Development and Implementation of the Visteon Integrated Starter-Alternator System with Ultracapacitors

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Abstract: This paper presents the design, development and implementation of the Visteon Integrated Starter-Alternator (VISA) system. The unique aspect of the vehicle's power system is that it utilizes the 300 volt ultracapacitors energy storage system, which is smaller and lighter than the 300 volt battery source. The under-hood engine package retains the size of the original Mondeo, a salient mechanical feature of the VISA to engine interface. This paper also presents the development and implementation of traction motor controller, the evolution of control strategy for charging and discharging the energy system and the overall power and mechanical system architecture.

Keywords: Hybrid electric vehicle, ultracapacitor, electric drive, induction motor, battery, inverter, control system, state of charge.

1. Introduction

Global warming of the planet and poor air quality of cities has forced the automotive industry, during the last decade, to address the needs of the hybrid electric vehicle (HEV) as well as electric vehicle (EV). An HEV with a starter-alternator [1] would play a significant role in protecting the legacy mother nature has bequeathed us. Feasibility of the pure EV is still challenged by the development of infrastructure and battery technology. In terms of near future goals, HEV is one potential solution [2-4]. In addition to reduced emissions from the internal combustion engine, starter-alternator has the potential to significantly improve the fuel efficiency. In contrast to the 300 volt battery operated starter-alternator system, the ultracapacitor VISA system proposed in this paper has the merits of smaller size, lighter weight, ability to precisely determine the state of charge of capacitors and very high current capability even close to the voltage limit.

A starter-alternator which is used with an internal combustion engine has been developed. An induction motor is used for starting the engine, which works as an alternator after the engine has started. The rotor of the induction motor is directly mounted to the engine crank shaft and the stator is mounted between the engine block and transmission's bell housing. The packaging of induction motor is achieved with minimum modifications to the engine and vehicle. The starter mode minimizes the fuel consumption by cranking the engine when it is least efficient [5], allowing the engine to shut down at zero vehicle speed and allowing the engine to restart instantaneously in less than 0.3 sec. This reduction in fuel consumption reduces the emissions, which is currently a global issue. In the alternator mode the capacitor energy is restored, the batteries are recharged and energy is supplied for ever-increasing electrical load of the entire vehicle.
2. System Configuration

The VISA system, shown in Figure 1, includes induction motor, inverter, DC/DC converters, three 1 farad ultracapacitors connected in series (0.3F at 300V) and 36 volt lead acid battery. The boost converter powered by the 36 volt battery can charge the capacitors to 300 volts in less than 3 seconds for the cold start. Fully charged capacitors can start the engine two to three times consecutively before recharging the capacitors. The regenerative action can charge the 36 volt battery, 12 volt battery and capacitors. The battery is reduced from 300 to 36 volts by using ultracapacitors as an energy source for the motor. This is quite significant in terms of weight and space reduction; an important concern with a 300 volt battery system. The lighter weight ultracapacitor system has the benefit of more compact packaging as well.

3. Engine Interface and Under-Hood Packaging

The VISA system is implemented on the European Mondeo. The concept vehicle has a production 1.8 L, IDI, turbo-charged diesel engine with manual transmission. No modifications are made to the wiring harnesses, but minor modifications are made to the plumbing, since some of the component fittings are displaced from the original location.

The VISA is directly mounted to the engine crank, replacing the flywheel. A picture of the engine, motor and clutch assembly is shown in Figure 2. The rotor of the motor is directly mounted on the engine crank, and the clutch is directly mounted on the rotor. The stator is bolted between the engine block and the transmission bell housing.

The prototype energy storage and controls are housed in the trunk of the vehicle but a future goal is to package the complete system under the hood and integrate the starter-alternator with the transmission's bell housing.

