BEAM PUMPING WITH VARIABLE SPEED DRIVES – PAST, PRESENT AND FUTURE

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ABSTRACT

Variable speed drives have changed the way beam pumping units keep wells pumped off, prevent failures, and extend the life of the pumping unit. VSDs, although slow to be accepted, are now a typical portion of the control mechanism used in pumping units. In this paper, we will review the history of VSDs in the oilfield, provide an overview of where they are now and take a glimpse into the near future of developments. We will also cover issues that VSDs bring into the field with power quality concerns such as additional harmonics. We will identify new technologies available now and in the near future to combat these power quality issues.

PAST

Pump off controllers (POCs) and time clocks were the primary methods of control for Rod Pumps during the 1980's. By determining how much run time per day was needed, a simple timed-contactor package was added to control the motors. NEMA D motors with high-slip were dominant since they allowed the motor to slip during startup but didn't provide high efficiencies.

In the early 1980's, manufacturers of variable speed controls were heavily into building SCR controlled DC Drives to control DC motors. One could even say it was the most common variable speed control during this time. The control was simple enough; vary the DC voltage to the motor and the speed varied linearly as well. The trend though was about to turn to AC motors, but the method was going to be a little trickier. AC motors' speed is strictly set by the line frequency (Hz or cycles per second) feeding that motor. So, in North America this is 60Hz and many international locations, this is 50Hz. The electrical design of the motor would set the speed, whereby "poles" give the motor its rated speed for a given frequency. Here are some typical speeds, with 6-poles being the most predominately used motor in the oilfields of North America.

$$Speed = \frac{120\ x\ F}{\#\ of\ poles}$$

# Poles	Speed (RPM) at 50Hz	Speed (RPM) at 60Hz
2	3000	3600
4	1500	1800
6	1000	1200

The speeds above do not account for slip which is somewhere on the order of 3-5% speed reduction at full load. So, in order to change the speed, the frequency needs to change. The solution to alter the motor applied frequency was to accept AC voltage and rectify it into DC voltage. Then the DC voltage could be "chopped up" and retransmitted to an electric motor in an AC format (although not a perfect sine wave).

The first methods used in the early 80's were referred to as "six-step" outputs. In other words, the voltage produced was in two-steps per cycle over 3-phases, instead of a sine wave. The terminology at this time was referred to as Variable Voltage/Variable Frequency (VVVF). Although a square wave voltage, the inductive characteristics of the AC motor "smoothed" the chopped voltage waveform into a more sinusoidal current. Figure 1 depicts the topology and resulting AC voltage and AC current as seen by the motor. The predominant electronic device used at this time in the output section was thyristors.

The VVVFs did make their way into the oilfields in the early 1980's in some trial runs. Most oilfield users' comments were that the units were large in size and their reliability was terrible. However, they did make an impact as wear and tear on the units was decreased. Being able to adjust the speed on the fly removed the need for sheave changes. Additionally, the ability to have separate upstroke and downstroke speeds allowed the pumping unit slower downstroke speeds preventing fluid pound. Sticking pumps with sanding problems were decreased because instead of stopping the unit, it could be slowed down, keeping the sand stirred up. The biggest advantage was keeping the well pumped down to gain maximum flow at all conditions. However, the large price and bulky size for such units kept the quantities in the oilfields to a minimum. Other comments were they were just not reliable with the end of line power in remote locations that an oilfield has. Most users stated they were always concerned with the life of the VSD.

Like most other technologies, it only improved as time passed. In the early 1990's, the use of transistors (over thyristors) on the output was coming into play. Bipolar Junction Transistors (BJTs) and Mosfets were available in larger amperage ratings. Then later in the mid 1990's, the IGBT, or Insulated Gate Bipolar Transistor, was the newest device on the market. It provided a safe on/off switch that was insulated from its firing circuit. This would greatly increase the reliability of the VSD and change the bad reputation that VSDs had received in the past. These new type of transistors could switch on/off in hundredths of millisecond (ms) and create a better output than that of the 6-step. By switching at these faster speeds, a better type of modulation came into play. This new type of modulation was called Pulse Width Modulation (PWM) whereby the DC voltage is chopped up into thousands of pieces per second and a true average varying voltage, varying frequency was derived. As stated earlier, since an ac motor is primarily inductive, the actual current to the motor would become even more sinusoidal than the six-step. Figure 2 depicts the topology of the VSD and its accompanying waveforms.

