Commissioning Experience with Dynamic Termination of Transmission Line Effects in an Extended Magnet Cable Application

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Abstract

Active magnetic bearing controllers generate current and voltage commands in response to axial and radial forces acting on rotating shaft. The subsystems that respond to these commands are known as power amplifiers. Due to advancements in power electronics and rapid industrial trend towards higher efficiency, compactness and lower cost, recent AMB's utilize switched mode PWM power amplifiers which regulate current in magnets by varying the ratio of on duration of switching device to switching period. With increasing no of AMB installations in hazardous areas for e.g. volatile gas compressors, it is imperative to provide a safe separation distance between the bearing and the control system itself. Transmission line effects can result in power cables connecting the PWM power amplifier to the bearing in such installations. These effects give rise to voltage and current reflections due to a mismatch of source, line and load impedance at high switching frequencies. They can cause insulation failures, overvoltage, ringing and improper operation of parts subjected to these voltages and currents.

A dynamic termination circuit was developed at Waukesha Magnetic Bearings to terminate these reflections on a strategic basis according to instantaneous PWM pulse amplitude and return most of the reflected energy to the DC link power supply. This paper discusses actual results seen during commissioning on site in which an AMB system was successfully employed to suspend a volatile gas compressor rotor shaft by mitigating transmission line effects in the power cables. It is also shown that this circuit can improve dynamic performance of PWM power amplifier and meet requirements of industrial AMB's in hazardous area applications.

1 Introduction

Magnetic bearing controllers typically employ H-bridge inverter or single phase inverter topologies for voltage and current regulation. Since $f \propto I^2$ (f *is force at bearing and* I *is magnet current*) and is always attractive, controllers that utilize bias current are required to produce only unidirectional current. The single phase inverter topology is suitably modified to include one active switching device per leg to produce unidirectional current (Chiba, Fukao, Ichikawa, & Dorell, 2005).

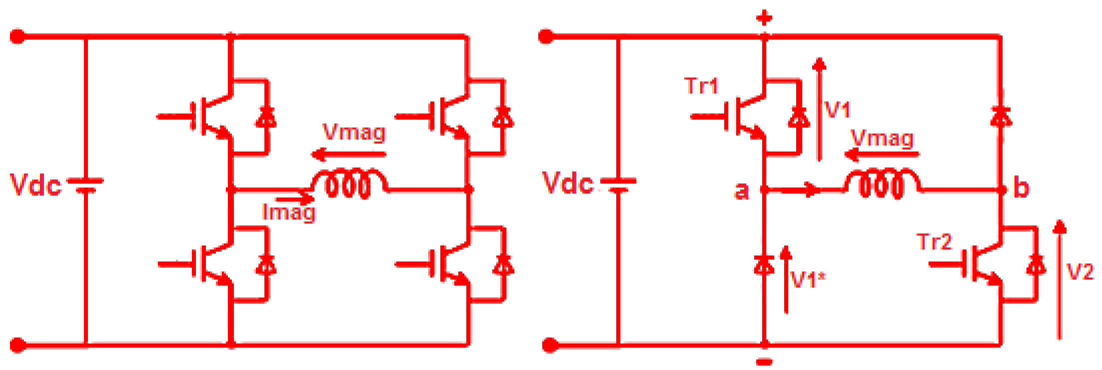

Fig 1

The advantage of using such converter is that amplifier efficiency is high due to use of only two controlled switching devices and less space required for mounting them. Moreover the control circuits are easier to implement. IGBT's are used as switching devices since they have voltage controlled gates. These gate drive circuits are simpler and faster. IGBT's interface more easily with drive low voltage control circuitry and they need smaller heat sinks due to lower power losses (Chiba, Fukao, Ichikawa, & Dorell, 2005).

1.1 Pulse Width Modulation

In order to control the switching devices in a modified single phase inverter, a switching scheme called Pulse Width Modulation is used. In a PWM scheme, the ratio of on duration of the switch to the switching period is varied to so that the average voltage is sufficient to maintain desired DC current through the load.

The switching waveforms in a single phase inverter with unidirectional current are shown below:

