ISSN (Print) : 2337-9030 ISSN (Online) : 2685-2608
PILLAR OF PHYSICS
JURNAL BERKALA ILMIAH FISIKA
Vol. 18 (1), 2024, page. 56-64
DOI : 10.24036/16172171074

THYRISTOR BASED MARX IMPULSE GENERATOR CIRCUIT PROTOTYPE FOR PULSED INDUCTIVE THRUSTER (PIT) PROPULSION SYSTEM

Aditya Adriano Karlo*, Yohandri, Asrizal, Mairizwan

Department of Physics, Universitas Negeri Padang, Jl. Prof. Dr. Hamka Air Tawar Padang 25131, Indonesia
Corresponding author. Email: akaditini@gmail.com

ABSTRACT

Pulsed Inductive Thruster is a type of electric propulsion system for spacecraft. It requires high voltages to operate, wherein a Marx impulse generator circuit is used. This circuit requires a switching component, which in the most basic form of such circuit is a spark gap switch. A spark gap switch undergoes rapid degradation whilst in use, which limits its lifespan before needing replacement; a hindrance for operations in space. To circumvent this problem, solid state switches might be used in the stead of spark gap switches. One such switch is a thyristor, whose feasibility was tested in this research. A four-stage basic form of the Marx impulse generator circuit had its spark gap switches replaced with thyristors, and a control unit fitted. Inputs at 2, 4, 6, and 8 volts were given, resulting in outputs at average 0.5, 1.4, 2.1, and 3.1 volts, with σ 0.095, 0.14, 0.1, and 0.1 respectively. These results do not indicate that thyristors might be feasible as an alternative to spark gap switches.

Keywords : Thyristor; Marx Impulse Generator Circuit; Pulsed Inductive Thruster

I. INTRODUCTION

Amongst the various electric spacecraft propulsion systems in development is pulsed inductive thruster (PIT) (figure 1). A pulsed inductive thruster generates thrust by ejecting quasi-neutral plasma generated within its reaction chamber [1][2][4][5][6]. By using an inducting coil, this quasi-neutral plasma is produced by applying an electric field across a gaseous propellant until its breakdown is achieved. Simultaneously, an electromagnetic field is generated within the reaction chamber, which causes Lorentz force to be generated on the charged particles. It is perpendicular to the electromagnetic field and the inducting coil. Thrust is in turn generated as a reaction to this force [1][2][5][6].

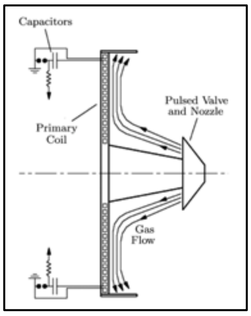

Fig. 1. Pulsed inductive thruster[2]

This process is repeated cyclically, with each cycle requiring electrical currents with a very high voltage for the brief process of breaking down the gaseous propellant and the generation of Lorentz force on it. This high voltage is generated by the use of a Marx impulse generator circuit[5][21].

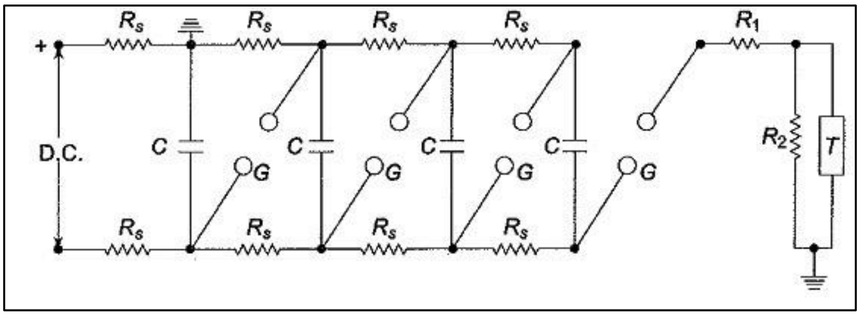

Fig. 2. A basic Marx impulse generator circuit [21]