VSDs were becoming more and more dominant in the variable torque market. VSDs allowed the use of NEMA B motors as well. NEMA B motors had less slip and increased efficiencies. More VSD manufacturers were coming on board. Centripetal pumps and fans were the largest user and still are today. The economics of variable speed in these markets provided immediate savings. For example, by decreasing to 50% speed would in turn decrease power consumption by the cube or 1/8th power. Locations where single phase power was the only source, VSDs were able to use that power and convert it to 3-phase with only some upsizing required. One might wonder with all these advancements if this was why so many manufacturers were added during this time.

However, in the mid to late 90's the oilfield would learn what most other industrial users of Variable Speed Drives had discovered: motor winding failures. As IGBTs became faster and faster, the switched DC voltages applied to standard AC motors would cause detrimental effects on the motor windings. The fast switching devices were slamming voltages of 650Vdc on/off to the motor at 1000's of times per second. The windings were not created for such torture and would eventually fail. Again, VSDs would get a bad reputation. They were referred to as large in size, costly, and motor killers.

By the late 1990's motor manufacturers had learned how to deal with these motor spikes by using various forms of spike resistant wires. Several had coined their patents with Inverter Spike Resistant wires (ISR™) and Inverter Rated Insulation System (IRIS™) to name a few. Newer generation IGBTs were predominant in the VSDs. Internal components of the VSD were being mass produced and costs were improving dramatically. It was almost as if the VSD might become a commodity item later on.

Initially the primary method of control was Volts per Hertz or V/Hz. In this method the speed of the motor was controlled by varying the applied voltage and frequency linearly from 0V/0Hz to 460V/60Hz. Even over-speeding could occur by raising the applied frequency beyond 60Hz. (However overspeeding the motor reduces available torque from the motor). See Figure 3. This worked well for variable torque loads where instantaneous overloading rarely occurred and precise speed control wasn't required. But for high profile loads where precise speed control was necessary, a new method of control came along, Vector control. This method utilized a feedback device on the motor, typically an encoder or resolver, where high counts of pulses were sent back to the drive informing the drive of actual motor speed. Typical encoders could produce 360 pulses per revolution (ppr), up to 10,000 ppr. This provided excellent speed control all the way down to zero RPMs. Due to space constraints, noisy environments and costs, users asked for something between exact speed control and V/Hz. At this time, VSD manufacturers began adding motor models within the control parameters. The processors could emulate that an encoder was attached (when it really wasn't) achieving a tighter speed control and termed Sensorless Vector control. Now, 3 methods existed: V/Hz, Sensorless, and Vector. See Figures 4, 5, and 6 for these control methods.

Having been exposed to all the new advancements in variable speed drive technology, would the oilfield now be willing to take advantage of VSDs? Well, some did, most didn't. Oil prices were below $25/barrel in the late 90's and into the early years of 2000's. Validating the Return on Investment (ROI) was long. VSDs were proving successful in other markets though. In Water/Wastewater plants and HVAC type applications, VSDs were dominant. In these variable type loads, the savings were predictable and immediate. Similarly the oilfield did try progressively more VSDs in the ESP and PCP driven applications but RPs were still lagging in VSD use. In most oilfields, only "problem wells" would get fitted with VSDs. Other forgiving wells would simply get sheave changes.

Around 2005, things would change for VSD usage in the oilfields. Oil prices were creeping up above $40/barrel. By 2006, the price had increased to $60/barrel. VSDs came down in price as more and more VSDs manufacturers began to compete. With these lower prices, smaller sizes and better technology, VSDs were being tried throughout the oilfields, however; many were skeptical for it added complexity to something that was formerly an on/off switch or timer. Pump off controller suppliers began adding a VSD to their units with the POCs controlling the VSD. This meant programming 2 components that didn't have the same look or feel.

Within a short amount of time, the programming of the VSDs was handled by the POCs from some of the larger suppliers. This quick setup reduced the start-up time for the user. Some independent VSD manufacturers had written "code" to control the well without the use of a POC or extra sensors.

