DRIVE SYSTEMS FOR OPERATION ON DEEP-SEA ROVs

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ABSTRACT Power systems for thruster actuators and other auxiliaries employed on work-class deep-sea ROVs subject to 300bar ambient pressures, are considered. Emphasis on 3×3 matrix converters for thrusters and 3×2 matrix converters for system auxiliaries, is given, along with experimental results showing operation during pressure cycling consistent with typical operational duties.

INTRODUCTION

Manufacturers of work-class deep-sea (up-to 3000m) underwater remotely operated vehicles (ROV's), Figure 1, are increasingly looking towards the replacement of the traditional drive system viz: hydraulic thruster actuators, by electrically-based technologies[1]; the perceived advantages being higher reliability, reduced overall weight, improved efficiency[1], and better overall control. Intensive research into appropriate motor/machine and power electronic drive systems is therefore fundamental, if the full potential of all/more electric actuation is to be realised.

Figure 1. Deep-Sea (3000m) Remotely Operated Vehicle (ROV). **(Photograph courtesy of Perry Slingsby[l])**

During deep-sea operation of the ROV, buoyancy constraints and cooling issues make it highly desirable to operate the power electronic drive systems in an oil-filled environment, subject to a high ambient pressure (up to 400bar), as opposed to being housed in a thick-walled metallic pressure vessel, subject to nominal atmospheric pressure (1bar). However, capacitors (particularly electrolytic capacitors), and semiconductor devices are known to be extremely sensitive to pressure due to their construction, and implode under pressures commensurate with 3000m sea depth (≈300bar). As the drive is to withstand ≈300 bar ambient, the components should ideally be able to withstand 1.33× this pressure (≈400 Bar) to provide an operating margin on the system. Consultation with electronic component manufacturers indicate that, whilst it may be possible to package devices appropriately, and maintain rated performance, the relatively low production quantities required for this type of application will have significant impact on unit costs.

Moreover, for electric thruster actuation, and control of other auxiliaries such as robot arms and camera equipment, the traditional recourse to Rectifier/Voltage Source Inverters (VSIs) and AC-DC converters, is not considered the most practical solution.

Here then, the paper presents the results of an investigation to determine what commercially available power electronic and signal-conditioning devices are appropriate for the design of motor drive systems that will maintain nominal operation in a high-pressure environment. Furthermore, the use of these components in 3×3 matrix converters, to convert a 3ϕ/3.3kV/60Hz input, to a 3ϕ/variable-voltage/variable-frequency output, suitable for powering variable-speed thruster actuators, and 3×2 matrix converters to provide 3ϕ/3.3kV/60Hz to 1ϕ/variable-voltage/variable-frequency or DC conversion for power auxiliary equipment, is considered.

POTENTIAL COMPONENT FAILURE MECHANISMS

Failure modes of the power electronic devices can be predicted by consideration of the components and their packaging. Possible failure mode include:

i) Total mechanical failure: Failure of devices due to the inability of the packages to withstand high ambient pressure, giving rise to total mechanical failure. This is a consequence of air voids or compressible materials within the packages reducing in volume under pressure, causing case implosion.

ii) Changes in device characteristics: Deformation of the device casing causing component characteristics to deviate outside the permissible operating range, and ingress of insulating transformer oils into non-sealed devices leading to changes in device operating characteristics.

iii) Temporary (reversible) failure: The elastic properties of some component packaging may lead to the creation of temporary short circuits within the devices, that may clear when the pressure is removed.

