International Rectifier

APPLICATION NOTE

Application Note AN- 1095

Design of the Inverter Output Filter for Motor Drives with IRAMS Power Modules

Cesare Bocchiola

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This Application Note give guidelines to design the dV/dt filter to be placed between the inverter and the motor in three-phase motor drives equipped with IRAMS power modules, with the purpose of matching the superior switching performances of these IR modules with the dV/dt limitations of state of the art electrical machines.

Introduction

Design of motor drives has recently been greatly simplified with the introduction of IR iMotion dedicated appliance power modules (the IRAMS family).
Most of the resources and time usually spent by drive system designers to develop the printed circuit board layout for the power section and to find the right IGBT gate drive network can now be dedicated to more know-how related activities, such development of suitable algorithms aimed to achieve the required dynamic characteristics of the drive system itself.
On the other side, even if the development of IRAMS family has been carried out with in mind the optimization of the trade off between the inverter's efficiency and EMI issues, there may be cases where the high commutation speeds of the inverter stage integrated in the IRAMS power modules call for additional EMI filtering techniques.
In particular, motor's manufactures still design motors under line frequency drive specifications, while application of high frequencies is known to generate some reliability issue in the motor itself, especially deterioration of bearings due to high common mode currents, as well as deterioration of winding insulation due to high differential mode voltages and dV/dt.
Some motor manufacturers have recently publicized dV/dt ratings for their products, usually around 5V/nsec.
Since state of the art IGBT commutation time can be far above these ratings (up to 10V/nsec or even more), a suitable mean to reduce dV/dt at the motor terminal may be required. Such mean is often a simple LC filter.
Advantages/disadvantages of such filters are discussed, and guidelines for its – approximate - design are given.
The following analysis is limited to the case short wires (less then 100 feet) are placed between the motor and the inverter. For wire length near and above this limit, different phenomena can take place – like generation of standing waves due to impedance mismatch between motor's and wire distributed impedance. Such standing waves can generate strong voltage and current oscillations, which cannot be simply filtered by a LC circuit. A complete analysis of such phenomena is outside the scope of this note but it is worth noting that, sometime, by simply placing the input filter near the motor's terminal instead of placing it on the inverter's board can reduce the effect of reflected currents.

Output Filter Design Guidelines

A general schematic of one inverter's leg driving one of the motor's phases is shown in Fig.1; a LC output filter has been added between the IGBT leg and the motor phase.
The motor's phase is simply represented as a big inductor (L2 in Fig. 1 – practically a constant current generator), placed between the motor's phase terminal and the motor neutral, while L1 and C1 / R2 realize the output filter.
V1 represent the DC link voltage. C8 and C9 are the collector-emitter capacitances of the IGBTs, which also play an important role during commutation.
Apparently, the design of the filter is very easy: by assuming ipk is the peak motor current, it is sufficient to choose C1 so that

C1 >= ipk/(dV/dt)max [1]

C1 takes care to smooth the transients generated by IGBT switching so that max dV/dt at motor's terminal is kept within the limits required by the motor's manufacturer or within the drive system EMI design specifications.
This is true, for sure, if the modulation scheme is such that the potential of the motor's neutral is not affected by high frequency transients; low frequency swing of the motor's neutral – usually at third harmonic of the fundamental modulation frequency - do not impair the following analysis, which only takes care of high frequency phenomena.

