SUCCESSFUL PERMANENT MAGNET MOTOR PERFORMANCE IN UNCONVENTIONAL GASSY WELL APPLICATIONS THROUGH MODERN VFD TECHNOLOGY

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1 ABSTRACT

High-volume, high-water-cut wells have historically posed significant production challenges due to the limitations of conventional artificial lift methods. Electric submersible pumps (ESPs) are typically the preferred solution for these applications, as they are capable of handling the large fluid volumes produced by modern extended-lateral wells. However, as electricity rates rise and power grid limitations become increasingly common, the need for more energy-efficient solutions has intensified. Permanent magnet motor (PMM) technology offers a potential solution by providing higher efficiency in these contexts. Despite this, many unconventional well applications experience rapid declines in total fluid rates and significant increases in gas production, both of which present challenges for ESP operation in gas-rich environments.

This paper compares the performance of PMMs using Vector Control versus Scalar Control, demonstrating the effectiveness of Vector Control in managing gassy conditions and mitigating the impact of sudden load variations caused by gas slugs.

A laboratory test setup was developed to simulate well conditions, incorporating typical surface equipment such as Step Up Transformer (SUT), Sine Wave Filter (SWF) systems, and a 5,000 ft ESP power cable. A dynamometer and three-phase power analyzer were used to load and monitor the PMM's performance. The PMM was subjected to sudden load changes to simulate gas interference, as well as drastic speed variations to mimic the purging modes employed in the field to manage gas slug events.

The results indicated that Scalar (V/Hz) mode led to current-torque mismatches and speed control instability, regardless of load changes. In contrast, Vector Control, the preferred method for PMM operation, successfully managed these challenges by maintaining rotor synchronization and efficiently responding to large load variations induced by gas interference. Vector Control ensured that output torque matched the desired current, even during rapid speed changes, allowing for decoupled speed and torque control with minimal additional requirements such as the specific PMM parameters (e.g., Ld, Lq, and back EMF) integral to the motor design.

This paper highlights the benefits of implementing Vector Control as the most effective and efficient control strategy for PMMs in applications involving rapid load variations, such as unconventional wells, where high efficiency and reliability are essential.

2 INTRODUCTION

Variable Frequency Drives (VFD) have been used with ESPs since the 1970s and have now become an essential component of the ESP System responsible for controlling the rotational speed and torque of the motor through the electrical frequency of the supplied voltage. VFD technology has evolved considerably since then with large increases in both performance and reliability. Power switching electronic components have evolved and brought more efficiency and capability to the ESP market. Since the invention of the first thyristor with control by GE in 1958 for the first drive to control AC induction motors like DC motors, there have been many other advances in materials and control algorithms to allow ESP operations to benefit from the latest technology.

VFDs are designed to broaden the application range, optimize efficiency, maximize well production, isolate electrical power disturbances, reduce starting stress, match production with surface facilities capabilities, handle gas of the ESP system, and many other functions. However, to do this it uses a method of control that impacts considerable motor performance. There are two primary methods: Scalar mode, also commonly known as Volts per Hz mode, and Vector control mode. Each method has its own sets of parameters to take into consideration and this paper will explore both in detail.

2.1 Scalar Control (V/HZ)

Scalar control of an AC electric motor is now generally used in an open loop control method that allows for speed variation through changes to the output voltage frequency. For ESP motor applications, the AC motor, both IM and PMM, does not contain any rotor position sensor, so an open loop control method is the only option for motor control. This control method maintains a constant voltage to frequency ratio based on the specific motor design to allow for constant flux within the motor stator. This produces a specific torque constant for the motor based on the voltage to frequency ratio. This allows for a simple operating model where speed changes are possible through increasing the electrical frequency of the voltage, and the VFD increases the voltage proportional to the frequency. As the frequency increases, so does the voltage, thereby maintaining a constant ratio between the two while the rotation speed of the system increases.

The simplicity of scalar control makes it a cost-effective option, especially for applications where precise speed regulation is not critical. For induction motors, actual mechanical rotational speed of the system will slip or lag the electrical frequency as load increases.

2.2 Vector Control

One vector control method called field-oriented control (FOC) is a method in which the stator currents of a three-phase AC motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control. Typically, proportional-integral (PI) controllers are used to keep the measured current components at their reference values. The pulse-width modulation

(PWM) from the drive defines the transistor switching according to the stator voltage references that are the output of the PI current controllers. Vector control is used to control AC synchronous and induction motors. It was originally developed for high-performance motor applications that are required to operate smoothly over the full speed range, generate full torque at zero speed, and have high dynamic performance including fast acceleration and deceleration.

The fundamental principle of vector control is to treat the motor's stator current as a vector that is split into two components: the magnetizing or flux component (d) and the torque-producing component (q). These two components are controlled independently, allowing for more accurate and dynamic control of the motor. The d-axis current component represents the magnetizing current, while the q-axis component represents the current responsible for generating torque. By controlling these components separately, vector control maximizes the torque production and optimizes the motor's performance across a wide range of speeds. Unlike scalar control, which operates based on a fixed voltage-to-frequency ratio, vector control dynamically adjusts the motor's current to ensure that the torque-producing component is kept orthogonal to the rotor flux. This results in higher efficiency, especially at low speeds or when high output torque is required. Vector control can be implemented in both open-loop and closed-loop configurations. Table 1 shows a comparison between the 2 control modes.

