A Novel Energy-Saving Smart Start-Control System for Diesel Engine

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Brief introduction to the work

With the rapid development of the economy, science and technology worldwide, diesel engines are widely used in traffic and transportation, engineering machinery, agricultural machinery and other industries for their high thermal efficiency and great energy efficiency. However, there are still crucial technical problems in diesel engines, especially in high-power diesel engines, such as difficulties to get started, large size of the start system, poor reliability with a high failure rate, too much consumption in starting battery and heavy emissions. It is important to solve the starting problems of diesel engines in order to save energy.

The conventional approach to improve the starting performance of diesel engines is to increase the power of the starting system. This may solve the problem to some extent, but it requires an increase in the start power and the battery capacity. When the load increases, energy consumption raises. It can accelerate the mechanical loss rate, shorten the life of diesel engines and augment the consumption in heavy metals, like copper and lead, and sulfuric acid as well. Therefore, the cost is increased and may result in a severe environmental pollution during the production, use and recycling of heavy metals and sulfuric acid under the current production conditions. There is also a problem in the oil supply when diesel engines start. In the early starting phase, diesel fuels in the cylinder cannot be ignited by compression. These fuels may dilute the engine oil when they enter the lubricating system and thus damage the lubricating system.

The methods described above are the conventional "positive thinking" solutions. Nevertheless, we applied the unconventional "converse thinking" in our technology. To reduce the starting load of diesel engines, we proposed a design idea of using the smart control to reduce the compressed air resistance in the air cylinders and to improve the starting performance of diesel engines". We made a complete smart energy-saving starting control system, including 4 parts that are a start switch, a smart controller, a valve control system, and oil supply solenoid valves, as shown in Figure 1. The working principle of this system can be demonstrated as below. By operating the smart controller which controls the valve control system, we can control the opening and closing of the intake valve when a diesel engine starts. The intake valve is turned on in the early stage of starting, reducing the resistance of compressed air in the air cylinder. The spinning speed of the crankshaft is rapidly increased with the drive of the starter, reducing the starting load of the diesel engines at source and improving the starting performance of diesel engines. At the early stage of starting, the oil supply solenoid valves does not supply oil so as to reduce the oil consumption and to reduce pollution emissions. While at the late stage of starting, when the crankshaft reaches the normal spinning speed, the intake valve the oil supply solenoid valves start to work. The diesel in the cylinder is ignited by compression and thus the starting of the diesel engine is completed.

