Active EMI Noise Cancellation

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***Abstract*—Active EMI noise cancellation can be an effective way to reduce the cost for filtering, volume and weight with motion control systems. The amount of EMI noise power generated is typically less than 10% of the nominal motion power. Direct (analog) feedback systems are limited by latency and therefore limited in cancellation bandwidth. Motion control systems have three main frequency components for disturbances: the power mains frequency, the pulse width modulated frequency (PWM) i.e. sampling frequency and the motion frequency, all with their inter-related harmonics. Digital signal processing compensation techniques offer alternatives but have restrictions. In this paper, these noise compensation bounds will be explored, and some solutions will be given.**

Keywords—PWM, EMI noise cancellation, FFT, IFFT, phase synchronization, compensation by inversion

I. Introduction

Electrical noise cancellation with motion control can be done in the conventional way, by using passive reactive or dissipative filtering elements at either or both: the (mains) supply, DC or AC: single or 3-phase or/and at the load output(s). When longer cables are used with PWM motion drives, reactors at the outputs are indispensable to reduce the capacitive cable and actuator load towards the output stages to protect these from over-currents. Often also phase-to-phase or phase-to-line related sine(-wave) filters are used to eliminate i.e. reduce the eddy current losses in the motor or actuator, because of the higher harmonics generated by the PWM drives. These switching harmonics then result in power losses in the sine(-wave) filter, where efficiency losses may be as high as 20% (otherwise turned into heat in the motor by eddy-currents). Filtering the phase lines only, leaves the option of the insulation breakdown detection which is often done with motion drives and other power converters. Breakdown detection blocks the possible use of Y-capacitors to PE (as these are responsible for causing earth leakage currents).

With mains operated PWM drives, the power electronics will typically be insulated from protective earth (PE) or even the neutral wire yielding a situation that either the switching noise appears at the load side when the supply side is filtered or most of the noise appears at the supply i.e. mains side when the output is filtered. In other words, there is a very strong interaction between the filtering applied at the output of the motion drives versus what is then needed complementary at the (mains) supply input. Here, the energy feedback motion drive systems (bi-directional) need to be included as well.

Strong RF emissions will be the result if the fast-switched signals from the PWM drive can reach the motor windings while being non- or poor shielded. The motor windings will have substantial capacitances to the motor housing and as motor houses are metal and typically mechanically/ electrically connected to a frame, ground currents will result which may upset sensor and encoders on these motion control systems.

As such, there are four interrelated requirements to make motion control systems:

1. inherent reliable: intra-system compatible system, including power quality (PQ), power integrity (PI) and signal integrity (SI)
2. formally compliant: inter-system compatible: EMC, safety (legally enforced)
3. as efficient as possible, minimum power losses, low noise
4. as economic as possible: minimum cost, weight and volume

II. Signal processing limitations

Starting with a normal (European) mains voltage, 230/400 Vac, 50 Hz, the peak-to-peak line-to-neutral voltage is 650 volts. When it would be sampled with an 8-bits ADC, the best-case resolution would be 650/256 = 2,54 volts/level, neither having any level margin above nor below. When sampling is done with 50 Ms/s = 20 ns/sample, and considering a max dV/dt of the mains voltage of ~51 kV/s, 78 ‘0 volt’ samples (500 volts full scale = 128 steps of ~3,9 volts) result at a single zero-crossing (without any noise being added). The number of samples within a window will be even worse when measured at the maximum or minimum of the voltages as the voltage derivative is ‘0’. The higher the sample rate, the more ‘zero-crossing’ moments will result with each ideal zero-crossing at low amplitude resolution.

However, when 50 Hz i.e. 20 ms is sampled with 20 ns interval, a resolution of 10^{-6} i.e. ppm’s should be achievable w.r.t the determination of the length of the period of the mains i.e. the mains frequency. The statistical mean or the median of the 78 zero-crossings can be used but this is not stable enough to determine the mains frequency and in particular the mains phase accurately.

