HIGH FREQUENCY COMMON MODE (L-G) PHENOMENA AND ASSOCIATED EFFECT ON ESP AND MECHANICAL RUN LIFE.

March 2021 Update: Proper Root Cause Failure Analysis uncovers the truth about ESP system failures. A Common Mode Filter added as a standalone component will aid in the overall run life of the ESP.

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White Paper:

High Frequency Common Mode (L-G) Phenomena and Associated Effect on ESP and Mechanical Run Life

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Knowledgeable resources are essential when conducting a failure analysis. The high frequency unfiltered common mode Line-to-Ground (L-G) noise associated with Pulse Width Modulation (PWM) Variable Speed Drive (VSD) operations can lead to electrical reflections and mechanical damage in Electrical Submersible Pump (ESP) systems. The Sine Wave Filters (SWF) that are applied to PWM VSDs today only filter the Normal Mode Line-to-Line (L-L) noise. Electrical anomalies can and will lead to mechanical failures. Using VSDs for well operations will induce electrical stress in many ways. Observed failures include:

- Thermal Failures due to high-frequency, skin-effect heating.
- Bearing Fluting due to high frequency discharges through the bearings.
- Shaft Breaking due to torsional harmonics.
- Through the unintended capacitance in the system, the high frequency content has also been observed to cause unexpected failures such as:
    - Tubing/Casing failures due to electro-etching.
    - Motor winding insulation failures.
    - Phase-to-phase and/or phase-to-ground failures to the cable, penetrator, and/or the Motor Lead Extension (MLE)/pothead.

This white paper will address the benefit of adding common mode filtering as a standalone component. By understanding the actual root cause of ESP failures, mechanical issues like rotor bearing failure and electrical failures can be attributed to not having common mode output filters on PWM VSDs.

The high frequency L-G PWM switching transient can even couple through Step-Up Transformers (SUT) and is reflected over long cable runs, resulting in voltage peaks that can be up to twice the surface transient voltage impulse at a reflection point (this can be in excess of 8000V peak at VSD carrier frequency intervals / 2100-4000 times per second). Further, the long, flat downhole wire runs present very little inductance and resistance while also presenting a high, unintended capacitance. This capacitance presents a low impedance to any unfiltered high frequency content. This leads to pre-mature electrical and mechanical failures. Application of properly designed Sine Wave

Filters (SWF) with the addition of L-G filtering components will greatly reduce the transient magnitude and aid in the overall run life of the ESP.

The ESP industry has typically addressed the failures of ESP systems by increasing the physical properties of the system (i.e., higher temperature, higher ampacity, better insulation, better bearings, etc.) however, such improvements only mask the issue and do not address the root cause of the failures. The remaining, high-frequency normal mode noise and even higher frequency common mode noise will invariably seek the next point of weakness in the system.

Effective Failure Analysis Determination (Root Cause)

Root Cause Failure Analysis

A "motor burn" in a failure report is not a proper RCFA.

A thorough failure analysis is necessary to understand the real problem.

To ensure an effective Root Cause Failure Analysis (RCFA) of ESP systems, it is important to collect as much data as possible prior to the equipment teardown and inspection. This includes, but is not limited to: equipment design data, operating conditions, fault data (controller information), equipment startup and installation logs, amp charts, operational history and pull reports. Other useful information includes test pump curves and acceptance, motor slant run test results, seal section or protector test reports.

Close review of the equipment will identify the failure modes of the ESP system. A thorough failure analysis may reveal failures in different components (i.e. cable, MLE, pump, intake, seal, motor, and sensor). In order to identify the root cause, analysis of the total operating system must be performed. For example, a motor may have a shorted stator, but this failure can be caused by a number of events. The events may include voltage surges from the surface, cable damage and arcing, MLE failures, poor splicing, fluid entering from a seal failure, pothead failures and/or manufacturing defects, but may also include other deficiencies or complications that are only discovered during a thorough analysis. A "motor burn" in a failure report is not a proper RCFA.

Many anomalies occur in an ESP system and nuisance tripping of the VSDs may occur (e.g. instantaneous overcurrent, zero crossing faults, erratic data transfer, etc.). The approach to finding Power Quality (PQ) related issues is to evaluate the one-line electrical system, safety and equipment grounding, VSD operation and setup, review ESP Dismantle Inspection and Failure Analysis (DIFA) reports, and conduct electrical group and production engineering interviews. Magney Grande Distribution (MGD) has performed many load side PQ studies that confirm that high frequency noise was present on a variety of ESP applications.

In the past 6 years, MGD has uncovered very unusual failures in ESP systems (motor (rotor) bearing fluting, penetrator, cable and pothead failures). These failures pointed MGD in the direction of analyzing the unfiltered, common mode noise present in the output of FPWM VSDs.

The high frequency content, associated with the PWM carrier frequency and its harmonics, that remains after sine-wave filtration as well as the higher frequency common mode noise associated with the switching transients of the inverter cause downhole failures in several ways:

Something to ponder…

It takes **less than 1 Amp** of high frequency current discharging across bearings to cause mechanical failure in a 12 to 18-month time frame!

- High voltage impulses (high frequency) act like a miniature lightning generator and send a continuous stream of "lightning-type impulses" downhole to pound on the insulation (likened to a jackhammer). While each impulse is below the magnitude to cause failure by itself, the steady stream of impulses accelerates insulation degradation.
- The laws of electricity with voltage source inverters (virtually all VSDs sourced for ESP applications) create voltage at the output inverter and allows whatever current at the individual frequencies to flow to the load equipment.
- The high frequency impulses will momentarily double at reflection points (penetrators, cable splices, MLE and motor coils); dramatically increasing voltage stress.
- The large, unintended capacitance created by the long downhole wire run allows for high frequency content (PWM Pulses) and higher frequency content (Switching Transients) to pass line-to-line and/or line-to-ground with very little impedance causing tracking in the insulation leading to line-to-ground and/or line-to-line failures.
- High frequency currents will cause skin effect heating (heating due to current flowing on the surface of the conductor), abnormally heating the conductor insulation. The weakest link in the electrical system is most susceptible. This is typically realized in the premature failure of feed through penetrators, splices, MLE (potheads), motor winding end turns, and mechanical bearing fluting. It may also abnormally heat ESP seal section.

- The common mode high frequency currents can also couple onto the motor shaft and discharge across the motor bearings (known as rotor bearing fluting).
  - It takes less than 1 Amp of this high frequency current discharging across bearings to cause mechanical failure in a 12 to 18-month time frame.

  Proper filtration of the VSD output dramatically reduces the incident of these failures.

- A properly designed SWF is able to prevent most of the high frequency phase-to-phase voltage and three phase currents from making it to the ESP electrical system, however a SWF such as this is prohibitively expensive to offer.

- None of the present-day manufacturers of VSDs for ESP applications, that MGD is aware of, filter phase-to-ground (common mode). They rely on the SUT to do the common mode filtering. However, the SUT does not filter out all of the common mode.

  - An ideal transformer would filter common mode noise, however ideal transformers do not exist. Real transformers have unintended reactance that does not adversely affect their performance at lower frequencies while providing paths for current at higher frequencies. The magnitude and frequency of the common mode noise observed in ESP systems make it adept at passing through the SUT.

  - It is recommended that a common mode filter be applied in addition to the standardly applied, properly designed SWF for maximum protection of the ESP system.

An added benefit of CMF

The CMF functions as a warning system to notify of a SWF failure.

PWM Output (With and Without a Common Mode Filter)

- Typical VSD systems utilized with ESPs, filter most but not all of the high frequency content associated with the PWM. In **Figure 1**, (Voltage Yellow, Current Green - Logarithmic Scale). The clusters are associated with the harmonics of the PWM carrier frequency. The highest voltage harmonic, other than the fundamental, in this instance was 153.6 Vrms at the 62nd while the highest current harmonic was 2.493 Arms at the 62nd harmonic.