3.1. VISA to Engine and Transmission Interface

To directly mount the motor on the engine, the flywheel is removed from the engine crank. The flywheel is not required because the starter-alternator directly starts the engine and the mass of motor's rotor compensates for the mass of the flywheel. The rotor adapter is designed to mount on the engine crank using the same mounting pattern used by the flywheel. The rotor adapter is also designed to mount
the clutch on the motor's rotor and the surface of the rotor adapter is designed for the clutch to engage. The rotor adapter incorporates sensing holes for the crank position sensor. A portion of the VISA stator is fitted inside the stator adapter, which also functions as a spacer to interface the VISA with the engine and transmission. The remaining portion of the VISA stator is slip fitted inside the transmission's bell housing.

### 3.2. Under-Hood Packaging Modification

Full advantage is taken of the room available inside the transmission's bell housing, which causes only a minor increase in the under-hood packaging length of the engine, starter-alternator and transmission. This minor increase in length requires minimal modifications in the production packaging.

The production starter and alternator are removed, thus creating additional space under the hood. The transmission mounting locations on the engine block are used to interface the engine, motor and transmission.

### 4. Induction Motor as Starter-Alternator

Three candidate motors for the VISA application are investigated: The induction motor, the switch reluctance motor and the permanent magnet motor. The motor selection has to be evaluated based on the cost of the power silicon, motor material and the performance advantages. The permanent magnet motor though has higher efficiency but it is relatively expensive, switch reluctance motor has the advantages of simpler stator winding and rotor structure, but it has potential of high noise due to the rapid change of the magnetic field. An induction motor is selected primarily due to the following four reasons:

1. Induction motors have a wide speed range which better match the specifications.
2. Induction motors can be completely de-energized and hence have a better failure mode and are more reliable in the case of short circuit winding failure.
3. Induction motors have advantages of ruggedness, low maintenance requirements, low cost and ability to operate in hostile environment.
4. Induction motors have high performance at lowest possible cost.

The motor design is a compromise between the start-up and the running requirements such as speed regulation and efficiency. A high rotor resistance is desirable for high starting torque where as a lower rotor resistance is more feasible for better running characteristics. The motor is designed for high starting torque for quick acceleration. Another motor design objective is to extend the constant power region and minimize the constant torque region because the motor is operating in generation mode most of the time. The motor ratings for VISA are shown in Table 1 and the desired torque speed characteristic of the induction motor for this application is shown in Figure 4.
Table 1 Motor Rating

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Voltage</td>
<td>300 V</td>
</tr>
<tr>
<td>Rated Power</td>
<td>8 kW</td>
</tr>
<tr>
<td>Base Speed</td>
<td>300 rpm</td>
</tr>
<tr>
<td>Peak Torque</td>
<td>280 N.m</td>
</tr>
</tbody>
</table>

Figure 4: VISA Design @ 300 DC Bus Voltage

4.1. Traction Motor Control

An Advanced Controller for Electric machine (ACE), a high performance real time control
system, is used to implement the four quadrant field orientation control for the starter-alternator. The field orientation allows the independent and efficient control of torque over a wide speed range. It has been reported in the literature [6-7] that the rotor parameters change with temperature and speed specifically, the rotor resistance. To overcome this problem, rotor parameters have been combined in slip gain($K_{slip}$) and torque gain($K_T$). This is shown in Figure 5. The motor is characterized at various speeds and temperatures both in motoring and generating modes. Experimental results reveal that $K_T$ and $K_{slip}$ depend on the operating mode of the machine i.e. motoring/generating, operating speed and flux current ($i_{ds}$) setting. After careful study of the test data, a gain scheduler for $K_T$ and $K_{slip}$ is developed and implemented.

5. **Ultracapacitors as Energy Storage System**

Following are the key factors which strongly influence the choice of ultracapacitors as the energy storage system.

1. Lighter weight and smaller size.
2. Longer life than conventional batteries.
3. High current capability even close to the voltage limit.
4. Precise state of charge measurement from the measured voltage of the capacitors.