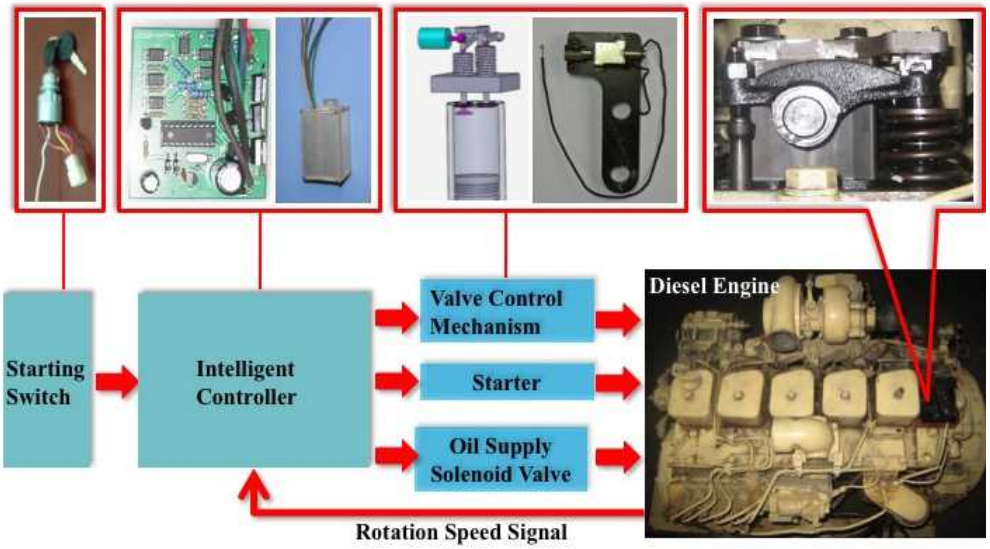

Figure 1 A smart energy-saving starting control system

We tested this proposed novel energy-saving smart start-control system with functional tests, cold start test, low battery capacity test, pressure-decreased push rod tolerance test, and wear test of the main components of diesel engine. The improvements are proven to be advanced and reliable by these careful experiments above, with the following technical advantages: 1) Energy conservation. The energy consumed in starting decreases 67.4 % and the consumption of oil reduces 82.5 %. 2) Reduction of wear and extension of the life of diesel engines more than twice. 3) Decrease in battery capacity from 120 Ah to 60 Ah. The consumption of lead and of sulfuric acid decrease 6.7 kg and 4.25 kg respectively. 4) Realization of low-temperature start. Diesel engines can be started at -25 ^{o}C without any heating measures. 5) High reliability. The control system can be operated 35,000 times without any problem, meeting the national standard.

The proposed novel energy-saving smart start-control system have a broad prospect of application and a great economic value. This system with simple structure and low cost can be added on to the diesel engine without changing its current structure. It costs only 100 yuan to get installed on the Donfeng diesel engine CY6105. We changed the manual decompression of the single-cylinder diesel engine into the automatic one, which facilitates the operation. For valve control technology, we solved the widely concerned crucial technical problem of “sub-cylindrical fuel conservation technology” and “automatic start-stop system”. If we consider the ownership of diesel engines is 60 million in China, 400 thousand tons of lead and 260 thousand tons of sulfuric acid can be conserved each year. It can further save 3.31 million tons of fuel consumption and the environment pollution caused by its ineffective emissions. The life of diesel engines can thus be increased. Therefore, the energy is conserved and the emission is reduced by decreasing the consumption in production and in maintenance.

Key words: Diesel engines, intake valve, energy-saving start, smart control system, starting load, battery capacity, energy-saving

1 Backgroud and significance

Diesel engines are widely used in traffic and transporta, engineering machinery, agricultural

machinery and other industries. However, there are still crucial technical problems in diesel engines, especially in high-power diesel engines, such as difficulties to get started, large size of the start system, poor reliability with a high failure rate, too much consumption in starting battery and heavy emissions.

In order to solve this problem, the conventional solutions are undertaken in a "positive thinking" way, which is to improve the starting performance of diesel engines by increasing the power match of the starting system. For example, increasing the starter power of diesel engines and increasing the capacity of the starter battery.

The methods described above are the conventional solutions. Nevertheless, we applied the unconventional "converse thinking" in our technology. To reduce the starting load of diesel engines, we proposed a design idea of using the smart control to reduce the compressed air resistance in the air cylinders and to improve the starting performance of diesel engines". This can solve the problem to some extent, but the cost and the consumption of heavy metals such as Cu and Pb are increased as well. The current production, use and recycling of heavy metals and sulfuric acid may cause a several damage in environment that cannot be controlled with current technologies.

These years, although many scientific institutes and companies have put a great number of investments in the R&D, the starting performance of diesel engines has not been obviously improved. Because of the out-of-date production technology of diesel engines and starters in China, the high-level engines used in special vehicles have relied on the imports from the developed countries for a long time.

After doing research and demonstration, starting from reducing the starting load of diesel engine, our group adopted the converse thinking method to innovate an energy-saving smart start-control system which can improve the performance of diesel engines' start and conserve energy at the same time.

2 Technical proposal

2.1 Design and principle

The starting load of diesel engine consists mainly of the inertial load of moving parts, friction, and compressed air resistance in the cylinder. The basic idea of this work is to "improve the performance of diesel engines' start by reducing the compressed air resistance with a smart control system".

With reference to the decompression start principle of single cylinder diesel engine, we designed and made the automatic decompression start control system of single cylinder diesel engine. Based on this system, with the intelligent control theory, we proposed a smart control system for multi-cylinder diesel engines. We tested the system working performance and its energy-saving performance by several tests.

The technical principle is to control intelligently the opening and closing of the intake valve when diesel engine starts. At the early stage of starting, the intake valve is turned on, but oil is not supplied. This reduces the resistance of compressed air in the air cylinder, and therefore the spinning speed of crankshaft is rapidly increased. While at the late stage of starting, when the crankshaft reaches the normal spinning speed, the intake valve the oil supply solenoid valves start to work and the engine finally starts.

The design goal is to reduce the starting load of diesel engine, to reduce the starter power and the battery capacity, to reduce the fuel consumption in the starting stage, and to extend the life of engine

with the reduction in wear of components, which eventually converse the energy consumption.

