ratings of the inductor were 13μH, and 25A at 20kHz. The LC parallel resonant circuit was constructed by connecting three 0.8μF capacitors in parallel to form the capacitive element of the tank while two 13μH inductors were connected in series to form the inductive element. The values of the components were chosen to obtain a resonant frequency of 20kHz. All voltage and current data presented here are in rms values. A schematic diagram of the test circuit is shown in Figure 1.

Characterization of the circuit was performed under electrical and thermal stresses applied simultaneously. The tests were carried out from room temperature to 200°C, with increments of 25°C, using a Hotpack oven as the environmental chamber. At a given temperature, the tests were performed at input voltage levels of 18, 36, 54, 72, and 90V. The current through each component, the voltage across the inductor L2, the chamber temperature and that of each device in the LC tank circuit were measured and recorded. At each test temperature, the data was taken after a soak period of 30 minutes to allow the various devices to reach thermal equilibrium.

Results and Discussion

The current flow through each capacitor as a function of temperature and applied voltage is shown in Figure 2. It can be clearly seen that the current increase is nearly constant over the voltage range form 18V to 90V. The slight divergence of the curves with increasing voltage reflects the small variation in capacitance value and dissipation factor of the three devices tested. Although only one curve is shown for each capacitor as a function of the applied voltage, it should be pointed out that the data depicted in this figure is representative of the results obtained for the three capacitors at all test temperatures from 25°C to 200°C. Therefore, it can be concluded that the temperature had little effect on any of the capacitor properties, i.e. capacitance and dissipation factor, as the value of the current at a given voltage did not change regardless of the test temperature.

The total parallel impedance of the three capacitors was calculated using the measured values of capacitance (C) and dissipation factor (DF) at the extreme temperatures of 25°C and 200°C. In these calculations, the capacitor losses are modeled as the equivalent series resistance (ESR). The theoretical value of the total current flowing in the three capacitors was then calculated for the two temperatures and plotted in Figure 3 along with the experimental value as a function of temperature and applied voltage. The slight differences between the theoretical and experimental values can be attributed to parasitic resistances in the circuit, which are not accounted for, and to some instrumentation errors.

The temperature rise measured on the case of each capacitor is shown in Figure 4. A similar trend is observed for the three capacitors at all temperatures except when the applied voltage exceeds 36V. Because of its inherent higher dissipation factor, as compared to the other two, capacitor C3 exhibited a higher case temperature at potentials above 36V. It is important to note that the initial increase in the temperature profile of the 25°C family of curves occurs as a result of the power losses from the circuit under test heating the chamber above the 25°C test temperature.

The theoretical and experimental curves for the inductor current as a function of applied voltage and temperature are shown in Figure 5. Circuit wiring losses are apparent from the difference in the slope of the experimental curves from the theoretical curves and are slightly larger than the losses shown for the capacitors in Figure 3. This is consistent with the experimental setup where the total current in the parallel-connected capacitors, a branch circuit with three current paths, was required to flow in a single current path in the series-connected inductors. Although linearity of the curves is indicative of the inductance being constant over the range of the applied voltage, the apparent slight concavity of the curves, which occurs only at higher voltages, suggests an increase in the magnetic core losses due to increased flux density.

Voltage sharing between the inductors is shown in

Figure 6. The value of the voltage measured across L2 is plotted together with the calculated voltage for L1. Ideally the voltage should divide equally between the two similar devices. However, small variations in the inductance and resistance values of the components contribute to the difference in their voltages. Also, errors in the two probes used to measure V_{in} and V_{L2} would be reflected in the calculated value for V_{L1}. Once again, the temperature had no effect on the components as the data in Figure 6 represents results taken at all temperatures, i.e. 25°C to 200°C.

Figure 7 shows the inductor temperature as a function of applied voltage and chamber temperature. Increasing the applied voltage causes the inductor temperature to increase due to core and copper losses. Inductor L2 exhibits a slightly higher temperature than inductor L1 due to its somewhat greater series resistance. Similar to its capacitor counterpart, the 25°C family of curves does not follow the trend of the curves at the other temperatures. This is anticipated because the chamber temperature is being raised by the circuit internal heating when power is applied at room temperature.