5.1. **Controller Characterization for Capacitor Voltage Variation**

The choice of ultracapacitors as an energy storage system influences the motor control strategy significantly. A stiff DC voltage source is used in the lab instead of ultracapacitors. However the bus voltage is varied from 300 to 150 volts to simulate the capacitor's voltage variation. The stiff voltage source in the lab gives longer time to characterize the induction machine at different voltage levels. A varying flux and torque command profile is developed, instead of constant flux command. The motor operating points for maximum torque/ampere are collected from the test data. Thus a characteristic lookup table results at various voltages across the entire voltage range of the ultracapcitors. It has been observed that by controlling the flux and torque command appropriately a constant torque of 280 to 150 N.m can be achieved while the voltage varies from 300 to 150 volts. These test results prove when the voltage varies from 300 to 150 volts, a minimum constant torque of 150 N.m can be produced, which appears to be sufficient to start the engine.

5.2. **Ultracapacitor's Capability Test**

This test is performed with ultracapacitors as the energy source, using flux and torque command profile developed in the last test. The induction motor and the engine are assembled together and installed in the car. The engine is started with the motor. It has been observed that the time required to charge capacitors, from 0 to 300 volts, is less than 3 seconds. Also the motor can accelerate the engine up to 800 rpm in less than 0.3 sec, which allows the engine to shutdown at zero speed. Furthermore, without ignition the motor can run the engine at 800 rpm for longer than three seconds with fully charged capacitors. These observations meet the specifications to start the engine successfully. Under normal operating conditions the engine is expected to start in less than 0.3 sec, and also ignition starts at about 250 rpm.

5.3. **Controller Design for Generation Mode**

The controller commands the motoring or generating mode based on the system status. An intelligent controller is designed for regenerative action of the starter-alternator. The controller checks the engine status and voltage level of different components like 12 volt battery, 36 volt battery and the ultracapacitors. Then the controller commands the motoring or regeneration mode based on the system
status. Figure 6 shows that the regenerative action brings the bus voltage back to 250 volt after it drops due to the engine starting. Note that the maximum bus voltage level set in this test is at 250 volts.

![Figure 6: In Vehicle Test Results for Bus Voltage and Currents](image)

6. **Vehicle Test Results**

The starter-alternator system is installed in the car and is tested to ensure functionality and performance. The vehicle system controller (VSC) and the VISA controller are both implemented in the ACE. The vehicle system controller sends a start command to the VISA controller. The VISA drive system generates torque to accelerate the engine. The fuel and ignition control start to work at an engine speed of 250 rpm. The starter-alternator keeps accelerating the crank shaft. When the engine is successfully started, the engine controller brings the engine to a speed higher than 800 rpm. The VSC at this point detects that the engine has successfully started and stops the motoring mode. The VSC monitors the energy storage system and enters in the generation mode if required. In this implementation no additional controller beside the ACE is used.

![Figure 7: Speed Curve during Engine Starting](image)

The scheme is tested in the vehicle and the results are presented in Figures 6 and 7. A start command is given at about 0.3 sec. VISA brings the engine to 800 rpm at about 0.6 sec. At this time the VISA drive system is switched to generation mode and charges the ultracapcitors and the battery at demand. One of the requirements for the starter-alternator is to start the engine as quickly as possible,
which proved to be less than 0.3 sec. When the vehicle is driven on the road, its STOP and GO function proved to be quite seemless.

7. Conclusion

A prototype starter-alternator system using ultracapacitors is designed, built and demonstrated. VISA to engine interface has been accomplished with minimal modifications in the under-hood packaging. Three 1F capacitors connected in series provide sufficient energy source to start the engine. A 36 volt battery is adequate to charge the capacitors for frequent starting purposes. The prototype system meets the torque/power specifications to start the engine successfully and supply the load in the regeneration mode. Future plans include better packaging of the energy storage system under the hood, and a design review to reduce the size of induction motor and inverter, and hence the system cost.

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References:


