Power Electronics Interface for a 100 W, 500000 rpm Gas Turbine Portable Power Unit

C. Zwyssig, S. D. Round and J.W. Kolar
Power Electronic Systems Laboratory
Swiss Federal Institute of Technology Zurich
8092 Zurich, SWITZERLAND
zwyssig@lem.ee.ethz.ch

***Abstract*—A 100 W, 500000 rpm generator/starter for a gas turbine based portable power unit has been constructed. The permanent magnetic synchronous machine has an 8 kHz fundamental frequency and stator inductance of 3 μH. The traditional voltage source inverter, VSI, is not an automatic choice for this type of machine due to the very high switching frequencies required. In this paper, voltage and current source topologies are compared for physical size, complexity and efficiency. Three topologies are selected for further investigation: the VSI with external inductances and high switching frequency, the VSI with block commutation and the current source inverter with block commutation. The paper presents the topology comparison, VSI design and experimental performance.**

I. INTRODUCTION

The increasing need for high energy density portable power devices has led to intense research and development efforts on mesoscale systems with power outputs up to a hundred Watts [1]. Gas turbine generator sets offer advantages over battery based portable power systems due to the high chemical energy density of fuel. The electrical system of a gas turbine portable power unit consists of a high-speed generator/starter (typically a permanent magnetic synchronous machine, PMSM), a power electronics interface and a control platform. However, majority of the research so far has only concentrated on the turbine design [2, 3], and little research effort has occurred on determining the requirements for and the design of the electrical system.

A 100 W, 500000 rpm generator/starter has been designed and constructed by the authors [4] to directly connect to the shaft of a 100 W gas turbine system. The machine has an 11 V_{RMS} phase voltage at the rated speed of 500000 rpm, in order to use low voltage, low on-resistance MOSFETs in the power electronics interface. At rated speed, the phase voltage fundamental frequency is 8.3 kHz and to reduce losses the machine has been designed with a slotless litz-wire windings and low loss stator core magnetic materials (Fig. 1). Due to the slotless winding and ironless rotor, the stator inductance has a very low value of 3 μH.

The complete drive system, as depicted in Fig. 2, has to operate in both motoring mode, in order to start the turbine, and generating mode, in order to provide electrical energy. The electrical output of the drive system is connected to a fixed dc voltage bus, which has a voltage level determined by

Figure 1. Generator with rotor removed. The cup-shaped litz-wire winding and low loss stator core can be seen.

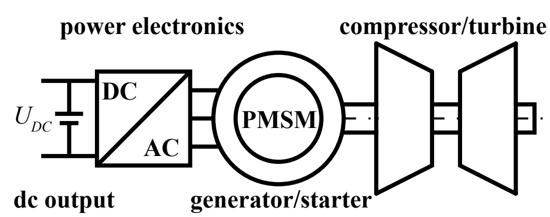

Figure 2. Power Electronics Interface in a Gas Turbine Generator Set.

the application. Therefore, the main requirement of the power electronics interface is that it is capable of two-quadrant, bidirectional operation. If the machine is used in an application where either just the generating or motoring mode is required then the converter could be unidirectional. At rated speed and power the power electronics interface has to supply phase currents of 3 A_{RMS} with a fundamental frequency of 8.3 kHz and peak phase voltages of 16 V.

In order to obtain a small and lightweight total gas turbine system, the power electronics interface must also be optimized for a low volume and weight. In addition, the efficiency of the whole drive system is critical in a portable gas turbine application [5].

The electrical machine volume scales proportional with the rated torque, therefore the use of a ultra-high rated speed leads to a very small generator/starter. In contrary, the size of the power electronics mainly scales with power rating and is minimized by choosing the correct topology through efficiency improvements and the use of high switching frequencies. For systems with high power ratings, the size of the control electronics is negligible compared to the power electronics. However, for the ultra high-speed machine with a power rating of 100 W the control electronics size becomes significant. Generally, the size of the control electronics scales with the complexity of the control method selected and the complexity depends on the topology and the modulation schemes used.