Variation in the resonant frequency of the LC tank as a function of applied voltage and chamber temperature is shown in Figure 8. The frequency varies less than 400Hz out of 20kHz, or about 2%, over the test matrix. This indicates good stability in the inductor and capacitor property values. In general, offsetting variation in component values could maintain a stable resonant frequency.

Conclusions

Electrical evaluation of an LC parallel resonant circuit was performed as a function of temperature from 25°C to 200°C and applied voltage of up to 90V at 20kHz. Advanced state-of-the-art high temperature power components were used in the design of the circuit. These components, which were developed in-house, comprised film capacitors and powder core inductors. The circuit was characterized in terms of component voltage and current, temperature rise, and frequency of resonance. The preliminary results indicate that the resonant circuit showed good stability and operated successfully over the entire temperature range and at various applied voltages without any appreciable change in its characteristic behavior. More testing, however, is required at the component as well as at the circuit level in order to address issues such as reliability, efficiency, durability, etc., which represent major requirements for future space power systems.

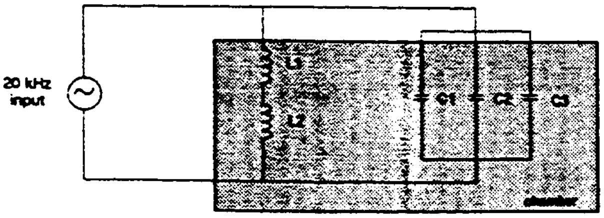

Figure 1. Schematic of the Resonant Circuit.

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References

[1] L. Mandelcorn, R. L. Miller and R. W. Lancaster "Twenty-four 200°C, 20kHz Filter Capacitors for NASA," Westinghouse Report 92-9TF3-NASCA-R1, NASA Contract No. NAS3-2669, January 7, 1993.

[2] 3M Company Proprietary Information.

Figure 2. Capacitor current versus applied voltage at different temperatures.

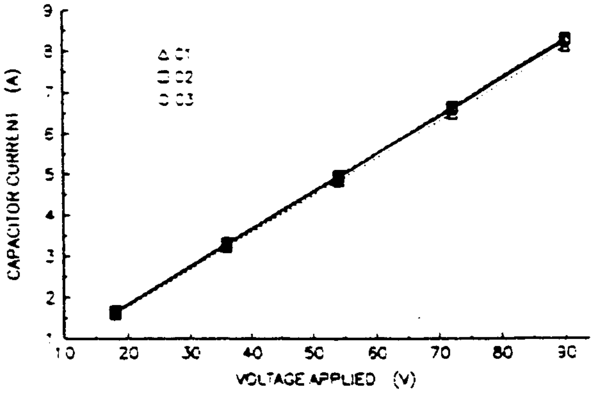


Figure 3. Total capacitor current as a function of applied voltage.

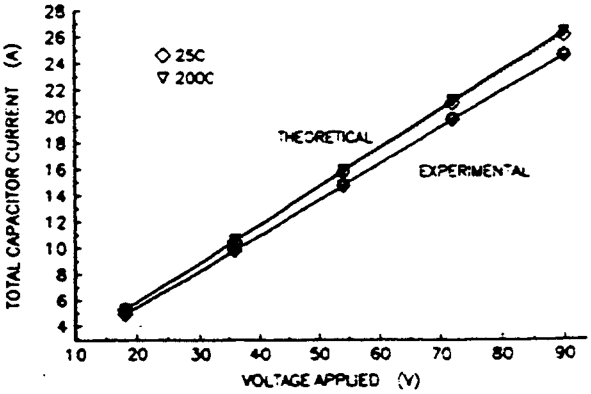


Figure 4. Rise in capacitor case temperature versus applied voltage at various test temperatures.

