Majlesi Journal of Energy Management **Vol. 2, No. 2, June 2013**

Derivation of Load Peak Voltage, Power Consumption and Potential Energy Management in a Thyristor Controlled Marx Impulse Generator for Capacitor Discharge Application

A. Toudeshki[1,2], N. Mariun[1], H. Hizam[1], N. I. Abdul Wahab[1],
M. Hojabri[3], Y. Ali Sai'd[4], O. Saadatian[5], M. Mansoor[1],
E. Saadatian[6]
1- Centre for Advance Power and Energy Research (CAPER), Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malayasia.
Email: arashtoudeshki@gmail.com (Corresponding author)
2- Sayed Al-Shohada College and Pre-University, Koye Baharan, Gol-khaneh Street, 81959 Khaneh Esfahan, Isfahan, Iran.
3- Faculty of Electrical and Electronics Engineering, University Malaysia Pahang (UMP), 26600 Pekan, Malaysia.
4- Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malayasia.
5- Solar Energy Research Institute (SERI), Level 3, Perpustakaan Tun Sri Lanang, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.
6- Keio-NUS CUTE, National University of Singapore (NUS), Singapore 119613, Singapore.

Received March 2012 Revised Dec. 2012 Accepted Jan. 2013

ABSTRACT:
Calculation of the load peak voltage, potential energy and power consumption of a Marx impulse generator, as a function of time, are presented. The equations are generalized and can be used to the design of any type of n-stage Marx impulse generator. The results were validated for a thyristor controlled Marx impulse generator with a maximum number of stages of 10 and 3 kV input DC voltage, which used 1 MΩ resistors and 33 nF capacitors in its topology.

KEYWORDS: potential energy management, power consumption, thyristor controlled, Marx impulse generator, calculation

1. INTRODUCTION

High-voltage impulse generators are one of the most important components for science and military applications, such as laser [1], x-ray [2-3], plasma [4], [5], ignition systems [6], etc. All these applications work based on the capacitor discharge method [7–9]. Due to the simple art topology and good performance, the Marx pulse generator is used in discharge capacitor application. Its topology consists of capacitors, resistors and switches [10]. It generates the pulses by charging the capacitors in parallel and discharging them in series into a load [11–13].

The rapid discharged of the electricity generates a high electrical power known as pulsed power. Pulsed power is the physical value that indicates the energy change per unit of time. The power depends on how fast the energy is released [14]. It is also described as a technology for storing and controlling the electric power [15]. The pulsed power, which has a wide area of application in science and technology, is a method that can be used to express the management or control of a constant power for a long period of time.

Many attempts have been made to improve the performance and develop the topology of the Marx circuit [16–19], and recently a portable [20] and smaller size [21] generator was presented. The basic mechanism of this circuit which is the charge and discharge of capacitors, remains the same [13]. In the capacitor discharge application [22–28], controlling the peak of the impulse voltage, which is applied across the load, is required. In recent years, the control, efficiency, reliability and pulse shape of pulsed power is improved by utilizing semiconductor switches [29–33], in the classic Marx generator design [10]. In many cases, the Marx impulse generator was enhanced by replacing the traditional spark gaps with solid-state devices such as thyristors [34]. This device provides a finer control at the time of the capacitor discharge process. Even so, the peak of the applied voltage across the load and the potential energy, as a function of time, need to be calculated.

This paper describes the derivation of load peak voltage and the potential energy management in a thyristor trigger controlled Marx impulse generator for the capacitor discharge application.

2. APPROACH

Figure 1 shows a simple four-stage thyristor controlled Marx impulse generator which has been used since 1980s [34]. However, in order to carry out a generalized derivation, it is assumed that the circuit consist of n stage (n is the number of stages). In general, the capacitors, C, are charged in parallel through the resistors, R. When the voltages of each stage became enough for making a breakdown in spark gaps, capacitors are connected in series, and the summation of their charged voltages is the peak value of the discharge pulse, release across the load [12]. The peak of this voltage can be maximized up to about the number of stages times the input DC voltage ($n \cdot V_{in}$). The thyristor is a solid-state switch, which acts as a controlled rectifier. This solid-state switch controls the discharge time at the desirable moment. Since the value of the voltage is depending upon the time, the peak of the voltage can be controlled by controlling the discharge time. This occur by applying a proper trigger pulse to the thyristor [35]. Theoretically, the thyristor can be switched ON when C is charged up to the possible breakdown voltage VB or when the trigger signal is applied to the gate of the thyristor. However, since only one thyristor is used for the circuit, and other switches are the traditional spark gaps which dependent on the spark gap's impedance [36], [37]; the peak of the applied voltage across the load may be dropped to a smaller amount [38]. This voltage drop is an uncertain parameter and depends on various ambient conditions [39]. For this study, it is assumed that the system is ideal and the effect of the air impedance is neglected.

