Sending PWM Down Extended Magnet Cables

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Abstract

With a high power active magnetic bearing system, rapid changes in the magnet coil current are achieved by switching a high DC link forcing voltage onto the inductive load for short periods of time using Pulse Width modulation (PWM). In the steady state the on time of the voltage is a very small proportion of the cycle period such that the average voltage is sufficient to maintain the DC current through the DC resistance of the load.

In some situations where it is necessary to have a large separation between the PWM driving amplifier and the load, the cable between behaves as a badly terminated transmission line. Significant reflections on the PWM pulse waveform are able to cause potentially damaging voltage overshoots up to around twice the original voltage.

Conventional source and or load termination impedances would introduce unacceptable power losses. Using filters to limit the bandwidth going down the cable is both costly and has broadly similar effect to reducing the forcing voltage. This paper describes tests of a dynamic termination method where most of the power that would otherwise be lost is returned to the source of the DC link, giving dramatic improvement in the waveform quality.

1 Introduction

An active magnetic bearing system works at operating voltages ranging from 300V to 600V. The power electronics deliver required output voltage utilizing a combination of switching circuits i.e. boost converter, amplifier etc. The PWM switching frequency is in the range of several kHz and the amplifier connects input power source to the bearing. During the process of maintaining magnetic field, the bearing magnets have core and copper losses and electrical power delivered by amplifier is not entirely converted to mechanical work at the bearing.

Typically the separation between the drive system comprising the amplifier and the bearing itself can range from a few metres to about 150 m. However, in installations where the bearing is in a hazardous area such as volatile gas compressor, the need for maintenance should be minimal since safety of personnel is of paramount importance and separation in excess of 150 m is often required. This distance gives rise to transmission line effects in the power cable connecting the drive system and the bearing. This paper deals with the application of transmission line theory, and its implications regarding the integrity of PWM signals from the point of view of a Magnetic Bearing System.

1.1 Basic Transmission Line Theory

A simple transmission line can be modelled with two conductors in parallel separated by an insulating medium. Whenever a voltage is applied across the conductors, current will flow in the line to create a voltage wave that travels along the line. The ratio of voltage to current V_0/I_0, depends on the physical characteristics of the conductors

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and is called the *characteristic impedance* Z_0 of the line [1]. Figure 1 below shows an equivalent circuit of a pair of parallel conductors with infinite length.

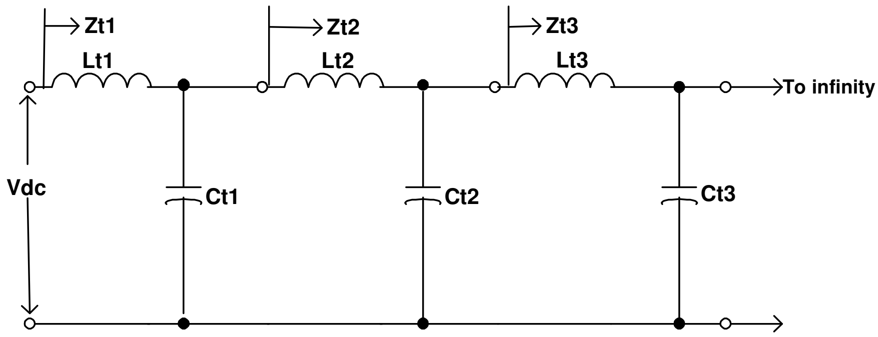

Figure 1: Equivalent circuit of parallel conductors with infinite length

A network of resistances, inductances, and capacitances constitute the characteristic impedance. These parameters are distributed along the length of the line. At high frequencies, the electric field of the line capacitance and the magnetic field of the line's inductance get rapidly charged and discharged. A voltage signal applied at one end of the line travels to the other end of the line depending upon its propagation delay.

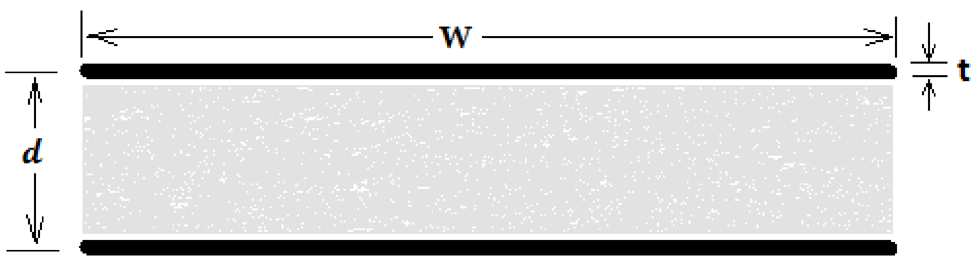

Figure 2: Cross section of a transmission line

Figure 2 shows cross section of a transmission line formed of two conductors of thickness t.

The inductance per unit length of the line is given by

$$L_0 = \mu \frac{d}{w}$$

μ is the total permeability = $4\pi \times 10^{-7}\mu_r$

μ_r is the relative permeability

d is the separation distance between the centres of the two conductors.

w is the length of the conductor.

Similarly the capacitance per unit length is given by

$$C_0 = \varepsilon \frac{w}{d}$$

ε is the total permittivity = $8.854 \times 10^{-12} \varepsilon_r$

ε_r is the relative permittivity

Propagation delay in transmission lines can be defined as the length of time it takes for the signal to propagate from one point to another through a conductor. If inductance and capacitance per unit length are known, the propagation delay and propagation velocity of the signal can be determined:

The propagation velocity of a signal on a transmission line is given by

$$v_p = \frac{1}{\sqrt{L_0 \times C_0}} = \frac{1}{\sqrt{\mu \varepsilon}}$$

While the propagation delay is

$$T_{delay} = \sqrt{L_0 \times C_0}$$

Lo is the inductance per unit length of the line.