PRESENT

As we move into 2013, the major players in the oilfields have VSDs in their locations. The VSD is typically paired with some type of POC or other well monitoring device such that the speed is adjusted to maintain pump off conditions or just shy thereof. The majority of the VSDs operate without feedback using the emulated encoder within the VSD, or more commonly referred to as Sensorless Vector control. In order to maintain tight speed regulation, Dynamic Braking Resistors (DRBs) were added as well. During negative torque cycles within the pumping unit, energy is returned to the VSD. This energy must be discharged thru resistor kits or more commonly DBRs. Alternatively some units do not use resistor banks, thus during negative torque cycles the motor is allowed to overspeed to avoid high energy inrush to the VSD. This is not acceptable in most cases as the motor is in a brief uncontrolled state.

The major benefits of VSDs include:

- Sanding issues
- Hard to start pumps
- Use of NEMA B motors
- Heavy oil and steam floods
- Energy management
- Speed changes without sheave changes
- Other situations where stopping would have an adverse affect.
- Accurate pump off control

FUTURE VSDs AND POWER QUALITY

As we have discussed throughout this paper, VSDs bring about a simple speed control device that greatly increases the life of a well. Now, let's look at the power quality issues that arise from typical VSDs. In this section, several rules of thumbs will be used; however a full power quality review will not be discussed since this could be a white paper in itself.

The most common form of VSD is that of a "6-pulse" or 6- components making up the rectifier section. (Refer back to Figure 2.) All of these devices are considered passive or perhaps even thought of a check valve. Electrical current can flow into the VSD from the line supply, but can't flow back to the line. Voltage on the input must be greater than internal voltage for the "valve" to turn on. As mentioned previously, this may be 6-diodes, 3-diodes/3-SCRs or 6 SCRs. With all these different input topologies, the supply to the VSD is standard 3-phase voltage with each phase 120 degrees apart from the other one. In this case with no separate filtering, the unit will exhibit between 50-75% harmonics when operating at full load amperage. In the recent past, most utility power companies are not concerned with these levels of power quality in Rod pumping applications. Nonetheless, utilities are slowly seeing this power quality issue and in the future will be more concerned as more and more VSDs are added to the oil fields.

So, what can be done for harmonic mitigation? Additional hardware can make these harmonics diminish substantially on 6-pulse drives. By adding passive filters, harmonics can be reduced below 10% and using active harmonic filters the content is reduced to less than 5%.

Drives with multi-pulse inputs are the most traditional form of VSD that can also reduce harmonics. The first is a 12-pulse drive that requires a special transformer added between utility power and the VSD. The transformer design has one primary winding (input) and two secondary windings (output). Essentially the transformer phase shifts the output by 30% between its two secondary windings. This 6-phase is fed into the 12-pulse VSD. (These are seen quite extensively in the ESP designs.) In doing so, harmonics can be reduced to 12-15%.

Furthermore, 18-pulse, 24-pulse and even now some 30-pulse VSDs may be used to lower the harmonics below 5%. However, all of these solutions still contain a passive front end and require a DBR to remove regenerated power coming back from unbalanced pumping units.

A newer technology that has been utilized in large centrifuges, automobile engine dynos and elevators has worked its way into the oil fields and the numbers are increasing. These are known as "Active Front End" Drives (AFE). Instead of passive devices that are shown above in the 6-pulse drives, active drives contain transistors (or switches) in the front section of the drive. The topology is shown in Figure 7. As you can tell, this simply mirrors that of the motor side configuration. There is also a boost regulator and small low-pass filter included, but will not be discussed in detail. The active-front end is capable of sending power to the VSD and returning power back to the grid. This provides solutions that were not discussed earlier. It removes the need to dump energy from the bus capacitors to a resistor bank. It also creates energy savings as this power can be absorbed by the line and used elsewhere in the system. Lastly, since it has an Active Front end, it can provide power throughout the sine wave. This will cause the harmonic content to be reduced to less than 5% at full load. Input waveform comparison is shown in Figure 8.

