Spark Energy and Transfer Efficiency Analyses on Various Transistor Coil Ignition Systems

Hua Zhu

University of Windsor

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Spark Energy and Transfer Efficiency Analyses on Various Transistor Coil Ignition Systems

By

Hua Zhu

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Mechanical, Automotive and Materials Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2018

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Spark Energy and Transfer Efficiency Analyses on Various Transistor Coil Ignition Systems

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May 7, 2018
DECLARATION OF ORIGINALITY

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ABSTRACT

The ever-growing demands to meet the exhaust emission regulations and fuel economy requirements have driven the development of modern spark ignition (SI) engines towards lean/diluted combustion strategies and engine downsizing. Currently, the transistor coil ignition (TCI) system is still the dominant ignition system applied in SI engines. However, the new development in SI engines demands higher spark energy and longer discharge duration to overcome the unfavorable ignition conditions caused by the diluted in-cylinder charge and the increased back pressure. Under these circumstances, higher energy transfer efficiency of the ignition system is also desirable. Therefore, this work investigates the factors that affect the spark energy and transfer efficiency of the TCI system.

The primary current, discharge current and spark gap voltage of the TCI system under the single-coil single discharge and dual-coil offset discharge strategy were measured. Based on the measurement, the spark energy and transfer efficiency were calculated. A numerical model was developed and demonstrated the capability to estimate the trend of spark energy and transfer efficiency of the TCI system. The model was then used to systematically analyze the effects of coil inductance and charging duration/frequency on the spark energy and transfer efficiency of the TCI system.
DEDICATION

This Thesis is dedicated to my parents, Shiming Zhu and Lianxiang Xu, and my brother, Rong Zhu, who have always been supportive while I pursue my goal.

Also, to my husband, Li Liang and my daughter, Kexin Liang. Without your love and support, all of my success and goals I have achieved would not have been possible.
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Finally, I would like to thank my family – my parents, my husband and my daughter for their love and support. This work is dedicated to them.
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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

\( E_p \)  Electrical energy stored in the primary winding  \([\text{mJ}]\)
\( E_{p,\text{loss}} \)  Resistive losses in the primary circuit  \([\text{mJ}]\)
\( E_{\text{spark}} \)  Electrical energy delivered to the spark gap  \([\text{mJ}]\)
\( E_{s,\text{loss}} \)  Resistive losses in the secondary circuit  \([\text{mJ}]\)
\( I_p \)  Primary current  \([\text{A}]\)
\( I_s \)  Secondary current  \([\text{mA}]\)
\( L_p \)  Inductance of the primary winding  \([\text{mH}]\)
\( L_s \)  Inductance of the secondary winding  \([\text{H}]\)
\( R_{\text{gap}} \)  Equivalent resistance of the conductive plasma channel  \([\Omega]\)
\( R_p \)  Total resistance of the primary circuit  \([\Omega]\)
\( R_{p,\text{cable}} \)  Cable resistance of the primary circuit  \([\Omega]\)
\( R_{p,\text{winding}} \)  Resistance of the primary winding  \([\Omega]\)
\( R_{\text{plug}} \)  Embedded resistance of the spark plug  \([\Omega]\)
\( R_s \)  Total resistance of the secondary circuit  \([\Omega]\)
\( R_{s,\text{cable}} \)  Cable resistance of the secondary circuit  \([\Omega]\)
\( R_{s,\text{winding}} \)  Resistance of the secondary winding  \([\Omega]\)
\( U_{\text{gap}} \)  Voltage drop across the spark gap  \([\text{V}]\)
\( U_p \)  Voltage drop across the primary winding  \([\text{V}]\)
\( U_{ss} \)  Supply voltage  \([\text{V}]\)
\( \eta \)  Energy transfer efficiency of the TCI system  \([\%]\)

Abbreviations

CAFE  Corporate Average Fuel Economy
CI  Compression Ignition
CO₂  Carbon Dioxide
<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>DCO</td>
<td>Dual Coil Offset</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>GHG</td>
<td>Green House Gas</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>Oxides of Nitrogen – NO and NO\textsubscript{2}</td>
</tr>
<tr>
<td>RT</td>
<td>Real Time</td>
</tr>
<tr>
<td>SI</td>
<td>Spark Ignition</td>
</tr>
<tr>
<td>TCI</td>
<td>Transistor Coil Ignition</td>
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CHAPTER 1.  INTRODUCTION

1.1 Background
The spark ignited (SI) combustion technology is one of the dominant powertrain technologies for light duty vehicles. In 2016, non-hybrid gasoline cars powered by SI engines accounted for 97% of new light duty vehicle sales in the United States [1-2].

SI engines have advantages over compression ignition (CI) engines regarding the exhaust after-treatment processes but suffering from thermal efficiency losses. Nevertheless, the legislative requirements for the fuel efficiency and exhaust emissions are continuously tightened. In the United States, EPA has set up the Corporate Average Fuel Economy (CAFE) standards to regulate the fuel economy for vehicles in recent years. Furthermore, some governments around the globe have established or proposed greenhouse-gas (GHG) emission standards to regulate the CO₂ emission. These markets in those countries covered 80% of the global passenger vehicle sales, thus the fuel efficiency and CO₂ emission regulations influence the business decisions of most major vehicle manufacturers [3].

1.2 Challenges on the ignition system of modern SI engines
The enhancement of fuel economy and the reduction of CO₂ emission imposed severe challenges on the development of modern SI engines. Advanced technologies and strategies have been deployed in recent years to improve the fuel efficiency of SI engines.

Lean and stratified combustion, along with engine downsizing using turbocharging, are employed to reduce the pumping work by less throttling, especially at lower engine loads. However, the turbocharged SI engines tend to suffer from higher knocking risks than those
of naturally aspirated engines. The tendency of knocking prevents an optimum combustion phasing [4-6].

Regarding knocking suppression, different techniques have been proposed, as reported in literatures. Among them, the exhaust gas recirculation (EGR) is considered to be a promising technique [7-8]. EGR, by introducing a percentage of exhaust gas to the fresh charge at the engine intake, was commonly used in diesel engines for the reduction of NOx because of lowered flame temperature [10]. Nowadays, EGR is also applied in SI engines to contain the NOx formation and to improve the engine efficiency under partial load. At high load, EGR could lower the burnt gas temperature by means of charge dilution, which reduces knocking risks [9-10]. Therefore, engine downsizing, lean/diluted, and stratified combustion are considered to be the promising techniques for future SI engines.

However, the implementation of the above-mentioned strategies brings unfavorable conditions for the complete combustion of the cylinder charge. An excessive lean mixture reduces the opportunities of forming an ignitable composition in the vicinity of the spark gap; the EGR and/or air dilution reduce the flame propagation speed, which makes ignition more difficult. All of these cause slower burning rates, leading to partial burns or even misfires. Significant cycle-to-cycle variations were often observed, because strong air motion was often implemented to enhance mixing and flame propagation [6] [11-12]. The increase of the cylinder pressure, which is often associated with turbocharging or supercharging, also leads to higher gas densities at the ignition site, which in turn requires higher breakdown voltage supplied from the ignition system.
To ensure stable ignition and fast burn under the above-mentioned conditions, the stabilization of ignition and initial combustion is of great importance. Therefore, the current ignition system of SI engines should be improved substantially.

1.3 Ignition process in SI engines

In SI engines, the ignition of the air-fuel mixture is initiated with a spark discharged plasma which creates a flame kernel. The flame kernel succeeds evolving in a self-sustaining manner by the energy release of combustion, in addition to the concurrent plasma expansion. Generally, the spark discharge process of the ignition system is considered in three phases: the breakdown phase, the arc phase and the glow phase [6].

