PRELIMINARY STUDY OF THE STARTING SYSTEM THROUGH THE ELECTRICAL PARAMETERS OF THE START-UP PROCESS OF THE DIESEL ENGINE

Jacek Caban[1], Jaroslaw Senko[2], Tomasz Slowik[3], Szymon Dowkontt[2]
[1]Lublin University of Technology, Poland; [2]Warsaw University of Technology, Poland; [3]University of Life Sciences in Lublin, Poland
j.caban@pollub.pl, jaroslaw.senko@pw.edu.pl, tomasz.slowik@up.lublin.pl, szymon.dowkontt@pw.edu.pl

Abstract. Despite continuous scientific and research work on new power systems for motor vehicles, machines and various devices, the combustion engine is still the dominant power supply system for this type of technical objects. The operation of a compression-ignition piston engine is initiated during the starting process and uses various starting devices and systems for this purpose. Currently, the most popular starting system for a piston combustion engine is the use of a system based on an electric starter. In general, the starting process of a compression-ignition piston engine depends on the following factors: technical condition of the starting system, technical condition of the engine, battery charge level, lubricating properties, engine standstill time, engine and ambient temperature, type of fuel, etc. The article presents research on the electrical parameters of the start-up process of a single-cylinder compression-ignition engine with variable fuel injection parameters and ambient temperature conditions. The increased fuel dose had a positive effect on engine starting and reduced load on the starting system. Knowledge of the values of the electrical parameters of the starting process is important not only for the user (vehicle driver, agricultural machine operator, etc.), but primarily for designers of modern starting systems for combustion engines and service personnel. The obtained results of testing the electrical parameters of an internal combustion engine during start-up may be helpful in designing new drive systems supported by a compression-ignition internal combustion engine.

Keywords: electrical current consumption, electric starter, technical condition, combustion engine.

Introduction

The diesel engine is currently the most common source of propulsion for road transport and agricultural machinery, both in the classic system and in the hybrid system, supporting the electric motor. Research on hybrid systems used in motor vehicles is widely described in the available scientific literature [1-3]. The diesel engine is currently still the most fuel-efficient internal combustion engine, but when cold its performance is suboptimal [4]. A compression ignition engine has advantages such as reliability, fuel efficiency, larger power range, longer lifetime and maintenance period, better torque characteristics, and higher power density compared to a spark ignition engine [5]. Modern compression-ignition piston engines must be able to generate the least harmful effects on the environment (noise and exhaust emissions) [6-8] and vibration [9; 10]. The level of emissions production depends on several factors [11]. Reducing noise emissions generated by diesel combustion engines from various means of transport was the subject of the following studies [10; 12; 13]. The issues of examining the composition of exhaust emissions from a diesel engine are widely discussed in the world literature [14-16], and also include studies of exhaust emissions generated during engine start-up [17; 18]. Currently, most research focuses on, among other things, exhaust emissions generated during the combustion of fuels alternative to diesel oil. Labaj and Barta [19] investigated the possibility of using ethanol in a diesel engines, Domański et al., [20] investigated selected biofuels, and Szmigielski et al., [21] testing the technological line for the production of alternative fuels. Research on biodiesel and its impact on greenhouse gas emissions was shown in [22; 23]. Ramalingam et al. [24] investigated the possibilities of obtaining bioenergy from waste foam fat (LFO) and citronella grass (NFCO). Compared to diesel, the NFCO blend reduced hydrocarbon, carbon monoxide, and particulate emissions by 6.48%, 12.33%, and 16.66%, respectively, while carbon dioxide and oxides of nitrogen emissions increased [24]. As stated in [25], the combustion of FAME rapeseed oil methyl esters resulted in a reduction in the particulate matter (PM) content in exhaust gases by an average of 40-60% for the engine speeds in the full load range compared to the combustion of diesel oil. As stated by Sarkan et al., [26] PM significantly contributes to environmental pollution, negatively affects human health and irreparably damages all living things. Furthermore, Dittrich et al. [27] studied the fuel control system when the engine uses LPG-Diesel dual fuel with different LPG proportions. They concluded that CO_2 and PM concentrations are reduced in dual-fuel vehicles. Interesting research on alternative fuels in dual-fuel diesel engines was also conducted by Cung et al., [28] and Lebedevas et al., [29]. A new direction of research is research

