APPLYING API AND NEMA SPECIFICATIONS TO LIMIT ELECTRICAL CURRENT PULSATION AND TORSIONAL VIBRATION OF SYNCHRONOUS MOTORS DRIVING RECIPROCATING COMPRESSORS

Paper No. PCIC-2019

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Abstract – Unsteady torque from a reciprocating compressor can cause angular oscillation of the motor rotor. The rotational system is electromagnetically coupled to the motor stator through the air gap flux. Proper sizing of a flywheel and the motor inertia are necessary to limit speed fluctuation and current pulsation.

Some current pulsation is to be expected; however, excessive levels can cause problems such as unstable current and power readings, failed motor synchronization during startup, nuisance trips during operation due to high current, increased stator temperatures, and flickering of lights.

This paper discusses how to evaluate current pulsation and compare them to allowable limits. The paper also gives background information on synchronous motors, exciter control, and V-curves, as well as modelling the synchronizing torque coefficient. Case studies are provided with recommendations for reducing speed fluctuation and current pulsation to acceptable levels.

Index Terms — API 546, API 618, NEMA MG-1, electrical current pulsation, synchronous motor, reciprocating compressor torque-effort, angular oscillation, torsional vibration.

I. INTRODUCTION

In the petrochemical industry, synchronous motors are commonly used to drive slow-speed reciprocating compressors. The examples in this paper have motors that operate in the 300 to 327 RPM speed range. The unsteady torque loading of the reciprocating compressor can cause angular oscillation (torsional vibration) of the motor rotor.

The torsional vibration of the combined rotational system is electromagnetically coupled to the stator currents through the air gap flux, which creates pulsation in the current waveform. Proper sizing of the flywheel and motor inertia is needed to limit the speed fluctuation and electrical current pulsation.

Mechanical designers working with reciprocating compressors should also understand the electrical equipment. For example, the motor air gap torque demonstrates a spring action (torque proportional to angular displacement) that is modeled by a synchronizing torque coefficient, or spring constant, P_r. Coefficients for synchronous machines are discussed by Kilgore and Whitney [1] and Shepherd [2].

Current pulsation levels of 20% to 40% are considered to be a normal level. API 546 [3] and NEMA MG-1 [4] specify a maximum limit of 66% for current pulsation in synchronous motors. In addition, API recommends limiting motor speed fluctuation to 1.5%, and that the rigid-body torsional mode has at least 20% separation margin (SM) from running speed. Excessive speed fluctuation and/or torsional vibration could possibly lead to rocking of motor poles and fatigue failures of the pole bolts.

Effectively limiting current pulsation requires the motor and compressor manufactures to work together in the design stage to ensure that the total inertia of the rotating system (motor + flywheel + compressor) is sufficient to smooth the torque and current pulsation inherent in motor-compressor systems. A flywheel is typically sized to tune other torsional natural frequencies (TNFs) between significant compressor harmonics. The equivalent electromagnetic (EM) spring of the motor and the torque effort of the reciprocating compressor should always be included in a steady-state torsional vibration analysis (TVA).

Methods for evaluating the percent current pulsation are discussed. This paper also provides several case studies. The last case study discusses how excessive current pulsation was identified in an existing compressor system. The problem was solved by performing a TVA and recommending a new motor with higher inertia. Measurements confirmed that the modified system had acceptable speed fluctuation and current pulsation.

II. SYNCHRONOUS MOTOR BASICS

These case studies involve large, slow-speed, synchronous motors with salient poles and a single outboard bearing. The drive-end of the motor shaft is bolted directly to the compressor crankshaft and flywheel through an integrally flanged connection.

Salient pole synchronous rotors are made by placing poles of stacked electrical steel symmetrically around the rotor which are wound with DC electrical coils so that the poles alternate in magnetic polarity between positive and negative. The result is that the poles of the rotor magnetically lock in synchronism to the poles of opposite polarity of the stator rotating magnetic field.

The synchronous speed of the motor, n, is a function of the number of rotor poles as shown in the following equation:

$$n = \frac{2 \, x \, 60 \, x \, f}{Number\ of\ Rotor\ Poles} \tag{1}$$

where:

n = synchronous speed (RPM),
f = line frequency (60 Hz for North America).

The DC coils mounted on the rotor are known as the field winding. The DC current for the field winding is provided in one of two ways: 1) "Brush" or "static" excitation where current from an external DC power supply is fed through brushes that ride on slip rings mounted on the motor's rotor, or 2) "Brushless" excitation where current provided by a rotor-mounted 3-phase AC generator is rectified to DC by a rotating rectifier wheel.