DEVICE OPERATION AT HIGH AMBIENT PRESSURE

The predicted failure mechanisms can be demonstrated in practice by subjecting a number of commercially available devices to the target pressure within an oil-filled pressure chamber. Provisional static tests can determine which device packages can mechanically withstand target pressures. To identify less dramatic failures, devices are mounted on a backing plate, and characterised electrically, both before and after the pressure cycling. Typical devices under consideration are shown in Figure 2. Power devices are mounted on a metal plate to provide mechanical stability to the package, and heat-sinking to allow representative tests to be carried out for device characterisation. Simple mechanical failure of the devices can be readily identified by examination of the packaging after pressure testing. Mechanical failure is often dramatic, some examples of which are shown in Figure 3, which shows the failure of the quartz window on a EPROM type device, the severe cracking experienced by the case of an intelligent power module (IPM), and the compression of TO5 packages.

Devices labelled ‘a’ & ‘b’ are TO5 packages with 1mm holes drilled into the casing to allow pressure equalisation.

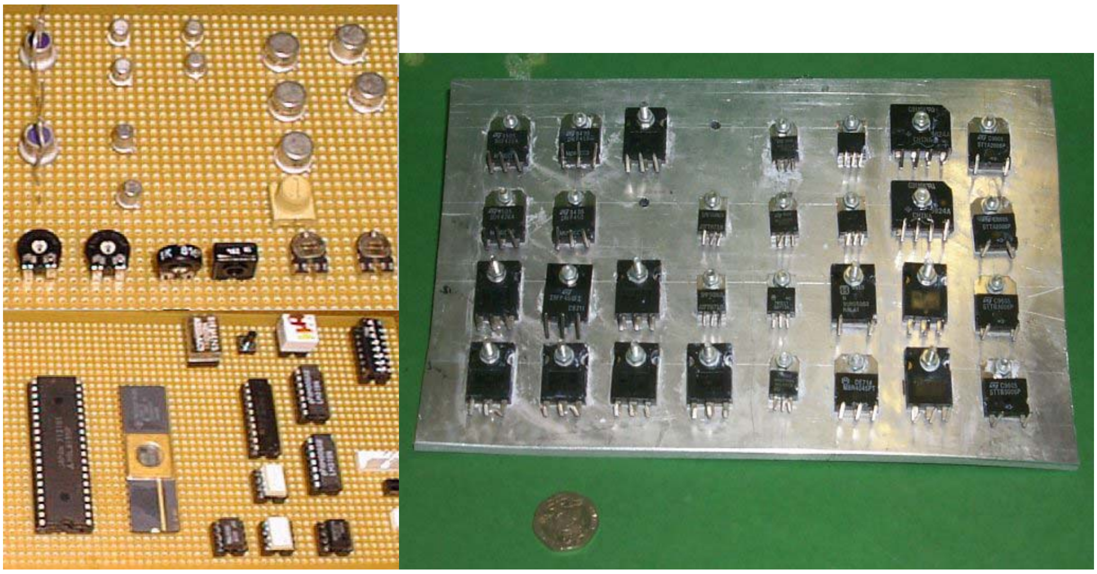


Figure 2. Typical mounted devices.

Figure 3 clearly shows that such procedures enable the devices to mechanically withstand the test pressure better than devices ‘c’, ‘d’ & ‘e’, which show damage due to the compression of the can lid. However, subsequent electrical characterisation of all the devices, ‘a’ → ‘e’, show that operation ultimately failed under pressure. The compression of the top of the device ‘cans’ is to such a degree that the impression caused by the top of the device legs is clearly visible in the depressed lid of the device.

Results obtained from testing various component types and packages are summarised in Table 1.

