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IMPROVED CHARGE PUMP FOR CAPACITOR DISCHARGE APPLICATIONS

ARASH MOHAMMADI TOUDESHKI

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By

ARASH MOHAMMADI TOUDESHKI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2013

DEDICATIONS

"To live a creative life, we must lose our fear of being wrong."

∼ Joseph Chilton Pearce ∼

"If you're not prepared to be wrong, you'll never come up with anything original."

∼ Sir Ken Robinson ∼

"We all leave footprints as we journey through life. Make sure yours are worth following."

∼ Bob Teague ∼

This thesis is dedicated to my beloved mother (Shahnaz) and father (Mahmoud) who have supported me all the way since the beginning of my life.
This is also dedicated to my beloved sister (Dr. Pegah), brother (Dr. Babak), brother in law (Dr. Shirzad) and my nieces (Ronia and Rogina).

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

IMPROVED CHARGE PUMP FOR CAPACITOR DISCHARGE APPLICATIONS

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ARASH MOHAMMADI TOUDESHKI

June 2013

Chair: Prof. Norman Mariun, PhD, Ir

Faculty: Engineering

High–voltage dc has a wide area of application in military, science and industry. Based on the energy equation, in order to produce more potential energy, due to limitations in increasing the capacitance, another parameter which is the voltage must be increased to a higher value. In the recent century, many types of high–voltage generators and voltage multipliers are introduced to do this task, and until now; their development and improvement are subject to be continued. Indeed, a charge pump is another type of voltage multiplier that can produce a dc voltage at its output. Unlike the voltage multipliers that employ to generate a low or high–voltage dc, charge pumps are generally used in low–voltage applications. In this thesis, a novel charge pump is developed for high–voltage applications. By re–designing a voltage multiplier circuit, it attempts to propose a novel charge pump configuration that can produce higher output dc voltage and stored potential energy. Since, the proposed circuit includes many energy storage components, understanding its performance and calculating the output voltage in time–domain seems to be very complicated and time–consuming process. Thus, a circuit theory is used to explain the performance of the circuit in a simple way. Furthermore, this theory offers an equation to explain the correlations between the output voltage and stored potential energy with the input voltage and number of stages. In order to evaluate the proposed circuit, simulation has been carried out, and its output results were compared with calculations. In order to identify a more precise behaviour of the output voltage parameters, in steady–state, and their dependence to the input voltage, number of stages and pumping frequency; an approximate mathematical model optimized for each parameter that can give an enhanced view of the circuit for better understanding of its behaviour. In addition, a new time–domain equation is suggested for the proposed charge pump. Moreover, based on the suggested time–domain equation, a suitable transfer function for both the transient and the steady–state response of the proposed charge pump is calculated. This transfer function can be used for modelling and simulating the circuit as a control system. Ultimately, a prototype circuit of the proposed charge pump with the ability of converting to the conventional circuit with the same values, and circuit parameters have been designed, optimized and fabricated; its output results were compared with the output results of the conventional circuit; and results of calculation and simulation. In this research, the novel charge pump is successfully designed, fabricated and validated. The results show its promised application in science and military.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAMBAHBAIKAN PAM CAS UNTUK APLIKASI PENYAHCAS KAPASITOR

Oleh

ARASH MOHAMMADI TOUDESHKI

Jun 2013

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Voltan tinggi arus terus mempunyai aplikasi yang luas dalam tentera, sains dan indutri. Berdasarkan persamaan tenaga, untuk menghasilkan tenaga yang lebih berpotensi, disebabkan batasan dalam meningkatkan kapasiti, parameter lain, iaitu voltan mesti ditingkat ke nilai yang lebih tinggi. Dalam beberapa abad, pelbagai jenis penjana voltan tinggi dan pengganda voltan diperkenalkan kepada tugas ini, dan sehingga kini, pembangunan dan peningkatan mereka masih diteruskan. Sesungguhnya, pam cas adalah jenis lain bagi pengganda voltan yang boleh menghasilkan voltan arus terus pada keluarannya. Tidak seperti pengganda voltan yang menggaji untuk menghasilkan voltan arus terus yang rendah atau tinggi, pam cas biasanya digunakan dalam aplikasi voltan rendah. Dalam tesis ini, novel pam cas dibangunkan untuk aplikasi voltan tinggi. Dengan merekabentuk semula litar pengganda voltan, ia cuba untuk mencadangkan novel konfigurasi pam cas yang boleh menghasilkan voltan arus terus dan potensi menyimpan tenaga. Kerana litar yg dicadangkan termasuk banyak komponen menyimpan tenaga, memahami prestasi dan mengira voltan keluaran dalam domain masa dilihat sangat rumit dan memakan masa proses. Oleh itu, teori litar digunakan untuk memperjelaskan prestasi litar

