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Research Article

Simulation and Experimental Study on Secondary Voltage of Dual-coil Ignition System

Jing Haiguo, Yang Liping, Ma Xiuzhen, Wang Xiaobin and Huang Shuai
Institute of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China

Abstract: With the intention of improving ignition performance of natural gas engine, a dual-coil ignition system was devised according to energy superposition principle. Using Multisim software and experimental apparatus, the variation of secondary voltage along with discharge time interval was studied by taking simulation and experimental methods. The results show that dual-coil ignition system can enhance the secondary voltage, increase spark duration and accomplish multiple discharge under different discharge time interval compared with single-coil ignition system. So the dual-coil ignition system is conducive to reliable ignition for natural gas engine under different working conditions and it provides a way to optimize the ignition system.

Keywords: Dual-coil ignition system, natural gas engine, secondary voltage

INTRODUCTION

The physical characteristics of mixture in combustion chamber and flow field near the spark plug have a great impact on the formation of flame and initial flame development. Initial flame has a significant impact on the stability and emissions of natural gas engine. So it has more requirements to ignition system in natural gas engine (Zhao *et al*., 1997). The requirements are different to ignition system under different working conditions to CNG engine. In cold start condition, temperature of combustion chamber is low, so high-energy and multiple times ignition is needed to generate initial flame (Hong-guang *et al*., 2010). In lean burn condition, combination gas is thin, combustion speed slows down and so long spark and high-energy ignition makes for increasing the flame volume and enhancing the operation stability (Yang, 2008). In equivalent ratio mixture conditions, cylinder pressure is high, thus kinetic energy of electrode particle is reduced and so high secondary voltage is helpful for overcoming resistance and forming ignition flame (Qiao *et al*., 2004). Ignition system has gone through three generations: traditional ignition systems, electronic ignition system and high-energy ignition system. Nowadays the focus of study at home and abroad is the electric controlled high-energy ignition system. Bae *et al*. (1998) developed a high-frequency ignition to improve the stability of initial flame in lean burn condition. Gunter (2003) invented a plasma acceleration ignition system to expand the boundary of lean burn. Gao *et al*. (2005) designed a rail spark plug ignition for large-bore CNG engine. However there are some disadvantages in these ignitions, such as high cost, poor versatility and so on. So it still has a remarkable value for the ignition system in coli discharge type. According to the type of energy storage, it can be divided into two kinds of coil discharge ignition, one is inductive ignition system and the other is capacitive ignition system. Nowadays researchers are paying more attention to improve this kind of ignition system. Qiao *et al*. (2004) developed a multi-capacitor discharge ignition system which was used to increase spark duration, however spark duration of capacitive ignition is very short and it is very difficult to control the time superposition. Wang (2010) developed a set of inductive ignition system and they achieved multiple ignitions in engine start-up phase. Nevertheless it calls for a lot time in coil energy storage compared with capacitive ignition system, which limits the frequency of ignition. Moreover spark advance angle is quite different from each other, which brings apparent cyclic combustion variation. With the purpose of improving performance of inductive ignition system, a dual-coil discharge ignition system was designed.

Design of dual-coil ignition system: In the purpose of realizing multiple discharges to inductive ignition system, meanwhile giving consideration to increase spark duration and secondary voltage, a dual-coil ignition system was developed by using two ignition coils according to energy superposition principle. The discharge laws were controllable by changing the discharge time interval of the two coils. The ignition system components were shown in Fig. 1. The system was composed of signal generator, ignition control module, 12V DC power supply, ignition coil, high-voltage diode, ignition cable and spark plug. The signal

Corresponding Author: Yang Liping, Institute of Power and Energy Engineering, Harbin Engineering University, Harbin,150001, China

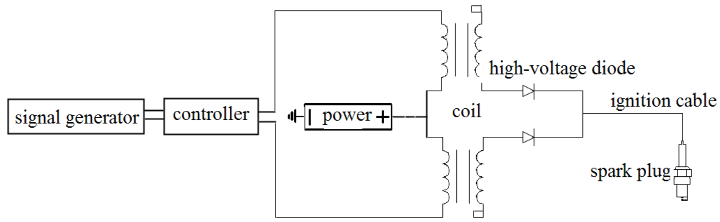

Fig. 1: Structure diagram of dual-coil discharge ignition system

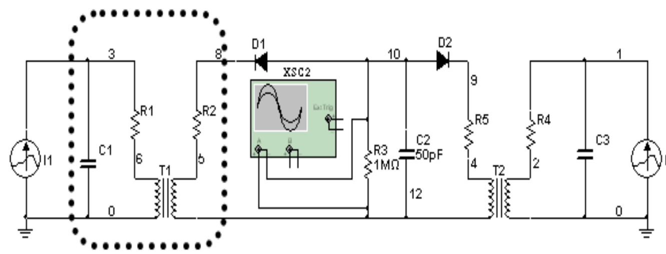

Fig. 2: Secondary voltage Simulation model of dual-coil ignition system

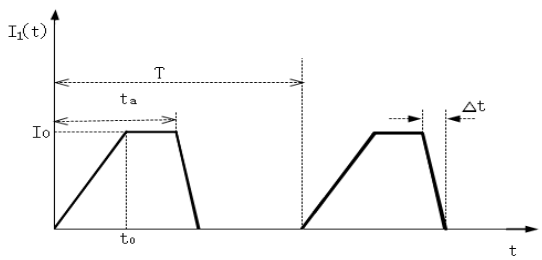

Fig. 3: Current waveform of primary coil

generator was used to provide simulate TDC signal and speed signal. The ignition control module was used to control charging time and discharge time interval of the two coils. To eliminate the interference between the two coils, two high-voltage diodes (D1 and D2) were used in secondary circuit.

