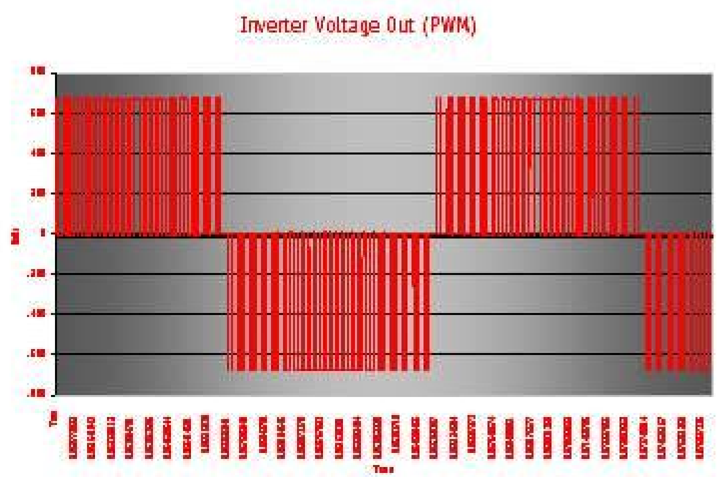
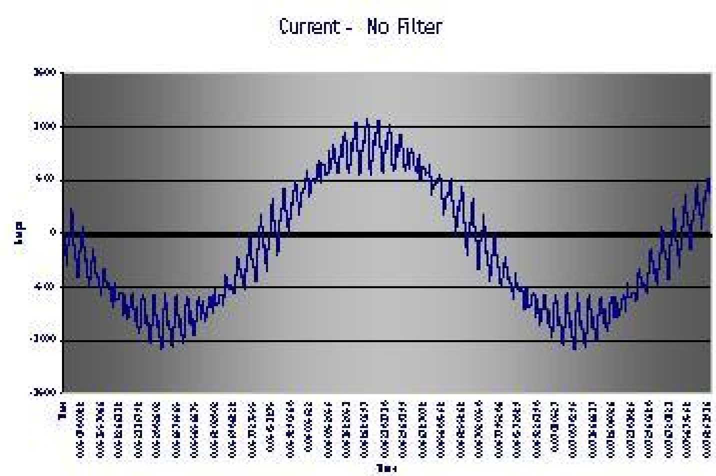
About The Author

Dean Mehlberg is the Vice President of Engineering at TCI (Trans-Coil, Inc.), Milwaukee, Wisconsin. He holds a BSET from the Milwaukee School of Engineering, is a member of IEEE and has worked in the area of low-pass filters since 1991. His recent work in adapting low pass filtering techniques for V/Hz drives control submersible pumps is highlighted here.

Carrier Suppression Makes Sense in Submersible Pump Systems

AC drives control motor speed by converting AC line voltage to a DC bus voltage, and then inverting that DC bus voltage to a controllable pulse width modulated (PWM) AC. Varying the fundamental frequency varies the speed at which a motor shaft turns. The drive inverter creates or synthesizes the desired fundamental voltage characteristics by switching the constant level DC bus voltage based on a particular mathematical algorithm, or modulation scheme. The frequency at which modulation occurs is called the carrier frequency, a term derived from work in the area of radio transmission in which the carrier "carries" the pertinent information. In the case of PWM drives, the carrier "carries" motor speed- torque information and the shaft responds accordingly.