A Marx impulse generator circuit operates as a voltage multiplier, giving out an electrical current in the form of pulses with its voltage amplified [3][7]. In its barest form, the circuit is comprised of several capacitors, resistors, and spark gap switches. These capacitors are connected in parallel with one another through resistors, and in series with a spark gap switch. In this configuration, the capacitors are charged as in a common R-C circuit. However, the moment the spark gap switch between the capacitors are closed, all the capacitors discharge in series. This has the effect of causing an increase of voltage between the ends of the line of capacitors. Equation 1 gives the output voltage of a Marx impulse generator circuit, where V_o is the output voltage, n is the number of stages, and V_i is the input voltage [3]. For the spark gap switches to be closed requires enough voltage between the electrodes in the spark gap switches to trigger a breakdown of its isolating medium viz. gas. This could be seen as an electrical arc between the electrodes.

$$V_o = nV_i \quad (1)$$

The performance of a spark gap switch (Figure 3) relies on the condition of its electrodes and isolating medium. These two factors affect the breakdown voltage as they determine the distance between the conducting material and impurities. However, repeated operations will lower their conditions. As arcing occurs when a spark gap switch is closed, this causes minute erosions on the electrode [13]; this increases the distance between the electrodes. Simultaneously, these materials eroded from the electrode might add impurities into the gaseous medium. An increase in breakdown voltage might cause irregularities when all spark gap switches in a Marx impulse generator circuit are expected to close almost simultaneously. On the other hand, impurities in the gaseous medium might cause continuous arcing between the electrodes, rendering the spark gap switch permanently closed[5].

Fig. 3. A spark gap switch

As the operation of a Marx impulse generator circuit relies, amongst other things, the switching ability of a spark gap switch, irregularities in closing a gap and the possibility of not breaking a connection at all limits the usage of spark gap switch for long term operation. This is compounded when the current nature of deep space missions is considered viz. unavailability of repair for spacecraft. It is for this reason that the need of an alternative to spark gap switches in Marx impulse generator circuit arose.

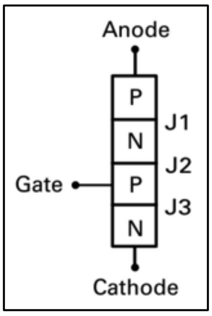

Fig. 4. Block diagram of a thyristor[14]

One electrical component with potentially suitable intrinsic switching characteristics is thyristor. Thyristor is a type of solid state switch, comprising of four alternating p and n type semiconductor layers (figure 4) [14][15]. In addition to being able to function as a switch, a thyristor also has a latching ability. In its normal state, a thyristor remains open, notwithstanding should it be connected to a current source with current above its holding current threshold. However, when its gate terminal is also given a trigger signal, the thyristor would then become closed. It would remain so, hence latched, even if the trigger signal is removed. From its closed state, a thyristor would only become open when both the trigger signal is removed and the electrical current falls below the thyristor's holding current threshold [15][16][17].

In its planned function to substitute a spark gap switch in a Marx impulse generator circuit, a thyristor's trigger and latching mechanisms are crucial. The operation of the circuit requires that its capacitors be discharged only when they are sufficiently charged. This means that the switching component connecting the capacitors in series must only be closed at a precise moment. For thyristors, this could be done by giving them trigger signal for their gates at that precise moment. The Marx impulse generator circuit also requires the full discharge of its capacitors. It is for this reason that it's necessary for its switching component to be able to maintain full connectivity as the process of discharge occurs, a need fulfilled by the latching mechanism of a thyristor.

