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The Operation of Free Piston Linear Generator Engine Using MOSFET and IGBT Drivers

Abdulwehab A. Ibrahim, A. Rashid A. Aziz, Ezran Zharif B. Zainal Abidin and Saiful A. Zulkifli
Department of Mechanical Engineering, Center for Automotive Research,
Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Tronoh 31750, Perak, Malaysia

Abstract: This study the dynamics of a two-stroke, hydrogen direct-injection, free-piston linear-generator engine with dual oppositely placed combustion chamber with two different motor drivers. The MOSFET driver was replaced by IGBT driver to improve the capacity of the engine system to enable the injection of higher current for initiating the combustion. The experiment was carried out using the MOSFET and IGBT drivers by motoring the engine without combustion using 3-battery and 5-battery configuration to compare the performance of the IGBT driver relative to the MOSFET driver. The result shows that the engine develops a higher in-cylinder pressure by using IGBT driver when it is running with both battery configurations. However, the engine was unstable when it is running with 5-battery configuration using IGBT driver.

Key words: Free-Piston engine, internal combustion engine, linear generator, two-stroke cycle engine, hybrid electric vehicle

INTRODUCTION

The depletion of the fossil oil and the stringent environmental policies have driven researchers to focus on finding technologies that are consistent with environment. As a result, more research has been undertaken in the internal combustion engine to develop more efficient and emission-free engines that persuaded the researchers to reconsider the development of free piston engine for vehicle propulsion and portable energy source applications. The development of free piston engine had been conceived in the past eighty years. Its development was initiated again after it was investigated that the engine has a potential of reducing emission and it can overcome the challenges of obtaining variable compression ratio that cannot be achieved in the conventional engine.

The free piston concept allows the piston to travel freely without limiting the endpoint of the piston, whereas, in the conventional engine, the motion of the piston is fixed by the rotating components that limits compression ratio of the engine. Hence, the free piston engine extracts power directly from the motion of kinematically unconstrained piston that moves between the combustion chamber and bounce chamber. There is no mechanical power or torque output that is obtained in conventional engine due to the presence of crank mechanism. The free piston engine offers a good opportunity for eliminating side load due to crankshaft and minimizing frictional loss owing to reduction in the number of moving parts. These features improve the mechanical efficiency of the engine and allow the engine to be more efficient, robust and compact.

Achten (1994), Aichlmayr (2002) and Mikalsen and Roskilly (2007) have assessed and presented in detail the concept, evolution, configuration and various applications of free piston engine that have been reported since 1925. In the early age, free piston engine was successfully used as air compressor and gas generators (Heywood and Sher, 1999). Many researchers have explored that the promising future application of free piston engine linear generator is to use as a power unit in hybrid electric vehicle (Hansson and Leksell, 2006) and micro power generation system for portable device (Aichlmayr, 2002; Aichlmayr *et al*., 2002a, b).

A free piston engine that can be used as a prime mover for linear electrical generator was developed by researchers at Universiti Teknologi PETRONAS (UTP) in collaboration with other two local universities for being environmental friendly and for using as a power generation unit to charge battery banks on-board for hybrid electric vehicle (Aziz, 2003; Zulkifli, 2007). The linear generator consists of stator coil, three phase tubular permanent magnet and translator shaft which is connected to the two oppositely placed pistons at its end points. The piston assembly is driven back and forth through the alternator's coils when the current is injected to the stator coils from the battery banks. The chemical

Corresponding Author: Abdulwehab A. Ibrahim, Center for Automotive Research, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

energy of the fuel is transformed into electrical energy by means of linearly moving piston assembly. The developed engine employs direct injection system designed for 5 KW and fuelled by compressed natural gas (CNG) and hydrogen. The developed prototype of UTP free piston linear generator engine is depicted in Table 1 and Fig. 1.

