Improving Motor Performance and Runtime in ESP applications with Novel Sinewave Filter

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Abstract *– In recent years, the Oil and Gas Industry has greatly improved efforts in evaluating the electrical system involved in operating Electrical Submersible Pumps (ESP). The negative effects that poor power quality has on ESP motors equipped with variable speed drives is generally understood by the industry. However, with a strong focus on optimization and reliability, improvements of the power quality provided to our ESP systems has tremendous potential to enhance the ESP lifecycle. This paper will provide a detailed description of the current mitigation technique involving the conventional designs of PWM sinewave filters. Additionally, this paper will outline multiple Case Studies that have been conducted on several wells with ESPs installed, that demonstrate the success of a new design approach for PWM sinewave filters yielding lower electrical distortion and significantly improved motor performance.*

A detailed analysis evaluating problems and premature failures was performed on existing ESP wells equipped with both "6-step" and PWM operation. Computer simulations executed to analyze the new sinewave filter design showed much lower voltage distortion (< 2%) as well as other important improvements in performance included a very low insertion loss (ie. < 3% drop in voltage at full load) and improvement in PF to near unity at the inverter output. To complete the study, sinewave filters were built, tested and installed in several wells. Field data was gathered providing power quality measurements for electrical distortion, current imbalance, motor temperatures, motor vibration and production rates.

The successful sinewave filter design used different tuned frequency parameters than conventional sinewave filters with clear data providing performance improvement. These results showed a substantial reduction in motor temperature leading to confidence in operations regarding the positive effect this would have on lifecycle of downhole equipment. The improvements can be streamlined across other ESP wells in the field leading to improved runtime, decrease in CAPEX & OPEX cost associated with ESPs and other surface equipment eventually leading to a strong cash flow performance for operators.

Index Terms — Electrical Submersible Pump (ESP), Artificial Lift, Pulse Width Modulated (PWM), Inverter, Sinewave Filter, adjustable speed drive (VSD), harmonics.

I. INTRODUCTION

Variable speed drives (VSDs) have become a standard part of Electrical Submersible Pump (ESP) systems. With the industry shift to unconventional plays (especially in the US market), VSDs have played a crucial role as a staple in all ESP designs. The operational flexibility created by VSDs allows for standardized pump designs, a wider operating range and improved electrical efficiency. In addition to these benefits, however, operators have discovered negative operational impacts as well. For instance, motor and cable insulation failure, higher motor temperature and vibration have contributed to lower run times. Therefore, many efforts have been exercised to find ways to increase runtime and lower operational costs due to the negative side effects of VSDs on the downhole system.

The front-end rectifiers of ESPs have been known to cause serious problems due to the high levels of current harmonics they generate and the subsequent voltage distortion that these current harmonics produce. Effective methods of eliminating these problems through harmonic mitigation equipment have been well documented [2][3][4], so will not be addressed further in this paper. Instead, the focus will be on the output side of the VSD and downhole.

In one oil field in the US Midwest, all ESPs designed for PWM inverter operation are equipped with sinewave filters in order to prevent overvoltage transients at the motors resulting from reflected wave phenomenon or harmonic resonance conditions. Unfortunately, on many of these ESPs the sinewave filters have failed, often after less than 6 months operation. This has either forced shutdown of the well until repairs could be made or the drives have been manually switched to 6-Step operation on those ESPs equipped with dual mode operation. In 6-Step mode, sinewave filters are not used, but this mode tends to operate with higher motor temperatures which also contributes to premature failures. When motors fail, replacement is prohibitively expensive since they require the use of a workover rig to remove the entire assembly. In addition to the OPEX cost needed to pull and replace the failed equipment, these premature failures also lead to extended downtime for oil production.

The engineering challenge was to design an effective and reliable PWM sinewave filter that extended the operating life of the PWM ESP and its associated downhole motor. This then would eliminate the need to switch to 6-Step operation and substantially reduce the resultant motor failures that were occurring in this operating mode.

II. THE IMPACT OF POWER QUALITY ON ESP SYSTEMS

While the subject of power quality in ESP systems is complex, it is useful for operators to have a high-level understanding of the subject. Poor power quality generates excessive heat, as well as mechanical and electrical stress.

Harmonic heating is observed throughout the ESP's electrical system which include the transformer, cable and motor. Current traveling down hole always generates heat. Generally, the heat load of this current is offset by cooling provided by the volume of well bore fluid that it moves. However, harmonic currents do not contribute to work in the motor. Therefore, all the heat from harmonic loads are expressed as motor temperature rise. A group of frequencies called negative sequence harmonics provide an additional source of heat in the system. Negative sequence harmonics rotate in the opposite direction of the fundamental. These signals make it slightly harder for the motor to spin forward. Since an equal amount of work must be done at the fundamental frequency to overcome negative sequence harmonics, the heat load generated by these frequencies is effectively doubled.

Poor power quality can cause mechanical stress to the motor. The fundamental frequency produced by a VFD is a signal that has a specific speed and direction. Relative to the fundamental, harmonic signals have different speeds, directions or both. The cumulative effect of these signals applied to the motor, is unstable torque applied to the motor shaft. This is often expressed as additional motor vibration. The torque applied to one end of the motor shaft may be slightly different than the other. This effect can be magnified by magnetic asymmetry of materials used to construct the rotor.

The loss of insulation integrity is a common cause of failure in ESP systems. The key contributing factors to insulation failure are voltage transients, voltage reflections and stray voltage. Much like briefly exposing a piece of pipe to excessive pressure will reduce the integrity of the pipe. In the same way, repeatedly exposing insulation to excessive voltage will eventually lead to failure. The primary source of excessive voltage is switching transients, which is when a sudden change in voltage that generates a brief but significant spike. The rapid switching of a VFD PWM output is a significant source of switching transients and will be discussed in greater detail later in this paper. Excessive voltage is also caused by reflective voltages. Since the motor and cable have large differences in a physical characteristic called impedance, high frequency harmonic waves will reflect off the motor windings and back up the cable toward the surface. This is very similar to the way sound waves reflect off hard surfaces toward the source causing an echo. Often, in ESP applications, these reflected waves will interact with another wave traveling towards the motor. When the two waves collide, they generate a very high voltage condition at a point in the cable or motor lead end (MLE). Finally, under certain conditions, stray voltages can be produced in the system that can damage insulation. The resistance value of insulation between conductors is related to the frequency of the signal. Very high frequency current can flow through conductor insulation, causing premature aging. High frequency currents can also exploit tiny flaws or voids in conductor insulation in a phenomenon known as partial discharge. There is a large body of published research on these topics, but they will not be discussed further here. Generally, minimizing high frequency signals and the conditions for excessive voltage are critical to reducing electrical stress on insulation.

III. OPERATING TOPOLOGIES OF ELECTRICAL SUBMERSIBLE PUMPS

A. 6-Step or Variable Voltage Input Drive

In their early years, adjustable speed drives operated as Current Source Input (CSI) or Variable Voltage Input (VVI) because the power devices available at the time did not offer high switching frequencies. Fig. 1 shows a typical VVI VSD schematic often referred to as 6-Step because six 60° steps are used to produce the output voltage in one complete 360° cycle (Fig. 2). As seen, the resultant voltage waveform is not sinusoidal, often with total harmonic distortion above 20%. AC motors can normally operate fine with this input voltage, provided no additional distortion is introduced from the application. In addition, the DC bus voltage must be controlled which requires an SCR input rectifier bridge rather than a simple diode bridge rectifier. This in turn, can introduce higher levels of input current harmonics, lower input power factor and voltage notching on the upstream distribution equipment.