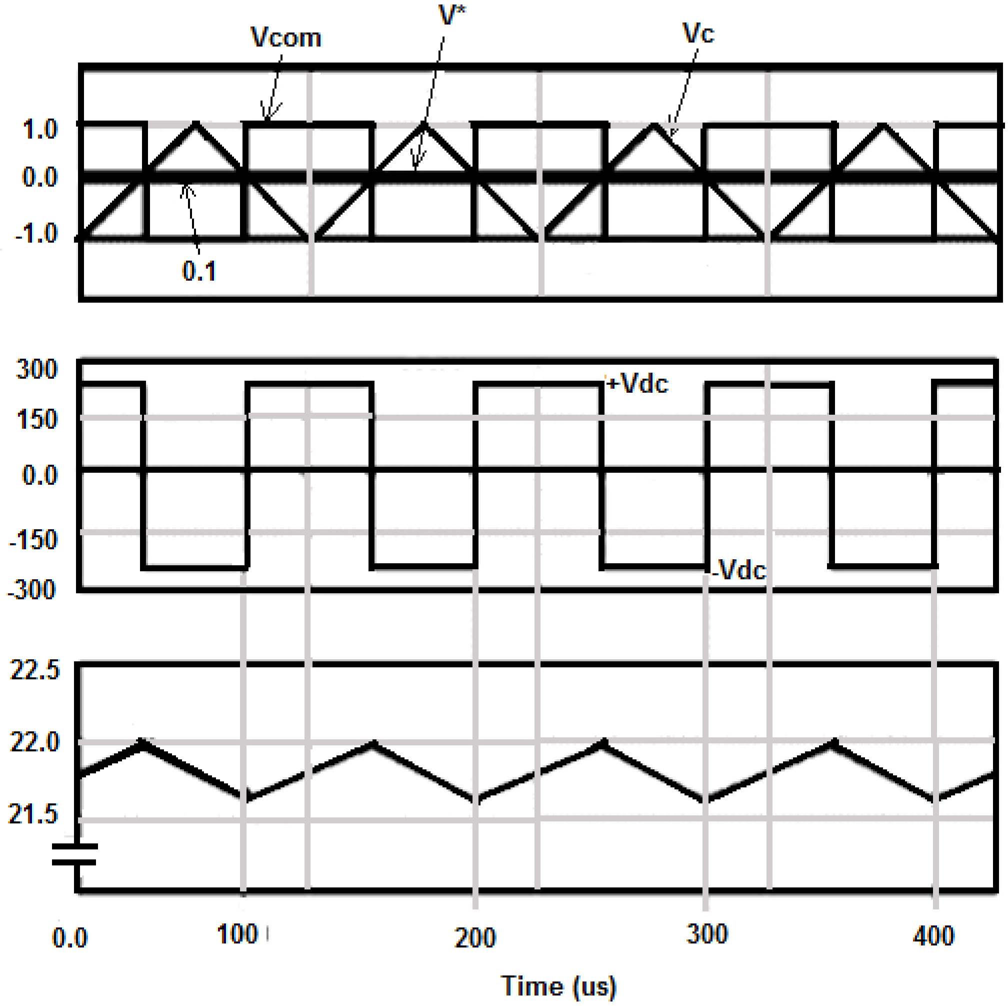

Fig 2

The triangular waveform V_c has a frequency f_c. The maximum and minimum values are +1 and -1 respectively. The required voltage command V^* and a comparator provide a digital signal V_{com} from comparison of V_c and V^*. The switching devices are operated using the comparator output signal. If V_{com} is high, the switching devices are turned on so that $+V_{dc}$ is applied to the winding. On the other hand $-V_{dc}$ is applied to the winding if V_{com} is low.

1.2 Transmission line effects as applied to an AMB system

The amplifier section of an AMB system generates a continuous train of rectangular pulses. These voltage pulses are carried to bearing through cables. The peak pulse voltage magnitude at the o/p of AMB amplifier is normally equal to DC bus voltage and contains steep fronted rise and fall times controlled by IGBT. However the peak pulse voltage at the bearing windings is not necessarily DC-bus voltage but is dependent on dynamics of amplifier-cable-bearing circuit defined by output switching voltage rise time, cable transmission line characteristics and bearing winding impedance to pulse voltage (Lawrence, Skibinski, Evon, & Kempkes, 1996). To experimentally observe the effect of cable length on magnetic bearing voltage, a 500M length of cable was connected between AMB amplifier and bearing with the system DC bus voltage at 300V.

Fig 3 below shows the pulse train at the bearing windings has momentary transient overvoltage at every switching point up to twice the DC bus voltage. These overvoltages may produce potentially destructive stress on winding insulation. This overvoltage phenomenon is known as transmission line effect (Lawrence, Skibinski, Evon, & Kempkes, 1996).

Such transients occur at every PWM switching instant defined by PWM carrier frequency. Voltages up to twice the DC bus voltage can get generated due to reflections at some cable length regardless of the type of switching device used. They are independent of amplifier output PWM frequency.

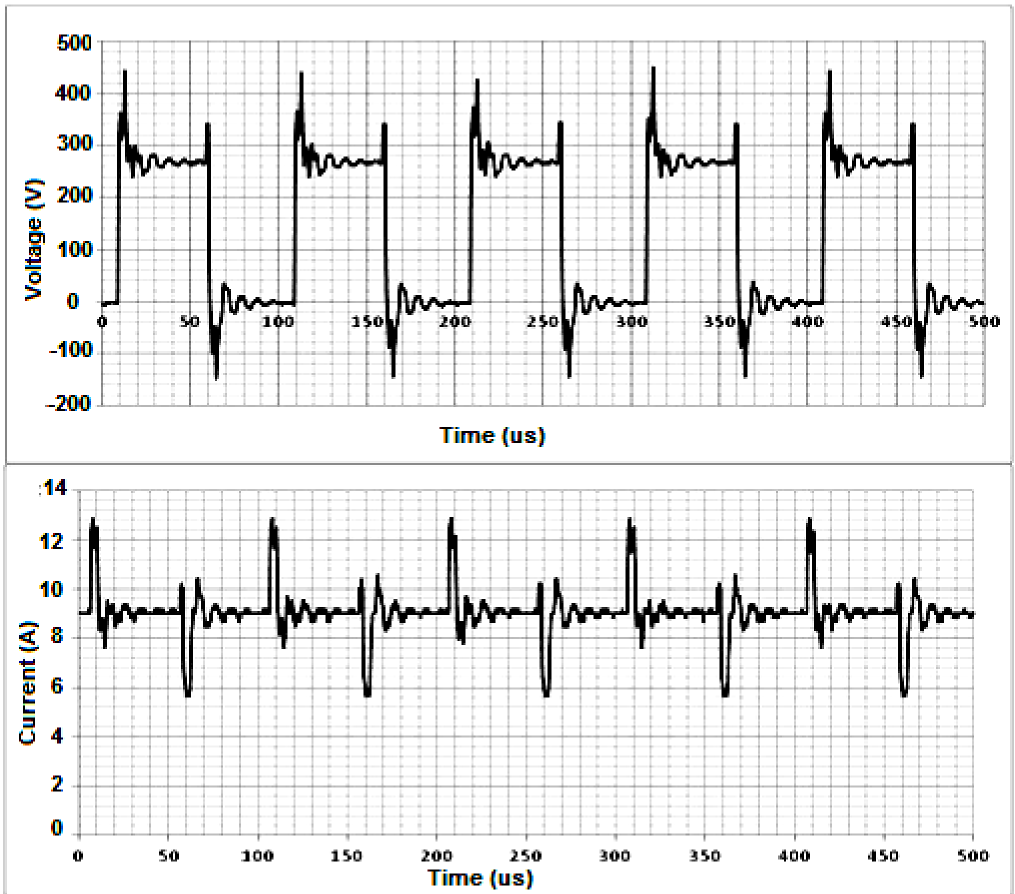

Fig 3

1.3 What causes it?

A transmission line modeled cable contains a network of inductances, capacitances and resistances which collectively constitute characteristic impedance of the line given by

$$Zo = \sqrt{\frac{Ro + j\omega Lo}{Go + j\omega Co}}$$

Lo is the inductance per unit length of the line.
Co is the capacitance per unit length of the line.
Go is the intrinsic conductance per unit length of the transmission line.

For modelling a lossless transmission line, *Ro* and *Go* are assumed to be zero and the equation becomes

$$Zo = \sqrt{\frac{Lo}{Co}}$$

Whenever the impedance of the source, line and the load are not equal, a mismatch will result. Due to this, a voltage signal applied or a current signal injected at the source is not fully absorbed at the load and excess energy is reflected back to the source, similar to a sound wave bouncing off a reflecting surface. This process of reflection continues until all energy is absorbed. Transmission line which is not terminated properly is called a mismatched line, and can distort the signal or even weaken it significantly when a reflected signal exactly cancels the forward one (Motorola Semiconductor products INC, 1980).

Variables affecting reflected wave magnitude are: Bearing and cable surge impedance; cable length; inductance of the load; magnitude of PWM pulse; rise time of PWM pulse; spacing of PWM pulses (Lawrence, Skibinski, Evon, & Kempkes, 1996).

Bearing and cable impedance mismatch mainly cause reflected wave phenomenon. The rise time of the PWM pulse primarily determines a critical cable distance L_c where the switching overvoltage will be developed. Cable lengths less than L_c will develop less overvoltage than those with lengths greater than L_c If the switching voltage rise time is known, the critical cable length which can cause overvoltage's can be determined (Lawrence, Skibinski, Evon, & Kempkes, 1996).

Bearing voltage = (1+Φ) V_{amp} (1)

The voltage reflection coefficient is given by

$$\Phi = \frac{Rload - Zo}{Rload + Zo} \qquad (2)$$

The current waveform looks triangular with quickly damping oscillations.

The current reflection coefficient φ is the ratio of the reflected to incident wave and is given by

$$\varphi = \frac{Zo - Rload}{Zo + Rload} \qquad (3)$$

Thus Φ = - φ. A positive voltage reflection due to large load impedance is associated with a negative current reflection and vice versa (Bolsens, Brabandere, Keybus, & Belmans, 2003).

Cable lengths < L_c will develop correspondingly less over-voltage than those determined by (1). Cable lengths > L_c will develop at over-voltages determined by (1) and possibly greater values, dependent on the spacing of PWM pulses.