Breakdown phase

Prior to the breakdown, the electrical field is built up between the electrodes of a spark plug. The increasing electrical field starts accelerating thermal electrons towards the anode. If the electrical field strength is high enough, the electrons will ionize molecules in the collisions and generate an avalanche-like increase in electrons and ions. In addition, low wavelength UV-radiation is being emitted by the excited atoms. Ionized streamers travel from one electrode to the other, building up conductive plasma channels between the electrodes of the spark plug. When the conduction is built between the opposing electrodes, the impedance in the between would decrease drastically. Figure 1.1 shows the schematic of the breakdown phase. The energy from the parasitic capacitor inside the spark plug is released. The breakdown phase proceeds under high-voltage (e.g. ~ 10 kV), high-peak current (e.g. ~ 200 A) and extremely short duration (e.g. 1 ~ 3 ns) [6] [36].
Arc phase

The breakdown phase is always followed by an arc phase. The energy stored inside cable and coil capacitances are released during the arc phase. The characteristics of the arc phase are controlled by the external impedance of the ignition circuit. For instance, the voltage across the electrodes is about 100 V and the current is greater than 100 mA. The arc phase is sustained by electrons emitted from the cathode hot spots thus it may cause erosion of electrodes [15].

Glow phase

As the current reduces, e.g. to less than 100 mA, the spark discharge transfers into a glow phase. The voltage drop between electrodes is typically 300 to 500 V [6] [15]. The glow energy is dictated mainly by the ignition coil. The glow phase generally lasts for a few milliseconds. During this long-lasting low-current discharge, the ignition circuit releases most of the electrical energy – in the order of tens of millijoules or higher [6] [15]. Due to the long discharge duration, the plasma channel in glow phase is sensitive to the flow field.
In case of strong air motion involved, the cross flow will stretch the plasma, causing a longer plasma channel with higher line resistance between the electrodes. If the flow velocity is high enough, the long plasma channel will be blown out and restrikes across the gap may occur.

1.4 Transistor coil ignition (TCI) system

Research results have shown that a stronger thermal expansion from a high energy spark discharge can help ensure that the flame kernel reaches a threshold radius which is believed to be critical for the flame kernel to evolve to self-sustainability. High energy ignition experiments have shown the effectiveness of extending the engine lean and dilution operation limits [12].

Based on this, various high energy ignition concepts and systems are proposed and developed in recent years. In practice, the improvements of the ignition processes are employed either by an intensified breakdown discharge, e.g. by seeking a larger ignition volume or a higher breakdown power, or by an enhanced energy delivery process during the glow phase e.g. a higher level of discharge current or a longer discharge duration [17].

Despite the progresses achieved in the advanced ignition technology development, the transistor coil ignition (TCI) system is still the most prevalent system currently applied to SI engines. It is popular for its simplicity in design, low in cost and robust in performance. The conventional TCI system mainly consists of a power supply, an inductive ignition coil, a transistor switch and a spark plug. This type of inductive ignition system can reliably provide the ignition energy at the selected time within one spark event for engines operated at near stoichiometric air/fuel ratios, even with the modest amount of EGR. However, the
energy delivery from a single coil single discharge event is limited because of the inherent limit of energy storage. Under highly diluted or lean conditions, the conventional TCI system may not supply enough electrical energy to the spark gap to realize robust ignition control. Research results over the past also show that the typical decaying discharge current profile of a conventional TCI system has drawback regarding combustion stability – especially under high dilution and low load conditions [23]. Thus, the question for the conventional TCI system arises whether it could be further improved to deliver more energy to the spark gap and what are the most promising approaches for the future research and development.

Aside from operating in the single-coil single discharge working mode, the ignition coil of the TCI system can also work under a high-frequency mode. Based on this concept, different advanced discharge strategies including single-coil repetitive discharge and dual-coil offset discharge strategies have been developed and investigated recently [14] [18-21].

A single-coil repetitive discharge strategy is mainly based on the conventional TCI system. By elevating the charging voltage from DC 12 V to a higher level, the ignition coil can be charged and discharged several times within a certain duration. Piock [18] demonstrated the development of a high frequency repetitive discharge ignition system incorporated into the Delphi powertrain control system. Bae [19] investigated the discharge characteristics of a high frequency multi-charge ignition strategy in flow conditions. Hese [20] characterized the impact of the multi-charge ignition system on stratified charge combustion and suggested that the improvement brought by this strategy was attributed to the series of high-power breakdown events. Figure 1.2 shows the waveforms of the single-coil repetitive discharge process [14].
The dual-coil discharge strategy uses two identical ignition coils connected to a common spark plug with two diodes. The diodes are used to isolate the high-voltage interference between the coils. According to different control strategies, these two coils can be charged simultaneously or in an alternating way. Southwest Research Institute developed a dual-coil offset (DCO) ignition system. In order to produce a long duration continuous spark discharge, the two coils are set up to work under a specific time sequence repetitively. Alger [21] employed the DCO ignition system on a 2.4 L 4-cylinder gasoline engine to investigate the EGR diluted operation. The results showed that the DCO continuous discharge extended the EGR tolerance by 5-10% over the conventional single-coil single-
spark strategy. Chen [22] tested a variable output ignition system, with a similar configuration of DCO system, on a 3.5 L V6 turbo-charge direct-injection gasoline engine. The results showed that a long duration discharge could extend the dilution limit and reduce the number of misfired cycles. Figure 1.3 is the waveforms of the dual-coil offset discharge process [14].

![Waveforms of dual-coil offset discharge process](image)

Figure 1.3 Waveforms of dual-coil offset discharge process [14]

The advanced discharge strategies mentioned above are able to deliver more electrical energy into the spark gap as desired. However, the TCI system, no matter the conventional single-coil single discharge or the high-frequency discharge strategies, all suffer from high resistive losses because of the high resistance of the components in the system.
Taking the TCI system under single coil single discharge strategy as an example, the resistive energy losses will rise non-linearly with the increase of the energy delivered to the spark gap. For example, if 100 mJ energy is to be introduced into one cylinder and the overall energy transfer efficiency of the ignition system is 5%, the energy delivered to the primary winding of the ignition coil needs to be 2 J; for a four-cylinder engine working under 6000 r/min, the average power demanded for the ignition system will be 400 W. This means the average current will be more than 30 A if the primary charging voltage is DC 12 V, which will generate an excessive amount of heat in the ignition system [14].

In order to deliver electrical energy to the spark gap more efficiently, an energy analysis originating from the power supply in the primary side to the remained electrical energy at the spark gap is important. The electrical energy transfer efficiency, which is defined as the ratio of the energy delivered to the spark gap to the total energy consumed in the primary side, is a significant performance indicator for an inductive ignition system. The higher energy transfer efficiency means more energy is available at the spark gap, and less resistive losses in the electrical circuit.

1.5 Objective of the thesis

TCI systems are crucial for future high efficiency clean SI engines. The enhancement of the existing system and the development of the advanced discharge strategies are both of great importance. The objective of this work is to investigate the effects of coil inductance and charging duration/frequency on the spark energy and transfer efficiency of the TCI system under single-coil single discharge and dual-coil offset discharge strategies. The primary current, discharge current and gap voltage of the TCI system were measured. Based on the measurement, the spark energy and transfer efficiency were calculated. A
numerical model was developed and demonstrated the capability to estimate the trend of spark energy and transfer efficiency of the TCI system. The model was then used to systematically analyze the effects of coil inductance and charging duration/frequency on the spark energy and transfer efficiency of the TCI system.

1.6 Structure of the thesis

This thesis is organized as follows:

Chapter 1 is an introduction to the research background along with reviews of relevant literature in this field.