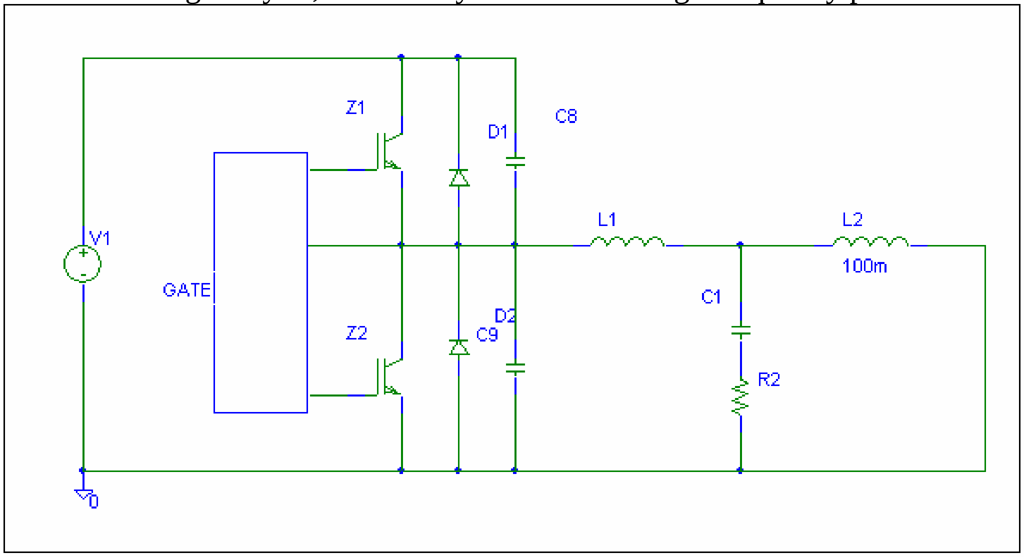


Fig.1

C1 cannot be used by alone. In fact, without a component able to limit current, very high current peaks would flow in the inverter leg's IGBTs due to C1.
Such high current peaks, aside from stressing the IGBTs, would trigger current protection circuitry, very often realized with shunt resistors in series with the low side IGBT emitters and, also, would impair current reading schemes (needed for control purposes), which often use the same shunt resistors.
Thus, an inductor L1 is needed between the inverter's leg central point and filter capacitor. Size of L1 will be such that current peaks in the IGBTs cannot trigger O/C threshold, at least.
Finally, a simple LC circuit, driven by very high dV/dt, would generate oscillations with a resultant C1 voltage much higher than the DC link, which is not exactly what the motor (and the filter components) have been designed for. Thus, a damping resistor is needed somewhere.
To avoid un-useful power dissipation, placing the damping resistor in series with C1 may be the only choice.
With the addition of L1, the condition expressed by Eq [1] is not more correct. In fact, due to the resonance between L1 and C1, the actual dV/dt will be determined by L1 too.
A more exact determination for the initial dV/dt is given by:

$$\frac{dV}{dt} = \frac{Vdc}{\sqrt{L1 * C1}} \qquad [2]$$

L1 will now be designed by taking into account that, at commutation, each IGBT sees:

a) motor's phase current
b) recovery current of the opposite free-wheeling diode
c) filter's peak current

There could also be a fourth component (some cross conduction) but this is usually avoided by the proper gate driver network design inside the IRAMS modules as well as a proper choice of externally applied dead time (see other IRAMS application notes).
The reason to consider also point b) is that, due to the high speed of IRAMS family, commutation di/dt is quite high, and, even if ultra-fast, free-wheeling diodes are integrated in the modules, at maximum junction temperature and maximum motor's phase current recovery current peaks may be not negligible.
Actual current peaks may be easily measured when using the IRAMSxxUP60A modules, by simply placing a current probe on the low side IGBT emitter(s), which are externally available.
After having taken into account recovery peaks, and having decided the O/C threshold to be used, the maximum allowed peak current contribution of the output filter may be determined. Let be Di such value.
Without R2, peak current due to the filter would be:

Di = Vdc / Zc [3]

Where Zc = squareroot (L1/C1) – characteristic impedance of the L1/C1 circuit
But, since LC circuit damping cannot be zero (severe oscillations would otherwise occur at the motor's terminals, as already explained) we also have to consider the effect of R2.
Critical damping is roughly achieved with a R2 value = Zc. Actually, lower value can also be chosen because of the effect of C8 and C9.
In case R2 = Zc, current peak in the IGBTs due to output filter will be given by :

Di = Vdc / (2*Zc) [4]

