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Innovative Design of an Automotive High Side Smart Switch Based Upon Frugal Engineering Concepts

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Abstract

Automotive electronics is increasingly playing a vital role in all vehicle subsystems. Since an electronic control system needs to be interfaced with the outside world, an electronic smart switch forms a key output interface with various loads such as solenoids, lamps, motors, relays, fans etc. Although integrated circuit based smart-switch semiconductor solutions are provided by all global semiconductor vendors, they prove more often than not to be overdesigned for majority of situations relevant to low end vehicles. They are also generously loaded with standard high-end features like thermal and overload protection which may not always be required. In addition, external transient protection and on-chip diagnostic features lend further complexity to the entire solution.

This paper proposes a novel smart switch design which can be optimally tailored to given output load requirements such as current profile, thermal requirements, protection on one hand and provides optimal pin count by combining diagnostic and command functions into a common terminal pin. Transient protection requirement may be minimized by judicious choice of the active device.

The smart switch system design employs system engineering techniques which lists performance requirements and explores alternate system designs to meet the same. All the alternatives are rated on various performance counts to arrive at the rightmost choice fitting a given application. The paper ends with a subsystem design design example which covers both hardware philosophy and a state machine based low level command/diagnostic driver. Future directions and opportunities for these solutions are discussed at the end.

Introduction

Automotive engineering since its inception has focused upon delivering more value consuming minimum resources to all the stake holders. Automotive embedded systems are no exception [1, 2].

One of the driving factors behind rapid penetration of electronic smart systems in automotive engineering is driven by the enhanced value proposition. Sensors and actuators in particularly are benefited from smart electronic interfaces to the outside world. [3] discusses exhaust actuator behavior at low ambient temperatures and proposes a software strategy for the same, ensuring successful operation for the active exhaust valves. [4] dwells upon intelligent auxiliary battery management based on associated information obtained through sensors. It discusses an intelligent strategy to preserve the battery state of charge under all use cases, temporarily turning off auxiliary loads whenever necessary. [5] presents a unique example of electronic subsystem control consisting of gasoline particulate filter and active exhaust tuning valve. [6] discusses effects of differential pressure measurement characteristics on high pressure EGR estimation errors on Spark Ignition engines. It offers solutions to minimize the error. All these studies highlight various aspects of intelligent embedded control of various automotive systems.

An embedded system by its very definition is embedded within its end application. It is an integral subsystem of an end application system. Naturally, interface with the other neighboring subsystems play a critical role in governing application system behavior on one hand and role of the embedded system on the other. Input device interface is relatively less complex as regards protections against transients, guarding against accidental short circuits or reverse polarity compared to output device interface. This is so due to inherent high impedance nature of an input subsystem. However, for using smart power switches to control output devices transient handling and protection circuits play a major role making its architecture complex. The literature describes various techniques for achieving the same. [7] describes a pulse width modulation (PWM) based smart switch for automotive application. The solution is equipped with built-in protections including a thermal shut-down. [8] offers a hybrid solution for implementing a smart switch. It employs a mechanical switch to handle large continuous current, aided by an electronic switch which takes over for make and brake operations. A significant gap in above cited research literature pertains to the lack of cous upon lean architecture which aims to enhance value benefit versus cost/resource consumption unlike other automotive subsystems. automotive technology trends such as engine down-sizing, drive-line optimization, copper weight reduction through in-vehicle networking, vehicle weight reduction through light weighting are some prime examples of lean system architectures driving automotive subsystems. In embedded software arena, foot print reduction and complexity reduction can be cited as some of the major trends towards lean architecture. However, a significant literature gap needs to be bridged in the area of lean architecture for implementation of smart output switches. As an attempt towards plugging this gap, the paper will be focusing upon high side smart switches to highlight key innovative measures towards enhancing "leanness" of the architecture. Idea is to improve upon value benefit versus cost/resource consumption ratio. The problem statement is summarized as below:

Challenges:

ECUs need to be interfaced with a variety of output devices. Integrated smart switch solutions provided by global semiconductor suppliers consist of a super set of system blocks catering across the diverse requirements. However, most of the output devices used for low end vehicles may need only a few of the system blocks so provided. This may lead to suboptimal value benefit versus cost/resource consumption ratio for the ECU implementation for low end vehicles.