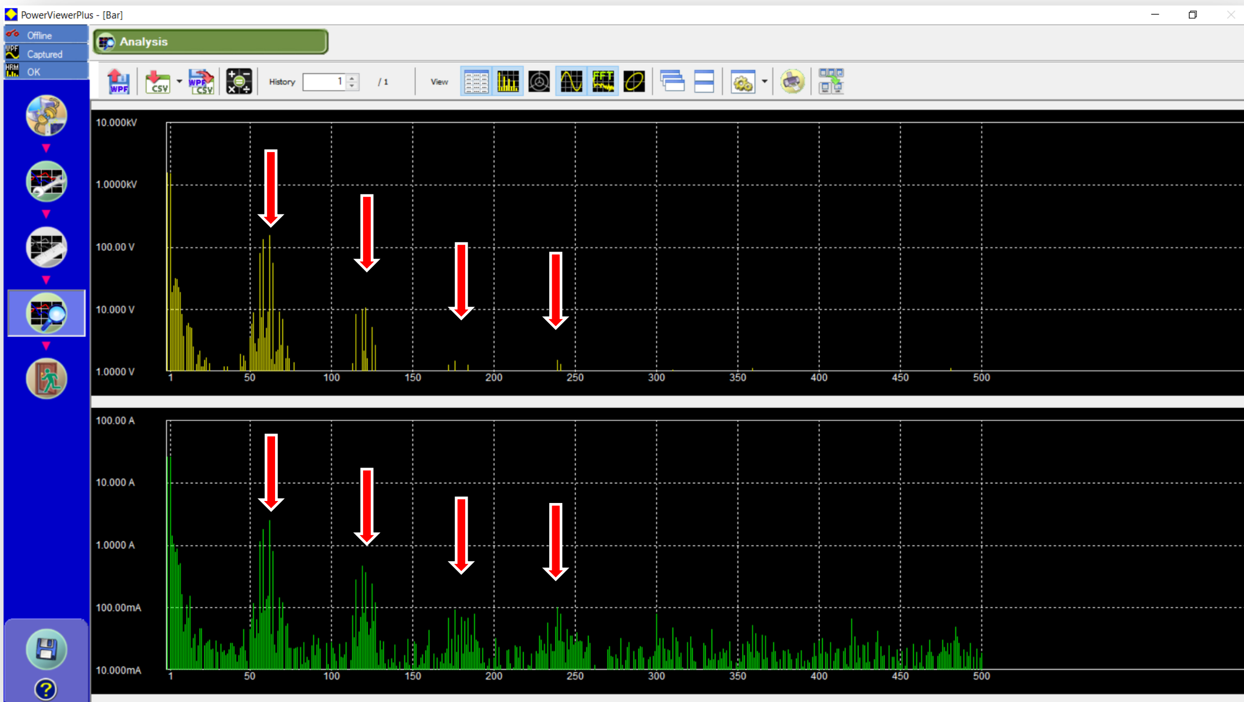

FIGURE 1: HARMONIC VOLTAGE PROFILE - FPWM – MV, NO CMF

- Significant high frequency content remains after SWF and SUT (see **Figure 2**).