Chapter 2 introduces the experimental setup of the multi-coil ignition research platform which is used in this study to measure the primary current, discharge current and gap voltage of different TCI systems.

Chapter 3 is an investigation of the spark energy and transfer efficiency of the TCI system under the conventional single-coil single discharge strategy.

Chapter 4 is a further investigation of the TCI system under the dual-coil offset discharge strategy. Detailed parametric analyses were conducted to identify the influences of coil inductance and charging frequency on the spark energy and transfer efficiency of the TCI system.

Chapter 5 summarizes the major findings of this thesis followed by brief comments on future work.
CHAPTER 2. EXPERIMENTAL SETUP

2.1 Multi-coil ignition research platform

To investigate the spark discharge characteristics of a transistor coil ignition (TCI) system, an advanced multi-coil ignition research platform was used. A simplified schematic of the experimental setup is shown in Figure 2.1. This platform consists of a constant volume combustion chamber and a multi-coil ignition system. The current and voltage waveforms were acquired during charging and discharging processes under varied back ground pressures. The energy and transfer efficiency of the investigated TCI system were calculated based on the electrical measurement results.

Figure 2.1 Multi-coil ignition research platform
2.1.1 Constant volume combustion chamber with optical access

The constant volume combustion chamber of the research platform has a working volume of 30 mL. There are two optical access windows opposite to each other. As shown in Figure 2.1, the spark plug is mounted on the top of the chamber body.

2.1.2 Multi-coil ignition system

A multi-coil ignition system was used to investigate different discharge strategies of a TCI system in this study. The coils can be charged and discharged simultaneously or in an alternating manner. As shown in Figure 2.2, the output terminals of the ignition coil are connected with a high voltage diode in series, and then connect to a common spark plug. The major function of the inline high voltage diodes is to enable independent discharging processes of each coil, especially when two coils are not charged and discharged simultaneously. Another function of the inline high voltage diodes is to prevent unexpected breakdown during a charging process.

![Diagram of multi-coil system](image)

Figure 2.2 Connection between the coil and spark plug of the multi-coil system
The multi-coil ignition system is powered by a DC power supply. The charging process of each coil is controlled by an insulated gate bipolar transistor (IGBT, V3040p) of automotive ignition type. A National Instruments real time (RT) computer with a field programmable gate array (FPGA) module was programmed to generate the control signal to the IGBT for different charging durations.

When the primary winding of each coil was charged, the primary current was measured with a Tektronix A622 AC/DC current probe. Tektronix A622 is a “long nose” style clamp-on probe that uses a Hall effect current sensor to provide a voltage output to the oscilloscope. The range of the current probe is from 50 mA to 100 A, with a frequency range up to 100 kHz.

The spark discharge voltage was measured through a Tektronix P6015 high voltage probe that was attached to a socket. The socket is plugged to the top of the spark plug. The P6015 is a ground-referenced 100 MΩ, 3 pF high voltage probe with 1000X attenuation [23]. Because of this high internal resistance of the P6015, the impact of the probe on the spark discharge process is negligible.

The discharge current was measured with a Pearson 411 current probe, which is a toroid shaped device. During the spark discharge process, the discharge current of the ignition circuit would excite inductive current signals within the probe.

All acquired data were recorded by a PicoScope 4824 high-precision oscilloscope. The recording was externally triggered by a spark energizing command signal from the RT-FPGA.
2.2 Impedance analyzer

A Keysight Technologies E4990A impedance analyzer was used to measure the inductance, capacitance and resistance of all components of the ignition system, and the coupling coefficient $k_{cp}$ of the ignition coil. The specifications of the impedance analyzer are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Spectrum frequency:</th>
<th>20Hz to 20MHz</th>
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<tr>
<td>Measurement accuracy:</td>
<td>±0.08%</td>
</tr>
</tbody>
</table>

When measuring the primary winding inductance or the secondary winding inductance of the ignition coil, the ends of one winding were connected to the measurement ports of the impedance analyzer by using a pair of Kelvin clips, whereas the ends of the other winding were kept open. The measurement circuit is shown in Figure 2.3.

Figure 2.3 Measurement circuit of the primary/secondary winding inductance
The leakage inductance is a self-inductance because of the imperfect coupling of two windings [25] [34] [43]. It results in a leakage flux. When short-circuiting the ends of the secondary winding while measuring the inductance of the primary winding, as shown in Figure 2.4, the leakage inductance of the primary winding was determined.

![Figure 2.4 Measurement circuit of the leakage inductance](image)

The coupling coefficient $k_{cp}$ of the ignition coil was calculated from the measured leakage inductance and the winding inductance by using equation (1) as in previous work [25] [34] [44].

$$k_{cp} = \sqrt{1 - \frac{L_{ss}}{L_p}}$$

where $L_{ss}$ is the leakage inductance value and $L_p$ is the primary winding inductance.

The impedance analyzer provides the impedance phase and amplitude spectrum of the measured objects within a certain frequency range. Because the low current glow phase of a spark discharge event lasts for a few milliseconds, the measured impedance spectrum from 20 Hz to 5 kHz was used in this study.
2.3 Spark plugs and ignition coils

An NGK BKR6E spark plug was used in the experiments of the TCI system with single-coil single discharge, and an iridium in-stock spark plug was used for investigating the advanced discharge strategies. The gap sizes of both spark plugs were confirmed to 0.86 mm. The resistances of the embedded resistor of the NGK spark plug and the iridium in-stock spark plug are 5 kΩ and 4.3 kΩ respectively. This embedded resistor is to suppress the electrical field noise of the spark discharge process.

Five types of ignition coils from different manufacturers were used to investigate the impact of inductances on the discharge characteristics of the TCI system. The inductance, resistance and coupling coefficient values of these coils were measured using the aforementioned methods, the results are shown in Table 2.2. The primary inductances of the tested coils are in the range from 2 mH to 5.7 mH; the secondary inductances are in the range from 8 H to 40 H.

Table 2.2 Parameters of ignition coils used in this study

<table>
<thead>
<tr>
<th></th>
<th>Coil A</th>
<th>Coil B</th>
<th>Coil C</th>
<th>Coil D</th>
<th>Coil E</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_p ) (mH)</td>
<td>5.7</td>
<td>5</td>
<td>2.9</td>
<td>2.37</td>
<td>2</td>
</tr>
<tr>
<td>( R_{p,winding} ) (Ω)</td>
<td>0.7</td>
<td>0.67</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>( L_s ) (H)</td>
<td>32.5</td>
<td>40.1</td>
<td>15.3</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>( R_{s,winding} ) (kΩ)</td>
<td>5.61</td>
<td>7.2</td>
<td>5</td>
<td>8.2</td>
<td>5.8</td>
</tr>
<tr>
<td>( k_{cp} )</td>
<td>0.97</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>
CHAPTER 3. TCI SYSTEM WITH SINGLE-COIL SINGLE DISCHARGE

3.1 Overview of the TCI system

Figure 3.1 shows a simplified schematic of a conventional transistor coil ignition (TCI) system used in this study. The TCI system is still the most prevalent system to ignite combustible mixtures in SI engines. It consists of a DC 12 V battery, an inductive coil that contains a primary winding and a secondary winding, a transistor switch, and a spark plug.