Root-causes:

Integrated switch architecture aims to be reusable across the applications such as inductive loads, resistive, capacitive loads as well as lamp loads characterized by cold- inrush currents. Hence it contains over current/over temperature protections required for the lamp-loads which are redundant for the other types. On-chip energy absorption/over voltage transient protection clamps are relevant for the inductive class but redundant for the other types. A common solution currently offered by global semiconductor vendors in the form of an integrated circuit smart switch ends-up providing both of the above system blocks for both categories of the loads. This means, for the lamp loads on-chip transient protection clamp becomes redundant. Also, for the inductive loads, over-current/overtemperature related blocks prove to be redundant. This approach also adds complexity to the entire architecture including micro-controller interface to a complex mix of on-chip protections and driving circuits. Another root cause stems from use of N-Mos architecture (N-channel MOSFET). As discussed in the later sections, N-Mos switch requires a complex charge-pump to elevate its gate voltage. The presence of a charge-pump adds complexity to the architecture apart from making the same costly. A charge-pump is based upon a switching oscillator which further results into EMI/EMC radiations.

Proposed Solution:

A thorough system engineering analysis of the currently prevalent integrated smart switch solution needs to be carried out. This will identify ways to arrive at an optimized and revised system architecture of a smart switch for a given application requirement. Performance metrics used for architectural assessment include cost and complexity, cost to benefit ratio, reduction in mean time to repair etc. Use of a P-channel power switch also eliminates the use of a charge-pump reducing cost, complexity and eliminating EMI/EMC radiations. Since a P-channel architecture is based on a pure DC architecture, EMI/EMC radiations are completely eliminated.

These concepts are highlighted by means of a real-life case study in subsequent sections.

Real Life Design Case Study

In this section we describe a real-life design problem for designing the output device interface. The end vehicle application was intended for a two-wheeler electrical vehicle. The loads to be driven are as below:

1.0 Motorized seat actuator for a two-wheeler scooter. Stall current @ 12 Volt DC, 5.5Amp, armature inductance 23 mH and armature resistance 2.2 Ohm.

2.0 Glove-box solenoid output 3 Amp. High current load (more than 1Amp typically) needs to be driven by a high side semiconductor power driver. This is so, since a low side driver of a high current load is vulnerable to accidental short circuit to chassis ground. A low current load on the other hand can be driven by low side drivers [3].

Application Requirements: High Side Switch Drivers for Motorized Seat Actuator and Glove-box Solenoid

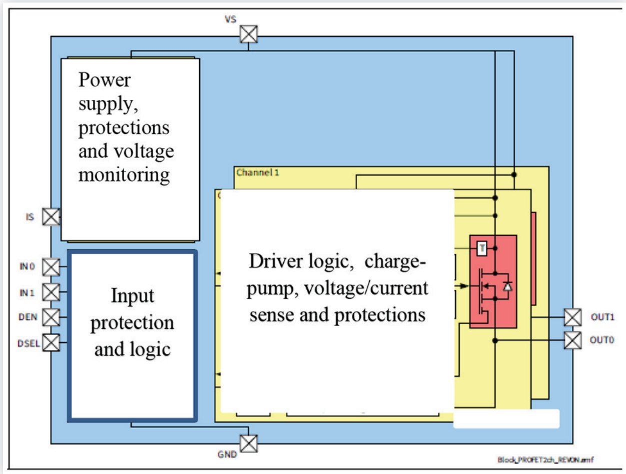
Let us understand application requirements meeting automotive norms for driving the motorized seat actuator as well as the glove-box solenoid drivers

1.0. Continuous and peak load currents to be supplied under automotive environmental conditions prescribed for the vehicle application.
2.0. Protection against accidental short circuit
3.0. Protections against electrical transients
4.0. Reverse polarity protection
5.0. Protection against inductive load switching transients
6.0. Adequate provision of diagnostics for reduction in mean time to repair.