dalam jalan yang mudah. Selain itu, teori ini menawarkan persamaan untuk menerangkan hubungan antara voltan keluaran dan tenaga potensi yang disimpan dengan voltan input dan bilangan peringkat. Dalam usaha untuk menilai litar yang dicadangkan, ia telah disimulasikan dan keputusan keluarannya dibandingkan dengan keputusan pengiraan persamaan yang telah dicadangkan. Dalam usaha untuk mengenalpasti kelakuan parameter voltan keluaran, dalam keadaan mantap, dan pergantungannya dalam voltan input, bilangan peringkat dan kekerapan mengepam; anggaran model matematik dioptimumkan bagi setiap parameter yang boleh memberi pandangan yang dipertingkatkan litar untuk pemahaman yang lebih baik untuk tingkah lakunya. Bagi aplikasi tentera dan saintifik, mengetahui perilaku domain masa bagi keluaran litar juga adalah penting. Dalam perkara ini, persamaan domain masa yang baru telah dicadangkan bagi pam cas ini. Selain itu, berdasarkan persamaan domain masa yang telah dicadangkan, satu rangkap pindah yang sesuai yang boleh menjelaskan kedua-dua fana dan keadaan mantap. Reaksi bagi pam cas yang dicadangkan, telah dikira. Rangkap pindah ini boleh digunakan untuk pemodelan dan simulasi litar itu sebagai sistem kawalan. Akhirnya, litar prototaip bagi pam cas yang dicadangkan dengan keupayaan menukar ke litar konvensional bersama nilai yang sama, dan parameter litar yang telah direka, dioptimasikan dan dibina; keputusan keluarannya dibandingkan dengan keputusan keluaran bagi litar konvensional; dn juga keputusan pengiraan dan simulasi. Dalam penyelidikan ini, novel pam cas telah direkabentuk, dibina dan disahkan dengan jayanya Keputusan menunjukkan ianya menjanjikan aplikasi dalam sains dan tentera.

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I certify that a Thesis Examination Committee has met on 14 June 2013 to conduct the final examination of Arash Mohammadi Toudeshki on his thesis entitled "Improved Charge Pump for Capacitor Discharge Applications" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

Arash M. Toudeshki

ARASH MOHAMMADI TOUDESHKI

Date: 14 June 2013

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LIST OF ABBREVIATIONS

ac	Alternating current
C	Capacitance
CDF	Cumulative Distribution Function
DC	Direct current
$-_{in}$	Input
m	Number of stage
MPVD	Multi–phase voltage doubler
n	Number of the last stage
NCP	New Charge Pump
$-_{out}$	Output
TPVD	Two–phase voltage doubler
t_{rise}	Rise–time
U	Potential energy
$\hat{V}$	Peak of the ac voltage
V_{dc}	DC voltage
V_{pp}	Peak to peak voltage
vs.	Versus

CHAPTER 1
INTRODUCTION

1.1 Background

1.1.1 Voltage Increasing Techniques

Since electricity was discovered, due to various applications, there is always a need for higher voltage level. However, the subsisted power supplies could produce very low–voltages, based on their source of energy or insulation limits. Engineers have always tried to find ways for generating a voltage, higher than the supply voltage. As a result, many methods have been suggested and utilized to do this task. Some of the most commonly applied methods for producing a voltage larger than the power supply voltage are as follows.

1. Step–up transformers
2. Voltage multiplier circuits
3. Level shifters
4. Charge pump circuits
5. Switched–capacitor circuits
6. Boost or step–up converters

Transformers were the first utilized systems, which were introduced to convert a low–voltage input to a high–voltage output. However, since a transformer needs huge amount of copper and iron in its structure, to isolate and wireless transmission of the input energy from primary to its secondary winding by magnetizing the core, losses can occur because of copper impedance and hysteresis (in high–voltage application since the extra gap exists due to the required insulation these losses are more significant). Furthermore, the size, insulation and cooling of transformers are the issues that need to be concerned (Lee et al., 2011).

