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A NEW FUEL-INJECTION MECHATRONIC CONTROL METHOD FOR DIRECT-INJECTION INTERNAL COMBUSTION ENGINES

Józef TUTAJ[*], Bogdan FIJAŁKOWSKI[**]

[*]Institute for Automotive Vehicles and Combustion Engines, Department of Mechanical Engineering, Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Kraków, Poland
[**]Institute of Technology, State Higher Vocational School in Nova Sandec, ul. Staszica 1, 33-300 Nowy Sącz, Poland

pmtutaj@cyf-kr.edu.pl, pmfijalk@cyf-kr.edu.pl

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Abstract: In this paper, a novel fuel-injection mechatronic control method and system for direct injection (DI) internal combustion engines (ICE) is proposed. This method and system is based on the energy saving in a capacitance using DC-DC converter, giving a very fast ON state of the fuel injectors' electro-magnetic fluidical valves without an application of the initial load current. A fuel-injection controller for the DI ICEs that provides a very short rising time of an electromagnet-winding current in an initial ON state of the fuel-injector's electromagnetic fluidical valves, which improves a fuel-injection controller reliability and simplify its construction, is presented. Due to a number of advantages of afore -mentioned fuel-injection mechatronic control method and system, it may be utilised for the DI ICEs with fuel injectors dedicated to all types of liquid and/or gas fuels, for example, gasoline, diesel-oil, alcohol, LPG and NPG.

Key words: Direct Injection, Internal Combustion Engine, Fuel Injection, Injection Control System

1. INTRODUCTION

Currently on automotive market, more and more automotive vehicles use internal combustion engines (ICE) with a spark-ignition and direct-fuel injection. The idea for directly injection consists in forming the mixture directly in a combustion chamber. To achieve this, the electromagnetic fuel injector (EFI) is placed in the combustion chamber and by an intake fluidical valve is flow only an air.

A special injection mechano-hydraulical (M-H) pump generates the fuel injection at high pressure (5 to 12 MPa). The task of the fuel injector is dosing and spraying of a fuel into the smallest particles to provide an adequate mixing of the fuel and air in a specific area of the combustion chamber. After activation of an electromagnet of the EFI by an appropriate current pulse, the fuel is injected into the combustion chamber due to the pressure difference inside and outside fuel injector.

The idea of direct injection (DI) of a gasoline is quite old (Bosch 2014, Zhao 2016), but mass production took place only since 1995 with the introduction of ICEs with the gasoline direct injection (GDI) by Mitsubishi.

Electronically controlled fuel injection is currently used more widely, both in ICEs with the spark ignition with different markings of the supply system (GDI, FSI, IDE, HPI, JTS, etc.), as well as – Diesel ICEs (HDI, JTD, CDI, DCI, TDI etc.).

EFIs for ICEs with the direct fuel injection need to convey the current pulse with the proper value of the instantaneous power to the winding of the fuel injection electromagnet in the initial phase of fuel injection's opening, due to the operation to be performed by moving the needle fuel injector with a specific mass in a relatively short ON state (Achleitner et al., 2007; Husted et al., 2014).

The purpose of this article is to present a new method of control and powering of the injector of the direct injection system, which uses the energy stored in the additional capacitor to fast force the winding current, and does not need to be taken into account when controlling the so-called "initial load phase" time (Fig. 2).

The paper presents the results of electric current measurements of the injector during experimental tests.

1.1. A fuel injecttion mechatronic control for direct-injection internal combustion engines

In conventional fuel-injection mechatronic control, the microcontroller generates the control voltage for the solenoid coil of the EFI equals 60 - 90 V that is necessary to activate the EFIs of ICEs with the direct fuel injection. The internal structure of the EFI is shown in Fig. 1.

The control voltage is so high so as to minimize a response time of the EFI's mechatronic-control signal and get a short time of the fuel injection, which should be less than time of the fuel injection for ICEs with the fuel injection into the intake manifold (Fig. 2).