For ESP applications, 6-Step drives are still often used because switching at lower frequencies can reduce the negative effects of the long cable runs between the drive and motor. By minimizing the number of switches in a cycle and reducing the magnitude of the change in voltage, the number and magnitude of voltage transients are reduced in kind. Despite this, destructive over-voltages can still be present and additional heat is generated in the motor.

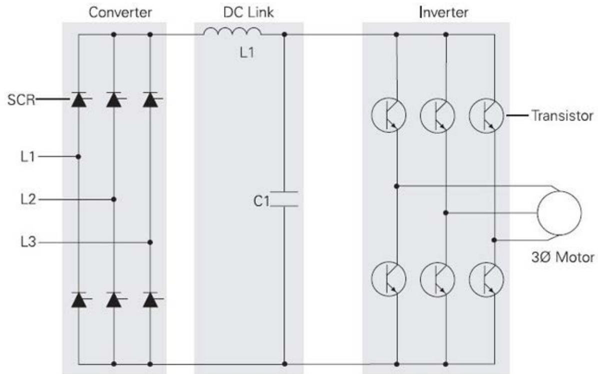


Fig. 1 Schematic Diagram for Typical 6-Step VSD with SCR Rectifier

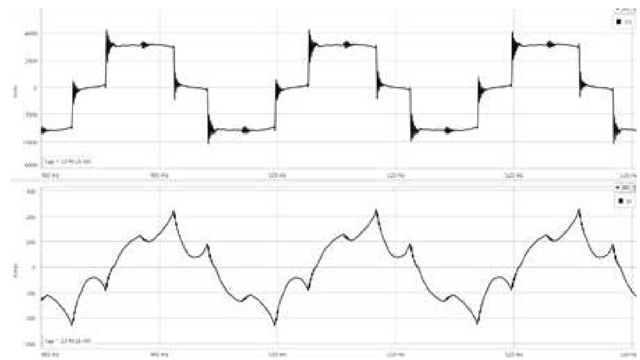


Fig. 2 Measured 6-Step VSD Output Voltage and Current Waveform

B. Pulse Width Modulated (PWM) Drive

PWM voltage source VSDs operate from a constant DC bus produced by an input diode bridge rectifier (Fig. 3). The inverter creates a simulated AC variable voltage and frequency by systematically switching the DC voltage to the output phases through six IGBT power switches. The inverter output line-to-line voltage is a series of pulses with constant amplitude at varying widths as shown in Fig. 4.

Insulated Gate Bipolar Transistors (IGBTs) have become the preferred switching devices for modern inverters because their high switching speeds allow for higher frequency PWM patterns which improve motor current waveforms and overall dynamic performance without introducing high switching losses. They do introduce negative effects however, which include high levels of harmonics, especially at the switching frequency. PWM has been known to cause Electromagnetic Interference (EMI) issues, both differential and common-mode, and overvoltages at the motor when long lead cables are used between the VSD and motor.

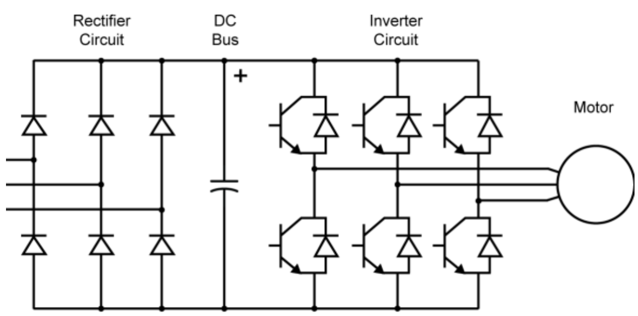


Fig. 3 Schematic Diagram for Typical PWM VSD with Diode Bridge Rectifier

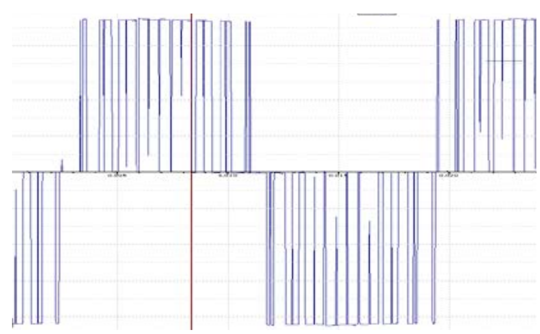


Fig. 4 Typical Output Voltage Waveform of PWM VSD

IV. ESP AND LONG MOTOR LEADS

In ESP applications, the location of the motor near the bottom of a deep well requires extremely long cable runs between the motor and the VSD located at the surface. A phenomenon known as 'reflective waves' can result in over-voltages at the motor terminals, often as much as twice the applied voltage. Reflective waves occur due to an impedance mismatch at the motor terminals and the fast rise times of the PWM DC pulses. As the inverter voltage pulse travels along the leakage inductance and capacitive coupling (LC network) of the cable (Fig. 5), a capacitance charge builds up in each LC section until it reaches the motor end. At this point, the higher impedance of the motor relative to the cable will reflect the voltage back along the cable producing a traveling wave. Once it reaches the inverter end, it will be reflected back but with a negative polarity. If this negative reflected wave reaches the motor terminals while voltage is still building up at the motor terminal from the initial reflection, it will reduce the voltage buildup and reflect back again. These reflections will repeat and depending on the relative length of the cable, up to twice the nominal voltage can develop at the motor terminals.

Fig. 6 shows estimated values of per unit (PU) voltage increase with respect to cable length and PWM pulse rise time [8]. Older slow switching devices produce lower over-voltages at longer distances. With their higher switching speeds, IGBTs introduce over-voltages at shorter cable lengths. Since most ESP installations are installed hundreds, even thousands of meters deep, the potential for a 2x PU voltage increase can generally be assumed. These over-voltages can lead to stresses on the motor insulation system resulting in reduced motor life.

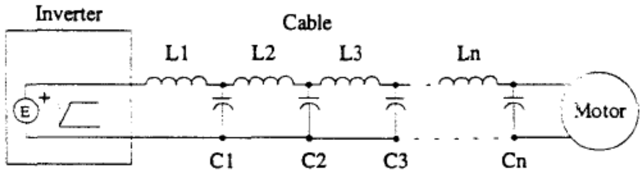


Fig. 5 Equivalent Circuit of Long Cables Similar to Transmission Line Effect [7]

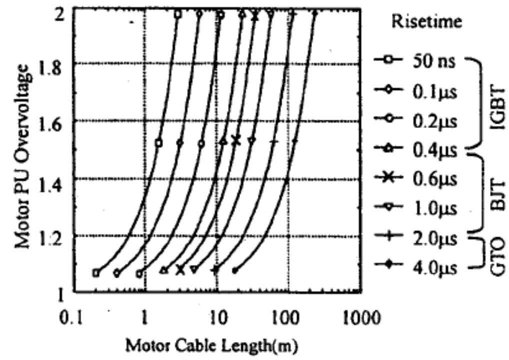


Fig. 6 Motor PU Overvoltage vs Cable Length and Rise Time [8]

When voltage steps are less frequent and rise times somewhat slower, as in 6-Step operation, there is less build-up of voltage and the inductance in the motor winding will more evenly distribute this overvoltage among the windings. However, experience has shown that the over-voltages are not eliminated entirely. Premature motor failures still exist due to these remaining over-voltages as well as the heating that results from higher losses in the motor.

Fig. 7 shows the voltage waveform at the secondary of the step-up transformer on a 1000 HP ESP system operating in 6-Step mode. Voltage distortion was over 20% with obvious over-voltages and ringing. Although there are only six voltage steps during each cycle, each step still has a fairly steep rise time. This, results in the voltage over shoot and ringing which contributes to premature motor failures. In PWM operation without filtering, this would be more severe because it would occur many more times in the pulsed DC voltage. The fact that it occurred six times each cycle in 6-Step operation, still caused premature motor failures and therefore, presented a serious problem.