This paper first compares the voltage source and current source topologies and different modulation schemes that could be used for this ultra high-speed application. Based on all the requirements for the portable power application three topologies are selected for further investigation. The topologies of a VSI with external inductors and a VSI with block commutation are constructed and the experimental performance presented.

II. CONVERTER TOPOLOGIES

The very high fundamental frequency, the very low stator inductance and the need for a small and lightweight design presents significant challenges for the power electronics interface. There are several possible converter topologies for connecting a dc voltage bus to a three-phase machine. A typical PMSM voltage source inverter (VSI) with fixed dc voltage requires a very high switching frequency or the addition of additional external phase inductors as shown in Fig. 3(a). The currents can be controlled to form sine (PMSM drive system) or square waves (brushless dc, BLDC, drive system) with a PWM or hysteresis controller. Only the BLDC control method is considered in this paper as it has a lower control complexity.

If a controlled dc voltage supplies the VSI, the VSI can be also switched at the fundamental frequency of the machine, which is commonly known as block commutation. The controlled dc voltage can be supplied with either a uni- or bi-directional dc-dc converter as shown in Fig. 3(a).

Typically, only VSIs are used for low power, low voltage standard PMSMs. However, due to the high fundamental frequency and the low inductance of the machine, there are two current source inverters (CSIs) worth considering, as only one external inductor is required. For these CSI topologies decoupling capacitors are required on the three phase outputs. To reduce the switching losses in the inverter, the switching frequency is made equal to the fundamental frequency of the machine; however, the CSI now requires an additional dc-dc converter to control the dc current level. The standard CSI (Fig. 3(b)) has a unidirectional current flow and therefore needs an additional full bridge converter to change the polarity of the input voltage for bidirectional power flow. For unidirectional power flow, a buck or boost converter is sufficient. If lower switching losses are not important then an inherently bidirectional current source ac-dc converter can be utilized as is shown in Fig. 3(c) [7]. With this topology, no additional dc-dc converter is needed, but there is additional complexity and switches required for each phase leg in the inverter. Another special topology that is considered is the Z-Source inverter as shown in Fig. 3(d) [8]. This inverter can offer bi-directional power flow, is capable of boosting the dc input voltage and has inherent protection from a bridge-leg short-through condition.

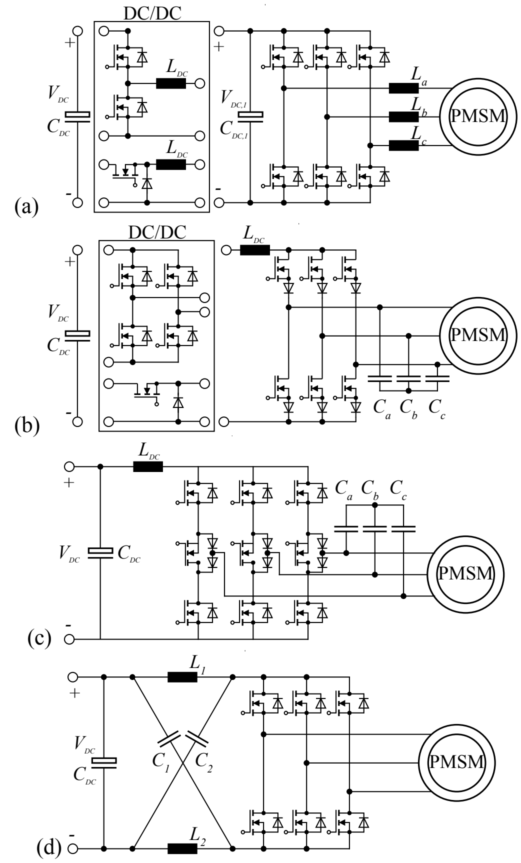

Figure 3. Possible Power Electronic Interfaces (a) VSI with external inductances (b) CSI with external capacitors (c) Bidirectional current source AC-DC converter [7], (d) Z-Source Converter [8]. Switching at fundamental frequency (8.3 kHz) the CSI and VSI need an additional DC/DC Converter.