2 Dynamic Termination circuit

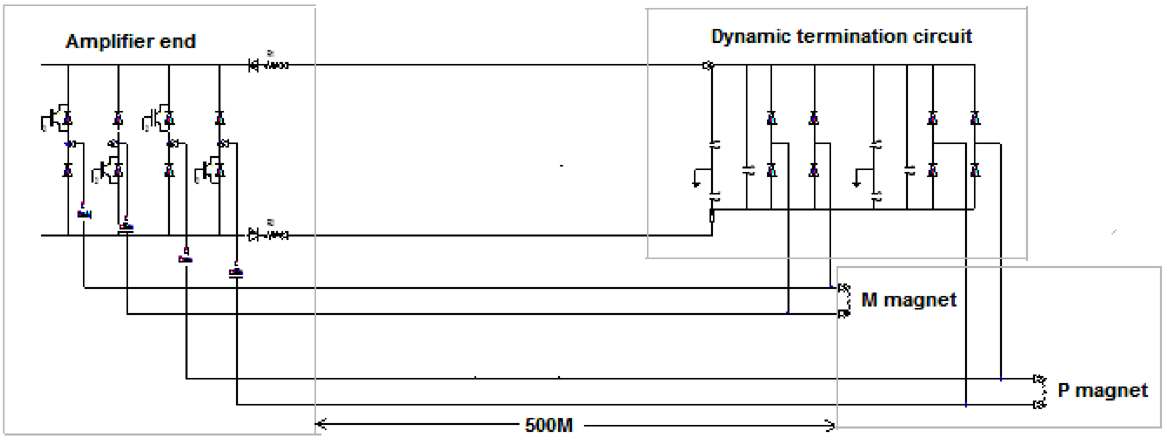

Fig 4

Waukesha Magnetic Bearings recently supplied an AMB system for an installation in a hazardous area. The separation distance between AMB control system and bearing was 0.5km. In order to ensure safety of personnel and equipment, all the components of the system near the compressor had to be ATEX approved. The system was to be commissioned in an area with high ambient temperatures up to +55ºC with limited facilities for cooling air flow near the compressor.

Due to nature of installation and local site conditions, it was decided that conventional techniques of mitigating transmission line effects in the power cables by making load impedance equal to characteristic impedance would not be suitable since heat losses would have to be dissipated locally and it would impose additional power supply requirements. An experimental verification to this effect was done and is described in (kumar, Wright, & Jayawant, 2012).

A patented dynamic termination circuit was developed to cut down the transmission line reflections and meet local site requirements.

A network of power diodes are used in this circuit which are placed near the bearing. They are connected to DC bus of the amplifier through series resistors on both +ve and –ve DC links. Decoupling capacitors are connected between earth and dynamic termination circuit voltage catcher rail to reduce ringing on currents routed back to amplifier. Further rectifier diodes are connected at the amplifier end in series with the resistors on offset catcher voltage rail to ensure current only flows back to the DC link.

The rating of diodes is at least twice the system DC bus voltage. The values of resistors and capacitors at dynamic termination circuit end are selected so that the excess energy in the cables can be dissipated safely. This is determined by experimental verification. It is important to choose resistors and capacitors correctly since they have an effect on switching voltage rise times at the bearing end.

The dynamic termination circuit also referred to as spike catcher is mounted on the compressor platform itself.

A schematic diagram of the actual cabinet-cable-spike catcher circuit setup on site is shown in Fig 5.