Table 1– Comparison Table Scalar Mode vs Vector Control Mode

Scalar Mode (V/Hz)	Vector Control Mode
Simple and Easy	Complex and Sophisticated
Single Variable Parameter (Frequency)	Two Parameters (Frequency & Phase Angle)
Linear relationship between frequency and voltage	Non-Linear relationship between frequency and voltage
No flux or torque control	Independent flux and torque control
Suitable for simple and steady applications	Suitable for high performance and dynamic apps
Low Efficiency and Power Factor	High Efficiency and Power Factor

3 LABORATORY TESTING

3.1 Laboratory Test Setup

A test system was designed using a 3.99" OD PMM to test on different VFDs with different control modes including electrical setup, data acquisition, and drive configuration. SUT, SWF, ESP Cable, dynamometer and three phase power analyzer were included in the setup – see Fig 1 for layout reference. The PMM was exposed to various load profiles to simulate field conditions under Scalar Mode and Vector Control Mode, including full load test, high speed test, fast varying load test, and high load start test. Testing consisted of sudden load changes to mimic gas interference, as well as drastic speed changes to simulate purging operating modes used in the field to ride through gas slug events.

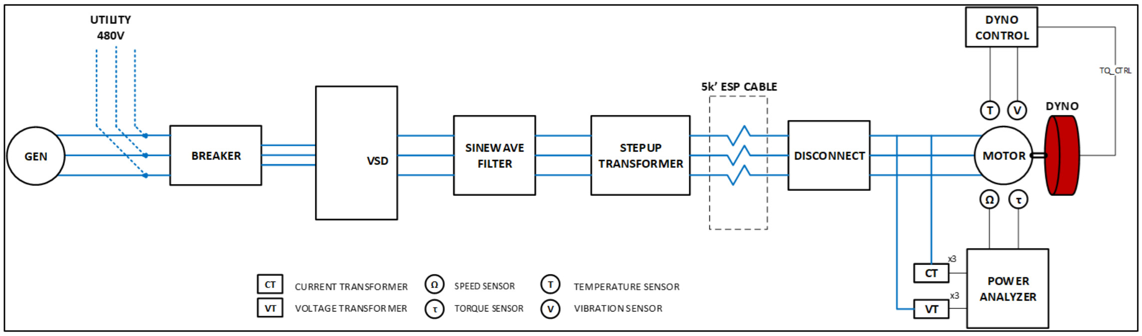

Figure 1 Electrical Test Facility Schematic

3.2 Lab Test Results

3.2.1 Scalar control mode

Scalar (V/Hz) mode was tested first, which is generally easier to use. The equipment specifications for the test setup are described below.

- Utility: 480V/3PH/60Hz/800A
- Variable Frequency Drive: 250KVA/480V/300A/120Hz
- Sine Wave Filter: 240Hz/305A
- Step Up Transformer: 400kVA/60Hz/3PH 480V/1396-4836V
- ESP Cable: #6 AWG 5000'
- Disconnect: 5000V/200A/3PH
- Motor: 3.99" PMM 300HP/2181V/77A
- Dynamometer: 13" Water Brake Absorber
- Power Analyzer: Yokogawa WT1800 Precision Power Analyzer

The drive was configured for Scalar control by inputting the PMM's Volts per Hz specification and did not change throughout the duration of the tests performed. Three main tests were performed in this setup to simulate different loading conditions seen in unconventional wellbores where drastic load changes occur due to high gas to liquid ratios.

1. No Load Starting
2. Medium Load Steady State Operation
3. Starts with Load and Load Changes

3.2.1.1 No Load Starting

The first test performed was under no load, voltage was stable, torque was stable 26.5-27.3ft-lbs, less than 1ft-lbs variation with speed between 3557-3624rpm, only 67rpm variation without any disturbance and it showed poor speed control even under this no-load condition, see parameter trends in Figure 2.

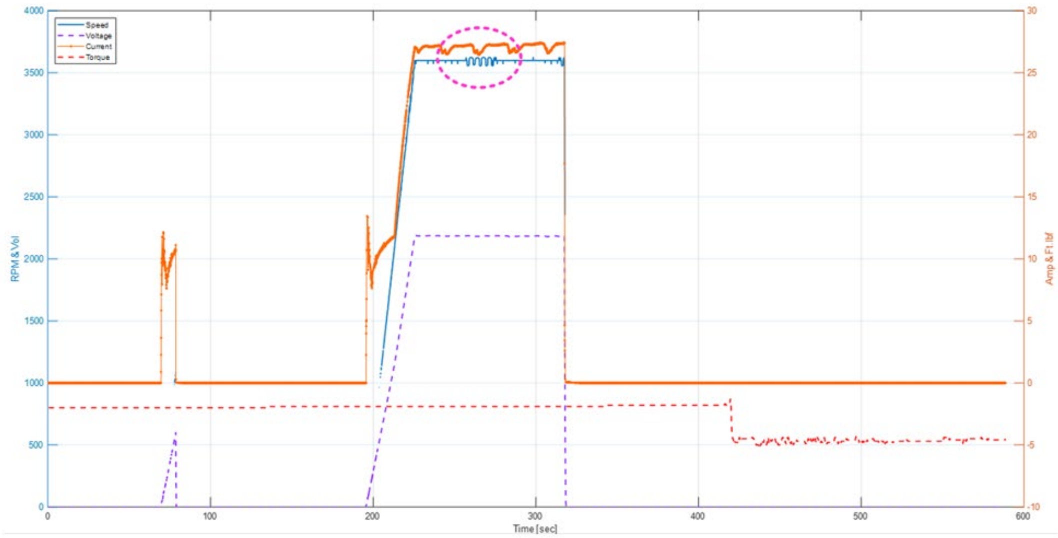

Figure 2 – PMM No Load Test under Scalar (V/Hz) Control Mode

Observation: Poor speed control

3.2.1.2 Medium Load Steady State Operation

Next, a medium load test was performed, voltage was stable, applied load was too high causing an overcurrent trip after the 372 second mark. However, before the overcurrent event the speed started to show a 73rpm swing with increased torque (3551-3624rpm) which confirmed poor speed control in medium load situation. See test parameters in Figure 3.

