MODELING AND COMPUTER SIMULATION OF A

MICROWAVE-TO-DC ENERGY CONVERSION ELEMENT

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Abstract

A microwave-to-DC energy conversion element consisting of a dipole antenna, a low-pass filter, a Schottky barrier diode, and a DC filter has been modeled using a distributed modeling technique that includes skin-effect losses in transmission lines. Computer simulation has shown seventy percent conversion efficiency and has indicated that the diode generates significant power at higher harmonics due to a resonance effect.

Introduction

The efficient conversion of DC electrical energy into microwave energy has been studied by many people for a long period of time because of its many applications in communication systems, radar, and microwave heating. The conversion of microwave energy into DC electrical energy, however, has had little study until recently because its application is limited to microwave energy transmission systems. The recent interest in microwave energy transmission has been generated by proposals to use microwaves for the transmission of power generated on an orbiting satellite to the earth for terrestrial use.[1]

A number of systems have been used for the conversion of microwave energy into DC electrical energy [2 to 9]. The best of these systems was approximately seventy percent efficient.[9] This was a distributed system which used relatively independent elements with each element consisting of a dipole antenna, a low-pass microwave filter, a Schottky barrier diode, and a DC filter. This paper concerns the modeling and simulation of the operation of one of the elements in this system.

The Conversion System

The distributed system under consideration contains a large number of dipole elements which are placed in front of a reflecting plane in such a manner as to receive all of the microwave energy of the proper frequency which impinges upon the receiving antenna. Each of the dipole antennas contains its own microwave-to-DC converter.[9] Thus the interaction between the antennas, from a energy conversion point of view, is minimal.

A block diagram of an individual energy conversion element is shown in Fig. 1. The dipole antenna is used to receive the microwave energy. The energy, after passing through a low pass filter, is converted into DC energy by means of a rectifier. The low-pass filter is designed to allow the fundamental frequency signal to reach the rectifier but to prevent any higher harmonics generated by the rectification process from reaching the antenna. The output of the element contains a capacitor to filter RF the DC output. Thus the system receives the microwave energy using a dipole antenna and traps the energy between the input filter and the output capacitor allowing the energy to escape only as DC at the output or a reflected fundamental at the input. Proper arrangement of the dipole antenna elements in the receiving antenna reduces the reflected fundamental.

The Energy Conversion Element Model

Previous attempts to model a microwave-to-DC energy conversion element using a lumped element model have proven to be unsatisfactory because of the high harmonic content in the current and voltage waveforms.[9] Thus the model that was developed is a distributed one using series inductances and parallel capacitances to model transmission line segments. The individual line segments were chosen to be small enough so the model would still have significance at the fifteenth harmonic.

The dipole antenna element is modeled as a voltage source in series with a resistance, a capacitance, and a quarter wavelength of transmission line of appropriate impedance. The five-section low-pass input filter is also modeled using transmission line elements. The output low-pass filter is simply modeled as a large capacitance. The load was assumed to be a simple resistance.

A Schottky barrier diode model in parallel with a transmission line segment between the input filter and the DC output filter as shown in Figure 2. The diode model consists of an ideal junction characteristic, a variable junction capacitance and a variable series resistance that are functions of the junction depletion, fixed series resistances that are associated with the bonding wire, the semiconductor substrate, and the ohmic contact, a series inductance primarily derived from the bonding wire inductance, and a parallel case capacitance.

As can be seen in Fig. 2, the primary elements in the model are the 48 series inductances and the 47 parallel capacitances associated with the transmission line incorporated into the antenna model, the input filter model, the transmission line segment between the input filter and the load and the DC output filter. The different transmission line characteristic impedances are modeled by assigning different values to the appropriate inductances and capacitances with each inductor and capacitor used to model approximately three millimeters of transmission line.

The model shown in Fig. 2 is deficient in that the only lossy elements in the energy converter that are accounted for are those associated with the rectifying element. The transmission line sections of the element also have losses associated with their resistance and the skin effect. These were taken into account by adding the circuit shown in Fig. 3 in series with each of the 48 transmission line inductances. The values of the three elements in the circuit were adjusted to give a weighted minimum difference over the first fifteen harmonics between the losses calculated using the skin-effect equation and those calculated using the circuit. The resulting difference was on the order of four percent.