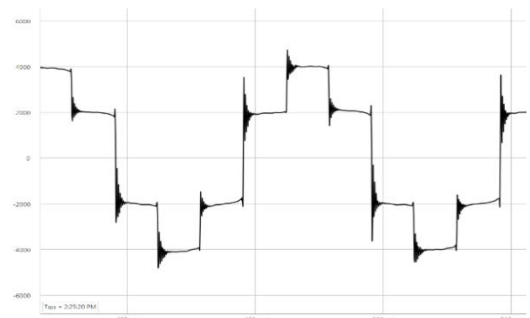


Fig. 7 ESP 6-Step Voltage at Secondary of Step-up Transformer

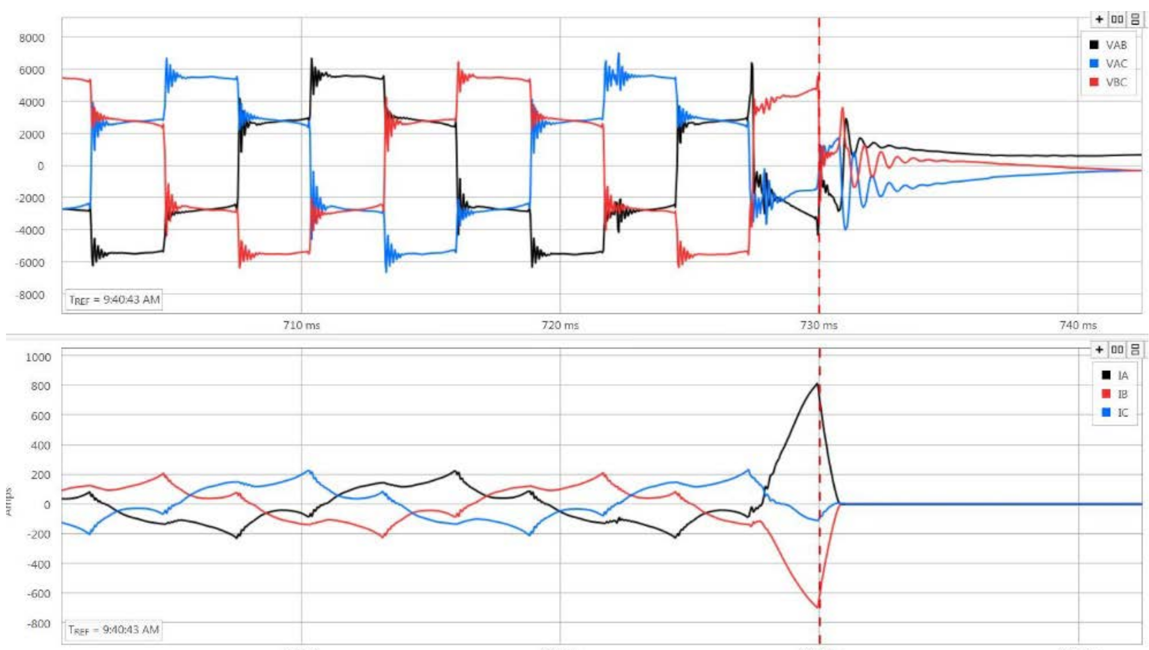


Fig. 8 Voltage and Current Measurements on an ESP Operating in 6-Step Mode at the Moment of Motor Failure

Fig. 8 shows voltage and current measurements on an ESP installation operating in 6-Step mode at the moment of motor failure. Prior to failure, the over-voltages and ringing in the voltage can clearly be seen. It should also be noted that insulation failure occurs at the instant that the switching transient is applying maximal stress. When the motor fails, current momentarily increases as it feeds into the fault and the voltage collapses. This is one example of many motor failures that were occurring across multiple wells in the oil field.

As previously mentioned, in PWM operation, the higher switching speeds and faster rise times lead to voltage overshoot which causes more severe ringing. Also, the motor winding appears more like a network of capacitive elements which leads to much higher voltages at the first turn of the motor winding. The resulting dielectric stress can lead to premature motor failure unless output filters are used to smooth out the PWM pulses. In addition, making the voltage more sinusoidal can also prevent inverter overcurrent faults that result from the charging and discharging of the cable capacitance with a pulsed inverter output voltage [8].

V. INVERTER VSD OUTPUT FILTERS

Conventional sinewave filters are intended to produce a near sinewave voltage from the pulsed DC voltages of a PWM inverter. Although these can be effective in many VSD applications, the extremely long cable runs and severe environments of most ESP applications, often result in premature filter failures forcing the operators to shut down the ESP or revert to 6-Step operation if available.

To achieve a near sinusoidal voltage, the filter's tuned frequency must be well below the switching frequency. In ESP applications, the IGBT switching frequency is usually in the 2 to 8 kHz range and typically, the larger the size of VSD the lower the switching frequency. Of course, the filter's tuned frequency must also be comfortably above the inverter's output fundamental frequency. Commonly accepted practice is to design for a cutoff frequency approximately 10x above the fundamental frequency and, at least, 2 to 2.5x below the switching frequency [9][10][11]. Therefore, a 600 Hz cutoff frequency would be suitable for a 60 Hz inverter output voltage with a switching frequency above 2 kHz.

However, when tuned to higher cutoff frequencies, it is important to damp potential resonance of the filter with the downhole cable and motor. Therefore, resistors would typically be added to produce a second-order RLC network as shown in Fig. 9. Unfortunately, in an effort to reduce cost, many manufactures offer filter designs without resistors. Without a way to damp resonance conditions, filter performance and reliability suffer. Fig. 10 shows the measured voltage waveform at the secondary of the downstream step-up transformer of an ESP equipped with a conventional sinewave filter. As can be seen, significant levels of high frequency voltage ripple remain.

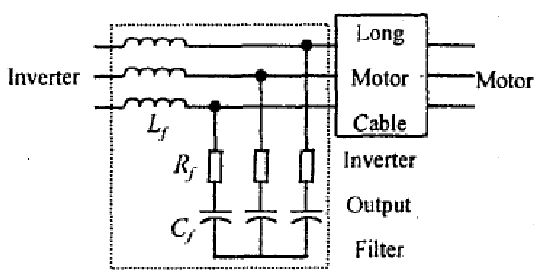


Fig. 9 Second-order Inverter Sinewave Filter [8]

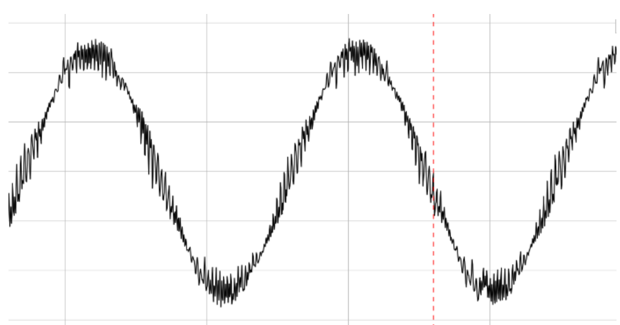


Fig. 10 Voltage Waveform at Secondary of Step-up Transformer with PWM ESP Equipped with Conventional Sinewave Filter

VI. IMPROVED SINEWAVE FILTER DESIGN

Design criteria for an improved sinewave filter focused on a target of < 3% voltage harmonic distortion and < 5% current harmonic distortion. Also, it was determined to be important that the design inherently limit system resonance without the need for damping resistors. Computer analysis was used to investigate several tuned frequency points for the filters.