Current limitation is not the only constraints for L1: in fact, when L1 and C1 resonate, the time corresponding to half of the resonance cycle should be lower than the minimum duty cycle applied to the motor's phases, otherwise, at very low duty cycles, no enough build-up of motor's voltage at the leg's central would be possible.
Neglecting the damping, and taking some margin for that, this imposes that:

$$\pi * \sqrt{L1 * C1} \leq Ton, \min \qquad [5]$$

Then, when combining together Eq [2] with Eq [5], a maximum dV/dt results, which is related to Vdc and to the choice of Ton,min :

$$dV/dt = \frac{Vdc * \pi}{Ton,\min}$$ [6]

This is an obvious result: achieving very small Ton means the need to commutate the leg's central very quickly!
We can now summarize the above arguments in a design procedure:

a) tentatively select C1 such that C1 = ipk/(dV/dt)max
b) check is Ton,min from Eq. [6] is compatible with the application constraints; if not, higher dV/dt has to be accepted.
c) Choose L1 such that
$$\pi * \sqrt{L1 * C1} \leq Ton,\min$$
d) Choose R2 = Zc or slightly higher (R2 = n*Zc with 1<n <2)
e) Set O/C protection such that O/Cth > Iphase,peak + Irecovery + Vdc/((n+1)*Zc)

Finally, some power dissipation is expected into R2. which cannot be neglected.
It may be shown that, in case R2 = Zc, the dissipated power is:

Pdiss = (Vdc^2)/(4*R2) * Ton,min * Fsw. [7]

Output Filter Design Example

Let's be Ipk,max = 5A and Vdc = 300V.
Parasitic capacitors C8 and C9 be such that dV/dt (without filter) is 10V/nsec.
This is too much for the motor, we need a dV/dt lower than 5V/nsec.
By Eq. [1]. choose C1 = 1nF (5A / 5V/nsec)
According to Eq. [6], Ton,min can be as low as 200nsec ; at 20kHz, this represents 0.4% of duty cycle which is far below the practical limits used.
From Eq.[5], it follows L2 = 4uH.
Zc results to be 63 Ohm, hence R2 >= 63 Ohm.
Let now suppose Irecovery = 5A. Di is, according to Eq [4], will be <= 2.4A.
Therefore, O/C protection will be set above 12.5Apk.
Rms current into R2 is 0.175A, which gives a power dissipation of about 2W.
Actually, by choosing R2 exactly equal to Zc generates some overshoot; for that reason R2 should be slightly higher. A R2 value between Zc and 2 x Zc is suggested.
Figure 2 and 3 show the voltage across the inverter's leg (before the filter) and across the motor (after the filter) for a R2 value = Zc and 2x Zc.
Even if the overshoot is well within the limits of motor's insulations and capacitor's voltage ratings, increasing R2 gives benefits without increasing much power dissipation.
But, do not increase R2 too much otherwise dV/dt will not be anymore limited by C1!