![Diagram of the TCI system]

The primary winding of the ignition coil is connected to the battery through the transistor switch. The secondary winding of the ignition coil is directly connected to the spark plug. During the dwell time shortly before the timing of ignition, the transistor switch in the primary circuit is closed for a few milliseconds, which builds up a magnetic field in the
primary winding. The maximum available electrical energy is stored in the magnetic field. At the timing of ignition, the primary circuit is interrupted by the opening of the transistor switch. The magnetic field in the primary winding drops suddenly, which induces a primary voltage up to 400 V negative for a short time. In accordance with the principle of the transformer, a high-voltage peak value up to 30 kV positive is induced in the secondary winding. Due to the high voltage, the mixture between the spark plug electrodes becomes ionized. Thereby an electric spark jumps over the electrodes [25-26]. Conductive ion channels then are built up across the spark gap.

When ion channels are built up between electrodes of the spark plug upon breakdown, the spark discharge process proceeds to the arc and glow phases. Figure 3.2 shows the typical discharge current and gap voltage waveforms of the glow phase observed in this study. The measurement was conducted with the experimental setup mentioned in Chapter 2, using Coil A and the NGK spark plug under atmospheric ambient conditions with a charging duration of 3 ms.

Figure 3.2 Discharge current and gap voltage waveforms of the glow phase
3.2 Current and voltage measurement and energy transfer calculation

Within the TCI system, the ignition coil operates as a dual-function device by serving both as a transformer and an energy accumulator [26]. The inductance and resistance values of the primary winding and the secondary winding determine the characteristics of the primary current, gap voltage and discharge current, as well as the energy distribution of the ignition system. To investigate the spark energy of the TCI system during the glow phase, for each of the five coils, the primary current, gap voltage and discharge current were measured. The spark energy and transfer efficiency were calculated based on the measurements. This section summarizes the measurement methods of the charge and discharge characteristics (3.2.1), and presents the calculation methods of the spark energy and transfer efficiency of the TCI system (3.2.2).

3.2.1 Measurement methods of the current and voltage

Figure 3.3 illustrates the electric circuit of a conventional TCI system used in this study. Table 3.1 is the descriptions of each symbol in the circuit. As shown in Figure 3.3, the primary voltage ($U_p$) and current ($I_p$) were measured at the upstream of the primary winding.
Figure 3.3 Electric circuit of the conventional TCI system

Table 3.1 Nomenclature of the TCI circuit in Figure 3.3

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{ss}$</td>
<td>Supply voltage</td>
</tr>
<tr>
<td>$R_{p,cable}$</td>
<td>Cable resistance in the primary circuit</td>
</tr>
<tr>
<td>$R_{p,winding}$</td>
<td>Primary winding resistance</td>
</tr>
<tr>
<td>$L_{p}$</td>
<td>Primary winding inductance</td>
</tr>
<tr>
<td>$L_{s}$</td>
<td>Secondary winding inductance</td>
</tr>
<tr>
<td>$R_{s,winding}$</td>
<td>Secondary winding resistance</td>
</tr>
<tr>
<td>$R_{s,cable}$</td>
<td>Cable resistance in the secondary circuit</td>
</tr>
<tr>
<td>$R_{plug}$</td>
<td>Spark plug embedded resistance</td>
</tr>
<tr>
<td>$I_{p}$</td>
<td>Primary current</td>
</tr>
<tr>
<td>$U_{p}$</td>
<td>Primary winding voltage</td>
</tr>
<tr>
<td>$I_{s,downstream}$</td>
<td>Discharge current measured downstream of the spark plug</td>
</tr>
<tr>
<td>$I_{s,upstream}$</td>
<td>Discharge current measured upstream of the spark plug</td>
</tr>
<tr>
<td>$U_{s,downstream}$</td>
<td>Discharge voltage of the downstream measurement</td>
</tr>
<tr>
<td>$U_{s,upstream}$</td>
<td>Discharge voltage of the upstream measurement</td>
</tr>
<tr>
<td>$U_{gap}$</td>
<td>Discharge voltage across the spark gap</td>
</tr>
</tbody>
</table>
In the secondary circuit (right side in Figure 3.3), the gap voltage can be measured directly at the tip of the central electrode towards the gap with a high voltage probe. This method is referred as “downstream measurement” in this work. However, attaching the voltage probe to the central electrode of the spark plug during the real engine operation is not convenient due to the high temperature and pressure of the combustion process. Another method is to attach the voltage probe to the top of the spark plug. This method is referred as “upstream measurement” in this work. By using the upstream measurement, the spark plug voltage instead of the gap voltage is acquired directly. The gap voltage \( U_{\text{gap}} \) is then calculated with equation (2).

\[
U_{\text{gap}} = U_s - I_s R_{\text{plug}}
\]  

(2)

Figure 3.4 illustrates the voltage waveforms acquired by both downstream and upstream methods. The difference value of the measured voltage by these two methods is the voltage drop across the embedded resistors of the spark plug.

![Figure 3.4 Discharge voltage from upstream and downstream measurement](image-url)
The discharge current was measured by placing the current probe at either upstream or downstream of the spark plug. As shown in Figure 3.5, the difference of the measured discharge current between the upstream and downstream measurement within the discharge duration is very small.

![Discharge current from upstream and downstream measurement](image)

Figure 3.5 Discharge current from upstream and downstream measurement

The spark energy, i.e. the electric energy delivered to the spark gap, is calculated by integrating the product of gap voltage and discharge current directly over the discharge duration, as expressed in equation (3).

\[
E_{\text{spark}}(t) = \int_0^t U_{\text{gap}}(t)I_s(t)\,dt
\]  

(3)

For downstream measurement, the measured voltage is the gap voltage, the spark energy thus is directly calculated according to equation (3). For upstream measurement, the spark plug voltage instead of the gap voltage is directly measured, thus the spark energy is calculated with equation (4).

\[
E_{\text{spark}}(t) = \int_0^t U_{\text{upstream}}(t)I_{s,\text{upstream}}(t)\,dt - \int_0^t I_{s,\text{upstream}}^2(t)R_{\text{plug}}\,dt
\]  

(4)
Figure 3.6 shows the calculated spark energy from upstream and downstream measurement methods using the NGK spark plug with an embedded resistor of 5 kΩ. It can be seen that different measuring points of the discharge voltage and current did not affect the calculated spark energy significantly. Therefore, the gap voltage and discharge current in the following sections were all measured by the upstream measurement method.

![Figure 3.6 Spark energy from upstream and downstream measurement](image)

3.2.2 Calculation of energy and transfer efficiency of the TCI system

The primary energy \( (E_p) \), which is defined as the energy stored into the primary winding during the charging process, is calculated with equation (5) \([14][34]\).

\[
E_p = \frac{1}{2} \times L_p \times I_{p,\text{max}}^2
\]  

(5)

where \( L_p \) is the primary winding inductance, which is typically within a few mH, and \( I_{p,\text{max}} \) is the cut-off current of the primary circuit \([14][34]\). The total resistance of the primary circuit is usually in the order of 0.5 Ω to 1 Ω. Although this resistance is relatively low, the primary current can be as high as tens of amperes during
the charging process. This means the primary resistive losses are not negligible. The primary resistive losses (\(E_{p,\text{loss}}\)) is calculated with equation (6) [14] [34].

\[
E_{p,\text{loss}}(t) = \int_{0}^{t_{\text{charge}}} I_p(t)^2 R_p \, dt \tag{6}
\]

where \(R_p\) is the total resistance of the primary circuit, and \(t_{\text{charge}}\) is the charging duration. The resistances of the battery and the transistor switch in the primary circuit are not considered when calculating the primary resistive losses because their values are negligible compared to the primary winding resistance.

The total energy consumed in the primary circuit is the summation of the primary energy and the primary resistive losses, as in equation (7) [14] [34].

\[
E_{p,\text{total}}(t) = E_p + E_{p,\text{loss}}(t) \tag{7}
\]

The energy transfer efficiency of the ignition system, which is defined as the ratio of the spark energy available at the spark gap to the total energy consumed in the primary side, is calculated with equation (8) [14] [34].

\[
\eta = \frac{E_{\text{spark}}}{E_{p,\text{total}}} \tag{8}
\]

where \(E_{\text{spark}}\) is the spark energy calculated using equation (3).