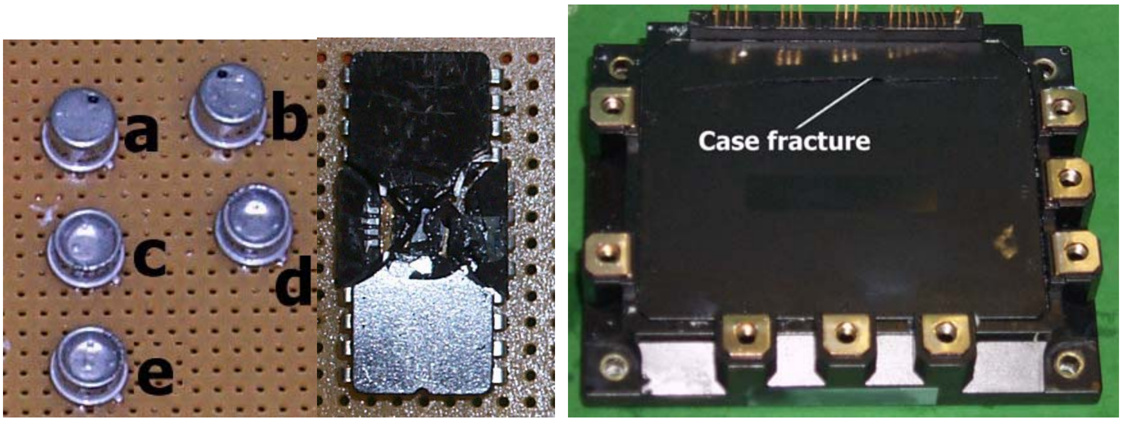


Figure 3. Mechanical failure after tests

As expected, solid encapsulation of devices offers improved protection against damage at pressure, with discrete power devices fairing significantly better than totally enclosed power modules. However, a number of devices that would be regarded as essential components of a drive system are susceptible to damage, i.e. large electrolytic capacitors. This has implications on the methodology used for the drive design, and the optimum drive topology for the application.

BJT E-line	Undamaged	Operational
BJT TO-5 / TO-18	Concave	Failed
BJT TO-5 / TO-18 (drilled)	Ok, hole in top	Failed
IGBT based IPM module	Cracked	Failed
EPROM windowed	Imploded	Failed
Logic (non-windowed)	Undamaged	Operational
Variable resistors	Undamaged	Failed
Current transducer	Undamaged	Operational
Current transducer (drilled)	Ok, hole in top	Operational
Resistors	Undamaged	Operational
Miniature inductors	Undamaged	Operational
ETD49 former/F44 core	Undamaged	Operational
Ceramic capacitors	Undamaged	Operational
Polyester capacitors	Undamaged	Operational
Tantalum capacitors	Undamaged	Operational
Polystyrene capacitors	Undamaged	Operational
Miniature Aluminium electrolytic	Undamaged	Out of specification
DC-link electrolytic capacitors	Concave	Failed
Optical devices	Undamaged	Operational

Table 1. Device test results.

POWER CONVERTERS

From component pressure tests, it is clear that alternatives to industry standard Rectifier/Voltage Source Inverters (VSIs), Figure 4, and AC to DC converters, which require large reactive energy storage components (electrolytic capacitors being particularly problematic), would prove of benefit for this application field. The matrix converter topology provides a solution to direct frequency and amplitude power conversion. Unlike the conventional inverters, i.e. Voltage Source Inverters (VSI) and Current Source Inverters (CSI), the matrix converter does not require a two-stage conversion process, eliminating the requirement for a DC link, and the associated large reactive energy storage components.

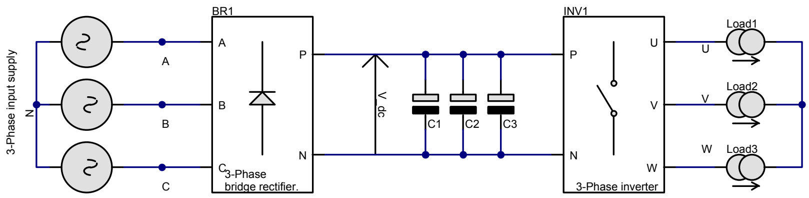


Figure 4. Configuration of a typical VSI.

Since matrix converters require no capacitance other than for small line filters to reduce switching harmonics, they provide an obvious choice for investigation. The required filter components can utilise pressure tolerant capacitor technologies such as foil, polypropylene or tantalum devices.