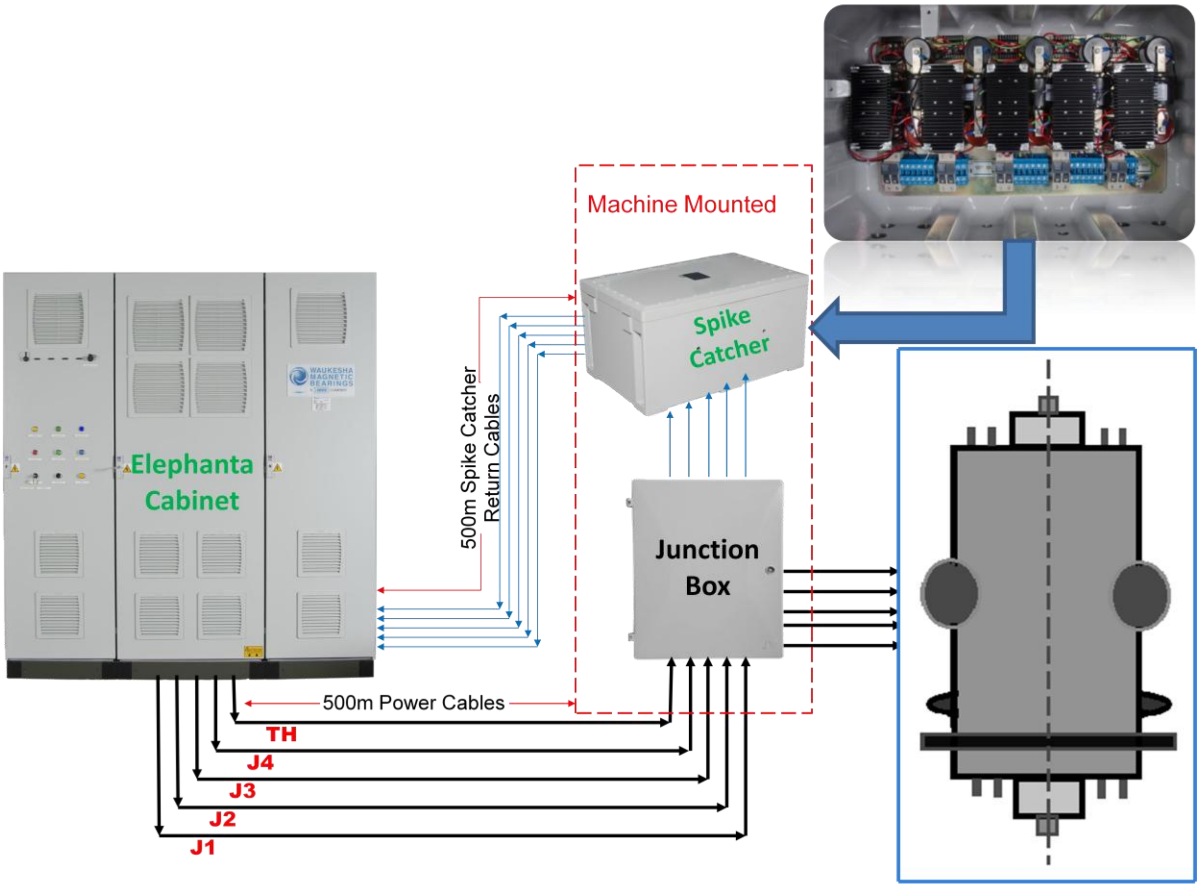

Fig 5

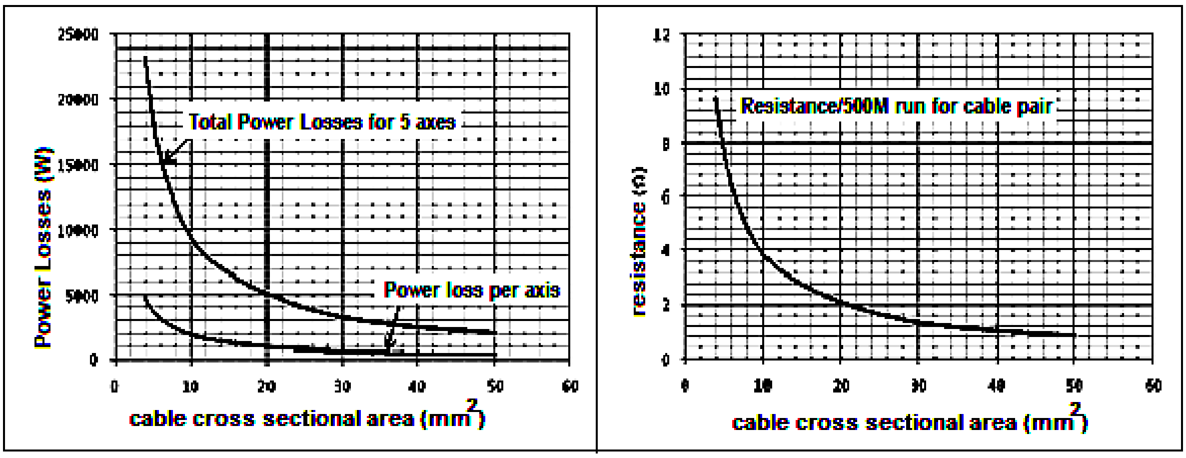

Fig 6

Although L-C parameters of a cable vary with gauge and cable construction, *Zo* remains relatively constant between 35 and 50 ohms for a 35mm² four core cable. It was also seen that the critical cable length at which overvoltage's occur depend on IGBT switching rise times. The power cable connecting the AMB system to magnet was Draka TSLP 0.6/1kV; 4×35FR/16mm² (4 core 35mm² conductor with a 16mm² overall screen). This was determined after calculating power losses for different cross sectional areas of cable for a 22A bias. Five such cables were used for connecting each axis to their respective magnets. The total length of power cable was 500M.Magnet power cables from each axis were connected into dynamic termination circuit through links on terminal blocks in a secondary junction box. Five 2 core+E, 2.5mm² power return cables were used to return recovered energy back to amplifier DC link. The circuit itself was housed in an ATEX approved EXd junction box located near the compressor.

3 Flux feedback

In order to obtain a high frequency response at fast switching speeds, current feedback is used in magnetic bearings controllers. The force at magnet is proportional to I^2 (where I is the current in the magnet). But in actual practise, the force at magnet is proportional to $Ø^2$ (where Ø is flux) and Ø is proportional to current. A transfer delay is caused by winding resistance and inductance. This is quantified even more due to inductance and capacitance of cable itself. Due to voltage drop across the cable and switching device in on state, a non-linearity in transfer function results. In canned bearings phase loss is introduced between current and flux due to shorted turn created by the can. In order to minimise phase loss and problems associated with long cables, we want to control flux rather than current.

