# Low-Volume Power Supply for Vehicular Fuel Injection Systems

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*Abstract-* This paper introduces a new power supply for solenoid fuel injectors of internal combustion engines. In comparison with the conventional solutions, the presented supply has smaller volume, higher reliability, and can be implemented with less expensive power stage components. The supply is a hybrid topology, combining boost and non-inverting buck-boost phases regulated by a digital load-interactive controller.

Experimental results obtained with a 12V-to-50V, 40W, 100KHz converter confirm operation without bulky and unreliable electrolytic capacitors, 11 times smaller output capacitance and two times faster dynamic response compared to the conventional single-phase boost solution.

# I. INTRODUCTION

Solenoid actuated fuel injection systems have resulted in major advances in internal combustion engines [1]. Those include reduced fuel consumption, pollution and noise levels.

The fuel injectors adjust the engine performance by varying the time the fuel is supplied to the cylinders. This is done through the instructions of the Engine Control Unit (ECU) [2] as shown in Fig.1.



Figure 1.Simplified block diagram for the engine injection system

The fuel is supplied using fast motion injector needles. The motion of these needles is controlled by solenoids requiring higher than the automobile battery supply voltage. Conventionally, the injectors are supplied by voltage step-up, boost converters [3], commonly called injector drives.

Solenoid fuel injectors will expose the injector driver to a pulsating inductive load current as shown in Fig.2.



Figure 2. Solenoid fuel injector load current

As illustrated, during the injection period, the converter has to deliver a specific amount of charge in a short period of time in the form of a particular output current waveform [4]. Therefore the injector power supply has to provide a pulsating power. However what makes fuel injector driver different from pulsed power supplies is that during the load transient the converter has to also maintain a tight output voltage regulation.

The pulsating load current makes the power supply design challenging. The converter needs to supply the load with high bursts of energy and, at the same time, maintain tight output voltage regulation. To meet both requirements, the boost converter is often over-designed. Large bulky output filter and increased size of semiconductors are normally present to satisfy the load transient requirement. The bulky output capacitor, which is usually electrolytic, increases the volume and cost of converter and at the same time reduces the converter reliability.

This paper introduces new converter topology with loadinteractive controller for supplying solenoid fuel injectors that has a smaller volume than the traditional boost solutions and does not require an electrolytic capacitor.

As demonstrated in Fig.3, the proposed system consists of a hybrid combination of a single phase boost and a multiphase Non-Inverting Buck-Boost (NIBB) phases. The boost stage is regulated by a linear controller and a non-linear load-interactive controller is used for NIBB phases. In this paper the presented voltage and current regulation system is named "One By One Input, Single Output" (OBOISO) controller.

The OBOISO controller receives the information regarding load transient time and load energy requirements prior to the load change time from the ECU through the *pre\_load* command.

Knowing the load information prior to the transient, the OBOISO controller stores an amount of energy in the NIBB phase inductors sufficient for meeting desired output voltage drop during transient. As will be described later, this eliminates limiting effect of inductor current slew rates and converter right half plane zero on system dynamic response and relaxes the requirements for the input filter.

By proper injection of the stored current in NIBB phase inductors during the load transients the converter achieves tight output voltage regulation with considerably smaller size of output filter and fast dynamic response. This allows for



Figure 3. Block diagram of the multiphase hybrid converter

utilization of ceramic output capacitors, increasing converter reliability. The application of the presented control method can also be extended to other so-called 'power aware' loads with pulsating current waveform.

### II. PRINCIPLE OF OPERATION AND SYSTEM DESCRIPTION

The proposed hybrid-topology converter consists of a parallel combination of a low power boost and a multiple number of non-inverting buck-boost stages. The block diagram for a three phase converter with one boost phase and two NIBB phases is depicted in Fig.3.

The boost phase is controlled by a peak current mode control method [5]. This phase is mainly responsible for steady state output voltage regulation. It will also perform the start-up sequence. The use of boost converter as the steady state regulator will reduce component count and also increase the overall efficiency due to reduced switching losses during steady state operation.

The non-inverting buck-boost phases are controlled by the OBOISO nonlinear control method and operate only during the load transients.

The OBOISO controller stores the required load energy during transient in NIBB inductors and output capacitor prior to the transient. This energy is released during the transient time. This method utilizes the NIBB inductors for storing the required energy during entire transient time rather than for one switching cycle. Since the required energy for load during transient is stored; the effect of energy transfer limiting factors during transient, i.e. right half plane zero in the converter topology and limited inductor current slew rate is eliminated. This will allow for minimization of output capacitor and faster dynamic response.

In addition since the NIBB inductors are discharged during load transient there will not be an additional heavy to light transient after the load transient time has passed.

#### A. Control Sequence

Fig.4 shows the required converter output current for solenoid fuel injector. The boost phase is operated by the linear controller at all times regardless of the load state. However depending on the state of the load, the OBOISO controller will function in one of its three modes of operation as illustrated in Fig.4.