Co is the capacitance per unit length of the line.

Similarly, the characteristic impedance can be calculated using the equation

$$Z_0 = \sqrt{\frac{R_0 + j\omega L_0}{G_0 + j\omega C_0}}$$

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

$$Z_0 = \sqrt{\frac{L_0}{C_0}} = \frac{d}{w} \times \sqrt{\frac{\mu}{\varepsilon}}$$

The characteristic impedance depends on the cross sectional area as well as material characteristics. Zo can be set at any desired value by changing length and width of the conductor.

Characteristic impedance and propagation delay of a transmission line are of particular relevance in this discussion. The characteristic impedance of the line is set by the diameter and spacing of conductors. This typically decreases and the propagation delay of the line increases with larger cross section conductors, unless the insulation thickness is also increased. 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. A transmission line that 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 [1]. It will also result in high currents at the switching edges and very high voltages at the load (i.e. at the magnetic bearing).

By making the load impedance equal to the characteristic impedance a constant ratio of voltage to current is maintained at a given frequency. It is important to maintain constant impedance at every point along the line to ensure good signal integrity or reflections may result.

1.2 Transmission line theory as applied to a magnetic bearing amplifier

Tests were carried out by making load impedance equal to the characteristic impedance on an example 200 metre cable reel suitable for use in power cabling between the amplifier and the bearing. The characteristic impedance was measured to be 43 Ω (where the tests measured the square root of the inductance per unit length divided by capacitance per unit length) [2]. A typical magnet coil will present an inductive reactance of between 1200 Ω and 1500 Ω which is effectively an open circuit. Terminating the reflections by making load impedance equal to the characteristic impedance of the cable would mean connecting a 43 Ω resistor in parallel with the magnetic bearing winding. However this would also incur a considerable power loss due to the relatively low value of resistance across the high operating voltage being supplied to the respective magnet bearing winding.

For an operating voltage of 600 V, the power loss $\frac{V^2}{R} = \frac{600^2}{43} = 8{,}372\ watts\ per\ magnet.$

The actual power loss across the 43 Ω resistor would be about 837 W since the power is being supplied in the form of a PWM signal and the full voltage will be applied for only a proportion of the time (typically about 10%). This power loss is still quite high [2].

Large heat dissipation may result due to resistive losses and will need to be dissipated at the load end. The power supply would need to supply the losses in addition to magnetic bearing power. Without a parallel resistor at the load end, a voltage signal will see an impedance much higher than the characteristic impedance of the cable and will nearly double in magnitude as it gets reflected back to the source end.

A 43 Ω resistor at the source end is also not a preferred option since it will be much larger than the impedance of the cable and will cause unwanted DC voltage drop in proportion to the magnet current. Typical magnet currents in excess of 20 A will cause significant I^2R losses and the cable resistance will need to be kept to a minimum. The resistance of a power cable of 35mm² cross sectional area lies in the range of 0.5 Ω to 0.6 Ω. Thus, the 43 Ω resistor would increase this total cable resistance by a large factor.

With a view to reduce power losses associated with the switching of the transmission-line-modelled magnet-power-cables and also feed the energy back into the DC link (i.e. power supply) of the magnet drive amplifier, a dynamic termination circuit has been developed. This circuit limits the voltage at the load without compromising the dynamic performance of the bearing driver amplifier.

2 Test Results

Initial tests were conducted at 300 V to observe the effect of reflections on voltage and current waveforms. A 500 m drum of 16 mm² 4-core screened cable was used for the test. To reduce the common mode inductance of many turns on a large drum, the cable was un-reeled folded in half and then re-reeled with bifilar winding. This reduced the common mode inductance to something more comparable with a linear cable run. Plots of voltage and current at the load end are as shown in Figure 3.

The voltage waveform can be seen to look like a decaying ring. The peak-to-peak value was measured to be 600 V. The frequency of the largest peak is seen to occur at 250 kHz. Successive peaks can be seen at start of each PWM cycle. This is true for both positive and negative excursions of voltage waveform. The effect is distorted voltage signal edges. The phenomenon can be also summarised as follows:

Whenever

$R_{Load} > Z_0$, there is a positive reflection. This will occur at the load end of the cable.

$R_{Load} < Z_0$, there is a negative reflection. This will occur at the source end of the cable.

At $R_L = \infty$ the largest positive reflection is obtained as seen in the first peak of the positive excursion.

At $R_L = 0$ the largest negative reflection is obtained as seen in the first peak of negative excursion.

