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DESIGN OF A MULTIPHASE BOOST CONVERTER FOR HYBRID FUEL CELL/BATTERY POWER SOURCES

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Abstract: *Fuel cell applications are gaining popularity in various industries. This paper showcases a power converter application in a fuel cell system designed to replace battery pack in industrial off-road vehicles. An interleaved three-phase boost converter is used in a power train of hybrid electric forklift. The converter controls a current draw from the fuel cell and, at the same time, maintains state of charge of an auxiliary battery while delivering power requested by traction and lift systems.*
Key Words: ***Fuel cells, boost converter, interleaving, DC-DC converter, high power, multiphase converters***

1. INTRODUCTION

Electric industrial vehicles are widely used where pollution caused by internal combustion engines cannot be tolerated. Users are forced to deal with lead acid batteries and maintenance/charging routines. Fuel cells based vehicles offer numerous advantages and are making rapid advances in penetrating the market. Safety issues are being adequately addressed, hydrogen generation and storage are becoming a routine and prices of the systems are dropping down. This all makes fuel cells potentially interesting for use in a wide range of applications. In addition to industrial vehicles, fuel cell use is being evaluated in automotive, chemical, food processing, telecom and many other industries.

Material handling industry is among the ones where fuel cells are likely to quickly gain wide acceptance. A fuel cell based system that replaces standard forklift battery pack has many advantages, such as: fast refueling, longer run time between refueling, longer life of the energy source and low maintenance requirements.

In a typical electric vehicle fuel cells are augmented by an energy storage element, such as supercapacitor, flywheel or battery. Such hybrid system makes some of the fuel cell deficiencies (the most important one being high output impedance) transparent to the final user.

Hybrid systems with small lead acid battery (Fig. 1) have many advantages in material handling applications. Most significant two are: (1) battery provides peak current handling capabilities and (2) it ensures reserve power to drive the vehicle to refueling station should hydrogen tank be completely depleted.

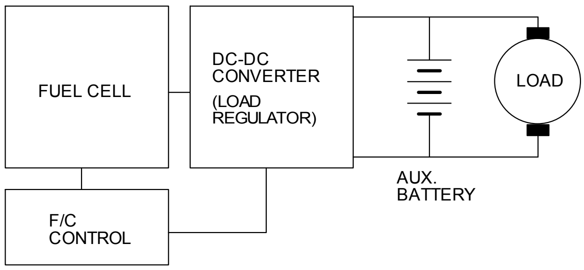

Fig. 1. *Block schematic of a hybrid fuel cell system*

Critical part of such fuel cell system is a load regulator. Its main role is to enable controlled current draw from the fuel cell. It also needs to maintain the auxiliary batteries in fully charged state and to regulate load current.

A 5kW DC/DC converter was built with this particular application in mind and practical aspects of its design are discussed in the following sections.

2. SPECIFICATIONS

Our design was driven in part by fuel cell design and partly by the end application. General specifications are fairly simple:

- Maximum power: 5,5kW
- Input voltage range: 24-36V
- Output voltage range: 36-60V
- Maximum output current: 150A

Application specific requirements are summarized as:

- Continuously variable control with automatic crossover:
- Input current (0-220A)
- Output voltage (36-60V)
- Low input current ripple: <1% of output current (critical for longevity of the fuel cell)
- High efficiency: 94% min at 2kW and 96% above 2,5kW
- Protection against reverse current (which may cause temperature rise and hazardous pressure build up)
- Ability to sustain peak load currents of up to 800A for short period of time (1-5 seconds)
- Low physical profile (load regulator needs to fit into a predefined space)
- Low, low cost (cost is one of the barriers to a wider acceptance of fuel cells)

3. TOPOLOGY CHOICE

There are several competing converter topologies for the fuel cell load regulation. Some recent developments are outlined in [1, 2, 3]. Common to those topologies is relative complexity and, consequently, high price.

Among various topologies, boost converters stand out for their simplicity (translating to low costs) and high efficiency. As the load voltage is higher than the fuel cell voltage and input inductors effectively control current ripple, boost topology seems to be a good basis for meeting most critical requirements.

Multiphase designs offer an opportunity to reduce overall size while further increasing efficiency as reported in [4, 5]. Increasing number of phases also reduces current ripple by partial or complete ripple cancellation (depending on the duty cycle). Detailed method for selecting optimum number of converter phases will be addressed in a separate paper. In this paper we will outline methodology that was used during development.

