SMART START-STOP SYSTEM FOR A CAMLESS ENGINE EMPLOYING ROTARY VALVES

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ABSTRACT
A start-stop system (SSRE) is proposed for a newly designed camless rotary valve engine. The system is an improvement on the Mazda’s Smart Idle Stop System (SISS), a start-stop technology considered to be one of the best in the industry. Both systems prevent engine idling by leveraging the principles of the direct fuel-injection engine, bringing about 10% improvement in fuel economy and fast restarting without sacrificing driving comfort. The SISS requires a starter motor to halt pistons in the optimum position when the engine is stopped. For the proposed system, there are no such requirements since the ignition system is independent of piston position. The system works best with engines having 6 pistons or more since then the system is able to identify at least one piston in the power stroke. The system has been successfully designed and programmed onto an ALTERA EPM7064SLC44-5 FPGA device.

KEY WORDS
SSRE, SISS, idling, direct fuel injection.

1. Introduction
The start-stop systems, sometimes called idling stop, automatically shuts down and restarts the internal combustion engine to reduce the amount of time the engine spends idling, thereby reducing fuel consumption and emissions. This technique is most advantageous for vehicles which spend significant amounts of time waiting at traffic lights or frequently come to a stop in traffic jams. The start-stop feature is present in hybrid electric vehicles, but also appears in vehicles which lack a hybrid electric power-train, called micro-hybrids [1]. In this case, fuel economy gains are typically in the range of 5% to 10%. Automobile accessories like air conditioners and water pumps typically designed to run off a serpentine belt on the engine, must be redesigned (using electric motors) to function properly when the engine is turned off.

Start-stop devices have been tested since the mid-1970s, when the Toyota Corporation fitted a Crown sedan with an electronic device that would automatically switch off the engine after sitting stationary for 1.5 seconds. Testing showed about a 10% improvement in fuel economy in Tokyo traffic [2]. This technology was also adapted by the Volkswagen Group in their Golf Ecomatic in 1994 and in the Volkswagen Lupo "3L" and the Audi A2 "3L" in 1999. These early implementations were considered rather disconcerting by many drivers, and the high pricing failed to yield these cars much commercial success.

In its C2 and C3 models of 2006, Citroen introduced a more refined system named “stop and start” using a combination of SensoDrive automated gearbox and an electronically controlled reversible alternator or integrated starter-generator (ISG) [3]. Other manufacturers such as Valeo[4] and Denso [5] developed an “integrated starter-alternator”, a form of IGS which combines the role of the starter and alternator into one unit.

Audi introduced its first start-stop system with automatic transmission on its A3 models. The cars are also equipped with brake energy regeneration which captures some energy during coast down to charge the battery. This has the effect of reducing the alternator load on the engine during acceleration, [6].

FIAT has introduced the FIAT 500 start&stop, which uses Bosch’s Start&Stop technology, [7]. Using the 500 Start&Stop, CO2 emissions on a 1.2L engine are 113 g/km, while fuel consumption can be reduced by up to 12%. However this system will not activate for cold starting.

Instead of using an integrated starter generator, BMW has used an enhanced-conventional starter developed by Robert Bosch GmbH. The starter can withstand the increased number of engine-starts as required by a stop-start vehicle.

The Mazda’s Smart Idle Stop System, (SISS), detects which piston is in the best position to restart quickest, i.e., the one in the combustion stroke phase, where air and fuel are in the cylinder, ready to be ignited. The mixture in this cylinder is ignited by the spark plug, forcing that piston down, resulting in a near instantaneous engine start time of 0.35 seconds, [8]. The company claims a fuel serving of up to 10%, [9].

The National Highway Traffic Safety Administration (NHTSA) in the US raised concerns about the “sudden lurching forward of certain non-hybrid vehicle in an automatic restart”, [10, 11]. Hybrid/electric assist vehicles experience almost no delay in power from a stop, due to the instant availability of power from the traction battery to the electric motor(s). Gasoline/microhybrids on the other hand generally experience slight delays. Start-stop systems are heavily reliant on the battery. Tests have
indicated that AGM batteries diminish in their ability to support start-stop functionality over time. [12]. While alternatives exist, virtually all automakers continue to use conventional AGM lead acid batteries.