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on the use of hydrogen as a fuel [30; 31]. Typically, exhaust emission tests focus on four standard exhaust gas components, but for example Garcia et al., [32] investigated more exhaust compounds, and Mikulski et al., [33], identify 23 compounds using FTIR gas analysis. The FTIR method was also used by Sejkorova et al. [34] to test engine oils.

As is known, the combustion engine must ensure reliable operation for a very long time [35-38] under variable load conditions. Interesting operational tests of the diesel engine power system were carried out, among others, [39-41]. Stoeck [42] presented a new methodology for testing Common Rail injectors in problematic cases, which extends the standard diagnostic procedure by analysing the resultant fields of the dosed fuel. Moreover, much attention was paid to the issue of diagnosing faults in the fuel supply system in the following scientific studies [43; 44], and the wear of piston-bush-cylinder system [45; 46] as well as diagnostics of the technical condition during the starting process of the combustion engine [47; 48]. The process of starting a diesel engine, despite many years of research, is a phenomenon that still attracts the attention of many researchers, which is reflected in numerous scientific works [49-51]. When starting a diesel engine, many negative phenomena and processes are observed that affect not only the engine, but also its surroundings [52; 53]. For example, Droździel in [54] presents the results of tests of the operational electrical parameters of the start-up of the combustion engine, carried out during real driving condition. The starting process is influenced by many factors, such as the quality of the engine oil, battery charge, technical condition of the engine and starting system, and engine temperature. The necessary mechanical energy needed to initiate independent operation of the combustion engine is transferred by driving the crankshaft using an electric starter [54]. Therefore, the technical condition of the starter has a significant impact on the successful starting of the combustion engine [55]. Dziubiński et al., [56] presents the issue of automotive starters faults in motor vehicles.

The article presents preliminary test results of the electrical parameters of the single-cylinder diesel engine start-up at constant parameters of fuel supply system at positive ambient temperature. The main goal of this research is to determine the electrical parameters of the starting process, which can then be used to design starting systems and for technical diagnostics of the starting system and engine.

Materials and methods

The main element of the test stand is a single-cylinder, four-stroke engine with direct injection manufactured by Ruggerini Diesel RY125. Table 1 contains selected technical data of the engine and starter. The starting system installation is characterized by a rated starter voltage of 12 V, the electrical capacity of the battery was 60 Ah, and the maximum starting current was 570 A. The starter battery was well charged (voltage range was 12.6 to 12.8 V).

Table 1

Ruggerini RY125 series engine technical specification [57]

Parameter	Comments
Engine work cycle	Four-stroke
Injection type	Direct
Type of cooling	Air
Displacement	505 cm3
Power	8,8 kW at 3600 rpm
Maximum torque	31 Nm at 2000 rpm
Number of valves	2
Compression ratio	20:1
Cylinder diameter	87 mm
Piston stroke	85 mm
Number of injector holes	5
Starter voltage	12 V (Bosch 0 001 107 090)
Rated power of starter	1.1 kW
Maximum rotational speed	300 rpm
Direction of rotation	Right
Number of pinion teeth	11

The test stand is equipped with equipment for measuring the characteristic parameters of the diesel engine start-up process at the Lublin University of Technology. This test stand has been previously described in detail in [52]. The current consumed by the starter is measured using the LEM HTA-1000 sensor with a range of 0 ÷ 1000 A with an accuracy of ± 1% and linearity of ± 0.5% attached to the starter power cord. The tests of electrical parameters of the start-up process of the diesel engine were carried out on the so-called cold engine at the ambient temperature. The engine oil and engine temperature were the same. 15 attempts were made to start the engine in a given test series at 4-hour intervals. The starting tests were carried out with the following determined engine parameters.