A. Comparison

The various VSI and CSI topologies and their different modulation schemes are compared for size, weight, and efficiency. The level of control complexity also plays a significant role as the control electronics can occupy a major portion of the total drive volume. The choice of the switching frequency has a direct effect on amount of control electronics and system efficiency. The number of MOSFETs and diodes in the current path affects the conduction losses and therefore the inverter efficiency, while the total number and size of the passive components is critical.

The advantages and disadvantages of the topologies are compared in Tab. I. The VSI and Z-Source inverter have the advantage of the lowest number of semiconductor elements and therefore potentially lower conduction losses. This is why the VSI converter is the preferred choice for most BLDC and PMSMs. The main disadvantage for this application is the extremely high current control-loop bandwidth that is required because of the ultra high-speed operation. This pushes the limits of current measurement, analog signal electronics, controller and gate driver design, and switching time.

TABLE I. COMPARISON OF CONVERTER TOPOLOGIES

	VSI (a) controlled	VSI (a) block	CSI (b)	CSI (c)	Z-Source (d)
Switching frequency	-	+	+	-	-
Current control bandwidth	-	+	+	-	-
Number of MOSFETs	6	8	10	9	6
Number of diodes	0	0	6	6	0
Conduction losses	+	0	-	-	+
Switching losses	-	+	+	-	-
Volume - passive components	0	0	-	+	-
Additional dc-dc converter	+	-	-	+	+
Control complexity	-	+	+	-	-

Furthermore, with a high switching frequency the switching losses are higher and a lower efficiency results. The switching frequency is reduced if external inductors are used.

The Z-Source inverter is not considered further as the inverter requires a high switching frequency, two external inductors and capacitors, and a special modulation pattern that requires more control complexity.

The problems of high switching frequency and current control bandwidth also exist for the inherent bidirectional CSI (Fig. 3(c)), which additionally has high conduction losses due to the large number of semiconductors in one current path. Therefore, this topology is not considered further.

The problems of high switching frequency and current control bandwidth can be overcome when the VSI or CSI is switched at the fundamental frequency of the machine. The switching losses and the control complexity for the three phase bridge legs are significantly reduced. However, the disadvantage is that an additional dc-dc converter is required to control the dc current. The current control bandwidth and switching frequency of the dc-dc converter can be selected to reduce switching losses since the dynamic behavior of the drive system is not critical. The main disadvantage is the increased volume caused mainly by the dc inductor. For the VSI with block commutation, this inductor can be made smaller since additional smoothing is provided with an output capacitor.

From this general comparison, three topologies are selected for further analysis using simulation and an experimental setup. The first selected topology is the VSI switched with square wave currents using a hysteresis controller as it has the simplest power electronics circuit and should result in a very small size. The only disadvantage is the high switching frequency and current control bandwidth. The second topology is the VSI operated with block commutation and an additional dc-dc converter. The advantage of this topology is that it can be modulated with a low switching frequency (low potential losses) and just the dc current level has to be controlled. The third selected topology is the CSI with block commutation switching as it has similar power electronics and control complexity as the VSI with block commutation and is an interesting alternative to the commonly used VSIs.

III. VOLTAGE SOURCE INVERTER

A. Controlled Square Wave Currents

To generate controlled square wave currents with the VSI, each phase current is individually controlled by high frequency switching of the upper bridge leg. Measurement of the current is achieved by using a shunt resistor. The required current control loop bandwidth is not achievable with typical small, low current digital signal processors (DSPs); therefore, the phase currents are controlled with an analog hysteresis controller. This is simply constructed using op-amps, analog switches, comparators and some logic. The current reference is set by the DSP, which also controls the fundamental commutation of the currents between the phases. The switching frequency is dependent on the hysteresis band, the value of the total inductance (external inductors plus motor inductance) and the dc voltage. To minimize the volume, the inductors are chosen to be as small as possible (5 µH). In order to avoid a too high switching frequency the hysteresis band is chosen to be a large value of 2 A (compared to the rated current), and results in a switching frequency of approximately 300 kHz. The simulation results of the electrical system for a rotor speed of 250000 rpm can be seen in Fig. 4, where the switching current ripple is significant compared to the average current. To reduce the current ripple a smaller hysteresis band could be used, however to still maintain an acceptable switching frequency the external inductors would have to be increased and that would result in a larger volume.

