AIAA SPACE Forum
17-19 September 2018, Orlando, FL
2018 AIAA SPACE and Astronautics Forum and Exposition

10.2514/6.2018-5171

Check for updates

Design and Development of an Electrostatic Charge Generator (ECG) for Deployment of Drag-Wires of UWDES

Chaithra Krishnaraj[1]
Crucible of Research and Innovation, PES University, Bengaluru, Karnataka 560085 India

Sneha Raibagi[2]
Department of Electrical and Electronics, PES University, Bengaluru, Karnataka 560085 India

Shrikanta Aradhya C S[1] and Yashwanth Amara[1]
Crucible of Research and Innovation, PES University, Bengaluru, Karnataka 560085 India

Sharanabasaweshwara Asundi[3]
Department of Aerospace Science Engineering, Tuskegee University, Tuskegee, AL 36088, USA

and

Srivatsa S K[4]
Department of Basic Sciences, Atria Institute of Technology, Bengaluru, Karnataka 560024 India

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

The design and development of an Electrostatic Charge Generator (ECG) presented in this article is a mechanism for deployment of drag-wires of Ultra-thin Wires Drag Enhancement System (UWDES). The UWDES is a hybrid de-orbiting system being developed for nano/micro-satellites in low/medium altitude Earth orbits. The ECG on-board the UWDES accomplishes electrostatic charging of drag wires on command. Here, it is preferred to charge the drag wires positively as altitudes of target spacecraft, which lie in the inner Van Allen radiation belt, are dominant of positive charges. For this purpose, the spacecraft bus voltage is stepped up to high potentials of 10 kV – 15 kV DC. This is supplied to an anode-cathode setup constituting the charge transfer mechanism, which works on the principle of field electron emission, to remove electrons from the wires, thereby charging it positively. The emitted electrons are collected and supplied to the spacecraft ground. The ECG and its related circuitry are designed for implementation on a circuit board, which will be housed within a hermetically sealed case of the UWDES. The design, simulation, construction and testing of ECG for experimental validation is reported here. We find that the high voltage generation system consisting of a DC – DC voltage multiplier circuit with AC link provides a robust method to achieve the desired high potentials. A grid like structure for anode and needle like structure for cathode is designed for the field emission to facilitate charge transfer. Alongside, the regulation and distribution will be taken care by an on-board electron gun and the spacecraft ground.

[1] Research Associates, Crucible of Research and Innovation, PES University, Bengaluru, Karnataka 560085
[2] Undergraduate Student, Department of Electrical and Electronics, PES University, Bengaluru, Karnataka 560085
[3] Assistant Professor, Aerospace Science Engineering, Tuskegee University, Tuskegee, AL 36088 AIAA Professional Member
[4] Professor and Head, Department of Basic Sciences, Atria Institute of Technology, Bengaluru, Karnataka 560024

Copyright © 2018 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

Nomenclature

ECG – Electrostatic Charge Generator
UWDES – Ultra-thin Wires Drag Enhancement System
TE – Thermionic Emission
FE – Field Emission
HVG – High Voltage Generator
EAED – Effective Area Experiencing Drag
VDG – Van De Graff generator
I – output current of the multiplier
N – Number of stages (one capacitor and one diode constitute one stage).
C – Capacitance of the Capacitor
f – Frequency of Operation

I. Introduction and Background

To mitigate the issue of space debris,[1,2] pico/nano/micro-satellites (PNMSats) have adopted largely passive deorbiting methods, which include drag sails/gossamers, electrodynamic tethers, etc. The complexity of deployment mechanism in comparison to the increase in effective area experiencing drag (EAED) has limited the use of these methods. These limitations have motivated the design of the novel Ultra-thin Wires Drag Enhancement System (UWDES).[3,4] The UWDES (Fig. 1) is envisioned for deorbiting nano/micro-satellites in low/medium-altitude Earth orbits. It employs numerous ultra-thin wires electrostatically deployed in the form of a three dimensional (3D) web-like structure to enhance the EAED of the spacecraft as shown in the Fig. 1. The novelty and a significant technological advancement of the proposed system[3,4] is that it utilizes both aerodynamic and coulomb drag to enhance drag of the host spacecraft and expedite its orbital decay. An electrostatic charging mechanism/system to deploy and regulate a tuft of ultra-thin wires to increase the host spacecraft's EAED is part of the novel design of UWDES. Unlike conventional deployment mechanisms, which use a host of moving mechanical joints/motors, the ultra-thin wires in the UWDES are deployed by charging them electrostatically. Due to the mutual electrostatic repulsion, the wires unwind and deploy into a 3D web-like structure. The mechanism/system, referred to as the Electrostatic Charge Generator (ECG), is further elaborated in this article.