Initial analysis was done for a 200 HP, 480V, 60 Hz ESP system. Figures 11a and b show inverter output voltage waveform and spectrum switching at 2 kHz. As expected, predominant harmonics are at the switching frequency and multiples of that frequency. Performance of the filter in reduction of switching frequency harmonics was quite poor with the filter tuned to 600 Hz – 10x the output frequency which conventional design practice recommends. vTHD (Voltage Total Harmonic Distortion) was nearly 9.1% (Fig. 11c and d) and iTHD (Current Total Harmonic Distortion) above 8.7% (Fig. 11e and f). This would indicate a resonance condition exists when tuned near 600 Hz. Adding resistors to the filter helped reduce the resonance but not enough to be comfortable with the design. Similar results were achieved for the 1100 HP, 480V, 60 Hz ESP system when designed for a tuned frequency of 600 Hz.

Fig. 11a Inverter Output PWM Voltage Waveform at 2 kHz Switching Frequency

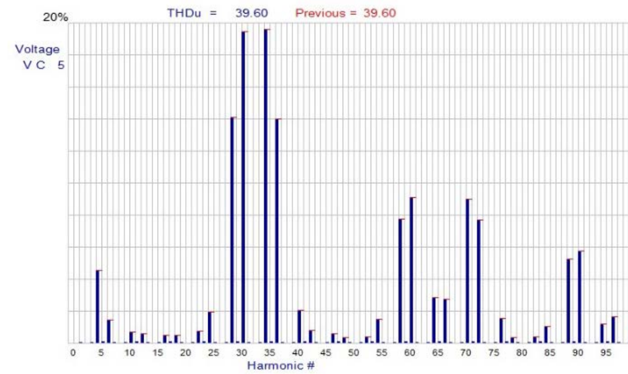


Fig. 11b Inverter Output PWM Voltage Spectrum at 2 kHz Switching Frequency

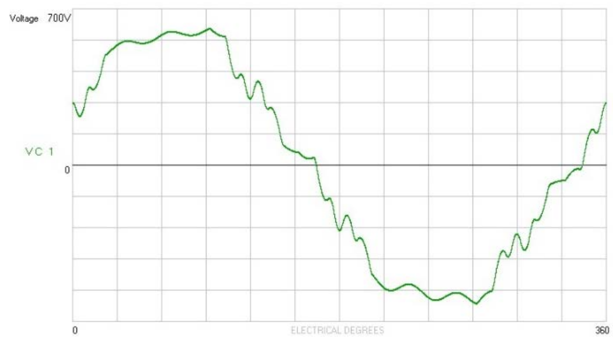


Fig. 11c Output Voltage Waveform for Sinewave Filter tuned to 600 Hz operating at 2 kHz Switching Frequency

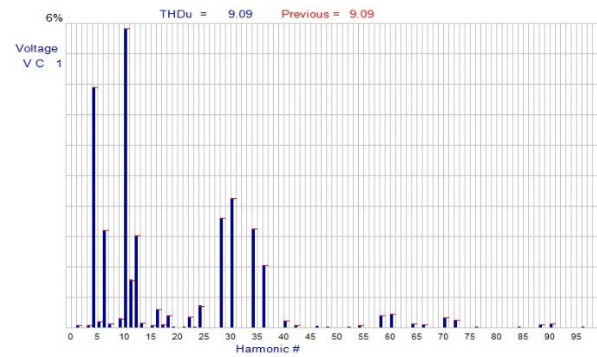


Fig. 11d Output Voltage Spectrum for Sinewave Filter tuned to 600 Hz operating at 2 kHz Switching Frequency

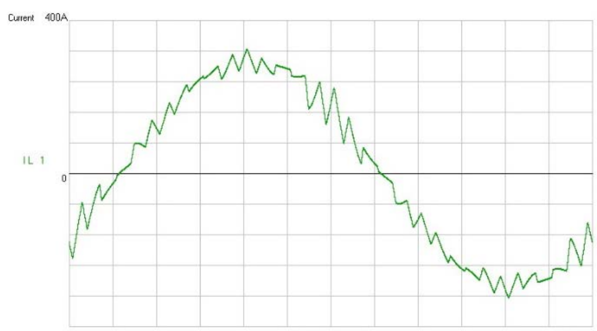


Fig. 11e Inverter Output PWM Current Waveform at 2 kHz Switching Frequency

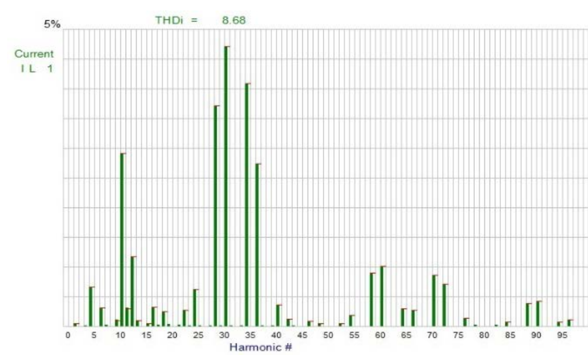


Fig. 11f Inverter Output PWM Current Spectrum at 2 kHz Switching Frequency

Better performance was achieved when the filter was tuned near 180 Hz with no apparent system resonance even without resistors. Figures 12a and b show voltage waveform and spectrum at sinewave filter output for a 200 HP, 480V, 60 Hz filter tuned to 180 Hz with vTHD < 2%. Similar results were achieved for the 1100 HP, 480V, 60 Hz ESP system. Other important improvements in performance included a very low insertion loss (ie. < 3% drop in voltage at full load) and improvement in PF to near unity at the inverter output.

Fig. 12a Output Voltage Waveform for Sinewave Filter tuned to 180 Hz operating at 2 kHz Switching Frequency

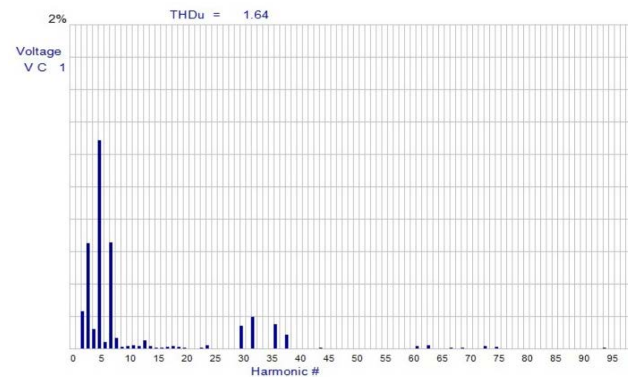


Fig. 12b Output Voltage Spectrum for Sinewave Filter tuned to 180 Hz operating at 2 kHz Switching Frequency

VII. MOTOR REACTIVE POWER COMPENSATION BY FILTER CAPACITORS

One advantage of sinewave filters is that their capacitors provide some compensation for the inductive reactive power of the motor [10]. The proposed design goes a step further by nearly fully compensating for this inductive reactance resulting in a power factor (PF) at the invertor output of near unity. In the simulation for the 1100 HP filter, motor displacement PF was assumed to be 0.82. By adding the appropriate amount of capacitance, the PF upstream of the filter can be improved to 0.98 which can reduce the inverter current by ~14%. Fig. 13 shows the real power draw of 886A and 144A of inductive current at both the motor and inverter with no sinewave filter installed. With the sinewave filter, its capacitors now provide the 144A of inductive current removing that requirement from the inverter. The reduction in load current substantially offloads the inverter reducing its losses and extending life expectancy. The addition of the proposed sinewave filter could also allow for slightly larger downhole equipment to be utilized without replacing the VSD. Reducing the capital requirements for an incremental increase in production.

