UNIVERSITI PUTRA MALAYSIA

HIGH-VOLTAGE IGNITION CIRCUIT FOR COMPRESSED NATURAL GAS DIRECT INJECTION ENGINE

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MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA

2007

Dedicated to,

My beloved Mother Zaibah Endut,
My loving Father Omar Ismail,
My faithful sister, brothers, relatives & friends

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

HIGH-VOLTAGE IGNITION CIRCUIT FOR COMPRESSED NATURAL GAS DIRECT INJECTION ENGINE

By

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March 2007

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Ignition system of an internal combustion engine is an important part of the overall engine management system. It is a means to provide enough high-voltage, minimum around 20 kV to form an arc across the gap of a spark plug and to control the ignition timing. Thus, it can provide a right time to burn the air-fuel mixture inside the engine.

With advances in technology, the ignition system has progressed from a contact point ignition system to an electronic ignition system and then to a digital distributorless ignition system. The increased growth of the ignition system design in both size and complexity has brought about the need for a simple and reliable ignition system to provide high-voltage output to be delivered to the spark plug and at the same time to adapt with the natural gas engine environment. Therefore, with the development of an economical and reliable ignition system, there is a growing interest in developing digital distributorless ignition system, which is programmable making it more flexible and superior to other conventional system.

This thesis presents the development of an ignition circuit for a coil-on plug ignition system of a natural gas engine. The main specification of the circuit is the implementation of the ignition power-switching device at the primary side of the circuit to provide high switching speed to turn on and off the device. The chosen power-switching device was Insulated Gate Bipolar Transistor or IGBT, which is more suitable to be implemented inside the circuit design compared to other power-switching devices. The selected IGBT, IRGB14C40L are specifically design for a ignition applications and small engine ignition circuit. It has low saturation voltage and high self-clamped inductive switching energy. The modelling and optimization of the ignition IGBT parameters is done in the PSPICE software to fulfill the real ignition power-switching device requirements. The other specification of the circuit design is the implementation of the snubber circuit, which can provide over-voltage protection at the primary side of the power-switching device. Finally, the testing of the circuit is done by applying a control signal at the input source terminal or at the gate terminal of the ignition IGBT. The complete circuit design is integrated with the high-voltage ignition coil and a special designed long neck spark plug for the natural gas engine purpose. The circuit has been tested to make sure it can provide the desired voltage so it can ignite the mixture of the air and compressed natural gas in the right cylinder and at the right time.

From the test results of the ignition circuit, it demonstrates that the performances of the ignition parameters such as the primary current and secondary voltage are highly affected by the device parameters like the ignition IGBT parameters, specifications of the high-voltage ignition coil as well as the control strategy of the switching-time to ignite the spark plug.

Abstrak tesis yang dikemukakan Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

LITAR PENYALAAN BERVOLTAN-TINGGI UNTUK ENJIN GAS ASLI TERMAMPAT SUNTIKAN TERUS

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Sistem penyalaan bagi enjin pembakaran dalam adalah satu bahagian penting bagi keseluruhan sistem pengurusan enjin. Ia adalah sumber yang boleh menghasilkan voltan cukup tinggi minimum sekitar 20 kV untuk menghasilkan arka merentasi ruang di antara palam pencucuh serta untuk mengawal masa pembakaran. Oleh itu, ia boleh menghasilkan masa yang sesuai untuk membakar campuran udara-bahan bakar di dalam enjin.

Dengan kemajuan teknologi, sistem penyalaan telah berkembang dari sistem penyalaan titik sentuh kepada sistem penyalaan elektronik kemudian kepada sistem penyalaan digital tanpa pengagih. Perkembangan rekabentuk sistem penyalaan dari segi saiz dan kerumitannya telah membawa kepada perlunya sistem penyalaan yang ringkas dan mampu menghasilkan keluaran voltan-tinggi untuk dialirkan kepada palam pencucuh dan pada masa yang sama untuk disesuaikan dengan persekitaran enjin gas asli. Oleh itu, dengan pembangunan sistem penyalaan yang ekonomik, dan berkemampuan, terdapat peningkatan minat dalam pembinaan sistem penyalaan digital tanpa pengagih yang lebih fleksibel kerana diprogramkan dan lebih hebat dari titik sentuh konvensional yang lain.