A representative fuel cell characteristic is shown in Fig. 1. It shows a typical V-I characteristic for one cell; multiple cells are stacked to form a fuel cell stack of required voltage.

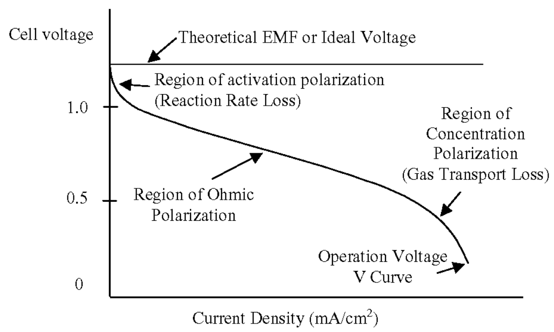

Fig. 2. *A typical fuel-cell load curve*

Wide input voltage range requirement is specified to cover most of this range. The 24V is the fuel cell's "knee" voltage (Region of Concentration Polarization in Fig. 1) - the fuel cell is in overload and output impedance is rising sharply. Clearly, this is not normal operation, as the system's current limits need to protect both, the fuel cell and the regulator. 36V, on the other hand, is the fuel cell's no-load (ideal) voltage and the only practical implication is ensuring that the voltage ratings of the associated equipment are adequately selected. In normal steady-state operation the output voltage varies very little and is typically around 28V.

Wide output voltage range: the actual system operates with 36V batteries and the 40-60V range is specified for possible future expansion to 48V system. In the 36V system, the converter's output voltage is set to keep batteries charged to 41V (slightly below the fully charged level to ensure that batteries can absorb recuperative braking energy).

Taking into account the practical considerations listed above, it is obvious that the converter's operating point is:

- Input voltage: 28V
- Output voltage: 41V

DC gain of a boost converter in continuous conduction mode (required for minimum current ripple) is given by

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-\delta} \tag{1}$$

where V_{in} and V_{out} represent input and output voltage, respectively and δ is a corresponding duty cycle.

For the actual steady state operating conditions, by using the Eq. (1), actual duty cycle is calculated as δ=0,32.

Multiphase converters have "zero input current ripple" points at duty cycle values that are located at $1/n$ intervals, where n equals number of phases. Two-phase converters have zero ripple at δ=0,5, three-phase converters at δ=0,33 and 0,66, four-phase at δ=0,25, 0,50 and 0,75, etc. This is described in literature [5, 6] and it is also addressed in the accompanying paper [7].

Generalized form of an input current ripple (ΔI_{in}) for multiphase interleaved converters is given by Eq. (2):

$$\Delta I_{in} = \left(\delta - \frac{i-1}{n}\right)(i - n\delta)\frac{V_{out}T}{L_{in}} \tag{2}$$

where

- n represents number of phases,

- δ is duty cycle,

- i is the interval between two duty cycle values resulting in zero ripple current,

- V_{out} is output voltage of the converter,

- L_{in} is inductance of the input inductor and

- T is a switching period.

Fig. 2. shows input ripple current vs. duty cycle for two, three and four-phase boost converters. Superimposed are the duty cycle range for specified input and output voltage variations (nominal range) and actual operating range, centered on steady state duty cycle of 0,32.

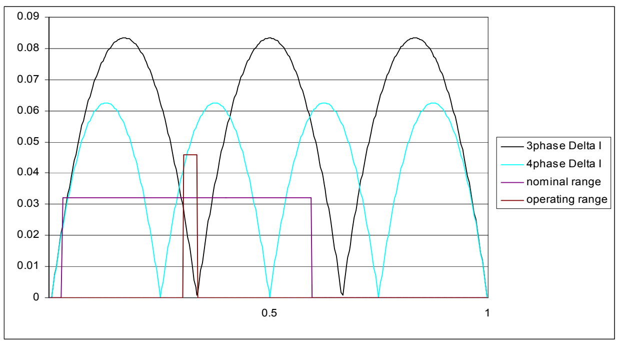

Fig. 3. *Input current ripple for 2 to 4 phase boost converters*

By examining Fig. 3. an interesting and somewhat counterintuitive phenomenon can be observed: for the actual steady state operation, a three-phase converter may actually have lower input current ripple than a four-phase converter. This is a great help in meeting requirements for low costs, considering reduced complexity of a three-phase vs. four-phase power conversion.