A. Synchronizing Torque Coefficient (P_r)

The magnetic centerline of the rotor poles do not line up exactly with the centerline of the stator poles of opposite polarity, but instead trails by the load angle. If the power factor (PF) and field current are held constant, the load angle of the synchronous motor varies in proportion to the magnitude of the load torque. In a steady-state condition, with the shaft load, PF, and field current all held constant, the synchronizing torque coefficient is:

$$P_r = \frac{Shaft\ Load}{Load\ Angle} \qquad (2)$$

where the shaft load is expressed in kW and the load angle expressed in electrical radians.

The synchronizing torque coefficient, also known as "the spring constant" of an electric motor, is a measure of the electromagnetic stiffness between the stator and rotor. The value of P_r for a given machine is dependent on:

1) Voltage and frequency of the power system,
2) Magnitude of the applied load,
3) Operating power factor (PF),
4) Power system impedance, and
5) Frequency of alternating torque.

NEMA MG-1 states that motor vendors should supply P_r values at rated voltage, frequency, load, and PF assuming negligible system impedance. Furthermore, the value of P_r for motors should be provided at a pulsation frequency equal to the motor's RPM in cycles per minute. Absent manufacture data, P_r can be approximated as the horsepower (HP) × 1.35 for unity PF, and HP × 1.8 for 0.8 leading PF motors per reference [5].

B. Motor Acceleration and Pulsating Torque

Most synchronous motors have copper or copper alloy bars inserted axially through the top of the pole shoe. These damper bars are then electrically shorted together by copper rings on each end to create what is alternatively called the amortisseur winding, damper winding, or squirrel cage winding. During acceleration the synchronous rotor acts like an induction rotor as most of the accelerating torque is generated in the damper winding; with some additional torque being generated from currents induced in the field coils. Once the rotor is accelerated to 93% to 98% speed, a field application control system applies current to the field winding, which pulls the rotor into synchronism. The field application control system is either mounted externally to the rotor in the case of static excitation, and in some cases of brushless excitation. It may also be located on a rotor mounted control wheel as in most cases of brushless excitation.

During acceleration, salient pole synchronous motors will exhibit a pulsating torque that occurs at twice the slip frequency of the rotor, i.e. the pulsating torque will decrease in frequency from 120 Hz at zero speed to approximately 5 Hz just before synchronization. Therefore, any TNFs below 120 Hz could be excited when starting the synchronous motor across-the-line.

Pulsating torque is caused by the change in the reluctance path between the low reluctance path at the pole centerlines and the high reluctance path seen at the centerline between poles. This pulsating torque can range from 40% to 120% 0-p (zero-peak) of rated torque depending on the salient pole design.

The pulsating torque can be amplified by TNFs which can cause fatigue damage during each start and eventual shaft failure. A time-transient torsional analysis is recommended to analyze the synchronous motor startup across-the-line [6]. Some plants may use an electrical soft-starter to minimize in-rush current and avoid high pulsating torque during startup.

C. Power Factor Control of Synchronous Motors

Since the field is powered from an external source, the synchronous motor can control the PF at the stator terminals. Typically, the synchronous motor is rated at either 100% PF, also called unity PF, or 80% leading PF. When operating at a leading PF, the synchronous motor will provide reactive power to the power system. When operating at unity PF, the synchronous motor is neutral with respect to absorbing or providing reactive power to the power system. This is different from an induction motor, which always operates with a lagging PF and absorbs reactive power from the power system.

The relationship between PF, shaft load, stator current and field current is related by a V-curve [7]. The V-curve will show that if field current is held constant, then as shaft load increases, the PF will lag more. Likewise, if the shaft load decreases, the PF will lead more. Ideally, the motor field current control logic would adjust the field current to maintain a constant PF as the shaft load changes. This type of control is known as PF control mode and is typically used in this type of application. An older type of control mode, known as constant field current control, will keep the field current constant and let the PF swing as the load increases and decreases. This type of control is often used when the average compressor loading changes very little over time.

D. Current Pulsation Analysis

The motor supplier typically performs a basic current pulsation analysis in the design stage. To perform this study, the motor vendor needs to be provided with the compressor crank angle diagram and the total system inertia. Varying torque load from the compressor causes the motor rotor to oscillate about the nominal load angle. This oscillation, in turn, induces currents in the damper winding that work to dampen the rotor oscillations. The damping power of the damper winding is proportional to the angular velocity of the rotor and is represented by the dampening power coefficient, P_d.

A thorough current pulsation study will take the compressor crank angle curve and break the torque down to its individual harmonics up to 8× operating speed. Values of both P_r and P_d need to be calculated up to the 8^{th} harmonic. These stiffness and damping coefficients are applied with respect to the motor pulsating torque and then the current pulsation is calculated at each harmonic frequency.

