Design Synthesis and Experimental Validation of an AMB Controller with a Power Dense Amplifier for Retrofit Applications

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***Abstract*—This paper describes the design, development and validation of a high power amplifier used to up-rate the axial power amplifiers of a standard AMB controller. The VA rating of the amplifiers was doubled whilst maintaining the original footprint of the amplifier.**

The thermal management and other constructional challenges presented by such up-rating and high power density are discussed, together with some of the techniques used to overcome them.

This up-rated system is suitable for retrofit applications where the controller is coupled to pre-existing AMB hardware. Preliminary results from such an installation are presented.

I. INTRODUCTION

A. *Retrofit requirements*

When considering selection of an AMB controller for an application in which the controller is replacing an existing controller, there are a number of constraints which apply, which would not necessarily apply in the case of a complete new bearing system design. By the very nature of the exercise, the controller which is being replaced is likely to be quite old and will almost certainly have been developed using outdated power semi-conductors. This may well mean that:

- The DC link voltage of the amplifier system is lower than would be selected for a modern design of controller.
- In order to achieve a required dynamic force capability the controller will have a minimum reactive power (VA) requirement and this may lead to higher currents than would be applicable with a more modern controller.

A simple solution to the problem of matching the VA requirements of the bearing to the voltage and current capabilities of the new controller would be to re-wind the bearing with a suitable number of turn and wire gauge together with replacement of the field cables. However, such rewind of the bearing may not be practicable due to such items as:

- Timescales for the controller exchange
- Not wanting to dismantle the machinery
- Existing pressure penetrator voltage ratings and wire gauges.
- Existing field cable runs being buried or otherwise inaccessible.
- Added cost

Where the DC link voltage of the selected controller is fixed and a bearing re-wind is ruled out, the cable and bearing insulation systems must be re-qualified for the higher DC link voltage, and then the only subsequent challenge is to select a controller of the correct current rating. This is likely to give a system with an increased VA rating and consequently better dynamic force capability – leading to operational performance benefits.

This re-qualification of the windings, cables and pressure penetrators would be either by review of the documented ratings of the components (they may have been originally selected with a margin which permits operation at the higher voltage), or by performing a insulation test at a voltage significantly higher than the proposed operational voltage. Such an insulation test carries significant risk, since in the event of a test failure the winding (or cable) would no longer be suitable for continued operation either with the new controller or the existing controller.

Where the DC link voltage of the selected controller can be modified to match the existing controller then the challenge is again to select a controller of the correct current rating. This is likely to give a system with unused VA rating within the controller, due to operation at reduced DC link voltage.

B. *Power electronic systems in magnetic bearings*

In magnetic bearing applications, power electronic systems are usually designed with high power-semiconductor switches and diodes in discrete form. The preferred method of achieving weight and cost reduction of these systems is through the use of higher switching frequencies and devices with low on state resistance. Though semiconductors have been driving force for power electronic system developments, passive components used in conjunction with switching devices have different form factors and poor thermal properties. The assembly of components on a single PCB results in poor volume utilization and low power densities [1]. Thermal management is done at component level and is based on single sided heat removal with bulky and heavy heat sinks. The passive components often operate at high temperatures even when exhibiting relatively low dissipation levels due to low thermal conductivity of passive materials. The production cost escalates due to the complex assemblies associated with discrete parts and labor intensive assembly processes. The design cycle time also increases since standardization of such circuits and parts becomes difficult.

C. *Impact of power electronic system design on reliability of magnetic bearings*

The demand for reliable magnetic bearing systems has resulted in development of amplifiers with novel thermal management techniques. It is worth noting that ambient air temperatures in AMB controllers have a direct impact on lifetime of these systems. Low operating temperatures improve reliability; whereas, higher temperatures offer more efficient material usage due to a higher electromagnetic excitation capability. Furthermore, the convection rate of heat to the ambient from any component surface relies heavily on the difference between surface and ambient temperatures. A uniform temperature distribution on the component surface will therefore result in more effective convection of heat to the ambient, due to a higher average temperature difference between surface and ambient allowing for a higher convection rate. This then results in overall lower component surface temperatures.