Tesis ini mempersembahkan pembinaan litar penyalaan bagi sistem penyalaan gelung di atas palam untuk enjin gas asli. Spesifikasi utama bagi litar ini adalah pelaksanaan peranti suis-kuasa penyalaan pada bahagian utama litar untuk menghasilkan laju pensuisan yang tinggi bagi menghidupkan dan mematikan peranti tersebut. Peranti suis-kuasa yang dipilih adalah 'Insulated Gate Bipolar Transistor' atau IGBT, yang lebih sesuai untuk dilaksanakan pada rekabentuk litar berbanding dengan peranti-peranti suis-kuasa yang lain. IGBT yang dipilih iaitu IRGB14C40L, adalah direka khas bagi aplikasi pencucuhan dan litar pencucuh enjin sederhana. Ia mempunyai voltan tepu yang rendah dan kebolehan mengapit yang tinggi bagi tenaga pensuisan aruhan. Pemodelan dan pengoptimuman bagi parameter-parameter IGBT penyalaan ini dilakukan di dalam perisian PSPICE untuk memenuhi keperluan sebenar peranti suis-kuasa penyalaan. Spesifikasi lain bagi rekabentuk litar adalah pelaksanaan litar 'snubber' yang boleh memberi perlindungan daripada lebihan-voltan di bahagian utama peranti suis-kuasa. Akhirnya, pengujian ke atas litar dilakukan dengan mengaplikasikan isyarat kawalan pada terminal sumber masukan atau pada terminal get IGBT penyalaan. Rekabentuk litar yang lengkap diintegrasikan dengan gelung pencucuh bervoltan-tinggi dan palam pencucuh yang direka khas mempunyai leher yang panjang bagi kegunaan enjin gas asli. Litar ini telah diuji untuk memastikan ianya boleh menghasilkan voltan yang dikehendaki untuk menyalakan percampuran udara dan gas asli termampat di dalam silinder sebenar dan pada masa yang sesuai.

Daripada keputusan eksperimen litar penyalaan, ia menunjukkan prestasi parameter-parameter penyalaan seperti arus utama dan voltan sekunder adalah lebih diakibatkan oleh parameter peranti seperti parameter-parameter IGBT penyalaan, spesifikasi gegelung penyalaan bervoltan tinggi serta strategi kawalan masa-penyuisan untuk menyalakan palam pencucuh.

ACKNOWLEDGEMENTS

First of all, with the humble gratitude, I would like to express my thanks and deepest praise to The Most Gracious and Most Merciful ALLAH Who has given me all strength, faith, confidence and patience to complete this project.

This project was sponsored by the Ministry of Science, Technology & Innovation (MOSTI) Malaysia under CNGDI: Engine & Transmission (Combustion & Ignition System Group), IRPA's Project No.: 03-02-02-0057-PR0030/10-04. Thanks a lot for their generous financial support.

My sincerest thanks to my supervisor Prof. Ir. Dr. Norman Mariun and member of my supervisor committee Assoc. Prof. Dr. Ishak Aris for their advice, support, understanding, criticism, guidance and encouragement to help me through this thesis and trying period of time. I will always be eternally grateful for their kindness

Finally, I would like to thank Universiti Putra Malaysia, my beloved father and mother, sister and brothers and to all my friends especially at Advanced Automotive Technology Laboratory (AATL), Dept. of Electrical & Electronics Engineering, UPM and Combustion Group, UKM for their moral support and encouragement.

I certify that an Examination Committee has met on **10 March 2008** to conduct the final examination of **Azimah binti Omar** on her **degree** thesis entitled "**High-Voltage Ignition Circuit for Compressed Natural Gas Direct Injection (CNGDI) Engine**" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the Master of Science.

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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.

AZIMAH BINTI OMAR

Date: 20 March 2008

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LIST OF ABBREVIATIONS

A/D Analog to Digital

AFR	Air-fuel Ratio
BJT	Bipolar Junction Transistor
CDI	Capacitive discharge ignition
CGSO	gate-source overlap capacitance
$(CH_3)_3CSH$	*Tertiary*-butyl mercaptan
CH_3-S-CH_3	Dimethyl sulfide
CH_4	Methane
CJC	collector-base junction capacitance
CJE	emitter-base junction capacitance
CNG	Compressed Natural Gas
CNGDI	Compressed Natural Gas Direct Injection
CO	Carbon monoxide
COP	Coil-on-plug
CR	Compression Ratio
Cs	capacitors
D	ratio of time
D.C.	Duty cycle
DLI	Distributorless semiconductor ignition system
di/dt	the rate of change of the current
dic/dt	current change ratio
dv/dt	the rate of change of the voltage
ECU	Electronic Control Unit
EMI	Electromagnetic interference
f	frequency
GDI	Gasoline Direct Injection

GM	General Motors
HC	Hydrocarbon
HO	High Output
IANGV	International Association for Natural Gas Vehicle
I_c	Collector current
IGBT	Insulated Gate Bipolar Transistor
I/O	Input/Output
Ip	primary current
Is	secondary current
IS	saturation current
ISE	base-emitter diode saturation current
ja	junction to the ambient
KP	transconductance
kV	kilovolt
L_{coil}	Coil inductance
LNG	Liquefied Natural Gas
LVP	Low Voltage Programming
L_P	primary inductance
LPG	Liquefied Petroleum Gas
L_{sn}	snubber circuit inductance
L_{st}	wiring inductance
mA	milliampere
MCU	Microcontroller Unit
mH	millihenry
mJ	millijoule