- Static fuel injection advance angle: 16.6° CA.
- Injector opening pressure: 26 MPa.
- Fuel dose: factory default for idling (FD1) and increased (FD2).
- Idle speed: 700 rpm for fuel dose FD1 and 1100 rpm for fuel dose FD2.
- Start-up temperature: ambient (21.15 to 21.90 °C).

Based on the analysis of the literature [58-60], it can be concluded that there are many definitions of cold and warm start-up as well as individual start-up parameters. In these tests, the start-up time (t_s – starter operating time) was determined based on the moment of obtaining a stable rotational speed of the engine crankshaft. On the other hand, the starter operation time was determined on the basis of the energy consumption time at the battery terminals. I_{max} is the maximum value of the current consumed by the starter at the beginning of the start-up, which is an indirect measure of the resistance to movement at the start of the engine. The next parameters tested were: the minimum voltage at the beginning of the start-up – U_{min}, maximum instantaneous starting power – P_{max} and average starting power – P_s (Eq. 2). The maximum instantaneous starting power was calculated from the following formula:

$$P_{max} = U_{max} \cdot I_{max}, \tag{1}$$

$$P_s = U_s \cdot I_s, \tag{2}$$

where U_{max} – maximum voltage at the battery terminals, V;
U_s – average voltage of sample of start-up at the battery terminals, V;
I_s – average current of sample of start-up, A.

Results and discussion

This part presents the obtained test results of the diesel engine start-up. Start-up tests were carried out at ambient temperature, which is widely used in the literature [18; 53; 61]. The value of the injector opening pressure in both measurement series was 26 MPa and this is the factory setting. The tests were carried out with 2 fuel doses: nominal fuel dose marked as FD1 and increased fuel dose marked as FD2.

Figure 1 presents the distribution of the values of the maximum current consumed by the starter at the beginning of the start-up for two measurement series.

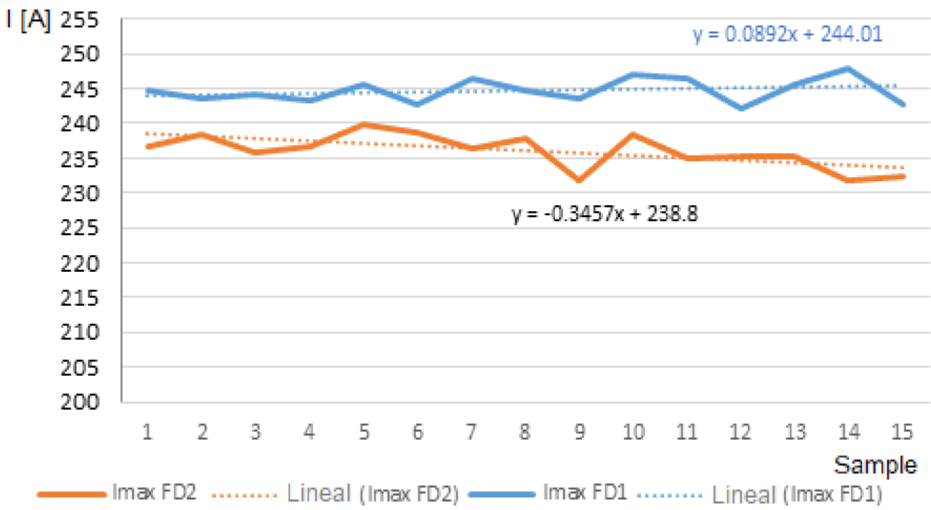

Fig. 1. **Values of the maximum current consumed by the starter for two measurement series**

Analysing the graph in Figure 1, it can be seen that the value of the starting current is higher in the first measurement series, which was carried out with the nominal fuel dose – FD1. The average difference in the I_{max} value between the series is approximately 8 A. It can be assumed that a larger dose of fuel accelerates the engine start-up and therefore the conditions in the combustion chamber were much better for starting the engine with lower current consumption by the starter.