2.2 Design and production of the automatic the decompression start control system of single cylinder diesel

2.2.1 Principle of manual starting

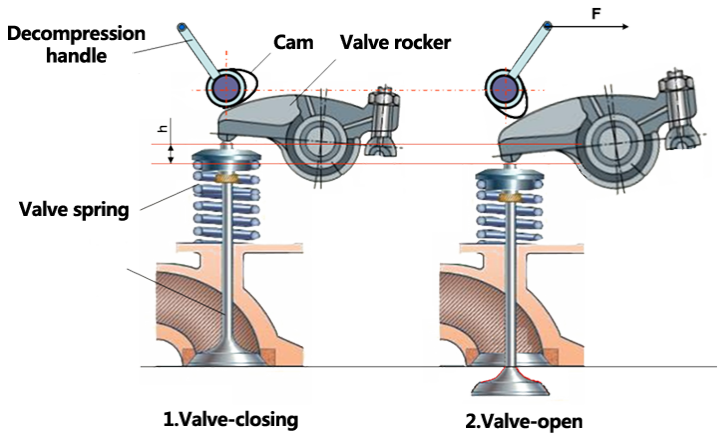

Figure 2 Schema of the manually decompression start system of single cylinder diesel engine

The figure shown above illustrates single cylinder diesel engine with a standard manual decompression starter. This device applies the direct compression of valve spring for decompression. Its principle is shown in Figure 2. There is a decompression handle and a decompression cam on the cylinder head. At the pre-start stage, by moving the decompression handle, the cam rotates against the valve-rocker arm, making the valve spring compressed. Therefore the intake valve cannot be closed properly. The whole system turns into the decompression state. At the late stage of starting, by releasing the decompression handle, the cam rotates counterclockwise due to the reset spring. The engine exit the decompression state and starts normally.

2.2.2 Design and production of the automatic the decompression start control system of single cylinder diesel

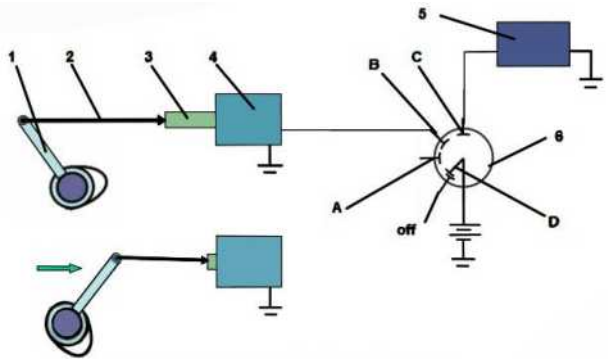

Figure 3 Schema of the automatic decompression start system of single cylinder diesel engine

1-Decompression handle; 2-Wire cable; 3-electromagnetic core; 4- electromagnet; 5-Starter; 6-Starting switch

We designed and make the special one-way solenoid and its mounting bracket. The solenoid can control the decompression handle by a wire cable to control the opening and closing of intake valve.

We designed and produced a novel three-state starting switch shown as the part 6 in Figure 3. In the state I, the movable contact D and the stationary contact A are joint. In the state II, the movable contact D joints firstly with the stationary contact B and then the stationary contact C. In the state III, the movable contact D and the stationary contact C are joint. The state II and the stae III can automatically return to state I.

The automatic decompression starting control system is shown in Figure 3. When the starting switch 6 is in the state I, the entire power supply of the vehicle is turned on. When the starting switch 6 is in the state II, the power supply of the solenoid 4 is turned on. The electromagnetic core 4 makes the decompression handle 1 rotates through the wire cable 2, letting the intake valve into the decompression state. The power of starter is then connected. The starter drives the crankshaft rotating. When the spinning rate reaches the normal rate, the starting switch 5 turns into the state III. The electromagnet is therefore disconnected and the depression handle is released. The intake valve exits the depression state and is back to the normal work state. The starter continues to drive the crankshaft rotating until the starting process is completed.

The automatic decompressed control system is designed with the principle above, whose main components are the starting switch and the electromagnet, as shown in Figure 4.