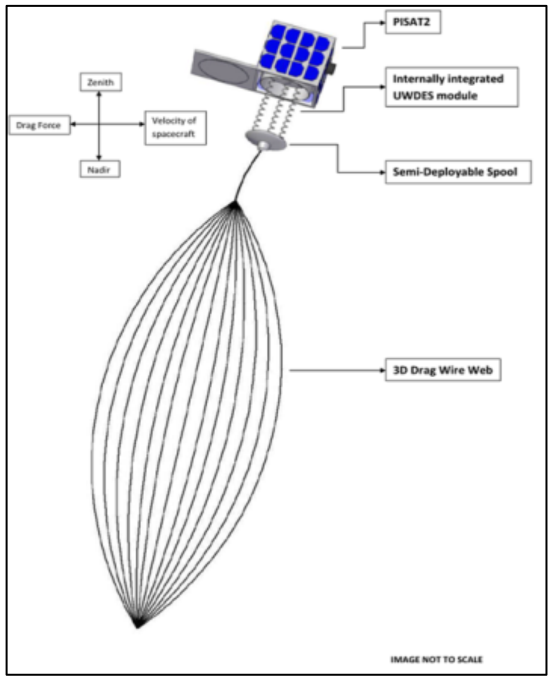


Figure 1. UWDES Concept Schematic

II. Evolution of the Electrostatic Charge Generator

Several experiments to evaluate performance of various materials and functioning of the concept of ECG were conducted. In one such experiment, a Van de Graff generator (VDG), shown in Fig. 2(a), was used to charge the tuft of thin polymer strips tied at both ends. Upon powering the VDG, the wires moved away from each other to form a web structure as in figure 2 (c). This experiment was done to simulate the payload module, in which an electrical contact would be used to interface the ECG and the payload container where the drag wires would be stowed. This was a conclusive proof of the proposed concept. Further, these experiments were repeated with different materials for wires and experimental setups to test suitability for space applications. It was realized that a miniature version of VDG is untenable for ECG on board a satellite. Several other high voltage generation designs, such as fly back transformer (Fig. 2(b)), cathode ray tubes, super capacitors, ion generators, voltage boosters and multipliers, were experimented with the focus of stepping up the DC voltage (10 – 20 kV) from a typical satellite bus voltage (3V- 9 V DC) to power an electron emission mechanism for charging the drag wires.

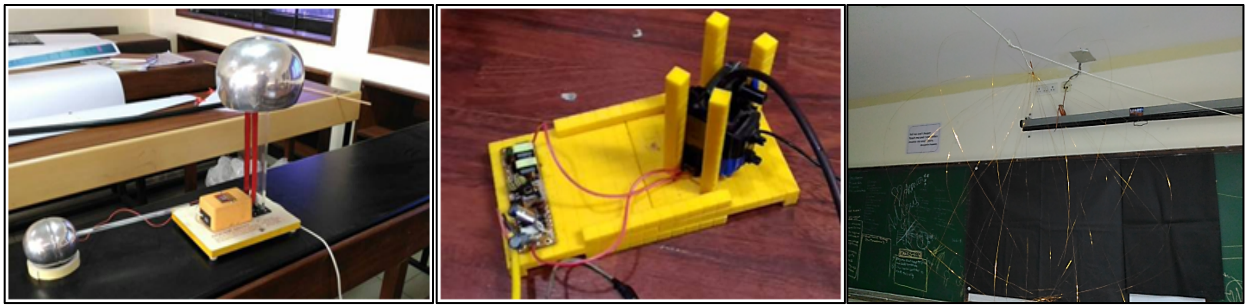


Figure 2. (a)Van de Graff Generator (b) Flyback Transformer and (c) 3D Wire web structure

One of the designs for an ECG system with an inverter and a voltage multiplier was designed and implemented on a PCB board for high voltage generation. This approach helped, on the one hand, achieve the required high voltages and on the other hand provided the necessary miniaturization. Among the many methods of charge transfer, the field electron emission proved to be an effective way to transfer charges in space environment. For this purpose, an anode-cathode setup is adopted, and analysis/testing is done accordingly. The details of the design, development and testing is described in the following sections.

III. Design and Working Principle of the ECG System

A functional block diagram of the ECG implementation on-board an active-charged variant of UWDES is shown in Fig. 3. Broadly, the ECG can be considered to consist of high voltage generator (HVG), charge transfer (anode-cathode) and charge regulation mechanisms (collector/sink, spacecraft ground and electron gun). When a command is issued for the activation of ECG onboard the UWDES, the bus voltage is stepped up to high potentials of ~ 10 kV – 20 kV DC by the HVG. This high positive DC voltage is used to facilitate field electron emission,[5] which removes electrons from the wires hence charging it positively. Here, it is preferred to positively polarize the drag wires as the spacecraft orbits targeted, which lie in the inner Van Allen belt, are dominant of positive charges.