D. *Thermal management of power electronic systems in magnetic bearings*

Components inside an amplifier dissipate power losses resulting in temperature rise of the component material as well as that of the neighbouring components. Depending on the properties of materials, they exhibit optimal and maximum temperatures. The optimal operation temperature of a component is a compromise between the lifetime or reliability of the component and the level of electromagnetic excitation of the component.

To reduce size and cost of amplifiers, research into new system integration and packing technologies has gathered momentum. To increase the power densities by improving material usage, a design technique is required that provides a good interaction between thermal management and integration technologies implemented towards reducing size of amplifiers. In most electrical designs, one strives to achieve the maximum functionality with the minimum material and lowest possible parts count. The same principle should be applied to the thermal-management system i.e. it should be as simple as possible, should not use many parts, and should use as little material as possible.

Amplifiers generally use multiple discrete semiconductor devices, which are mounted on a heat sink to dissipate heat. In order to provide isolation between heat sink and device and prevent short circuit, an interface pad made of epoxy or a polymer, filled with ceramic particles such as boron nitride or alumina is used. The ceramic particles are added enhance thermal properties of the interface pad which also acts as a heat conduction path. The interface pad being a conformable material also helps to reduce the contact resistance between the metallic surfaces of the heat sink and the device. However, the interface pad is a source of high thermal resistance in the overall conduction path between device and heat sink.

II. DESIGN TECHNIQUES

A. *Parameters affecting amplifier volume*

Amplifier size and construction is dependent on the following factors:

- Sizes of passive components such as transformers and chokes. These are affected by inter-winding isolation material in inductor and transformer structures.
- Electrically conductive paths. They include cable routes, electrical package pins and tabs, cable cross sectional areas and material for wire bonds.
- Thermal cladding, thermal interface and potting material.
- Thermal layers on PCBs dedicated to cooling.
- Capacitor housings or brackets to increase rate of cooling.

B. *TMLD and TDR*

In this paper, thermal management effectiveness is evaluated by two figures of merit:

Thermal Management Loss Density (TMLD) and Thermal Design Rating (TDR)

TMLD addressees the *effectiveness* of the implemented material and parts used for thermal management by *volume*, while TDR addresses the *thermal performance* of implemented material and parts [2].

$$TMLD = \frac{P_{losses}}{V_{tm}} \tag{1}$$

P_{losses}: $total\ power\ dissipation.$
V_{tm}: $volume\ of\ all\ material\ contributing\ toward\ thermal\ management\ of\ the\ converter.$

A high TMLD value is preferred as it gives greater power density.

$$TDR = e^{-1/2\frac{(T-T_{optimal})^2}{2T_{dev}^2}} \tag{2}$$

$$T_{dev} = \frac{T_{max} - T_{optimal}}{4}\ ;\ T_{dev} > 0$$

T_{max} : $component\ maximum\ temperature$;
$T_{optimal}$: $component\ optimal\ operating\ temperature$
T_{dev}: $Temperature\ deviation$

Components with similar TDR values can be grouped together. High power density results in higher component operating temperatures. The flipside is that reliability is reduced. In order to achieve both higher power density and higher component reliability, TDR values should be taken into account along with values for TMLD [2].

C. High current PCBs

Often overlooked but an important building block in amplifiers is the power PCB itself. Most of the PCBs used for low power applications are manufactured with copper traces made of copper weights ranging from ½ oz/Ft² to 3 oz/Ft². For high power applications, boards can be manufactured with copper weights between 4 oz/Ft² to 20 oz/Ft².

With higher copper weights, designers can avail advantages [3] such as:

- Higher endurance to thermal strains and increased mechanical strength at connector sites.
- Increased amperage capacity.
- Overall reduction in size of amplifier by incorporating multiple copper weights on same layer of circuitry.
- Reduced cable routing.