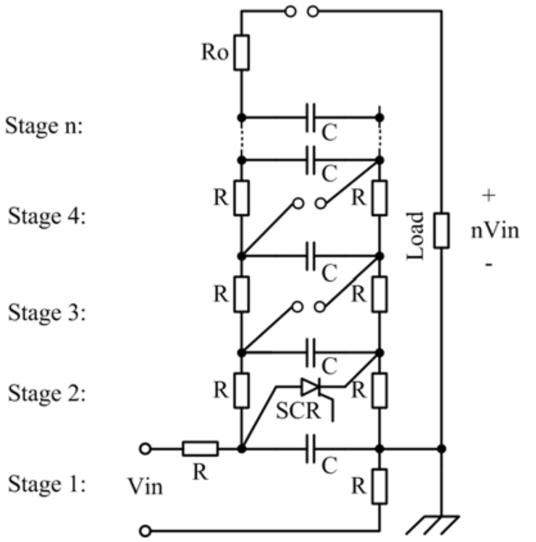

Fig. 1. Thyristor controlled, n-stage Marx generator [34]

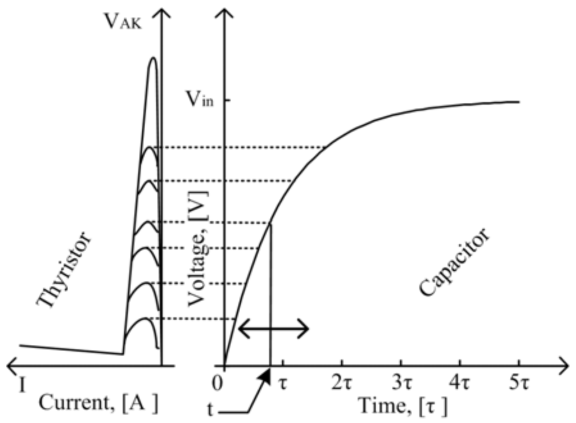

Fig. 2. Turn ON characteristics of thyristor vs. voltage across the capacitor in each moment of t

3. DERIVATION OF LOAD PEAK VOLTAGE, POTENTIAL ENERGY AND POWER

By triggering the thyristor when the voltage of C exceeded the breakdown voltage of air gap switches, all air gaps can be switched ON and capacitors change to series connection. After that, the voltage across the total capacitance value of $\frac{C}{n}$ can discharge through the load. The turn ON characteristics of the thyristor vs. voltage across the capacitor in the first stage is shown in Figure 2.

Therefore, the peak of the output impulse can be calculated via capacitor charging theory [40], as (1).

$$V_{c,1}(t) = V_{in}\left(1 - e^{-t/\tau_1}\right) \qquad (1)$$

where τ_1 is the charge time constant for the first stage which can be calculated via (2).

$$\tau_1 = 2 \cdot R \cdot C \qquad (2)$$

Time of the trigger pulse for the first stage can be calculated by solving equation (1) based on the time t.

$$t = -\tau_1 \cdot \ln\left(1 - \frac{V_{c,1}(t)}{V_{in}}\right) \qquad (3)$$

The τ for other stages can be calculated using equation (4).

$$\tau_n = 2 \cdot n \cdot R \cdot C \qquad (4)$$

where n is the number of stages. Based on equation

(1), in each stage, the capacitor voltage at the moment of t can be calculated by (5).

$$V_{c,n}(t)=V_{c,(n-1)}\left(1-e^{-t/\tau_n}\right) \tag{5}$$

This equation can be expanded and written as in equation (6).

$$V_{c,n}(t)=V_{in}\prod_{k=1}^{n}\left(1-e^{-t/(2\cdot k\cdot R\cdot C)}\right) \tag{6}$$