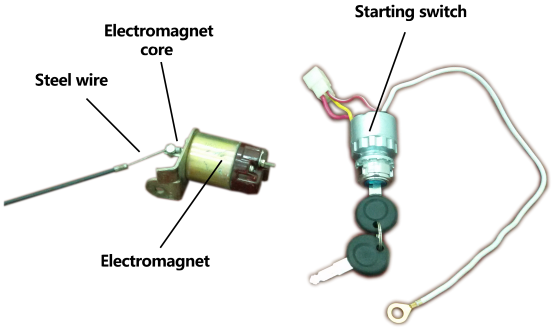

Figure 4 Components of the automatic control system

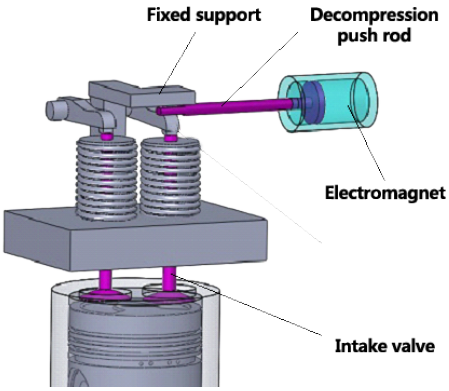

Figure 5 Schema of the valve control component

2.3 Design and production of the energy-saving starting control system of cylinder diesel

2.3.1 Principle of decompression start

Multi-cylinder diesel engine is not equipped with the decompression start component, so we cannot compress directly the valve spring to decompress the engine. Therefore, a valve control component is needed to control the opening and closing of the valve with litter power to conserve the energy.

The designed valve control component mainly has a mounting bracket, a decompression handle and an electromagnet. The mounting bracket is installed directly on the valve rocker arm support of the diesel engine, as shown in Figure 5.

When the component is in the decompression state and the intake valve is open, the front of the valve handle moves downward. When the distance between the front of the valve handle and the fixing support is larger than the thickness of the decompression handle, the decompression handle will move to the left side and insert between the valve rocker arm and the mounting bracket with the help of the electromagnet. When the intake valve is closing, the front of the valve rocker moves upward and press the decompression push rod which limits the displacement and makes the intake valve open. The

energy-saving depression start is therefore achieved.

When the component is in the decompression state and the decompression handle is not clamped, the decompression handle moves to the right side due to the offset spring and the electromagnet, stopping the control of the intake valve. The intake valve is back to the normal working state and thus the entire start-up process is completed.

2.3.2 Intelligent control theory

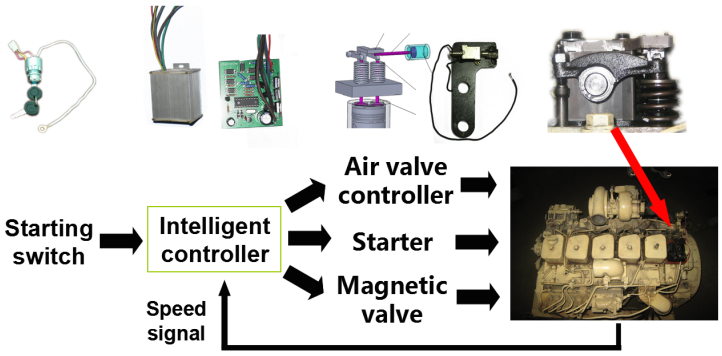

Figure 6 Schema of the energy-saving intelligent control starting system

As shown in Figure 6, the intelligent control system is mainly made of a start switch, an intelligent controller, a valve control component, etc. When the diesel engines starts, the starting switch rotates to the starting point, sending the start signal to the intelligent controller. The controller then analyze the control signal and control the starter, valve and oil supply solenoid with the output signal, making all the valves decompressed and the intake valve open. The oil supply solenoid is also closed which decreases the compressed air resistance during the start-up. Due to the reduction in the start-up, the rotate speed of the crankshaft is increased. At the late stage of starting, when the intelligent controller detects that the rotate speed of the crankshaft reaches the starting speed, a signal is then sent to the valve control component. The valve control component is no more in the decompression state and the intake valve works normally. The oil supply solenoid opens, offering oil to the cylinder. With the help of the inertia of the crankshaft and the starter, the diesel engines is eventually started.

When the diesel engine shuts down, the starting switch turns to the turn-off position. When the intelligent controller receives the shutdown signal, a signal is sent to the valve control system making all the valves into the open state and the system is therefore decompressed. When the rotation speed is zero, the intelligent controller and the valve controller stop working leaving all the intake valves open for the next start.

2.3.3 Design and fabrication

As shown in Figure 7, the intelligent energy-saving control system is made up of a starting switch, an intelligent controller and a valve controller.