Thus, the expanded model not only takes into account the losses associated with the Schottky barrier diode but also the losses associated with the skin-effect at various frequencies.

Simulation of the Operation of the Energy Conversion Element

The currents and voltages in the above expanded model can be described by 146 first order differential equations and several nonlinear algebraic equations. A computer program was written to integrate the equations on a digital computer using a predictor-corrector method. The simulation was run with a fixed set of parameters for a sufficient period of time to achieve steady state operation. Some of the results of the simulation are shown in Figures 4 and 5.

Fig. 4 shows both the diode junction voltage and the external diode voltage as functions of time. Fig. 5 shows both the diode junction current and the diode lead current as functions of time. As can be seen, the voltage waveforms are not simple rectified sinusoids, but rather complicated functions containing many harmonics. In fact, the presence of a rather strong fourth harmonic is rather easily detected. A study of the lead and junction currents in Fig. 5 indicates that there is a strong resonance effect in the diode model.

As is shown in Fig. 6, the diode junction capacitance, lead inductance and case capacitance form a resonant loop. When the diode is reverse biased this loop rings, since it is very underdamped. With the diode turned off, the loop has a resonant frequency of about 11 GHz and a Q of about 30.

Under steady-state conditions, the simulation indicated an efficiency of slightly over seventy percent with about eighty percent of the power loss in the diode and the remaining twenty percent in the various transmission line sections. Thus, although most of the energy loss is in the diode, skin-effect losses in the transmission line sections of the converter contribute significantly to the reduction in efficiency.

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Conclusion

It has been shown that a microwave-to-DC energy conversion element can be modeled using a distributed modeling technique that includes skin-effect losses in transmission lines. A computer simulation using the model has shown an efficiency of seventy percent with most of the energy loss coming in the diode rectifier as expected. The simulation has also shown that there is a resonance effect in the Schottky barrier diode that tends to generate strong higher harmonics.

References

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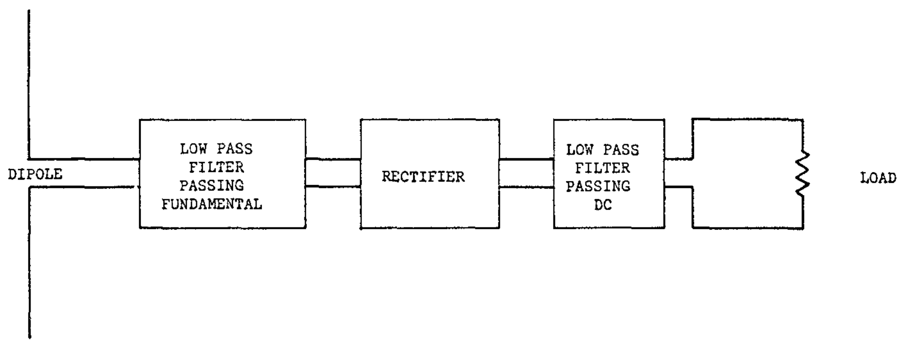

Figure 1. Dipole-filter-rectifier Element.

