OVERCOMING THE PREVIOUS LIMITATIONS OF VARIABLE SPEED DRIVES ON SUBMERSIBLE PUMP APPLICATIONS

James Mullinix, Steve Breit and Gary Skibinski
Wood Group ESP, Inc.

ABSTRACT

There is an ever-increasing use of variable speed drives in submersible pump applications. However with all new applications new problems can be encountered. The long cable lengths associated with submersible pump equipment have limited the effectiveness of variable speed drives. Many drives have to use external filters, inductors and conditioners to keep from damaging the cable and motor. The extra costs associated with this equipment, as well as the custom use, limit the overall effectiveness. VSG (Variable Sine-wave Generation) technology has been developed to overcome these limitations, as well as providing the user all the flexibility that initially attracted them to Variable Speed Drives.

PART I – DESTRUCTIVE FORCES

- Output Current Harmonics
- Reflected Wave

OUTPUT HARMONICS – WHAT IS IT?

IEEE 519 - 1992 defines a harmonic as, "A sinusoidal component of a periodic wave of quantity having a frequency that is an integral multiple of the fundamental frequency". There are numerous papers and articles published that address specifically input harmonics or line harmonics specific to variable speed drives.

Generation of harmonic currents as applied to power electronic equipment is defined as non-linear because it draws non-sinusoidal current. Six step variable speed drives produce non-sinusoidal output currents. Fig 1 We can establish that Six-step variable speed drives produce output harmonics as a result of their non-sinusoidal output currents. Fig 2

REFLECTED WAVE – WHAT IS IT?

The inverter section of a Pulse Width Modulation (PWM) drive does not produce a sinusoidal output voltage waveform; instead they generate a continuous train of pulses as in Fig 3.

These voltage pulses are "transmitted" to the motor terminals via the motor cable. Peak pulse voltage at the drive output is equal to the drive DC bus magnitude and contains steep fronted rise and fall times controlled by the GTO, BJT, or IGBT semiconductor switching device used in the drive. Peak pulse voltage at the motor terminals is not necessarily V_{dc} bus but is dependent upon the dynamics of the drive-cable-motor circuit, which defines the drive output voltage rise time, cable transmission line characteristics, cable length, and motor impedance to the pulse voltage. Fig 4 shows the pulse train at the motor terminal has momentary transient over-voltages at every switch point, up to twice the V_{dc} bus pulse voltage from the drive. These over-voltages may produce potentially destructive voltage stress on the motor insulation.

PART II – FORCES AT WORK

The typical total harmonic distortion (THD) of a PWM inverter output voltage is between 80% and 180%, depending on operating speed. Motors have been designed to handle the excessive heat associated with dissipation of harmonics, however these motors will not handle the voltage levels associated with the Reflected Wave, which can be two to three times the V_{DC} bus level depending on the cable and motor characteristics.

Simply put, THD translates into wasted energy that must be dissipated at the motor in the form of excess heat and reduced system efficiency. The reduced efficiency has long been tolerated, as the production efficiency gained by using variable frequency drives far out weighed the expected losses.

PART III – LIMITED SOLUTIONS

Many output harmonic mitigating devices are available to aid with the fore mentioned problems. The most common are:

- Simple line inductors
- Limit filters
- Sine-Wave filters

LINE INDUCTORS

Line Inductors are the simplest and lowest cost method to effect the voltage waveform. This type of filter typically reduces the dv/dt transmitted to the motor.

Disadvantages of line inductors - Harmonic current distortion is only improved 30 – 40% at best. The voltage drop associated with them will affect motor performance if maximum voltage is required by motor. They do not help reflected wave and voltage distortion.

LIMIT (DV/DT) FILTER

Limit filters are designed using an inductor, capacitors and diodes to minimize losses and condition the voltage. This type of filter is used to reduce both the dv/dt and the voltage peaks seen at the motor.