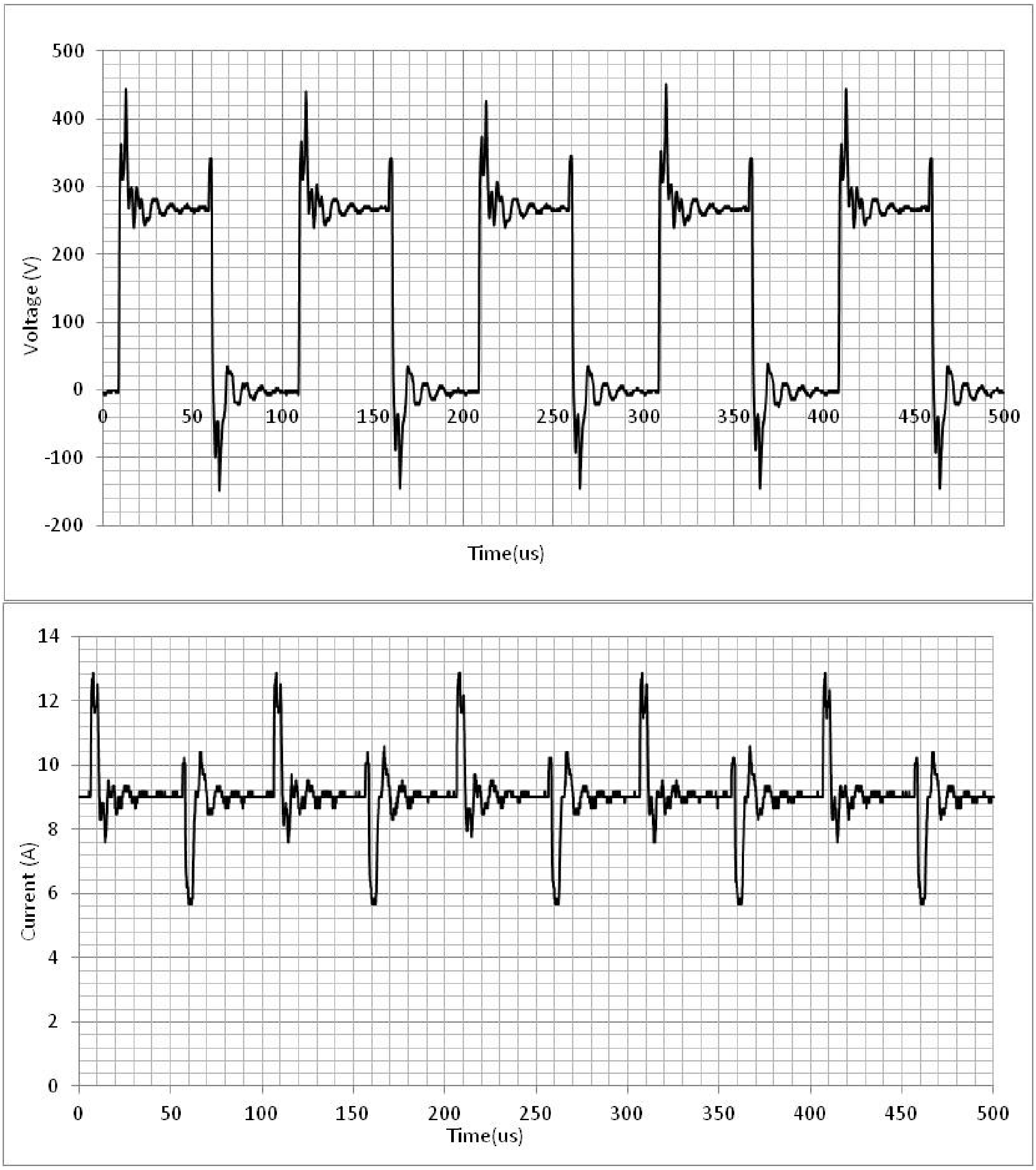

Figure 3: Plots of voltage and current at the load end of a 500 m cable without termination

The voltage reflection coefficient is given by

$$C_{vref} = \frac{R_{load} - Z_0}{R_{load} + Z_0} = 0.977$$

The current waveform looks triangular with quickly damping oscillations.

The current reflection coefficient C_{iref} is the ratio of the reflected to incident wave and is given by

$$C_{iref} = \frac{Z_0 - R_{load}}{Z_0 + R_{load}} = -0.977$$

Thus C_{vref} = - C_{iref}. A positive voltage reflection due to large load impedance is associated with a negative current reflection and vice versa.

Plots of signal rise and fall times are shown in Figure 4.

Looking further at voltage waveform, it can be said that the leading edge of the waveform travels to the load end in time T while the trailing edge has reached a distance equal to T – 50 µs. At time T + 50 µs, the entire signal has reached load end and gets reflected since it is not terminated in the load. The resulting line voltage is then the superposition of the incident wave and reflected wave. It may also be described as combination of two separate waves, i.e. negative wave (leading part of the signal) and positive going wave, which has not yet reflected. Similar considerations apply to current signal.

In summary, the transient behaviour of the transmission line delays arrival of voltage signal until time $t = T_D$.

V_{load} at $0 \leq t \leq T_D$ is at quiescent voltage (0 in this case)

Voltage signal will get reflected at the end of the cable.

$V_{load} = V_{incident} + V_{reflected}$ at $t = T_D$.

The transient behaviour of the cable delays the arrival of the reflected voltage from the load until $t = 2T_D$.

V_{source} at $0 \leq t \leq 2T_D$ is at source voltage.

$V_{source} = V_{incident} + V_{reflected}$ at time $t = 2T_D$.

