Piezoelectric Transformers for Space Applications

Alfredo Vázquez Carazo
Department of R&D Engineering, Face Electronics, LC
427 W. 35th Street, Norfolk, Virginia 23508, USA

ABSTRACT

There is a considerable excitement in the space community about the possibility of performing useful missions in space using vehicles that are much smaller in size than current spacecrafts. Lower cost and new type of missions made of this small satellite very attractive for future missions. Spacecraft in the mass range of 1 to 10 kilograms are often referred to as “nanosatellites”. However, the suite of useful missions for nanosatellite is limited by the dearth of space components of suitable scale. Present day nanosatellites are often drifting, uncontrolled packages of instrumentation of very limited capability. The vital subsystem functions of propulsion, power conversion and storage, attitude control, attitude sensing, data storage, command and data handling, and telemetry, tracking and control, are not well supported by these components availability of a number of small, low-cost nanosatellite components in these subsystem areas. This paper introduces the advances on applications based on piezoelectric transformers for nanosatellites.

INTRODUCTION

The field of satellite engineering is currently experiencing a radical transformation. Historically, this field has been driven by applications requiring the utmost in performance with little or no concern for cost or manufacturability [1]. These systems have been primarily built for military applications, where performance for specialized use can justify higher cost. The current transformation of the field involves a dramatic shift from defense applications to those driven by the commercial and consumer sector, with a drastic shift in focus from design for performance to design for manufacturability. This transformation also entails a shift from small production volumes to mass production for the commercial market, and from a focus on performance without regard to cost to a focus on minimum cost while maintaining acceptable performance.

Commercially speaking, three current trends are fueling interest in satellite systems: 1) Direct-to-the-home television and direct broadcasting; 2) Wireless hand-held mobile phones; and 3) Growth in the number of personal computers used by individuals across the globe. In order to address these trends, government agencies like NASA and Air Force, and commercial industry such as Iridium and Teledesic, believe that multiple satellite constellations are the future. Currently there are, at least, 14 distinct plans for satellite constellations (> 10 satellites flying in formation), for everything from cellular phones to high speed Internet. The main reason are: 1) higher performance by distributing functions to separate satellites; 2) reduced cost by increased manufacturing and distributing redundancy; 3) better upgradability for ever changing industries like communications and the internet.

This demand and trend in the satellite industry has motivated government agencies and civil entities to seek advanced technologies that will extend near-earth satellite capabilities. These improvements will not only conserve power, space, and weight resources, but also will meet the demands for cost reduction. The initiatives can be divided in two groups. The first involves,
alternative technologies now being considered to improve the existing satellite payloads. The major goal of this initiative is to reduce weight and save space while optimizing performance and reducing the cost of manufacturing full size satellites. The second development path, which has made progress in the past years, is the approach to smaller spacecraft, such as Micro and Nano Satellite. Both of these initiatives represent a huge opportunity for the use of highly integrated technologies such as piezoelectric transformers designed to replace the existing conventional magnetic transformers.

PIEZOELECTRIC TRANSFORMERS IN THE POWER DISTRIBUTION SYSTEM OF SATELLITE

Figure 1 shows the general schematic of a power distribution system for a satellite. The input power comes into the power module from a DC voltage bus that is generally driven from high efficiency Gallium Arsenide solar cells. Typically a DC/DC regulator is included to regulate the voltage of the main distribution bus. This bus distributes the input energy to the different systems of the satellite such as the storage system (charge of batteries to provide energy when the satellite operates without solar energy), the payloads (communication systems, detectors and sensing devices) and the propulsion. The voltage level in each of these units is in general different from the other and also different from the regulated bus. Consequently, modules to converter the voltage levels from low voltage to high voltage (step-up) or from high voltage to low voltage (step-down) are required. Conventionally, the use of heavy, bulky and low efficient magnetic transformers has been the selected solution for this conversion. But an alternative solution is available now. Under two-ongoing NASA SBIR Phase II research programs and one recently granted DOD SBIR Phase I, Face Electronics, LC [2.3] is the pioneer in applying piezoelectric transformers technology in many demanding areas for space applications. These projects are briefly introduced in this paper.

Figure 1. Power distribution system for a satellite
Piezoelectric transformer to replace the magnetic transformer used in TWTAs

Traveling wave tube amplifiers (TWTAs) are the principal elements of any public or private satellite payload. This type of amplifiers is essential for providing RF energy to carry the communications back to earth [5.6]. Two parts are commonly identified in TWTAs, the electron beam tube, or TWT, and the electronic power conditioner, or EPC. Due to the nature of TWT, EPC is required to supply a number of high voltage levels (in the multi-kilovolt range) to drive the cathode, the multistage depressed collector, and the anode voltage. To generate these voltages, a large and fairly complex magnetic high-voltage transformer enclosed in the EPC is conventionally used. The basic components in the energy conversion chain of a satellite communication payload including the magnetic transformer are shown in Figure 2 (left). An example of a typical TWTA payload configuration is shown in Figure 2 (right).

The electromagnetic transformer is the component of the TWT that has experienced less sophistication and remains the classical state-of-the-art magnetic technology [7,8]. For example, in open-air transformers (limited at lower voltages up to 10kV), this bulky, heavy, and magnetically noisy component represents about 10 to 20% of the total volume occupied by the EPC. The volume requirements can increase up to 50% of the total volume of the EPC module if large voltage epoxy-coated transformers are used. In addition, the magnetic transformer represents a large portion of the power supply mass contained within the case. Therefore, the case and other components must be shielded to protect components from the RF/EMI noise generated by the transformer, increasing size and weight of the final power module. As a result, magnetic transformers represent a significant portion of the payload volume and mass of the satellite or spacecraft TWTA.