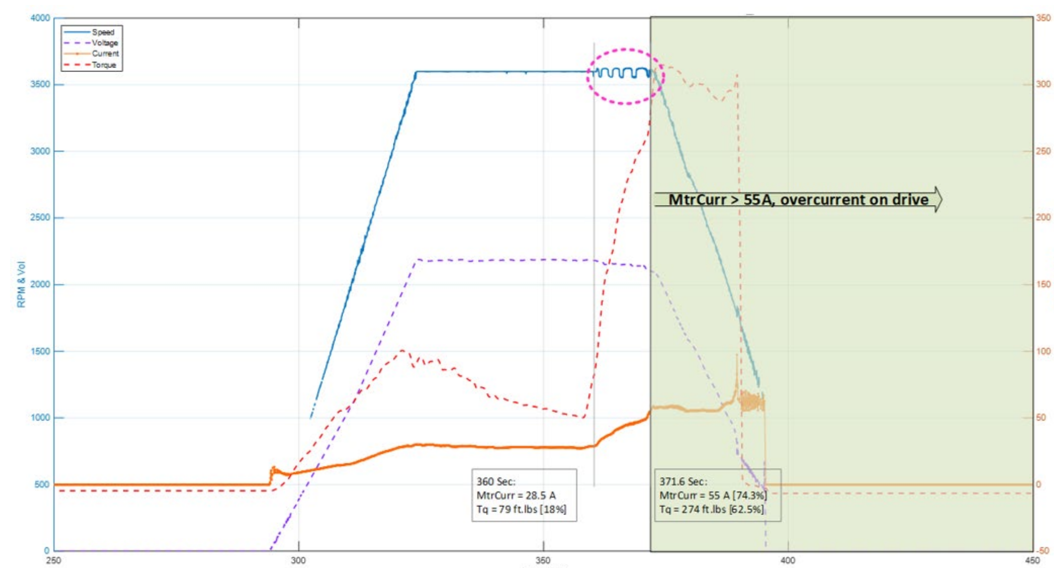

Figure 3 – PMM Medium Load Test under Scalar (V/Hz) Control Mode

Observation: Poor speed control

3.2.1.3 Starts with load and load changes

Next, a total of 6 starts with load were performed. 4 of 6 failed to start the motor, then after finally being able to start the PMM, it shut down twice after losing rotor synchronization when load or speed were suddenly changed. See overall trends in Figure 4. In Figure 5, a detailed view for Run 5 is shown where the PMM started with load, ramped to 120Hz, then load was increased to 37%, later speed was changed to 90, 75 and 65Hz respectively, then load was increased again to 61% (highest load on the test) and after a couple of seconds, motor system lost rotor synchronization and lost speed.

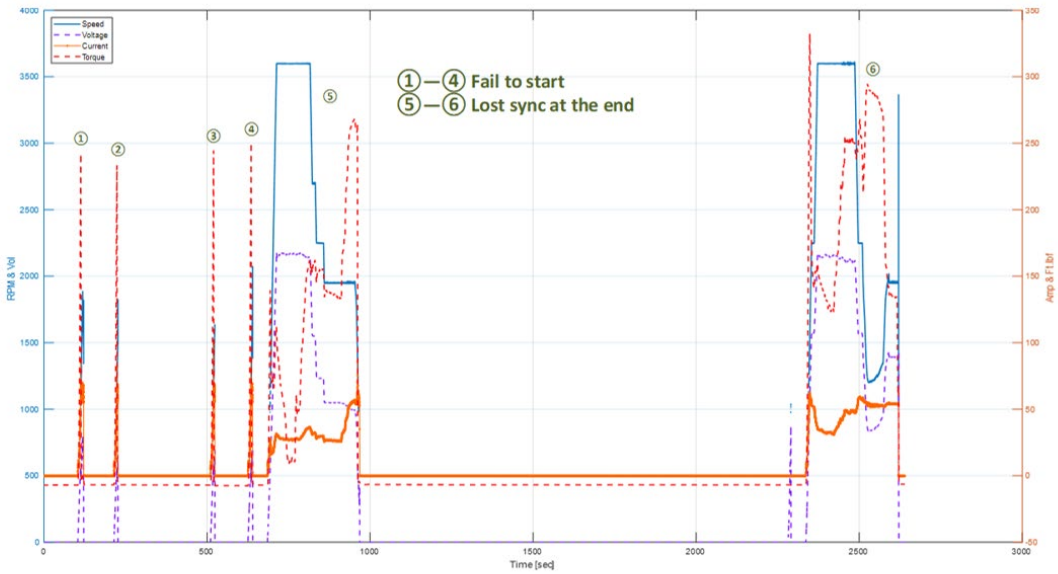

Figure 4 – PMM Load Start and Variable Speed and Load Test under Scalar (V/Hz) Control Mode

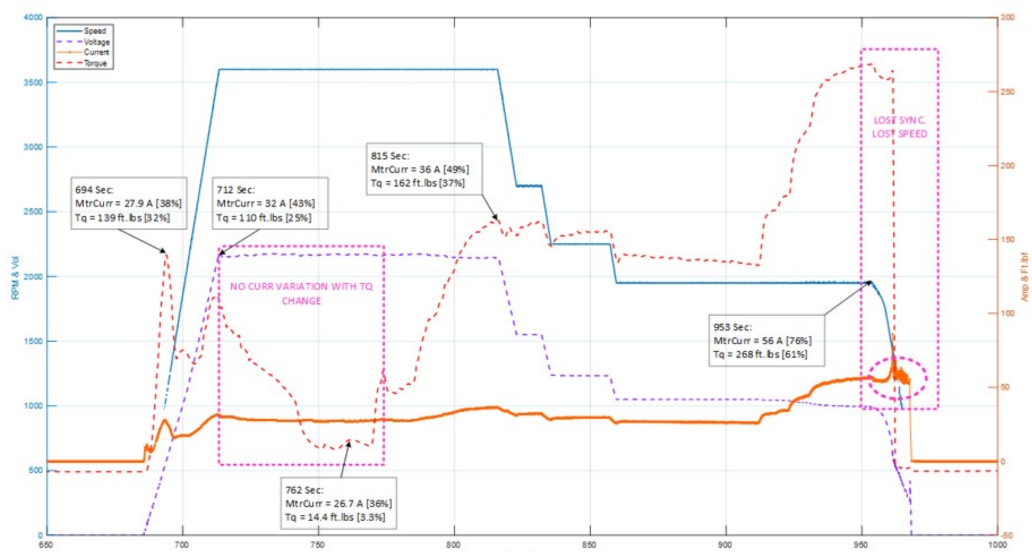

Figure 5 – Run 5 PMM Load Start and Variable Speed & Load Test under V/Hz Control Mode