By manufacturing PCBs with higher copper weights, high current circuits can be combined with thicker copper plating in the vias. Plated through holes will eliminate the need to add duplicate layers in parallel, thereby eliminating any concern of load sharing among multiple layers. Measuring temperature rise in boards becomes simplified and failures due to thermal stresses are minimized, the overall advantage being a cooler running and more reliable PCB [5].

Approximate current for a given track dimension in external layers is

$$I_{ext} = 0.048 \times dt \times 0.044 \times w \times th \times 0.725 \qquad (3)$$

While for internal layers is

$$I_{int} = 0.024 \times dt \times 0.044 \times w \times th \times 0.725 \qquad (4)$$

I_{ext} *and* I_{int} *are currents* (A); dt: *temperature rise* $(°C)$; w : *width of trace* (mm); th: *thickness of trace* (mm)

Commonly used dielectric material is FR4 with maximum operating temperature of 130°C. Higher temperature polyamides are also available with 250°C rating.

Electrical vias can substantially reduce the thermal resistance of a PCB. They are commonly used in medium and high power density boards. In principle each via is a copper sleeve through the board or through a part of the board (blind or buried via). In addition to its electrical function, a via can also be used as a thermal short.

D. Gate drive design

Gate drive design: A good gate drive design revolves around selecting a device that satisfies ideal conditions as much as possible. The design can then be optimised to realize the best amplifier performance.

In general four parameters V_{gg+}, R_g, I_g and drive layout are the parameters that should be considered very carefully. V_{gg+}(Positive gate bias voltage) is the voltage across gate and emitter with IGBT conducting and it affects on state loss and switching speed. R_g is the value of gate turn on resistor and affects switching performance of the device.

$V_{CE(sat)}$ is inversely proportional to V_{gg+} for a fixed value of collector current I_c. For a gate threshold voltage $V_{ge(th)}$, gate drive current

$$I_g = \frac{V_{gg+} - V_{ge(th)}}{R_g} \qquad (5)$$

An increase in V_{gg+} reduces the switching time of the device and switching losses become smaller. This also increases I_g which charges gate emitter capacitance C_{ge} faster which leads to quicker increase in collector current I_c. This in turn leads to an increase in $\frac{dI_c}{dt}$. Large values of $\frac{dI_c}{dt}$ and $\frac{dV_c}{dt}$ indicate lower switching losses and switching speed which is an advantage but from an EMI point of view, it is desirable to limit them. A device with good built in diode recovery characteristics can limit rates of rise of collector current and voltage [4].

To achieve a good balance between switching losses and EMI, a commonly used technique is to select smaller value of R_g and reduce switching losses by increasing I_g. This method also reduces $\frac{dV}{dt}$ and in turn surge voltages caused by miller effect. However, minimum R_g values are limited by characteristics of freewheeling diode of IGBT on opposite side in multi-pack IGBT's. So a turn off gate resistor $R_{g(off)}$ and a turn on resistor $R_{g(on)}$ can be used. They can be accordingly adjusted for optimum performance. It is preferred to not share stray inductance of IGBT leads and PCB tracks between common emitter terminal and power emitter terminal of device since they can have undesirable effect on switching speed of the device [3].

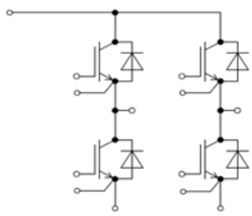

Figure 1. IGBT with separate common emitter and power emitter.

III. RETROFIT EXERCISE

A. Requirements summary

Waukesha Magnetic Bearings worked with a leading rotating equipment manufacturer with a retrofit solution to replace an aging controller with more sophisticated AMB controller to realize higher dynamic force and computational capabilities, and exploit benefits offered by modern power electronic devices. A low cost AMB controller 'Zephyr' was chosen for the retrofit since the product offered significant advantages such as increased reliability, ease of assembly, small lead times and less space requirements.

Figure 2. Zephyr Controller.

In order to match the VA requirements of the bearing to the voltage and current capabilities of Zephyr an upgrade of axial amplifier was deemed necessary due to constraints imposed by existing mechanical setup. This included:

- The requirement that the existing windings be retained.
- The maximum static load (and the consequent maximum static current) when operating at full gas density and full power.