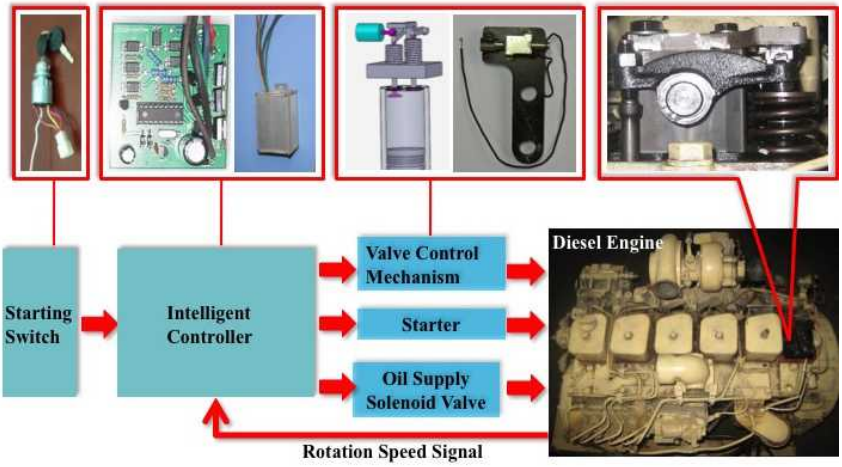

Figure 7 The energy-saving start control system

（1）Choose the starting switch

We choose the equipped starting switch of the diesel engines without any other modifications.

（2）Design and fabricate the intelligent controller

Figure 8 Principle of the intelligent controller

The input signals of the intelligent controller include the starting input, rotate speed input, turn-off input. We designed an intelligent controller that sends output signals controlling the valves, the starter and the oil supply solenoid, as shown in Figure 8. This intelligent controller, as shown in Figure 7, is fabricated by an electronic company but all the rights are reserved.

（3）Design and fabrication of the valve controller

The valve controller can be installed directly onto the present diesel engine with different size depending on the type of the engine. Here we take Dongfeng CY6105 as an example to design and fabricate the valve controller.

Design and fabrication of the fixing bracket. We measured the size of the valve rocker arm and its support. We fabricated the fixing bracket with the steel 45 according to the stress distribution, the strength and rigidity of the calibrator.

Design and fabrication of the electromagnet and the decompression handle. The chosen electromagnet has the initial tension of 20 g, the stroke of 12 mm, and the rated voltage of 12 V. We made the decompression push rod welded with the electromagnetic core in shape of cylinder with a diameter of 8 mm. The electromagnet is fixing on the support with bolts in order to control the valves, as shown in Figure 6.

2.3.4 Installation and test of the system

We chose the Dongfeng CY6105 (Figure 9) diesel engine and removed the valve chamber cover.

The valve was directly fixing by the fixing bolts of the valve rocker arm, as shown in Figure 10. After the system is installed, as shown in Figure11, the test was undertaken successfully at the first time.

3 Test and measurement

3.1 Functional test

We performed the functional test of the installed Dongfeng CY6105 diesel engine with the NK400 internal combustion engines electrical test bench. It was found that the system as design satisfied all the requirements of the energy-saving start of diesel engines.

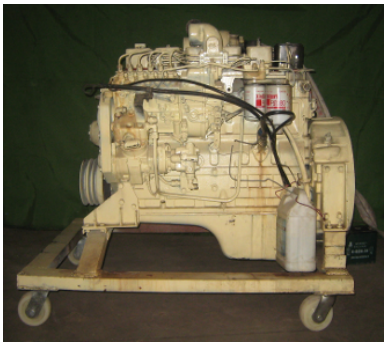

Figure 9 Schema of the Dongfeng CY6105 diesel engine

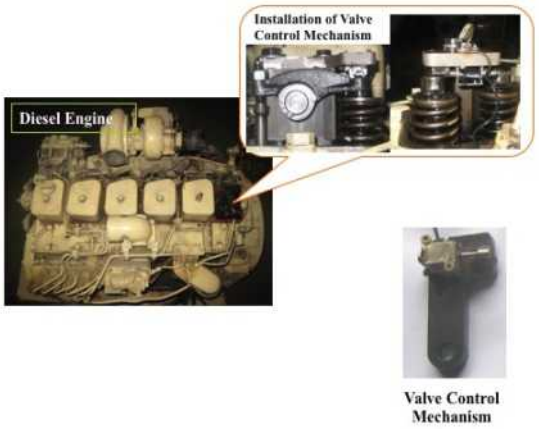

Figure 10 Schema of the valve controller

Figure 11 The valve controller installed on the diesel engine

This project is highly approved by the Dongfeng Motor Electric Co.Ltd. They provided us free test on their products in Dec. 2013. The functional test is currently finished with the results shown below in Figure 12 and Figure 13.