TRADITIONAL 6-switch INVERTER

Static tests on devices have enabled the selection of suitable component technologies that survive under pressure. From these, a low power brushless-dc drive has been developed to facilitate active component testing under representative operating conditions. To limit damage if failure occurs, the system is designed to be severely over-rated, with a current limited supply delivering the DC link to the power stage, Figure 5. Since large DC-link capacitors are known to collapse under pressure, in contrast to a nominal VSI design, minimal DC-link smoothing was on-board, the power being fed into the test chamber through long supply leads. Prior studies have shown that PM brushless-dc motors can be designed to operate at depth [3].

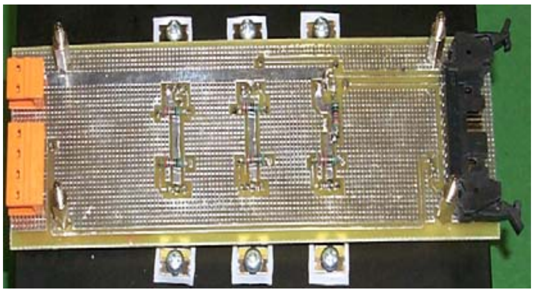


Figure 5. 500W Power stage

The drive has been subjected to a number of pressure cycles, as shown in Figure 6, to simulate operation on a descent to the maximum working depth of the ROV. (A target pressure of 400 bar, 33% over the maximum working pressure at 3000m, leaving an adequate safety margin of 1000m.)

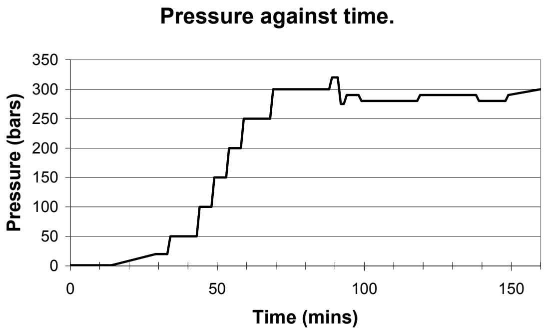


Figure 6. Drive test pressure cycle.

The applied pressure is increased in 50bar steps and held constant at each increment to allow the pressure on individual components to stabilise; operation is then verified and recorded. Figures 7 & 8 show the motor phase voltage, and the motor phase currents as the pressure is increased. It is apparent from the figures that the motor operation was unaffected.