TABLE I. VA RATINGS OF THE 2 CONTROLLERS

Parameter	Existing controller	Zephyr controller
Radial Bearing Current (peak)	30 A	27A
Radial Bearing Volts	160 V	390 V
Axial Bearing Current (peak)	60 A	27A
Axial Bearing Volts	160 V	390 V

It can be seen from the Table I that the peak VA requirement of Zephyr on the axial bearing could only be matched with an amplifier rated for 60A i.e. more than 2 times that offered by standard amplifier rated for 27A. The redesign methodology used to up-rate axial amplifier along with the field test results are discussed in the sections that follow.

B. Amplifier design

It has been discussed in earlier sections that reliability increases with lower operating temperatures while higher temperatures allow more efficient thermal usage due to increased electromagnetic excitation capability. It has also been pointed that, a design technique that provides a good interaction between thermal management and integration technologies can increase the power densities of amplifiers and significantly reduce cost per Kilo-watt.

One of the amplifier re-design constraints was that the retrofit amplifier had to fit in the same area envelope as the existing one i.e. 140mm ×205mm (W×L). The current density of the amplifier PCB would then have to increase from 0.1883A/cm² (27A current) to 0.419A/cm² (60A current). This is a manifold increase in current density that can only be achieved by novel thermal management techniques and low component count.

Figure 3. Existing Zephyr Amplifier PCB.

In order to evaluate TMLD of IGBTs for this exercise, different packages were evaluated for their suitability.

TABLE II. TMLD RATINGS FOR DIFFERENT PACKAGE TYPES FOR 60A CURRENT

Package type	TO-3P	TO-247	EasyPack	SOT-227
P_{losses}(W)	90	90	90	90
V_{tm}(mm^3)	3095	3488	12478	20473
TMLD (W/cm³)	29.07	25.80	7.212	4.39
T_{rise} above ambient (°C)	112	101	40	31.7

To achieve a balance between TMLD and temperature and thereby obtain better reliability figures, the EasyPack module and SOT-227 modules were considered for further study. Both modules do not require thermal interface pads for isolation which can be a barrier to efficient cooling.

The EasyPack module offered significant advantages over SOT-227:

- Ease of assembly onto a PCB.
- Separate common emitter and power emitter terminals which reduce effects of stray inductance on device switching speed.
- Modular package with multiple devices as opposed to a single device in SOT package.

The next challenge was to design a PCB capable of carrying 60A(peak) current. In order maintain a balance between device temperature and favourable track temperature (40°C above ambient) for 60A, the track width was determined to be at least 3.06mm for external layers and 7.96mm for internal layer. This was calculated based on IPC-2221 formula with 12 oz/Ft² copper weight. The copper weight was a trade-off between high current and optimal temperature rise for reliable operation of the amplifier. A further design challenge was presented with surface mount components associated with gate drive and current sensor circuits. The footprints could not be included on the 12oz PCB due to the practical difficulties associated with etching small pads and tracks with this thickness of copper. The solution was to split the card into 2 separate sections, one 12 oz/Ft² cu and a second 2oz/Ft² which carried all the SMD components. The SMD components have high TDR values and were mounted on a daughter board which was connected to power board through a network of copper vias and edge plates.

The gate drive circuit was designed with few components using methods described in section II. A turn-on and a turn-off gate resistor were used to achieve minimum values of gate resistance. This resulted in an increase in I_g which charges gate emitter capacitance C_{ge} faster leading to quicker increase in collector current I_c . Achieving an optimum value of V_{gg+} for I_g was easier since the IGBT device from Infineon itself had small $V_{ge(th)}$. Further a compatible gate drive IC from Infineon was chosen which matched device input impedances well and thereby helped in maximum transfer of power from source to the device.

The use of a daughter board aided the layout process and gate-emitter loop could be kept as small as possible. Moreover with separate common emitter and power emitter terminals on this device, parasitic inductances were reduced significantly and SMD components could be placed close to the device which reduced EMI. The power PCB was designed to be 4 layer, with wider track lengths on inner layers to enable dissipation of heat efficiently. The daughter board was designed with 2 layers.