Therefore, by applying the trigger pulse to the thyristor, they would release the stored energy to the load. At the time of t, the peak of output voltage for n-stage system can be calculated as (7).

$$V_{load}(t)=\sum_{h=1}^{n}\left(V_{in}\prod_{k=1}^{n}\left(1-e^{-t/(2\cdot k\cdot R\cdot C)}\right)\right) \tag{7}$$

Moreover, the possible potential energy [10] as a function of time, which can be released to the load, can be calculated using (8).

$$U(t)=\frac{1}{2}C\left(V_{load}(t)\right)^2 \tag{8}$$

Hence, equation (8) can be expanded and shown as equation (9).

$$U(t)=\frac{1}{2}C\left(\sum_{h=1}^{n}\left(V_{in}\prod_{k=1}^{n}\left(1-e^{-t/(2\cdot k\cdot R\cdot C)}\right)\right)\right) \tag{9}$$

Finally, the power consumed in order to produce this potential energy, as a function of time, can be calculated via derivative of the potential energy with respect to time as equation (10).

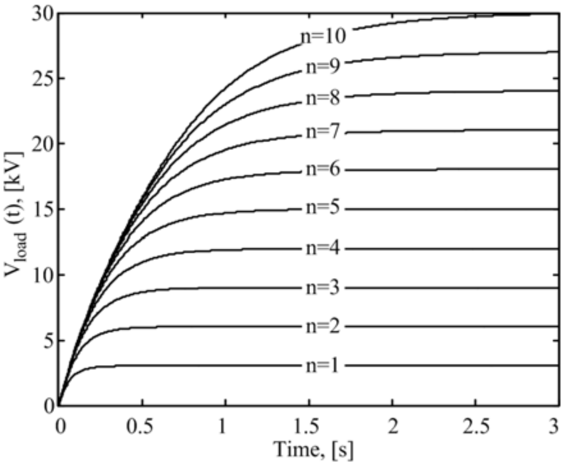

Fig. 3. The load peak voltage

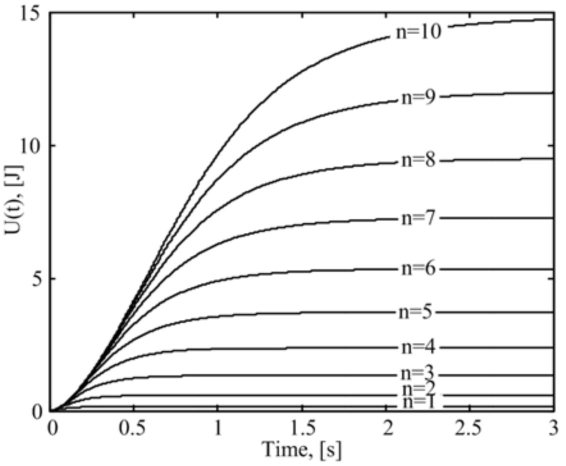

Fig. 4. The output potential energy

$$P(t)=\frac{d}{dt}U(t) \tag{10}$$

By calculating equation (10), then equation (11) will yield.

$$P(t)=\frac{V^2\cdot A\cdot B}{2\cdot R} \tag{11}$$

where A in (11) can be calculated by (12).

$$A=\sum_{h=1}^{n}\left(\prod_{k=1}^{h}\left(1-\Gamma_{t,k}\right)\right) \tag{12}$$

and B in (11) can be calculated by (13).

$$B=\sum_{h=1}^{n}\left(\sum_{k=1}^{h}\left(\frac{\Psi_k\cdot\Gamma_{t,k}}{k}\right)\right) \tag{13}$$

In equation (13), Ψ_k can be calculated via (14).

$$\Psi_k=\prod_{x=1}^{k-1}\left(1-\Gamma_{t,x}\right)\cdot\prod_{x=k+1}^{h}\left(1-\Gamma_{t,x}\right) \tag{14}$$

where $\Gamma_{t,k}$ is

$$\Gamma_{t,k}=e^{-t/\left(2\cdot k\cdot R\cdot C\right)} \tag{15}$$

and $\Gamma_{t,x}$ is

$$\Gamma_{t,x}=e^{-t/\left(2\cdot x\cdot R\cdot C\right)} \tag{16}$$

To validate the derivation, equations for the applied peak voltage across the load, the potential energy and the power as a function of time are plotted and investigated. Values of 33nF for capacitors, 1MΩ for resistors, and input DC voltage of 3kV were chosen, where the number of stages varies from 1 to 10.