Scalar control mode caused the PMM to experience current torque mismatch and speed control issues regardless of the load throughout the testing. For all loads, the PMM's operating current was always higher than the rated current at the operating load which means the PMM was not running as efficiently as it is able to. This current load mismatch indicates poor current control which is a result of running in scalar control mode. Poor current control resulted in the system losing rotor sync due to either change of speed or change of load which is unacceptable for ESP control.

Observation: Scalar control could lead to current torque mismatch, which could result in drive overload and motor out of synchronization. Drastic change of load torque or motor speed could also result in desynchronization. Once the motor is out of synchronization, the ability of the drive to re-synchronize is limited by the scalar control algorithm.

3.2.1.4 Conclusion of Scalar Testing

- Poor **speed control**, which seems regardless of the load
- Throughout the tests, the percentage of current is always higher than the percentage of load. This **current load mismatch** indicates poor current control, which is caused by not using proper control mode for PM.
- The system could go **out of sync** due to either change of speed or change of load.
- Start up is smooth when it starts.

3.2.2 Vector control mode

The next series of tests were performed under similar conditions (no load, full load, high speed and fast varying load test) using the Vector control mode within the same VFD. Thus, the only major change to the system was setting up the drive with Vector control.

The equipment specifications for the test setup are described below:

- Utility: 500kw/480V/3PH/60Hz
- Variable Frequency Drive: 520KVA/480V/620A/120Hz
- Sine Wave Filter: 240Hz/420A
- Step Up Transformer: 400kVA/60Hz/3PH 480V/1396-4836V
- ESP Cable: #6 AWG 5000’
- Disconnect: 5000V/200A/3PH
- Motor: 3.99” PMM 170HP/1270V/68A
- Dynamometer: 13” Water Brake Absorber
- Power Analyzer: Yokogawa WT1800 Precision Power Analyzer

The PMM chased the load effectively with the VFD using vector control to ride through large load variations due to high gas interference simulation.

3.2.2.1 No Load Starting and Full Load Testing

The initial No Load test confirmed the drive was properly set up, motor reached full nominal speed, voltage at full speed, light load was 97.6% of the nominal voltage, motor current was at 33.1% of the nominal current when load was at 34.6% of the nominal load.

Then a Full Load Start Up test was successfully performed where the PMM maintained 3600rpm, motor voltage ~1230v and stable throughout the run, full load of 248ft-lbs was reached and motor current was at nominal current of 68A at full load.

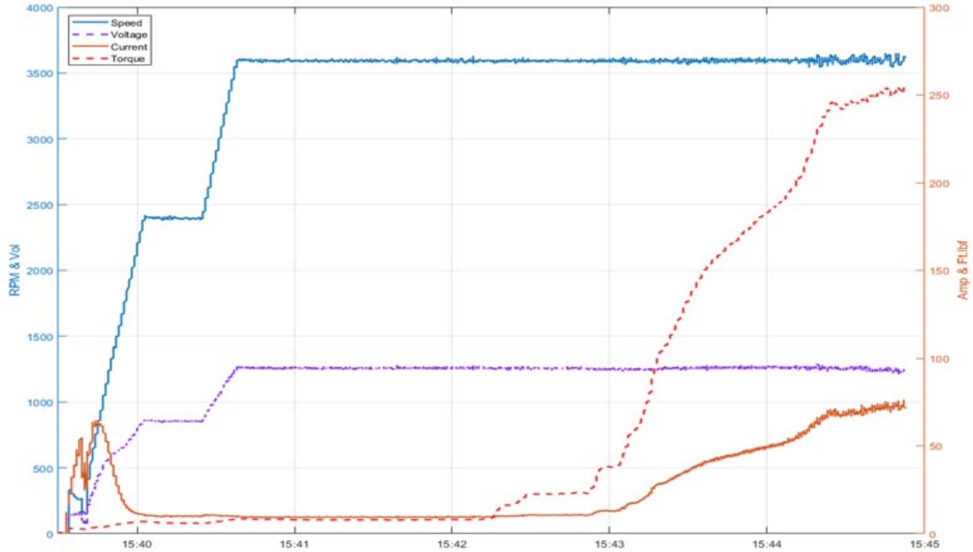

Figure 6 – PMM No Load Start and Full Load Tests Under Vector Control Mode

3.2.2.2 Fast Varying Load

Next, Fast Varying Load Test was performed, and the PMM showed stable operation, peak torque reached, and exceeded rated torque of 248ft-lbs. RPM was stable with a minor speed drop during the rapid torque ramp up of 90 ft-lbs. per second, going back smoothly to set frequency and test was completed successfully with no drive fault, see Figure 7.