Whilst the latching mechanism could automatically be set off through the intrinsic characteristics of a thyristor, it is not of the same case for its trigger mechanism. This mechanism requires an external signal for it to be set off. With this in mind, AND gates and op-amps as comparators could be used to control when this signal would be given[8][9][10]. The op-amp comparator could be paired with a capacitor in the Marx impulse generator circuit in such a way that it would compare the voltage in that capacitor to the voltage given as an input to the circuit. When the capacitor has a voltage equal to that of the input, the comparator paired to the capacitor would then give out a signal. This signal would then travel to an AND gate. Should there be enough sufficiently charged capacitor, the final AND gate would give out the trigger signal to all the thyristors, causing them to become closed. This process would provide control for the overall operation of the modified Marx impulse generator circuit

Similar researches had been done to investigate the feasibility of substituting solid state switches in place of spark gap switch in a Marx impulse generator circuit [18]. One paper mentions a significant loss of energy due to very high switching repetition in a circuit with thyristors [19]. Another calls for specialised thyristors to be used in such a substitution of spark gap switches in a Marx impulse generator circuit [20]. Meanwhile, one tested the feasibility of MOSFET switches [21]; MOSFET has several similarities to thyristors.

II. METHOD

A. Preparation of the modified Marx impulse generator circuit

The prototype was assembled in accordance with the schematic in figure 5.

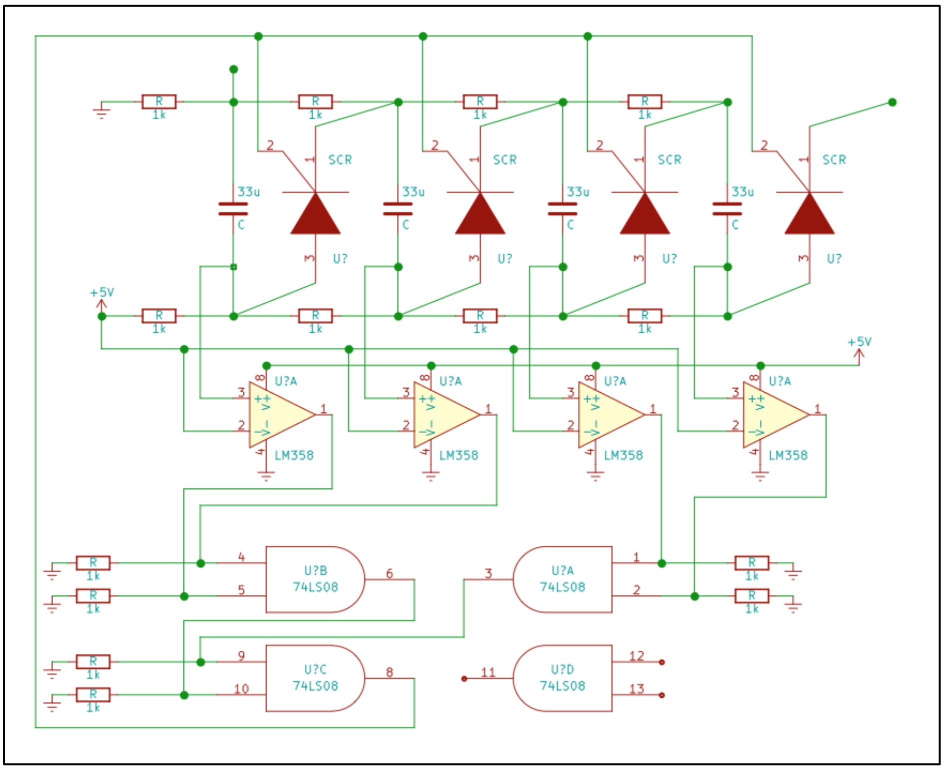

Fig. 5. The modified Marx impulse generator circuit

This circuit utilizes 1k resistors, 33µF/50V electrolytic capacitors, IC 74LS08, IC LM358, 2P4M thyristors, and jumper wires. As shown in Figure 6, the modified Marx impulse generator circuit consists of two parts: the stage generator and the control unit.