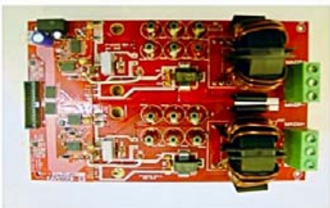

Figure 4. Up rated Zephyr Amplifier PCB.

A well designed layout should also cater to reducing electrical stress on gate low voltage control ICs. Electrical stresses can be caused by switching transients which are a result of mismatch between source and load impedance and high slew rates of control IC's [6]. EMI filters are necessary to reduce ringing on output lines and it is important that they do not overheat. Heating alters the properties of inductor cores and performance degradation can occur at high temperatures. PCB mounted versions of common mode filters with current ratings up to 50A (convection cooled) and 80A (forced cooled) have recently become available in market. They are dense packages with nano-crystalline cores which allow greater inductance values and higher current capacities, which was not possible until a few years ago. However these cores are brittle and age quickly at elevated temperatures. Forced convection cooling was necessary to obtain necessary performance at 60A (peak) currents. Similarly a parallel combination of PCB mounted differential mode filters was used to increase current handling capacity to 60A.

IV. TEST RESULTS

The amplifiers were assembled onto a common heat sink. A cross flow blower with an air flow rate of 217.77cu.ft/min was used to cool the main heat sink and two axial fans with a flow rate of 100cu.ft/min were used for reasons discussed above. The cross flow blower lowered the main heat sink temperature by about 7.5°C, while the axial fans lowered the temperatures of passive components by 16°C. The Boost-brake module which provides the 390V DC link voltage to the amplifiers retained its power rating of 3kW. To cope with the increased power requirement of the axial bearing (and the associated increase in DC link ripple current), the reservoir capacitance associated with this axis was doubled.

Figure 5. Up rated Zephyr Controller

A thermal profile of major components was plotted during in-house testing and is shown in Figures 6 and 7. The current magnitudes in amplifiers for the duration of this test are given in Table III. It was seen that the up rated axial amplifier was running almost at same temperature as the radial amplifiers for 2.5 times increase in current. This can be attributed to choice of the device at the design stage, layout of the board and the uniform heat distribution provided by thicker PCB tracks.

TABLE III. IGBT TEMPERATURES ON EXISTING AMPLIFIER AND UP-RATED AMPLIFIER AFTER 2 HOUR CONTINUOUS RUN

Axis	IGBT temperature(°C)	Bias Current(A)
J1P	69	20
J1M	70	20
J2P	68	20
J2M	68	20
J3P	67	20
J3M	67	20
J4P	67	20
J4M	67	20
ThP	66	50
ThM	64	50