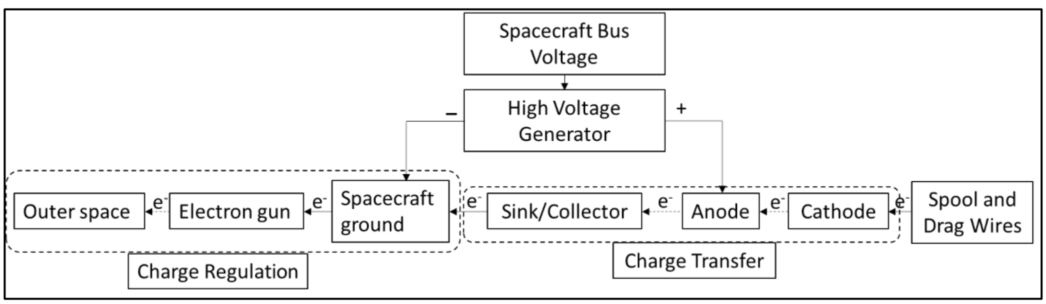


Figure 3. Functional Block Diagram of ECG - Working Principle

A. High Voltage Generator

An electric schematic of the HVG is shown in Fig. 4. The approach adopted for stepping up the voltage is a DC-AC-DC method. The working principle includes conversion of an input voltage of 5V DC into approximately 1000V AC using an inverter, which is then converted into a few kV DC using voltage multiplier circuit. The merit of this circuit is the production of high voltage at very low currents. The following subsystems are the main constituents of the HVG – (i) DC to AC inverter and (ii) multiplier circuit.

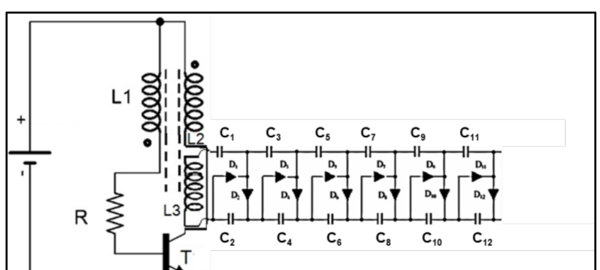


Figure 4. HVG Electric Schematic

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

1) DC to AC Inverter

The DC to AC inverter works on the concept of Joule Thief.[6] It is a self-oscillating voltage booster circuit. The power source is derived from the satellite bus voltage (3V-9V DC). The DC to AC inverter mainly consists of a high frequency switching transistor, a resistor, and a transformer /inductor. There are three paths through which the current flows through the circuit. Initially, the current flows through the resistor, the primary coil of the transformer and enters the transistor through the base-emitter channel. Current through the base initiates the collector current, which flows through the secondary coil of the transformer. This current induces a positive voltage in the primary coil. The process repeats in a feedback loop until the base of the transistor is saturated and the collector-emitter channel is fully open.

Since large current flows through the secondary coil, it possesses very high energy. After a while, the current through the secondary coil becomes constant, due to which no more current is induced in the primary coil. This gradually reduces current flow through the base of the transistor. The process repeats in a feedback loop until the transistor is completely turned off. Now that the transistor is turned off, the current will flow through the load with the transfer of the large amount of energy stored in the secondary coil leading to a spike up in the output voltage of the DC-AC inverter. Joule thief is incorporated for our circuit where a resistor of 270Ω, a high switching transistor and a high frequency step-up transformer are used. This is then cascaded with a voltage multiplier circuit, which acts as a load for the invertor circuit. The DC-AC inverter[7, 8] uses a high frequency ferrite core transformer with very high turn's ratio. It is a step up transformer with two phase primary and one phase secondary transformer. (Since it is a high frequency transformer, the transistor must also be working with the same frequency. If the frequency is insufficient, loading occurs). The main purposes of using a high frequency transformer are:

- In a transformer, the flux is directly proportional to the current. As the frequency increases, the current reduces, which in turn reduces the flux. As a result, the size of the core reduces, which addresses the size constraint. As a matter of fact, such transformers are frequently found in many household devices
- As the frequency increases, the capacitance of the capacitor can be reduced. Since it is difficult to get a high value capacitor for a very high voltage rating, using high frequency proves advantageous.

2) Voltage Multiplier Circuit

A simple Cockcroft Walton voltage multiplier circuit[7] is adopted for high voltage generation. It is a multistage voltage multiplier with a ladder of diodes, capacitors and is used to convert AC signal into pulsed DC in a multiplicative fashion (a simple voltage doubler concept implemented in several stages) producing high voltages at low currents. In general, the output of the Cockcroft circuit is $2 \times V_{max} \times N$, where N is the number of stages of the multiplier. The multiplier in ECG design is a 6-stage multiplier. The factors like number of stages and frequency of the input signal highly influence the ripples in the output DC. Hence, care is taken in designing the multiplier so as to reduce the ripple factor.

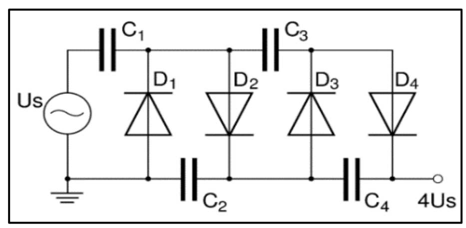


Figure 5. A 2-Stage Voltage Multiplier Circuit

The working principle adopted for the multiplier[8] is the voltage doubler phenomenon (Fig. 5). During the negative half cycle of the input, the capacitor C_1 charges through the diode D_1 to V_{max}. During the positive half cycle, the V_{max} gets arithmetically added to the potential of C_1 and C_2 gets charged through D_2 to $2V_{max}$. In the next negative cycle, the C_3 charges to $2V_{max}$ through D_3. During the next positive cycle, the voltage adds up to the capacity of the C_3 and C_4 charges to $4V_{max}$.