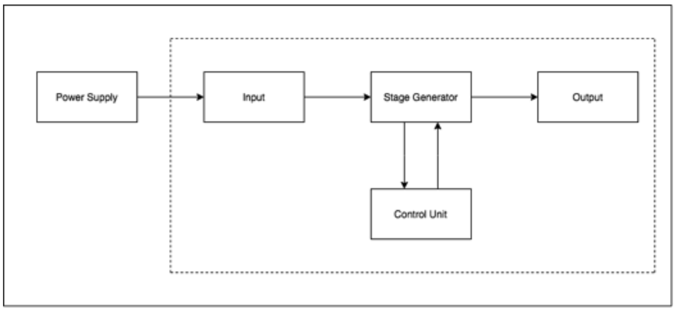

Fig. 6. Block diagram of the modified Marx impulse generator circuit

The stage generator consists of 33µF/50V electrolytic capacitors, 2P4M thyristors, and 1k resistors. The capacitors are assembled parallel to one another, with the resistors connecting them. Input voltages would be given through this circuit. The capacitors are also connected to one another in series through the 2P4M thyristors. The cathode terminal of the last thyristor in this series connection becomes the positive output terminal of the modified Marx impulse gnerator circuit, whilst the other end of the series, i.e. the anode of the first capacitor of the same connection, becomes the negative output terminal.

Meanwhile, the control unit consists of 74LS08 [12] and LM358 [11] type ICs, and also 1k resistors. Two LM358 units are used. Each of the non-inverting terminal of the op-amps within the units are connected to the positive terminal of the input to the modified Marx impulse generator circuit, whilst their inverting terminal are connected to each capacitors. The output terminals of the four op-amps within the LM358 IC are connected to the input terminals of two AND gates within the 74LS08 IC. In turn, the output terminals of these AND gates were connected to the input terminals of another AND gate within the same unit. The output terminal of this final AND gate are connected to the gate terminals of the four thyristors.

B. Testing for output voltage

Precautions were taken to ensure accurate measurements during the test, namely by checking the conditions of the electrical components and equipment to be used. For equipment this means doing proper calibration of the oscilloscope and multimeter, and for electrical components checking that they were not burnt out and had their proper characteristics e.g. forward-blocking for thyristors until triggered.

Testing for the output voltage was first started by attaching the probes of the oscilloscope to the output terminals of the circuit as shown here in figure 7. This is followed attaching a power supply unit to the input terminals, without giving them any voltage. After this preparation was done, the power supply was set to give out a direct current with a certain voltage, beginning at 2 volts. Readings for the peak voltage were then taken from the oscilloscope and noted. Ten readings were done for each magnitude of input voltage. Simultaneously, the shape of the output voltage was also noted. This process is repeated for input voltages of 4, 6, and 8 volts.

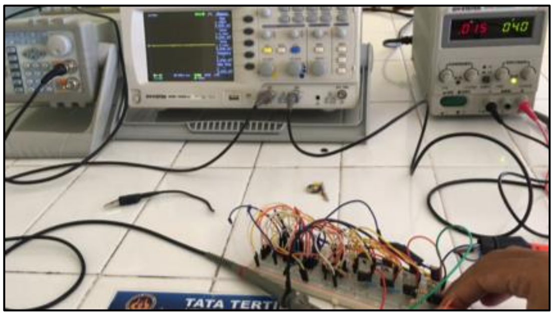

Fig. 7. Testing for the output

The performance of this modified Marx impulse generator circuit is judged from the voltage and form of the electrical current produced by the circuit. The voltage given in the reading would determine the reliability of the circuit to produce a near constant output, and its closeness to the desired output voltage. The circuit's reliability would be determined by calculating the standard deviation [22] (Equation 2) of each set of readings for each input voltages.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} |x_i - \mu|^2}{N}} \quad (2)$$

Where σ is standard deviation, x_i is the i^th voltage reading, μ is the average of the readings, and N is the number of readings.

On the other hand, closeness would be determined by calculating the percentage error (Equation 3) of the experimental output to the desired output.

$$y = \left(\frac{|x_t - x_m|}{x_t}\right) \times 100 \quad (3)$$

Where y is error in percent, x_t is the theoretical/desired output voltage, x_m is the experimental output voltage. The desired output voltage is given by Equation 1. This calculation was done to every output voltage and average output voltage measured for every input voltage given to the modified Marx impulse generator circuit.