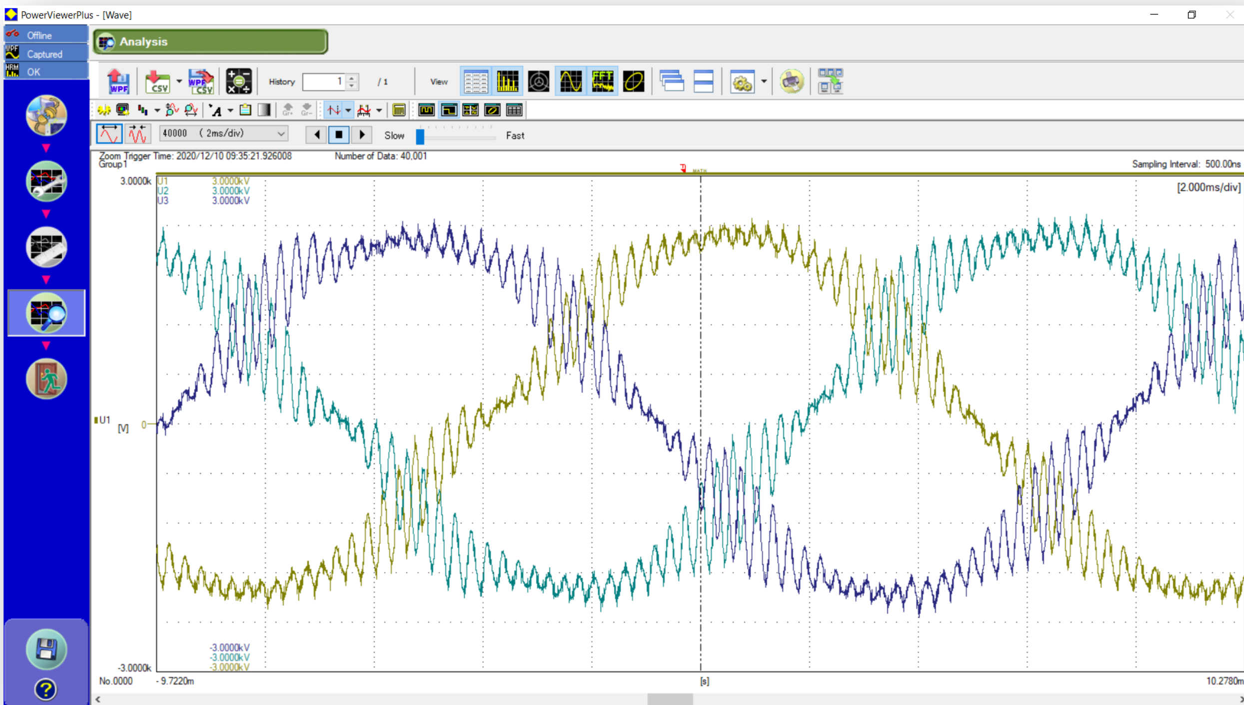

FIGURE 2: VOLTAGE WAVEFORMS-FPWM – MV, NO CMF

- The switching transients of the inverter bridge are a significant source of common mode noise. The frequency associated with these transients allow them to pass through the SUT relatively unhindered and they are unimpeded by the line-to-line filtering action of the SWF. **Figure 3** (Yellow – SUT Primary, Purple – SUT Secondary) displays a detailed view (100Msa/s displayed at 10us/div) of a series of randomly selected, common mode producing waveforms recorded simultaneously on either side of the SUT.