Disadvantages of Limit filters - Can only improve harmonic current distortion to 30 – 40% at best. It will help with the leading pulse associated with the reflected wave. The voltage drop associated with them will affect motor performance if maximum voltage is required by motor. They must be sized specifically for long cable lead applications, and they will not correct voltage distortion. They will also require a custom design if operation frequency is above 60Hz.

Where cable lengths exceed 1000 feet, dv/dt limiting hardware solutions are not entirely effective. For example, a limit filter installed on applications with cable lengths in excess of 1000 feet is generally not effective in eliminating the 3 pu and 4 pu reflected wave magnitudes. Similarly, the watts loss increase and effectiveness decreases, as well motor over voltage has been seen to exceed 1.75pu. Thus, a different solution is required beyond 1,000 **ft.** cable lengths. Other dv/dt limiting hardware solutions are available that slow the unfiltered PWM pulse rise time, however they are also generally ineffective at reducing the transient reflected wave voltage spikes at the motor terminals for cable lengths beyond 1,000ft.

SINE WAVE FILTER

Sine wave filters include output inductors; shunt capacitors and when necessary damping resistors to form a conventional low pass filter. This filter is designed to allow high frequency fundamental current to pass to the motor. If the filter is designed correctly, the result is a sinusoidal power being applied to the motor in both terms of the voltage and the current.

Disadvantages of Sine wave filters – Typically sine wave filters have been designed with a 5Khz carrier frequency requirement. Most VSD manufactures require you to de-rate the VSD when used with a high carrier frequency. In addition, applications above 60hz, or with cables in excess of 1200 ft, require custom designed filters specific to that application.

Although simple, the conventional low pass sine wave filter design has high KVA losses associated with it. First, to obtain low THD performance, the design requires a large output capacitor and this creates a large reactive current demand, which must be supplied by the VSD at startup. This reactive current reduces the KVA available to the load at startup. This lack of current can result in unstable system operating conditions and load oscillations at startup with resultant shutdown of the drive system.

To obtain a low THD, the sine wave filter design requires, in addition to the load, large reactive filter KVA at the fundamental frequency, which must be supplied by the VSD. Thus, the low pass filter must use a significantly larger inverter rating for the same size load powered without a filter.

PART III – VARIABLE SINE WAVE GENERATION

Variable Sine Wave Generation (VSG) was designed to produce a "Near Perfect" sine wave in respect to voltage and frequency. This latest technology has been granted a US patent. The voltage and current waveform in Fig. 5 & ***6*** represents the next generation of variable speed drives, We have established that output harmonics are a result of non-sinusoidal current waveforms; furthermore the Reflected Wave is a result of a PWM voltage waveform. VSG technology

allows us to clear the final two obstacles with respect to previous generation Variable Speed Drives. This latest technology breakthrough overcomes both output harmonics as well as the reflected wave.
VSG is suitable for applications up to 15,000 feet without custom designs; furthermore it does not require the Variable Speed Drive to be over sized with respect to the application. This is evident when we compare the input current requirements with the available output current.

This technology was engineered to meet the specific problems associated with high KVA and long cable length applications, specifically Electrical Submersible Pumps.

REFERENCES

S. Breit, "THD (Total Harmonic Distortion, The effect on Electrical Submersible Motors", 1997 ESP Workshop

G. Skibinski, Riding the Reflected Wave – IGBT Drive Technology Demands New Motor and Cable Considerations

IEEE 519-1992

NEMA MG 1-1993, Revision 1, Section IV

LIST OF SPE PAPERS DISCUSSING HARMONICS & SUBMERSIBLE MOTOR PERFORMANCE

K. Packard, "Reduced Operatino Harmonics on Variable Speed Drive Applications", April 1995, SPE Gulf Coast Seciton, SPE Roundtable

D. Shipp, "Power Quality Analysis for a West Texas Oil field fed by Adjustavle Speed Drives, april 1995, SPE Gulf Coast Seciton, SPE Roundtable.