High Side Switch Driver Implementation: Alternative 1-Integrated Circuit Smart Switch

A designer scans to through semiconductor datasheets for an off the shelf solution from global automotive semiconductor

FIGURE 1 System block diagram for the high-side smart switch.



companies. Motive is to find a closest match meeting the requirements. Semiconductor application engineers of various suppliers can assist in this exercise. To minimize the component count for the case under discussion, it makes sense to look for a dual smart switch for our two output devices for the application under consideration. Current, voltage, wattage, temperature and features overview of various candidate solutions need to be scanned for arriving at the most probable choice.

Adopting this selection process, it was evident that the integrated dual smart switch Infineon BTS7008 [11] (or any equivalent alternative) prima facie meets our requirements. It can provide maximum 7.5 Amp current loads including high in-rush types. Ours is a motorized actuator and worst-case scenario occurs when the motor is stalled due to any obstruction/ friction. It would draw 5.5Amp. This switch would definitely meet the requirement of another load, namely 3Amp glove box solenoid.

Hence this dual smart switch can be assessed against various performance metrics to understand how closely it meets our requirements.

The figure 1 illustrates the system block diagram for the smart switch.

Assessing the Smart Switch for Major Functional Blocks Against Application Requirements Referring to figure 1 we can identify below major system blocks:

- Power output switching circuit

  This block is responsible for managing power delivery to the load by driving the switch on and off. Apart from the power switch it contains driver circuit which interfaces with the microcontroller on one hand and with the power switch gate input on the other
- Protections

  This block provides protections against overvoltage, over current, reverse polarity and over temperature
- Diagnostics

  It provides diagnostics to identify root cause behind various malfunctions such as open circuit, short circuit, over temperature etc. The key motive being to reduce the mean time to repair in case of a malfunction.

Assessing Power-Switch and Associated Driver Blocks The power semiconductor technology used by the smart switch is invariably DMOS [12]. One significant fallout of the same is use of NMOS power switch as the high side switch. This entails the on-state gate voltage to be at much higher than the source voltage. As a near ideal switch, both source and drain of the power switch being at battery potential, the gate voltage needs to be boosted up higher than the battery voltage. A "charge-pump" circuit pumps-up this voltage to the required level [10]. This circuit consists of a high frequency oscillator of 2.5MHz frequency. For automotive application this can pose EMI/EMC challenges

The table 1 below rates this solution against various performance metrics. Charge-pump based driver reduces the performance rating of the first two rows. This suggests use of a different circuit concept which eliminates the use of a charge-pump based circuit. The same will be explored in later sections.

The insights derived from the table 1 can be summed-up as below:

Pain-point:

The integrated power switch contains a complex charge-pump circuit to boost the gate voltage above supply bus for driving the switch into an "on" state. This leads to further problems such as adverse impact on EMI/EMC, increase in the overall cost of implementation due the need of a high frequency oscillator which forms the core of the charge-pump

Root-cause:

The DMOS process used for IC fabrication entails formation of a power NMOS switch. Gate voltage of an NMOS switch is always higher than the source voltage. This automatically means that during "on" state of the switch gate voltage needs to be pumped-up above the supply rail.

Possible Solution:

Use of a PMOS power switch-based architecture. With PMOS the gate voltage can be lower than the supply voltage and a charge-pump is not required in gate circuit.

Assessing Protection Related Blocks Major protections required really are over voltage, reverse polarity and over current [3].

Over voltage conditions occur during load-dump transients or inductive switch-off transients. Internal voltage clamp in the form of a Zener/transient absorber diode clamps the over voltage appearing across drain and source below avalanche break down voltage of the power switch Mosfet. During inductive load shut down, the internal clamping diode needs to successfully dissipate the inductive transient energy during the load turn off. For those inductive loads which tend circuit. Short-circuit detection is retained as a strategy. However, since it is based on a simple digital input, the cost is minimized. The benefit in terms of reduction of repair time can be witnessed due retry strategy which auto-restores the switch operation after an accidental short-circuit. Row 5 again wins over the previous architecture featuring complex digital and analog micro-controller interface. Reuse of the output drive pin of the micro-controller is gain fully re-configured as a digital input pin for diagnostics. Hence zero increment of micro-controller pins for diagnostic interface earns five out of five rating.

Let us sum-up the insights employed to arrive at the proposed architecture for diagnostic:

***Pain-point*:** A complex mix of analog and digital signal processing and interfaces governed the diagnostic scheme for integrated switch architecture. This consumed multiple CPU pins, it also required enable pin to minimize current drain due to analog current signal.