Changing the sample rate higher will increase the bandwidth and will make a clear detection of the ‘zero-crossings’ worse. Changing the resolution will reduce the error w.r.t. the zero-crossings. But even with 16-bits amplitude resolution, the number of zero-crossings will be ~3 as a minimum at the sampling rate: 20 Ms/s given. 18 or 24 bits resolution is preferred to obtain a single crossing, but still only suited in an ideal case without any mains noise added.

As most mains related rectifiers turn on and off around the voltage zero-crossing, much noise is expected. In other words, don't look for the zero-crossings nor the minimum and maximum level occurrences to determine the mains frequency correctly.

Additionally, the record length taken determines the lowest frequency that can be detected and determines the frequency resolution after FFT in the frequency domain. All frequencies obtained will be multiple integers of the lowest frequency recorded i.e. inverse proportional to the record length taken. For a 1 second record length, the minimum frequency and the frequency resolution will be 1 Hz. When taking shorter records e.g. 200 ms, the minimum frequency will be 5 Hz. In the latter case, sampling at 50 Ms/s to obtain 25 MHz bandwidth max. (Nyquist), the number of samples will already be 10^7. Higher upper bandwidth or higher frequency resolution requires more record length i.e. deeper memory is required to be followed by more mathematical effort for the (D)FFT.

When the time signal is sampled at a fixed sample rate and a defined record length all frequencies obtained after FFT are assigned to their frequency 'bins' being equal in width to the lowest frequency. If the record length is 200 ms, the frequency bin at 50 Hz contains all signals within the 47,5 – 52,5 Hz and are all called 50 Hz. With 50 Ms/s, 5 Mio spectral lines at 5 Hz interval, all complex frequency components; amplitude, phase, are necessary to enable the full reconstruction of the signal in the time-domain, irrespective of the ADC resolution taken.

Taking reference x-tal based samples of a non-synchronous (to the x-tal used) periodic signal will typically result in a record where the first versus the last sample are non-periodic w.r.t. the signal as sampled in the record. Various options are known w.r.t. filtering the time record samples such that the beginning and end samples are always zero: Hamming, cosine-square, Kaizer and many other time-domain filter definitions exist. Another approach is to use zero-padding at the end of the 'period' to reach a full virtual period of 2^N samples. The latter has the advantage that no energy is added nor left out w.r.t. the original signal. The above-mentioned constraint w.r.t. the frequency bins remain as the signal is mapped to those bins with their represented phases such that the least squared error results w.r.t. the original time-domain signal. Such FFT results cannot be used easily with Model-Order-Reduction (MOR) as all frequency domain complex data information will be required for further analysis and thereafter if a time-domain response reconstruction is required.

III. Problem Definition

As indicated, motion control systems bear typically three main frequency components which are of concern. The simple challenge will be to measure these signals in time: over a period long enough to cover the least common multiple of all three frequencies and short enough to follow any changes to those signals. Then these signals shall be add the originals with the right amplitude and opposite phase; 3- (delta-) or 4-wire (star-configuration) in a motion control drive system. This can also be applied to any 3-phase mains side or a 2-wire DC-bus driven side. Similar approaches can be used with DC-motor in H-bridge drive systems, but the multiple poles of the commutation as created by the two or multi-finger commutation system must be taken into account. The commutation noise will be synchronous to the rotation speed (but not every pole commutation will be the same).

Motion control systems have one main advantage, they are slow when compared to the computational speed of modern electronic motion control systems. When for each fundamental frequency signal component: mains frequency, rotation frequency and PWM frequency, half a period is taken (excluding DC), the next half period will AC-wise be very close to identical to the inverse of the first half. Fast acceleration, deceleration and jerk will occur which are mostly known by the digital motion control system in advance.

Modern complex motion control systems are a combination of feed-forward and feedback systems. Active EMI noise cancellation can be done in a similar way. Fortunate, with digital motion control systems, the PWM or sampling frequency is known, the motion i.e. rotation frequency is known, the mains frequency remains the only unknown factor, but is less critical. The mains noise will be near to 100 Hz (single phase supply, double rectification) and its multiples or 300 Hz (for a 3-phase mains system, 6-pole rectification, being unipolar after the input mains rectifier or half these frequencies being bi-polar at the mains entry side.