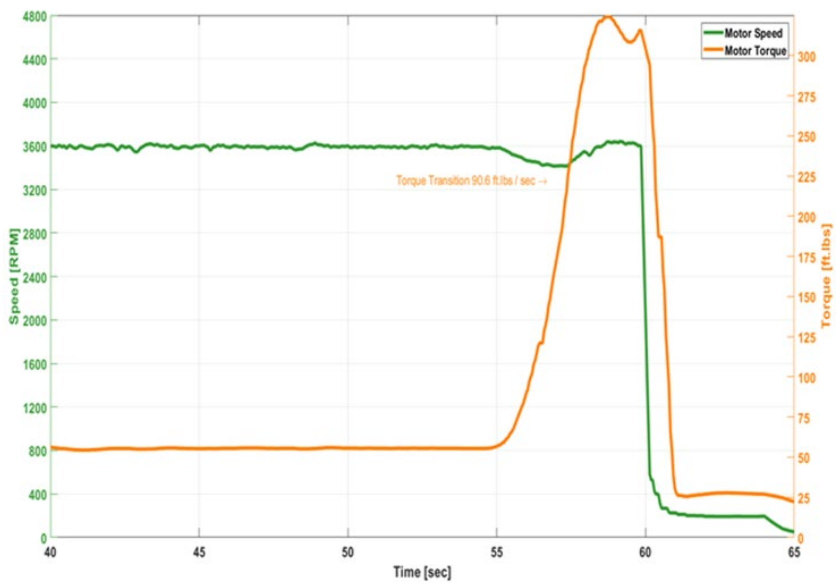

Figure 7 – PMM Fast Varying Load Test under Vector Control Mode

The Vector control mode test results confirmed output torque matched the desired current regardless of sudden speed changes, decoupling speed from torque control without any special requirements other than specific PMM parameters based on motor design, like Ld, Lq and back EMF.

A brief graphic depiction of variations in different PMM designs that can affect the Ld and Lq variables are outlined well from Kang[6]. This graphic below highlights how the uniqueness of a PMM design can affect these variables, so care must be taken and a thorough understanding of the PMM design.

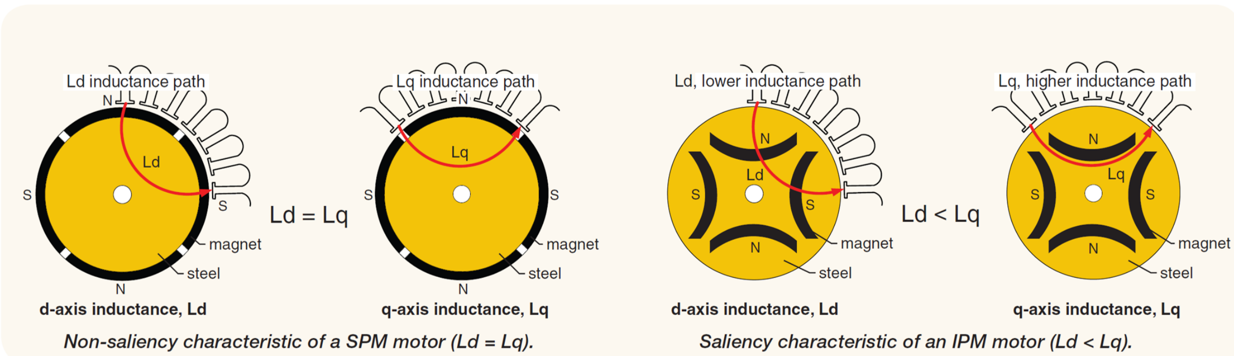

Figure 8 – PMM variations in Ld and Lq as a function of rotor magnet design, Kang[6]

ESPs in High Gas Production wells typically experience pump gas locking events which require gas mitigation solutions. The VFD via various techniques is used to flush out gas from the pumps which is why fast varying load tests are necessary to simulate these conditions of loading and unloading gassy wells. This is required to validate the PMM's performance so the ESP system can successfully operate under these well conditions.

3.2.2.3 Conclusions of Vector Control Testing

- Exceptional speed control
- Percentage of motor torque and percentage of motor current are matched for most of the load range
- Vector control enables stable operation through high load start and fast load varying testing
- The rotor remains synchronized through load and speed variation
- The overall dynamic performance of the motor, such as transient and stability, under vector control is superior to the performance under scalar control

3.3 PMM Efficiency Test – Scalar Vs. Vector Control

PMM performance tests were conducted with the two different control modes with the same VFD. The test setups consisted of a 300HP 3.99" PMM which resulted in higher efficiency under vector control mode and higher output power vs current.

- Utility: 480V/3PH/60Hz/800A

- Variable Frequency Drive: 561KVA/480V/675A/120Hz
- Sine Wave Filter: 120Hz/600A
- Step Up Transformer: 400kVA/60Hz/3PH 480V/1396-4836V
- Disconnect: 5000V/200A/3PH
- Motor: 3.99" PMM 300HP/2181V/77A
- Dynamometer: 13" Water Brake Absorber
- Power Analyzer: Yokogawa WT1800 Precision Power Analyzer

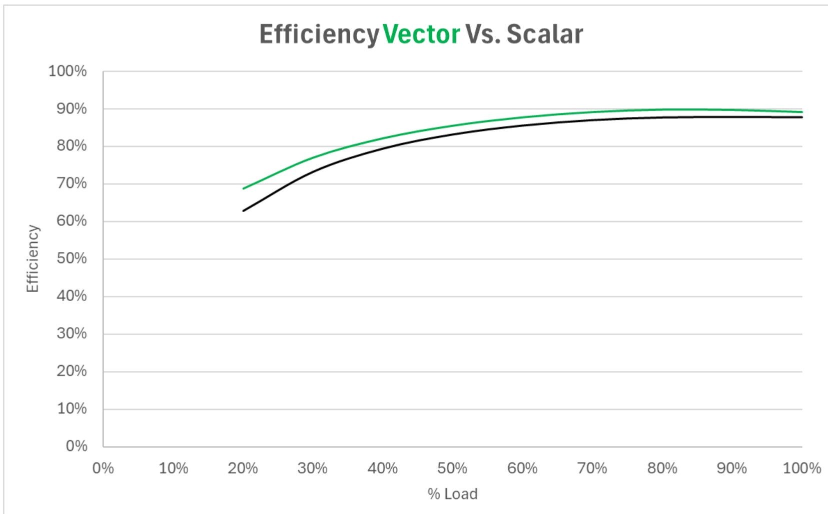

Figure 9 –Motor Performance Test – PMM Scalar vs Vector Control Mode

From Figure 9, it's clear the control mode is critical to obtaining the maximum efficiency of the PMM. This is particularly true at lower load levels where the difference grows significantly.