ms	millisecond
MPI	Multi Point Injection
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
n	turn ratio
NG	Natural Gas
NGV	Natural Gas Vehicle
NO_x	Nitrogen oxides
N_P	Primary windings
N_S	Secondary windings
Pd	Power dissipation
PIC	Peripheral Interface Controller
PWM	Pulse Width Modulation
RON	Research Octane Number
R_P	Primary resistance
RPM	Revolution per Minute
R_S	Secondary resistance
Rs	resistors
$R_{\theta ja}$	thermal resistance from junction to ambient
$R_{\theta jc}$	thermal resistance from junction to case
$R_{\theta cs}$	thermal resistance from case to sink
$R_{\theta sa}$	thermal resistance from sink to ambient
SCR	Silicon-controlled rectifier
SI	Spark Ignition
SI	Semiconductor ignition
SOA	Safe Operating Area

subckt	Subcircuit
T	period
T_a	ambient temperature
t_{cycle}	time to complete one cycle
TDC	Top Dead Center
TI	Transistorized ignition
T_j	junction temperature
t_{on}	time the switch is on
TS	turn-off delay time
T_{scf}	Trillion standard cubic feet
VAF	forward early voltage
V_c	Collector voltage
V_{ce}	Collector-emitter voltage
$V_{CE(sat)}$	Collector-emitter saturation voltage
V_{fr}	fall period voltage
V_{ge}	Gate-emitter voltage
V_{pulse}	Pulse Voltage
VTO	threshold voltage
W_s	safe ignition energy
µs	microsecond
ΔV	voltage oscillation

CHAPTER 1

INTRODUCTION

1.1 Background of the Ignition System

The main purpose of an *ignition system* is to ignite the air-fuel mixture in the combustion chamber at a proper time. In order to maximize engine output efficiency, the air-fuel mixture must be ignited so that maximum combustion pressure occurs approximately at 10 degrees after Top Dead Center (TDC). However, the time from ignition of the air-fuel mixture to the development of maximum combustion pressure varies depending on the engine speed and the manifold pressure. For example, ignition must occurs earlier when the engine speed is higher and later when it is lower [1].

The development of the ignition system has moved on from the conventional contact-point ignition system to the digital distributorless ignition system. The rapid design of the system is to fulfill the ignition system requirements, together with the advancement of the current engine design. In this project, the ignition system would be installed in the Compressed Natural Gas Direct Injection or CNGDI engine. It is a new engine design technology with the modification on the combustion chamber, ignition system, injection technology, fuel system, and engine management system. Different engine design gives different engine performance. Therefore, the performance of the ignition system inside the CNGDI engine and gasoline engine has some differences on the ignition parameters. Such critical ignition parameters are firing voltage, firing current, spark voltage, and spark duration [2].

Theoretically, the ignition voltage required by the spark plug is the maximum high-voltage necessary for spark discharge, which can exceed 60 kV. The high-voltage builds up field strength between the spark gap's electrodes, so that the spark gap is ionized and thus become conductive [2]. Unfortunately, the implementation of the GDI (Gasoline Direct Injection) ignition system inside the CNGDI engine cannot fulfill the ignition system requirement. The main factor is the changes of the engine environments when the combustion chamber is mixed-up with air-gas mixture. Natural gas needs higher firing voltage to ignite the air-gas mixture as compared with the gasoline fuel.

1.2 Problem Statement

The difficulty to ignite the natural gas with low voltage comes from the effect of the contents of the natural gas. There is around 90% of methane inside the natural gas with one carbon atom and four hydrogen atoms attached together. The remainder comprises of ethane, propane, butane, and other components [3]. Meanwhile, the gasoline fuel is made up of molecules composed of hydrogen and carbon arranged in chains. It has seven to eleven carbons in each chain for the configurations of heptane, octane, nonane and decane [4].

As a comparison between methane and gasoline, the strength of the carbon-hydrogen covalent bond in methane is the strongest even compare with the other hydrocarbons, and thus its uses, as a chemical feedstock is limited. This is the characteristic of methane, which will affect the ignition performance inside the internal combustion engine. It is also reported to have higher octane rating around 130 RON; but it does not have enough energy to ignite the air-fuel mixtures at higher compression ratio [5].

Therefore, the needs to supply high-voltage ignition system have become the main issue in the combustion and ignition process of the natural gas engines. There are two ways to get the high-voltage supply to the ignition coil, by applying the high-voltage to the primary side of the ignition circuit or switch-off the current flowing through the primary side very quickly.

The first way is not applicable, as the current in the primary circuit will rise very quickly with a large applied voltage. Consequently, the increase of the current will also saturate the transformer core at the primary side of the ignition coil. The increase of the current in a short time will finally blow the power-switching device. The second way is depending on the characteristic of the power-switching device to switch-off in limited time and the amount of voltage it can deliver.

In this project, to overcome the problem mentioned above, a high voltage circuit topology is proposed by implementing a protection circuit and suitable IGBT device, IRGB14C40L. The IGBT unit would be implemented in the electronic ignition circuit design by modelling and optimizing the parameters of the device in the PSPICE software. After that, the ignition circuit would be integrated with the microcontroller unit to control the spark timing.