Because of the mentioned limitation of the transformer, another method must be found, which can produce high–voltage, especially in electrostatic applications that the output voltage of the supply is important, more than its current. Respectively, a cascade configuration of voltage doublers which could produce an output voltage higher than the input voltage, as a function of its number of stages, has been introduced (Cockcroft and Walton, 1932).

In the circuit of Cockcroft and Walton (1932), huge vacuum tubes were used. Compared to those similar circuits today, it had a big size, high–voltage drop, high–losses, high–energy transmission path and output impedance, low voltage–gain, slow output rise speed, and it was costly.

Some of these problems were almost solved or reduced by the invention of the semiconductors and topological development of the conventional Cockcroft and Walton (1932) voltage multiplier (Dickson, 1976; Karthaus and Fischer, 2003; De Roover and Steyaert, 2010; Chung et al., 2011; Qiang et al., 2012). However, the problem of the low voltage–gain and long rise–time still remain.

The amount of the voltage can be increased by using level shifter circuits. This circuit can rapidly increase the voltage value, and it was a low–power system. Moreover, it includes many MOSFET switches in its configuration (Liu et al., 2010). This limits utilizing this circuit in a high–voltage application, but it was suitable only for low–voltage application.

DC–DC switching boost or step–up converter was an alternative to produce an output voltage, which was higher than the input voltage. The principal of these DC–DC converters were based on controlling the duty–cycle of switch and dealing with the energy between magnetic inductors and capacitors (Deng et al., 2012). However, due to some practical limits such as electromagnetic interferences, voltage drop, poor insulation, low breakdown voltage of the switches, high impedance of the energy transmission path and losses are impractical for high–voltage applications.

Switched–capacitor was an option which was employed to attain higher voltage gain with fewer numbers of stages and number of electronic and passive components as well (Makowski and Maksimović, 1995; Starzyk et al., 2001). However, the problem with this type of voltage multipliers was the low breakdown voltage of switches; difficult control and switching of a switch between the source and capacitor without any proportional element; and complexity in its configuration, which limit the potentiality of using this voltage multiplier in high–voltage application. However, since this configuration has a high–voltage efficiency and lower output and transmission path impedance compared to the traditional methods, it is only suitable for low–voltage on–chip applications.

Another regular method to generate a voltage larger than the available supply voltage is the charge pump circuit (Shin et al., 2000; Pylarinos and Rogers Sr, 2003). Unlike the other traditional DC–DC converters, which employ inductors, charge pumps are only capacitors and switches (Dickson, 1976).

1.1.2 Capacitor Discharge Application

One of the applications that requires a voltage higher than the available power supply voltage is the Marx impulse generator (Toudeshki et al., 2012b). This generator is producing high–voltage impulses based on the capacitor discharge technique

(Toudeshki et al., 2013). In this technique, capacitors charge in parallel connection and discharge the stored energy to the load, when capacitors are connected in series. Before discharge occurs for a Marx impulse generator, the output voltage peak can be attained to the maximum of m times greater than the input DC voltage.

Although the Marx impulse generator is a circuit that is used for increasing the input DC voltage to a higher level, this circuit also needs a high–voltage DC source, in its input. This requirement is for making a sustainable insulation breakdown in the air gaps. Therefore, the Marx impulse generator itself needs another DC voltage multiplier circuit for providing its required high input DC voltage.

1.1.3 Summary of Background

All the mentioned methods which were used in order to achieve a voltage which is higher than the source, had some advantages and disadvantages and none of them was perfect. However, by utilizing the advantages of each configuration, it is expected that a new circuit with better performance can be proposed. Although the proposed circuit topologies look simple, due to existence of many switches, passive energy storage components, voltage drops and transmission of the ac electrical power through the circuit's components, the exact performance of the circuit is complicated and needs to be simplified.

The circuits that is discussed in this thesis, sometimes called "voltage multiplier" and often "charge pump". It is believed that both names are correct and can be use to call this circuit. However, since the transformers and boost converters are also multiplying the applied input voltage to a constant value, it is preferred to call the Cockcroft and Walton; Dickson's class circuits as "charge pump", which this name can show the natural functionality of these types of circuits. This is the reason why this name is appeared in the title of this thesis.