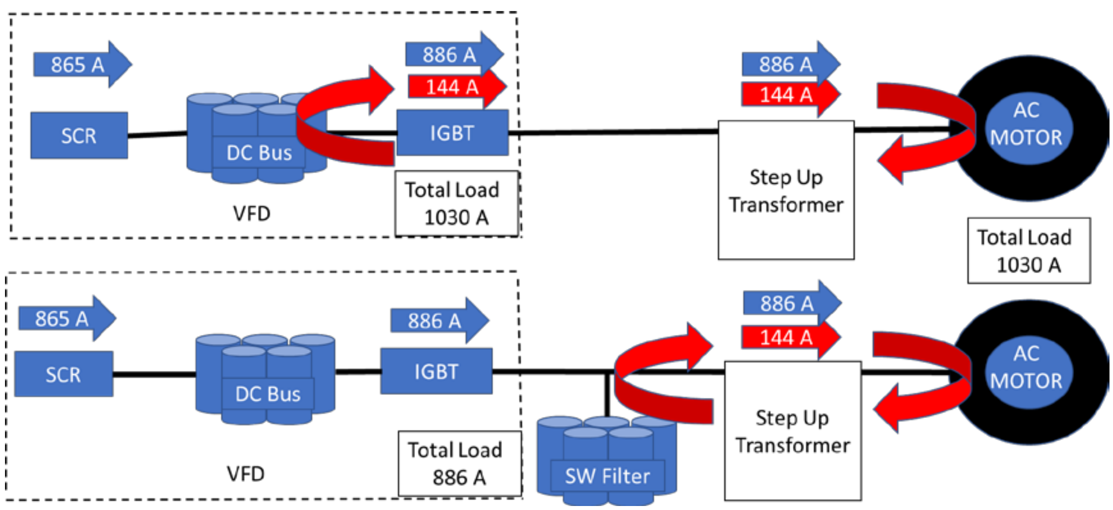


Fig. 13 Reduction in Inverter Current due to PF Correction at Sinewave Filter Input

VIII. FIELD CASE STUDIES AND MEASUREMENTS

A. Case Study 1: 200 HP, 480V, 60 Hz ESP

The operators of an oil field in the US Midwest experienced many catastrophic sinewave filter capacitor bank failures in existing ESP wells, often after only 6 months or less operation. After several unsuccessful attempts to repair the filters, they were abandoned and the VSDs were operated in 6-Step mode. Often however, this resulted in motor failures occurring consistently after only a few months to < 18 months of operation. Commonly, failures were electrical in nature (typically insulation breakdown shorting to ground). Power quality meters recorded high levels of voltage switching transients at the secondary of the step-up transformer downstream of the VSD, similar to Fig. 7. A decision was made to investigate the possibility of incorporating sinewave filters that were more suitable for the application. A 200 HP well was chosen for the initial pilot.

As described in Section V, computer simulations for a design that matched the commonly accepted practice of tuning the filter to at least 10x the output frequency of 60 Hz (ie. 600 Hz), resulted in poor performance. Quite high levels of distortion remained in the output voltage of the filter (Fig. 11c and d). After performing several iterations, an optimal design tuned near 180 Hz was found to have excellent simulation results as shown in Fig. 12a and b.

Fig. 14 shows the decrease in motor operating temperature while Fig. 15 shows the improvement in motor vibration that was achieved after the filter was installed. In addition to the increased oil production, this filtered PWM install also led to a record operating runtime (Fig. 23). Previously, the longest runtime record while running in unfiltered 6-step was 984 days. As of the writing of this paper, the well continues to run after 2,092 days. This type of runtime extension plays a significant impact in the OPEX cost associated with downhole failures as well as preventing unplanned downtime to operations.

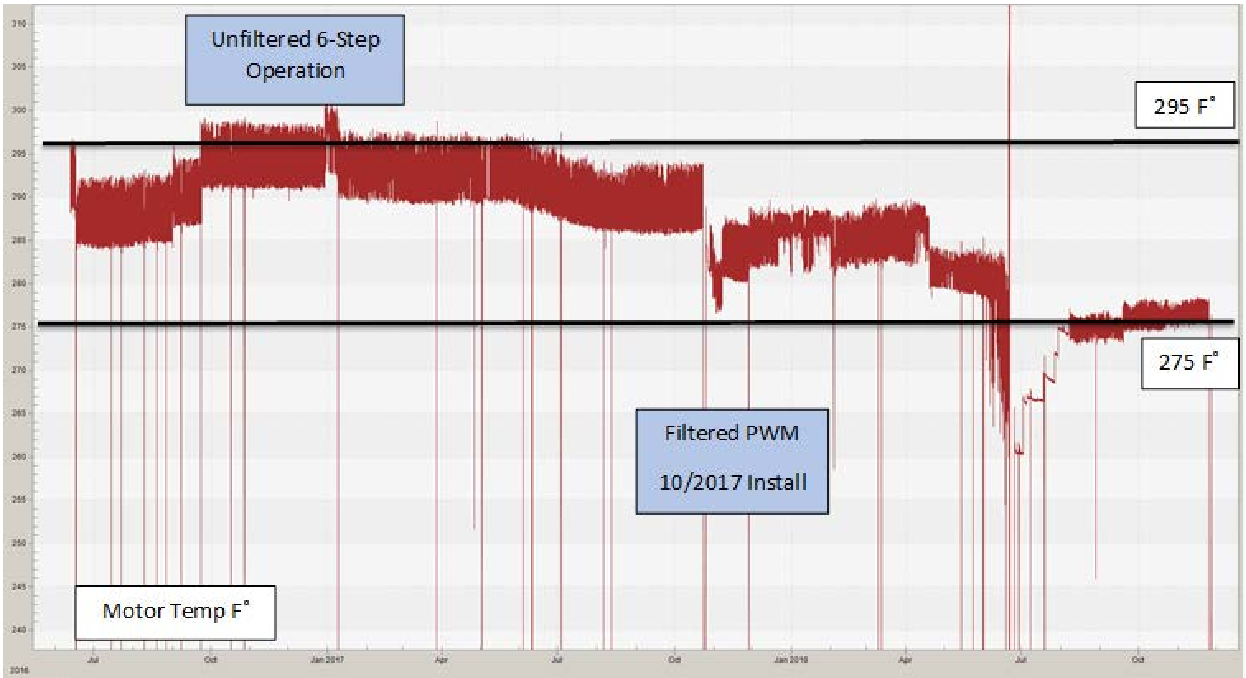


Fig. 14 Significant Drop in Operating Motor Temperature post Filter PWM install.