1.2. An initial load phase

The winding of the fuel-injector's electromagnet is powered by a pulse-width-modulated (PWM) voltage of value equals 12 – 14 V, in order to stabilize the current value of about 1 A.

An initial load phase prepares the gasoline fuel injector fuel to open in a short time, through the initial activation of the fuel injector (approx. 1.5 ms before the beginning of opening of the EFI) to generate the initial value of the EFI’s electromagnet-winding current.

The EFI’s solenoid coil consists of an electrical circuit RL, and therefore a presence of the inductance L (several mH) in depending on the type of the EFI and its resistance R (0.5-2 Ω) causes that at the EFI’s solenoid-coil supply voltage of a constant value, the current rises from zero to a steady-state value limited by the resistance R of the EFI’s solenoid coil.

The initial load phase allows bringing faster floating of the EFI’s needle during opening of the electromagnetic fluidical valve by the primary saving of an electrical energy in the inductance.

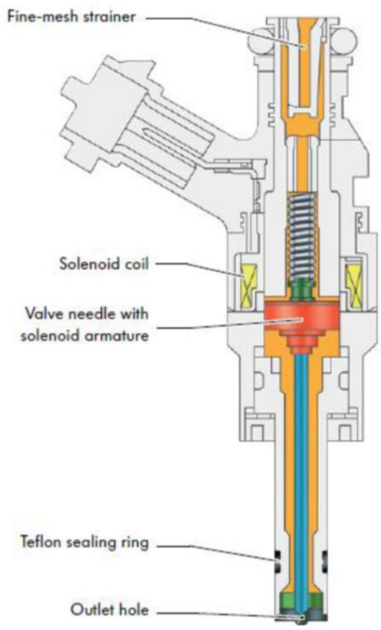

Fig. 1. Electromagnetic fuel injector (Bosch, 2014).

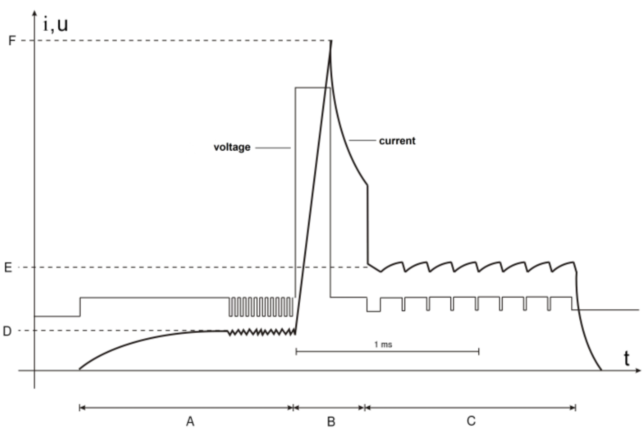

Fig. 2. Waveforms of the fuel-injector's current and voltage: A - initial load phase: B - excitation phase; C - hold-up phase; D - initial load current; F - excitation current; E - hold-up current

1.3. An excitation phase

An excitation phase is for causing a rapid increase of the EFI’s needle by temporarily increasing the current flowing through the fuel-injector’s solenoid coil. The EFI’s electromagnet winding is supplied on a following ways: by means of an electrical valve (electronic switch) that for a short time commutate the voltage of about 80-90 V, which increases the winding’s current to an instantaneous value of about 11-12 A. Afterwards, the EFI’s solenoid coil is switched to the voltage of 12-14 V, and causes a decrease in the forcing current impulse. It should be noted that the relatively high current flows only for a very short time of about 0.5 ms without any causing any thermal overload of the electromagnet’s winding.

The high instantaneous value of the power-pulse control will cause decreasing of the opening time of the EFI. The width of the voltage pulse (the voltage wave-form of the EFI’s electromagnet solenoid coil supply in Fig. 1) must be controlled with high accuracy, because even a small change in the duration of the voltage strongly influences the instantaneous value of the electro-magnet-winding current.