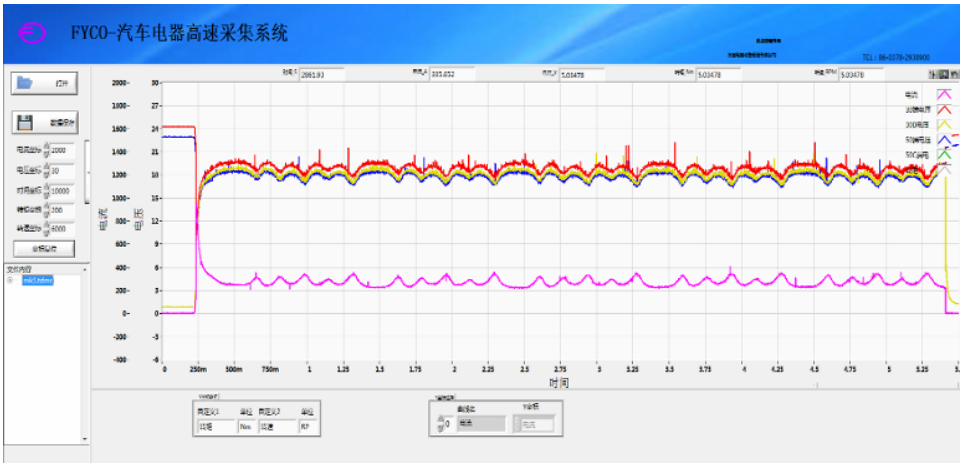

Figure 12 Test curve of conventional starting

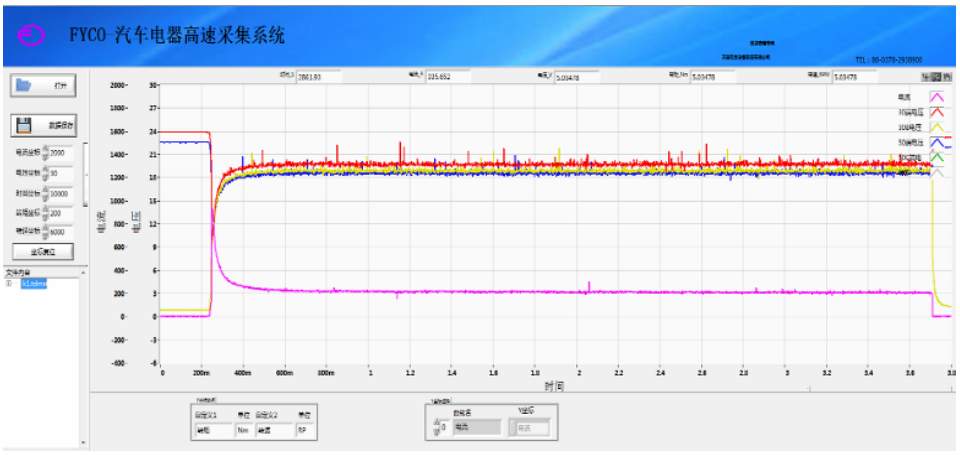

Figure 13 Test curve of energy-saving starting

（1）Current characteristics of conventional starting (Dongfeng CY6105 diesel engine with the power of 5kW at the ambient temperature of 1.3℃)

In Figure 11, the pink curve represents the current characteristics of starting. To start properly, the average maximum peak current is 380 A and the lowest peak current is 140 A. The fluctuation impact of current is more than 240 A. The start time and the oil supply time are both 5.375 s.

（2）Current characteristics of energy-saving starting (Dongfeng CY6105 diesel engine with the power of 5kW at the ambient temperature of 1.3℃)

In Figure 12, the pink curve represents the current characteristics of starting. The curve is smooth and stable around 180 A. The start time is 3.7 s and the oil supply time is 0.94 s, which suggests that the intelligent control reduces the resistance of compressed air during starting and thus reduce the impact load suffered by main components of the diesel engine.