In steady state the solution converges to

$V_{load} = V_{source} [R_{load}/(R_{load}+R_{source})]$

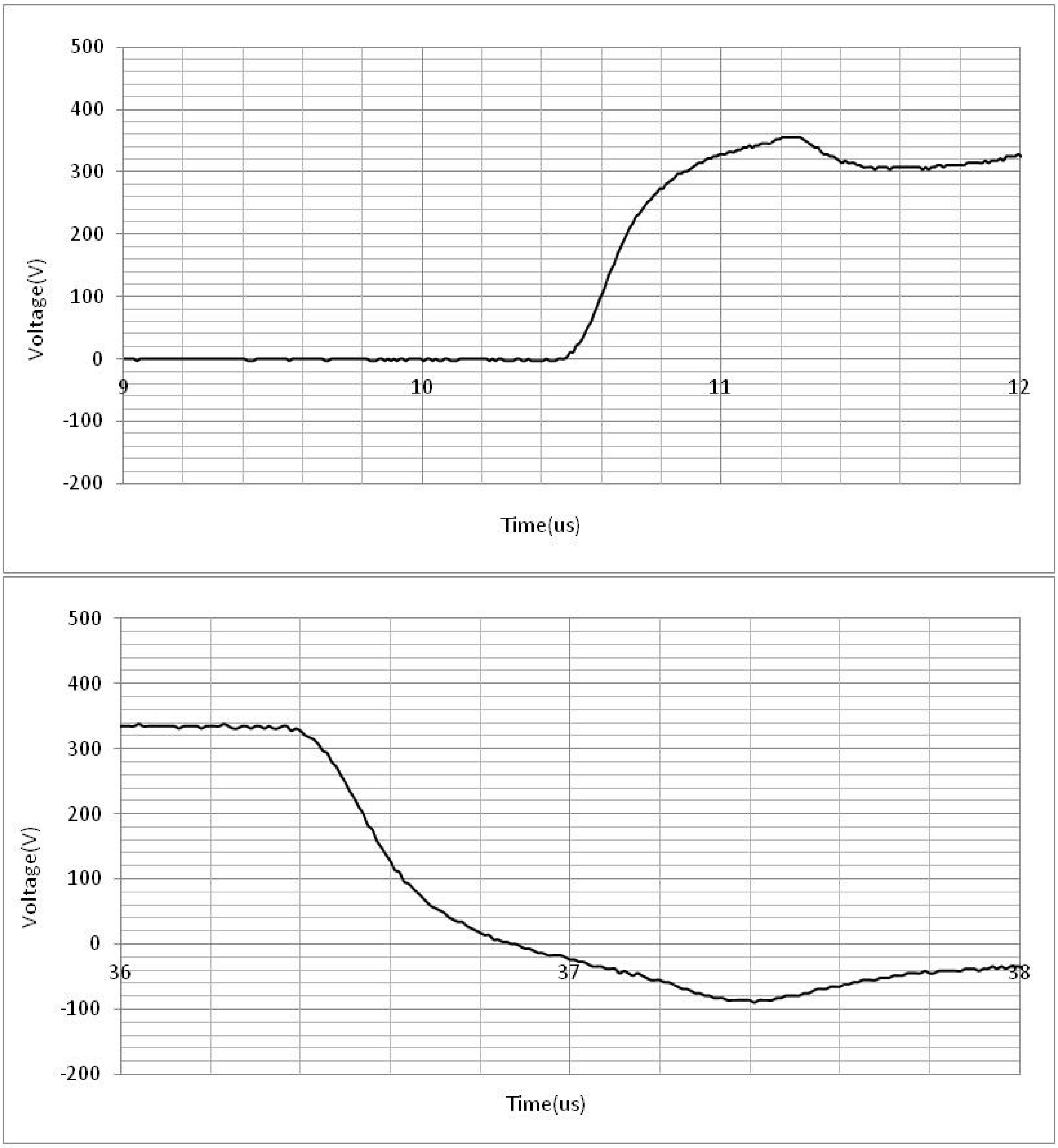

Figure 4: Plots of Voltage signal rise and fall times

(Rise and fall times were measured to be 750ns and 450ns respectively)

3 Dynamic Termination Circuit

Figure 5 shows the schematic diagram of the dynamic termination circuit.