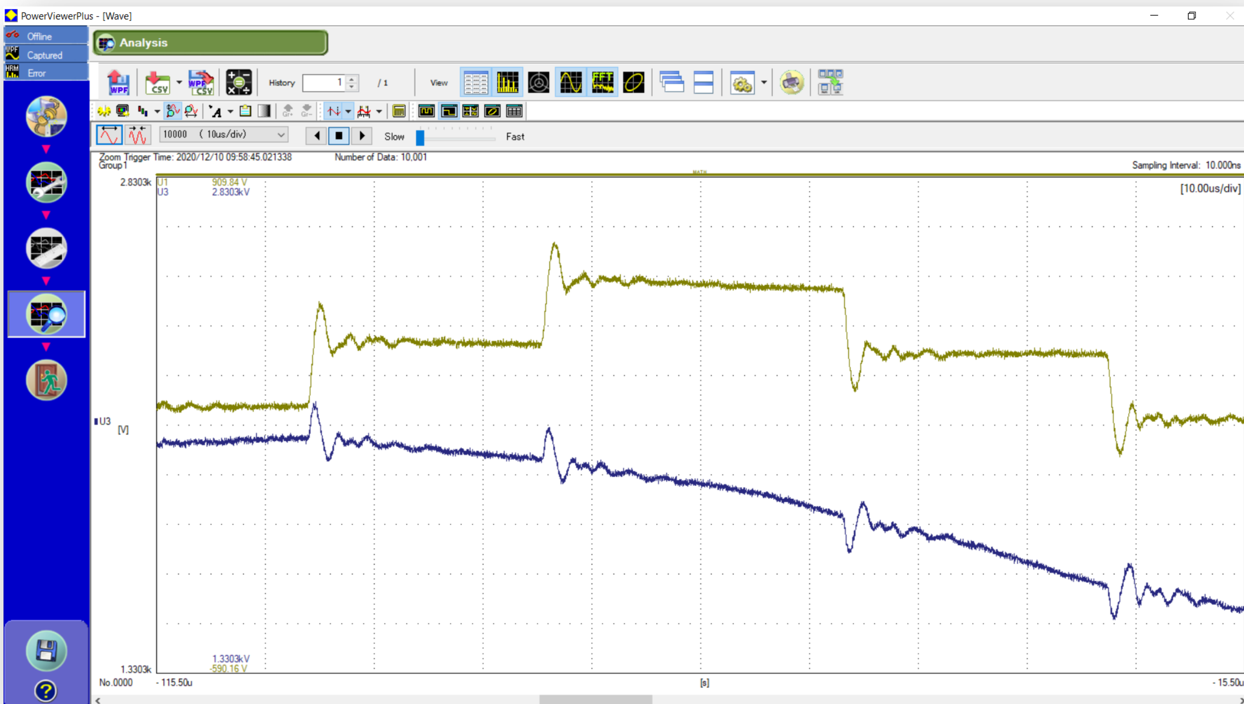

FIGURE 3: OBSERVATION OF COMMON MODE - FPWM – MV, NO CMF

- The CMF assists the action of the SWF by reducing the magnitude of the high frequency content associated with the PWM carrier frequency (see **Figure 4:** Voltage - Yellow, Current – Green, Logarithmic Scale). This is to be compared directly to **Figure 1** as these were collected on the same day before and after installation of a CMF and the VSD was running at the same frequency (57Hz) in each instance. The highest voltage harmonic, after CMF installation, was 58.7 Vrms at the 62nd while the highest current harmonic was 1.000 Arms at the 62nd harmonic.

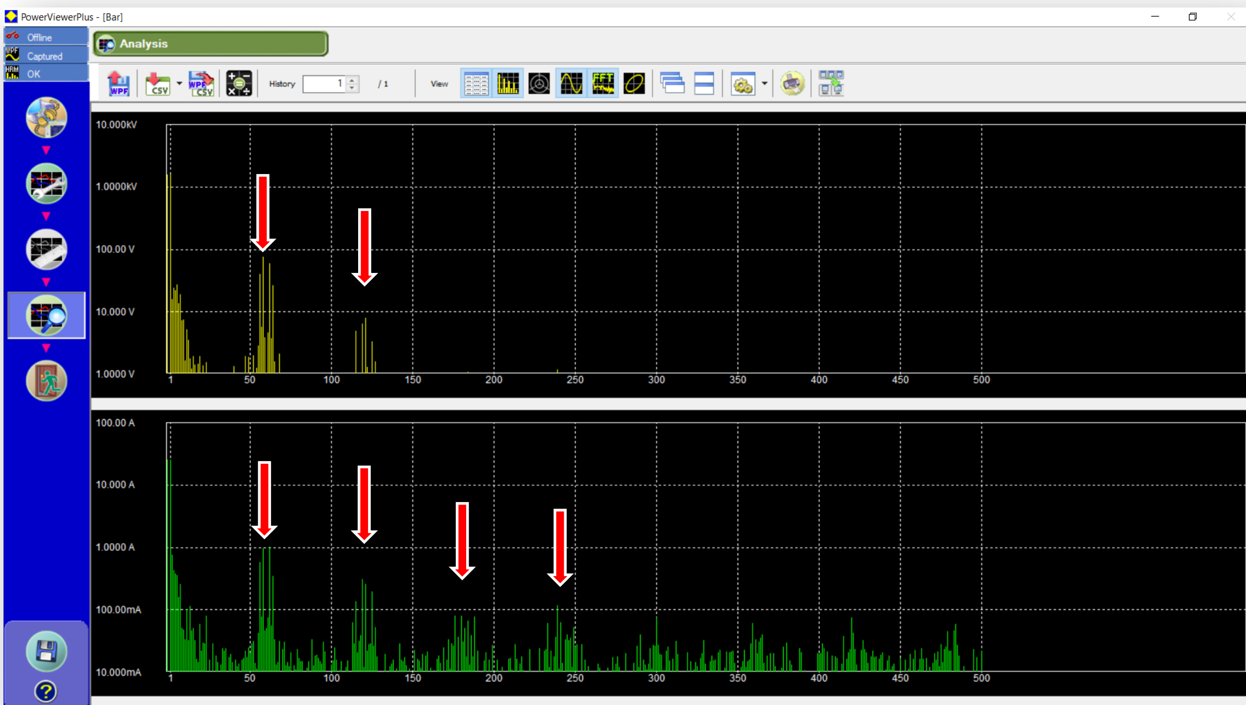

FIGURE 4: HARMONIC VOLTAGE PROFILE - FPWM – MV, WITH CMF

- The reduction of high frequency content is also visible in the voltage waveforms after installation of the CMF (see **Figure 5**). This is for direct comparison to **Figure 2**.