This feature was used in the AMB system during actual compressor run. Further the transfer function plots showed improvement in terms of system gain and phase.

4 Test results with dynamic termination circuit

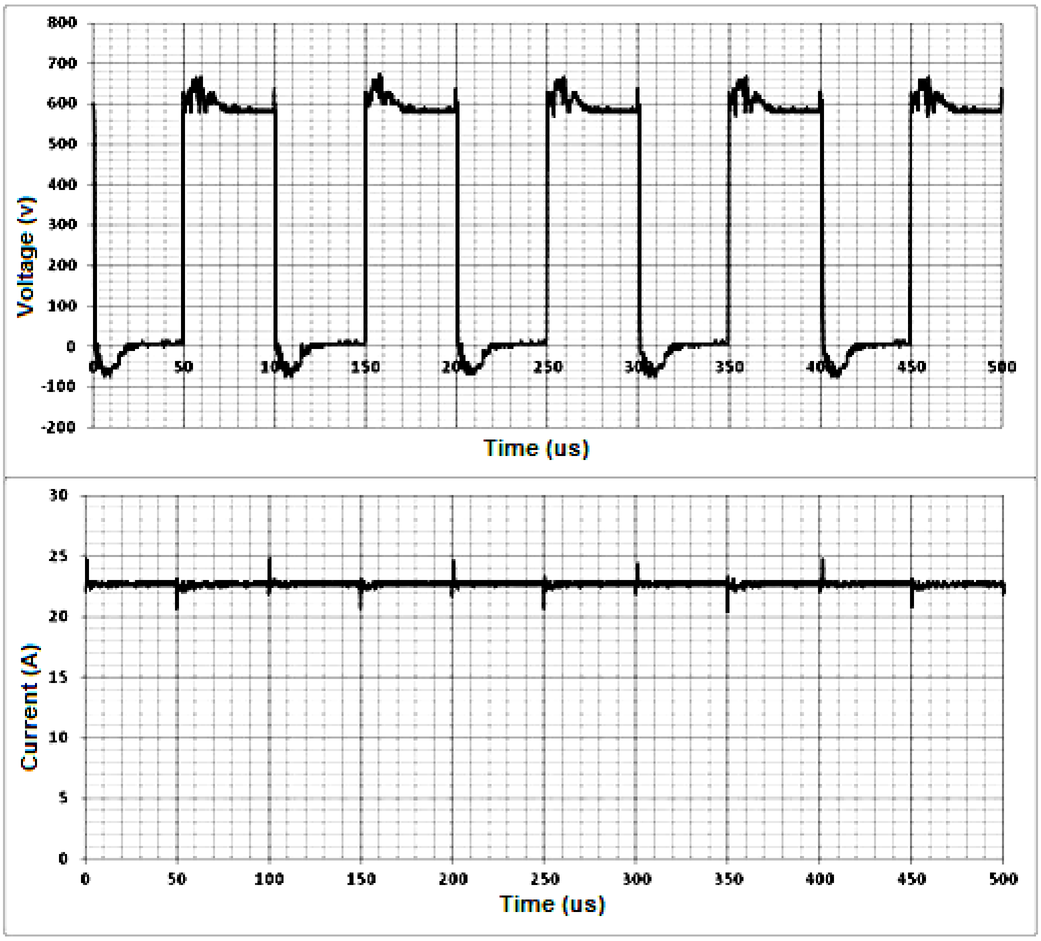

Fig 7

Tests were conducted at 600V with a bias current of 22A. The plots of voltage and current are shown in Fig 7. The ringing on voltage and current was seen to reduce significantly. The peak to peak value was measured to be 685V. Whenever the load voltage exceeded 600V the diode connected to positive DC rail would conduct. For voltages lower than 0V, diode connected to negative rail would conduct. Some spikes can be seen at the start of each cycle and this was due to on state voltage drop of diode and cable itself. Since most of the reflection was diverted through catcher diodes, the voltage rings on magnet were reduced substantially. Moreover the current waveform looks very much better with quickly decaying rings. From a system point of view these waveforms would not cause any additional stress on bearing winding insulation, devices and the cables themselves. A rotational run of compressor was done with speed up to 10,000rpm and the waveforms were seen to be quite stable.