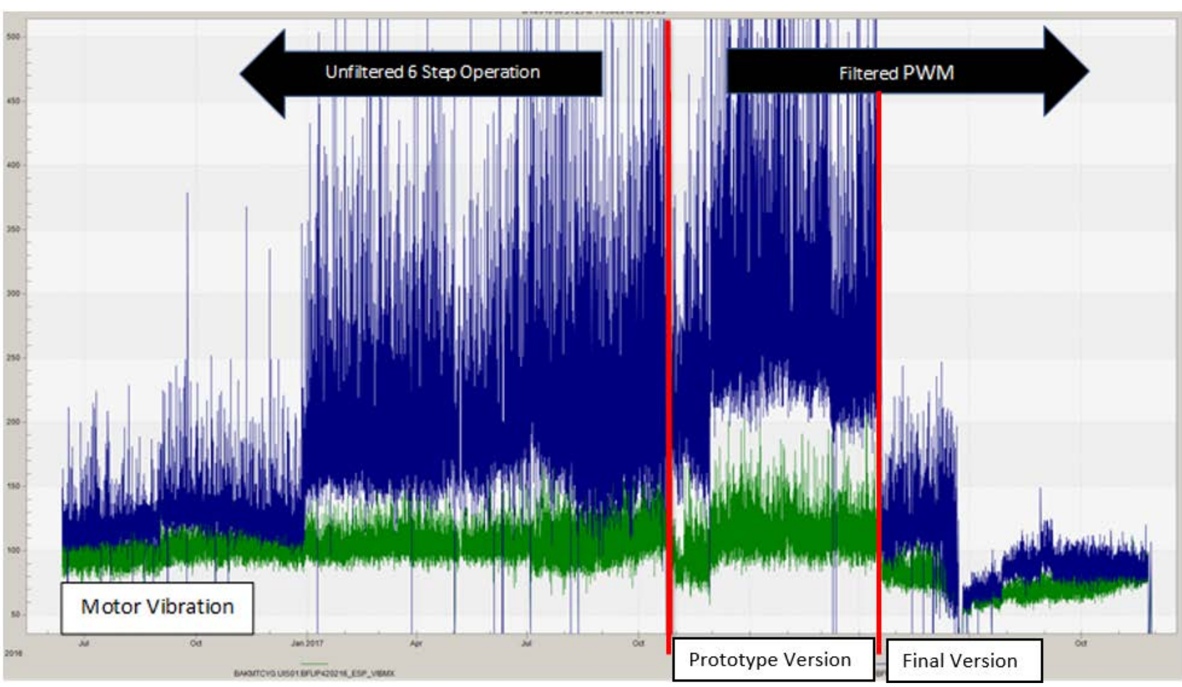


Fig. 15 Motor Vibrations were Substantially Reduced following Filtered PWM install

After the initial success on the 200 HP system, the goal was to take the learnings and application to other areas of the field facing premature failures. These given case studies have been conducted in a mature waterflood asset that is reliant on source water volumes to help maintain an Injection Withdrawal Ratio (IWR) of 1 or higher to reach reservoir management goals. In order to accomplish this, large ESP systems are designed to produce in upwards of 25,000 bwpd typically with 1100 HP systems. Historically, the well design struggled with reliability and often saw runtimes between 6-12 months. Not only did these premature failures lead to higher workover costs and equipment costs but, more so, the injection plant downtime led to large voidages in the reservoir leading to lost reserves. Therefore, this larger well design was chosen for the second installation.

B. Case Study 2: 1100 HP, 480V, 60 Hz ESP

An 1100 HP, 480V, 60 Hz sinewave filter was designed with a tuned frequency of 180 Hz. After installing the new sinewave filter at the existing well, the ESP was restarted in PWM mode.

Fig. 16 1100 HP Sinewave Filter Installation

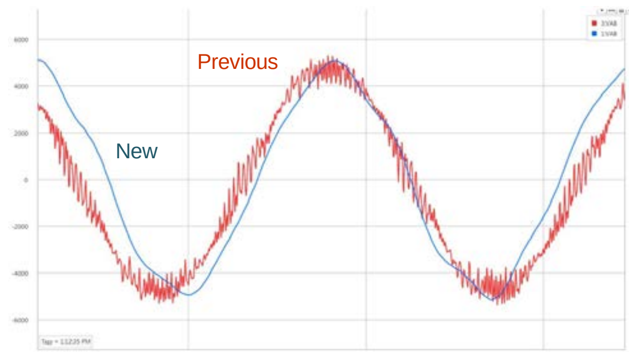


Fig. 17 Comparison of Voltage Waveforms on 1100 HP PWM ESPs Equipped with New and Conventional Sinewave Filters

Fig. 17 shows a side by side comparison of the output voltage waveforms of both a new design sinewave filter and a conventional design sinewave filter on an 1100 HP ESP operating in PWM mode. The higher frequency ripple with the previous filter is clearly evident.

Fig. 18a and b also show the measured output voltage of the new sinewave filter. Although the voltage distortion at 6.1% was higher than the simulation results (Fig. 12a), it was comfortably below the 8% recommended by IEEE Std 519, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems [12]. Also, there was no evidence of harmonics around the PWM switching frequency (ie. 33rd harmonic or 2 kHz) which confirmed the effectiveness of the filter. And this voltage distortion was much lower than the 28% distortion measured previously under 6-Step operation (Fig. 19a and b).

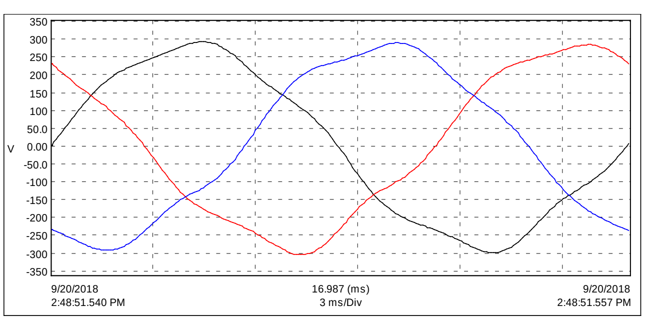


Fig. 18a Measured Output Voltage Waveform for 1100 HP Sinewave Filter operating at 2 kHz Switching Frequency

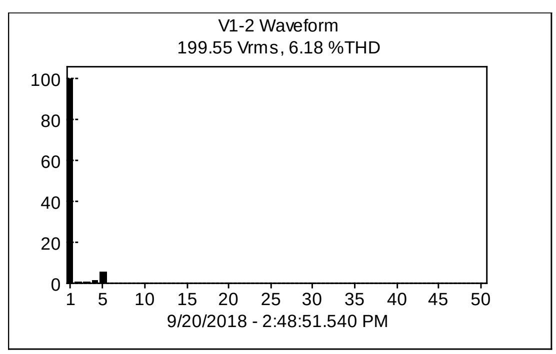
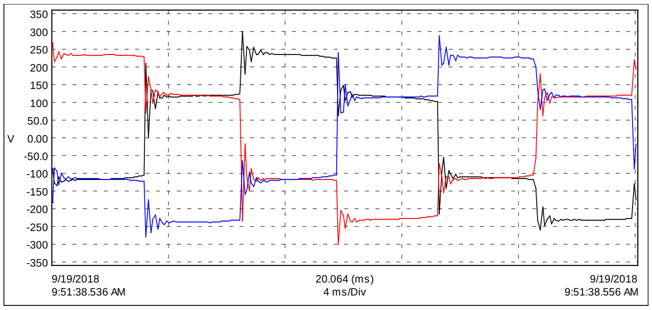


Fig. 18b Measured Output Voltage Spectrum for 1100 HP Sinewave Filter operating at 2 kHz Switching Frequency



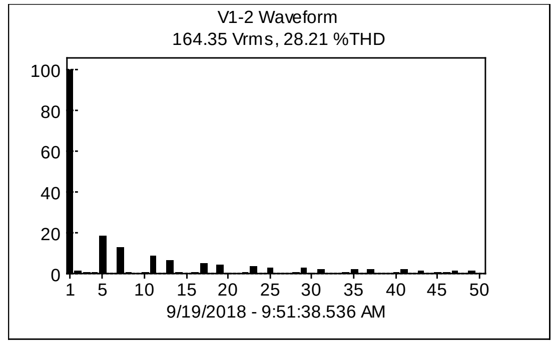


Fig. 19a Measured Output Voltage Waveform for 1100 HP ESP operating in 6-Step Mode

Fig. 19b Measured Output Voltage Spectrum for 1100 HP ESP operating in 6-Step Mode

Almost immediately, a significant reduction in motor operating temperature was observed. Fig. 20 shows the drop in motor operating temperature after switching to PWM mode operation with the sinewave filter. The high spikes in temperature occur when the ESP has been restarted after being shutdown. Although momentary, these increases in motor temperature put substantial stress on the motor. These momentary temperature spikes are particularly detrimental to ESPs due to the impact on self-equalizing motor seals. Motor oil in the seal expands and is discharged into the well bore when the motor temperature rises and contracts as it cools, bringing well bore fluid into the seal. While to some degree the well bore fluid contamination in the seal is unavoidable, it is believed that eliminating severe temperature spikes will dramatically improve the life of the motor seal section. Motor seal failures are not typically thought of as an 'electrical' failure but electrical thermodynamics can have an impact on the mechanical integrity. After installing the sinewave filter and operating in PWM mode, the startup motor temperatures were reduced by nearly 40° F. This is especially important due to the reactive and volatile nature of a Water Source Well (WSW) operating in a mature waterflood.