Zulkifli *et al.* 2008 has studied the starting strategy for free piston engine linear generator by employing the air-spring character of the engine cylinders prior to combustion that is mechanical resonance and electrical motoring with open-loop and rectangular current commutation. In the study, mechanical simulation model integrated with electrical model of linear generator was developed to determine the required starting parameters by reciprocating the translator. It was shown that if a sufficient large, fixed-magnitude force is constantly applied on the translator in the direction of motion, the system can be reciprocated and resonated to the full required amplitude. Therefore, higher motoring force leads to higher velocity of translator for initiating the combustion.

Since the motoring force is directly proportional to the amount of current injected into the coil, a higher constant force require a higher current supply from the source. For motoring the UTP free piston linear generator, a standard automotive battery was used for energizing the coils with fixed DC voltage. Sustainable operation of the

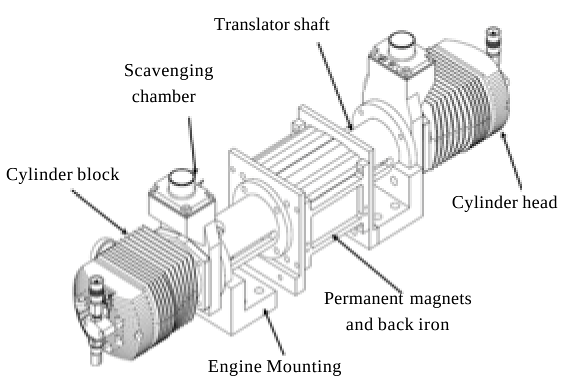

Fig. 1: UTP two-stroke, free-piston linear generator engine prototype

Table 1: General specification of the UTP free piston engine linear generator prototype

Bore	76 mm
Design stroke	34.5 mm
Engine capacity	313cc/cycle
Nominal compression ratio	14:1

UTP free piston engine linear generator couldn't be achieved for higher voltage supply using MOSFET (Metal Oxide Semiconductor Field Effect Transistor) driver that prevents the engine from reaching the required full amplitude to start the combustion. Hence, it is required to address the problem of the driver mechanism of the system. Therefore, this study discusses the upgrading of the driver and the experimental work performed on UTP free piston linear generator engine. While many studies have been conducted on free piston linear generator engine through mathematical modeling and simulation, there has been far less rigorous researches on free piston linear generator engine through experiment. This research is worth value for future study of free piston linear generator engine.

MATERIALS AND METHODS

The experiment was performed on a two-stroke, direct injection, UTP free piston linear generator engine with two oppositely placed combustion chamber, which has a specification of 76 mm bore, 36.7 mm nominal stoke length and 313 cc cycle^{-1} engine capacity. Using data acquisition system, cylinder pressure, the amount of current flowing into the coil and the corresponding piston linear displacement data for both cylinders was gathered. An electrical power was supplied from the standard 12-Volt battery bank to the engine through the alternator's coils for motoring the engine without combustion.

MOSFETs and IGBTs (Insulated Gate Bipolar Transistor) are used in most today's modern power electronics equipment and systems to switch at high speed. Both are voltage controlled devices as they can be turned on and off by controlling the voltage across their gate-source junction. The MOSFET inverter driver of UTP free piston linear generator was replaced by IGBT driver for improving the capacity of the driver for injecting higher current to the alternator's coil. The type of the IGBT driver that was installed by replacing the MOSFET driver for upgrading the engine system was IGBT SKiiP 342 GB120-3DUL. As shown in Fig. 2, the controller send switching gate signals to IGBT driver through PCB by converting the 5 V signals to 15 V at the gate driver. The current was injected from the automotive battery bank to UTP free piston linear generator engine through IGBT driver. Figure 2 shows an experimental set up of the IGBT driver for free piston linear generator engine and Fig. 3 shows an experimental set up of the MOSFET driver for free piston linear generator engine.