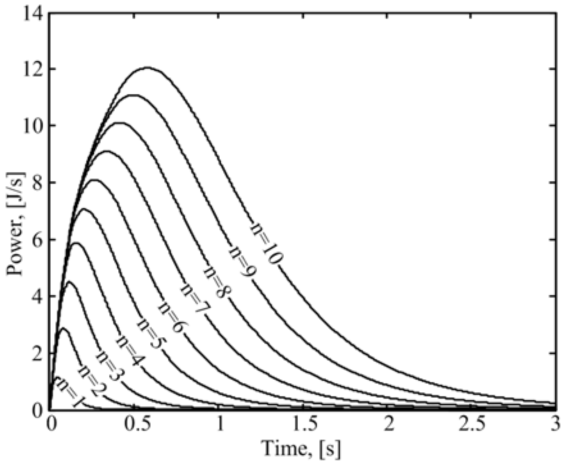

Fig. 5. The power consumption

4. DISCUSSION

As a result, the peak of the voltage which can be applied across the load, in each triggering time, for each stage, is shown in Figure 3. In addition, the possible output potential energy, in each triggering time for each stage, is shown in Figure 4. Finally, the power consumption of the Marx impulse generator, which is the derivative of the energy, in each triggering time, for each stage, is shown in Figure 5. Based on these results, the peak voltage, and the potential energy at a certain moment will be saturated and as the time increases, the amount of the peak voltage and the potential energy do not change much. In Figure 5, as the peak voltage and the potential energy curves saturated, the power curves are reduced to zero. It can be concluded that by triggering the thyristor, after some time, the maximum voltage and the potential energy do not change very much and are saturated. It must be noted that by increasing the number of stages, since the order of the system increases, the charging time of the equivalent capacitor of the Marx impulse generator increases as well. Therefore, the control region as a function of time enlarges. Based on this, increasing the number of stages has advantages of increasing the peak of the output voltage, potential energy and controlling region. However, the disadvantage is longer charging time for the capacitor when the number of stages is increased, remains. Therefore, an improved circuit topology in the future may be able to solve this existing problem.

5. CONCLUSION

In this paper, the voltage peak, as a function of time, for a thyristor controlled Marx impulse generator was derived. Moreover, the potential energy, as a function of time, was also derived. The results obtained from this paper, verified for a 10-stage thyristor controlled Marx impulse generator, and may help to estimate the approximate peak voltage, applied across the load; and the stored potential energy, for each moment when the thyristor is triggered, for an n-stage Marx pulse generator.

REFERENCES

[1] V. M. Orlovskii, A. N. Panchenko, and V. F. Tarasenko, "**Electric-discharge high-peak-power CO2 laser**," *Quantum Electronics*, Vol. 40, No. 3, pp. 192, 2010.

[2] S. Saboohi, S. L. Yap, L. S. Chan, and C. S. Wong, "**Effects of Inter-electrode Gap and Discharge Voltage on EUV Emission from Stainless Steel Vacuum Spark Plasma**," *Sains Malaysiana*, Vol. 41, No. 7, pp. 879–884, 2012.

[3] S. Saboohi, S. L. Yap, L. S. Chan, and C. S. Wong, "**Investigation of the Temporal Evolution of X-Ray Emission From a Copper Vacuum Spark Plasma**," *IEEE Transactions on Plasma Science*, Vol. 40, No. 12, pp. 3390–3394, Dec. 2012.

[4] C.-S. Ha, D.-H. Kim, H. J. Lee, and H.-J. Lee, "**Development of an energy controlled DC pulse discharge for atmospheric pressure plasma applications**," *in 2010 Abstracts IEEE International Conference on Plasma Science*, 2010, pp. 1–1.

[5] L. W. and Z. D. and K. Fei, "**The Impact of Electrode Configuration on Characteristics of Vacuum Discharge Plasma**," *Plasma Science and Technology*, Vol. 14, No. 2, pp. 122, 2012.

[6] X. Luo, Q. S. Luo, Y. G. Cao, and L. Shi, "**Hardware Design of Electronic Ignition System for Special Electromechanical Device**," *Applied Mechanics and Materials*, Vol. 58, pp. 491–494, 2011.