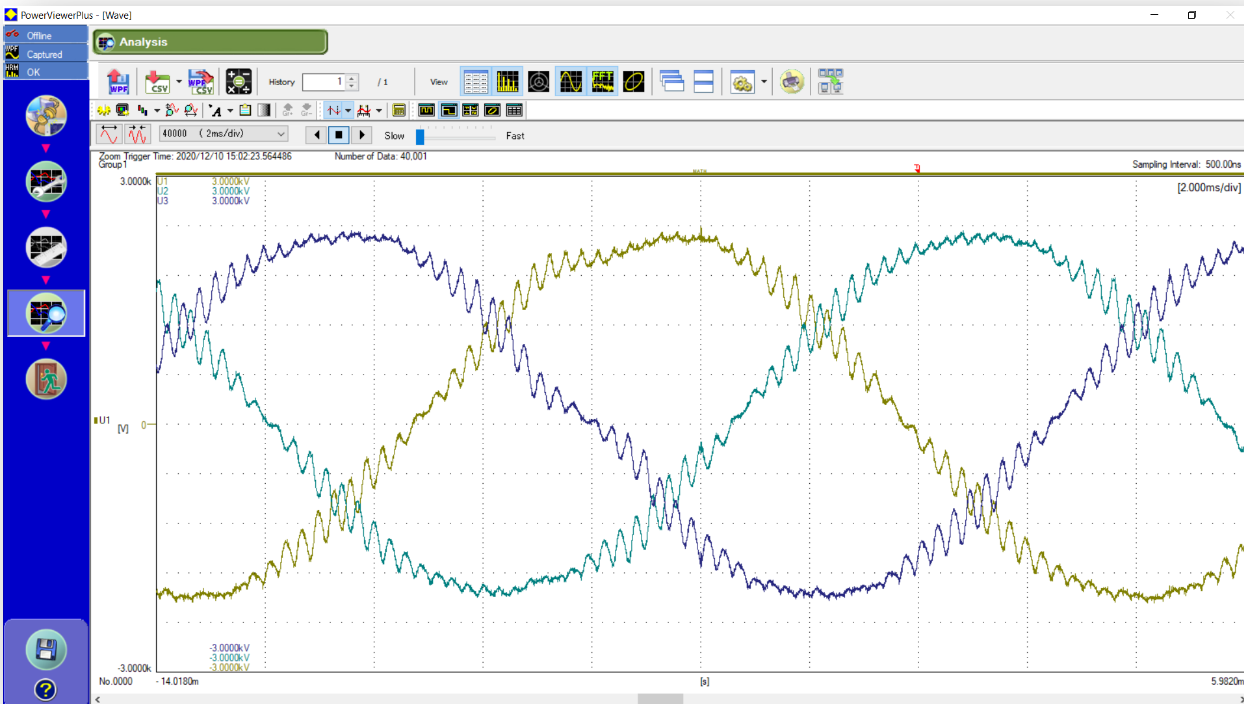

FIGURE 5: VOLTAGE WAVEFORMS-FPWM – MV, WITH CMF

- The CMF is a resistive-capacitive load that presents low impedance to high frequency both line-to-line and line-to-ground (see **Figure 6**) while presenting a high impedance to the low-frequency content such as the fundamental frequency. This allows the CMF to almost exclusively draw high frequency content. In this instance, a range of 1.274 Arms to 1.416 Arms was observed to each phase of the CMF. This is high frequency content that would otherwise be causing damage to the system.