Root-cause: Multiple protection mechanisms discussed in previous sections each required a diagnostic interface both analog or digital depending on the protection requirements.

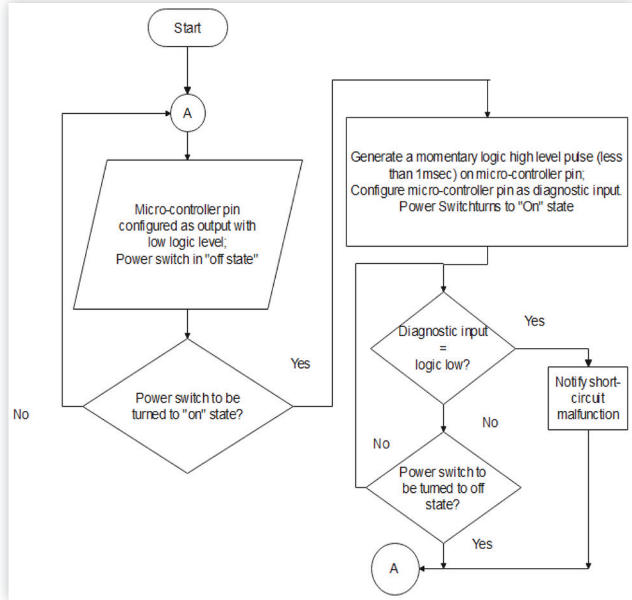
Proposed Solution: Since only short-circuit condition is to be diagnosed, A single CPU pin is reused for both command pulse as well as the diagnostics by alternately configuring the same as output and input. This leads to a frugal engineering solution driven by a common CPU pin and simple digital logic

Summary and Concluding Remarks

Figure 7 summarizes the overall implementation strategies for the revised architecture. The power-switch initialized into an "off" state. Micro-controller pin configured as "output low logic level" maintains the off state. Whenever an application command wishes to turn on the power switch, a logic high pulse is issued to the micro-controller output. This latches the power-switch into an "on" state. The micro-controller input can now safely be re-configured as diagnostic digital input since the latch no longer needs a base drive current from the same. During a short-circuit condition at the output, the latch is rest into an "off" state. This protects the power-switch on one hand and generates diagnostic message in the form of logic low input level read by the micro-controller on the interface pin. If and when the short-circuit condition disappears on its own, the micro-controller will be able to successfully turn the latch into "on" state again through an application dependent retry strategy. For turning the power-switch from "on" state to "off" state, the micro-controller interface pin needs to be configured as an output with a logic low level. This one pin interface for the micro-controller exploits the fact that after turning on the latch, the interface pin can be assigned a role of diagnostic input as a latch does not need a sustained drive input to maintain its "on" state.

The revised architecture consumes only a single CPU interface as against three pins (command, diagnostic and diagnostic enable) of the integrated architecture. It also replaces multiple component multiple protection/diagnostic subsystems of integrated architecture with a single transistor, four resistors and a single Zener diode.

FIGURE 7 Flow-chart indicating the driving and diagnostic/protection strategies for the revised architecture based on "on" and "off" states



This paper addresses a vital area of ECU interface to the outside world viz. output device interface. System design optimization in this area is multiplied manyfold since any single ECU needs to be interfaced with multiple output devices such as actuators, motors and illumination devices etc. Integrated circuit smart switches are popular choice with the ECU designer in line with the prevalent practice. However, these solutions are likely to consist of system blocks not relevant for a given application. This is particularly true for devices not featuring heavy inrush currents like lamp-loads. A simple discrete circuit switch is proposed which would improve cost to benefit ration particularly for low-cost vehicles such as two wheelers and low end four wheelers. The architecture may be further explored for packaging into a hybrid integrated circuit tailored around the PMOS switch.

Considering future course of research and development in this area, an SoC (System on Chip) solution for the high side switch can be considered. The novel solution also can be further evaluated by assembling the same on PCB and PCB level performance metrics could be evaluated on the same lines as performed in [13]

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Definitions/Abbreviations

ECU - Electronic Control Unit

PCB - Printed Circuit Board.

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