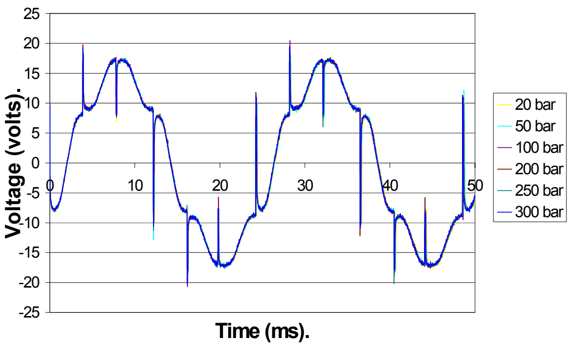


Figure 7 Motor terminal voltage

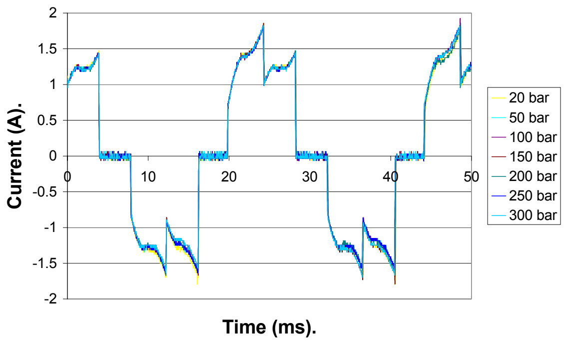


Figure 8 Motor phase current

Total failure of the drive occurs when the applied pressure exceeds 300bar, as indicated by current limiting of the DC-link. Normal operation resumes, however, as the pressure is released to 275 bar. The cycle is then repeated. On raising the pressure, the drive repeatedly fails, with normal operation resuming after the pressure is subsequently reduced. The failure is indicated in Figure 9, which shows the phase current rising to the point where the DC link current limit is reached (4A), and the rotor stalls. This behaviour, as the applied pressure is cycled, clearly demonstrates the potential for reversible failure of the system due to the sensitivity of components to pressure. It also highlights the fact that static pressure tests alone are insufficient to determine whether a component will operate successfully when subjected to high ambient pressures. 'Soak' tests are also ultimately required to give prolonged operation of the drive under increased pressure, and allow identification of failure mechanisms due to oil ingress into the device packages.

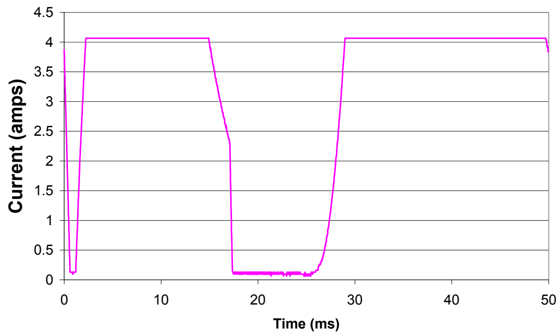


Figure 9. Phase current during fault condition

OPTIMISED DRIVE TOPOLOGY

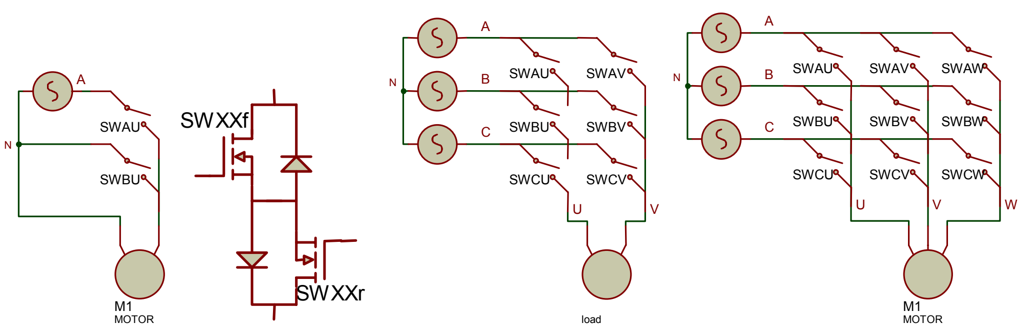
The results of the static pressure tests on individual components highlights the inability of electrolytic capacitors and power electronic IPM's to survive when subjected to pressures commensurate with deep-sea operation. This has a major impact on the selection of a suitable drive topology for this environment. Typically, a thruster unit is rated at around 12kW, requiring a power electronic drive system of a comparable rating. For normal operation, it would be usual to design a drive as a VSI, around a commercially available IPM. However, as two of the essential components may not survive, alternative choices have to be pursued viz. Current Source Inverters (CSI's), and Matrix Converters, both of which require significantly less DC-link capacitance than a typical VSI topology.

Ongoing work aims establish the optimum trade-off between the two competing drive topologies. The results will be presented in due course.

Further consideration of the design of a sub-sea drive system, is that of heat dissipation. Traditionally, drive design includes the careful consideration of the thermal management system for the power electronic devices. Deep-sea operation of drive systems would, in-effect, provide an infinite heat sink for the power devices, as the oil-filled containment would be in direct contact with the sea-water. This will have a beneficial impact on the size of the final drive, as the necessary heat sink normally occupies a significant amount of the drive volume.

1×1 switching matrix

Initially, a single-phase AC-AC regulator, consisting of two bi-directional switches configured in a half bridge arrangement, Figure 10(a), is considered. This forms a basic subset of a standard matrix converter arrangement, Figures 10(c) & (d). Each bi-directional switch consists of two MOFSET's internally connected in common source mode, Figure 10(b), within a C4-10s1 smartpack.