III. RESULTS AND DISCUSSION

Figure 7 shows the modified Marx impulse generator circuit, assembled per the schematic in Figure 5. Output is given in another breadboard for easier access. A capacitor was later connected between the output terminals to provide load. The grey and black probes seen connected here are the probes connecting the output terminals of the modified Marx impulse generator circuit to the oscilloscope.

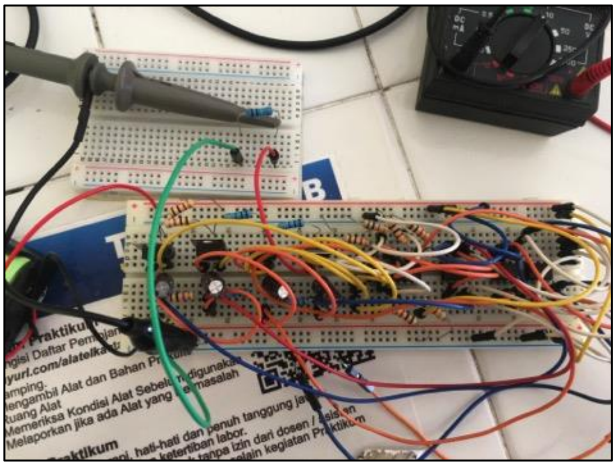

Fig. 7. The assembled modified Marx impulse generator circuit

A. Output Voltage

Table 1-4 shows the output voltage given out by the modified Marx impulse generator circuit. Table 5 shows the average output voltages.

Table 1. 2V Input

No.	Vout (*V*)	Error (*%*)	σ
1	0.48	94.0	0.095
2	0.58	92.8	
3	0.62	92.3	
4	0.4	95.0	
5	0.32	96.0	
6	0.6	92.5	
7	0.48	94.0	
8	0.58	92.8	
9	0.4	95.0	
10	0.5	93.8	

For an input of 2 volts, the modified Marx impulse generator circuit gave out an average output of 0.5 volts. This gives out an error of 93.8% to the expected output voltage of 8 volts. The standard deviation is given to be 0.095.

Table 2. 4V Input

No.	Vout (*V*)	Error (*%*)	σ
1	1.4	91.3	0.14
2	1.3	91.9	
3	1.4	91.3	
4	1.2	92.5	
5	1.7	89.4	
6	1.6	90.0	
7	1.5	90.6	
8	1.5	90.6	
9	1.4	91.3	
10	1.3	91.9	

For an input of 2 volts, the modified Marx impulse generator circuit gave out an average output of 1.4 volts. This gives out an error of 91.3% to the expected output voltage of 16 volts. The standard deviation is given to be 0.14.

Table 3. 6V Input

No.	Vout (*V*)	Error (%)	σ
1	2.2	90.8	0.1
2	2.1	91.3	
3	2	91.7	
4	2.2	90.8	
5	2	91.7	
6	2.2	90.8	
7	2.1	91.3	
8	2	91.7	
9	2.3	90.4	
10	2.1	91.3	

For an input of 4 volts, the modified Marx impulse generator circuit gave out an average output of 2.1 volts. This gives out an error of 91.3% to the expected output voltage of 24 volts. The standard deviation is given to be 0.1.

Table 4. 8V Input

No.	Vout (*V*)	Error (%)	σ
1	3.2	90.0	0.1
2	3.1	90.3	
3	3	90.6	
4	3.2	90.0	
5	3.2	90.0	
6	3.1	90.3	
7	2.9	90.9	
8	3.1	90.3	
9	3	90.6	
10	3.2	90.0	

For an input of 2 volts, the modified Marx impulse generator circuit gave out an average output of 3.1 volts. This gives out an error of 90.3% to the expected output voltage of 8 volts. The standard deviation is given to be 0.1.