The secondary resistive losses (\(E_{s,\text{loss}}\)) is calculated by integrating the product of the discharge current (\(I_s\)) and the total secondary circuit resistance (\(R_s\)) over the discharge duration, as in equation (9) [14] [34].
\[ E_{s,\text{loss}}(t) = \int_0^{t_{\text{discharge}}} I_s(t)^2 R_s \, dt \]  

(9)

where, \( R_s \) is the total resistance of the secondary circuit, including the secondary winding resistance and the embedded resistance of the spark plug, and \( t_{\text{discharge}} \) is the discharging duration. Because the resistance of the high voltage cable used in the secondary circuit is negligible compared to the secondary winding resistance, this cable resistance is not considered in the calculation of the secondary resistive losses.

The primary current, discharge current and gap voltage of five types of coils were measured by using the experimental setup described in Chapter 2 under atmospheric ambient conditions. The primary energy and spark energy of the ignition system were calculated based on the measurement results. Among the five types of ignition coils used in this study (Table 2.2), Coil A and Coil B have comparatively higher inductances than those of Coil C to Coil E. Coil E has the smallest primary inductance and secondary inductance.

Taking Coils A and E as examples, Figure 3.7 shows the acquired waveforms and the calculated spark energy with a charging duration of 3 ms. The cut-off current of Coil A is only one third of the cut-off current of Coil E because the primary inductance of Coil A is almost three-times that of Coil E. The discharge current of Coil A is half of that of Coil E because of the higher secondary inductance and lower cut-off current.
Figure 3.7 Charge and discharge characteristics of Coil A and Coil E

Figure 3.7 also shows that 27 mJ spark energy was delivered to the spark gap by Coil A and 17 mJ spark energy was delivered to the spark gap by Coil E. The main reason is that the coil with both higher primary and secondary inductances has lower cut-off current and discharge current, resulting in less resistive losses and thus higher overall energy transfer efficiency.

Also noted in Figure 3.7, Coil E was saturated at 2.8 ms charging duration, thus no more electrical energy could be charged into the primary winding afterward. This is because the primary inductance of Coil E is very small (2 mH).
Coils with higher inductance (e.g. Coil A) can deliver more energy to the spark gap when charging for the same duration, as shown in Figure 3.7. However, higher inductance requires a larger number of windings and a bigger area of winding cross section, thus, lead to a bigger size of coil.

3.3 Modeling of the TCI system

To further investigate and generalize the impact of coil inductance on the charge and discharge characteristics of the TCI system, a numerical model was developed to emulate the primary current, gap voltage and discharge current of the TCI system during the glow phase. The model includes two sub-models, a transformer sub-model to emulate the energy transfer of the ignition coils and a spark gap resistance sub-model to describe the dynamic change of the conductive ion channels between the spark gap during the glow phase.

3.3.1 Modeling of the equivalent gap resistance

During the spark discharge process, conductive ion channels are formed between the spark gap after a breakdown event occurs. According to the typical discharge current and gap voltage waveforms during the glow phase, discharge current drops from a maximum value \( I_{s,\text{max}} \) to zero; gap voltage is in the order of 400-500 V and increases as the discharge current decreases. This suggests that the resistance of the conductive ion channel is not a constant value during the glow phase. According to the previous research results, the conductive ion channel resistance varies as a function of the discharge current and depends on the electrode material, gap size and gas type, density, and temperature in the ion channel [27-29]. Several models have been proposed in the literature to emulate the gap resistance during the glow phase [27-29].
To evaluate different ignition coils reproducibly and to minimize the variability and noise caused by the spark gap, the researchers in the automotive industry often use a zener diode instead of a real spark plug to measure and calculate the output energy of different ignition coils. This test method is defined in SAE J973 [31]. This standard mainly describes the electrical performance and test methods of ignition systems. In this standard, a zener diode is connected to the secondary winding of the ignition coil to simulate the gap voltage by permitting the current to flow through it when the voltage exceeds a certain value [31].

Previously, a simplified circuit model with a constant spark gap voltage and a constant gap resistance was proposed to approximate the voltage and resistance of the ion channels during the spark discharge process [34]. The spark energy calculated by this model was similar as the spark energy measured by the zener diode method. However, this constant gap voltage and constant gap resistance cannot represent the dynamics in a realistic discharge.

To describe the dynamic changes of the gap voltage and gap resistance during the glow phase, an equivalent gap resistance (R_{gap}) is proposed in equation (10). It is defined as the ratio of the gap voltage (U_{gap}) to discharge current (I_s).

\[
R_{\text{gap}} = \frac{U_{\text{gap}}}{I_s} \quad (10)
\]

Experiments were conducted by using the NGK BKR6E spark plug under atmospheric ambient conditions. The gap size of the spark plug was 0.86 mm. Air was used as gas media. Coil A and Coil B were used to investigate how R_{gap} changes as I_s decreases during the glow phase. The primary winding inductances of Coil A and Coil B are 5.7 mH and 5 mH
respectively; the secondary winding inductances are 32.5 H and 40.1 H respectively.

During the experiments, the charging durations of both coils were modulated to produce a peak discharge current \( I_{s,\text{max}} \) within the range of 10 mA to 130 mA. \( R_{\text{gap}} \) is derived with equation (10). The calculated \( R_{\text{gap}} \) values are plotted in Figure 3.8 as a function of the discharge current. When \( I_s \) increases from 10 mA to 30 mA, \( R_{\text{gap}} \) drops from \( \sim 50 \, \text{k}\Omega \) to \( \sim 10 \, \text{k}\Omega \). However, when \( I_s \) increases beyond 30 mA, \( R_{\text{gap}} \) drops less than a few kiloohms.

![Graph showing the relationship between equivalent gap resistance and discharge current.](image)

**Figure 3.8** Empirically derived results of the equivalent gap resistance

Pischinger and Suit [25] [30] have proposed a power function to describe the relationship between the gap voltage and the discharge current during the glow phase of a spark discharge. Combining this power function with equation (10), an expression for \( R_{\text{gap}} \) is derived as shown in equation (11).

\[
R_{\text{gap}}(t) = a \times I_s(t)^{-b}
\]  

(11)

\( a \) and \( b \) are two empirical parameters, derived from curve fitting based on the experimental data. \( a \) and \( b \) depend on the electrode material, gap size, and gas type, density, and
temperature across the gap. A non-linear least square method [32] was applied. Upon best fitting, the derived regression for $R_{\text{gap}}$ is expressed in equation (12).

$$R_{\text{gap}}(t) = 180.77 \times I_s(t)^{-1.19}$$ (12)

Figure 3.9 depicts that the model is an excellent fit of the experimental data.

![Figure 3.9 Curve fitting results of the equivalent gap resistance](image)

### 3.3.2 Modeling of the TCI circuit

A transformer model was adopted from Tan [34], who proposed a simplified model with a constant gap voltage and gap resistance to describe the charge and discharge characteristics of the TCI system. However, the equivalent gap resistance model was used to replaced the constant gap voltage and gap resistance in this study. This model includes the charging and discharging processes of the TCI system. For simplicity, the parasitic capacitance and inductance of the system have not been considered. Figure 3.10 shows the electric circuit used for model derivation.
Charging process

During the charging process, the switch in the primary circuit is closed for a certain duration. The primary current flows through the primary circuit and gradually increases. As the primary current increases, the primary energy gradually stores in the magnetic field of the coil. In this process, the build-up of the primary current is slow (in the order of milliseconds). The voltage induced within the secondary winding is not high enough to generate a breakdown across the spark gap. In this case, the secondary circuit is treated as an open circuit and the primary circuit of the TCI system is simplified into an L-R charging circuit as shown in Figure 3.11.
Therefore, the primary current $I_p$ is estimated according to equation (13) [14] [34].

$$I_p(t) = \frac{U_{ss}}{R_p} \times (1 - e^{-\frac{R_p}{L_p}t})$$  \hspace{1cm} (13)

where $R_p$ is the total resistance of the primary circuit.