Figure 4. Typical pulsating repetitive load current waveform for inductive load

### A.1. OBOISO Halt Mode

During this mode of operation, all the NIBB phases are in their steering state as shown in Fig.5.a. In this state the NIBB phases are disconnected from both input and output filters. During this time interval, OBOISO controller receives energy requirement per injection and time of occurrence of next fuel injection from the ECU. Based on the load information, the OBOISO controller determines the proper time to start precharging and the required charging current for the NIBB inductors, i.e., *i<sub>peak</sub>*.

# A.2. OBOISO Pre-charge Mode

In this mode of operation, the inductors of NIBB phases will be charged one by one as shown in Fig.6 until all inductors are charged up to the current  $i_{peak}$ . In order to charge the inductor of each NIBB phase, the state of its switches alters between '*charging*' state, Fig.5.a, and '*steering*' state, Fig.5.b.



Figure 5. Different switching states of the non-inverting buck-boost phases



Figure 6. Pre-charging inductors of two non-inverting buck-boost phases

As shown in Fig.6 this operation will charge inductor of each phase with a constant duty, i.e.  $D_{ch}$ , reducing the average converter input current. After the inductor of each phase is charged it will be operated in the 'steering' state, disconnecting its inductor from the input filter. Starting the process of charging inductors before the transient provides enough time to perform charging inductors of NIBB phases one after another. Therefore at any moment only inductor of one phase can be connected to the input source. As shown in Fig. 6 this will limit the maximum converter input current to  $i_{peak}$ . This reduces maximum input current compared to a multiphase converter in which the inductors of all phases are being charged concurrently.

Reduction of peak and average values of converter input current will relax the requirements for the input filter.

#### A.3. OBOISO Injection Mode

During '*injection*' mode, the NIBB phases will inject current from their pre-charged inductors phase by phase.



Figure 7. Inductor and load output currents during load transient

Current injection for each phase is performed by changing the state of its switches from '*steering*' state, Fig.5.a, to '*discharge*' state, Fig.5.c.

As illustrated by Fig.7, current injection from NIBB phases is done in a way that the output voltage drop will never exceed the desired value, i.e.  $V_{drop}$ . Therefore, the average converter output current will follow the load current waveform and a tight output voltage regulation with programmable voltage drop is achieved.

# III. PRACTICAL IMPLEMENTATION

### A. Energy Storage Components Selection

The selection of the output capacitor, the NIBB phase inductors and number of NIBB stages (*N*) is based on an iterative optimization procedure which attempts to minimize the size and cost of the converter for a given load energy  $E_{loads}$ 

$$E_{load} = E_c + N \times E_{nibb} , \qquad (1)$$

where  $E_c$  is the amount of energy delivered by the output capacitor and  $E_{nibb}$  is the energy supplied by each NIBB phase during transient.  $E_c$  and  $E_{nibb}$  are found as

$$E_{c} = \frac{1}{2} \times C_{out} \times (V_{out}^{2} - (V_{out} - V_{drop})^{2}), \quad (2)$$

$$E_{nibb} = \frac{1}{2} \times L_{nibb} \times i_{peak}^2 \,, \tag{3}$$

where  $V_{out}$  is the desired output voltage and  $V_{drop}$  is the maximum allowed output voltage drop.

The inductors of NIBB phases will be selected based on values of  $L_{nibb}$  and  $i_{peak}$ , found in the optimization process such that

$$I_{sat} > I_{peak}$$

where  $I_{sat}$  is the inductor saturation current.

On the other hand the converter components are selected for a specific load. For loads with other energy requirements the converter will operate with a value of  $i_{peak}$ , different from the value found in optimization process. Therefore, to avoid inductor core saturation the converter has to be designed for the maximum load energy requirement, i.e.  $E_{load,max}$ .

# B. Controller Implementation

The controller architecture, shown in Fig.3, consists of a linear controller which is used to control the boost phase and the OBOISO controller for controlling the NIBB phases. The digital to analog converter that interfaces the digital controller and analog current loop for both controllers is realized by a 1-bit sigma-delta converter and a first-order low-pass filter [6]. The OBOISO control logic is a finite state machine (FSM), which cycles through different operation modes of the



Figure 8. FSM of the proposed digital controller

converter, depending on the pre-load information and the conditions in the circuit. The state transitions of the OBOISO controller FSM are shown in Fig. 8.

As shown in the controller FSM algorithm, upon receiving the *pre\_load* data the controller has to determine values of  $i_{peak}$  and duration of '*pre\_charge*' mode.

The value of  $i_{peak}$  for a specific load can be found through equations 1 to 3. In the practical implementation of the controller, the values of  $i_{peak}$  corresponding to different load energy levels are pre-calculated and stored in a look up table. Therefore depending on the received load information, proper value of  $i_{peak}$  will be selected by the controller.

The required time for charging up inductors prior to a load transient,  $t_{ch}$ , can be found by

$$t_{ch} = N \times \frac{i_{peak} \times L_{nibb}}{D_{ch} \times V_g} \quad . \tag{4}$$

The time duration of '*pre\_charge*' mode of the OBOISO controller can be equal or greater than  $t_{ch}$ . However in order to minimize the power losses due to steered current in the pre-charged inductors, the minimum value, i.e.  $t_{ch}$  is selected. The value for  $t_{ch}$  is also selected from a look up table based on the received load information.