The cylinder pressure measurements were taken using a Kistler 6061B piezoelectric pressure transducer that was connected to Kistler charge amplifier type 5037B

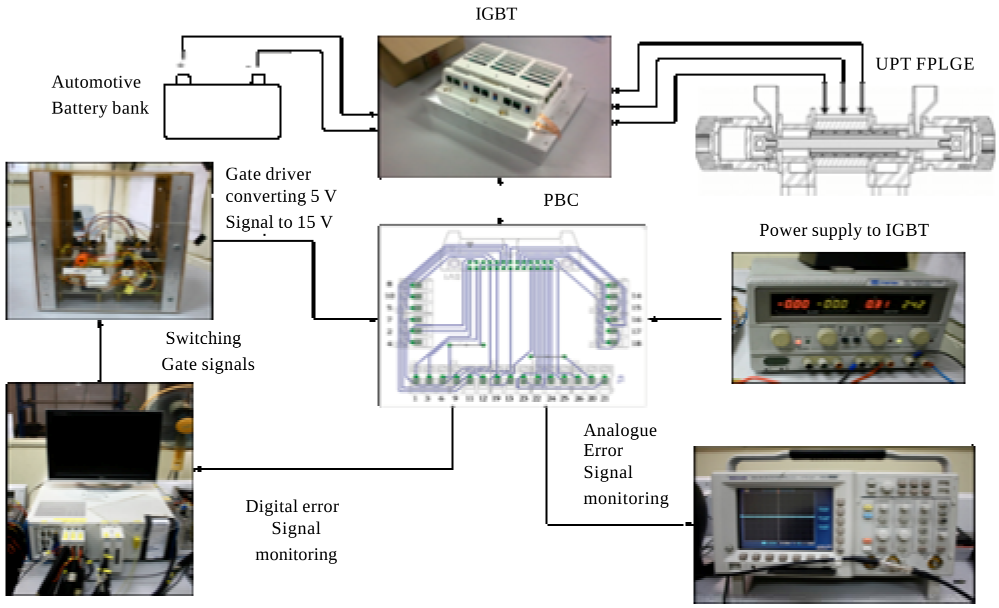

Fig. 2: Experimental setup of IGBT driver for free piston linear generator engine

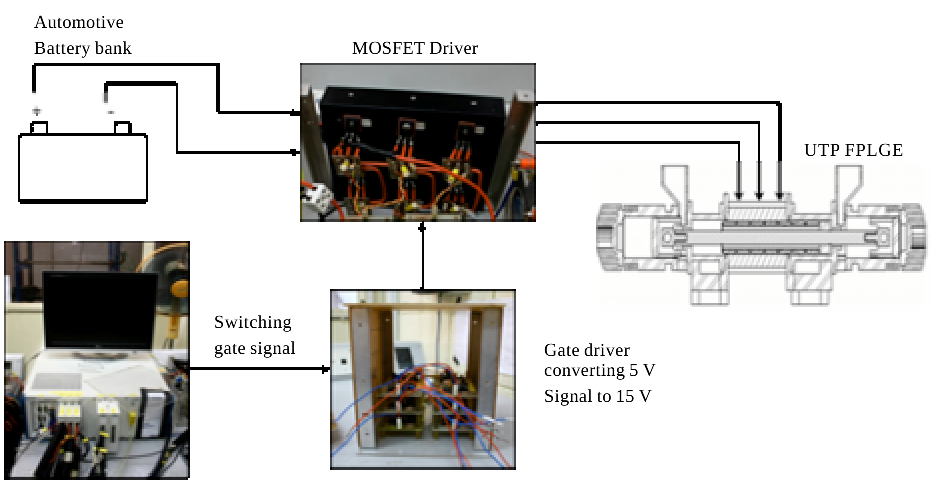

Fig. 3: Experimental setup of MOSFET driver for free piston linear generator engine

to convert charge to voltage. Unlike conventional engine, free piston engine requires a linear displacement magnetic encoder (Baumer MLFK-08T7101) for measuring the linear displacement that was used as input to the controller for controlling the switching point of the power switches.

The amount of current injection for motoring the engine and the maximum switching end-point of the piston were executed by using PXI embedded controller and LABVIEW software. With the help of developed LABVIEW program, the data was logged at 0.125 mm linear displacement resolution and a maximum of 75 consecutive engine cycles could be recorded for different engine operating scenario. The collected experimental data were post-processed by using MATLAB software. The detail result of the experiment is presented in the subsequent sub-sections.