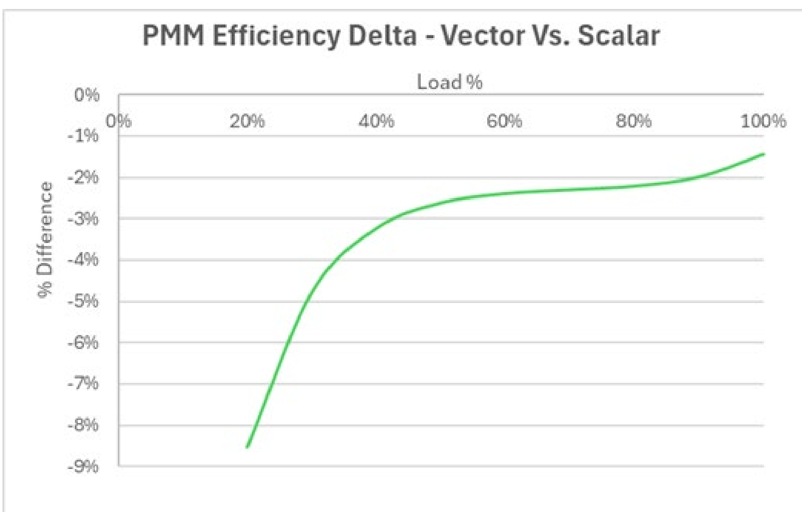

Figure 10 – PMM Scalar vs Vector Control Efficiency Difference

Another way to view this is to plot the output power relative to the motor current. This better highlights how this would relate to a real ESP application where pump load is known. The example in Figure 11 plots HP as a function of current.

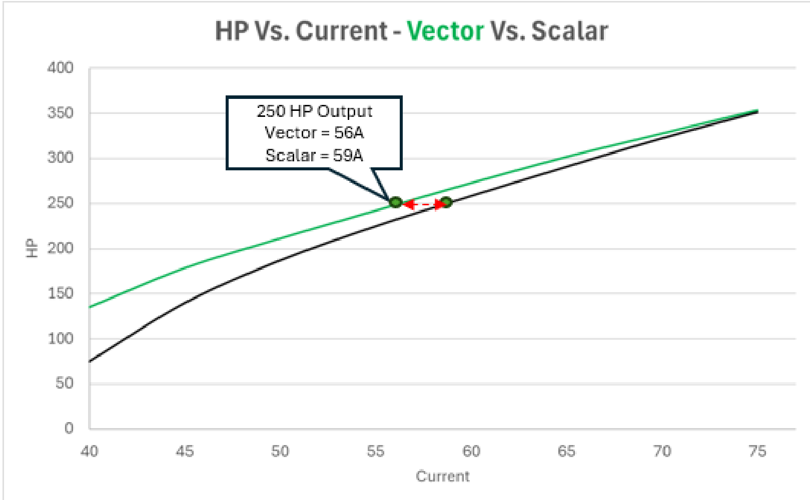

Figure 11 – Output Power Vs Current – PMM Scalar vs Vector Control Mode

The following test was run at 120Hz, 3600RPM. The load went from 20% to 100% for both Scalar and Vector control mode. As demonstrated in the following figure, the voltage for the vector control run was held more consistently than the scalar control run, while the scalar control run also saw un elevated voltage with the increase of the load. The vector control displays more desirable current characteristics throughout the comparison run as well. Not only was the current lower with the vector control run, but the current was also less noisy than the scalar run.