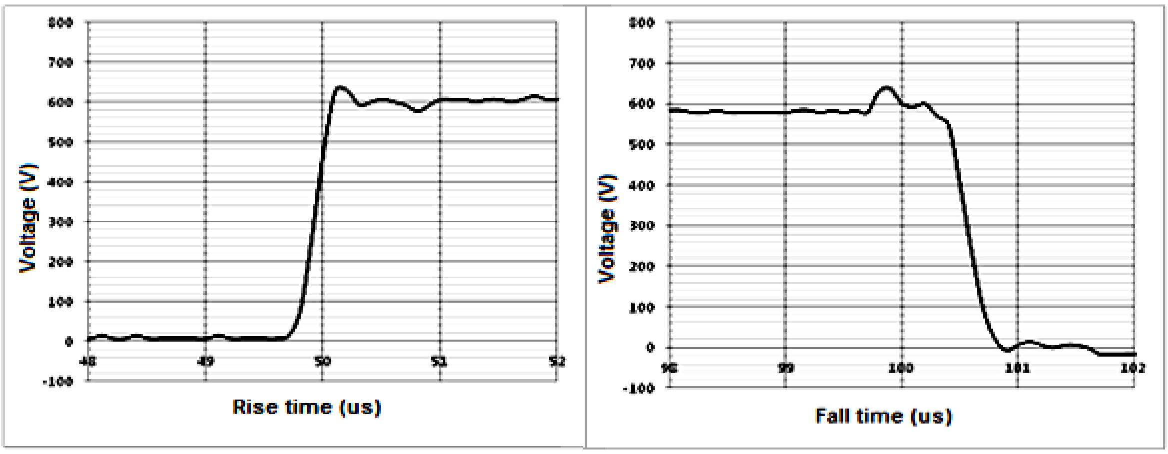

Fig 8

$$L_c = 772.8 \times T_{rise}\ (us);\ (L_c is\ critical\ cable\ lengt\ in\ feet)$$

For this application $T_{rise} = 160ns\ which\ gives\ L_c = 123\ feet.$

It can be seen from above equation that IGBT rise time affects the critical cable length at which overvoltage would occur. Faster the rise time, shorter cable length at which overvoltage's can occur and vice versa. Thus it can be concluded that with higher device switching speeds, stress on bearing windings and insulation has increased. The rise time of switching voltage was seen to have hardly varied with cable length and magnet current. The turn off time was also seen to be fairly same. It was investigated in (Lawrence, Skibinski, Evon, & Kempkes, 1996) that switching device rise times have an effect on length of cable which can produce overvoltage's up to twice the DC bus voltage. It can already be seen that with dynamic termination of transmission line effects, the designer has greater flexibility in choosing cable lengths since the circuit functions on instantaneous PWM pulse amplitude.

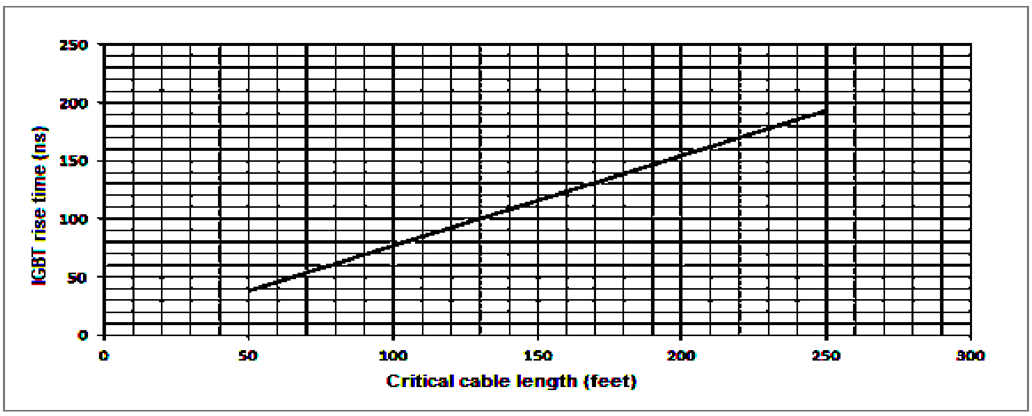

Fig 9

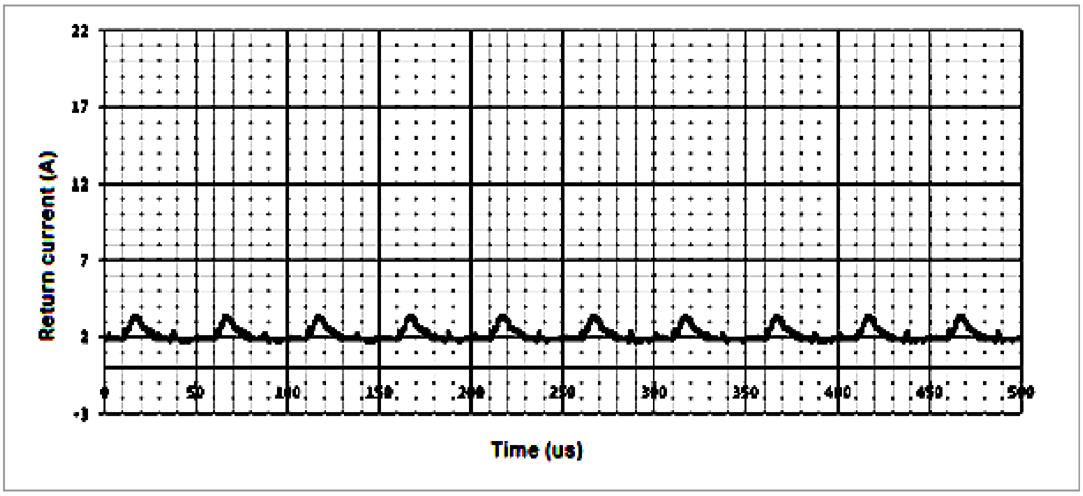

Fig 10

The currents which are routed from the circuit have small spikes which are thought to be capacitive discharge currents from the power return cable itself. These currents are adequately damped in the amplifier by use of common mode and differential mode chokes.