Due to physical limitations in power electronics devices, switching speeds have practical limits, but are continually increasing with technological advancement. Therefore, maximum carrier frequencies are also limited but are increasing. Bipolar junction transistors (BJT's) used in early AC drives operated with carrier frequencies in the 500-1500 Hz range with rise times of 0.5 to 5 microseconds (m s), several orders of magnitude better than SCR's and GTO's. However, this frequency range often created a situation where carrier related voltages induced mechanical "noise" in the form of torque ripple on the shaft as well as acoustical sound from the motor frame itself. An audible noise, at some harmonic frequency of the carrier, would be heard, and sometimes easily coupled to equipment such as air ducts great distances from the motor itself. If the noise was too objectionable, after-market filtering was offered as a solution. These filters eliminated most of the non-fundamental voltage excitation by attenuating it with a low-pass filter (inductor/capacitor and dampening resistance) with a break frequency that is higher than the fundamental but lower than the carrier. Selection of the corner frequency was somewhat critical in that the amount of attenuation can have destabilizing effects on some inverter topologies. Extra filtering also creates extra losses, and costs money. Doctoral dissertations have been written on filter design characteristics and are beyond the scope of this article. That being said, a simple L-C-R low pass is the form of filter for suppressing carrier energy in this discussion. The simplicity of this form of filter limits design efforts and maximizes performance/cost ratios.

My first work with this type of filter took place over ten years ago. It was the first effective output filter for drives operating large HVAC air handling systems that created objectionable acoustic noise levels. It was a big filter, and the cost was prohibitive for universal use on PWM drives. Thus, the initial concept of a low pass high performance output filter for "suppressing" carrier frequency was only used to control audible noise in a limited number of applications in motor/drive systems.

Today, carrier suppression has a new place in special duty motor drive systems.

Insulated gate bipolar transistors (IGBT's) allow operation at much higher carrier frequencies, along with much faster switching speeds. Thus, noise from mechanical and magnetic responses in motors have essentially been eliminated. Sense the adult human ear is less sensitive to sound frequencies above 10 KHz. The mechanical resonance points of the motor laminations at 2x the carrier frequency, will usually be less objectionable or beyond detection of the human ear. In addition to quieter systems, drives now tout smaller size, lower motor temperatures, precise shaft control and faster response with a carrier frequency range of 3 kHz to 30 kHz.

Today's IGBT's switch at speeds up to 50 nanoseconds (ns). The high frequency components contained in those steep edges of each pulse create new applications challenges. We will not review the much discussed over-voltage "reflected wave phenomena" related to fast switching speeds and long motor leads. Instead, we will discuss when it is economically sound to filter PWM voltage utilizing similar technologies to those developed many years ago, but for far different reasons.

One area that has shown economic justification for equipment that filters the carrier from the PWM drive output, is in the oil pumping industry where extremely long leads and extremely expensive maintenance costs are associated with well-pump or cable failure. A well shutdown can cause high cost in the loss of product generation, and removal and replacement of damaged equipment. Mid-horsepower drive/motor pumping systems (75-500 HP) utilize low voltage drives (<600V) to convert, and then transform the energy to a higher voltage to send it down long leads (down deep wells) to drive medium voltage motors specially designed for submersed duty. The choice to use a low voltage drive is an economic one. Low voltage switches and the drives that house them are qualified, reliable and inexpensive in these horsepower ranges, while medium voltage drives are much more complex, more expensive and not readily available.

The criticality of the load is of primary concern for engineers designing these systems. Stated another way, the load is located in a remote or untouchable place, and that, combined with the fact that the process is so critical, makes downtime and frequent maintenance shutdowns intolerable