4. POWER TRAIN

Simplified representation of the three-phase boost converter power stage is shown in Fig. 3. The switching frequency is set to 25kHz which results in 75kHz input and output ripple. Low switching frequency helps increase efficiency and lower radiated emissions.

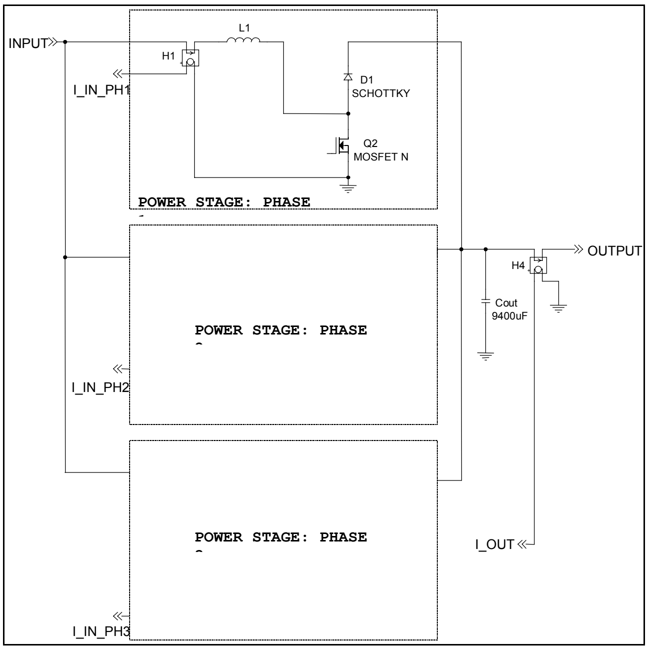

Fig. 4. *Block schematic of the three-phase boost converter*

One unusual thing to notice here is that this converter does not utilize synchronous rectification. Rather, we opted to use Schottky rectifiers instead. Tests with synchronous rectification showed peak efficiency improvement of about 0,5%. At this power this is not insignificant, however, there are three reasons that made Schottky diodes prevail in this design: (1) they are less expensive than mosfets with equivalent ratings - there is a total of 18 diodes in the circuit and price savings are significant, (2) during fault conditions, typical drivers keep synchronous rectifier switch closed, which will cause reverse current and create hazardous condition; solving this problem would increase complexity of the control scheme and further increase unit price and (3) standard rectifiers enable significantly better load sharing among the phases during fast load transients.

5. CONTROL CIRCUIT

The three phase PWM generator is shown in Fig. 4.

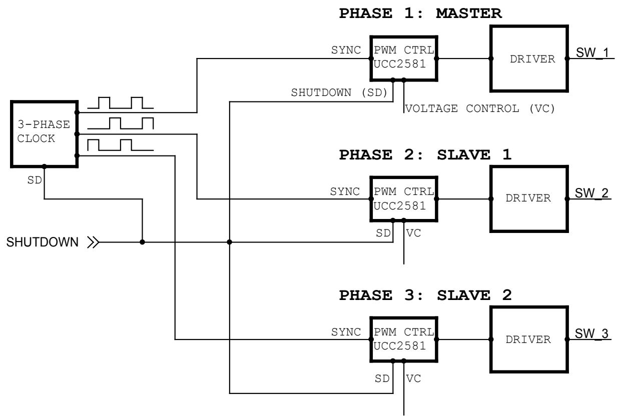

Fig. 5. *Block schematic of the PWM control circuit*

Three-phase clock circuit ensures synchronized and interleaved operation of the individual phases. Each phase has its own dedicated PWM controller with individual duty cycle control. Fig. 5. shows simplified error amplifiers.