B. Block Commutation

When block commutation is used with the VSI, the dc current is controlled and the phase currents are dependent on this dc current level. The switching frequency of the dc-dc converter is chosen such that switching can be generated by the PWM outputs of the DSP as this reduces the number of parts. From the selected switching frequency the dc-dc converter's output inductor and capacitor values are selected. Since small ceramic high value capacitors are now available, the dc inductor is set to a low value of 50 µH to reduce its size and the dc capacitor has a value of 40 µF. This results in a relatively smooth dc voltage when a switching frequency of 100 kHz is used. The dc current is measured using a shunt resistor. The signal is amplified and then directly sampled with the DSP and used for control. Furthermore, the switching of the phase legs are directly controlled by the DSP. All this reduces the complexity of the control electronics and compensates, to a certain extent, for the additional volume required by the dc-dc converter. The advantage of this approach is that no additional phase inductors are required, therefore minimizing the weight and volume. Simulation results from the VSI with block commutation can be seen in Fig. 5. The phase current is relatively constant and does not contain any high frequency

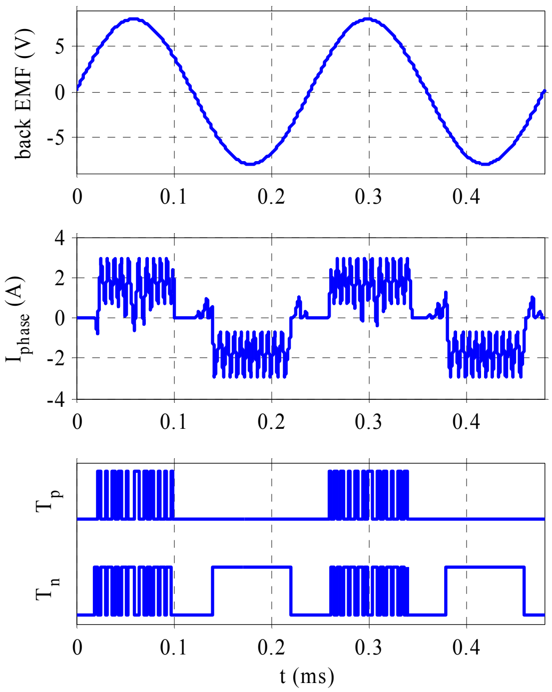

Figure 4. Simulation of the drive system with a VSI and additional external inductances ($L_a = L_b = L_c = 5$ µH, $V_{DC} = 35$ V). Machine back EMF, phase current and switching signals for the phase leg are shown. The switching frequency is approximately $f_s = 300$ kHz.

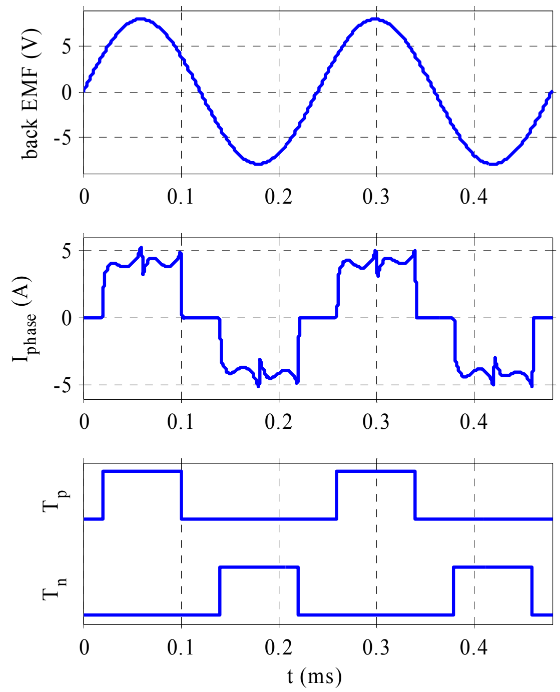

Figure 5. Simulation of the drive system with a VSI and block commutation. Machine back EMF, phase current and switching signals for the phase leg are shown. The dc-dc converter is switched with $f_s = 100$ kHz and has an inductor of $L_{DC} = 50$ µH and a capacitor of $C_{DC,1} = 40$ µF.

switching. The switching of the dc-dc converter is not shown in this figure.