![Chart 1. Idle stop vehicle benefits in Europe.](image)

Start-stop vehicle are more popular in Europe as the fuel efficiency gain is higher on the European certification cycles. [13]. Chart 1 shows an average start-stop improvement of 10%.

The proposed smart-start-stop system for a camless rotary valve engine [14], works on the same principles as the mazda’s SISS, but with the added advantage that it is independent of piston position and operates a lightly loaded engine. The SSRE system doesn’t rely on trapped fuel mixture in the cylinder. Since the valves operate perpendicular to the piston motion, they can open to administer fuel mixture without the engine cranking. Poppet valve based engines will require the engine to turn in order to achieve this. Furthermore, with the engine disengaged from the gearbox, the engine become lightly loaded since the spring loaded cylinder-head is replaced by a rotary valve cylinder head. Details of the design are covered in sections 4 and 5.

2. Conventional Start-Stop Systems

The start-stop or idle stop system are designed by different companies. They all do the same thing; temporary stop the engine when it’s idling and restart it again when its time drive off. As briefly discussed in the introduction, different companies implement this system differently. However, there three main ways to implement a start-stop system; using a dedicated starter motor, using an integrated starter generator or using direct combustion [15].

Using a dedicated starter motor, the motor has to withstand several start cycles. Furthermore, the conventional AGM lead acid batteries were not designed for this kind of repetitive use. BMW uses an enhanced-conventional starter which can withstand the increased number of engine-starts. Such a system as shown in figure 1 is no different from a conventional starter system.

![Figure 1. Independent starter and generator](image)

Another way to implement a start-stop system is to use an integrated starter generator, ISG, which can either be belt driven or integrated into the crankshaft as shown in figure 2. Integrated Starter Generators are normally used with hybrid electric vehicles. Here, the start-stop procedure is straightforward; when a vehicle stops at a traffic light or in heavy traffic, the engine is switched off. When the vehicle is ready to move again, the ISG will turn the engine at idling speed before the ignition system kicks in to resume the Otto cycle. Hybrid systems also support regenerative braking. However, ordinary AGM lead acid batteries are not capable of driving the ISG and can’t accept frequent recharges from the ISG.

Controlled Power Technologies, (CPT) has developed a start-stop technology, known as SpeedStart, [16]. According to CPT, SpeedStart represents the development of the world’s first bespoke belt-driven Integrated Starter Generator (B-ISG) capable of starting a 2-litre diesel engine or 3-litre petrol engine with a conventional 12-volt electrical system. The technology has been showcased using a Volvo S40 equipped with a 2.0-litre common-rail diesel engine. The 12-volt system is powerful enough to start the engine in almost half the time required by a normal starter motor and it also avoids the need for expensive super capacitors. SpeedStart is a low speed high power generator which offers a comfortable, efficient and powerful engine cranking capability. The system consistently delivers an almost silent as well as fast starting event and will repeatedly crank a 2.0-litre diesel power-train under a wide range of operating conditions.
3. Operating Principle of the SISS

Figure 3 shows the operating principle of Smart Idle Stop System (SISS), developed by Mazda. When the driver stops the vehicle at a red traffic light or traffic jam, the engine stops automatically and sets itself to be ready for a prompt restart. As soon as the driver presses the clutch, the engine quickly and quietly injects fuel directly into the cylinder and igniting it to force the piston down and set the crank in motion. The engine is controlled with precision to make this happen [8]. Conventional idle-stop systems rely solely on the use of an electric motor to restart the engine. As such, they require a relatively long amount of time to achieve combustion in the engine when it restarts. This means a lag between the moment the accelerator pedal is pressed down and the car begins to move, as well as vibration and noise.