Conclusion of the functional test: 1) compared with the conventional starting, the diesel engine can be started properly with the intelligent energy-saving control. The maximum peak current decreases 53%, from 380 A to 180 A without obvious impact current. This improves the starting performance of the diesel engine. 2) the starting time decreases 31%, from 5.375 s to 3.7 s. The energy consumption decreases 67.4%, which realizes the conservation of energy. If we start the engine 10 times per day, every engine can conserve 151 g oil per day, therefore 55.115 kg per year. If this technology is widely applied nation-wide, and there are 60 million engines in China, 3.3067 million tons of oil can be conserved and related environment pollution can also be reduced.

The experiments in Dongfeng Motor Electric Co.Ltd shows that this system does not have any bad impact on other performance of the diesel engine. The cold start test and the reliability test are undergoing. If it reaches the standard of the diesel engines of Dongfeng, this technology will be applied on their engines.

3.2 Test of reduction in battery capacity

A standard Dongfeng CY6105 diesel engine is equipped with two 12 V, 120 Ah battery. We tested the battery with only 50% and 16% of standard capacity. Results are shown in Table 1.

Table 1 Comparison of battery start time of energy-saving start and of conventional start

Start mode	Conventional start	Energy-saving start	Ration to the standard capacity	Battery capacity

Start time	0	127	16%	Two 12V, 20 Ah
Start time	223	725	50%	Two 12V, 60 Ah
Ambiance temperature	20℃	20℃		

Results show that 1) the conventional start cannot make the diesel engine started if the battery is charged with only 16% of its standard capacity. However, with the intelligent start, the engine can start 127 times after charged once. 2) with the intelligent start, the engine can be started 725 times after charged once, which meets the requirement of the engine starting.

If the battery is equipped as 50% of the standard capacity, reducing from 120 Ah to 60 Ah, the consumption of Pt will reduce 6.7 kg and the consumption of sulfuric acid will reduce 4.25 kg. If there are 60 million engines in China, 402 thousand tons of Pt and 225 thousand tons of sulfuric acid will be conserved each year.

3.3 Cold start test

The purpose of this cold start is to test the performance of the intelligent system at a low temperature and to test whether the engine can be properly started when the battery capacity is decreased, as shown in Figure 14. Results show that the system can be properly started at -25℃ without any additional heating measures when the battery is continuously charged.

Figure 14 Cold start test

Figure 15 Test bench of wear resistance

3.4 Wear resistance test

We designed and fabricated a wear resistance test bench for CY 6105 diesel engine, as shown in Figure 15. We counted the times that the decompression handle suffered impact. The test bench worked 1000 hours continuously which equals to be started 600 thousand times. Results show that the wear is slight, about 0.01 mm-0.02 mm, which meets the standard.

3.5 Wear test of main components during energy-saving start

It is said that about 70% of the wear of diesel engine is caused during the first 6 seconds after stared. We can therefore deducted that the working condition can largely impact the wear of diesel engines. We tested the start performance of two engines, in which the first one was equipped with the intelligent control system and the second one is a new standard engine, under the same condition. Results are partially shown in Table 2.

Table 2 Test results of the 1st diesel engine (conventional start)

No. of test	MCGS_TIME	Voltage of the port 30	Voltage of the port	Voltage of the port 50	Main current	Temperature No.1	Temperature No.2

			30B				
1	2013-12-28	17.32999992	16.65999985	17.42000008	72.69999695	3	4
2	2013-12-28	15.68000031	15.09000015	15.97000027	93.69999695	3	4
……	……	……	……	……	……	……	……
17181	2014-4-7	19.31999969	19.13999939	19.46999931	173.6999969	17	17
17182	2014-4-7	19.22999954	19.17000008	19.45000076	174.1000061	17	17
……	……	……	……	……	……	……	……
31515	2014-5-4	18.69000053	18.60000038	18.95999908	158.3999939	18	17
31516	2014-5-4	18.59000015	18.51000023	18.92000008	158.1000061	18	17

Table 3 Test results of the 2nd diesel engine (energy-saving start)

No. of test	MCGS_TIME	Voltage of the port 30	Voltage of the port 30B	Voltage of the port 50	Main current	Temperature No.1	Temperature No.2
1	2014-3-10	17.46999931	17.60000038	17.36000061	208	13	13
2	2014-3-10	20.59000015	20.09000015	20.01000023	195	13	14
……	……	……	……	……	……	……	……
17181	2014-4-14	30.52000046	18.63999939	18.35000038	354	18	19
17182	2014-4-14	31.34000015	19.29999924	18.86000061	343	18	19

Results show that when the start time increases, the start current of the 1st engine increases slowly, which implies the start load is increasing with the start time but with a low rate. When it reaches 44721 times, it can still be started. The start current of the 2nd engine increases rapidly. It reaches 386 A when it starts 17181 times, which implies the increasing rate too great that the diesel engine cannot do any start test.