1.4. A holding-up phase

Holding-up phase allows you to continue a power supply (opening of the EFI), limiting the saved electrical energy needed to held the EFI’s needle in the open position by a few milliseconds, depending on the required fuel dose. The EFI’s solenoid coil is supplied as follows: with the PWM controlled voltage of about 12-14 V; and the current of about 2.5-3 A. The duration of the holding phase (1-5 ms) determines the size of the dose of fuel injected into the combustion chamber of the ICE. Loss of current pulse closes the EFI.

The above-described method for controlling fuel injectors for DI ICEs by many car manufacturers has significant drawbacks. The use of an initial-load-phase’s current pulse (the prediction pulse opening the fuel injector) causes as well an additional fuel-injector’s thermal load – an additional heating of the windings of the electromagnet coil during the initial-load phase of the EFI’s opening, as troublesome fuel-dose control. Because the synchronization pulses control of fuel injectors should take into account the additional lead time of the initial-load phase and convert a position angle of the crankshaft), for the EFI’s opening at a predetermined angular position of the crankshaft of the ICE.

A second shortcoming of this control method is a disadvantageous shape of the current pulse in the electromagnet winding of the fuel-injector during an excitation phase (Fig. 2).

The shape of the current pulse in the excitation-phase control like a ‘peak’ that results in generation of harmonics with higher frequencies and increasing of larger eddy-current losses in a magnetic circuit of the EFI. The exact stabilization of the excitation-phase duration due to the fact that in the case of un-controlled extension of this impulse may be destroyed the EFI (the electromagnet-winding current - resulting from the higher supply voltage of 80-90 V and lower impedance could be achieved in the long run value of tens of amperes).

2. A NEW METHOD AND FUEL MECHATRONIC CONTROL SYSTEM FOR DIRECT-INJECTION INTERNAL COMBUSTION ENGINES

In Fig. 3 is shown a fuel-injection mechatronic control system for DI ICEs that is based on an electrical energy accumulation in a capacitor and fast transfer of the power to the EFI’s electromagnet solenoid coil.

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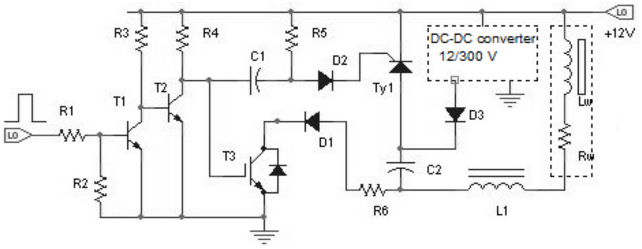


Fig. 3. Schematic diagram of the fuel-injector controller for DI ICEs

The capacitor C2 collects electricity using the diode D3 is charged from the output voltage 12/300 V of the DC-DC converter. With the emergence of the input control pulse is actuated at once the thyristor Ty1 and isolated-gate bipolar transistor (IGBT) T3. The energy stored in the capacitor C2 is in a very short period of time transferred to the additional inductance L1 and the fuel-injector's electromagnet winding. After discharging the capacitor C2, a function to maintain the current of the EFI's electromagnet through the IGBT T3 by means of the two-terminal circuit consisting of the high-voltage pulse diode D1 (400 V, 5 A), and additional resistor R6. A value of the resistor R6 determines a value of the holding current (Fig. 3). Since the energy stored in the capacitor C2 depends only on the output voltage of the DC-DC converter and its capacitance, and therefore the value of this energy can be easily stabilized and the EFI is protected from damage even in the case of a wrong control pulse appearance (e.g. due to interference). After an exchange of energy between the capacitor C2 and the EFI's electromagnet winding Rw, Lw during the holding-up phase, the commutation system consisting of components: L1, R6, D1, T3, holds up the current in the EFI's electromagnet winding. Very fast exchange of energy between the capacitor C2 and the additional inductance L1 and EFI's electromagnet winding Lw, Rw lasts approximately 0.3 ms (instead of approx. 0.5 ms in a conventional fuel-injection control system). It means that there is no need for an initial-load-phase pulse of the EFI, which simplifies the control and reduces heat losses in the EFI's electromagnet winding (no initial-load-phase current of approx. 1 (A) during approximately 1.5 (ms). An additional advantage (in addition to faster opening of the EFI) is preferable to form of a forcing pulse shape, which reduces the losses in the magnetic circuit of the EFI. The schematic diagram of the 12V / 250-300V DC-DC converter is shown in Fig. 4.