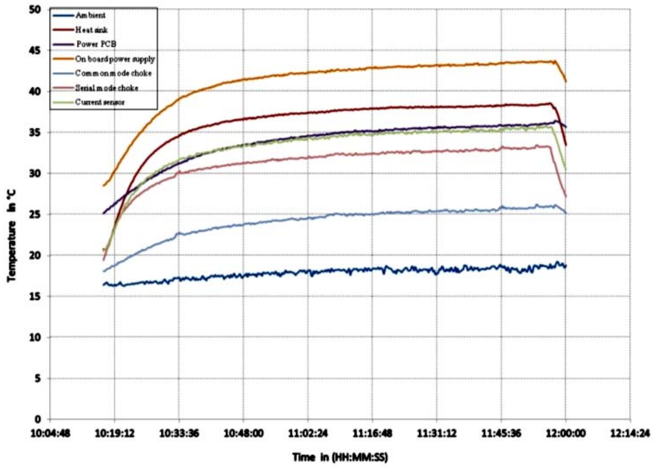

Figure 6. Thermal profile of retrofit axial amplifier

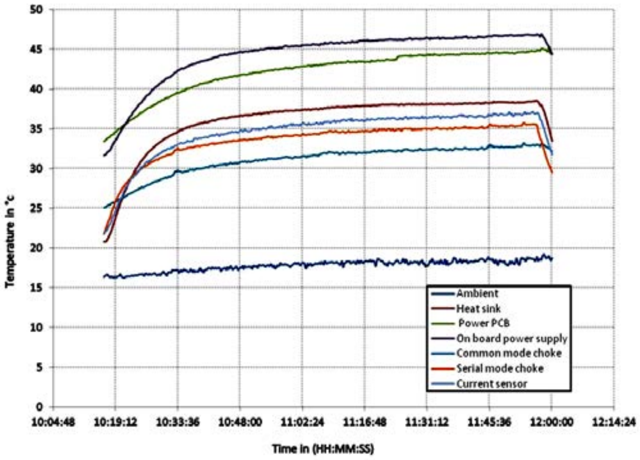

Figure 7. Thermal profile of existing radial amplifier

From the thermal profiles, it can be seen that the retrofitted amplifier PCB is cooler by 8°C. The passive components (common mode and serial mode chokes) can be seen to be running cooler by 6°C. The ambient temperature internal to Zephyr was maintained around 40°C catering to good reliability, high power densities and a nice thermal balance.

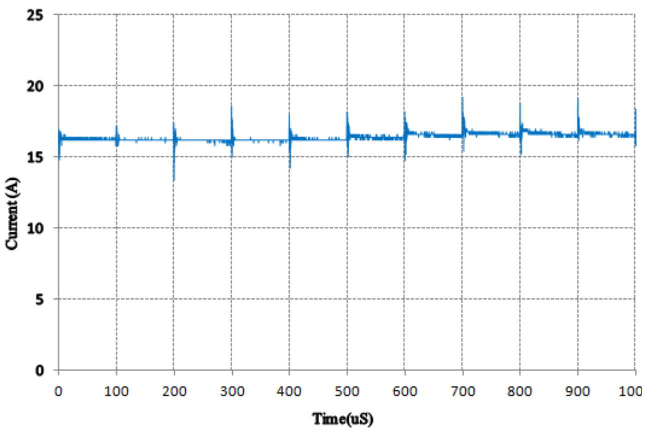

Figure 8. Current waveform of the retrofit amplifier

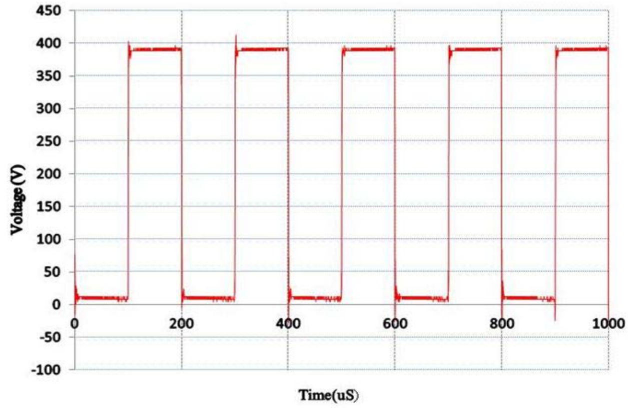

Figure 9. Voltage waveform of the retrofit amplifier

Figures 8 and 9 show plots of load current and voltage from the actual installation on site. It can be seen that the ringing on lines is only marginal. The switching transient at turn-on is small. The axial current needed for levitation was 16A. The turn-off transient also reduced due to use of a dedicated ‘gate turn-off resistor’. The layout was kept simple with use of a low component count on the power card. This minimized track routing complexity and possibility of earth loops which are a pre-dominant cause of EMI.

V. CONCLUSIONS

Thermal management of amplifiers in magnetic bearings is crucial for systems requiring high reliability and power density. This paper demonstrates the optimization of design can be done by using high current PCBs; devices with good TMLD and TDR values and a gate drive which provides a balance between switching losses and EMI. The techniques discussed in this paper have been demonstrated (through field experience) to produce good results in the design of amplifiers for a retrofit application.

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