The total current pulsation is calculated by summing the pulsation at all frequencies. The study provides the predicted current pulsation of the motor-compressor system, or a table of predicted current pulsation levels versus total inertia of the drive train. It is assumed by the motor manufacturer that the alternating torque is no worse than that given in the compressor crank-effort diagram, i.e. that no TNFs are excited. This simplified current pulsation analysis is reasonable when the SMs are adequate as defined by API. However, a detailed TVA would still be required by API to calculate TNFs, shaft stresses, etc.

III. RECIPROCATING COMPRESSOR TORQUE

Motor designers should be aware that reciprocating compressors have varying load torque that is typically much higher than for rotating equipment [8]. A reciprocating compressor will produce significant alternating torque at multiples of operating speed (called harmonics or orders). Normally, the highest amplitudes of concern are from 1× to 3× operating speed. Compressor harmonics above 3× running speed are generally lower level unless amplified by a TNF.

The Gas Machinery Research Council (GMRC) published a document [9] with guidelines on how much alternating torque to expect from a reciprocating compressor. As shown in Table 1, the torque is typically smoother for larger number of compressor cylinders, but still much greater than would be produced by a centrifugal compressor, pump or fan.

TABLE 1
MOTOR DESIGN TORQUE

Compressor Throws	Mean Torque	Alternating Torque
2	100% Rated	±250% Rated
4	100% Rated	±200% Rated
6	100% Rated	±150% Rated

A steady-state torsional analysis is recommended to analyze all compressor load cases. To smooth the varying torque of the reciprocating compressor, a large motor inertia and/or flywheel is normally required. It may be necessary to adjust the total system inertia to limit angular oscillation and speed fluctuation. The coefficient of speed fluctuation, C_s, is defined as:

$$C_s = \frac{\omega_{max} - \omega_{min}}{\omega_{avg}} \tag{3}$$

where:

ω_{max} = maximum speed,
ω_{min} = minimum speed,
ω_{avg} = average speed.

According to Almasi [10], limiting speed fluctuation to 1% to 2% p-p (peak-to-peak) is generally recommended for electrical systems. API specifies a speed fluctuation limit of 1.5% p-p.

TABLE 2
SPEED FLUCTUATION AND OSCILLATION

Percent Speed Fluctuation (p-p)	Oscillation (deg p-p)
1%	0.57
1.5%	0.86
2%	1.15
3%	1.72
5%	2.86

The following equation can be used to relate the coefficient of speed fluctuation to angular oscillation:

$$\textit{Oscillation} = C_s \times 180 / \pi \tag{4}$$

where oscillation has units of deg p-p and is assumed to occur at 1× operating speed.

IV. NEMA STANDARD MG-1

Additional phenomena affecting current pulsation are outlined in the National Electrical Manufacturers Association (NEMA) Standards Publication No. MG-1, specifically, Sections 21.35 – 21.37 of the 2014 edition [4].

A. Torsional Natural Frequency of Oscillation

As described in NEMA MG-1, Section 21.35.1, synchronous machines connected to an "infinite electrical system" have an undamped natural frequency of oscillation. For the single-degree of freedom (SDOF) system, the electrical supply is considered to be infinitely rigid, the magnetic stiffness between the stator and rotor (air gap) is the spring, and the inertia is the entire rotating system (motor, flywheel, and compressor). The TNF of oscillation for the rigid-body mode is computed as:

$$f_n = \frac{35200}{n}\sqrt{\frac{P_r \times f}{Wk^2}} \tag{5}$$

where:

f_n = natural frequency (cycles per minute or CPM),
n = synchronous speed (RPM),
P_r = synchronizing torque coefficient (kW/rad),
f = electrical line frequency (Hz),
Wk^2 = polar moment of inertia (lb-ft^2)

B. Compressor Factor

Compressor factor, C, is a parameter that is used to help ensure that motor current pulsation is maintained within specified limits. A higher compressor factor is considered better than a lower value. The compressor factor that will be provided by a synchronous motor is a function of the total Wk^2 of the system (motor, flywheel, compressor) and is computed by the formula:

$$C = \frac{0.746 \times Wk^2 \times n^4}{P_r \times f \times 10^8} \tag{6}$$

where:

Wk^2 = polar mass moment of inertia (lb-ft^2),
n = synchronous speed (RPM),
P_r = synchronizing torque coefficient,
f = electrical line frequency (Hz).

The required compressor factor is determined by the physical characteristics of the compressor, such as the number of cylinders, crank angle, reciprocating weights, cylinder loading (unloaders, pockets, etc.), number of stages, and operating conditions (gas type, pressures, etc.). NEMA provides a table with a range of C values for various compressor configurations to limit current pulsation. The columns in the NEMA table are labeled as 66%, 40%, and 20% current pulsation.

Although there are 295 applications listed in the NEMA table, it cannot encompass every type of compressor used in industry. As discussed in one case study, there were no examples of 6-throw compressors. Therefore, specifying an allowable SM may be a better approach. As discussed in the next section of the paper, API and reference [5] state that this torsional natural frequency of oscillation, f_n, should differ from any forcing frequency by at least a 20% SM.