In order to start the engine quickly, the SISS or i-stop uses combustion energy from the initial stage of restarting the engine. However, the following conditions must be satisfied while the engine is stopped:

1. The computer control system must be able to determine which cylinder to fire immediately after starting the engine. With the assistance of a starter motor, the engine is stopped exactly when a piston is halfway through the cylinder to be fired. (2) An adequate amount of clean air must exist in the combustion chamber of the cylinder to be fired and (3) the engine must be able to inject fuel directly into the combustion chamber to be fired. This is possible if we use a direct-injection engine that can deliver fuel to the combustion chamber at high pressure.

Mazda's use of principles unique to the direct injection spark ignition (DISI) engine, restarts the engine in just 0.35 seconds, about half the time of most other competing systems, while minimizing noise and vibration and drain on the batteries [17].

4. Overview of Electronically Controlled Rotary Valve Engine

The principle of operation of the Electronically controlled Rotary Valve (ECRV) engine summarized in figures 4 and 5, is discussed in detail in [18]. The flow chart of figure 5 demonstrates how the control unit is constructed from using two Otto cycles. Figure 4 shows the physical justification of using two Otto cycles. V1 and V2 are valve openings which correspond to e1, i1, c1 and e2, i2, c2 respectively. During the first Otto cycle, the valve opening v1, exposes the cylinder to e1(exh1), i1(int1).and c1(cmpr1+pwr1). At the same time, v2 exposes the same cylinder to e2, i2 and c2. At the end of this cycle, the ECRV motor would have moved 180°. During the second Otto cycle, v1 exposes the cylinder to e2, i2 and c2 while v2 exposes the same cylinder to e1, i1 and c1. For the two Otto cycles, the crankshaft would have moved four revolutions for a single revolution of the ECRV motor, considerably reducing valve wear. A camshaft would have done 2 revolutions. Note that exhaust channels e1 and e2 are combined in the cylinderhead, so are input channels i1 and i2, and closed channels c1 and c2.
The combined Otto cycles of figure 5a yield 8 states. During the power and compression strokes, the valves remain closed. This is labelled as a single state, c, as far as the valve is concerned. Hence each of the valve disc slots v1, v2 in figure 4 goes through 6 states labelled e1, i1, c1, e2, i2, c2. The six state motor of figure 5c is used to operate the valve disc.

The valve of PDS controls the transition from one Otto cycle state to the next. During the exhaust and compression strokes, the piston moves up and PDS=1. During power and intake strokes, the piston moves down and PDS=0, as depicted in figure 5b.

Valve timing loss may occur after battery replacement or other factors. The system will automatically correct (valve) timing. If for example, when we are in state pwr1 of figure 5a, we expect that PDS=0, otherwise we stay in state pwr1 until it is so. This ensures that the value of PDS correctly matches the direction of the piston for correct timing.

For pwr1 and cmp1 states, the v1 is closed (i.e., v1 will be on position c1). According to figure 5c, for cls1, the coils A1, A5, A6, will be positively energised whilst the remaining coils A2, A3, A4 will be negatively energised. Therefore the coil equation c1 = A1, A2, A3, A4, A5, A6 = 1000112 = 23H. The reader need to note that when the ecrv motor moves v1 to position c1, v2 will also move to c2 since the two are on the same disc. For pwr2 and cmp2, v2 will be moved to c2 using c2 = A1, A2, A3, A4, A5, A6 = 0111002 = 1Ch. Similarly we can derive equations for other states.

Looking at pwr1 state again, we see that the fuel signal F=0 and the spark signal S=1. The assignment of the outputs at each state is consistent with the engine Otto cycle theory.

The flowchart of figure 5a forms the basic rotary valve engine control unit (called engine full control module, EFCM, because it also handles fuelling and sparking). The truth table of the EFCM, shown in table 1, describes the functionality of the EFCM.

5. Start-Stop System for Rotary Valve Engine

In order to restart the engine by combustion using the mazda’s SISS, the pistons must be stopped at exactly the correct position to create the right balance of air volume in each cylinder. The SISS must provide precise control over the piston positions during engine shutdown to accomplish this. The SISS indexes each cylinder and initiates fuel injection before the engine begins to rotate. Because of the absence of a spring loaded camshaft system, the torque required to turn a rotary valve engine with the gearbox disengaged is minimal. The rotary valves are operated by software controlled solenoids not the crankshaft. Therefore, the engine remains easy to turn. With the absence of the power hungry starter, the spark plugs can deliver a good spark. As a result, fuel mixture at atmospheric pressure will provide enough combustion pressure to turn the engine. The normal ignition system takes over once the engine starts turning.