(a) (b) (c) (d)

Figure 10. Matrix converter topologies (a) signal phase AC-AC converter. (b) bi-directional switch architecture. (c) three-phase to single-phase converter (d) three-phase to three-phase converter

3×2 switching matrix.

The long (up-to 4000m) 'umbilical' tether employed to connect the ROV to the surface vessel, is used both for mechanical support, and to contain communication and power lines. For reasons of distribution efficiency, power is transmitted at high voltage, usually in excess of 3kV, in the form of a balanced three phase system [3]. However, onboard the ROV, the transmission voltage is stepped-down using a large low frequency (50Hz) transformer. Since many sub-systems require a single-phase supply, the use of a three-phase to single-phase matrix converter allows a balanced three-phase load to be presented to the supply. Figure 11, therefore shows the practical implementation of a 3×2 matrix converter structure, Figure 10(c), capable of providing compact, lightweight, three phase to single conversion, to provide a single-phase supply from the three-phase input.

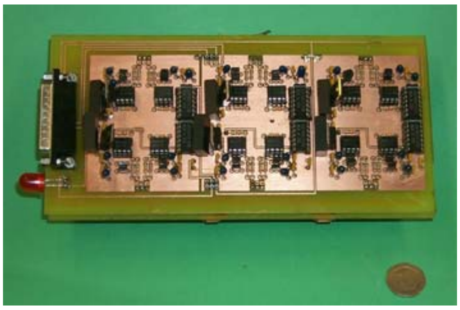
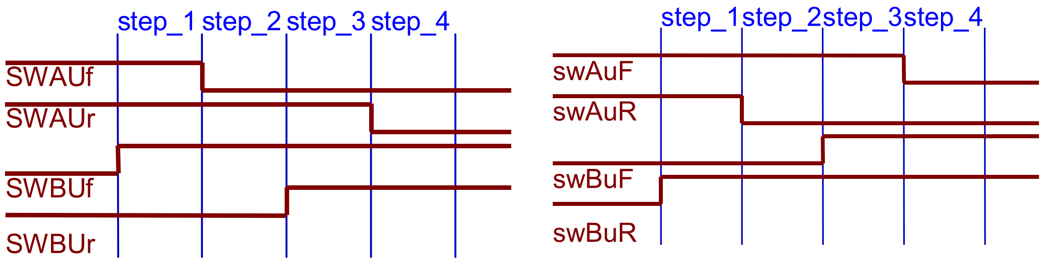


Figure 11. 3x2 matrix converter

Figure 12. Bi-directional switch

A rectifier control algorithm [5] with voltage commutation was used to control the converter. 4-step voltage commutation was selected over current commutation as no additional measurements, hence circuitry, was required to achieve the desired operation, the four step in the commutation process are illustrated in Figure 13. The converter was shown to operate at various frequencies up to and beyond the desired operating pressure. Investigation into the detailed operation of the converter identified a current spike occurring at the third event of each four-step commutation sequence. These spikes occurred without a load connected to the converter output, however a shoot-through condition was discounted due to the position of the spike in the commutation sequence. The cause of these spikes has been identified as the parasitic capacitance of the switching devices, illustrated in Figure 12.



(a) (b)

Figure 13. (a) Voltage Commutation for the case $A_N>B_N$. (b) Voltage Commutation for the case $B_N>A_N$.

Results obtained from converter tests, under low input supply line voltage conditions (30Vrms), with and without load cables attached, are shown in Figure 14. The switching event illustrated, by way of example, was from the zero vector A (AuAv) to the power vector BuAv. It is shown that the small distributed capacitance of the load cables increased the spike flowing through devices Bu and Av due to the transient voltage change across it, whilst the current flowing though the phase not involved in the commutation action, phase C, remains constant independent of load. Under ideal conditions, no current would flow in phase C as no commutation event in that phase had taking place. However, it can be see from Figure 14 that the current flowing through phase C is the difference in the currents in phases A & B, and is attributed to current flow in the parasitic capacitances of the switches in phase C.