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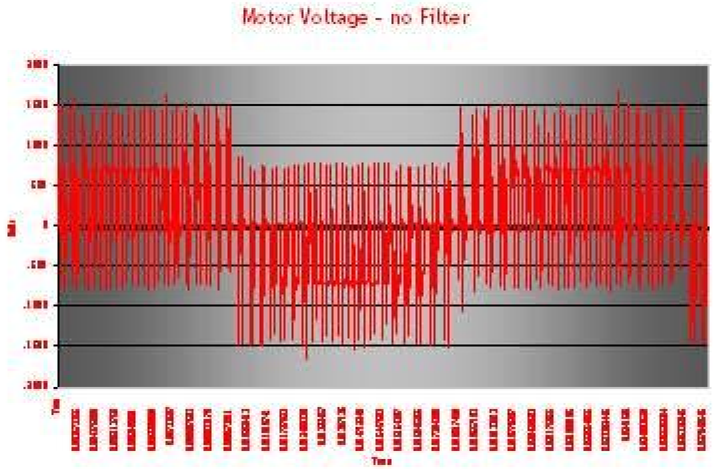
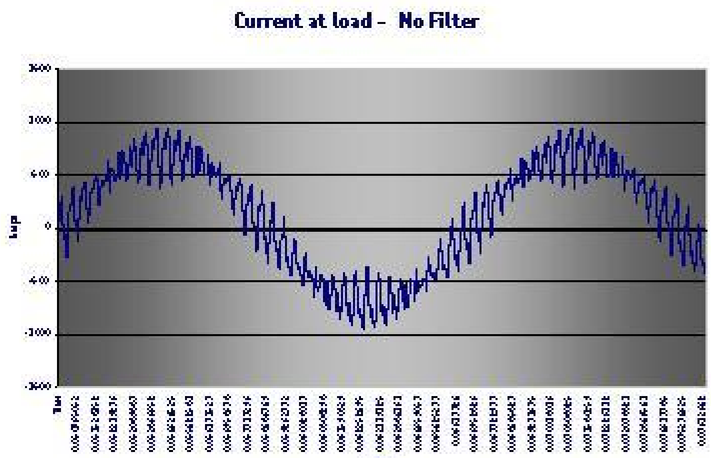
So why do we wish to reduce or suppress the energies contained at the carrier frequency?

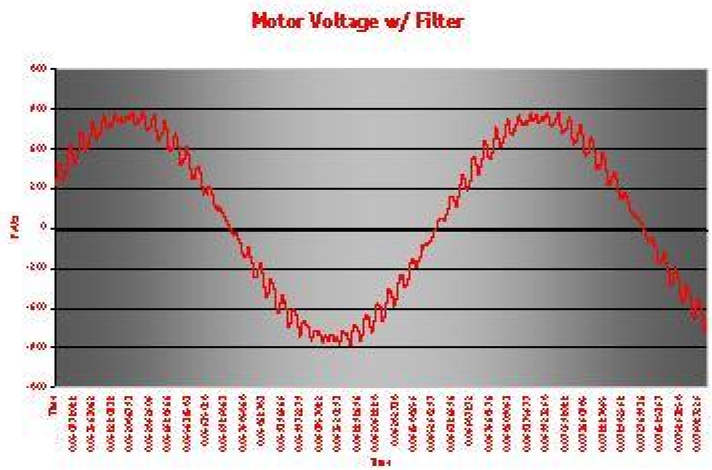
Consider that the construction of a transformer is similar to that of a motor. It is made of wire and iron core and similar insulating materials, and susceptible to the damaging effects caused by high dV/dT and the repetitive pulse environment. In these applications, care is taken in the selection of the transformer to make sure that it can handle PWM excitation. However, failures caused by insulation breakdown, caused by partial discharge, corona generation or other destructive phenomena related to high dV/dT can occur in the transformer. In addition, the transformer voltage step-up exacerbates these effects on the cable and the motor. Transformers are usually placed close to the inverter and the close (<20 feet) proximity combined with robust design practice will usually minimize transformer failures. But protection prior to the transformer is still a good idea. In addition, the long leads following the transformer and the motor is still subjected to reflected wave phenomena, and the resulting damaging over-voltage condition.