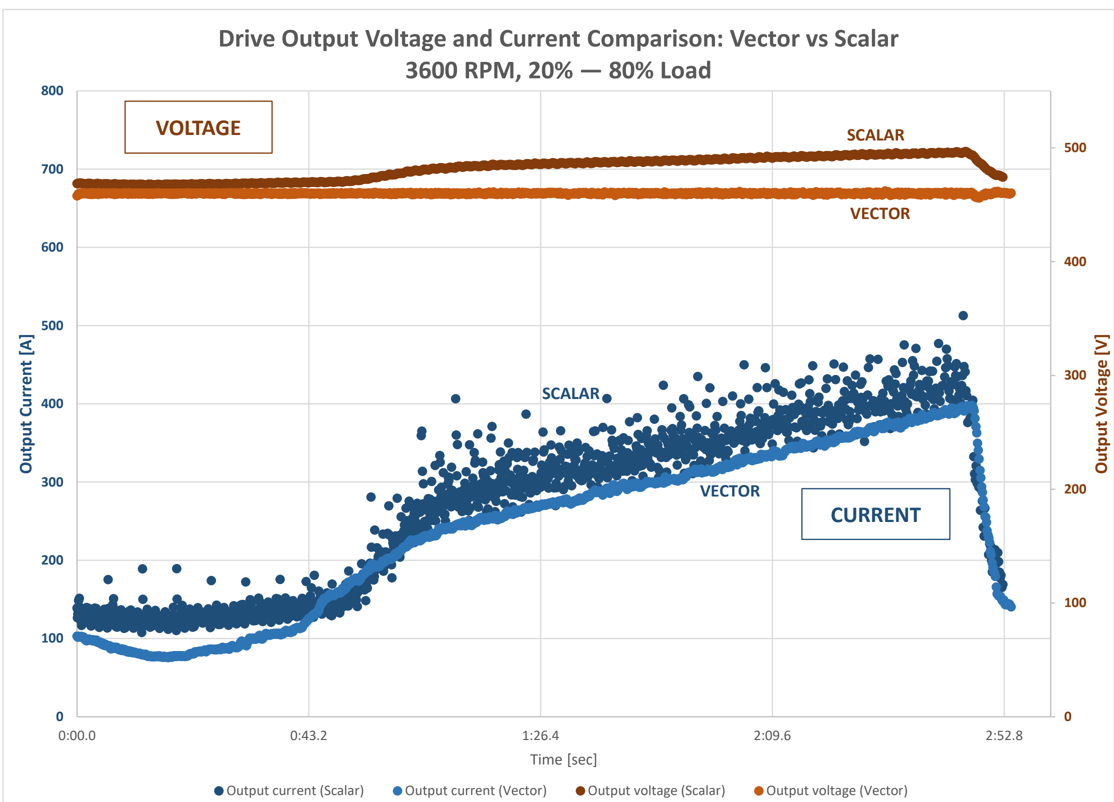

Figure 12 – PMM Scalar vs Vector Control Mode

3.3.1 Conclusion of Efficiency Testing

- Efficiency advantage for vector control has been established by the lab testing, with more noticeable difference between the vector control and the scalar control in the mid to lower load range.
- The superiority of the vector control comes from both the VFD output voltage and the VFD output current. Additionally, the smoother output current for vector control provides larger stability margin which provides further evidence of a more elegant control algorithm.

4 CASE STUDIES – PERMIAN BASIN GASSY APPLICATIONS

Permian Basin unconventional reservoirs are challenging environments for ESP system performance due to the high amount of gas produced when the well has declined in production and pressure, especially on those where enhanced oil recovery using CO_2 is applied. The free gas leads to pump locking, system shutdowns, reduced system reliability, and production loss which negatively affects well economics.

In order to improve ESP system reliability and enhance drawdown and production, several gas handling operating modes are used to operate the ESP system to purge the pumps and keep the motor from heating significantly. However, this involves sudden changes to speed and load. The following case studies confirm Permanent Magnet Motors can ride through these events successfully when proper VFD setup is configured.

4.1 Case Study #1 – Howard County, TX

This case study looks at a high GLR well running in vector control mode with an algorithm that is controlling the PMM speed as load increases and decreases from the system to optimize production as heavy gas volumes enter the pump.

Subject well has 5-1/2” 23# casing, 2-7/8” 6.5# tubing, 1750 Pumps set at 7000’, producing 500Bfpd with 98% WC and 1000scf/stb Gas Liquid Ratio. See well overall 1-day operating trends in Figure 13.

Figure 13 – 1 Day Operating Trends for high GLR Application with PMM – Howard County

The operating trends in Figure 14 show a time window of around 1.5 hours where many speed and load changes are experienced. Looking at the notated time series, there are 8 events highlighted. This process is automated through the VFD and the PMM is being controlled by a properly configured Vector control mode within the VFD.

1 – Load begins to drop, VFD initially increases speed to try to regain load but cannot, so gas ingested by pump causing pump load to fall.
2 – VFD begins slowing unit down in attempt to purge gas from pumps.
3 – Set time period elapsed and VFD increases speed but load is not recovered.
4 – VFD begins slowing unit down to go through another purge cycle.
5 – Second set period elapsed and VFD increases speed again.
6 – Load has still not recovered and VFD begins slowing speed again.
7 – Third set period elapsed and VFD increases speed again.
8 – Load starts to increase and VFD goes back into current chasing mode where production resumes normally.

With the VFD configured correctly for this PMM, the Vector control mode does not have any issues with maintaining rotor synchronization and matching the proper current needed to keep the ESP system operating.

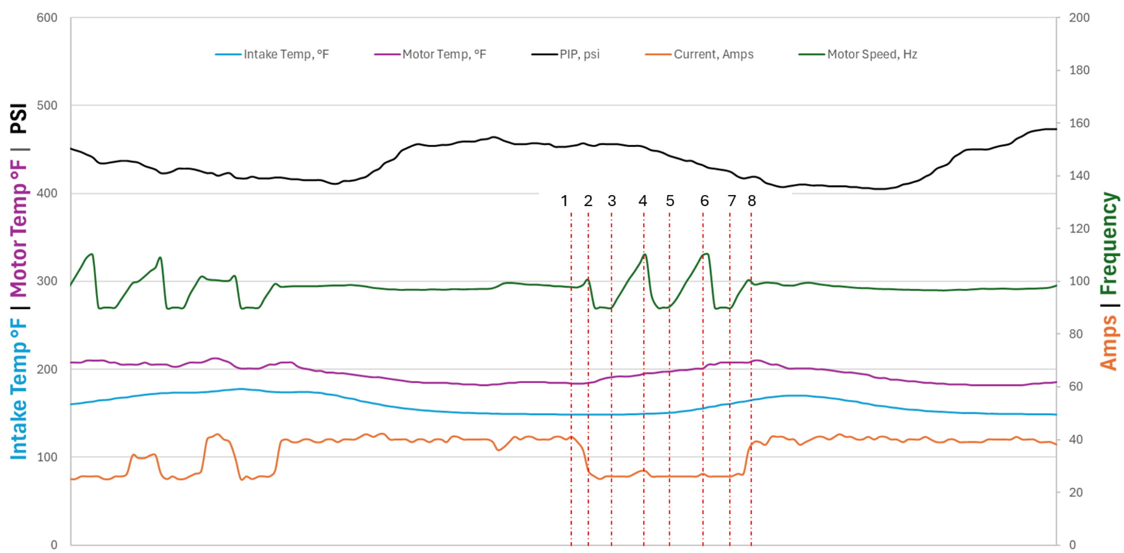

Figure 14 – 1.5 Hour Operating Trends for high GLR Application with PMM – Howard County

4.2 Case Study #2 – Martin County, TX

This case study looks at a very high GLR well with low water cut and low flowing pressure running in Vector control mode, successfully handling frequent load changes from the system due to gas slugging even though unit is running on set frequency.