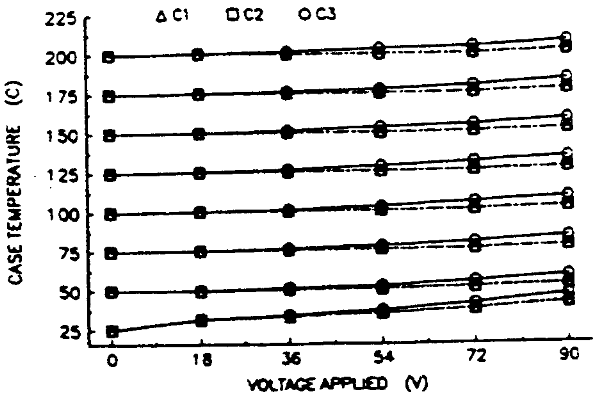


Figure 5. Inductor current as a function of applied voltage.

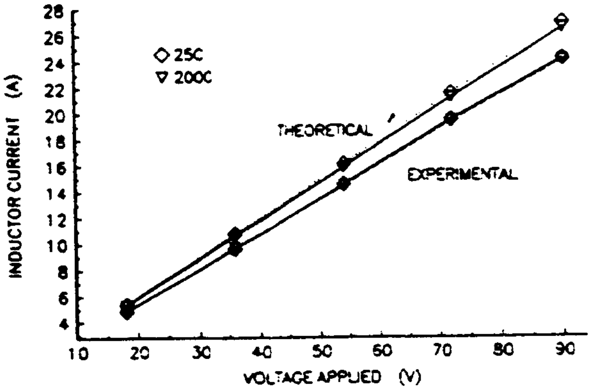


Figure 6. Inductor voltage versus input voltage.

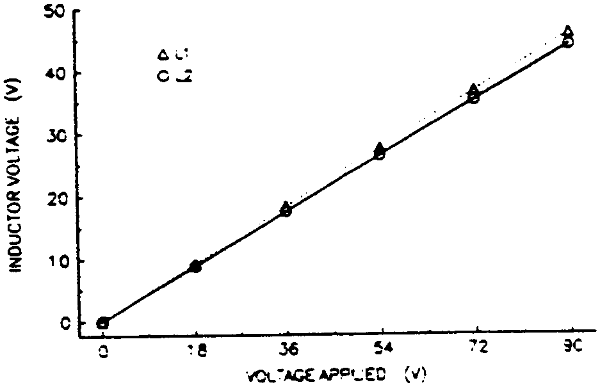


Figure 7. inductor temperature versus applied voltage at different temperatures.

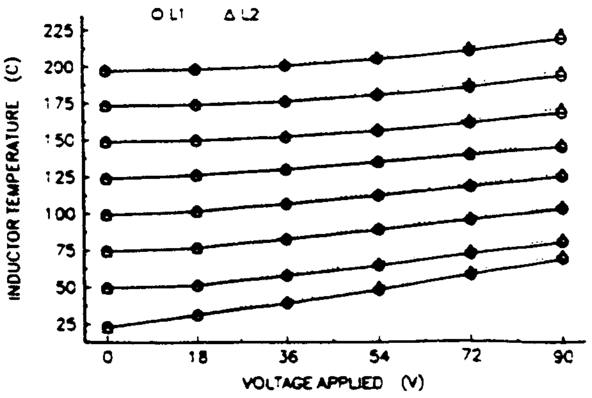
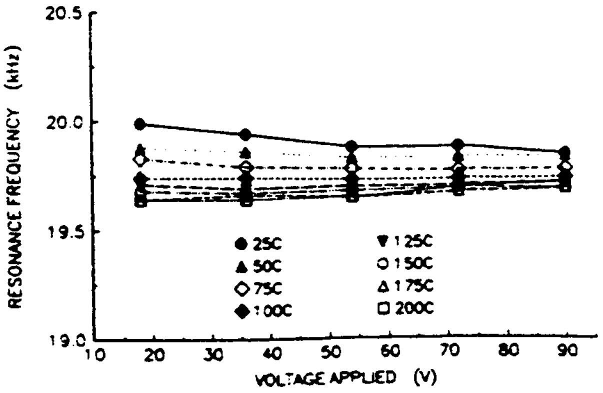


Figure 8. Circuit resonant frequency versus input voltage.



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