**Discharging process**

At the end of the charging process, the switch open of the primary circuit forces the primary current to drop from a maximum value ($I_{p,\text{max}}$) to zero immediately. The abrupt interruption of the primary current induces a high voltage across the secondary winding. Once the voltage difference between the spark gap reaches the breakdown limit, conductive ion channels are formed across the spark gap. At this point, continuous current flows through the secondary circuit and the energy stored in the magnetic field is released through the secondary circuit. The voltage across the spark gap is often in the range of a few
hundred volts to sustain the continuous flow of free ions across the spark gap. Because the primary current is forced to zero immediately at the end of the charging process, the primary circuit is treated as an open circuit and the secondary circuit is simplified into an L-R discharge circuit, as shown in Figure 3.12.

![Figure 3.12 Electric circuit of the discharging process](image)

So $I_s$ is described using equation (14) [14] [34].

$$I_s(t) = I_{s,\text{max}} - (I_{s,\text{max}} + \frac{U_{\text{gap}}}{R_s})(1 - e^{-\frac{R_s}{L_s}t}) \quad (14)$$

where $R_s$ is the total resistance of the secondary circuit, including the secondary winding resistance and the embedded resistance of the spark plug. $I_{s,\text{max}}$ in equation (14) is derived by equation (15).

$$I_{s,\text{max}} = k_{cp} \times I_{p,\text{max}} \times \sqrt{\frac{L_p}{L_s}} \quad (15)$$

where $k_{cp}$ is the coupling coefficient between the primary winding and the secondary winding, which is calculated with equation (1).
In equation (14), $U_{\text{gap}}$ is an unknown parameter and related to the change of gap resistance. Using the equivalent gap resistance model (equation (10) and equation (12)), $U_{\text{gap}}$ is expressed with equation (16).

$$U_{\text{gap}}(t) = 180.77 \times I_s(t)^{-0.19}$$  \hspace{1cm} (16)

Combining equation (14) and (16), $I_s$ is expressed as a function of time, the coil inductances and the circuit resistances, as in equation (17).

$$I_s(t) = \left[ \frac{e^{-1.19 \frac{R_s}{L_s}} \times \left(-180.77 e^{1.19 \frac{R_s}{L_s}} + 180.77 + R_s I_s^{1.19}_{\text{max}} \right)}{R_s} \right]^{0.84}$$  \hspace{1cm} (17)

**TCI model results**

The developed model was applied to Coil A and Coil B. Figure 3.13 shows the modeled and measured results. The derived model captured the trends of the measured primary current, discharge current and gap voltage during the charging and discharging processes. Thus, the model estimated spark energy, by large, agrees with that of the experimental data. However, the model over-predicated the measured primary current and discharge current, likely because of the exclusion of the parasitic inductance and capacitance etcetera. Measurement errors of the coil parameters, especially in the primary inductance, is another reason of the discrepancy between the model prediction and observational data.
3.3.3 Validation of the TCI model

In order to verify that this model can be used to estimate the spark energy and transfer efficiency for a wide range of ignition coils, four types of ignition coil with different coil inductances were used for model validation. To calculate the spark energy and transfer efficiency under different primary energy level, the charging durations of each coil were modulated from 1 ms to 6 ms progressively with 1 ms increment. The simulated and experimental results of the spark energy and transfer efficiency for these coils are plotted in Figure 3.14 to Figure 3.17, one figure for each of the four coils.

Figure 3.13 Modeling results of Coil A and Coil B
Figure 3.14 Spark energy and transfer efficiency of Coil A

Figure 3.15 Spark energy and transfer efficiency of Coil B
The model-measurement comparison indicates that the developed model performed relatively well. Because of the measurement errors of the coil parameters and the parasitic inductance and resistance of the experimental system, differences still exist between the simulated and the experimental results. For Coil D and Coil E, the differences between the simulated and experimental results become larger, 24% and 26% respectively, when the...
coils are close to saturation as indicated by leveled-off of the spark energy (around 160 mJ) in Figure 3.16 and Figure 3.17.

3.4 Parametric analyses of impact of coil inductances

Once the simplified model has been demonstrated the capability to estimate the trend of spark energy and transfer efficiency of the TCI system with single-coil single discharge as the primary energy varies, the model was used to systematically analyze the effects of coil inductances on the spark energy and transfer efficiency of the TCI system.

Simulations of both primary and secondary inductance variations were conducted. Considering the differences between simulation and experimental results caused by the saturation of coils, simulations were conducted under 50 mJ, 100 mJ and 150 mJ of primary energy levels. For each primary energy level, \( L_p \) was set from 2 mH to 6 mH with 0.5 mH increment and \( L_s \) changed from 8 H to 40 H with 2 H increment. \( R_{p,winding} \) and \( R_{s,winding} \) were kept as constant values (0.7 Ω and 7.2 kΩ respectively) and the charging voltage was DC 12 V in all simulations. Contour maps of the transfer efficiency of different coil inductances under three primary energy levels are shown in Figure 3.18 to Figure 3.20, one for each primary energy level.
Figure 3.18 Energy transfer efficiency (Primary energy 50 mJ)

Figure 3.19 Energy transfer efficiency (Primary energy 100 mJ)
The shaded blue areas in Figure 3.18 to Figure 3.20 are the identified regions where the secondary voltage is lower than 30 kV because of the insufficient step-up ratio of the ignition coil configuration. To ensure a breakdown across the spark gap, the output voltage of the ignition coil should exceed a breakdown threshold to initiate the spark discharge. According to Paschen law [35-36], the breakdown voltage is a function of gas density and spark gap size. For a spark gap of ~1 mm, it is estimated that the breakdown voltage can exceed 30 kV in a modern boosted SI engine [17].

As illustrated in Figure 3.18 to Figure 3.21, for the TCI system with single-coil single discharge and charged under the same charging voltage, it was observed that:

1) For coils with the same inductance, the increase of the primary energy leads to lower energy transfer efficiency. This is mainly because the higher primary energy leads to higher primary resistive losses.

2) When the primary energy level is constant, energy transfer efficiency rises with the increase in both primary inductance and secondary inductance.
In addition, the ratio between $L_s$ and $L_p$ determines the step-up voltage ratio of the ignition coil, as shown in equation (18). To ensure a breakdown across the gap, the combination of $L_p$ and $L_s$ cannot be chosen arbitrarily.

$$\text{Turn ratio} = \sqrt{\frac{L_s}{L_p}}$$ (18)

Figure 3.21 shows the relationship between the turn ratio and the transfer efficiency of the TCI system under 50 mJ of primary energy level. The shaded area is the identified region where the secondary voltage is lower than 30 kV because of the insufficient step-up ratio of the ignition coil. When the primary energy level is constant, for coils with the same primary inductance, higher turn ratio leads to higher energy transfer efficiency; for coils with the same turn ratio, bigger coils with higher primary and secondary inductances have higher energy transfer efficiency, as expected.