This Martin County well has 5-1/2” 20# casing, 2-7/8” 6.5# tubing, 1750 Pumps set deeper than the Howard County well at 8500’, producing 750Bfpd with 56% WC and considerably higher Gas Liquid Ratio approximately 2200scf/stb.

Operating trends on Figure 15 show frequent gas slugging for over a month of operation with current, pump intake pressure, tubing pressure and motor temperature fluctuation matching consistent load changes on ESP system.

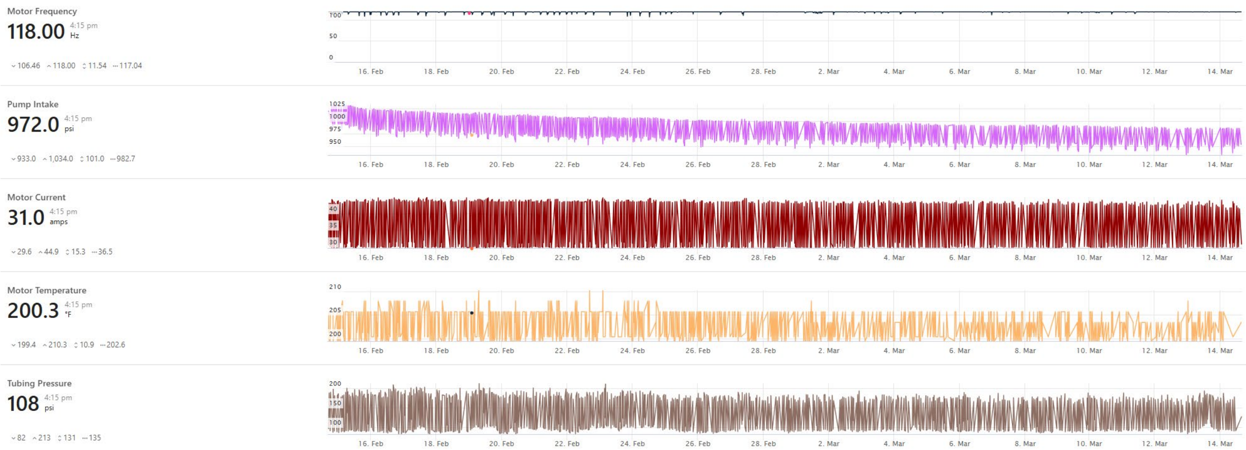

Figure 15 – 1 Month Operating Trends for high GLR Application with PMM – Martin County

Motor load changes from 35 to 55% in less than 2 minutes, with ~6 to 7 cycles per hour (see details on Figure 16), representing over 150 cycles per day at a constant drive output frequency of 118Hz. With the VFD configured correctly for this PMM, the Vector control mode does not have any issues with maintaining rotor synchronization and matching the proper current needed to keep the ESP system operating.

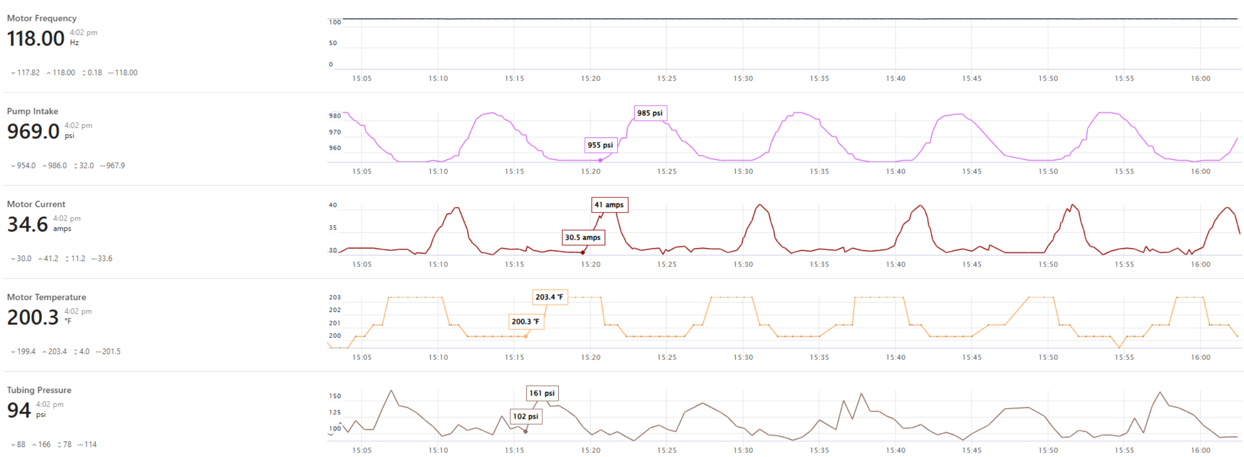

Figure 16 – 1 Hour Operating Trends for high GLR Application with PMM – Martin County

5 CONCLUSIONS

- ESP Systems using PMM demands special control algorithms for an effective control of the motor like Vector control which is the best option since it can control unstable loads.
- The scalar control has been to a large degree replaced in high-performance motors by vector control that enables better handling of the transient processes.
- PMMs can be successfully controlled with modern VFD technology through rigorous front-end engineering and testing.
- VFD setup for PMM applications differs from IM and proper configuration of the VFD is required to ensure rotor synchronization.
- Proper VFD setup is required to ensure successful ESP operation with PMM.
- Unconventional wells with large load variations due to high gas production are great applications for PMM.

6 REFERENCES

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