Methods of evaluate the dual-coil ignition system: Many messages are contained in secondary voltage, such as the maximum voltage, voltage rise rate, spark duration, the stability of the spark and so on. So secondary voltage is taken as the index to evaluate the dual-coil ignition system. In this study secondary voltage is analysed by simulation and experimental methods.

Simulation of secondary voltage: Using Multisim software, Secondary voltage was simulated. Secondary voltage simulation model of dual-coil ignition system is shown in Fig. 2.

One coil of the system is taken as the example to explain the model. R_1 is primary coil resistance; R_2 is secondary coil resistance; L_1 is primary coil inductance; L_2 is secondary coil inductance; C_1 is equivalent capacitance of the primary coil; I_1 is a variable current source which is used to replace the DC power supply. $R_3$and C_2 are simulated load.R_1, R_2, L_1, L_2 and C_1 are all provided by manufacturer, I_1 is obtained by experiment, which shape is shown in Fig. 3 below.

The computational formula of I_1 in one revolution is shown in formula 1:

$$I_1 = \begin{cases} \frac{U}{R_1}[1-\exp(-R_1 t/L_1)] & 0 \le t \le t_0 \\ I_0 & t_0 \le t \le t_a \\ I_0-(t-t_0)\frac{I_0}{\Delta t} & t_a \le t \le t_a+\Delta t \\ 0 & t_a+\Delta t \le t < T \end{cases} \tag{1}$$

where,

U = The voltage of primary coil
I_0 = The maximum primary current
t_0 = The primary current rise time
t_a = The primary current charging time
Δt = The primary current fall time
T = The study cycle time

Generally there are three kinds of simulated load.

- 50pF capacitor and 1MΩ resistor in parallel is taken as simulated load when there is some soot in spark plug.
- 50pF capacitor and 100KΩ resistor in parallel is taken as simulated a little load when there is a little soot in spark plug.
- 50pF capacitor is taken as simulated load when there is no soot in spark plug.

А.Л.РУмянцев et al pointed out that 50pF capacitor and 1MΩ resistor in parallel was typical for the secondary load of ignition system (Umyantsev

Table 1: Experiment instruments

Name	Type
Signal generator	RIGOL DG1022
High-voltage probe	TeKtronix P5100A
Oscilloscope	RIGOL DS1102E

et al., 1987). So it was chosen as simulated load to simulate the change of secondary voltage

Experiment of secondary voltage: Secondary voltage is distinctly influenced by discharge environment, such as temperature and pressure. So the experiment was carried out when spark plug was placed in constant temperature and pressure environment.

Instruments in experiment are shown in Table 1. The signal generator is used to provide simulate TDC and speed signals, high-voltage probe is used to measure the discharge voltage in spark plug load; The oscilloscope is used to display and store the measurement results.

RESULTS OF SECONDARY VOLTAGE

Accordingly, there are two kinds of secondary voltage results, one is simulation results and the other is experimental results.

Simulation results of secondary voltage: Figure 4 to 8 is respectively simulation wave of secondary voltage in single-coil mode, in dual-coil mode with no time interval, in dual-coil mode with 50us interval, in dual-coil mode with 100us interval and in dual-coil mode with 200us interval.

Figure 4 shows that the maximum secondary voltage in the single-coil mode is about 30.3KV. Spark goes out after secondary voltage keeps about 120us and then the left energy is used up in the form of secondary voltage shocking. Spark duration is about 110us if the spark plug breakdown voltage is 10KV. Compared with the single-coil mode, in the dual-coil mode with no time interval, Fig. 5 shows the secondary maximum voltage rises from 30.3KV to 38.5KV, spark breakdown capacity is stronger, while the discharge duration doesn't change significantly; in dual-coil with 50us and 100us interval, Fig. 6 and 7 show that the maximum voltage changes a little, spark duration increases significantly and the incremental time is the same as time interval; in dual-coil mode with 200us interval, Fig. 8 shows that the secondary voltage appears two distinct peaks, the second coil starts to discharge when the discharging of the first coil has ended, the entire discharge process is equivalent to double ignition.

Experimental results of secondary voltage: Figure 9 to 13 is respectively experimental wave of secondary voltage in single-coil mode, in dual-coil mode with no time interval, in dual-coil mode with 0.4.