B. Charge Transfer Mechanism

The charge transfer mechanism broadly consists of two electrodes, cathode and anode, and a sink/collector as shown in Fig. 3. The cathode is a bunch of needle like structures, which is connected to the spool on which the drag wires are attached and stowed. The needle structures tend to lose electrons easily because of concentrated electric field and surface charge density. The anode is a metallic grid, which is supplied with positive high voltage DC from the HVG. This produces a positive electric field which is strong enough to remove/emit electrons out of the cathode material and accelerate them towards the anode. Due to the deficiency of electrons, the cathode and hence the spool and the wires are positively charged. The electrons accelerated towards the anode are collected on the collector/ sink, which is a metallic structure connected to the spacecraft ground. These electrons are then shot out to space using an electron gun to avoid the saturation of spacecraft ground with electrons.

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

IV. Design Specifications

A. High Voltage Generation

1) Frequency of the input signal

In order to build a voltage multiplier circuit[9] of high performance, it is required to have a low percentage of ripple in the DC output. Since the ripple voltage highly depends on the frequency of the input signal, it is required to set an optimum frequency for the circuit. According to the ripple voltage equation,

$$V_{rip} = \frac{I\left(N^2 + \frac{N}{2}\right)}{8fC}$$

it is clear that for a fixed capacitance (C) and number of stages (N), V_{rip} is inversely proportional to the frequency (*f*). For I = 1µA, N=12 and C=510pF, Table 1 shows the reduction in ripple with increasing frequency. The ECG system is designed to operate at a frequency of 22 kHz. Table 1 also shows the relation between ripple voltage and the frequency of operation.

Table 1: Reduction in Ripple with Increasing Frequency

Frequency(kHz)	Ripple Voltage(V)	Ripple Percentage (%)
0.1	367.8	6.13
0.5	73.8	1.23
1	36.6	0.61
10	3.6	0.06
22	1.8	0.03

2) Capacitor selection

The capacitance of the capacitor is inversely proportional to frequency of the input signal. Since the frequency used is very high, a low capacitance will serve the purpose. The output of the multiplier circuit is given by the equation,[10]

$$N \times V_{max} = 10kV$$

$$V_{max} = 0.833kV$$

$$N = \sqrt{\frac{V_{max} \times f \times C}{I}}$$

$$C = \frac{N \times 2I}{V_{max} \times f} = \frac{6 \times 2 \times 10^{-6}}{0.833 \times 10^3 \times 22 \times 10^3}$$

$$C \sim 10^{-12}\ F$$

It is clear from the above equation that the capacitance to be chosen must be in the pico-farad range with a high voltage rating. Therefore, capacitors of 510pF capacitance with 15kV rating are considered.

3) Diode selection

Peak inverse voltage for all the diodes in a multiplier circuit must be at least

$$2V_{max} = 2 \times 0.833kV = 1.66kV$$

Output of transformer obtained:

$$V_{max} = 1.414kV$$

$$2V_{max} = 2.828kV$$

Therefore, diodes must be rated for 2kV and above. Since we are dealing with high frequency input signal, it is necessary for the diode to have low reverse recovery time. Thus, UF4007/BY448/GP02-40 is used for this circuit, which almost met the specification requirements.

4) Transistor selection

As it is clear that the circuit works on a high frequency, a high frequency switching transistor (preferably NPN Si transistor), TIP41C is chosen.

B. Charge Transfer Setup

Electrons of the neutral drag wires are removed in order to charge it positively. Thermionic electron emission (TE) and field electron emission (FE) are two types of charge transfer processes. As TE involves heating of the electrode which is directly connected to the wires, containing the heat from leaking to other systems and wires is a challenge. Also implementation of a TE based system is more complex because it has more parts and electric circuits compared to that of FE based system. Hence, the FE system suits best for the ECG[11].

V. Design Simulation and Implementation

The circuit is simulated using the Multisim software. The inverter and the multiplier were simulated separately. Fig. 6 shows the simulated schematic of the 6 stage multiplier of HVG. The DC-AC inverter circuit is given an input of 5V DC and an output of 1.48kV is obtained at the secondary of the transformer. The multiplier is given an input of 900Vrms at 22 kHz AC voltage. Initially, an output of 5.467kV is obtained in the simulation and did not match the theoretical value of $12V_p$. The limitation was the use of 1N4007 diode in the multiplier circuit which has a low recovery time and low voltage rating (1kV). But the simulation proved that the circuit works. Later, UF4007 diode with high recovery time was used for rigging up the breadboard circuit, which gave the expected results. The Multisim software was short of components like UF4007 diodes which were necessary to obtain correct results.