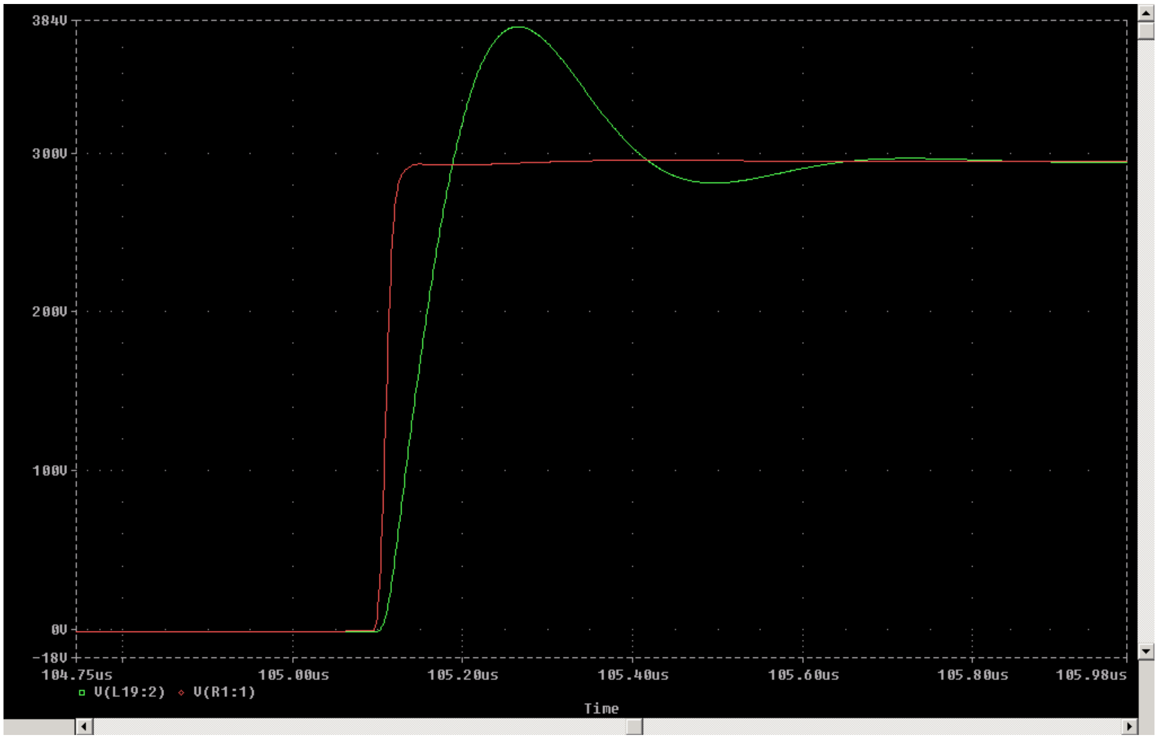


Fig 2 : R2 = Zc

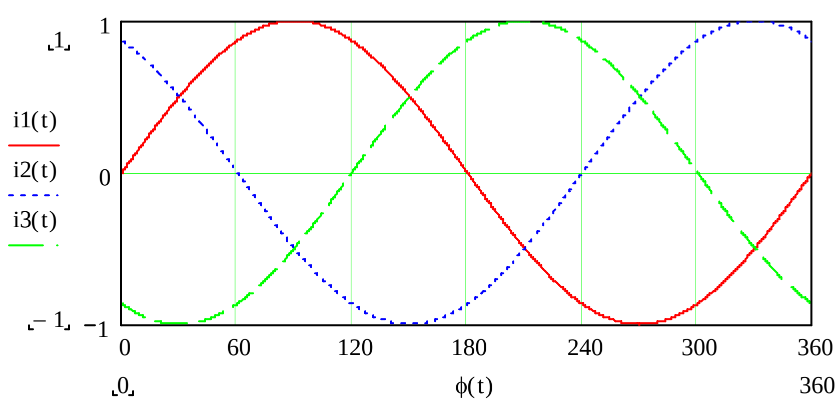
Fig. 3 : R2 = 2 x Zc

Filter Coupling in multiphase inverters

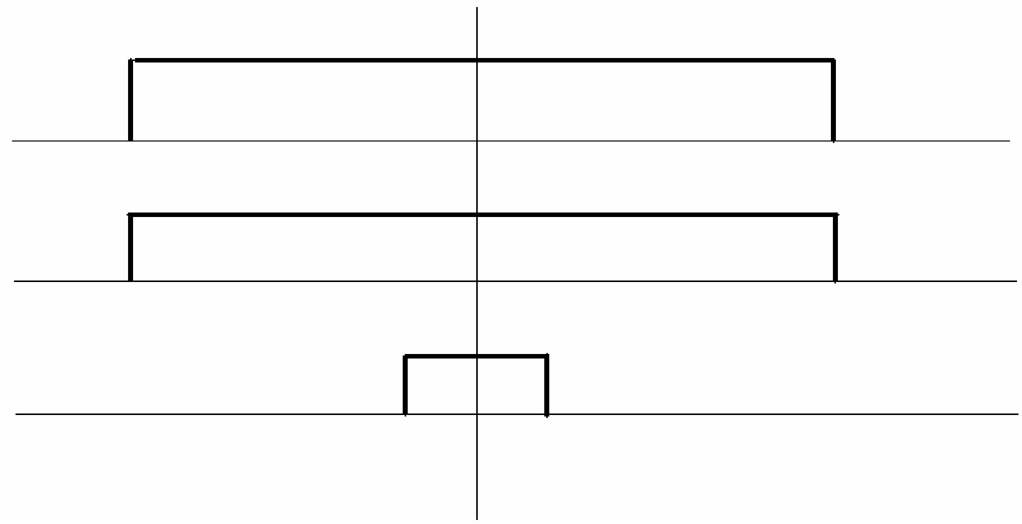
The present analysis has just covered the design of a single leg, but, of course, the design for the other legs in a multi-phase inverter follows the same procedure.
When considering all the motor's phases, coupling of the inductors around the same magnetic core is sometime used, for space and cost reasons.
From a magnetic core design point of view, it is a good choice indeed, at least for a three-phase system where, in case of isolated neutral, sum of the three currents is zero all the time. So, the magnetic core may be designed to only withstand transient currents due to commutation, no DC current.
On the other side, when looking at the dynamic behavior of the coupled system, three main questions arise:

a) how the commutation on one phase reflects on the other phases ?
b) is there any summing or canceling effect when commutations occur at the same time instants ?
c) do the filter cell design guidelines above presented change to achieve the same dV/dt on the motor and the same current peaks in the inverter ?

To answer the first question, it may be easily found that coupling introduces commutation spikes generated by the phase which is commutating, on the phases which are not .
Then, what it happen when two phases are commutating at the same instant ?
To discuss that, let's consider the three normalized average voltages at the center of the three legs, which are sinusoidal, 120° phase shifted between each other; and the inverter's duty cycles when two of the voltages are equal to each other, in magnitude and sign.



This occurs at 30° and then every 60°.
At 30°, for example, duty cycles – hence commutation instants – may be as follows:



Therefore, two legs are commutating at the same precise instant.
The currents are not usually equal at these instants, because of the phase shift between voltages and currents (motor's PF is rarely = 1).
On the other side, when two currents become equal to each other, the duty cycles will be different, so commutation instants do not superimpose.
