STMicroelectronics enables electronic control of the next generation of Gasoline Direct Injection (GDI) engines.

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Abstract

Gasoline direct injection (GDI) combustion with lean stratified operation allows to reduce engine toxic emissions and achieve significant benefits in terms of fuel consumption. However, use of gasoline stratified charges can lead to several problems, such as a high engine instability and increased particle emissions. Use of multiple injection strategies allows to mitigate these problems, but it requires the injection of small fuel amounts forcing the traditional solenoid injectors to work in their "ballistic" region, where the correlation between coil energizing time and injected fuel amount becomes highly non-linear.

STMicroelectronics enables the implementation of a control system able to manage the delivery of small quantities of fuel. The system is based on a particular feature found on the coil voltage command signal during the de-energizing phase. On the basis of this information, the injector needle closing time and then, in turn, the actual amount of fuel injected can be calculated and adjusted.

Introduction

Future emission regulations require the development of gasoline combustion engines with improved efficiency in order to obtain a strong reduction of the toxic emissions (manly NOx, CO, unburnt hydrocarbons and particulate matter), coupled to the reduction of fuel consumption and hence carbon dioxide emissions. A significant fuel consumption benefit is achieved by means of gasoline direct injection (GDI) engines that operate with "lean stratified" mixture. In this operation mode, the fuel is injected directly into the cylinder during the compression stroke. This allows stable combustion of mixtures having a low content of fuel (lean mixtures). However, use of gasoline stratified charges can lead to several problems. In particular, due to the oxygen excess in the combustion stroke, the NOx emission levels are generally higher than in traditional gasoline engines. Moreover, the short time for mixture preparation and the so-called spray "wall impingement" (impact of the fuel spray with the colder cylinder walls) can be responsible for engine instability and high particulate matter (PM) emissions. On the other hand, the reduction of the particulate at the exhaust of gasoline direct engines represents a crucial aspect, also considering the introduction of EU6 emission legislation, which strongly pushes toward a lowering of the number of particulate particles emitted by the engines. A potential effective way to mitigate the problems of GDI stratified operation and reduce the wall impingement is the use of multiple fuel injections, like in Diesel engine, splitting up the total fuel injection into several smaller (and shorter in duration) shots. The first effect of this approach is the reduction of the jet penetration into the combustion chamber thus reducing the wall wetting and decreasing the particulate formation. Moreover, it has been demonstrated that the use of multiple injection strategies allows to obtain combustions with an efficiency close to the thermodynamic optimum. This permits lower combustion peak temperatures with an important reduction of NOx emissions, which strictly depend on the maximum temperature reached in the combustion chamber.

However, multiple injection strategies are not easy to achieve by using the traditional GDI solenoid injectors. The management of small injections forces GDI solenoid injectors to work in their so called "ballistic" mode. The ballistic behavior appears at small injection pulse-width when the pulse is cut-off before the valve fully lifts up. In these conditions, the correlation between the electrical command and the injected amount of fuel becomes highly nonlinear, the valve motion is unstable and the fuel delivering cannot be controlled with optimum precision.

Figure 1 shows the characteristic curves of the injection rate obtained for two different injectors belonging to the same family. The graphs represent a samples of the typical dispersion. For both the injectors, the correlation between the pulse command duration and the injected fuel amount appears linear and repetitive for pulse durations greater than 400 µs and for injected fuel greater than 2.8 mg. For command pulse width lower than 400 µs, the correlation becomes highly non-linear and, for some pulse durations, may also invert the trend and decrease the fuel quantity at the increasing of the electrical command.

In the non-linear region, for very short injection command pulses, the injector needle starts the closure before having reached the widest lift position: this effect is known as ballistic mode.

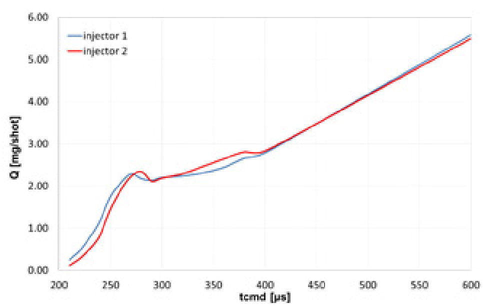

Figure 1. Characteristic curves of the injection rate obtained for two injectors belonging to the same family.

It has been reported that the causes of the non-linear behavior mainly rely on the inertia of the injector spring-mass system, the reduction of the electro-magnetic forces exerted by the coil, friction variations and more. All these have an unpredictable effect on the dynamic of the needle lift due to manufacturing tolerances and ageing effects, too. This is the reason for which, up to now, the non-linear region has not been used in the traditional injection strategies for commercial GDI engines.

In order to achieve the desired injection target also during ballistic operation, and to extend the use of solenoid injectors to short injections, real time information about the actual fuel amount delivered at ballistic are needed. On the basis of these information, the injector energizing time can then be adjusted in real time by means of a closed loop algorithm to obtain the requested injected quantity.

STMicroelectronics solution

In our laboratories, we have found that the injection voltage signal itself contains clear information about the actual quantity of fuel delivered. The graph in Figure 2 illustrates a comparison between the injector voltage signal and the corresponding injected mass flow rate for a coil energizing time of 300 µs. The gasoline mass flow rate has been measured by means of a Fuel Injection Gauge Rate meter working on the Bosch tube principle. The analysis of the two curves depicts that the voltage signal shows an inflection at the same time when the injected mass flow rate is annulled. This time corresponds to the injector needle closing time and it occurs during the switch-off phase, when the injector coil is de-energized and a self-induction voltage is created.