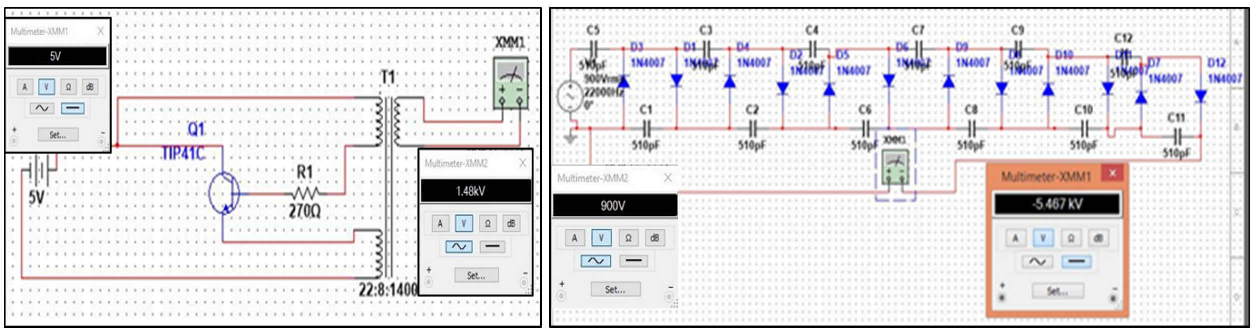


Figure 6. (a) DC-AC Inverter and (b) Voltage Multiplier of HVG

After validating the circuit's performance on the bread board, the same was designed and fabrication of the circuit on a PCB board was done. Special care was taken during the placement of the components and selecting the connectors because of the high voltages involved. Figure 7 shows the fabricated PCB for HVG.

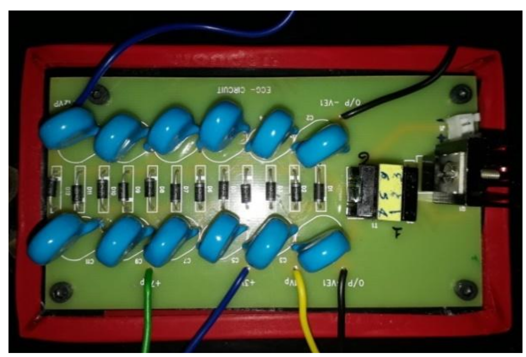


Figure 7. Fabricated HVG PCB Board

Since the output voltage is very high, it required special high voltage measuring devices for the measurements. In regard to this, measurements were done in two ways: 1) Using an AC-DC high voltage probe (Fig. 8(a)) connected to the output terminals of HVG. Parameters such as voltage, current and frequency were measured. 2) Using a sphere gap setup (Fig. 8(b)). The spark length and the corresponding voltage were measured for various input voltages. The stage by stage results are discussed in detail in the next section.

With respect to charge transfer a setup including iron nails as cathode and a honeycomb structure made out of aluminum as anode was done. The high voltage DC was generated using fly back transformer. This setup performed as expected and served as the proof of concept. As the system was bulky and power consuming, this is not suitable for space applications. The latest design includes microns thick carbon fibers as cathode[12] and a grid of aluminum as anode. This is placed inside a container which acts as the collector. This achieved the required performance with much needed compactness[13] and low power consumption essential for space applications.

VI. Experiments, Results and Analysis

Various experiments were conducted with the fabricated HVG PCB board and the following analyses were made. Table 2 and 3 show the analysis performed on the transformer of the inverter. The results thus obtained demonstrate that the chosen transformer best serves the purpose of voltage boosting and matches the required specifications for HVG.

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

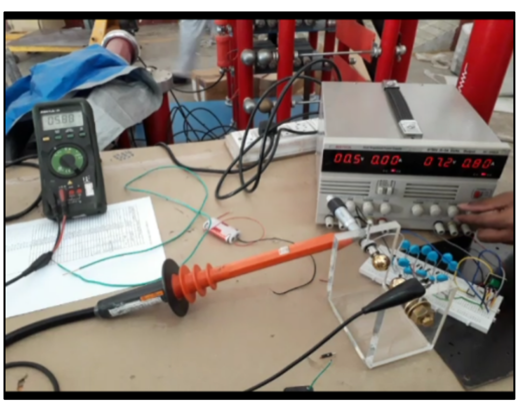
Table 2: Inductance and Resistance Values for Transformer Windings.

Sl.no	Component	Inductance	DC Resistance	AC Resistance
1	Transformer winding L1	391µH	2.1Ω	2.2Ω
2	Transformer winding L2	22µH	0.4Ω	0.93Ω
3	Transformer winding L3	752µH	220Ω	508Ω

Table 3: Transformer Specifications with no. of Turns in Primary and Secondary Windings.