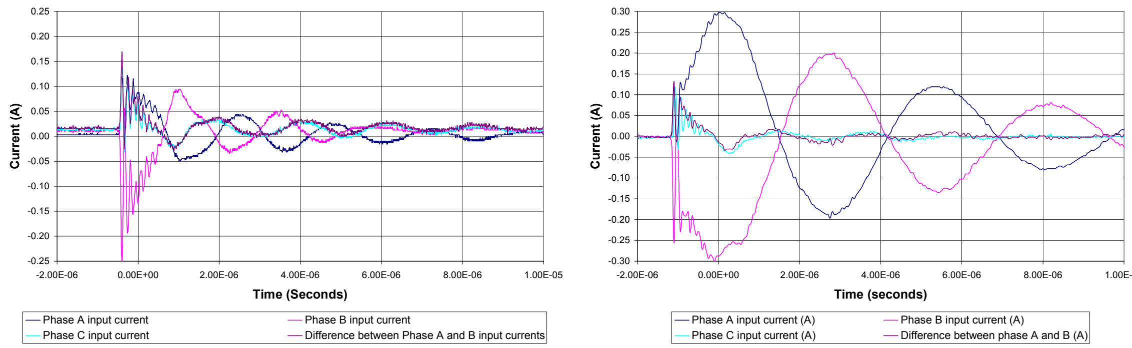


Figure 14. Current spike occurring on the 3rd commutation event (a) without the capacitive load (b) with capacitive load.

3×3 switching matrix.

Matrix converters also provide a method of direct three-phase to three-phase conversion with variable frequency and voltage control of the converter output. Methods of direct conversion are conventionally achieved using topologies such as the VSI, however, as discussed previously, these are not the preferred solution for long-term, reliable, operation in a high-pressure environment. The full matrix converter architecture requires 9 bi-directional switches connected in a matrix between the three inputs and the three outputs, allowing any input to be connected to any output, Figure 10(d) (see also Figure 15). This flexibility allows direct control of phase, frequency and displacement factor, which can ultimately be controlled to unity.

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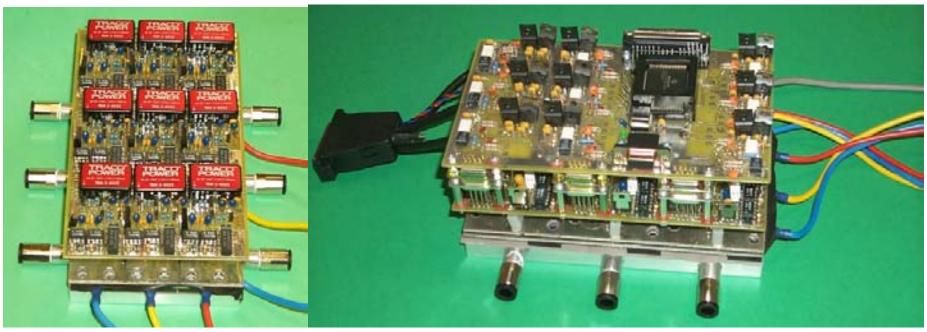

Figure 15. 3x3 matrix converter. (a) showing the Gate drive arrangement (b) complete converter with commutation control board.

Simulations of the 3x3 matrix converter have been carried out in the Saber package. Various control algorithms have been evaluated to find the most computational efficient method to implement on the target system. Results shown, Figure 16, are taken from simulations using a rectifier input control algorithm, with output space vector modulation, and voltage commutation for reasons stated previously. The implementation of the chosen control strategy is on-going, together with pressure tests of the final system. Practical results will be presented in due course.