#### IV. EXPERIMENTAL PROTOTYPE AND RESULTS

#### A. Experimental Setup

To verify the effectiveness of the proposed design, a prototype with two non-inverting buck-boost phases is



Figure 9. Load current waveform as used in experiments

developed. The digital controller is implemented on an FPGA consisting of the PI compensator, OBOISO controller and  $\Sigma\Delta$  converters.

The experimental results are based on having a load profile for a solenoid fuel injector with following requirements: (a) No steady state load current, only a leakage current of 100mA, (b) inductive load, (c) peak current 15A and (d) pulse duration of 75 $\mu$ s. The current waveform of the load is illustrated in Fig.9. The parameters of the prototype system are listed in Table. I.

$f_s$	100KHz
$C_{in}$	90µF ceramic rated at 16V
Cout	25µF ceramic rated at
	100V
Lboost, Lnibb	47μΗ
Vin	12V
Vout	50V

Table.I. Experimental prototype-converter parameters

#### B. Experimental results

In this section, the converter response to the load transient form two different controllers is shown.

Fig.10 shows the response of a conventional single phase boost converter with a peak current mode controller. The output capacitor used in this experiment is chosen to satisfy maximum output voltage drop of 3V and has a value of  $275\mu$ F.

Figures 11 to 13 demonstrate the OBOISO controller performance when applied on the hybrid converter topology with two non-inverting buck-boost phases and  $25\mu F$  output capacitor size.

Fig.11 illustrates the proposed converter output current along with input and output voltages and load current. Based on the result shown in Fig.11, the proposed converter achieves same amount of output voltage drop compared to a single phase



Figure 10. Load transient response. PI controller. up: output voltage 2V/div, mid: input voltage 1V/div. low: boost converter inductor current 10A/div. low: load current 10A/div. Horizontal time scale 100µs/div

peak current mode controlled converter and two (2) times faster dynamic response with eleven (11) times smaller size output capacitor without increasing the size of input voltage deviations compared to a PI controller as is the case for fast non-linear controllers[7,8]. Moreover as shown in Fig.11, the output current of boost phase is small during transient and during steady state operation the converter output current equals the current of boost phase which is supplying the output leakage current of 0.1A as described above.

Fig.12 illustrates the pre-charging of NIBB phases' inductors and the way current injection is performed. As shown the inductor currents during *pre-charging* period is in good agreement with current waveforms shown in Fig. 6. Also during the *injection* period the inductor currents are injected one by one through similar method as shown in Fig.7 resulting in the expected output voltage waveform.



Figure 11. Load transient response showing converter output current. up: output voltage 2V/div, mid: input voltage 1V/div. low: converter output current 10A/div. low: load current 10A/div. Horizontal time scale 100µs/div.



Figure 12. Load transient response showing inductor currents of NIBB phases. Up: output voltage 2V/div, up-mid: input voltage 1V/div. low: NIBB phase #1 inductor current 10A/div. low: NIBB phase #2 inductor current 10A/div. Horizontal time scale 100µs/div



Figure 13. Load transient response showing converter input current. BOISO controller. Up: output voltage 2V/div, up-mid: input voltage 1V/div. low: converter input current 10A/div. low: load current 10A/div. Horizontal time scale 100us/div

Fig.13 shows input current of the converter along with input and output voltages and load current. The input current is in good agreement with the theoretically predicted input current waveform of Fig. 6. The input current before and after charge-up state is only the quiescent current of the boost phase to maintain the output voltage. Therefore the converter does not take any significant power from the input filter

# V. CONCLUSIONS

A flexible power supply for solenoid fuel injectors has been proposed. The power supply is created as a combination of boost and non-inverting buck-boost topologies. The introduced OBISO non-linear control method assumes that the information about load energy and time of occurrence of load transient is known based on information available from engine control unit. The proposed converter can be also used in other applications with power aware loads and pulsating load current.

The converter has low power dissipation during steadystate condition by only operating the low power boost phase. Moreover utilizing non-inverting buck-boost phases during transient controlled by OBOISO non-linear controller achieves fast response to load transients and reduced size of output capacitor without negatively affecting size of capacitor in input filter. Reduction in size of output capacitor allows for utilization of more reliable and smaller ceramic capacitors instead of electrolytic capacitors.

The use of modular configuration with one steady state converter and additional phases to accommodate load transients eliminates the need to accommodate soft start sequence due to inrush currents, reduces the size of the overall system. The utilization of hybrid boost/buck-boost configuration reduces component count for the steady state regulator. The use of the boost converter will also be advantageous in steady state efficiency and lower input current ripple. A prototype board with two non-inverting buck-boost phases was created. Experimental results revealed that in comparison to a conventional single phase boost converter , the proposed converter achieves same output voltage drop with eleven (11) times less output capacitor size and twice (2) faster response during load transients without increasing size of input voltage drop and hence input filter capacitor which is the case for the existing fast non-linear controllers.

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