C. Current Source Inverter

By moving the dc capacitor of the VSI to the ac side and splitting it into three parts, the CSI has a similar operation as the VSI with block commutation. The three capacitors are required to decouple the dc current from the machine phase currents. The phase current magnitude is dependent on the controlled dc inductor current level. However, the dc inductor of the CSI is larger than the inductor in the dc-dc converter of the VSI.

The CSI needs reverse blocking switches, which are constructed using a series MOSFET and diode. Since the current flow is unidirectional in the CSI, a full bridge dc-dc converter is needed to obtain the bidirectional power flow. The control of the CSI is similar to the VSI with block commutation, where the phase legs are switched with fundamental frequency. An overlapping time for the switching between different phase legs has to be inserted in order to guarantee continuous dc current flow.

Fig. 6 shows the simulation of one phase current and switching signals produced by the CSI. From the phase current waveform, it can be seen that the current is almost constant during the switch's on time apart from the ripple produced by the dc-dc converter. The switching instant causes high frequency oscillations in the current because of the resonant circuit formed by the motor inductances and the decoupling capacitors. These oscillations can be damped with a resistor in parallel with the capacitor. For the simulation, decoupling capacitors with a value of 100 nF are used and the oscillations are damped with a resistance of 15 Ω in series with a capacitor of 47 nF. The dc inductor is 100 µH and the dc-dc converter is switched with 100 kHz. The oscillation after the switching of a phase leg can clearly be seen, but are damped effectively.

IV. Test Bench Setup

The test bench setup (Fig. 7) consists of two identical machines on one common shaft with one high-speed ball bearings on each end. One machine is operated as driving motor, and the other machine as a generator. Each generator/motor has a stator diameter of 16 mm and a length of 15 mm. The stator of the generator is supported by bearings such that, over a moment arm, the torque can be measured with a force sensor. With this test bench, different stator core magnetic materials, stator winding types and rotor sleeve materials are tested. The nominal values and the parameters of the machine are given in Tab. II and III.

The individual parts of the complete drive system, including power and control electronics, stator and rotor, are shown in Fig. 8. The power and control electronics have been constructed to occupy the lowest possible volume by using a four layer PCB, SMD electronic components and a small Microchip DSP (dsPIC30F5016). The six power MOSFETs can be seen mounted on left-hand end of the lower PCB. The control electronics occupies more space than the power

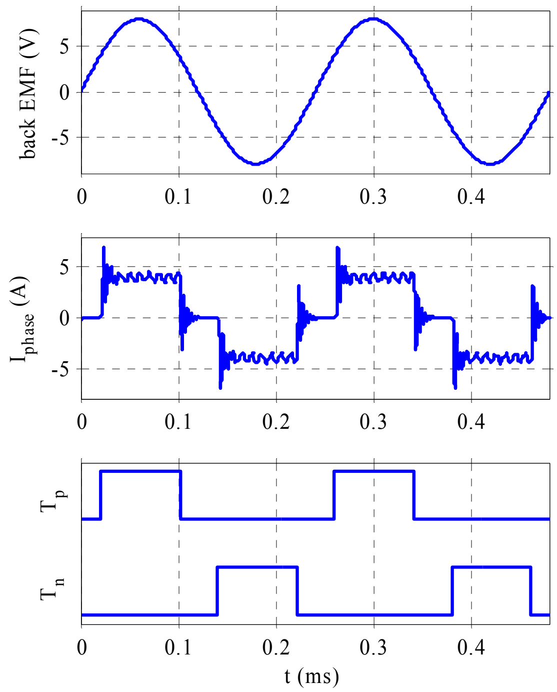

Figure 6. Simulation of the drive system with a CSI with block commutation. Machine back EMF, phase current and switching signals for the phase leg. The decoupling capacitors are $C_a = C_b = C_c = 100$ nF, the dc-dc converter is switched with $f_s = 100$ kHz and has an inductor of $L_{DC} = 100$ µH.