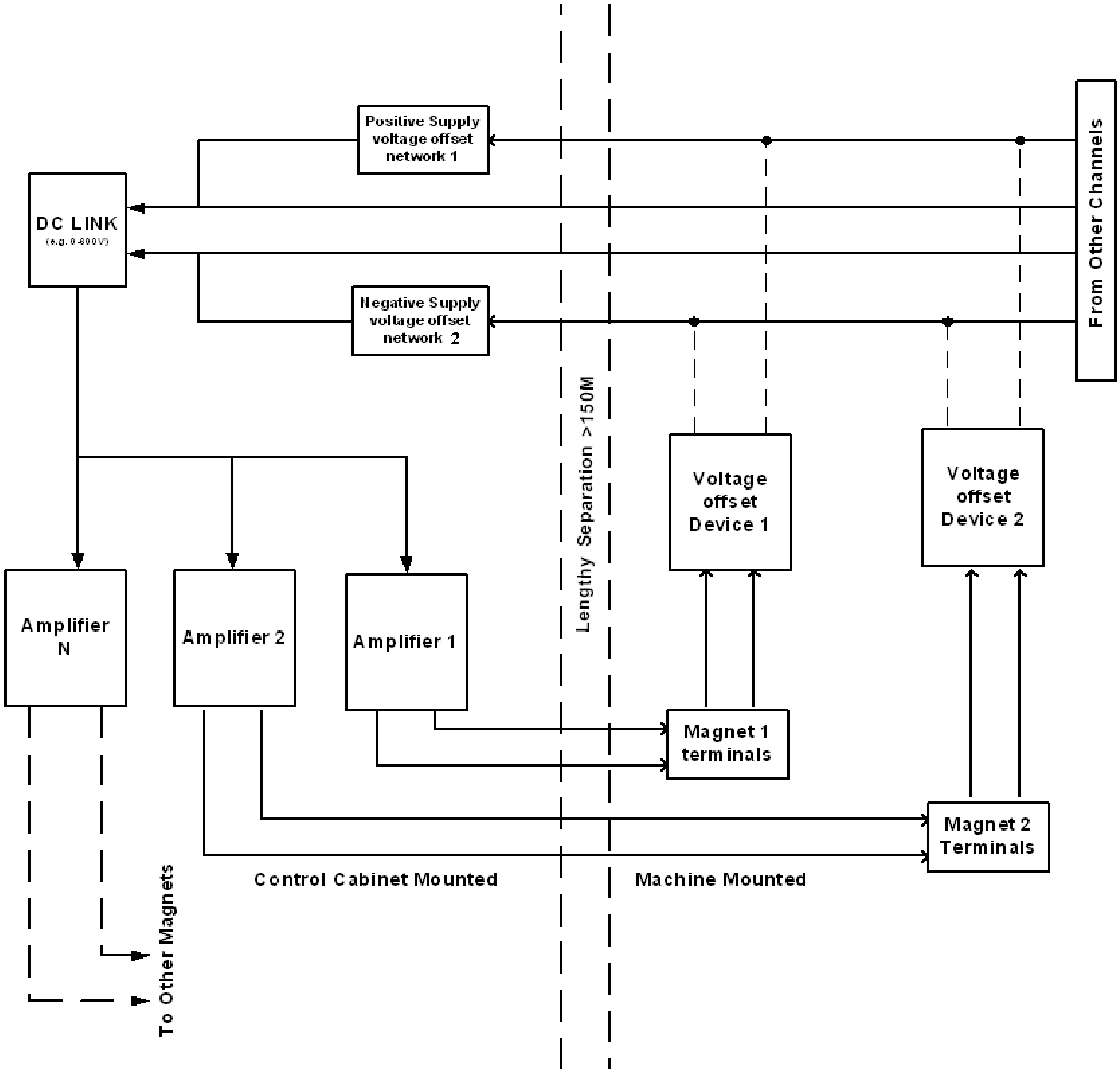

Figure 5: Schematic diagram of the dynamic termination circuit

For each magnet, a network of voltage offset devices, i.e. diodes, is used. These are placed near the bearing and each one connects to a pair of catcher rails that are at voltages slightly beyond the DC link voltage rails. Each voltage-offset device further comprises a network of decoupling capacitors connected between earth and each offset catcher voltage rail. To regulate the voltage at which the diodes conduct, resistors are connected in series between the respective DC link voltage rail and offset catcher voltage rail. Different network topologies consisting of active or passive components can be used to connect the voltage offset devices to the DC link. A typical circuit diagram is shown in Figure 6.

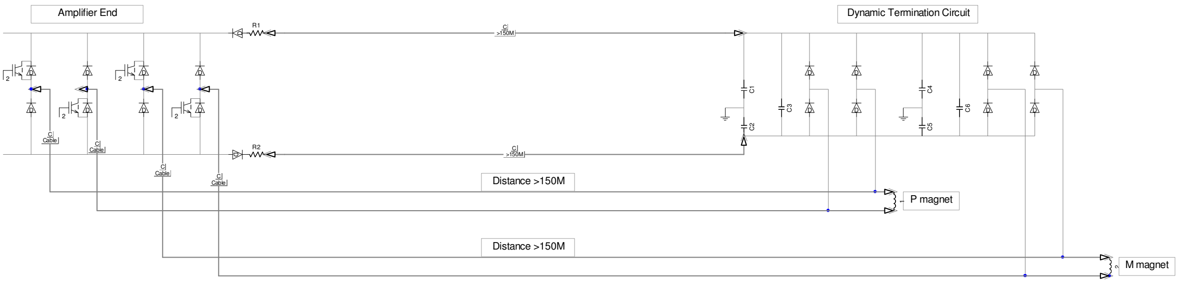

Figure 6: Typical circuit diagram

The networks that offset the catcher rails from the DC link rails may be positioned either at the amplifier end of the overall magnetic bearing system or at the bearing end. Secondary clamping diode networks may be used directly between the DC link voltage rails and the magnet terminals.

A variation of the afore-mentioned magnetic drive bearing circuit may also be used for machine drive applications, typically with three poles per connected device rather than two.

Further rectifier diodes are connected at the amplifier end in series with the resistors in offset catcher voltage rails. These are a safety measure to ensure current only flows back to the DC link.

4 Test Results with Dynamic Termination Circuit

Tests were conducted at 300 V for a load current of 8 A. The plots of voltage and current are shown in Figure 7. It can be seen that the voltage waveform looks rectangular and the oscillations seen previously have reduced significantly. The peak-to-peak value was measured to be 355 V.

The operation of the dynamic termination circuit can be explained as follows:

At the bearing end, the leading edge of the waveform travels to the load end in time T while the trailing edge has reached a distance equal to T-50us. At time T+50us, the entire signal has reached the load end. The first reflection gets diverted through the voltage offset device connected to the positive rail. Any oscillation that has not diverted gets reflected. However, since the first oscillation has the largest peak, it gets diverted along with successive oscillations which have much lower peaks. The resulting line voltage is then the superposition of the incident wave and the reflected wave. Since most of the reflection gets diverted through the dynamic termination circuit, the resulting line voltage is the actual PWM signal with very few oscillations.

For Vsignal > 300 V, voltage offset device connected to +DC voltage rail conducts.

For Vsignal < 0 V, voltage offset device connected to -DC voltage rail conducts.

As described earlier, a positive voltage reflection causes a negative current reflection and vice versa.

The current signal profile at the input to the cable is seen to have significant glitches after each voltage transition, becoming flat during the latter part of the time up to the next voltage transition. This is the case for both on and off portions. The glitches are discussed further in Appendix A. At the load end of the cable, the current flowing into the magnet coil can be seen to be unaffected by the glitches.