Most recently, larger utility companies have not required a low harmonic content from Rod Pump VSDs. Some smaller Cooperatives have required that consumers keep their levels below 8% harmonics. IEEE has established guidelines to help users determine reasonable harmonics. This is referred to as IEEE519-1992, in particular Tables 10.2 and 10.3 within this specification. The specification in many cases gets abused and overused because it was actually meant for entire facilities that have a single common power connection, not for a particular device connected within the system. Despite this fact, with heavy marketing, many manufacturers have touted meeting this spec with their device. Furthermore, the specification calls for measurements to be taken at "Full Load over 15 minutes”. Within the loading of a Rod Pump there is no such thing as full load for 15 minutes as the load is cyclic. Again, this has been pushed down from a few utilities as a requirement, yet the nature of the load defies this logic in rod pumping. It would however, be admissible with PCPs and ESPs.

The harmonic mitigation methods described previously are summarized in Table 1, particularly their reduction characteristics and relative cost. Looking into the future, power quality will begin to become stricter as an increasing amount of VSDs get added to the grid. Oil producers and VSD providers in the oil field will need to be aware of this early on. Performing Power quality predictions or analysis will then be essential. There are many 3rd party tools available to predict power quality based on the type of loads one might find on a power grid.

CONCLUSION

Variable Speed Drives have altered the way users design Rod Pumps. They allow the use of more efficient NEMA B type motor to be used. They allow infinite speeds to avoid sheave changes. Their slow-startups reduce wear on the pumping unit, rods and pump. Indeed, the future may bring some challenges as harmonic content is examined by the utility providers. Staying one step ahead will provide a means to deal with such requirements.

Table 1
Harmonic Mitigation Techniques

Mitigation Technique	THD (current)	Relative Cost
6-pulse VSD, no reactor	50-75%	$
6-pulse VSD with 3% reactor	35-40%	$
6-pulse VSD with 5% reactor	25-35%	$
12-pulse VSD	12-15%	$$
Harmonic Filter (passive LCL)	7-10%	$$
18-pulse VSD	4-6%	$$$
Active Front End or Active Harmonic Filter	3.5-5%	$$$

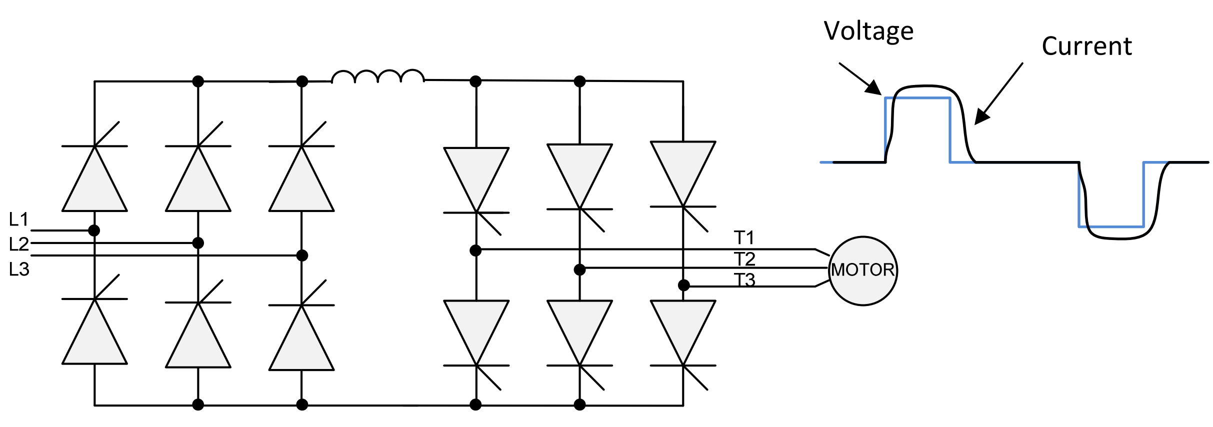

Figure 1 - Six step topology utilizing thyristors and resultant voltage/current on the motor.