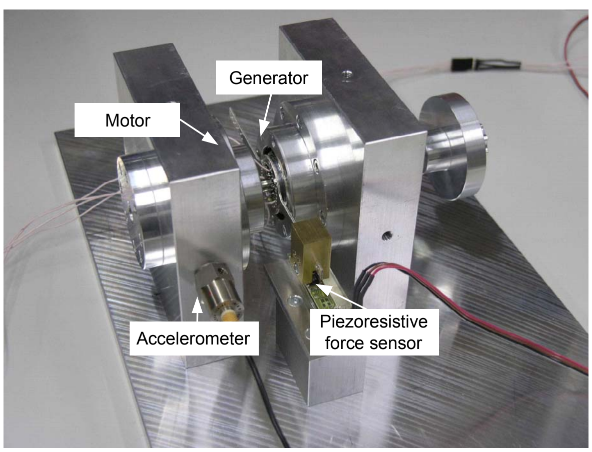

Figure 7. Photograph of the test bench showing the motor and generator.

TABLE II. NOMINAL VALUES OF THE PM MACHINE

Connection	Y	
Number of pole pairs	n_p	1
Rated current	I_n	3 A
Rated frequency	f_n	8.3 kHz
Rated power	P_n	100 W
Rated Torque	T_n	2 mNm

TABLE III. PARAMETERS OF THE PM MACHINE

Stator resistance	R_s	0.1 Ω
Stator inductance	$L_d = L_q$	3 µH
Magnet flux linkage	ψ_m	0.306 mVs

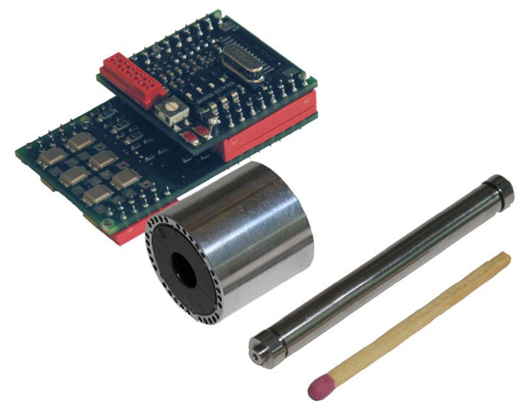

Figure 8. Photograph of the individual parts of the high-speed drive system: power and control electonics, stator and rotor.

devices, although the heat sink and external passive components are not shown as they are dependent on the topology and the losses. The rotor position is measured using three hall-latch sensors that are installed close to the machine and are switched with the stray field from the permanent magnet in the rotor. The rotor position can also be obtained using sensorless methods such as back EMF measurement during zero phase current or by back EMF estimation.

V. EXPERIMENTAL RESULTS

The experimental power electronic hardware shown in Fig. 8 is a VSI and experimental measurements have been made for both block commutation and controlled square wave current operation. The motor is fed with currents from the custom-built VSI and the generator is loaded with a three phase resistive load. Fig. 9 shows the current waveform and the switching signals for one phase leg for the controlled square wave current control method. External inductances of 5 µH are used and the motor speed is 250000 rpm. The switching frequency of the inverter is slightly lower than that shown in the simulation since a reduced dc voltage is used. At this reduced voltage level the losses are reduced and no heat sink is required to cool the power MOSFETs.

Fig. 10 shows the current waveform and switching signals for the VSI operated with block commutation. The dc voltage is controlled externally. In contrary to the controlled current commutation, the current waveform is dependent on phase inductance and resistance, back EMF waveform and the switching times. As can be seen in the measured current, the waveform is not symmetrical due to a slight error in the signal generated by one of the hall-latch signals. If sensorless control is implemented then the waveform symmetry can be improved