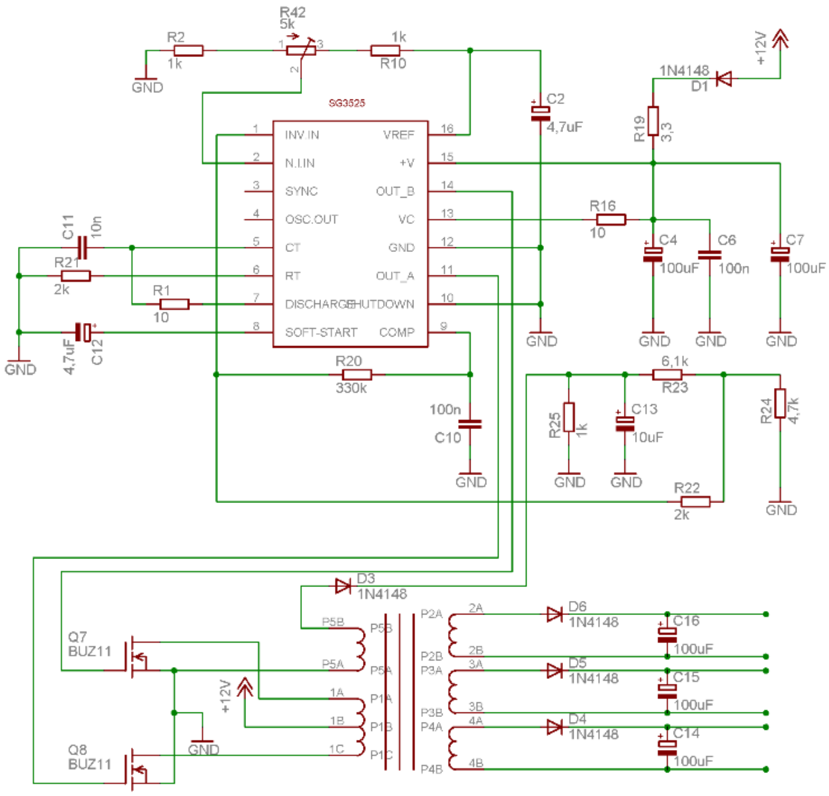


Fig. 4. Circuit diagram of the 12V / 250-300V DC-DC converter

An auxiliary voltage of 250 - 300 V is generated by the DC-DC converter with a feedback loop to stabilize the output voltage using the application specified integrated circuit (ASIC) type SG3525.

2.1. Mathematical model of the pressure dynamics

In this paper, we exercise a mathematical model describing the pressure dynamics in the common rail (CR) rail that is projected and experimentally validated in di Gaeta et al. (2009, 2011, 2012). This mathematical model depicts the electrical dynamics of the EFI (fluidical valve), ignoring the effects owing to the movement of its plunger (i.e. inductance variations and back-electromotive force), and the actuation circuit utilized to drive the EFI fluidical valve) as well. According with this alternative the pressure, say p(t) bar, in the CR depends on the mechano-hydraulical (M-H) pump rotational speed and EFI current i(A), and it can be de-composed into two components, namely the mean pressure term, say pa(t), and the residual pressure, p(t), relating the ripple around the mean value. The CR dynamical system is then given by:

$$\frac{di}{dt} = \frac{R}{L} i + \frac{V_b}{L}\left(\frac{a\delta(t)+b}{100}\right), \tag{1a}$$

$$p_a(t) = c(N)i + d(N), \tag{1b}$$

$$p(t) = p_a(t) + \eta(t), \tag{1c}$$

where: δ (%) is the duty cycle expressed in percentage terms of the PWM signal used to actuate the EFI hydraulical valve, a and b are parameters of the EFI actuation circuit, L (H) and R (Ω) are the EFI (hydraulical valve) inductance and the electric resistance of solenoid coil, respectively, whereas V_b (V) is the chemo-electrical (CH-E) storage battery voltage supplying the power circuit and N (rpm) is the rotational speed of the M-H pump that is equal to N + Nc/2 with Nc being the ICE rotational speed.