Figure 2 shows the distribution of minimum voltage values at the battery terminals at the beginning of the start-up for two measurement series.

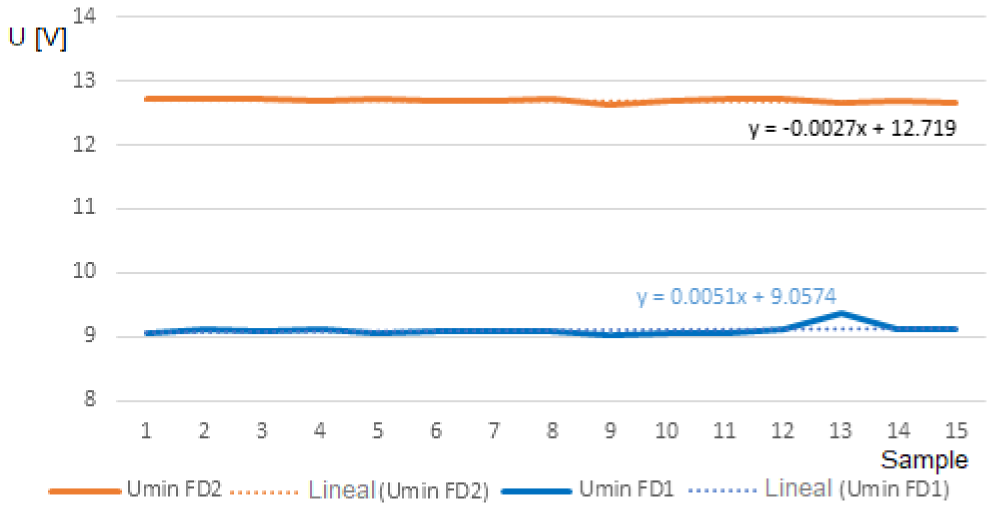

Fig. 2. **Minimum voltage at the battery terminals at start-up for two measurement series**

Analysing the graph in Figure 2, it can be seen that in the case of the second series, carried out with an increased dose of FD2 fuel, lower values of voltage drop on the starting battery were obtained. This may indicate, similarly to the I_{max} current, that in a series with an increased fuel dose – FD2, there are more favourable conditions in the combustion chamber to initiate the engine start-up and its independent operation.

Figure 3 presents the distribution of the maximum instantaneous starting power values – P_{max}.

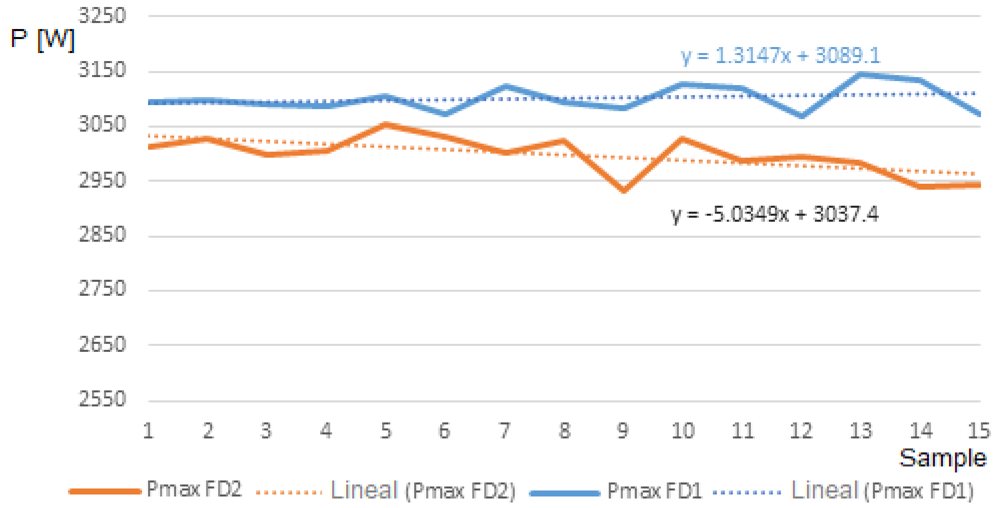

Fig. 3. **Maximum instantaneous starting power for two measurement series**

As a consequence of the two previous parameters, when analysing the graph in Figure 3, it can be seen that in the case of the second series, conducted with an increased dose of FD2 fuel, lower values of maximum starting power occurred.