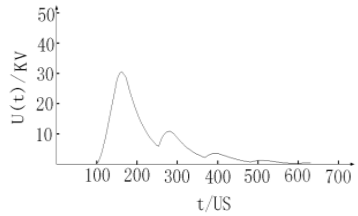

Fig. 4: Simulation wave of secondary voltage in single-coil mode

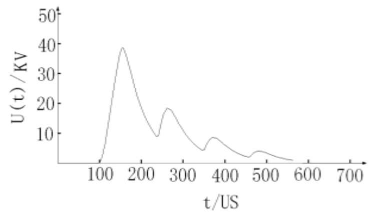

Fig. 5: Simulation wave of secondary voltage in dual-coil mode with no time interval

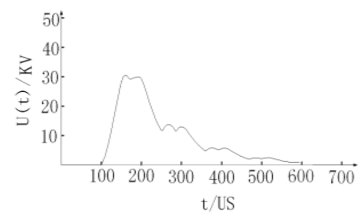

Fig. 6: Simulation wave of secondary voltage in dual-coil mode with 50us interval

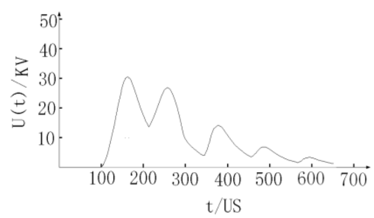

Fig. 7: Simulation wave of secondary voltage in dual-coil mode with 100us interval

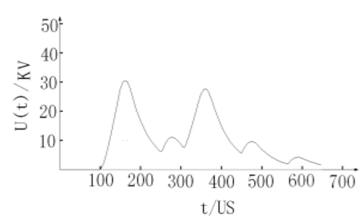

Fig. 8: Simulation wave of secondary voltage in dual-coil mode with 200us interval

- ms interval, in dual-coil mode with 0.8 ms interval and in dual-coil mode with 1.1us interval. The experiment was carried out in the air, so the experimental numerical value was not homologous to simulation results. Nevertheless, the most important thing we keeped a watchful eye on were changing trends.

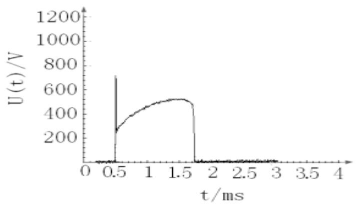

Fig. 9: Experimental wave of secondary voltage in single-coil mode

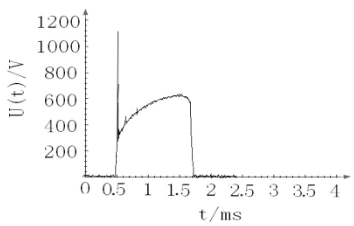

Fig. 10: Experimental wave of secondary voltage in dual-coil mode with no time interval

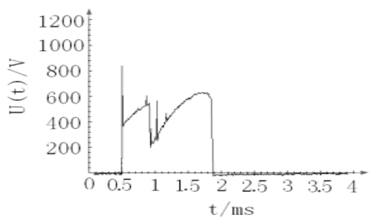

Fig. 11: Experimental wave of secondary voltage in dual-coil mode with 0.4ms interval

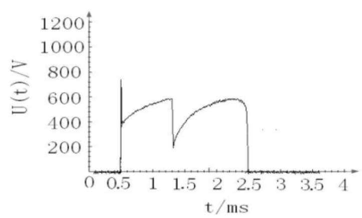

Fig. 12: Experimental wave of secondary voltage in dual-coil mode with 0.8ms interval

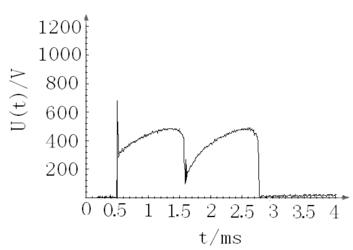

Fig. 13: Experimental wave of secondary voltage in dual-coil mode with 1.1ms interval

Figure 9 to 13 shows that secondary voltage increases to 700 V rapidly in single-coil discharge mode when primary current is cut off, spark plug is breakdown and ignition starts, voltage between two end of the spark plug is keep at about 500 V until the discharge ends, spark duration is about 1.15 ms; compared with single-coil mode, in the dual-coil mode with no time interval, spark duration changes a little, nevertheless the breakdown voltage increases from 700 V to 1100 V; in the dual-coil mode with 0.4 ms and 0.8 ms interval superimposed waveform appears in discharge process, the incremental time was 0.4 ms and 0.8 ms in proper order; in dual-coil mode with 1.1us interval the second coil starts to discharge when the secondary voltage drops below 200 V, the spark goes out then, the entire discharge process is equivalent to double ignition.

CONCLUSION

- Contrast to single-coil mode, in the dual-coil mode with no time interval the maximum secondary voltage increases about 30% both in simulation and experience, spark breakdown capacity is stronger. While in the dual-coil mode with some time interval, the maximum secondary voltage changes a little.
- Contrast to single-coil mode, in the dual-coil mode with no time interval spark duration changes a little. However in the dual-coil mode with some time interval, spark duration increases, the incremental time was the same as time interval, if the time interval is longer than spark duration in single-coil mode, double ignition appears.
- The spark character of dual-coil ignition system can be modulated according to the working conditions of CNG engine, so it furnishes a way to accomplish reliable spark under different working conditions.

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