Motor temperatures during continuous operation also dropped significantly from 260° F to 245° F or over 5%. Also, the measured voltage drop of < 3% across the filter while running at top speed was as per design. Previous sinewave filters introduced a voltage drop of around 10%. With a lower voltage drop, voltage to the motor was proportionately higher which decreased motor current and its associated losses. This contributed to the net reduction in motor operating temperature. Given these results, the well saw a dramatic improvement in runtime by 70%.

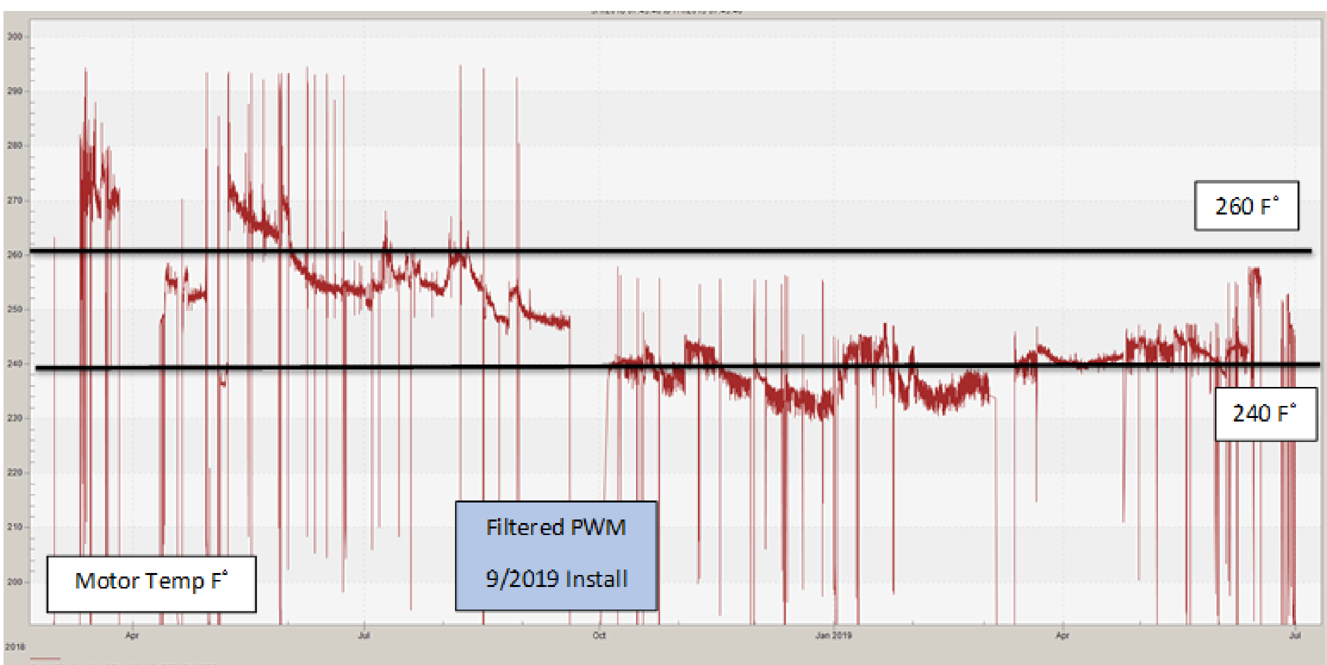


Fig. 20 Drop in Motor Operating Temperature during Start-up after Switching to PWM with Sinewave Filter

C. Case Study 3: 250 HP, 480V, 60 Hz ESP

A filter was built and installed on an existing 250 HP well which originally was not equipped with a sinewave filter. At this site, the combination of reduced motor temperature and reduced VSD current, resulting from PF improvement, allowed the operator to increase well production by increasing VSD operating speed. The given well historically carried a higher fluid level than intended by the operator due to the motor temperature restriction. Previous efforts to increase production by increasing VSD operating speed resulted in excessively high motor temperatures requiring that the experiment be abandoned. Even at the increased VSD speeds, motor vibrations were substantially reduced (Fig. 22). The success in oil production increase inspired the operator to consider other well sites where increased production might be possible by simply installing a sinewave filter and increasing the size of the step-up transformer if required. This type of approach is especially important when you consider the scalability across the field. Not every well can cover the individual CAPEX to upgrade the system on surface and downhole. Once the filter was installed, it allowed the operator to achieve the highest operating frequency historically and improved the drawdown by 50%. Not only did surface runtime improve on the ESP system but the incremental oil gain led to production optimization.

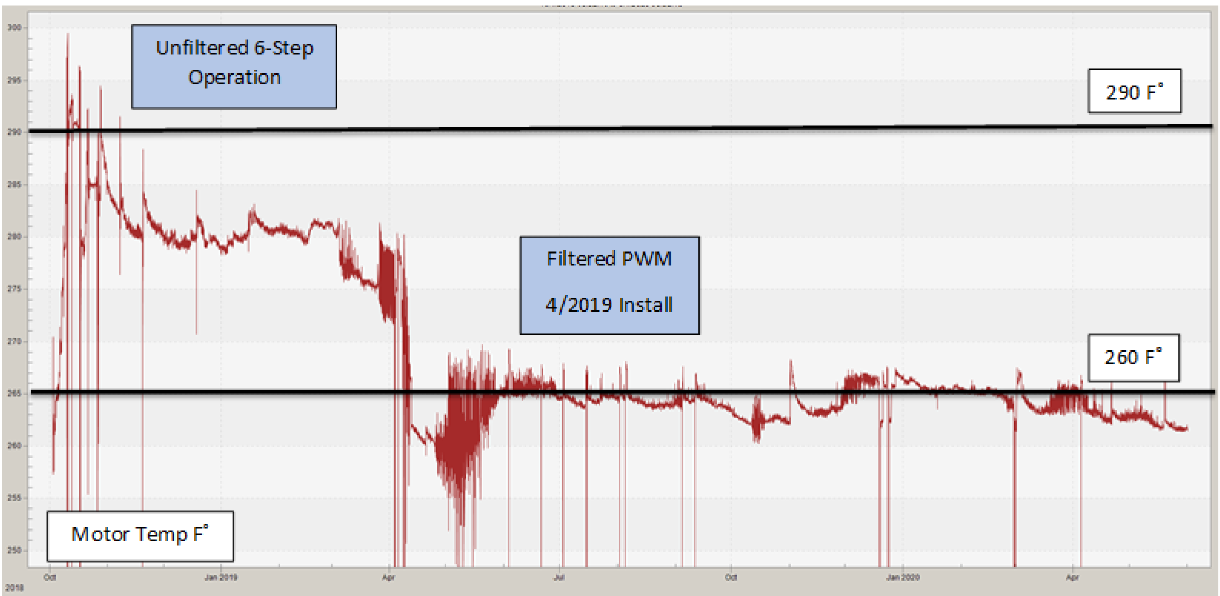


Fig. 21 After installing Sinewave Filter, the ESP Motor experienced a 25F˚ drop in Motor Operating Temperature