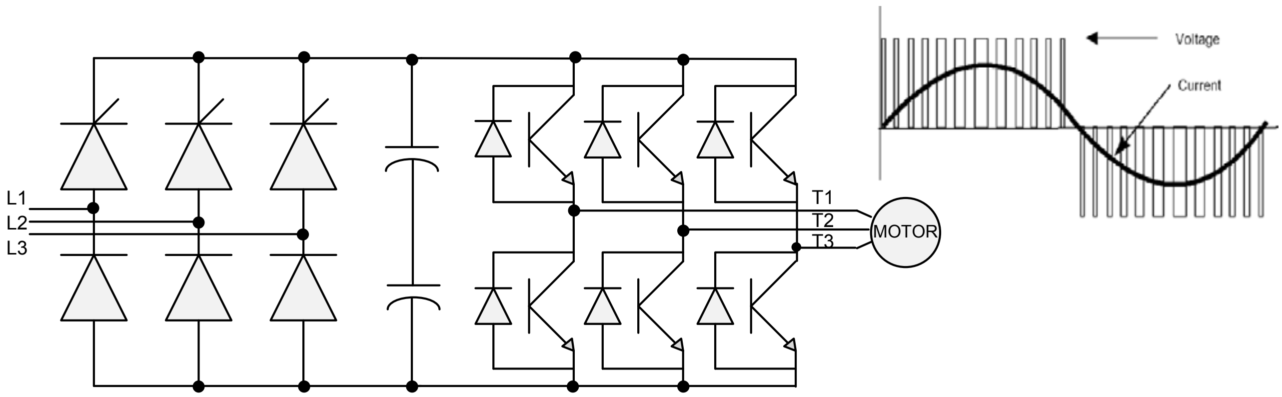

Figure 2 - Pulse Width Modulation utilizing BJTs and IGBTs and resultant voltage/current on the motor.

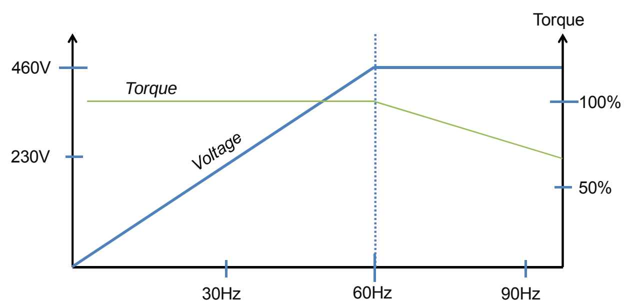

Figure 3 - V/Hz pattern with torque produced.

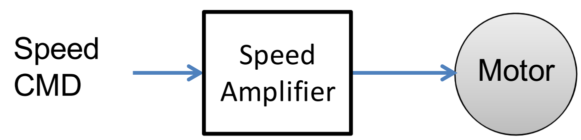

Figure 4 - V/Hz control diagram.

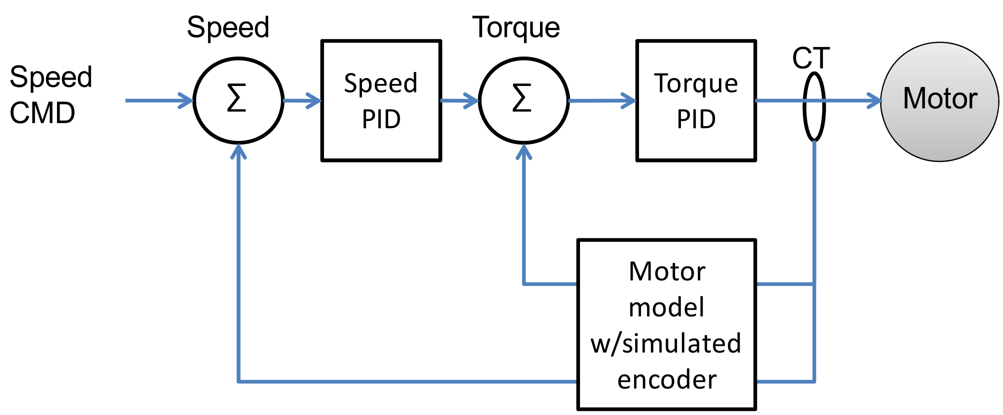

Figure 5 - Sensorless (Encoderless) Vector Diagram.