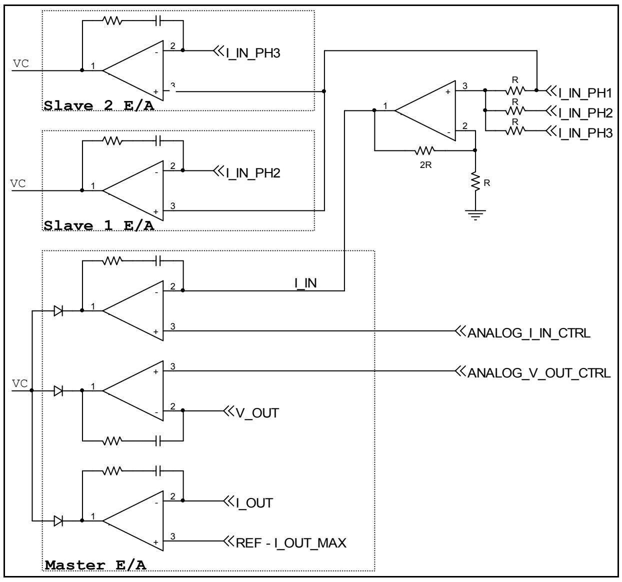

Fig. 6. *Block schematic of the error amplifiers section*

The unit operates in master-slave operation to ensure accurate current sharing. Master error amplifiers respond to control signal for input current and output voltage, OR-ing their outputs ensures that, at any point in time, only an error amplifier with lower error voltage is in control of the circuit. Third error amplifier sets output current limit and has fixed reference signal.

Slave amplifiers that control phase two and three have only one task - to closely replicate input current of the phase one. This ensures very accurate current sharing among the phases.

6. TEST RESULTS

Prototype converter is shown in Fig. 6.

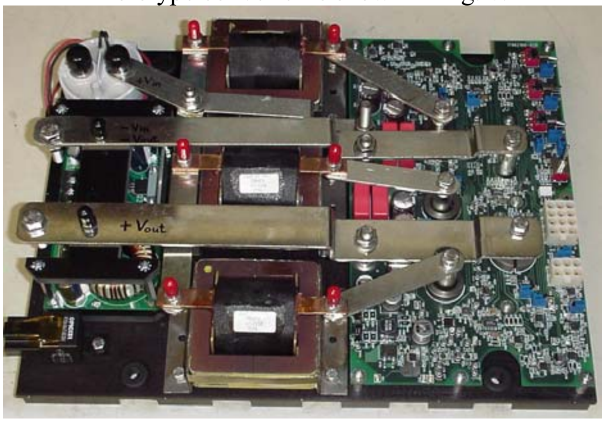

Fig. 7. *Photograph of the 5kW converter*

The three input inductors are easily identifiable on the photograph. Heavy bus bars are designed to handle up to 250A of input current and 150A output current with minimum loss.

The waveforms shown in this paper are taken for the following operating conditions:

- input voltage: 28V
- output voltage: 41V
- input current: 151,5A
- output current: 100A

Each phase's input current (synchronized to the phase one drive signal) is shown in Fig. 7.

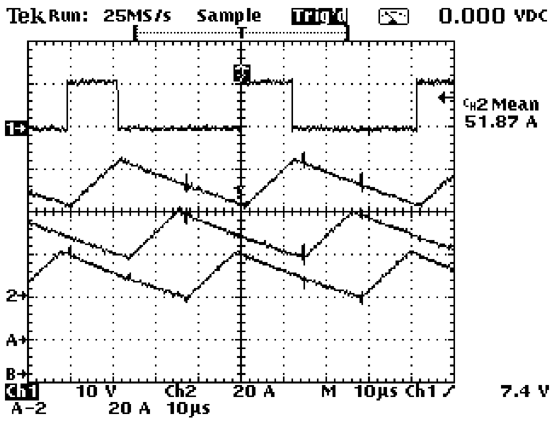

Fig. 7. *Phase 1 drive signal and three input inductor currents*

Current ripple of each phase is $20A_{pk-pk}$. Fig. 8 shows total input current and illustrates benefits of interleaving.

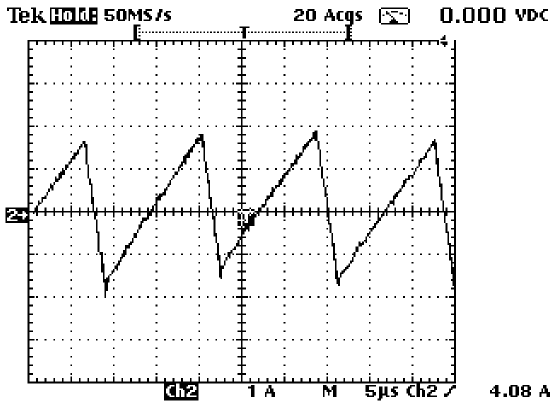

Fig. 8. *Input current ripple*

Frequency of the ripple current has tripled and absolute value has reduced to less than $4A_{pk-pk}$. If the input is bypassed by capacitance of only 1800µF, input ripple current drops to less than $1A_{pk-pk}$, which is less than 0,5% of maximum rated current of 220A.