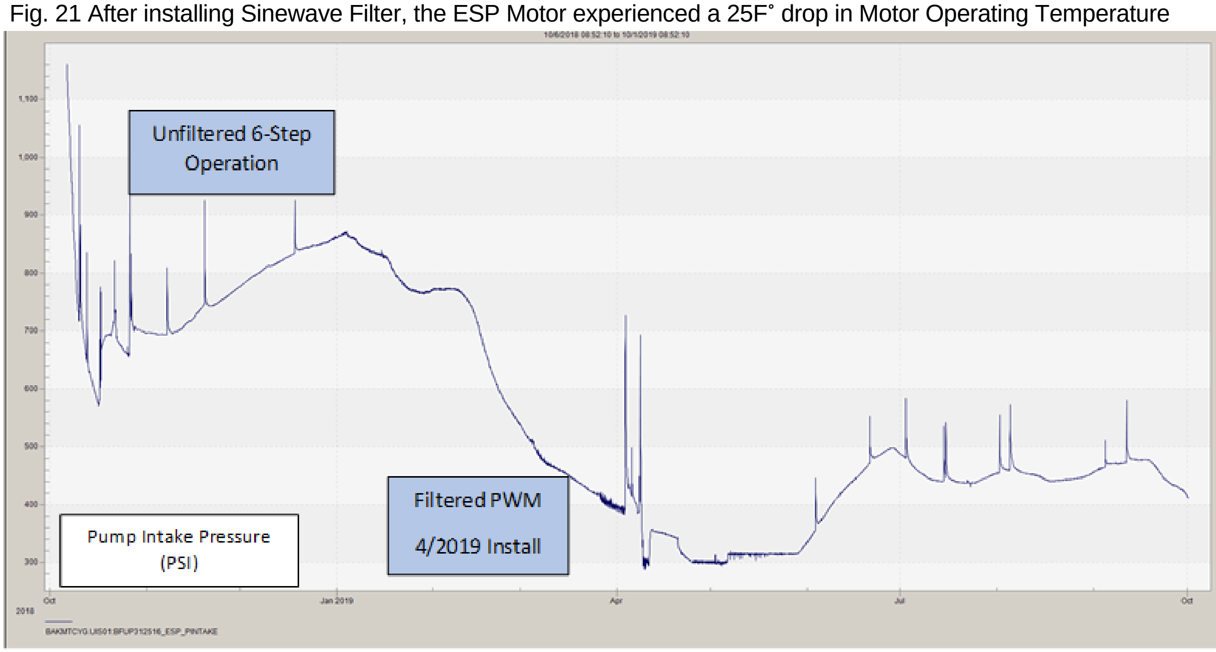


Fig. 22. Pump Intake Pressure (pip) Target achieved on Oil Producer once Electrical Limitations were removed while running in a Filtered PWM Mode

XI. CONCLUSIONS

Successful application of sinewave filters on ESP wells fitted with PWM VSDs in a mature waterflood oil field in the US Midwest was documented. Sinewave filters of conventional design were failing prematurely which forced the operators to switch from PWM to 6-Step operation. However, in 6-Step mode, the high VSD output voltage distortion and over voltage transients associated with reflective wave phenomenon and resonance with the step-up transformer and downhole cables were causing premature motor failures due to high temperatures and insulation fatigue. The unfortunate consequence of switching to 6-Step operation led to nonoptimal oil recovery, increased field OPEX, and waterflood injection downtime issues.

The successful sinewave filter design did not follow the commonly accepted practice of tuning the filter to no less than 10x the output frequency because computer simulations showed high distortion levels when designed this way. This is a great example of taking unorthodox approaches to find new ways to maximize the current technology the operator owned in the field. A design based on tuning at 3x the output frequency showed better performance in simulations and therefore was chosen for 480V, 60 Hz ESPs of 200 HP, 1100 HP and 250 HP ratings. Moving forward, this approach has been implemented across other assets for the operator proving the scalability and versatility of the technology and findings.

Field measurements matched simulation results very well and substantial reductions in motor temperature were easily documented and sustained. These operating improvements in combination with the elimination of over voltage transients and ringing has significantly increased the life expectancy of the motors with record runtimes achieved at all well sites. Fig. 23 shows the runtimes between failures for the wells of each Case Study. Except for 2021, each year with a bar reflects a failure in that year. 2021 shows YTD with no failures as of the time of this writing. After the sinewave filter installations, Case Studies 1 and 2 have set new runtime records while Case 3 continues to operate without failure but has not yet reached the previous record runtime operating duration. As a result, the operator has realized substantial cash flow improvements and further application of these sinewave filters at other well sites are anticipated.

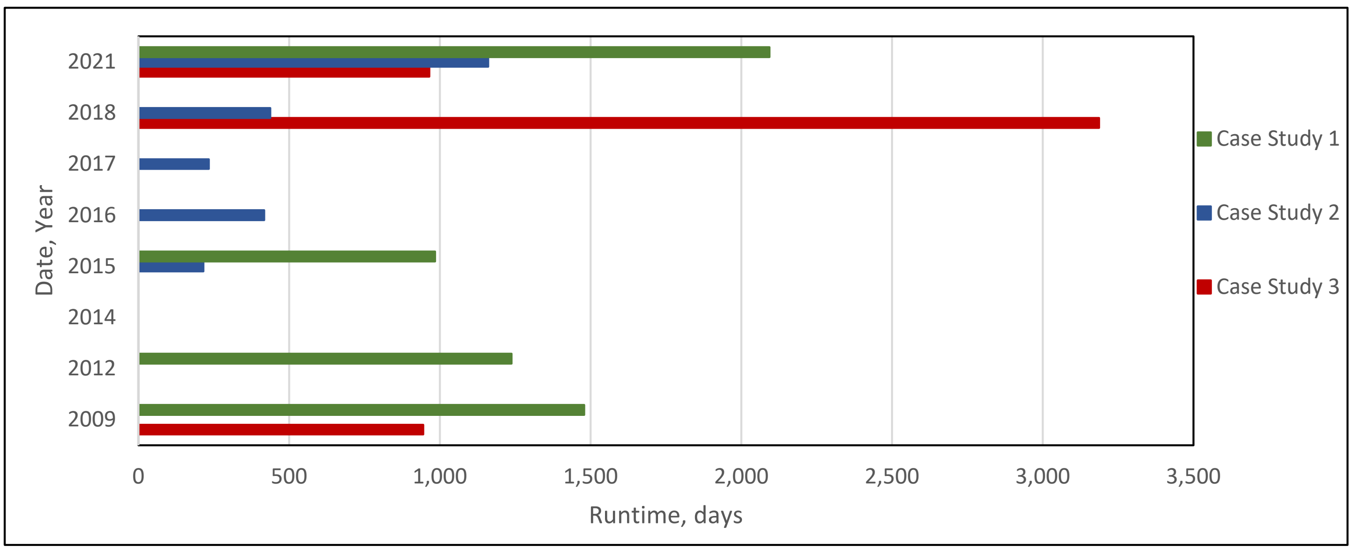


Fig 23. Runtime between Downhole Failures recorded for Three Case Studies. Case Study 1 & 2 both exceed previous Runtime Records after PWM Filter install (10/2017 and 9/2018 respectively)

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II. VITAE

Anthony (Tony) Hoevenaars (BESc’79) is President and CEO of Mirus International, Brampton, ON, Canada, a company specializing in the treatment of power system harmonics. With over 35 years of direct experience in resolving electrical power system problems, beginning in the 1980s as Chief Facilities Electrical Engineer at an IBM manufacturing facility in Toronto, Tony has earned an international reputation as a power quality and harmonics expert. As a Professional Engineer, Tony has published various papers on power quality. He is an active member of the IEEE having presented papers at PCIC conferences in 2003, 2008, 2009, 2010, 2014, 2015, 2016, 2018 and 2019.

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