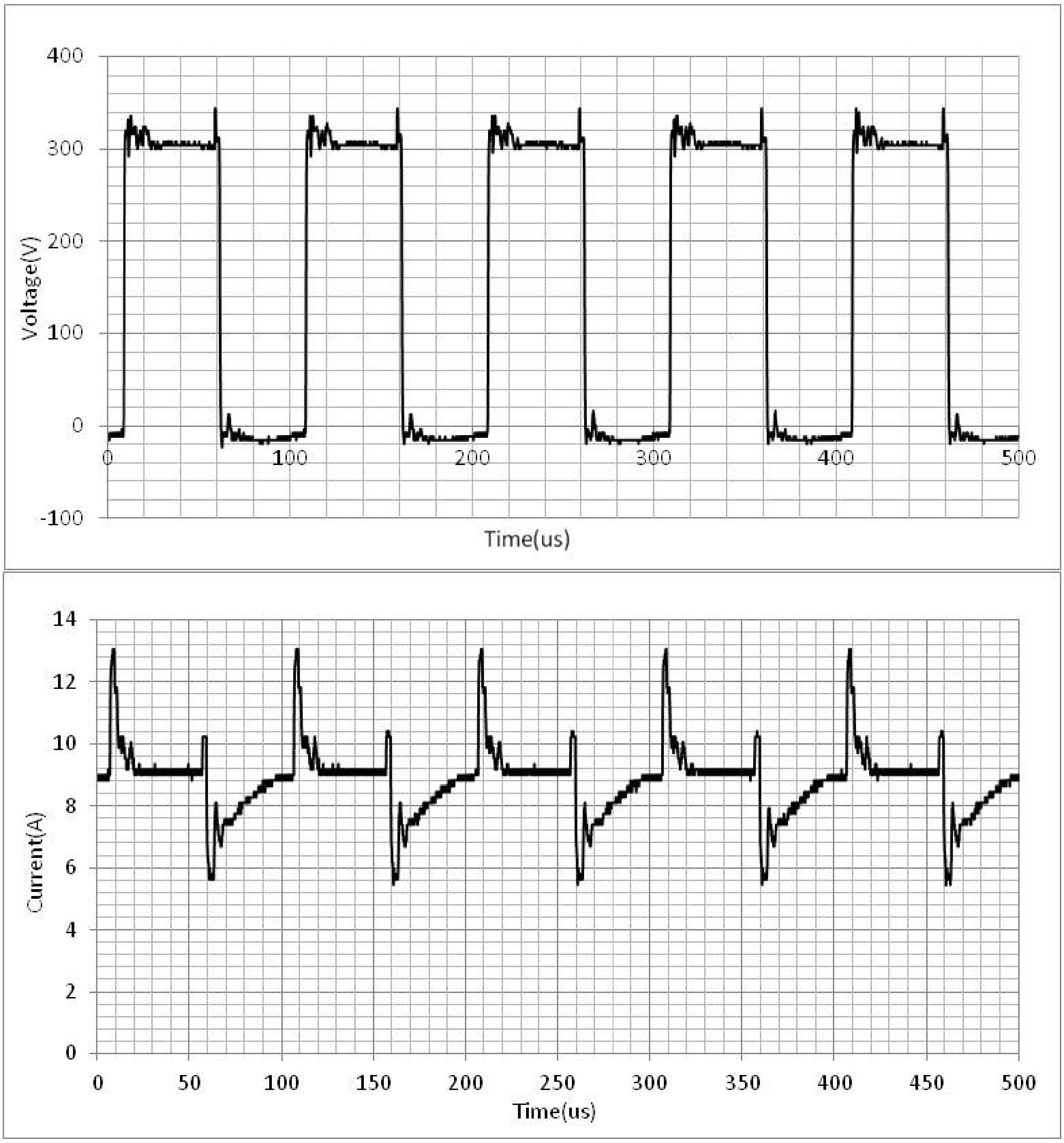

Figure 7: Plots of load voltage and drive current for a 300 V system with a bias current 8 A.

Further tests were further conducted at 600 V, 15 A and plots of voltage and current are as shown in Figure 8.