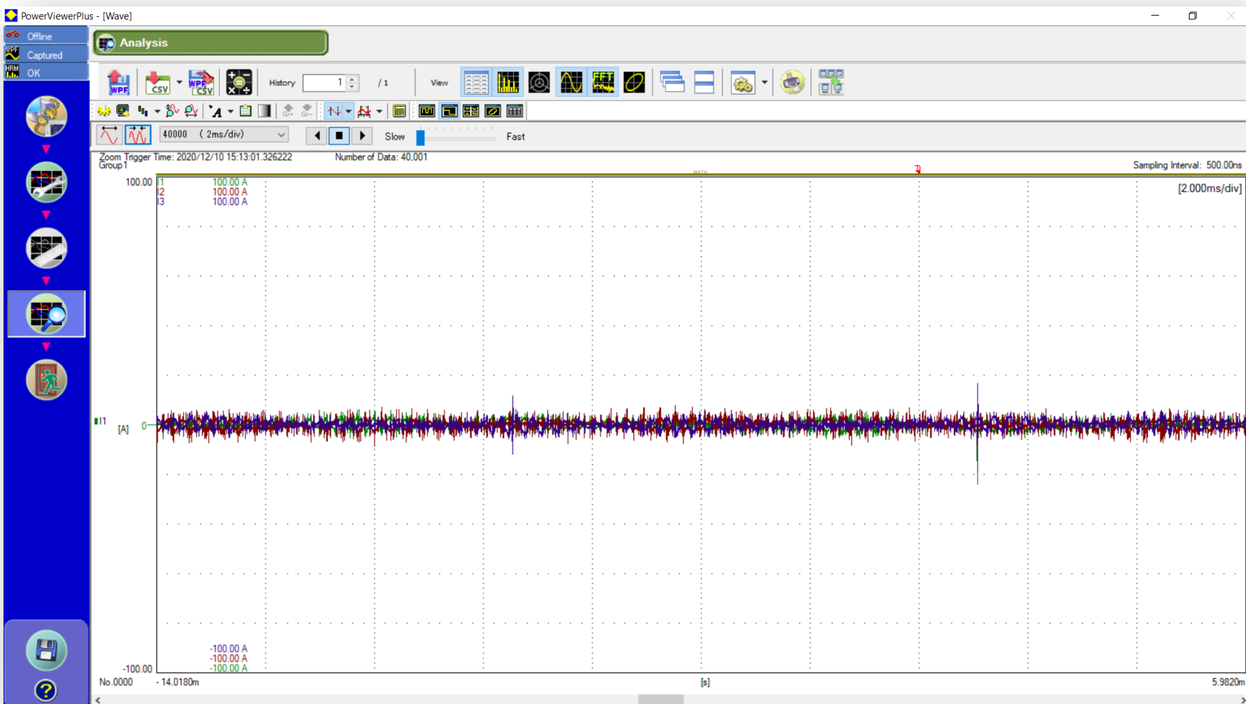

FIGURE 6: FPWM-MV – CURRENT INTO CMF

- The CMF not only augments the action of the SWF by further reducing high-frequency harmonic content but also reduces the higher frequency common mode noise. **Figure 7** (Yellow – SUT Primary, Purple – SUT Secondary) is displayed with the same scale as **Figure 3** for direct comparison as this was recorded under the same set of conditions after installation of a CMF. Note the significant reduction in magnitude and ringing of the transients present in **Figure 7** as compared to **Figure 3**.