Fig. 9 shows output current ripple, peak-to-peak value of which does not exceed 500mA, again well within the spec. Ripple frequency of 25kHz is due to the slight imbalance of the individual phase currents (approx. 2%). More accurate current sensing reduces this imbalance at somewhat higher cost and it was not deemed to be of a practical value for this application.

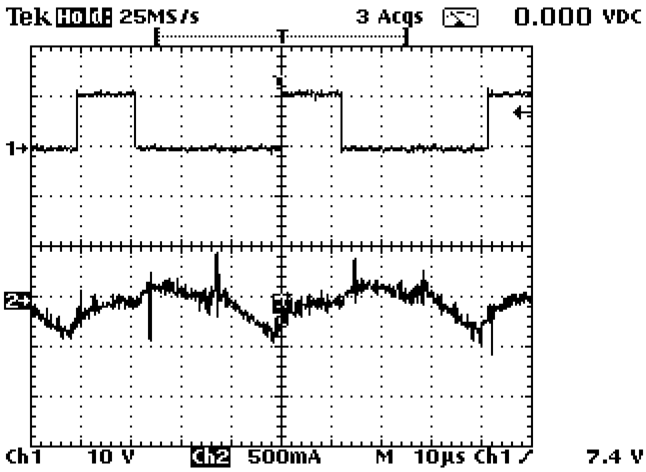

Figure 9: *Output current ripple*

Final confirmation of the successful design approach is the efficiency plot, shown in Fig. 10. Measured peak efficiency approaches 98%.

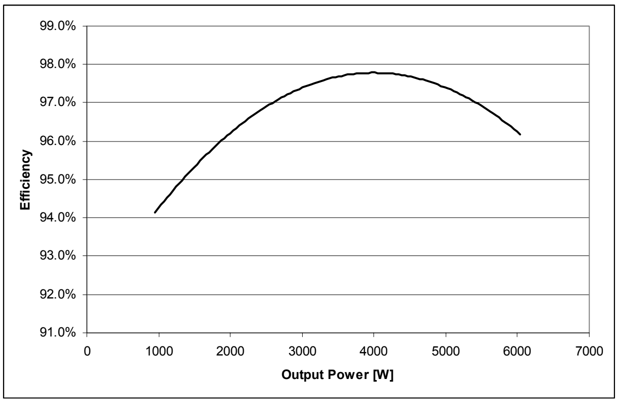

Fig. 10. *Efficiency plot*

More importantly, specification requirements are met with a wide margin, as efficiency exceeds 94% at 1kW (specified at 2kW) and exceeds 96% for output power above 2kW.

7. CONCLUSION

Fuel cells are making fast progress toward becoming cost-effective and safe for use in many applications. Battery pack replacement in electric forklifts is one application where they may find very appropriate home.

In order to satisfy very demanding load as presented by traction and lift systems in a forklift, the fuel cell system requires a load regulator to enable efficient energy transfer. This paper presents a solution based on non-isolated interleaved boost converter, rated at 5kW.

Review of the specifications sets a stage for initial design considerations. However, deeper understanding of the application opens a route for optimizing the design. By analyzing the converter's steady-state operation it was discovered that a three-phase design offers lower input current ripple than equivalent four-phase design. This, somewhat counterintuitive, conclusion comes as a result of converter operating close to a zero-ripple-current duty cycle, as dictated by its steady-state input and output voltages.

Block schematics of the power stage and basic control circuit are shown in the paper, outlining strategy for meeting imposed requirements. The power train is discussed in Section 3 and control stage in Section 4.

A prototype converter was built and the most interesting results are discussed in Section 5. The converter's input current ripple is below 0,5% and peak efficiency nears 98%, exceeding requirements by a wide margin.

Functional testing was performed in laboratory setting with peak loads of 12kW without any negative effects on the converter or fuel cell. The system has been installed in three forklifts operating in an industrial environment for the last 4 months. The forklifts are used by a battery manufacturer to move finished products packaged on 1500kg pallets. This presents a significant load on the vehicle's power system.

8. REFERENCES

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