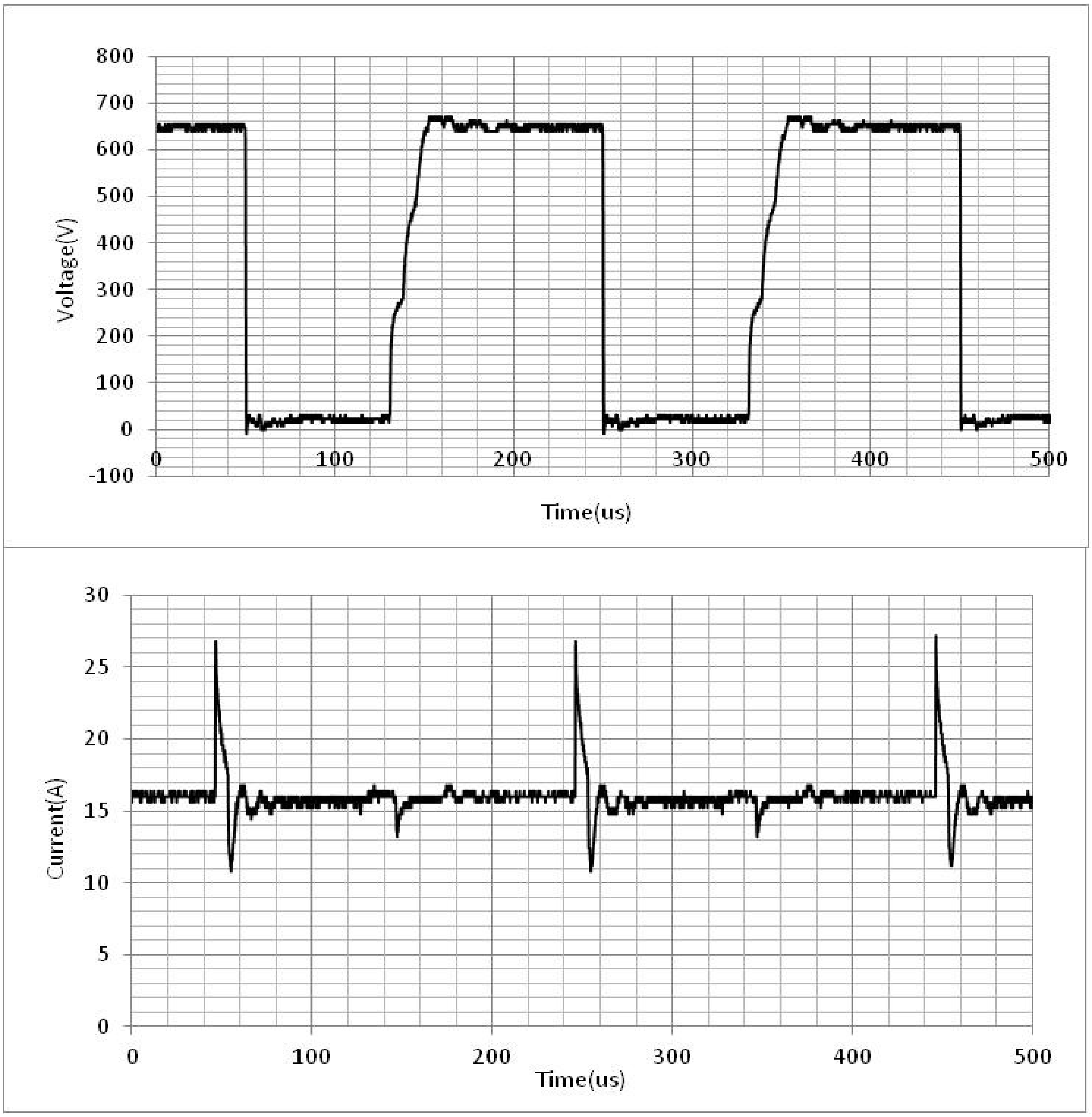

Figure 8: Plots of load voltage and load current for a 600V system with a bias current of 15 A

The plot of voltage signal rise and fall times with dynamic termination on a 300 V system is shown in Figure 9.