RESULTS AND DISCUSSION

After the IGBT drive r installed, a number of pre- experimental tests were performed to test the new setup. Then the engine was allowed to run continuously by injecting the current to the alternator's coil through IGBT driver using 3-battery and 5-battery configuration.

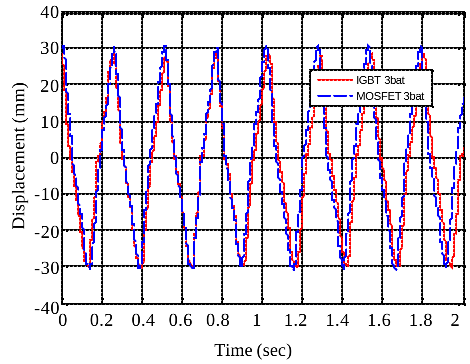

Fig. 4: Displacement versus time for 3-battery configuration using IGBT and MOSFET driver

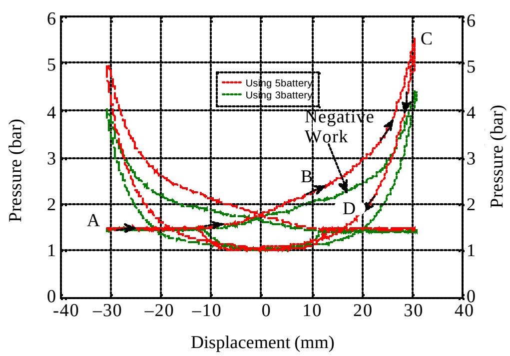

Fig. 5: Absolute pressure versus displacement for 3-battery and 5-battery configuration using MOSFET driver

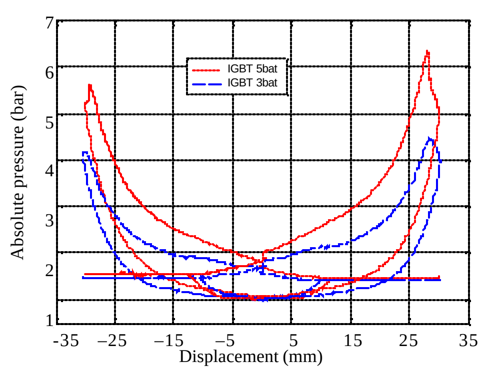

Fig. 6: Absolute pressure versus displacement for 3-battery and 5-battery configuration using IGBT driver

The 3-battery configuration experiment injects a current to the alternator's coil using a maximum of 36V that is supplied from three automotive batteries (each 12V)

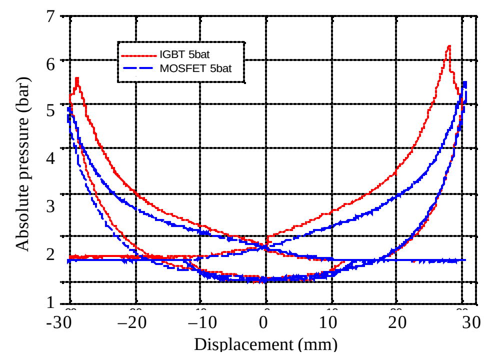

Fig. 7: Absolute pressure versus displacement for 5-battery configuration using IGBT and MOSFET driver

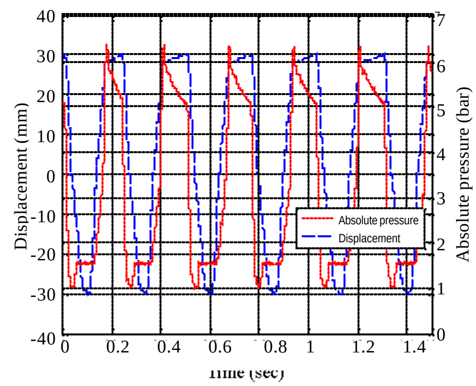

Fig. 8: Absolute pressure and displacement versus time for 5-battery configuration using IGBT driver