Table 5. Average Output Voltage

Vin (*V*)	Vout (*V*)	Error (%)
2	0.5	93.8
4	1.4	91.3
6	2.1	91.3
8	3.1	90.3

The results of this experiments show that the voltages generated by the modified Marx generator circuit are much smaller from the output voltages calculated using Equation 1. Considering that the modification done to the Marx impulse generator circuit (as shown in Figure 2) is solely the substitution of its spark gap switches to thyristors (as shown in Figure 5), this raises the question as to the feasibility of thyristors to be used this circuit.

One possible explanation for this lowered output voltage could be that the thyristors failed to close simultaneously altogether. This would have caused only a partial discharge of the capacitors in the stage generator. Whereas the connection between the output terminals would have gone through all the capacitors, that connection now went through a few of the capacitors and through the resistors on the negative input rail. However, by the design of the modified Marx impulse generator circuit, this should not be possible. The control unit of the circuit relies on all the capacitors to be adequately charged, before it would give out the trigger signal for the thyristors. In turn, this would have triggered all the thyristor simultaneously. For this reason, the capacitors must've discharged simultaneously as well.

Another possible explanation is that whilst the capacitors were simultaneously discharged, a significant portion of the charges in the capacitors was transferred back into the power supply. This would've dramatically reduced the voltage in each capacitors, and in turn, the voltage between the output terminals. This could be the more likely culprit, for the modified Marx impulse generator circuit lacks diodes that would otherwise help control the flow of current.

On the other hand, in regards to the small standard deviation values shows that the results of each test are close to one another i.e. little variation of the voltage of the electrical current produced by the modified Marx impulse generator circuit. This small degree of variation is also shown by the percentage errors, which when calculated from the output voltages from each measurement and the average of each set of measurements of each input voltage remain at about 90%. Both could also indicate that the processes in the circuit viz. charging/discharging and triggering occurred repeatedly with little variation, and that outside factors might have not affected the results of the tests at all, or at least significantly enough.

B. Output Waveform

Figure 8 shows that the oscilloscope detected a rapid increase of voltage between the output terminals of the modified Marx generator circuit, followed by a fall. The rapid increase of voltage denotes the brief period of discharge of the capacitors in the stage generator. As these capacitors were discharging, the control unit would stop giving a trigger signal to the thyristors. The charge within each of the capacitors would continue to decrease as time went. When enough of it decreased to cause the current each capacitor gave to fell below the holding current of the thyristors, which are connected between the capacitors, it caused the thyristors to become open. This caused the connection between the capacitors, and in turn the output terminals, to be broken.

As a result, the period wherein the detected output voltage rose was followed by a period of a fall. In this period, the capacitors were disconnected and were also in the process of being once more charged. It is to be noted that the gradual decrease seen in Figure 8 was due to the capacitor being used as a load at the output.

Fig. 8. Output waveform

The waveform does not show a continuous voltage, but rather a pulse. It also indicates that the thyristors and the control unit connected to them were able to maintain a form of control of the electrical currents between the output terminals.

IV. CONCLUSION

The modified Marx impulse generator circuit, which uses thyristors in place of spark gap switches, is able to generate a pulsed output signal. However, the voltage generated by the modified circuit is substantially lower than the output voltage it was expected to generate. The output generated by the circuit is rather stable, as shown by the small variation of the output voltage being generated by the aforementioned circuit. Points out that the issue might originate from the thyristors themselves, when used in this fashion. As such, the actual feasibility of thyristors as a replacement for spark gap switches in a Marx impulse generator circuit comes into question. It may be that future improvements to the design may overcome this problem.

REFERENCES

[1] D.M. Goebel and I. Katz, *Fundamentals of Electric Propulsions: Ion and Hall Thrusters*. California, United States of America: Jet Propulsion Laboratory California Institute of Technology, 2008.

[2] K. Polzin, A. Martin, J. Little, C. Promislow, B. Jorns, and J. Woods, "State-of-the-Art and Advancement Paths for Inductive Pulse Plasma Thrusters", *Aerospace*, vol. 7, no. 105, Jul. 2020.