By the comparison of the cylinder pressure and the tests performed on the general test bench, the 1st engine can work properly. The load characteristics and the out characteristics are basically the same as those of a standard one with only a decrease in the index (within 10%). The engine can work properly. However, the 2nd engine cannot start properly. After opening the engine body, we found that the wear between the cylinder and the piston, the wear of the connection rod bearing shell and that of the crankshaft bearing reach the criteria of an overhaul (GB/T 3799.2-2005). It was heavily abraded.

Conclusion: the intelligent energy-saving control system can reduce the wear in main components of diesel engines and extend its life more than twice. The system was safely operated 44721 times, which reaches the standard of 35 thousand times (JB/T6707-1993).

3.6 Conclusions of tests

The intelligent energy-saving control system can reduce the start load of diesel engine, reduce the necessary battery capacity and reduce the impact suffered by the main components. It can greatly reduce the wear in main components. The engine can therefore be started at low temperature (-25℃). Its main components (decompression handle, electromagnet, intelligent control part) can be safely used 350 thousand times, meeting the standard and achieving the goal of improving the diesel start performance and of reducing emissions.

4 Innovative points

(1) We proposed a intelligently controlled method of reducing the compressed air resistance to improve the start performance of diesel engine start. By intelligently controlling the opening and closing of the intake valve, the resistance of compressed air is therefore reduced and the start load of diesel engine is decreased at source. The performance of diesel engines is therefore improved.

(2) We proposed an oil-supply control method, where the oil is not supply at the early stage of start. The oil consumption is therefore reduced as well as the emissions. This method has applied for the national paten.

(3) We designed and fabricated the intelligent start control system. The intelligent control of the opening and closing of valves solve the problem of the intelligent energy-saving control of diesel engine start, which automates the diesel engine start.

(4) We designed and fabricated the automatic depression start control system for the single-cylinder diesel engine. With the novel three-position start switch and the control system, the automatic depression start problem is therefore solved.

5 Prospect of application

This intelligent energy-saving start control system solves the problem of the intelligent opening and closing control of the intake valve, which reduces the start load of diesel engines at source.

This smart design with simple structure costs little in fabrication. It costs only 100 yuan to be added directly on the diesel engine.

In this work, the “intelligent control of valve” can be further used to develop the “automatic start and stop system” and the “separated cylinder oil cut-off oil-saving” technologies.

Energy is well conserved and emissions are obviously reduced. This innovation can greatly reduce the necessary starter power and the necessary battery capacity, as well as the consumption of heavy metals, such as Cu and Pd, and sulfuric acid. Oil consumption is therefore reduced. The reduction in the impact load and in the wear of the main components can thus extend the life of diesel engines.

This work successfully solves the crucial problem encountered in the development of the starting technology, which fills in the blanks in this domain and is approved by the leading companies, such as Weichai and Dongfeng. If it can be applied worldwide, considering that there are 60 million diesel engines in China, 402 thousand tons of Pd, 255 thousand tons of sulfuric acid and 3.3069 million tons of oil can therefore be conserved per year. Pollution emissions are reduced. It has a broad prospective in the future.

Reference

[1] 阿尔弗雷德.克拉普尔，中国第一汽车集团公司技术中心译．起动机-发电机一体化技术（ISG）．北京理工大学出版社，2008：109-120

[2] 罗红英．内燃机及动力装置测试技术［M］．哈尔滨工程大学出版社，2006：138-157

[3] 朱仙鼎．中国内燃机工程师手册［M］．上海科学技术出版社，2000：562-579

[4] 蒋德明．高等内燃机原理［M］．西安交通大学出版社，2002：67-89

[5] 邬继金．汽车电器原理与维修［M］．北京理工大学，2011：46-57

[6] 机动车及内燃机用起动机技术条件．JB/T6707-2006

[7] 商用汽车发动机大修竣工出厂技术条件．GB/T 3799.2-2005