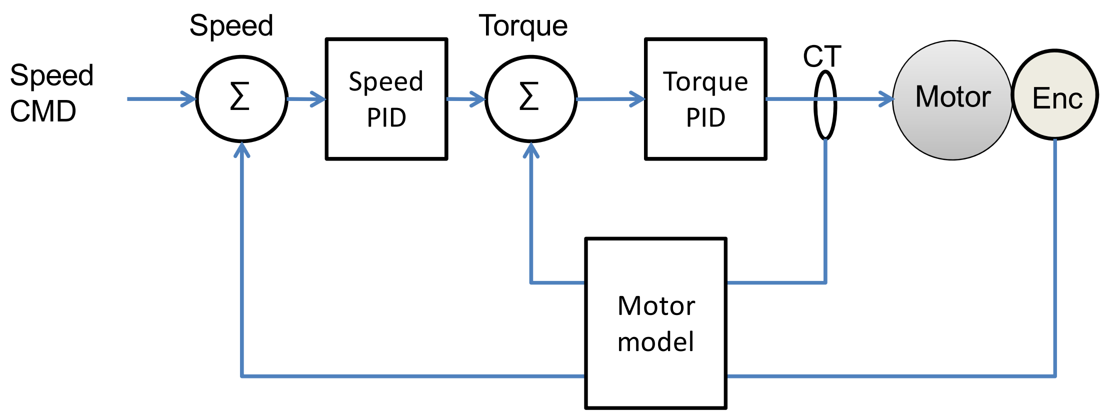

Figure 6 - Vector Control Diagram.

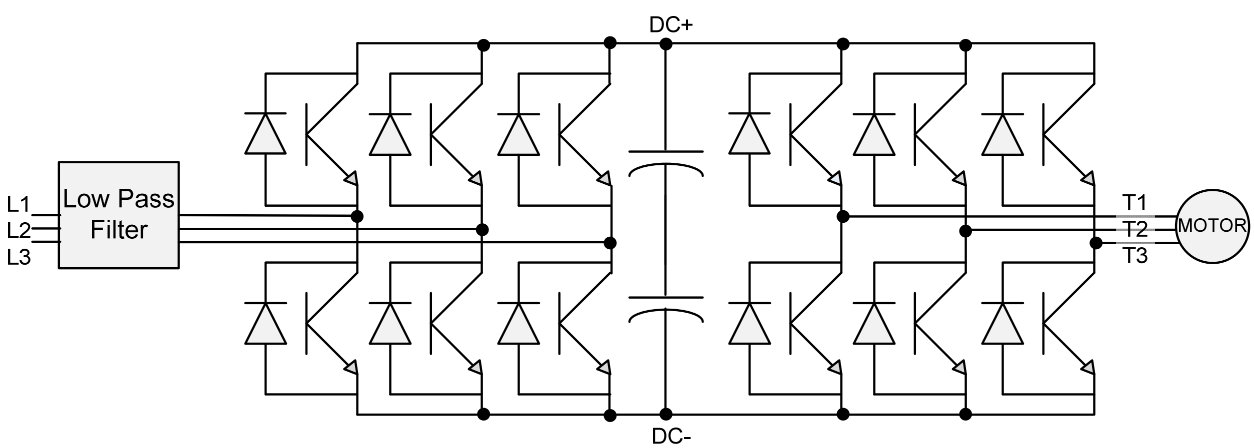

Figure 7 - Active Front End Drive

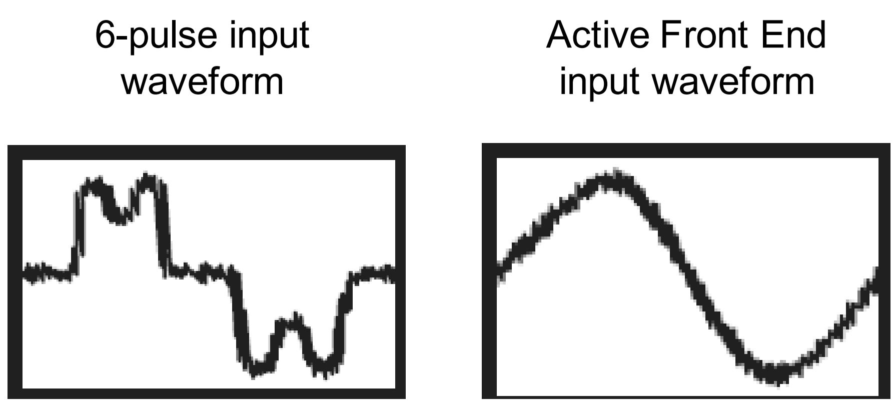

Figure 8 - 6-pulse waveform vs. AFE waveform.