D. Cashmore, "Induction Motor Performance for A Variable Terminal Voltage", April 1992, SPE Gulf Coast Section, ESP Workshop

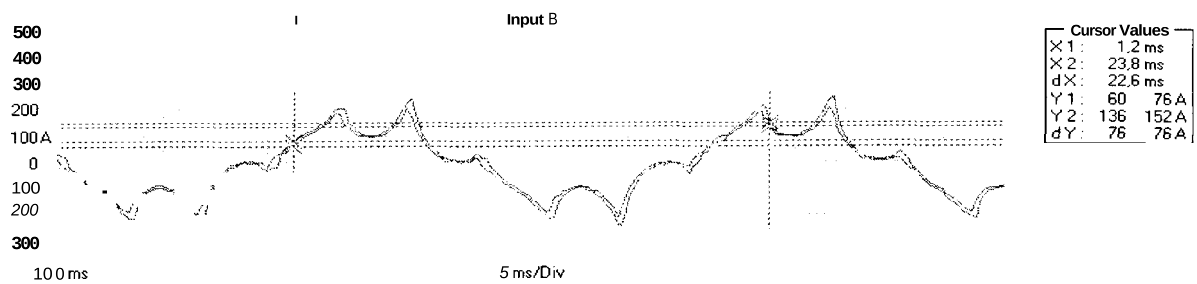


Figure 1 - Six Step Current Wave Form

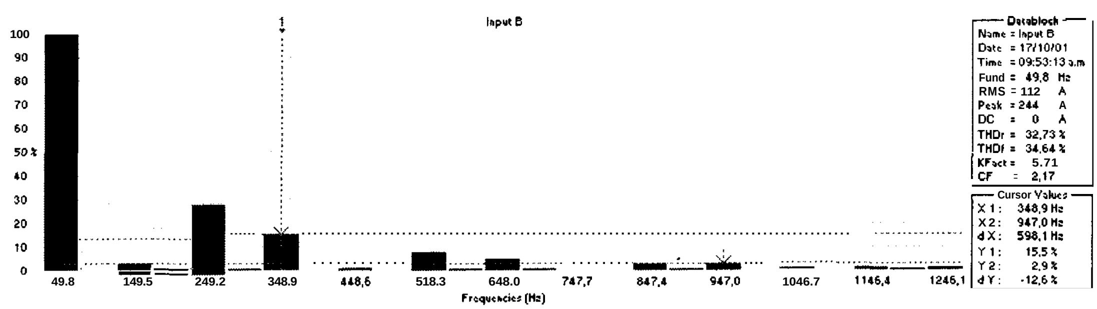