Sl.no	Parameter	Value
1	Frequency of operation	22kHz
2	*Primary Winding L1:*	
	Input Voltage	16.2V AC
	Input Current	18.2mA
	Impedance	(2.1+24.567j) Ω
	No. of turns	22
3	*Primary Winding L2:*	
	Input Voltage	3.28V AC
	Input Current	140mA
	Impedance	(0.4+1.328j) Ω
	No. of turns	8
4	*Secondary Winding L3:*	
	Output Voltage	1280V AC
	Output Current	15µA
	Impedance	(220+47249j) Ω
	No. of turns	1400
5	Efficiency	94-96%

With a supply of 3.08V DC to the inverter circuit, output obtained was 1280 V_{rms} AC at 21.922 kHz. This is stepped up to a sufficiently high voltage (few kilo volts) using the 6-stage multiplier. Two methods of measurements (Fig. 8(a) and (b)) are preferred – using high voltage AC-DC probe (rated to measure -30kV to +30kV) and a sphere gap apparatus (two brass spheres of 50mm diameter each). Specific temperature and pressure conditions decide the high voltage output. Hence, at pressure = 685.78mmHg and temperature = 28^0C, we obtained the measurements. The same is graphically represented in Fig. 9.



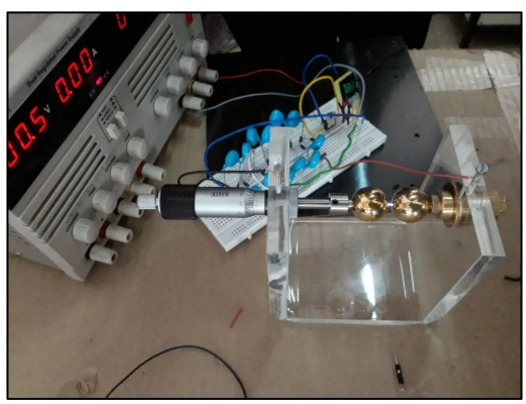


Figure 8. (a) Measurement using AC-DC probe and (b) Sphere Gap Apparatus

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

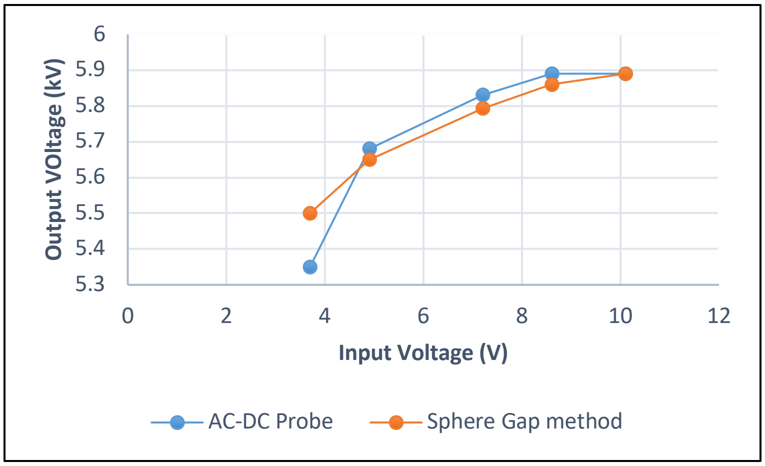


Figure 9. Output Voltages measured in two ways Against the Input DC Voltage

* From standard table of measurement for sphere gap method, 1.5mm = 5.50kV at 28^{0}C.

From the above results, it is shown that the maximum output obtained is 6kV DC from the HVG. Further increase in the output voltage can be achieved either by increasing the number of multiplier stages or by using high voltage rated diodes for the multiplier circuit.The output is measured using an oscilloscope and waveforms are as shown below. HVG is powered on with an input voltage of 3.36V DC voltage from a DC power supply. A 100x oscilloscope probe rated up to 2.5kV, is used to measure the output of the transformer on an oscilloscope. Fig. 11(a) and 11(b) depict the input to the primary winding L_1 and L_2 of the high frequency transformer, respectively. RMS voltage obtained is 16.2V at 19.76 kHz for winding L_1 and 3.28V at 21.88 kHz for winding L_2. The oscillating signal is generated by the switching action of the transistor in the inverter.