[7] S. C. Agarwal, "**Analysis of the thermally stimulated capacitor-discharge method for characterizing localized states in amorphous semiconductors**," *Physical Review B*, Vol. 10, No. 10, pp. 4340, 1974.

[8] W. M. Rosellini, P. B. Yoo, N. Engineer, S. Armstrong, R. L. Weiner, C. Burress, and L. Cauller, "**A Voltage Controlled Capacitive Discharge Method for Electrical Activation of Peripheral Nerves**," *Neuromodulation: Technology at the Neural Interface*, Vol. 14, No. 6, pp. 493–500, 2011.

[9] S. Müller and R.-J. Zahn, "**Air Pollution Control by Non-Thermal Plasma**," *Contributions to Plasma Physics*, Vol. 47, No. 7, pp. 520–529, Nov. 2007.

[10] A. Toudeshki, N. Mariun, H. Hizam, and N. I. A. Wahab, "**The energy and cost calculation for a Marx pulse generator based on input DC voltage, capacitor values and number of stages**," *in IEEE International Conference on Power and Energy (PECon 2012),* , 2012, pp. 745–749.

[11] W. L. Willis, "**Pulse voltage circuits**," Los Alamos National Lab., NM (USA), United States, 1980.

[12] J. O'Loughlin, J. Lehr, and D. Loree, "**High repetition rate charging a Marx type generator**," *in Pulsed Power Plasma Science*, 2001. PPPS-2001. Digest of Technical Papers, 2001, Vol. 1, pp. 242–245 vol.1.

[13] S. Roy and A. Debnath, "**Procedural Perfection in Impulse Shape Generation for Indoor Type**

Impulse Test of Power Transformers," *Global Journals of Engineering Research*, Vol. 10, No. 7, 2010.

[14] K. S. Cha, T. H. Kim, and S. J. Kim, "**Pull-out Characteristics of Expanded Anchor Using Pulse Discharge Technology**," *in Pan-Am CGS Geotechnical Conferernce*, 2011.

[15] S. Moran, "**The Basics of Electric Weapons and Pulsed-Power Technologies**," *RDT&E, Acquisition, and Warfare Management*, Vol. 7, No. 4, pp. 50, 2011.

[16] T. Prabaharan, A. Shyam, R. Shukla, P. Banerjee, S. Sharma, P. Deb, R. Verma, R. Kumar, R. Das, and B. Das, "**Development of 2.4 ns rise time, 300 kV,~ 500 MW compact co-axial Marx generator**," *Indian Journal of Pure & Applied Physics*, Vol. 49, pp. 64–72, 2011.

[17] D. Benzel and M. D. Pocha, "**1000-V, 300 ps pulse-generation circuit using silicon avalanche devices**," *Review of Scientific Instruments*, Vol. 56, No. 7, pp. 1456, 1985.

[18] R. P. Gupta and W. Murray, "**Pulsed high electric field sterilization**," *in Pulsed Power Conference*, 1989. 7th, 1989, pp. 58–64.

[19] R. J. Baker, "**High voltage pulse generation using current mode second breakdown in a bipolar junction transistor**," *Review of scientific instruments*, Vol. 62, No. 4, pp. 1031–1036, 1991.

[20] J. Wang, L. Dong, and Y. Fu, "**Modeling of UHF voltage multiplier for radio-triggered wake-up circuits**," *International Journal of Circuit Theory and Applications*, Vol. 39, No. 11, pp. 1189–1197, 2011.

[21] S. C. Glidden and H. D. Sanders, "**Solid State Marx Generator**," *in Power Modulator Symposium*, 2006. Conference Record of the 2006 Twenty-Seventh International, 2006, pp. 314–317.

[22] S. V. G. Vardigans and D. De Cogan, "**A bipolar pulse tester for semiconductor devices**," *Journal of Physics E: Scientific Instruments*, Vol. 19, No. 12, pp. 1016, 1986.

[23] J. F. Kolb, S. Kono, and K. H. Schoenbach, "**Nanosecond pulsed electric field generators for the study of subcellular effects**," *Bioelectromagnetics*, Vol. 27, No. 3, pp. 172–187, 2006.

[24] M. Reberšek and D. Miklavcic, "**Advantages and disadvantages of different concepts of electroporation pulse generation**," *AUTOMATIKA*, Vol. 52, No. 1, pp. 12–19, 2011.