Figure 2 - Six Step Current Wave Form Harmonic Spectrum

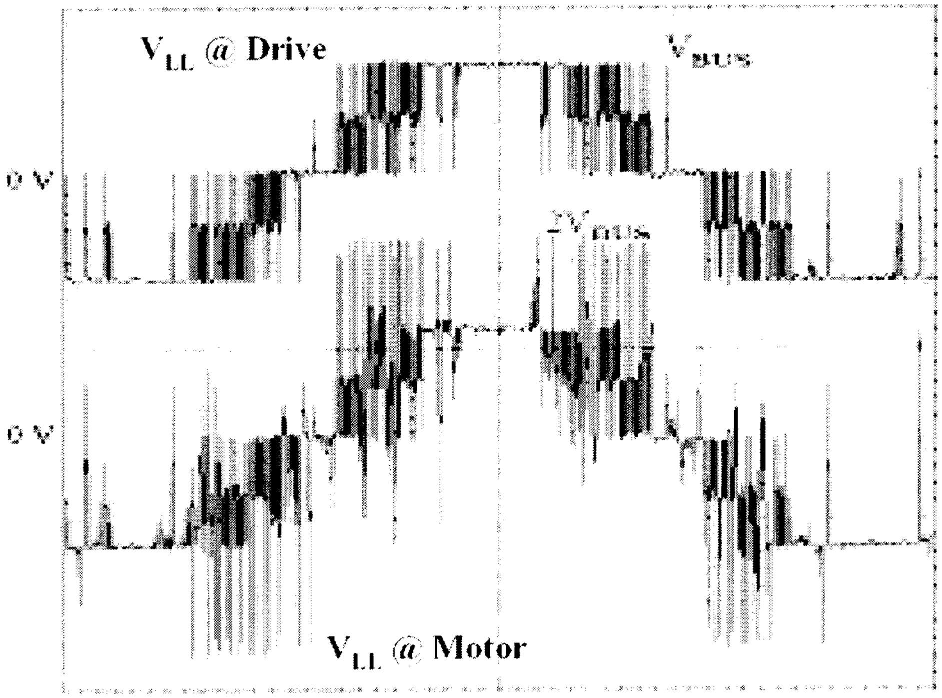


Figure 3 - PWM Waveform

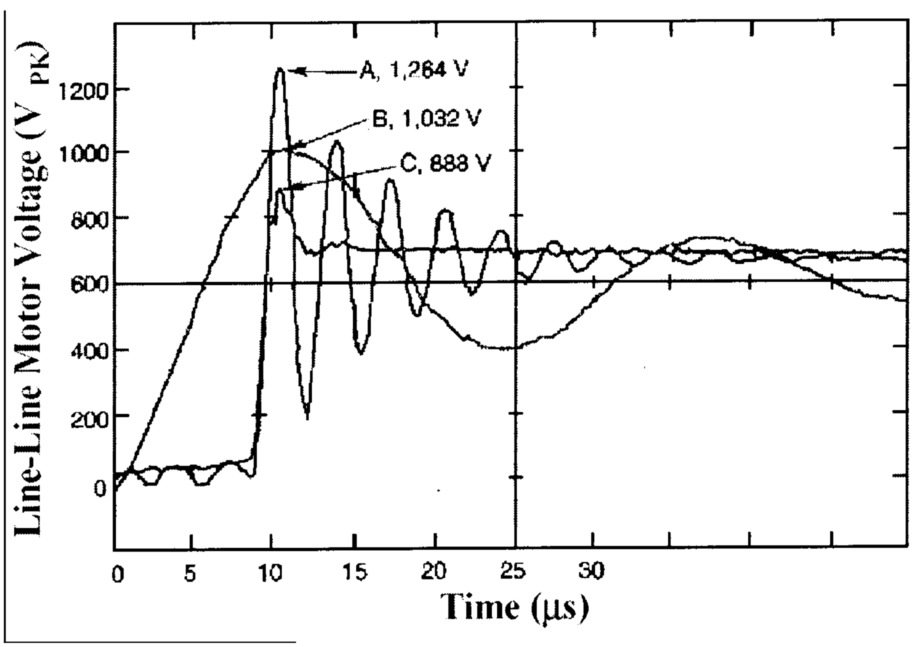


Figure **4** - Transient Voltage Waveform

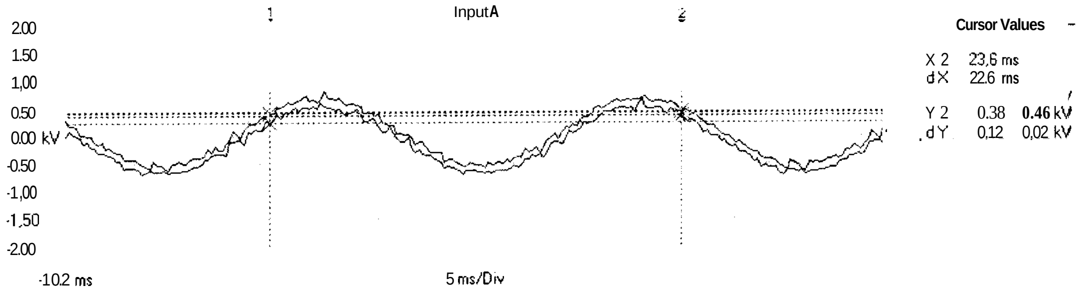


Figure 5 - VSG Voltage Wave Form