In any case, in a system with isolated neutral the sum of the three currents is always zero and, having one current opposite sign with respect to the other two's, the sum of the two currents with equal sign is – at the maximum – equal to the maximum peak current in each phase.
For these reasons, there is not any time instant where the coupling between the inductors gives conditions worse than a single inductor commutating the whole peak current.
This is also true when space vector modulation is applied: even if the phase voltages are not sinusoidal, the phase currents are.
This partially answer also question b). To completely answer question b) cancellation effects of the filter's current peaks, due to the coupling, need to be investigated.
But, it may be also easily seen that no cancellation effects may occur. One reason is that, when two currents have the same sign, the third one has an opposite sign. The commutation instant is slightly different depending on the sign of the current, and this is due to the dead time.
When the leg is sourcing current, commutation instants are determined by the high side IGBT; on the other side, when the inverter leg is sinking, commutation instants are due to low side IGBT. Thus, two currents of opposite signs will also have commutations shifted by the dead time.
Finally, to answer question c) let's consider that, in case of coupled inductors, filter capacitors Cf are reflected by transformer action, which yield, in turn, roughly half dV/dt than expected by single inductor per leg design.
The conclusion is therefore that, even in case of coils wound on the same magnetic core, design of Lf and Cf can follow the same guidelines as for three separate inductors; the net result will be better than expected.

CONCLUSIONS

Even if the development of IRAMS family has been carried out with in mind the optimization of the trade off between the inverter's efficiency and EMI issues, there may be cases where the high commutation speeds of the inverter stage integrated in the IRAMS power modules call for additional EMI filtering techniques.
A simple damped LC filter between the inverter leg and the motor phases has been described, and design guidelines have been proposed.