[3] H. Krieger, *Strahlungsquellen für Technik und Medizin, 3. Auflage*. Berlin, Germany: Springer Spektrum, 2018.

[4] P. G. Mikellides and N. Ratnayake, "Modeling of the Pulsed Inductive Thruster Operating with Ammonia Propellant" *Journal of Propulsion and Power*, vol. 23, no. 4, pp. 854-862, Jul. 2007.

[5] I. Hrbud, M. LaPointe, R. Vondra, C. L. Dailey, and R. Lovberg, "Status of Pulsed Inductive Thruster Research", *AIP Conference Proceedings*, vol. 608, pp. 627-632, 2002.

[6] R. G. Jahn, *Physics of Electric Propulsion*. San Francisco, United States of America: McGraw-Hill, 1968.

[7] C. Siebauer, T. Peikert, H. Garbe, and S. Potthast, "Realisierung von einfachen Quellen zur Untersuchung der Störfestigkeit von IT-Netzwerken", *Elektromagnetische Verträglichkeit (EMV): Internationale Fachmesse und Kongress für Elektromagnetische Verträglichkeit*, Feb. 2016.

[8] T. L. Floyd and D. L. Buchla, *Electronic Fundamentals: Circuits, Devices and Applications, Eighth Edition*. Harlow, United Kingdom: Pearson Education Limited, 2014.

[9] R. Moghimi, "Amplifiers as Comparators?", *Analog Dialogue*, vol. 37, no. 2, pp. 6-10, Apr. 2003.

[10] Electronics Tutorials. (2015) Op-amp Comparator. [Online]. Available: https://www.electronics-tutorials.ws/opamp/op-amp-comparator.html

[11] *LM2904, LM358/LM358A, LM258/LM258A Dual Operational Amplifier*, Fairchild Semiconductor, 2002 .

[12] *DM7408 Quad 2-Input AND Gate*, Fairchild Semiconductor, 2001.

[13] F. Llewellyn-Jones, 1963, "The Mechanism of Electrode Erosion in Electrical Discharges: Physical Basis of the Low Erosion Rate of the Platinum Metals", *Platinum Metals Review,* vol. 7, no. 2, 1963, pp. 58-65, 1963.

[14] Littelfuse Inc, *Fundamental Characteristics of Thyristors*. Chicago, United States of America: Littelfuse Inc., 2013.

[15] J. Specovius, *Grundkurs Leistungselektronik: Bauelemente, Schaltungen und Systeme*. Wiesbaden, Germany: Vieweg+Teubner, 2009.

[16] U. Nicolai, *Thyristor Triggering and Protection of Diodes and Thyristors*. Nuremberg, Germany: Semikron, 2018.

[17] *Thyristor Design Guide*. Littelfuse Inc., n.d.

[18] H. Singh, and C. R. Hummer, "High Action Thyristors for Pulsed Applications", *12th IEEE International Pulsed Power Conference*, pp. 1126-1128, Jun. 1999.

[19] M. Jung, W. Mayerhofer, M. Edele, O. Gstir, T. Schweizer, E. Zeyfang, and E. Ramezani, ”Test of Fast SCR'S As Spark Gap Replacement", *Digest of Technical Papers Tenth IEEE International Pulsed Power Conference*, pp. 729-732, Jul. 1995.

[20] N. Rishi, P. S. Ponmurugavel, and R. D. Kumar, "Attempt To Replace Spark Gap By Thyristor In Marx Circuit", *International Conference on Power, Energy and Control (ICPEC)*, pp. 225-226, 2013.

[21] G. Saraf, A. Bansode, A. Khule, S. Rangari, and S. U. Shinde, "High Voltage DC Generation using Marx Generator", *International Journal of Advanced Research in Computer and Communication Engineering*, vol. 6, issue 5, pp. 611-615, May 2017.

[22] United States National Institute of Health. (n.d.) *Common Terms and Equations: Standard Deviation*. [Online]. Available: https://www.nlm.nih.gov/nichsr/stats_tutorial/section2/mod8_sd.html