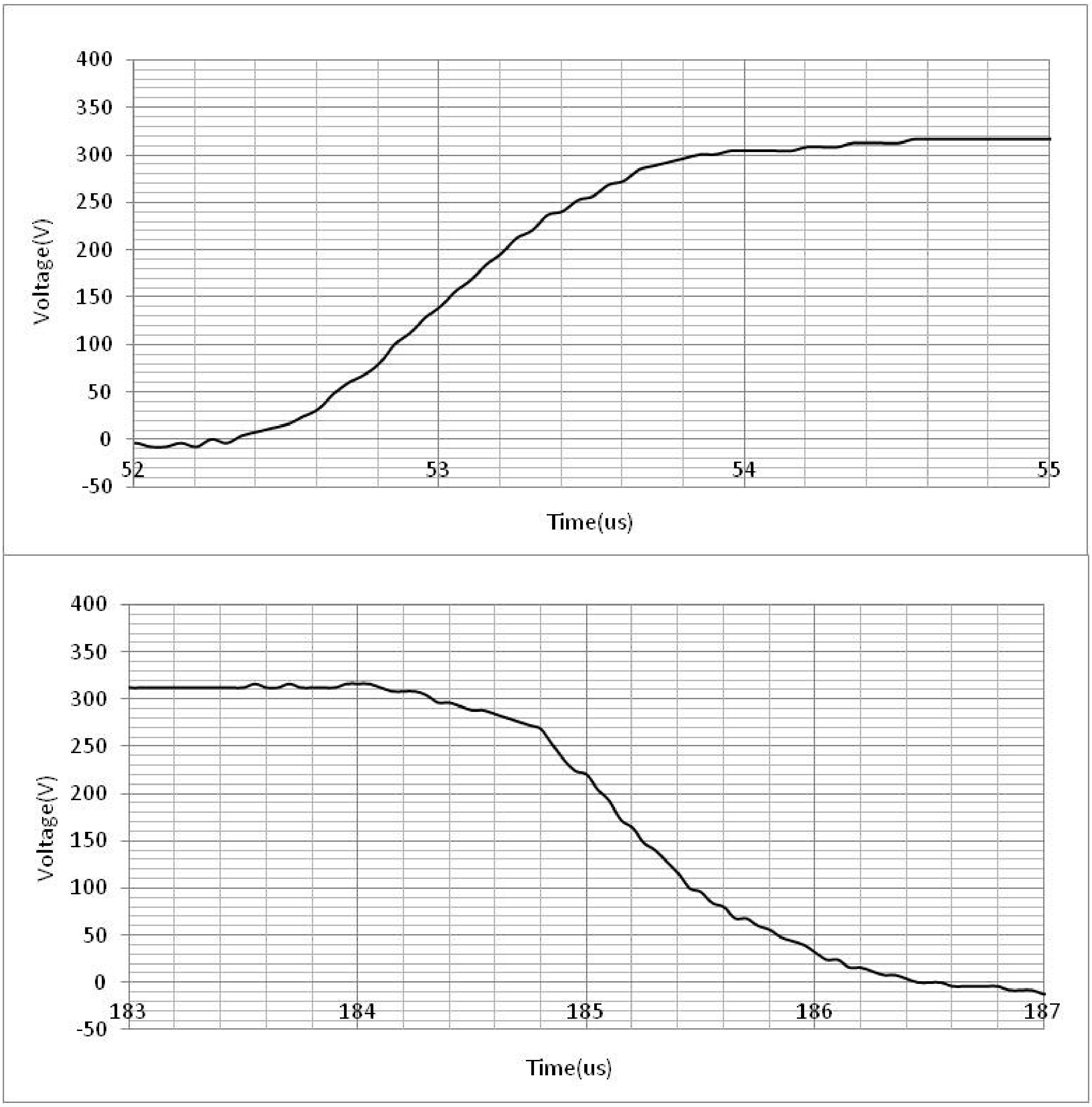

Figure 9: Voltage rise and fall times with dynamic termination on a 300 V system

With use of a dynamic termination circuit, the overshoot is seen to reduce to approximately 80 V. The majority of the energy recovered from the reflections is routed back to the DC bus with just a small proportion absorbed in positive and negative voltage offset networks connected in the return power lines. The power dissipated in the voltage-offset resistors allows them to be mounted on small heat sinks. It should be noted that the RC time constant should be smaller than the frequency of first overshoot or reflections may find their way back to the load [3]. Unlike resistor termination networks, the power dissipated in the circuit is significantly smaller. Furthermore EMC and cross talk effects also get reduced. A further advantage of the dynamic termination circuit is that it gives plant designers maximum flexibility since no chokes or high power damping resistors are required.

A comparison of power dissipation in the circuit for different load currents is shown in the Table1 below.

Bus Voltage (V)	Load current (A)	Dynamic termination Circuit current (A)	Power dissipation in the circuit (W)
600	5	2.06	101.8
600	10	2.24	120.42
600	15	2.7	174.96
600	20	3.0	216
600	25	3.28	258.20
600	30	3.58	307.59
600	35	3.94	372.56
600	40	4.30	443.76

Table 1: Variation of power dissipation with load current

The power dissipation is seen to be significantly lower than using parallel termination impedance which can dissipate power up to 8372 W as seen earlier. The signal rise and fall times are seen to increase due to loading. From the point of view of reducing transmission line effects, smaller rise and fall times are recommended. No active devices are required and no special assembly techniques or control circuits. Moreover no special cooling methods are required and natural air convection cooling is sufficient.

6 Conclusions

Various termination methods are available for mitigating transmission line effects present in extended magnet cables. Due to the high power losses, conventional methods of using series and parallel connected impedances are not suitable, especially for systems with high amplifier reactive power [4].

The dynamic termination circuit presented here provides much better performance in terms of PWM signal quality, current waveforms and power dissipation over conventional methods.

Test results show the circuit gives good performance at cable lengths of 500m and the circuit offers the potential to realise separations of up to 1km.

References

[1] Motorola Semiconductor Products INC. Transmission Line Effects in PCB Applications AN1051/D.

[2] Dr Derek Wright. Magnetic Bearing Drive Circuit. UK Patent No GB2486664, Waukesha Bearings Ltd, July 2012.

[3] B. Bolsens, K. De Brabandere, J. Van den Keybus, J. Driesen and R. Belmans. Transmission line effects on motor feed cables-terminator design and analysis in the Laplace-domain. Catholic University of Leuven, Belgium. IEEE: Electric Machines and Drives Conference, 2003.

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A Appendix A

Dealing with a disrupted current waveform

Ideally the current waveform should be a smooth DC level, as is the case for the current flowing from the far end of the cable into the magnet coil (see the lowest waveform in Figure 7). In practice, the current at the sending end of the cable contains a significant glitch following each voltage transition. These glitches are present on even relatively short cables. They used to be thought of as the currents needed to charge and discharge the capacitance between the cable core and the adjacent cores and screen. For a long cable the charging glitch becomes a rectangular pulse of amplitude equal to the input voltage divided by the characteristic impedance of the cable, typically 600 V / 30 Ω = 20 A, and duration equal to twice the delay of the cable. When the dynamic termination is applied this pulse can become dispersed. A hard termination using a diode connected directly between the magnet cable core and the catcher rail gives a less dispersed pulse at the expense of a higher DC return current. If a resistor is placed in series with the diode to give a softer termination, then the pulse dispersion and the return current are less but there is a significant un-recovered power loss in the resistor.

The existence of the current pulse or glitch is a significant impediment to accurate sampling of the current. For some PWM pulse widths the current sampling instant will be clear of the glitch whilst for others it can land on the pulse peak, giving a variation in sampled value of up to the peak amplitude of the glitch. The result is that an extremely high noise level can 'erupt' as the magnet coil current passes through certain values.

There are two ways to avoid the noise problem that can be caused by sampling around the glitch. One is to sample the current at the receiving end of the cable, adjacent to the magnet coil, where the glitch is not present. The other is to use flux feedback so that the bandwidth taken from the current feedback path is limited to a value well below the PWM carrier frequency. Where load-end current sampling is used or where there is a flux feedback sensor winding, the analogue current value, or a pseudo-current value derived from the flux coil, can be returned to the control loop either digitally or by means of a 4-20 mA analogue current loop interface.