Figure 3.21 Relationship between the turn ratio and transfer efficiency

Figure 3.22 shows the relationship between the primary inductance and the charging duration. It can be seen that coils with higher primary inductances need longer charging
duration to store the same amount of energy into the primary winding under the same charging voltage. This prolongs the time lag between the ignition command and the actual spark event, which might not be favorable for ignition control under higher engine speed. This is the drawback of the coils with higher inductances although the increased inductance can improve the transfer efficiency of the TCI system.

Figure 3.22 Relationship between charging duration and primary inductance
CHAPTER 4. TCI SYSTEM WITH ADVANCED DISCHARGE STRATEGIES

4.1 Overview of the advanced discharge strategies

The spark energy delivered from the single-coil single discharge of the transistor coil ignition (TCI) system is limited due to its energy storage capability. In order to realize robust ignition control under highly diluted and/or lean combustion, a trend of the advanced ignition system is to deliver more energy to the spark gap. Based on the existing TCI system, the application of the advanced discharge strategies is able to introduce more energy into the spark gap [11]. The advanced discharge strategies include single-coil repetitive discharge, dual-coil simultaneous discharge, and dual-coil offset discharge. The main difference of the advanced discharge strategies from the conventional single-coil single discharge is the application of high charging and discharging frequency.

4.2 Single-coil repetitive discharge strategy

The single-coil repetitive discharge strategy is based on the TCI system. By elevating the charging voltage of the primary winding, the ignition coil can be charged and discharged under a certain frequency to generate multiple discharge events during the discharge process. Figure 4.1 illustrates the discharge process of the single-coil repetitive discharge strategy acquired by the experimental setup described in Chapter 2. The charging voltage was elevated to DC 18.3 V and the charging frequency was 5 kHz. The charging duration for the first charge event was longer (1 ms), then the following charge event stored adequate energy into the primary winding again. As shown in Figure 4.1, the energy stored in the primary winding is not fully released when the discharging process is interrupted by the next re-charging process. The residual energy is still stored in the primary winding at the
end of each discharging process, causing the primary current starting at a level above zero at the beginning of the next charging cycle. By picking up the current value at both ends of each charge event, the amount of energy stored in the primary winding can be calculated.

![Graphs showing Command, Primary current, Secondary current, Gap voltage against Time (ms)]

Figure 4.1 Single-coil repetitive discharge strategy

The repetitive discharge strategy can generate multiple breakdown events. A higher charging frequency might be required under engine applications to generate a sufficient number of breakdown events during the discharging process. Smaller primary and secondary inductances with the increase of the charging voltage are necessary to guarantee a fast charging and discharging process [14].
4.3 Dual-coil discharge strategy

The dual-coil discharge strategy comprises two normally identical inductive ignition coils connected to a common spark plug. Two diodes are used to isolate the high-voltage interference between two coils. Figure 4.2 shows the simplified schematic of the dual-coil configuration investigated in this study.

![Figure 4.2 Schematic of the dual-coil configuration used in this study](image)

4.3.1 Dual-coil simultaneous discharge strategy

With two coils discharging through a common spark plug, two coils in this strategy can be charged simultaneously or in an alternating mode under a certain frequency. When two coils are charging simultaneously, the system could behave similarly as a single-coil repetitive discharge strategy. The effect is the discharge current level would be doubled compared with the single-coil system under the same charging voltage and frequency. Figure 4.3 shows the voltage and current waveforms of a dual-coil simultaneous discharge strategy acquired by the experimental setup described in Chapter 2 under DC 18.3 V charging voltage and 5 kHz charging frequency.
4.3.2 Dual-coil offset discharge strategy

When two coils of the dual-coil system are working under a specific charging timing offset, which means one coil is charging during the discharging process of the other coil and conversely, the current will continuously flow through the spark gap as long as one of the coils is active. Figure 4.4 shows the waveforms of a dual-coil offset discharge strategy under DC 18.3V charging voltage and 5 kHz charging frequency.
Compared with the single-coil repetitive discharge and the dual-coil simultaneous discharge, the dual-coil offset discharge strategy only generated one breakdown event during the discharging process. This is because the second coil already has started discharging process before the start of the re-charging process of the first coil. The working principle of each coil remains the same as that of the single-coil repetitive discharge strategy. The entire discharge duration of the dual-coil offset strategy is controlled by changing the number of the charging events. The discharge current level is controlled by adjusting the control parameters of the strategy, including the coil inductances, the charging voltage, the charging duration of the first charge event and the charging frequency.
The main advantage of the dual-coil offset discharge strategy is the continuous plasma channels during the discharge duration. Comparing to the single-coil single discharge, each of the dual coils is working under a higher charging and discharging frequency. The major point of this research for the dual-coil offset discharge is to investigate how this high-frequency working mode influences the spark energy and transfer efficiency of the TCI system.

4.4 Single-coil single discharge vs. dual-coil offset discharge

To compare the single-coil single discharge and dual-coil offset discharge strategies, tests are conducted by using both strategies with Coil A and an in-stock iridium spark plug.

For comparison purposes, to get the similar amount of spark energy for both strategies, and at least 50 mA of discharge current level for dual-coil offset discharge, experiments were all conducted under DC 17.5 V charging voltage with a charging duration of 4 ms. For the dual-coil offset strategy, the charging duration of the first charge event was 2 ms and the charging frequency was 1 kHz.

Figure 4.5 shows the measured primary current, discharge current and gap voltage of the single-coil single discharge. Figure 4.6 shows the corresponding measurement results of the dual-coil offset discharge strategy. It can be seen that unlike the triangle shape of the discharge current of the single-coil single discharge, the discharge current of the dual-coil offset strategy is almost constant at 50 mA within the first two milliseconds of the discharging process.
Figure 4.5 Waveforms of the single-coil single discharge
In addition, the cut-off current of the single-coil single discharge is almost twice as that of the dual-coil offset discharge strategy under the same charging voltage, causing more primary losses. Figure 4.7 is the energy analyses for both strategies. When delivering the same amount of electrical energy to the spark gap, the transfer efficiency of the dual-coil offset discharge is higher than that of the single-coil single discharge because of the lower primary resistive losses in the dual-coil offset discharge case.
4.5 Parameter analyses of the dual-coil offset discharge strategy

To further investigate how charging duration, charging frequency and coil inductance affect the spark energy and transfer efficiency of the dual-coil offset discharge strategy, experiments and simulations were conducted by varying these parameters.

4.5.1 Impacts of charging duration and charging frequency

For the dual-coil offset discharge strategy, the charging voltage, duration of the first charge event, and the alternating charging frequency determine the discharge current level of the TCI system.

To store an adequate amount of energy into the primary winding, the charging duration of the first charge event is usually longer than the following charge events. Under the same charging voltage, extending the first charging duration will elevate the discharge current level.

The charging frequency and the duty cycle determine the charging and discharging durations of each of the subsequent charge events. For example, when set up 1 kHz charging frequency and 50% duty cycle, both charging and discharging durations of each charge event are 0.5 ms. To maintain the continuous plasma channels across the spark gap,
two coils of the dual-coil offset discharge strategy should work under a specific charging timing offset, which means that one coil is charging while the other is discharging. The offset time of two coils should be equal or smaller than the discharge duration of each single discharge event.