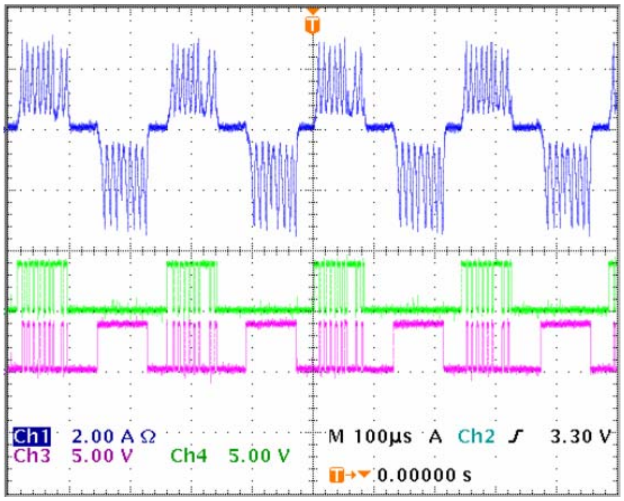

Figure 9. Phase current and switching signals of one phase leg operating at 250000 rpm for the VSI with controlled square wave currents and fixed dc input voltage.

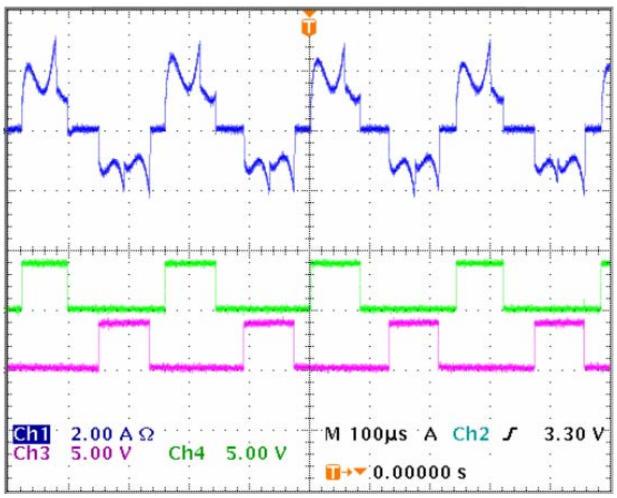

Figure 10. Phase current and switching signals of one phase leg operating at 250000 rpm for the VSI with block commutation and controlled dc input voltage.

because the switching times are not derived from external sensors but the back EMF itself.

VI. System Evaluation

The main requirements for a portable power electric machine system are low volume and low weight. Low volume and weight are achieved for the electrical machine by operating it at an ultra high-speed of 500000 rpm. For the power electronics interface, the volume and weight are more or less proportional except for any external inductances since they are heavier than the electronics and capacitors. Therefore, by minimizing the size of the power electronics interface should also lead to a minimum weight.

For low power rating converters, the control electronics occupies a major part of the volume. Therefore, reducing the level of control complexity is critical. Both the VSI and CSI operated with block commutation have a reduced control complexity compared to the high frequency switching operation of the controlled square wave current mode. If the volume of production is sufficiently high then the control electronics can be further integrated into one chip. However, for this work it has been assumed that these machines would be used in low production volume applications.

To eliminate the need for a rotor position sensor, the controller has to implement sensorless control. Sensorless control relies on the accurate measurement of the machine's back EMF. The VSI operated with block commutation enables a low-noise back EMF measurement to be made as no switching occurs during the measurement. For the VSI with active current control there is always a high switching frequency occurring and additional techniques are required to obtain an accurate back EMF measurement. For the CSI with block commutation there are high frequency oscillations between the machine's inductance and decoupling capacitors that also makes the back EMF measurement more difficult.

The total electrical efficiency of the drive system is an important factor, especially where it is used in a portable power application since more fuel is required to be carried for a low system efficiency. For the power electronics interface, the major losses come from the conduction and switching losses. The machine has been designed to minimize the current losses at the fundamental frequency of 8.3 kHz, but the power electronics impresses other current harmonics in the machine. Therefore, it is important to determine not only the losses of the power electronics and machine separately, but the losses of the complete drive system. Dc electrical power to mechanical power efficiency measurements (and vice versa) will be undertaken and compared for different topologies and modulation schemes. From the simulation work and the initial experimental measurements, the drive system with the VSI and block commutation indicates that it should have the highest efficiency and the lowest control complexity.