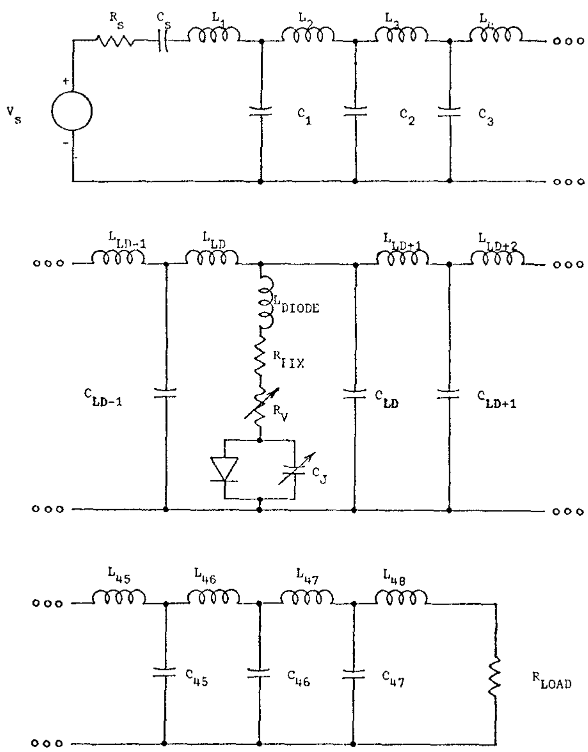

Figure 2. Complete Model for Rectifying Antenna Element

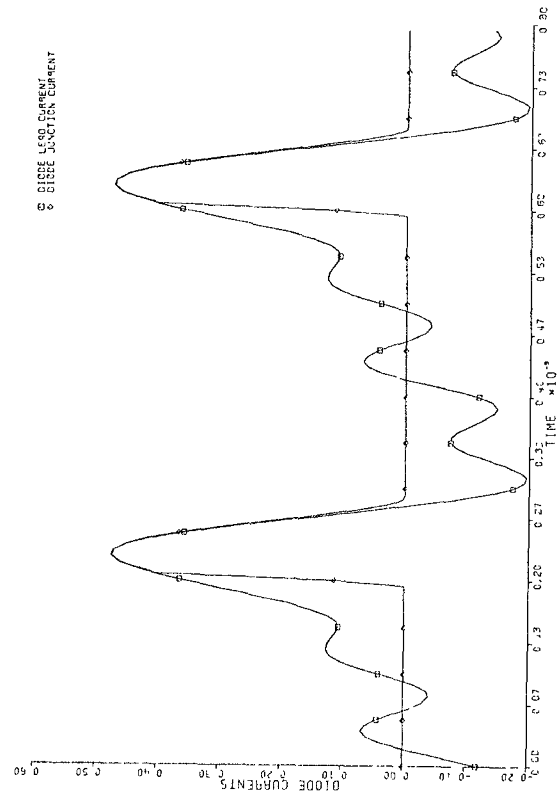

FIGURE 5 DIODE CURRENTS VERSUS TIME

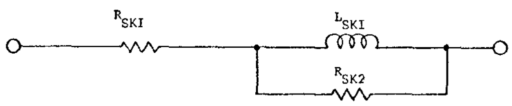

Figure 3. Circuit Model for the Skin Effect

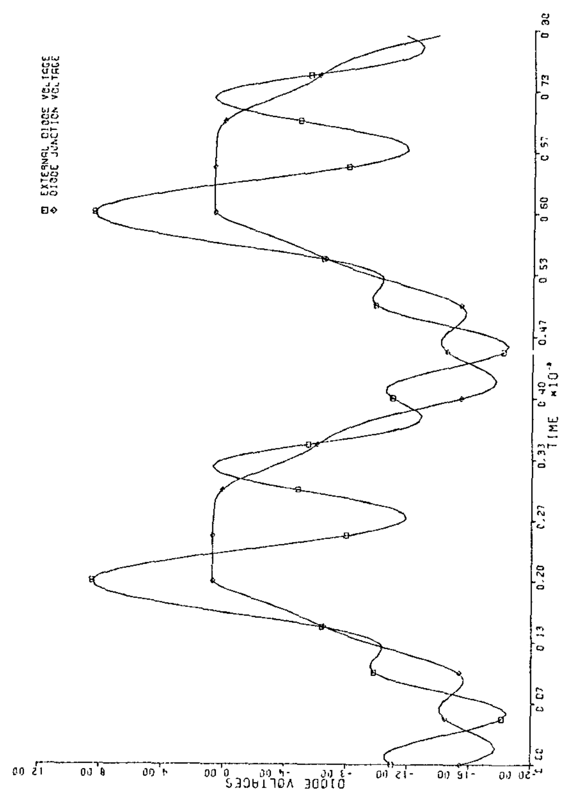

FIGURE 4. DIODE VOLTAGES VERSUS TIME

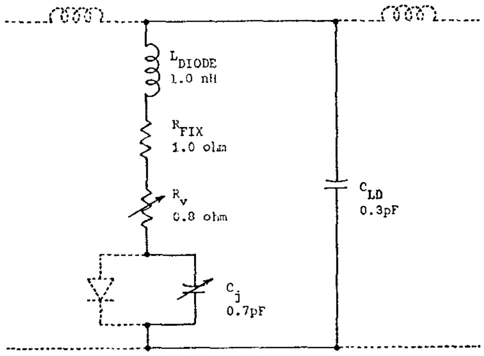

Figure 6. Diode Resonant Loop Under Reverse Bias