The flowchart or ASM (algorithmic state machine) chart of figure 5 can also be represented by the truth table 1. Code Table 2 represents the truth table of Table 2. The code table was designed using Altera Max Plus II AHDL text editor, similar to VHDL. The code table was successfully compiled and programmed into the EPM7064LC68-7 device. The simulation results of the
EFCM are presented in Figure 6. The results obtained concur with the code table and the ASM chart of figure 5a.

Figure 6 shows the timing waveform for the EFCM. At a positive clock edge (shown by arrows), transition from one state to the next is controlled by the value of PDS as described in the ASM chart of figure 5. Simulation starts at t=0.0nS with the EFCM at state s4 (pwr2). One can observe that the EFCM remained in the same state for a period of 2 clock pulses since PDS is low. A spark will be delivered at this time (S=0) with the fuel injector closed (F=0). State s6 is an intake stroke.

Table 1.
Truth Table for engine control unit, EFCM for a single piston engine

<table>
<thead>
<tr>
<th>Present State</th>
<th>INPUT</th>
<th>Next State</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0 (pwr1)</td>
<td>0</td>
<td>S0</td>
<td>23, 0, 0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S1</td>
<td></td>
</tr>
<tr>
<td>S1 (exh1)</td>
<td>0</td>
<td>S2</td>
<td>0E, 0, 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S1</td>
<td></td>
</tr>
<tr>
<td>S2 (int1)</td>
<td>0</td>
<td>S2</td>
<td>07, 1, 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S3</td>
<td></td>
</tr>
<tr>
<td>S3 (cmp1)</td>
<td>0</td>
<td>S4</td>
<td>23, 0, 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S3</td>
<td></td>
</tr>
<tr>
<td>S4 (pwr2)</td>
<td>0</td>
<td>S4</td>
<td>1C, 0, 0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S5</td>
<td></td>
</tr>
<tr>
<td>S5 (exh2)</td>
<td>0</td>
<td>S6</td>
<td>31, 0, 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S5</td>
<td></td>
</tr>
<tr>
<td>S6 (int2)</td>
<td>0</td>
<td>S6</td>
<td>38, 1, 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S7</td>
<td></td>
</tr>
<tr>
<td>S7 (cmp2)</td>
<td>0</td>
<td>S0</td>
<td>1C, 0, 1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>S7</td>
<td></td>
</tr>
</tbody>
</table>

The intake channel will be open (A=38\_H), fuel will be administered (F=1) and the spark is not discharged at this point (S=1). These observations are consistent with the ASM chart of figure 5.

Table 2.
Code Table for the EFCM using Altera Max PlusII

```vhdl
-- VHDLM 4.5
-- VHDL 2008

library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;

entity demo_efcm is
end entity demo_efcm;

architecture demo of demo_efcm is
begin

PROCESS(clk, reset, PDS) BEGIN

IF (RESET = '0') THEN
  reset <= '1';
ELSIF clk'EVENT AND clk = '1' THEN
    reset <= '0';
  END IF;
END PROCESS;

process(clk, reset, PDS) begin
    if clk'EVENT and clk = '1' then
        s := s + 1;
        if s > 7 then
            s := 0;
        end if;
        case s is
            when 0 =>
              if (PDS = '0') then
                A <= '1';
              else
                A <= '0';
              end if;
              F <= '1';
              S <= '1';
            when 1 =>
              if (PDS = '1') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '0';
              S <= '0';
            when 2 =>
              if (PDS = '0') then
                A <= '1';
              else
                A <= '0';
              end if;
              F <= '1';
              S <= '1';
            when 3 =>
              if (PDS = '0') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '1';
              S <= '1';
            when 4 =>
              if (PDS = '0') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '1';
              S <= '1';
            when 5 =>
              if (PDS = '0') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '1';
              S <= '1';
            when 6 =>
              if (PDS = '0') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '1';
              S <= '1';
            when 7 =>
              if (PDS = '0') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '1';
              S <= '1';
            when others =>
              if (PDS = '0') then
                A <= '0';
              else
                A <= '1';
              end if;
              F <= '1';
              S <= '1';
        end case;
      end if;
END process;
end architecture;
```