Under flow conditions, high charging frequency is preferable to maintain the continuous plasma channels across the spark gap. Figure 4.8 shows the voltage and current waveforms of the dual-coil offset discharge strategy using Coil C under 40 m/s of cross-flow velocity. The charging frequency was 1 kHz. Under strong cross flow conditions, the actual discharge duration became shorter than the ideal value (0.5 ms), causing the plasma channel broken (discharge current approaching zero). This is mainly because the strong cross flow stretches the plasma channel during the discharge process. Due to the stretch, the path of the plasma is prolonged, resulting in an increase of the spark gap resistance. A restrike occurs if a certain value of the plasma channel length is exceeded, leading to the formation of a short circuit arc. Thus, the plasma channel holding period becomes shorter [38-39]. If the offset timing of two coils does not change, the discharge current tends to approach zero before the starting of the next discharge event. The plasma channel cannot be retained any longer when the discharge current decreases to zero. To maintain continuous plasma channels across the spark gap, an effective way is to increase the charging frequency and make the offset timing of two coils shorter than the actual discharge duration of each single discharge event.
Figure 4.8 Dual-coil offset strategy under flow condition (f=1 kHz)

Figure 4.9 illustrates the discharge waveforms under the same flow conditions but using 2.5 kHz charging frequency (0.2 ms charging and discharging duration). By increasing the charging frequency, the plasma channel was retained within the discharging process.

Figure 4.9 Dual-coil offset strategy under flow condition (f=2.5 kHz)

Although higher charging frequency is preferable under flow conditions, for the same coil under the same charging voltage, higher charging frequency means shorter charging duration. The discharge current level would become lower than that of using lower
charging frequency. Thus the charging voltage is usually elevated for the same coil with the same inductances to get a desired discharge current level.

To investigate the effects of charging frequencies on the spark energy and transfer efficiency of the dual-coil offset strategy, 4 sets of experiments were conducted by using Coil C under 4 charging frequencies: 1 kHz, 1.25 kHz, 1.66 kHz and 5 kHz. In order to obtain a similar amount of spark energy and 50 mA of discharge current level, the charging voltage of the experiments under each charging frequency was elevated. The charging durations of all experiments were 4 ms.

Figure 4.10 shows the discharge current waveforms under each charging frequency. The peak values of the discharge current at the beginning of each discharging process are all the same because the charging durations of the first charge event under all frequencies are 2 ms. When the charging frequency increases from 1 kHz to 5 kHz, the average discharge current level drops correspondingly. Moreover, the discharge current waveforms under 5 kHz charging frequency illustrates a decaying trend because the charging duration of each single charge event is curtailed.
Figure 4.10 Discharge current under different charging frequency

Figure 4.11 shows the calculation results of spark energy and transfer efficiency for each charging frequency. Within the same charging duration, the charging frequency does not have strong effects on the energy transfer efficiency of the TCI system. The energy transfer efficiency is slightly lower when the charging frequency is 5 kHz because of the decaying trend of the discharge current profile.
4.5.2 Impacts of coil inductances

Coil inductance is another important influential factor on the spark energy and transfer efficiency of the dual-coil offset discharge strategy. Based on the TCI model previously developed in Chapter 3, a dual-coil offset discharge model was established to further investigate the effects of the primary and secondary inductance values on the spark energy and transfer efficiency of the dual-coil offset strategy. Coil A and Coil C were used to verify the model. Coil A has a larger inductance ($L_p$: 5.7 mH, $L_s$: 32.5 H) while Coil C has a comparatively smaller inductance ($L_p$: 2.9 mH, $L_s$: 15.3 H). The calculated spark energy and transfer efficiency of simulation and experiments for both coils under different primary energy levels are shown in Figure 4.12. The estimations from the derived model for both coils agree well with the experimental results. Differences of the energy transfer efficiency between the simulation and experimental results are within 5%.
After the dual-coil offset discharge model being validated, simulations of varying both primary and secondary inductances were conducted. During the simulation, $L_p$ was varied from 2 mH to 5 mH with 0.5 mH increment, and $L_s$ was changed from 10 H to 40 H with 2 H increment. $R_{p,\text{winding}}$ and $R_{s,\text{winding}}$ for both coils were kept as 1 $\Omega$ and 5 k$\Omega$ respectively in all the simulations. To obtain at least 50 mA discharge current level, all simulations were conducted under DC 24 V charging voltage and 2.5 kHz charging frequency. The total charging durations of all simulations were 4 ms. Contour maps of the spark energy and transfer efficiency are presented in Figure 4.13 and Figure 4.14 respectively.

As illustrated in these figures, when the charging voltage and charging frequency kept the same, it was observed that:

1) For coils with the same secondary inductance, the increase of the primary inductance leads to lower spark energy, which is not beneficial for the lean/diluted combustion. The main reason is the charging rate of coils with higher primary
inductance is slower than that of coils with lower primary inductance, causing less amount of energy stored into the primary winding within a short charging duration. Figure 4.15 shows the contour map of the primary energy.

![Contour map of the primary energy](image1)

**Figure 4.13 Contour map of the spark energy**

![Contour map of the transfer efficiency](image2)

**Figure 4.14 Contour map of the transfer efficiency**
2) For coils with the same primary inductance, the spark energy increases while the energy transfer efficiency slightly drops as the secondary inductance rises.

Figure 4.16 shows the relationship between the turn ratio and the energy transfer efficiency of the dual-coil offset discharge. The shaded area is the identified region where the secondary voltage is lower than 30 kV. For coils with the same turn ratio, primary inductance has stronger effects on the improvement of the energy transfer efficiency.

Figure 4.15 Contour map of the primary energy

Figure 4.16 Transfer efficiency with different turn ratios
CHAPTER 5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions of thesis work
This study investigated the charge and discharge characteristics of the transistor coil ignition (TCI) system using both experimental and simulation methods. The scope included spark energy and transfer efficiency of the TCI system with the conventional single-coil single discharge and the dual-coil offset discharge. The major findings of the research are summarized in the following sections.

5.1.1 Method for electrical characteristics measurement of TCI system
1) The gap voltage was calculated from the measured spark plug voltage at the top of the spark plug by subtracting the voltage drop across the embedded resistor of the spark plug.
2) The discharge current was measured both at upstream or downstream of the spark plug.

5.1.2 TCI system with single-coil single discharge strategy
Under the same charging voltage:
1) It was observed that with the same coil inductance, the energy transfer efficiency reduces as the primary energy increases. This is mainly because the higher primary energy leads to higher primary resistive losses.
2) With a constant primary energy level, bigger coils with higher inductance have better energy transfer efficiency but suffering from longer charging duration. This longer charging duration prolongs the time lag between the ignition command and the actual spark event, which may not favorable for ignition control under higher engine speed.
3) With a constant primary energy level and same primary inductance, higher secondary inductance leads to lower discharge current, making it difficult to sustain a stable plasma channel under the condition of a higher back pressure and intensive in-cylinder charge motion.

5.1.3 TCI system with dual-coil offset discharge strategy

Under the same charging voltage and duration:

1) Between the single-coil single discharge and dual-coil offset discharge strategy, the latter has higher energy transfer efficiency when the same amount of energy was delivered to the spark gap. This is mainly because of the lower primary resistive losses in the dual-coil offset case.

2) Under the flow conditions, charging frequency of the dual-coil offset discharge strategy must be high enough to maintain continuous plasma channels across the spark gap.

3) For coils with the same secondary inductance, the increase of the primary inductance leads to lower spark energy.

4) For coils with the same turn ratio, primary inductance has stronger effects on the improvement of the transfer efficiency.

5.2 Future work

In this study, a spark gap resistance model for spark plug with 0.86 mm gap size under ambient condition (1 atm) has been developed. The next step of this project is to expand the gap resistance model to estimate the equivalent gap resistance during the glow phase by considering the influence of the gap size, electrode material, background pressure, and gas type and temperature.
The TCI model developed in this work is capable of capturing the trend of the spark energy and transfer efficiency of the TCI system. The next step is to further improve the model and use it to analyze the spark energy and transfer efficiency for a wider range of ignition coils (e.g. coils with primary inductance less than 2 mH or with secondary inductance higher than 40 H).
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