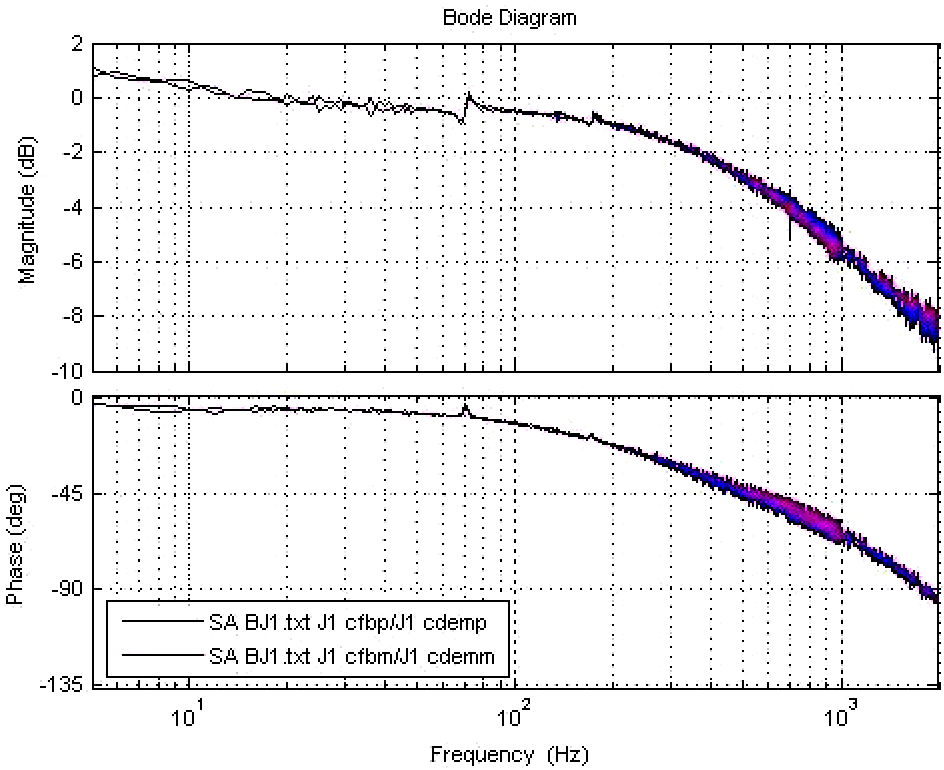

Fig 11 Transfer function plot of cfb/cdem for P and M magnets

A transfer function plot of AMB system for J1 axis is shown in Fig 11 above. It was seen that system stability problems at baseline level did not arise. No modes were seen in the TF plot in the frequency ranges of test. There could be modes above 56 kHz due to length of cable under test but this is still well beyond the dynamic range of AMB system (Elder & Maslen, 2010). The 45º point on the plot was seen to be 570Hz. All the axes showed similar characteristics.

The AMB system was levitated and power dissipation in the spike catcher circuit was recorded for different bias currents.

Bus Voltage (V)	Bias current (A)	Spike Catcher Thrust axis return currents-(A)		Power dissipation in Spike Catcher Thrust axis circuit (W)	Total power for 5 axes (W)
		P channel	M channel		
600	8	1.31	1.52	48.21	231.05
600	10	1.43	1.59	52.58	253.9
600	12	1.53	1.76	59.50	289.5
600	14	1.66	1.82	64.54	315.7
600	16	1.77	1.89	69.64	342.2
600	18	1.81	1.93	72.00	355
600	20	1.83	1.96	73.52	363.6
600	22	1.86	1.98	75.04	372.2
600	25	1.94	2.04	79.40	395

Table 1: Power dissipation within spike catcher for different bias currents.

It can be seen that the power dissipation in the circuit is significantly smaller than conventional resistor termination networks since most of the recovered energy is routed back to DC link power supply (Wright, 2012). The return currents for +DC bus and –ve DC bus match each other due to similar cable characteristics. The circuit components themselves were mounted on small heat sinks and their heat losses could be safely dissipated near in the hazardous area without any forced cooling requirements. Overall the performance of the circuit was as expected.

5 Conclusions

Critical cable length depends on IGBT switching rise times. With faster switching rise times, overvoltage's can occur at shorter cable lengths.

Dynamic termination circuit offers designer's greater flexibility in design of AMB systems with longer cables since this circuit can be used with devices having different rise times.

Implementation of this circuit is easy and no complex control methods are required.

No system stability problems arise with this circuit and performance of AMB system is comparable to those with shorter cable lengths.

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