Face Electronics proposal considers the use of piezoelectric transformer for replacing the high voltage magnetic transformer of the EPC. The starting point of this development is a new proposed modular design, “TAP-SONER”. This modular concept allows scaling up the performance of a single transformer. Furthermore, the modular design allows providing the different voltages and power levels required for the TWT. The same modular concept could be used for step-down applications requiring piezoelectric transformers. “TAP-SONER” is envisioned as the next step in expanding the application range of the PT technology to very high voltages and high power levels, such as those required for driving TWTs. The concept is based on adapting the Transoner basic product in a modular way that increases the power and voltage performance of the single unit.

Figure 3 (left) shows the basic approach to the “TAP-SONER” concept to be developed. The final outcome will be a significant reduction in size, weight and magnetic interferences. Figure 3 (right) shows the first demonstration built in the technology demonstration phase of the project.

Figure 2. (Left) Typical energy conversion in a satellite system from solar cells to TWTA payloads. (Right) Commercial TWTA payload configuration (courtesy of Boeing-Hughes).
Figure 3. (Left) “TAP-SONER” modular concept using Transoner technology applied to TWT. (Right) First prototype developed during the Technology demonstration phase.

This first prototype includes the elements driving four different modules of the “TAP-SONER” concept. Each module includes a piezoelectric transformer and all the requiring control components, thus forming a DC-DC converter. The DC input voltage from the 48V regulated bus voltage is converted into a high frequency switching signal to drive the input of the PT.

Advanced Propulsions Concepts using Piezoelectric Transformers for being incorporated in “Micro” and “Nano” satellites

One of the most promising propulsion techniques for small satellite is the Pulsed Plasma Thrusters (PPTs) [9,10]. PPTs have recently been proposed for primary propulsion of small spacecraft for orbit raising and life extension (attitude control, station-keeping, and primary propulsion) of low earth missions [11-13]. The PPT is a device in which electrical power is used to ablate, ionize, and electromagnetically accelerate atoms and molecules from a block of solid propellant material. A sample schematic of a conventional PPT system is shown in Figure 9 (left).

Due to the intrinsic properties of piezoelectric transformers for reaching very high voltage gains with small size, they become an interesting alternative for replacing the current components used in the thruster ignition system. This research program proposes to demonstrate a replacement technology for use as the conventional discharge initiation (DI) circuit of the Pulsed Plasma Thrusters (PPT) used for propulsion of spacecraft (Figure 9.b). The existing DI circuits performs the capacitive discharge through a high voltage magnetic transformer is large, heavy, un-reliable, dependent on spark-plug conditions, and magnetically noisy. Face proposes a new igniting concept using piezoelectric technology for spark generation without the need for a high voltage switch, a discharge capacitor or a coupling magnetic transformer. The final goal of this project is to develop and integrate this technology in small size spacecraft using PPT.

Figure 10 (left) illustrates the proposed design (“IGNIT-SONER”), which is capable of replacing conventional magnetic-capacitive based discharge initiation transformers, the capacitive element and the solid-state high voltage switch of the currently used DI circuit of a PPT. As envisioned, a piezoelectric ignition device electrically controlled with a low voltage will be used to generate the total amount of voltage and power required for each of the propellant modules.
This solution is very compact in design and will permit the complete elimination of the discharge initiation transformer as well as the discharge capacitor and the high voltage switch. Additionally, the solution is expected to be integrated in the spark plug of the thruster, thus reducing size and weight compared with the conventional solution. The solution will also eliminate electromagnetic interferences produced by currently used high voltage pulse magnetic transformers. The IGNIT-SONER discharge initiation concept is sketched in Figure 10 (right).

Some of the unique properties provided by this system are:

- It has inherent multi-strike capability to minimize misfire. A series of high voltage pulses may be selected from the control logic circuit as the firing strategy. These pulses may be applied, for instance, at an interval of 50-200 µs and constantly applied to the spark plug until it initiates a spark. At that point the secondary voltage decreases dramatically due to the change in the impedance of the plasma between the electrodes of the spark plug.
- It adaptively adjusts the amount of spark energy by controlling the number of pulses or the spark duration as the engine operation condition change thereby reducing plug wear.
- The alternating polarity of the spark current effectively promotes re-deposition of spark plug metal, resulting in improved plug durability. While the metal re-deposition does not offer a 100% recovery on the plug, it will extend the life of the spark plug and thus, extension of space missions’ life.
- The solution will have minimum EMI.
- It will be able to be integrated close to the combustion chamber and thus eliminating external components such as magnetic transformer and discharge capacitor, thus having compact size and lightweight.
- It is easily controllable with an external low voltage logic control circuit.
CONCLUSIONS

The field of satellite engineering is currently experiencing a radical transformation. In order to match the current demands on cost reduction in satellites multiple government and civil entities are taking several initiatives to reduce weight and save space while optimizing performance and reducing cost in the existing payloads in standard satellite as well as in the future generation of smallest satellite, such as Micro and Nano Satellite. Under two on-going SBIR research programs granted by NASA, Face Electronics has become the pioneer in applying piezoelectric transformer technology to spacecraft systems. A significant change in the way piezoelectric transformers could be used in spacecraft has been introduced in this paper. In addition, an overview of the current research programs on this field has been described, including:

- Improvement of the main payload of satellite communication systems, the Traveling Wave Tube, by replacing the conventional magnetic transformers with piezoelectric technology.
- Development of new integrated ignition systems for small satellite thrusters by using piezoelectric transformer technology. These new piezoelectrically controlled igniters will optimize the combustion efficiency while reducing the side of comparable systems based on magnetic-capacitive systems.

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