Figure 6. Timing waveform for the EFCM
Figure 7 shows the engine control system incorporating the start-stop facility. The EFCM is event driven by PDS. When the engine is running normally, the pulse transition detector, PTD, will produce two signals, clk_pds to drive EFCM and sig_pds to give the EFCM the direction of the piston. The PTD produces these two signals from the PDS signal. When the engine is stopped, the fuel output F will be disabled via the stop module.

To restart the engine, the system uses combustion without the assistance of a starter motor. Furthermore, no requirement is placed on the position of the pistons. When the start button (ignition key) is pressed, the 555timer will operate the start module which will produce PDS_int pulses. PDS_int mimics PDS and will operate PTD through the XOR1.

This will cycle the EFCM through the Otto cycle states, opening valves, injecting fuel mixture and ultimately firing cylinders which are in the power phase. However, because the engine is not turning, we need the true value of PDS to indicate direction of the pistons lest we fire pistons going in the wrong direction. From figure 7, we can see that PDS will enable the spark (via AND2) using the true direction of the piston. If the engine were to rotate backwards, we will be firing pistons going up instead of down. This is achieved by inverting the value of PDS in real time using the DIR input. Following a stop command, the activity sensor inhibits any starting attempts until the engine has come to a halt.

Figure 8 shows the design of the completed system using ALTERA Max Plus II Design Software.
6. Discussions of the Findings

The start-stop design was successfully tested on a single piston engine. Unlike the Mazda’s SISS design, the SSRE design exhibits a true combustion since a fuel mixture (not just fuel through the fuel injector) can be administered into the cylinder. The rotary valve engine is light to turn; therefore unpressurised fuel mixture can easily turn it upon ignition.

However, there are three worst case scenarios for a single piston engine. The first scenario states that if by chance the engine stops with the piston at exactly TDC, upon firing the cylinder, the engine could turn either way. In the second scenario, the engine may also stop with the piston moving upwards or downwards. Firing an upward moving piston will force it downwards, making the engine turn the wrong way round. The third scenario is when the piston is exactly at BDC. Firing the cylinder will result in no motion at all. For the 4-in-line crankshaft of figure 9, the second scenario doesn’t pose any problem because when two pistons are moving up, the other two will be moving down for combustion. The in-line 6 crankshaft doesn’t suffer from any of the scenarios. Looking at figure 10, when pistons 1 and 6 are at TDC, one of piston 2 or 5 will be in the power stroke and is 60° (180° -120°) away from BDC. When the cylinder for this piston is fired, it will bring about rotation.

7. Conclusion

Studies have shown that Start-Stop systems have proven effective in congested city driving where vehicles spend a considerable time idling, [19, 20]. These energy-saving systems use a starter generator instead of the typical alternator and starter combination found on conventional vehicles. These starter generators use heavy duty batteries as found in Hybrid cars. The Mazda SSIS system uses a combustions method in conjunction with a starter generator whose purpose is to reposition pistons to an optimum power phase position before the vehicle stops. In the proposed SSRE system, no starter generator is required as the engine turning torque is minimized due to substitution of the conventional spring loaded valve train system with the rotary valves. Therefore a piston anywhere along the power phase will be able to turn the engine when fired. The system has been successfully tested using a single piston engine. Our discussions indicate that our proposal will work better with a 4 piston engine and even better for an engine with more than 4 pistons. The benefits of the proposed SSRE system include the following: better engine performance and reliability because of the use of rotary valves instead of poppet ones [14, 18], less complex engine control unit, better fuel economy and less pollution during engine restarts since no un-burnt fuel will be emitted when using combustion restarting.

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