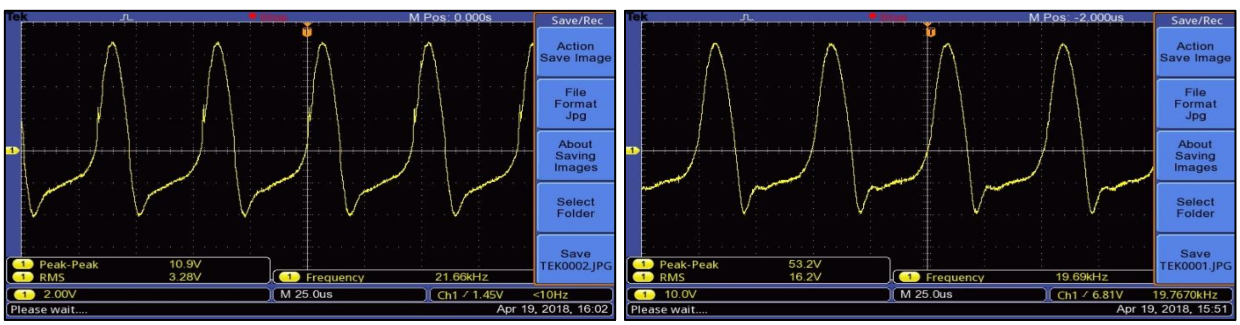


Figure 10. (a) Input Voltage for Primary Winding L_1 and (b) L_2

This verifies that the operating frequency is approximately 22 kHz. Due to change in current flowing through the primary winding, L_2 produces a varying magnetic field which induces current in the primary winding L_1. This cycle continues until the transistor saturates. Figure 12 shows high frequency oscillating AC output signal of the secondary winding L_3. Output voltage is 600 – 900V AC at a frequency of 21.88 kHz when the multiplier is cascaded as a load to the transformer. It is evident from the graph that the distortion in the pulsating signal is very less which accounts for an efficient transformer action as part of a self-oscillating voltage booster.

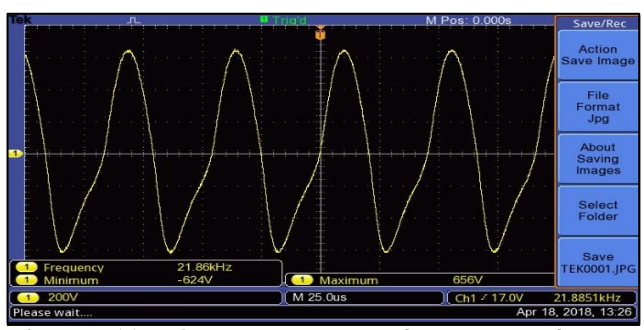


Figure 11. Output Voltage from Transformer Winding L_3

Figure 12 shows the current through the collector of the transistor and the primary winding L_2 of the transformer. The spikes are due to the high frequency switching action of the inverter resulting from the mutual induction between primary winding L_1 and L_2 in the corresponding positive and negative half cycles. The sine wave indicates the switching between the base-emitter and collector-emitter channels of the transistor. Figure 13 indicates the

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171

voltages corresponding to the collector-emitter and base-emitter channels of the TIP41C transistor. The two waveforms are the result of the switching action leading to the generation of high frequency oscillating pulses. This switching action accounts for the mutual induction between primary windings L_1 and L_2.

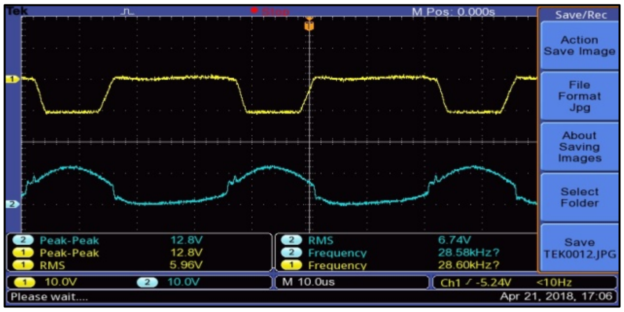


Figure 12. Current through the collector and primary winding L_2 is depicted.

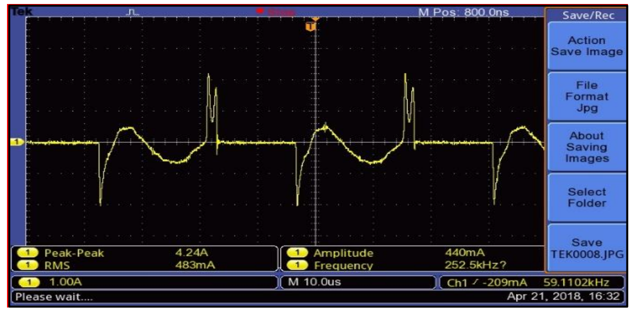


Figure 13. The measured collector-emitter voltage (yellow) and base-emitter voltage (blue) showing the generation of high frequency oscillating pulses.

With regards to the charge transfer, experiments were conducted using the latest design, i.e. carbon fibers as cathode and a grid of aluminum as anode with the high positive DC voltage from the HVG. Initially the set-up was enclosed in a metallic spherical container,[14] but the compactness and high potential, was causing arching and corona discharge. This was undesirable as the wires won't get charged. Later the metallic container was replaced by a plastic container which is an insulator; this prevented the arching and corona discharge. The tuft of wires was charged and the 3D web structure was formed. The amount of charging depends on the value of DC potential and the environment factors like humidity and temperature. More the humidity, lesser the charging. The experiments will be conducted in vacuum condition for more accurate results.