IV. Suitable Solutions

When FFT is used on full integer number of periods in a record of the signal considered e.g. by using zero-crossing detection (even by using fractional samples using linear interpolation in-between the samples), a rectangular input filter can be used over that full integer number period time record. The record can be interpolated to become a 2^N-record, where 2^N is the least number higher than the remaining number of samples left over from the initial record taken. Doing so, assures that the lowest frequency of the signal is an integer sub-harmonic of the signals looked for. Also, the higher harmonics are exact at the (center) position needed without any energy dispersion to other frequency components as the remainder of the frequency 'bin' is empty. Formally, only single spectral lines remain after such an FFT. Now, the entire signal in the frequency domain can be expressed by a condensed vector representing all relevant complex information: amplitudes and phases of the signal with the period resolution equal to one over the 'left-over' initial record length. A such, the highest order of Model-Order-Reduction (MOR) is achieved without any loss of the original data. Further limits can be set to the number of harmonics to be considered to represent the original signal correctly with minimal error.

If the active EMI noise cancellation is running synchronous to the motion control system, then both the actuators' motion frequency and sampling frequency are known upfront or even forecastable in case feed-forward control systems are used.

At the cable interface, each of the 3-phase wires can be compensated for or the just the combination of the 3 (or 4 in a star-configuration application). In the latter case, only the residual common-mode voltage and residual common-mode current has to be compensated for at the drive side interface to eliminate their root cause for RF-emission, covering the full frequency range. The remaining issue remains to assign an extra wire and to select a 'cold' reference point to which these common-mode voltage and current are compensated for as a 'wrong' selected reference point will increase the RF emission. Furthermore, after making the drive's output (and input) signals common-mode 'free' this needs to be supported with a full balanced i.e. geometrically rotation symmetric load by the cable and actuator load connected.

If the actuator and cable are cross-sectional rotation symmetric and common-mode 'free', the crosstalk to other nearby cables will only result from the geometrical unbalance to the 'summed' wires. A thin electric shield rather than copper foils and tight multi-strand braiding might be enough to eliminate this nearby crosstalk effect too.

Commercially-of-the-shelf (COTS) active and passive circuit solutions are available to compensate for the common-mode currents. The common-mode voltage on the interface are often ignored, though common-mode voltages/ currents are the dominant factor w.r.t. RF emission and nearby crosstalk.

As indicated, **4** causes of EM-interference from motion control systems can be defined when the entire motion control system is assumed fully shielded:

- common-mode voltage/current at input (supply)
- common-mode voltage/current at the output (load)

The common-mode voltages can be obtained easily by using RC coupling networks to all phase and/or neutral wires and by combining these phase signals to a single common node voltage against a given reference node. Adding an additional 'compensation' wire to inject the opposite signal can be an option or the compensation signal has to be injected/ distributed to all of the wires equally.

The common-mode current can be measured using a current clamp across all wires. Adding an additional wire to inject the opposite signal will be an option or one has to induce the correction signal to all of the wires equally distributed. For most motion control applications, the PE wire can be used without affecting electrical safety.

ACTIVE CORRECTION EXAMPLE

Assume a motion control signal is obtained carrying 3 main signal components: 50 Hz (mains), 11 Hz (motion) and 9 kHz for the PWM. For simplicity sake, we take all signals sinusoidal at equal amplitude which are then summed up show in the time-domain as given in figure 1. Other factional related signals can be used too, and these conditions and the solution thereto will be shown with the final paper i.e. at the presentation.