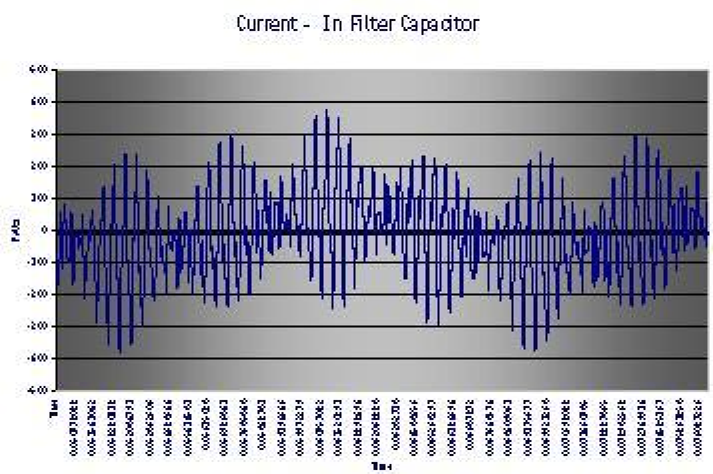


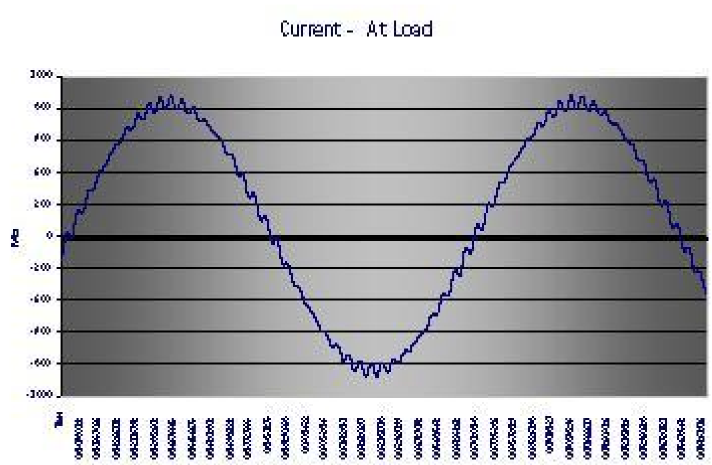


In less critical applications, off the shelf filters that have a break frequency in the sub-20 kHz range reduce the effective dV/dT of the PWM pulses sufficiently to protect motors with leads up to 1000 feet, depending on dV/dT. But, they are limited in the amount of reduction that they can provide. They will typically try to hold dV/dT below 1000 volts/m s. However, the sheer length of the leads in oil wells is too great for higher frequency dV/dT filters to operate reliably.

So-called "sine-wave" filters that highly attenuate the carrier energy are required to protect leads and motors. Low voltage, pre-transformer filtering is the most economical. It is always best to mitigate a problem at the root cause. In addition, stepped-up fast waveform voltages are much more difficult to control, making medium voltage filters complex, much more costly and fewer competent sources. Therefore, many wells now have low voltage "sine-wave" filters installed close to the inverter output and the transformer. These filters are very similar to the after-market filters of ten years ago. But, they have been optimized and standardized to work with many drive topologies. They utilize special duty reactors and capacitors that can safely accommodate the high frequency PWM components and associated losses and standard power resistors are utilized for the dampening element.







Carrier attenuating sine wave filters have an insertion loss and a phase shifting component. Serious consideration has to be given to the drive topology in order to be applied successfully. All vector drives may have to be reconfigured to accept the insertion of inductive impedance and the possible high peak current spike associated with the filter capacitor. If not, the drive may not perform reliably. Some volts/Hz drives may experience stability issues due to phase shifting and the feedback loop bandwidth modification. Make sure to coordinate all system variables with the drive manufacturer's application engineering group, and the filter provider.

Last and perhaps most importantly: filter installation has to be coordinated to include fault-monitoring mechanisms. Although the filter is a simple L-R-C circuit that is easy to construct and install, failure could be catastrophic, since the loss of the filter, the capacitor in particular could be unknown to the system. The cable and motors would be vulnerable to the same stresses as they were prior to the installation of the "sine-wave" filter. Therefore, considerations must be made to monitor the effectiveness and integrity of the filter. Monitoring of the output waveform is the preferred method. The protective device should be capable of continuously monitoring for dV/dT and peak voltage. An alarm signal or automatic shutdown method should be incorporated.

Of course, when the motor is accessible, other mitigation techniques are available. When it is not, as in the submersible pump application, mitigation equipment should be communicative, robust and based on proven technologies.