Figure 4 presents the distribution of average starting power values – P_s for two measurement series.

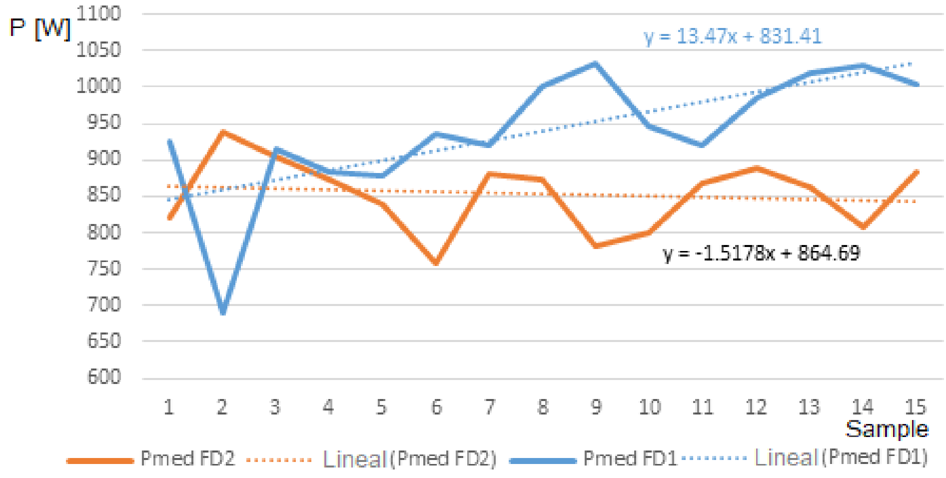

Fig. 4. **Average starting power for two measurement series**

Analysing the graph in Figure 4, it can be seen that in the case of a series of tests conducted with an increased dose of FD2 fuel, lower values of the P_s parameter occurred. It can therefore be concluded that with an increased fuel dose, the average starting power decreases, which means that we need to provide less energy to initiate the operation of the combustion engine in these ambient conditions and with given injection system settings. Providing more energy in the fuel (FD2) resulted in lower values of electrical parameters at the given starting parameters, and lower compression pressure values were also obtained, which indicates that despite the larger amount of fuel in the cylinder, it did not translate into greater load of the starting system. Perhaps due to the fact that the starting tests were carried out at ambient temperatures (approx. 21 °C), a larger dose of fuel resulted in faster ignition of the fuel-air mixture and easier start of the engine, without generating a greater load on the starting system.

Conclusions

The results of experimental tests of the electrical parameters of the starting process of a diesel engine with variable fuel injection parameters at a positive ambient temperature are presented.

1. For the series of measurements with a dose of FD1 fuel, higher values of the measured electrical parameters: I_{max}, P_{max} and P_s, were obtained compared to the FD2 fuel dose.
2. The presented tests of the electrical parameters of the combustion engine in the start-up process may be helpful in configuring other drive systems supported by the internal combustion engine, for example stationary electricity generation systems.
3. Knowing the electrical start-up parameters, they can be used to diagnose starting system faults and some engine faults, and this direction of research will also be developed in the future.

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Author contributions

Conceptualization, J.C.; methodology, J.C. and J.S.; software, J.C.; validation, J.C. and T.S.; formal analysis, J.C.; T.S. and S.D.; investigation, J.C., and J.S.; data curation, J.C. and T.S.; writing – original draft preparation, J.C., J.S., T.S. and S.D.; writing – review and editing, J.C., T.S. and J.S.; visualization, J.C.; project administration, J.C.; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

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