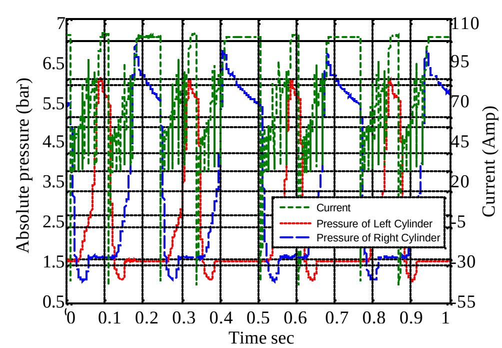

Fig. 9: Absolute pressure and current versus time for 5-battery configuration using IGBT driver

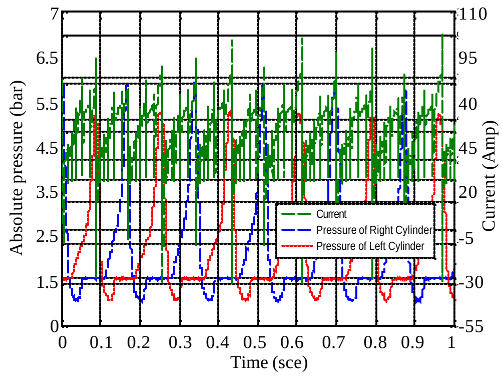

Fig. 10: Absolute pressure and current versus time for 5-battery configuration using MOSFET driver

Fig. connected in a series, where as the 5-battery configuration supplies 60 V. It is observed that there is no significant difference of engine frequency for 3-battery configuration using IGBT driver and MOSFET driver as shown in Fig. 4.

Figure 5 shows the absolute pressure versus displacement curve for the left and right cylinder of the engine by motoring the engine without combustion using MOSFET driver setup for 3-battery and 5-battery configuration. It shows that the pressures in the left and right cylinder are not equal in both configurations. This can be attributed to the fact that there is a leakage in the left cylinder. The maximum pressure is observed in the left and right cylinders for 5-battery configuration (4.949 and 5.566 bar respectively) than for 3-battery configuration (4.026 and 4.441 bar respectively) due to higher engine frequency in 5-battery configuration. Furthermore, it is investigated that the compression profile (curve A-B-C) is higher than the expansion profile (curve C-D-A). Hence, the region under the curve A-B-C-D-A is a negative work due to the work done by motoring force applied to the piston.

Figure 6 shows the absolute pressure versus displacement curve for the left and right cylinder of the engine by motoring the engine without combustion using IGBT driver setup for 3-battery and 5-battery configuration. The result portrays that higher pressure developed in both cylinders using IGBT driver than MOSFET driver for the same 3-battery and 5-battery configuration. Using IGBT driver, the maximum pressure is observed in the left and right cylinders for 5-battery configuration (6.38 and 5.66 bar respectively) than for 3-battery configuration (4.478 and 4.169 bar respectively) as shown in Fig. 7.

However, it is investigated that the engine is slightly unstable when it is running with 5-battery configuration using IGBT driver due to the fact that the pressure drops before it reaches to top dead center (TDC), where as the engine is stable using MOSFET driver (Fig. 10). As shown in Fig. 8 and 9, the piston stays longer time at TDC while the piston switching from the right cylinder to the left cylinder and the pressure drops slightly before it reaches to TDC due to the fact that the switching mechanism of the IGBT driver stays-on for longer period at near TDC.

CONCLUSIONS

The experimental result shows there is no significance difference in the frequency of the engine for IGBT and MOSFET driver. However, the higher pressure is developed in the left and right cylinders using IGBT driver with 3-battery configuration and 5-battery configuration. However, the engine is unstable when it is running with 5-battery configuration using IGBT driver.

It is concluded that using IGBT driver avoids the capping limit placed by MOSFET driver that cannot provide higher current for injecting to the alternator's coil. In the future, the experiment will be further expanded to use up to 8-battery configuration and to run the engine with combustion.

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