[25] B.-L. Qin, G. V Barbosa-Canovas, B. G. Swanson, P. D. Pedrow, and R. G. Olsen, "**Inactivating microorganisms using a pulsed electric field continuous treatment system**," *IEEE Transactions on Industry Applications*, Vol. 34, No. 1, pp. 43–50, 1998.

[26] T. Y. Tsong, "**On electroporation of cell membranes and some related phenomena**," *Bioelectrochemistry and Bioenergetics*, Vol. 24, No. 3, pp. 271–295, Dec. 1990.

[27] K. Huang and J. Wang, "**Designs of pulsed electric fields treatment chambers for liquid foods pasteurization process: A review**," *Journal of Food Engineering*, Vol. 95, No. 2, pp. 227–239, Nov. 2009.

[28] H. Akiyama, T. Sakugawa, T. Namihira, K. Takaki, Y. Minamitani, and N. Shimomura, "**Industrial Applications of Pulsed Power Technology**," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 14, No. 5, pp. 1051–1064, 2007.

[29] J. A. Casey, R. Ciprian, I. Roth, M. A. Kempkes, M. P. J. Gaudreau, and F. O. Arntz, "**Marx Bank Technology for Accelerators and Colliders**," *in IEEE International Power Modulators and High Voltage Conference*, Proceedings of the 2008, 2008, pp. 124–127.

[30] C. J. T. Steenkamp and M. P. Bradley, "**Active Charge/Discharge IGBT Modulator for Marx Generator and Plasma Applications**," *IEEE Transactions on Plasma Science*, Vol. 35, No. 2, pp. 473–478, Apr. 2007.

[31] L. M. Redondo, J. F. Silva, H. Canacsinh, N. Ferrao, C. Mendes, R. Soares, J. Schipper, and A. Fowled, "**Solid-state marx type circuit for the ISOLDE voltage target modulator**," *in Pulsed Power Conference*, 2009 IET European, 2009, pp. 1–4.

[32] G. E. Dale, H. C. Kirbie, W. B. Haynes, C. E. Heath, T. A. Lopez, F. P. Romero, and R. M. Wheat, "**Design and Application of a Diode-Directed Solid-State Marx Modulator**," *in 2005 IEEE Pulsed Power Conference*, 2005, pp. 1211–1214.

[33] L. M. Redondo, H. Canacsinh, and J. F. Silva, "**Generalized solid-state marx modulator topology**," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 16, No. 4, pp. 1037–1042, 2009.

[34] S. G. E. Pronko, M. T. Ngo, and R. F. K. Germer, "**A solid-state Marx-type trigger generator**," *in IEEE Conference Record of the 1988 Eighteenth Power Modulator Symposium*, 1988, pp. 211–214.

[35] I. A. Lesk, "**Germanium PNPN switches**," *Electron Devices*, IRE Transactions on, Vol. 6, No. 1, pp. 28–35, 1959.

[36] K. H. Tsui, A. V. F. Silva, I. B. Couceiro, A. D. Tavares Jr, and C. A. Massone, "**Resonant narrowing of the nitrogen laser pulse by plasma impedance matching**," *IEEE Journal of Quantum Electronics,* Vol. 27, No. 3, pp. 448–453, 1991.

[37] X. Cai, X. Zou, X. Wang, L. Wang, Z. Guan, and W. Jiang, "**Over-volted breakdown and recovery of short nitrogen spark gaps**," *Laser and Particle Beams*, Vol. 28, No. 03, pp. 443–450, 2010.

[38] M. Ekenberg, E. Olofsson, R. Reinmann, and B. Johansson, "10. **The Effect of ln-Cylinder Air lnjection on the Combustion Process in a Stoichiometric Air Assist G-Dl Engine Diluted with Residual Gas**," *Direkteinspritzung im Ottomotor 3.: Forschungsergebnisse und aktueller Entwicklungsstand bei der Benzin-Direkteinspritzung.*, Vol. 3, pp. 188, 2001.

[39] G. A. Mesyats, **Pulsed power. Springer Science+ Business Media**, Incorporated, 2005.

[40] S. Westerlund and L. Ekstam, "**Capacitor theory**," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 1, No. 5, pp. 826–839, 1994.