The VSI with controlled square wave currents results in the smallest size for the power electronics. However, there is a trade off between high-frequency switching losses, which enlarges the cooling heat sink, and the size of external inductors. The size of the heat sink and the inductors increases the size and weight significantly. In addition, the high switching frequency and large current hysteresis band results in additional copper losses in the machine since the currents contain higher harmonic frequencies.

The selection of the optimal power electronics interface is dependent on the required application and whether bi-directional power flow is necessary. In a portable power application, both the size/volume and efficiency are important. The system specifications of efficiency and size for the complete gas turbine generator set has not yet been fixed and therefore the selection of the optimal power electronics interface is still to be determined for this application. In the near future, the CSI will be experimentally tested and the efficiency measurements of the drive system implemented with each of the three interfaces will be reported in a further publication.

VII. CONCLUSION

A 100 W, 500000 rpm generator/starter for a gas turbine based portable power unit has been designed and constructed. The generator/motor is a PMSM that has a fundamental frequency of 8.3 kHz and a stator inductance of 3 μH. The traditional VSI used for low power PMSM is not an automatic choice for a high-speed, low power machine since the VSI has to be operated at an extremely high switching frequency, which increases control complexity and produces additional losses.

VSI and CSI topologies are compared for bi-directional power flow, with the specification of a small size, low complexity and high efficiency. The use of a VSI with block commutation offers low switching losses, simple control and easy implementation of sensorless control. For operation with bi-directional power flow, the VSI with high frequency current control has the smallest size even considering the use of external inductors. The CSI with block commutation requires additional power semiconductor devices and has additional conductional losses.

The selection of the optimal power electronics interface is dependent on the required application. For the portable power application, both the size/volume and efficiency are important. Experimental measurements are currently been undertaken to determine the optimal power electronics interface. From the simulation work and the initial experimental measurements, the drive system with the VSI and block commutation indicates that it should have the highest efficiency and the lowest control complexity.

REFERENCES

[1] S. A. Jacobson and A. H. Epstein, "An informal survey of power MEMS," ISMME2003, Tsuchiura, Japan, December 1-3, 2003, pp. 513-520.

[2] K. Isomura, S. Tanaka, M. Murayama, H. Yamaguchi, N. Ijichi, T. Genda, N. Saji, O. Shiga, K. Takahashi, and M. Esashi, "Development of micro-turbo charger and micro-combustor as feasibility studies of three-dimensional gas turbine at micro-scale," Proc. ASME Turbo Expo 2003, Power for Land, Sea, and Air, Atlanta, Georgia, USA, June 16-19, 2003, Paper GT2003-38151.

[3] J. Peirs, D. Reynaerts, and F. Verplaetsen, "Development of an axial microturbine for a portable gas turbine generator," Journal of Micromechanics and Microengineering, vol. 13, no. 5, 2003, pp. 190-195.

[4] C. Zwyssig, J.W. Kolar, W. Thaler, M. Vohrer, "Design of a 100 W, 500000 rpm permanent-magnet generator for mesoscale gas turbines," IEEE Industry Applications Conference 2005, Conference Record of the 40th IAS Annual Meeting, Hong Kong, October 2-6, 2005, vol. 1, pp. 253-260.

[5] B. Schneider, M. Bruderer, D. Dyntar, C. Zwyssig, M. Diener, K. Boulouchos, R. S. Abhari, L. Guzzella and J. W. Kolar, "Ultra-High-Energy-Density Converter for Portable Power," The Fifth International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications, Tokyo, Japan, November 28-30, 2005, pp. 81-84.

[6] F. Hinrichsen, I. Koch, W.-R. Canders, "Current source IGBT-inverter for low inductive synchronous machines," Proc. of the 35th IEEE Power Electronics Specialists Conference, Aachen, Germany, 2004, vol. 4, pp. 2849-2853.

[7] N.A. Rahim, T.C. Green, and B.W. Williams, "Three-phase step-down reversible AC-DC power converter," Proc. of the 26th IEEE Power Electronics Specialists Conference, Atlanta, USA, 1995, vol. 2, pp. 973-978.

[8] F. Z. Peng, "Z-source inverter," IEEE Transactions on Industry Applications, vol. 39, no. 2, pp. 504–510, Mar./Apr. 2003.