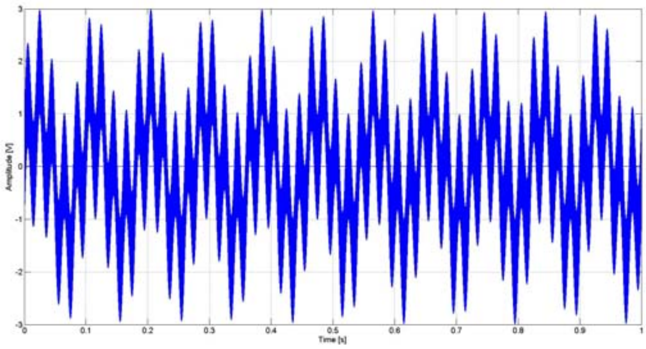

Figure 1 - Composite signal of 3 frequencies added

When an FFT is taken from the above signal, the three signals have an equal amplitude of '1'. Taking a proper FFT means taking the least common multiple (lcm) of the frequencies used as a sampling frequency. In this specific application, the time record is 1 second long i.e. the 11 Hz signal occurs 11 times, 50 Hz occurs 50 times and 9 kHz occur 9000 times, all starting at '0' at the 1 sample and being all '0' at the last sample of the record. As such, a rectangular filter i.e. no time-domain filter needs to be taken to obtain a correct FFT, see below.

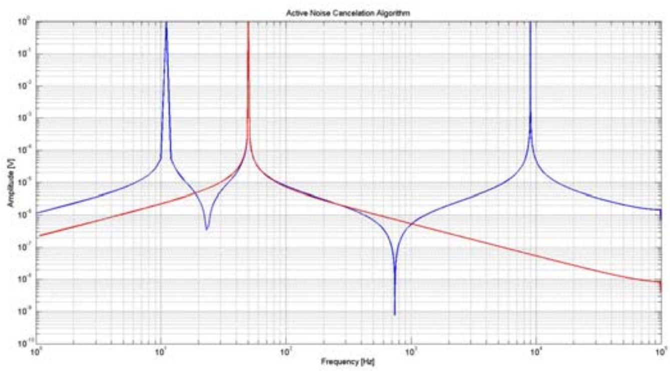

Figure 2 - Composite signal in the frequency domain (blue) and after cancellation (red). After filtering i.e. cancellation only the mains component remains!

If a record period of 1 second is taken and sampling speed is 1 Ms/s, exactly 11 periods fill the frame as well as 9000 periods for the PWM. Those two noise signals: motion and PWM shall be cancelled. If the record is delayed by 55,555 µs and added to the original record, the 9 kHz vanishes. If the record is delayed by 45454,5 µs, the 11 Hz signal is cancelled too. However, while doing these long record operations, one doesn't have the time to do the fractional correction with interpolation and typically integer record shifts can be done easily: 45454,5 becomes 45455 and 55,55 becomes 56 samples delay. For the both of then, an error is made by which NO full compensation of the signal(s) results. The out-of-phase compensation has an error of 0,45/55,55 period which yield about 40 dB of compensation at max.

Using the re-sampling technique when synchronizing the sample rate i.e. record length to the least common multiple, together with some decimation techniques results in compensations as deep as 80 dB or even more as can be seen in figure 2. The algorithm has been tested dynamically and will be implemented in hardware.

CONCLUSIONS

Standard passive filtering techniques are typically large in volume and weight and dissipate or reflect power inside a motion control system. Active filtering is limited by its control bandwidth.

Zero-crossing detection of low-frequency signals with high sampling rate and low-resolution results in low resolution phase detection.

The use of FFT is often misinterpret, w.r.t. frequency accuracy which is totally determine by record length and sampling rates [1-5].

Digital motion control systems provide the necessary details to enable active noise cancelling which is fully synchronize-able with the source frequency signals without artifacts. Knowing the motion control signals in advance together with the latency of the noise data measurement, manipulation and reconstruction enables accurate and fast compensation.

Compensating the noise of a motion control system is only possible in combination with other implementation measures to limit the unintended mode conversion of differential or line-to-line disturbances into common-mode disturbances in cabling and actuators connected.

Taking filtering precautions at the output or supply side level needs to be complementary as most motion control systems are at the actuator driver side 'floating' from its references i.e. PE.

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