VII. Conclusion and Future Work

The threat of space debris is real and serious. It can potentially thwart all future space explorations through satellite launches and render the space unusable. Critical space based services and capabilities like navigation and weather forecast will be crippled. Space debris mitigation is the long term solution for the sustainable use of space. A reliable and effective satellite deorbiting system like UWDES will be of high value to the international space community. The ECG being the heart of UWDES plays a critical role in deciding the configuration and orientation of the wire web structure and hence the EAED of the spacecraft. The proposed electrostatic deployment mechanism was conceived as part of a course in Satellite Design conducted by Dr. Sharanabasaweshwara Asundi (Author) at PES University, Bengaluru, India, which involved brainstorming students to come up with a novel payload idea.[15]

The requisite design and development of the ECG has been done and we have realized the same on a PCB that provides the necessary high voltage (~10 – 20 kV DC). This high voltage was achieved by stepping up the on-board satellite bus voltage (~3 – 10 V DC) using a DC-AC-DC circuit. The functioning of the circuit and development of the high voltages were measured using high voltage DC probes and sphere – gap methods. Both the approaches provided agreeable results as shown in the Fig. 10.

This idea/concept of deployment in a future pilot launch is being considered; experiments are being conducted to realize an engineering design model of the ECG. Further simulation of operation of ECG circuit to improve its electrical performance has been taken up. Testing in space environment conditions are critical for successful deployment and these tests are being planned to be performed in thermos-vacuum chamber. Simulation and mathematical modeling in this regard is being carried out and multitude of software like 42, COMSOL Multiphysics, VSim, etc., are being explored. Charge regulation and distribution has to be next tested to complete the overall functionality of ECG.

UWDES is proposed to fly as primary payload on the second student satellite of PES University called PISAT-2. This technology demonstration mission will validate the use of ECG as a deployment mechanism and the analysis of its performance can help improve the system and make it reliable. Due to the virtue of charged 3D wire web structure, UWDES can be used for atmospheric/ionospheric studies also. Here the tuft of wires can act as a sensing probe and enable study of charge distribution and its density in the ionosphere. ECG is envisaged to play an important and substantial role in this application.

References

[1] Mark Gracia, "Orbital Debris", https://www.nasa.gov/mission_pages/station/news/orbital_debris.html.

[2] Luca Rossettini, "Op-ed | Space Debris: Prevention, Remediation or Mitigation?" https://spacenews.com/op-ed-space-debris-prevention-remediation-or-mitigation/

[3] S. Asundi, A. Manjunath, V. Ravi, C. Krishnaraj, N. Gattu, Y. Amara, V. Agrawal, "Ultra-thin wires as drag-enhancing system, method of deployment, and use", PCT/IN2018/050094, filed 11 Feb. 2018.

[4] S. Asundi, V. Ravi, C. Krishnaraj et al., "A Technology Demonstration Mission to Validate On-orbit the Utility of Charged Ultra-thin Wires Drag Enhancement System", Proceedings of AIAA SPACE '17 Forum, Orlando, FL, September 2017 doi: https://doi.org/10.2514/6.2017-5117

[5] Shaik, A., "Electric field electron emission", http://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/electron-emission/electricfieldelectronemission.html

[6] Jason Poel Smith, "Joule Thief Battery Charger: Bring Back the "Dead", https://makezine.com/projects/joule-thief-battery-charger/

[7] M. Rashid, *Power electronics handbook.* 3rd ed, Burlington, MA: Butterworth-Heinemann, c2011.

[8] R. W. Erickson and D. Maksimovic, *Fundamentals of power electronics*, Springer, New York, 2001

[9] Nikhil M. Waghamare, Rahul P. Argelwar, "High Voltage Generation by using Cockcroft-Walton Multiplier", International Journal of Science, Engineering and Technology Research (IJSETR), Vol. 4, Issue 2, February 2015.

[10] VMI Multiplier Test Capabilities, http://www.voltagemultipliers.com/html/multipliers.html

[11] Okawa, Y., Kitamura, S., Satomi Kawamoto, Iseki, Y., Hashimoto, K., & Noda, E. (2007), "An experimental study on carbon nanotube cathodes for electrodynamic tether propulsion", *Acta Astronautica*, 61(11-12), 989-994. doi: 10.1016/j.actaastro.2006.12.017

[12] Tang, W., Shiffler, D., Harris, J., Jensen, K., Golby, K., LaCour, M., & Knowles, T. (2016). "Field emission characteristics of a small number of carbon fiber emitters". *AIP Advances*, 6(9), 095007. doi: 10.1063/1.4962921

[13] Liu, H., Kato, S., & Saito, Y. (2009). "Effect of Cathode–Anode Distance on Field Emission Properties for Carbon Nanotube Film Emitters". *Japanese Journal of Applied Physics*, 48(1), 015007. doi: 10.1143/jjap.48.015007

[14] Seymour, L., "Electric Field Inside and Outside of a Sphere". https://ucscphysicsdemo.wordpress.com/physics-5c6c-demos/electric-field-inside-and-outside-of-a-sphere/

[15] Asundi, S., and Rao, D., "A Systems Pedagogy and a Novel Brainstorming Approach to Initiate Pico/Nano/Micro-Satellite (PNMSat) Engineering Research and Development at Academic Institutions in India," *Journal of Engineering Education Transformation,* Vol. 32, Issue 1, July 2018, pp. 103-114

Downloaded by IOWA STATE UNIVERSITY on January 12, 2019 | http://arc.aiaa.org | DOI: 10.2514/6.2018-5171