1.2 Problem Statement

Since about a century ago, many methods for producing a voltage larger than the available supply voltage are known, such as Cockcroft and Walton (1932); Falkner (1973); Dickson (1976); Makowski and Maksimović (1995); Starzyk et al. (2001); Karthaus and Fischer (2003). However, considering the advantages and disadvantages of each method shows that some unsolved problems still remain. The main problem is the low–voltage gain capability of the existing circuits. Although the voltage gain of Makowski and Maksimović (1995) and Starzyk et al. (2001) circuit configurations were significantly greater than other methods, they are impractical for high–voltage applications. On the other hand, the maximum voltage gain of the existing configurations which can be employed for high-voltage application such as Cockcroft and Walton (1932) and Karthaus and Fischer (2003) cannot be more than two times number of stages times the input voltage. Thus, in order to attain a higher voltage gain, using the same number of stages, the circuit configuration needs to be improved. In addition, it is found that calculating the output voltage by following the actual performance of the charge pump is difficult and time–consuming. Moreover, calculating the output voltage as a function of time is also a complex and time-consuming process. In order to design a charge pump, knowing the output voltage value as a function of number of stages and other significant parameters is necessary. On the other hand, the long transient time is another problem that exists on this topic, and needs to be improved.

1.3 Aim of study

In order to produce a higher amount of potential energy, the aim of this study is to improve on the performance of the existing charge pump configuration for high–voltage application. Respectively, a novel charge pump configuration should be proposed. A new numerical–graphical technique need to be demonstrated for describing the numerical correlations between the voltage gain of the proposed novel charge pump and the previous charge pumps. The exact behaviour of the proposed charge pump circuit must be obtained by clarifying its optimal model. By knowing more information regarding the performance of the proposed charge pump circuit, it can be utilized for different fields of applications.

1.4 Objectives

The main objectives of this study are as follows.

i. To propose a new circuit configuration of charge pump that can be utilized in high–voltage applications.

ii. To find a simple method that can explain the performance of the proposed circuit.

iii. To generalize an approximate mathematical model for calculating the output voltage of the proposed charge pump configuration, in steady–state.

iv. To suggest a time–domain model for the proposed and conventional charge pump systems.

1.5 Research Contributions

The most significant contributions of this study are as follow:

a. Introducing a novel charge pump configuration that can be utilized in high–voltage application.

b. Simplifying the complex performance of the proposed circuit (in a theoretical, numerical and graphical ways), understandable for future applications.

c. The graphical and analytical presentation of the output gain correlations between the previous and the proposed novel charge pump circuits.

d. Finding the optimal value of the input capacitance.

e. Generalizing a new approximate mathematical model for the output voltage components of the proposed novel charge pump configuration, in steady–state, as a function of the input voltage, number of stages and pumping frequency.

f. A universal model as a function of time that can explain the time–domain response of both conventional and proposed novel charge pump circuits.

g. Proposing an open–loop control system and investigating the stability of the charge pump, based on the sinusoidal input voltage and its time–domain response, for both conventional and proposed novel charge pump circuits, that can be used to simulate the performance of both charge pump circuits for future studies.

h. Simulation, experimental test, measurement and data analysis of the proposed novel charge pump circuit.

1.6 Scope and Limitations of the Study

The main purpose of the novel charge pump circuit is for storage of the potential energy in a capacitor. This stored energy will be used in capacitor discharge application. Therefore, the load of this circuit is assumed as a pure capacitive load during all design, calculation, test and evaluation process. The experimental circuit design optimization is carried–out based on the biggest value of energy storage component (100 nF) with maximum breakdown voltage of 1 kV, which was available in the electronic market in Malaysia, to achieve the required DC output of 3 kV and

0.45 J potential energy, from an initial 6 to 9 V DC power supply, for the capacitive discharge application. However, theoretically this method can be also generalized for different values of voltage gain and number of stages.

1.7 Outline of Thesis

This thesis includes five chapters, as the following. Chapter 1 (the current chapter) is the introduction of this thesis and introduces the background, statement of the problem, aim of study, objectives and the scope and limitations of the study. Chapter 2 is the literature review. The general methodology of this work is presented in Chapter 3 and the results, and their discussions are given in Chapter 4. Finally, the work is concluded in Chapter 5.

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