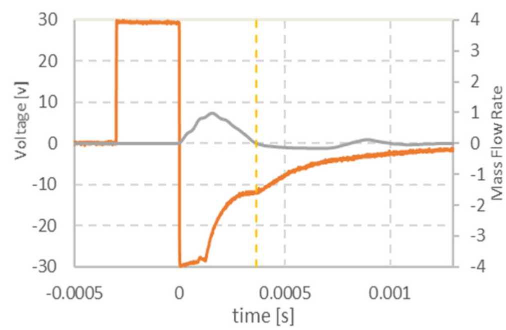

Figure 1. Comparison between differential voltage command signal and the corresponding injected mass flow rate, for a coil energizing time of 300 µs.

Being able to measure the time of needle closing means being able to measure injected fuel mass. In fact, it can be demonstrated that for solenoid injectors, when there is no variation in opening delay, fuel mass amount is directly correlated with needle closing time. On the basis of this, it becomes clear that processing the injector voltage signal allows real-time calculation of the actual amount of fuel injected during the ballistic mode. This fuel amount can then be compared with a desired target fuel mass value previously defined and loaded in the engine control maps. As a result of this comparison, a correction value for the coil energizing time can be defined and implemented.

The above-described control strategy enables the use of GDI solenoid injectors for very short injections, when ballistic behavior occurs, enabling the use of multiple injection strategies in GDI engines.

STMicroelectronics has a complete product portfolio (see Figure 3) for the full electronic control of next generation of GDI engines. It includes devices able to manage ballistic injections and ensure, using multiple-injection strategies, an optimal engine functioning in the entire range of engine operating conditions.

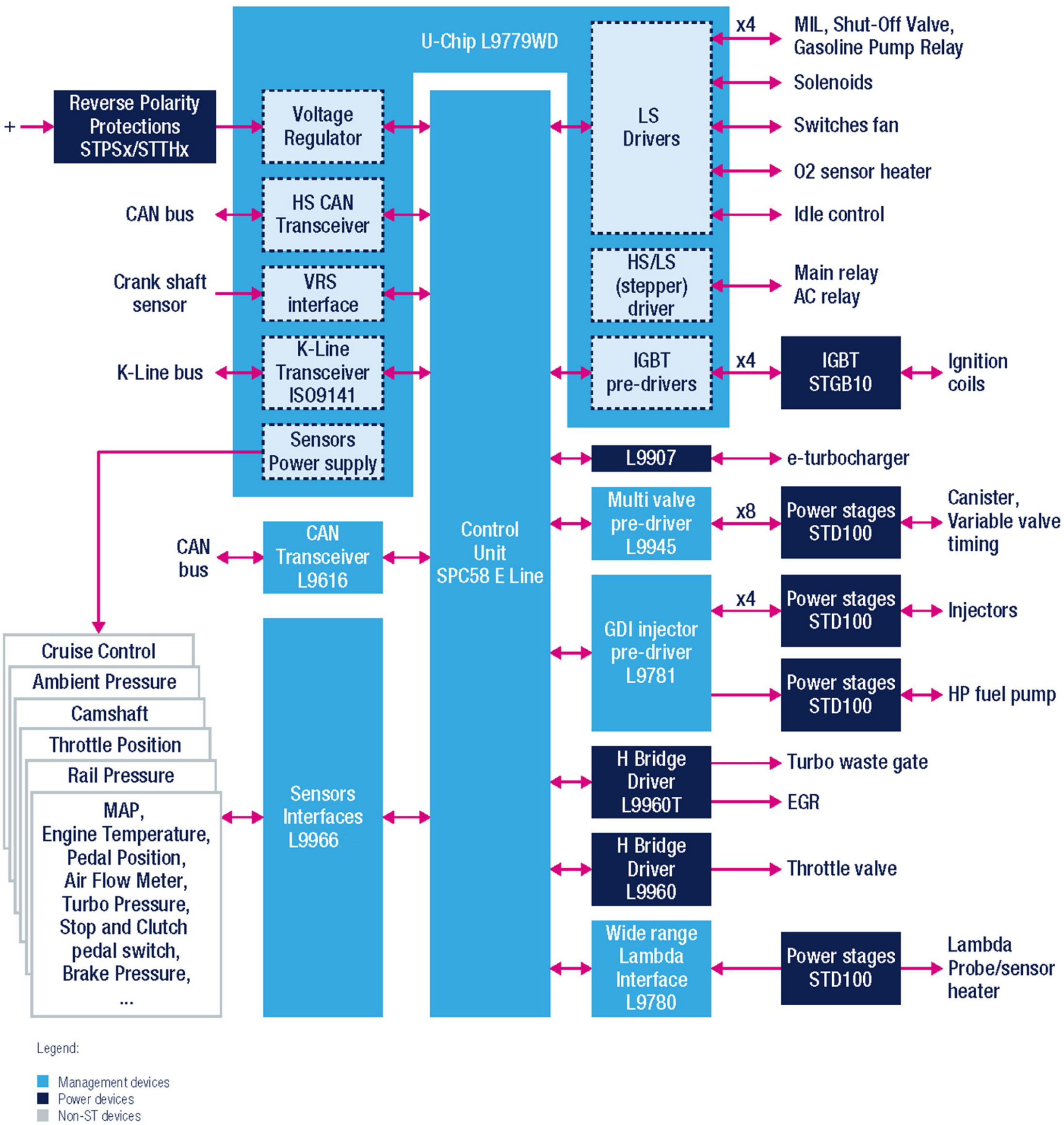

Figure 2. STMicroelectronics devices for electronic control of the next generation of GDI engines.