The terms c(N) and d(N) in (1) depend on the M-H pump rotational speed N and have to be experimentally identified. According to the approach in di Gaeta et al. (2009), we mathematically model them as third-order polynomials of the form:

$$c(N) = \sum_{k=0}^{3} c_k \left(\frac{N}{10^3}\right)^k, d(N = \sum_{k=0}^{3} d_k \left(\frac{N}{10^3}\right)^k. \tag{2}$$

2.2. GDI injector's mathematical model

Since for the design of basic automotive control loops, namely air-to-fuel ratio (AFR) control, the control variable to be designed is the mass of fuel to be injected, a relation between this control variable and the time of injection is essential for the integration of the CR in the entire ICE control system (Gupta et al., 2011; Jiangjian et al., 2007; Tang et al., 2009; Yan and Wang, 2011).

In this paper, we advise and validate by means of experimental data a simple but effective static mathematical model for the injected mass that obtains the following mathematical structure:

$$m_{inj} = T_{inj}\, r_1 \sqrt{\Delta P} + (q_1 \Delta P + q_0), \tag{3}$$

where: m_{inj} (mg) is the actual injected fuel mass, r_1, q_0 and q_1 are the mathematical model parameters to be tuned via experiments while ΔP (bar) is the pressure difference between the upstream EFI (rail pressure) and the downstream EFI (ambient pressure during tests).

Once the mathematical model of the injected fuel mass (Eq. 3) is available, the inverse relation describing the injection calibrated time as a function of a desired fuel mass is:

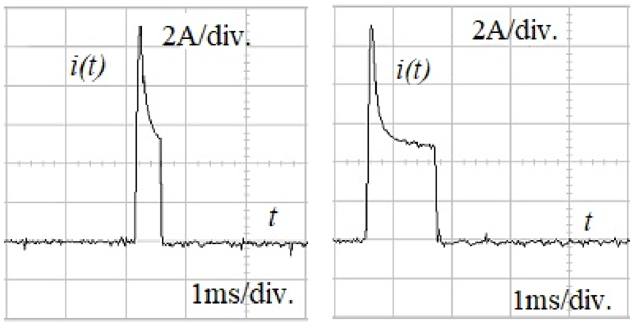
$$T_{inj} = \frac{m_d - q_1 \Delta P - q_0}{r_1 \sqrt{\Delta P}}, \tag{4}$$

where: m_d (mg) is the demanded fuel mass to be sprayed into ICE cylinder at the injection pressure *ΔP* determined by the AFR control duty (Corno et al., 2008; Gaeta et al., 2012).

3. THE MEASUREMENT WAVEFORMS OF THE FUEL-INJECTOR'S CURRENT PULSES

In Fig. 5 are shown waveforms of the current pulses for DI ICEs of fuel for two cases of the fuel-dose control.

In waveforms can be observed a very short forcing-current-pulse rise time to peak value of approx. 11 A, without the use initial-load phase and the ability to obtain short time of opening of the EFI.



a) b)

Fig. 5. Waveforms of the fuel-injector's current pulses for DI ICEs of fuel for two cases of the fuel-dose control: a) a small amount of fuel, b) a large amount of fuel

4. CONCLUSION

In the paper the fuel-injection mechatronic controller for DI ICEs that provides a very short rise time of the EFI's electromagnet solenoid coil current in the excitation phase of opening without the use of initial-load phase, which improves the reliability of the electronic driver and simplifies its construction, is presented.

Thanks to the numerous advantages of the above-described fuel-injection mechatronic control system and method for controlling the fuel injection can be utilized for DI ICEs with the EFIs suitable for different liquid and/or gas fuels, for example, gasoline, diesel-oil, alcohol, methane, liquefied petroleum gas (LPG) and so on.

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