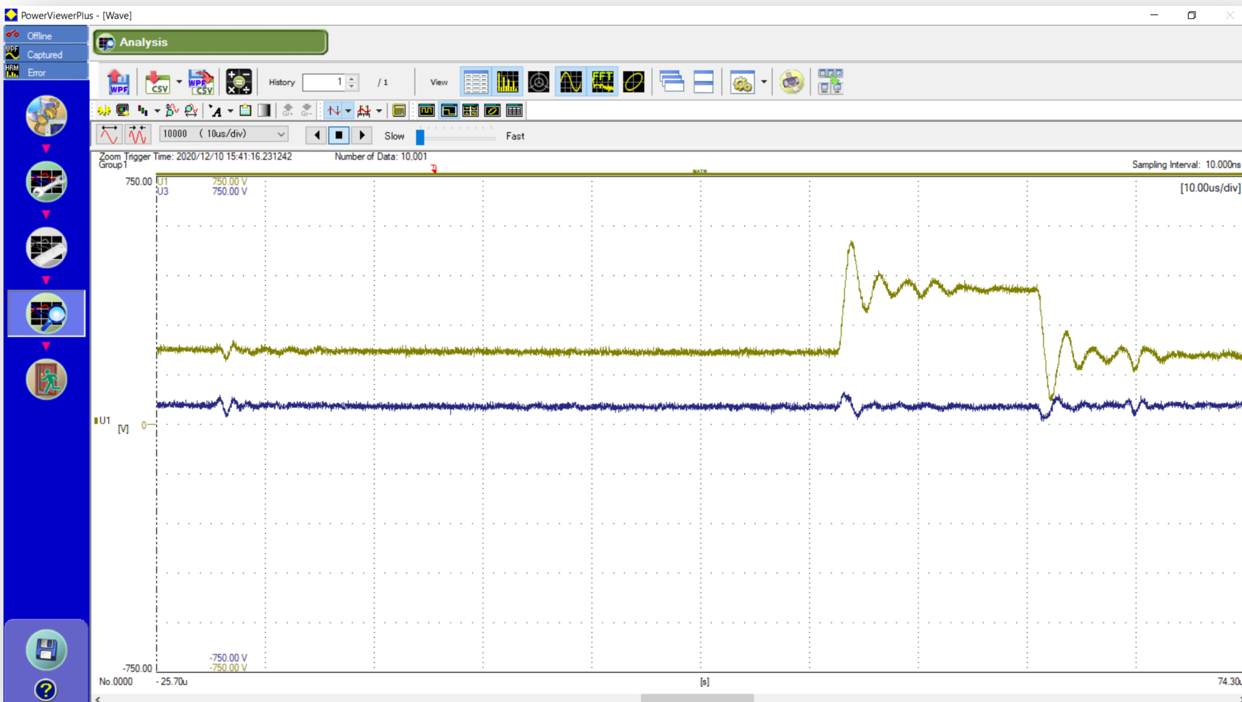

FIGURE 7: OBSERVATION OF COMMON MODE - FPWM – MV, WITH CMF

- The CMF was designed as an auxiliary filter and relies upon a properly designed and fully-functional SWF. SWF components degrade over time and can experience loss of functionality due to excessive heat. In the event this occurs while a CMF is installed, the CMF will begin to draw more high frequency current as the PWM output of the VSD is less filtered.
  - Excessive high-frequency current to the CMF will eventually cause a change in state of the fuses which initiates an error signal to the VSD. In this way, the CMF further functions as a warning system to notify that SWF failure has occurred thereby notifying personnel that repairs are required to the SWF before damage has occurred in the downhole environment.

Conclusion

Close examination of relevant data and all equipment will help in identifying the failure modes of the ESP system. A thorough failure analysis may reveal failures in different components (i.e., cable, MLE, pump, intake, seal, motor, sensor, tubing/casing, etc.), but in order to properly identify the root cause, a thorough analysis of the entire system must be conducted. As previously stated, a motor may have a shorted stator and this failure can be caused by a number of events. The events may include voltage surges from the surface, cable damage and arcing, MLE failures, poor splicing, fluid entering from a seal failure, pothead failures and/or manufacturing defects, but may also include other deficiencies or complications that are only discovered when a thorough Root Cause Failure Analysis is performed possibly including analysis of the VSD and its SWF components. It must be emphasized that a quick find, such as a "motor burn" or "well conditions" in a failure report, does not reveal the true cause of the problem.

CMF-MV

A Medium Voltage Common Mode Filter (CMF-MV) is a cost-effective solution.

It has been proven that a Common Mode Filter augments the function of the SWF by reducing the high-frequency content both line-to-line and line-to-ground. In turn, this leads to increased run life of cable, penetrators, splices, MLE/potheads, tubing/casing, and motors.

The Common Mode Filter is designed to work with the existing Sine Wave Filter that is presently installed in FPWM VSDs. Further, the CMF provides a notification in the event of SWF degradation. As such, the CMF is a cost-effective addition to FPWM VSDs.