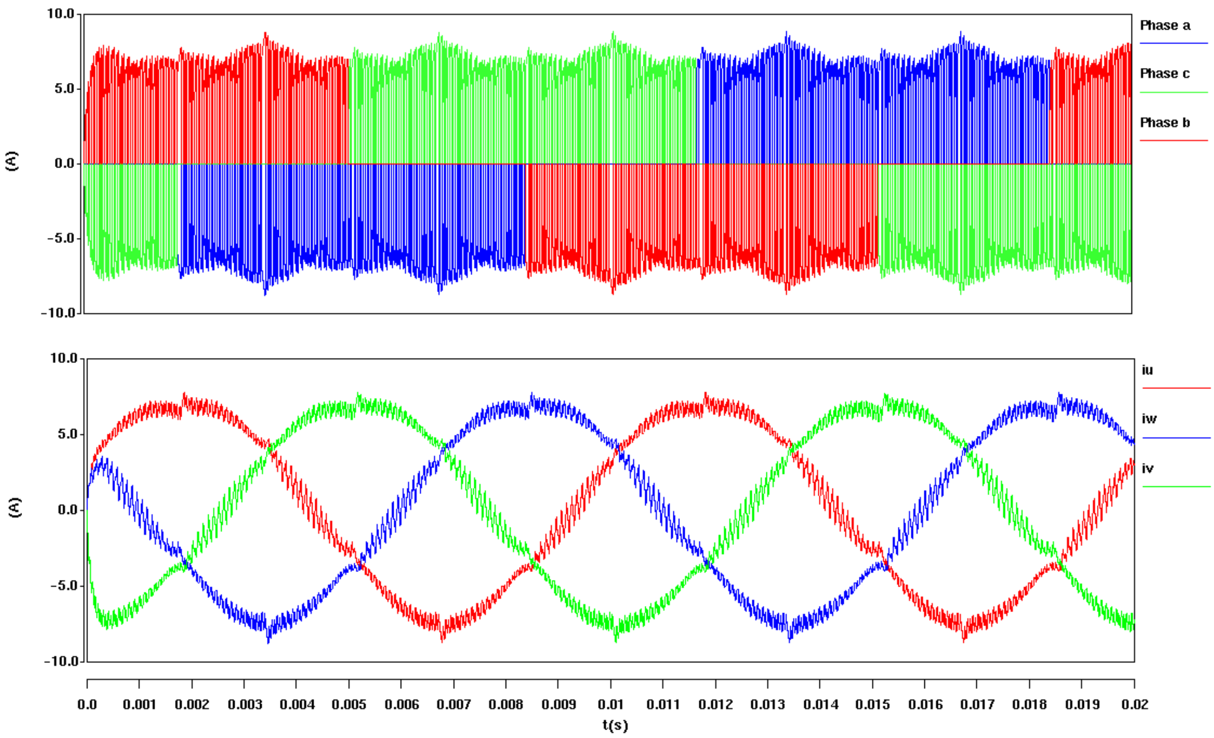

Figure 16. Simulation results of the 3x3 matrix converter Phase a, b and c are input currents, iu, iv and iw are output current to star connected load.

Conclusions

This paper describes the results of an investigations into pressure tolerant commercially available electronic components selected for a novel deep-sea, underwater vehicle, and matrix converters for motor drive applications, in which power and control must be possible at 300bar ambient pressure.

Deep-sea operation of electrical drive systems offers a number of distinct challenges over standard operation; critical component in standard drive systems cannot be relied upon to either survive, or operate satisfactorily at high ambient pressure. Alternative drive topologies to the standard VSI have therefore been identified. The observation of a recoverable fault in components, which do at first inspection, survive the ambient pressure, implies that rigorous testing of the final drive design under the final operating pressure, is necessary.

Practical results of the implemented 3×3 matrix converter will be presented, illustrating the circuit operation under representative pressurised conditions.

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