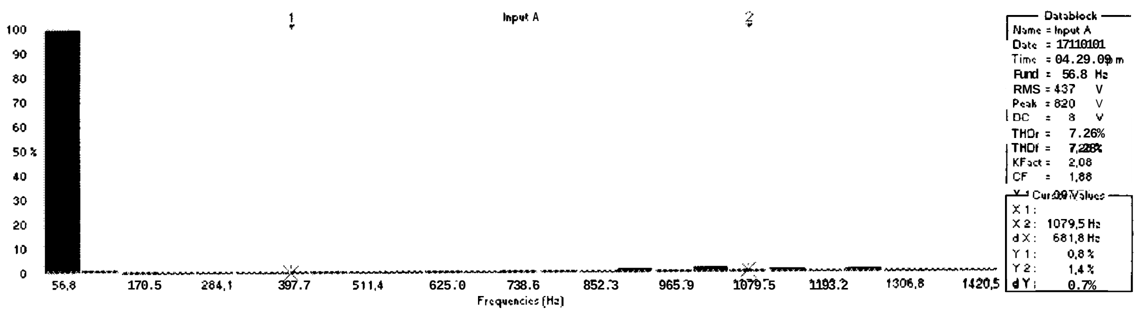
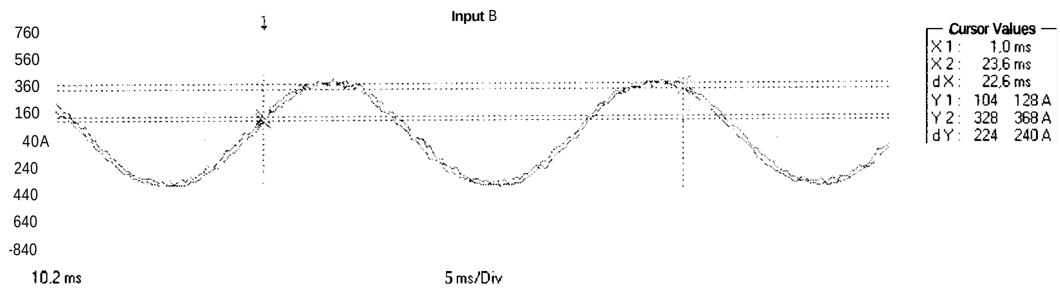


Figure 5A - VSG Voltage Wave Form Harmonic Spectrum



Figuer 6 - VSG Current Wave Form

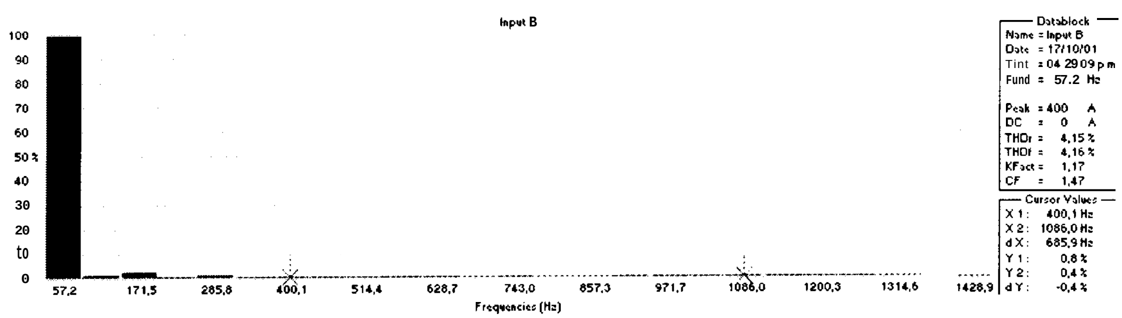


Figure 6A - VSG Current Wave Form Harmonic Spectrum