V. API STANDARDS 546 AND 618

API Standard 546 [3] addresses brushless synchronous machines 500 kVA and larger. API Standard 618 [11] covers reciprocating compressors for the petroleum, chemical, and gas industries. Both standards specify that a torsional vibration analysis should be performed in the design stage.

API 546 states that current pulsation under the actual operating conditions shall be within the limits stated within API 618 or NEMA MG-1. The NEMA limit is 66%; however, current pulsation can be reduced through larger rotor inertia and/or additional flywheel inertia. In many instances, 40% current pulsation or less is specified by the end user to reduce light flicker on power systems with weak short circuit capacity. API 546 also states that in order to verify performance, it may be necessary to measure the current pulsation once the motor has been installed and is operating under full load.

API 618 specifies that a torsional vibration analysis shall be performed on all machines being furnished. TNFs of the complete driver-compressor system shall not be within 10% of any operating shaft speed or within 5% of any multiple of operating shaft speed in the rotating system up to and including the tenth multiple. For motor-driven compressors, TNFs shall be separated from the first and second multiples of the electrical power frequency by 10% and 5%, respectively.

For synchronous-motor-driven compressors, API has three additional requirements:

- *The combined inertia of rotating parts of synchronous motor-compressor installations shall be sufficient to limit motor current variations to a value not exceeding 66% of the full load current for all specified loading conditions, including unloaded operation with cylinders pressurized to their normal suction pressures. See IEC 60034 [12] or NEMA MG-1.*
- *The inertial characteristics of the rotating parts of the compressor and of the drive train shall be such that rotational oscillations will be minimized. Undesirable oscillations include those that cause damage and those that result in harmful torsional and/or electrical system disturbances. For initial design purposes, peak-to-peak speed oscillation of the rotating system shall be limited to 1.5% of rated speed at full load and partial cylinder loads if step unloading is specified.*
- *The torsional stiffness and the inertia of all rotating parts shall provide at least a 20% difference between any inherent exciting frequency of the compressor and the torsional frequency of the motor rotor oscillation with respect to the rotating magnetic field.*

It is believed that the "torsional frequency of the motor rotor oscillation" is referring to f_n as previously defined in NEMA.

When performing a steady-state TVA, it is recommended that an equivalent torsional stiffness (K_{em}) be included between the motor rotor and stator (ground) to simulate electromagnetic (EM) effects. To estimate this torsional spring, the following equation was developed by rearranging (5) and solving for K_{em}:

$$K_{em} \approx 5.07 \times 10^6 \frac{P_r \times f}{n^2} \tag{7}$$

where:

K_{em} = Torsional stiffness due to EM effects (in-lb/rad)
P_r = Synchronizing torque coefficient (kW/rad)
f = Electrical line frequency (Hz)
n = Synchronous speed (RPM)

VI. EVALUATING CURRENT PULSATION

Ideally, the three electrical current phases for the motor should be balanced (having same amplitude), purely sinusoidal (no harmonic distortion or noise), and occurring only at the line frequency. However, unsteady load torque from the reciprocating compressor causes angular oscillation of the motor rotor which results in current pulsation. Since current is related to torque, the current amplitude will modulate instead of being constant. There are several ways to evaluate the motor current and pulsation as discussed below.

A. Graphical Method

The graphical method is performed on the time-wave form of the motor electrical current as shown in Figure 1.

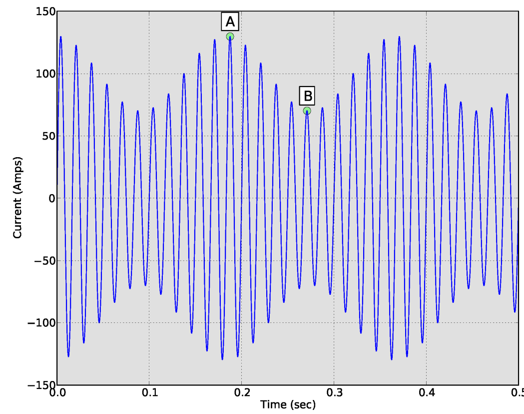

Fig. 1 Electrical Current with Pulsation

The first step is to determine the envelope by subtracting the minimum (point B) from the maximum (point A). Next, the amplitude (0-p) needs to be converted to root mean squared (RMS) commonly used for the motor full load amperage (FLA) rating. This is approximated by dividing the value by $\sqrt{2}$. The final step is to compute the percent current pulsation by dividing by the FLA and multiplying by 100%. The formula for percent current pulsation is:

$$\frac{(A - B) \times 100\%}{\sqrt{2} \times FLA} \tag{8}$$

For this example, assume that FLA=71 amps RMS, A=130 and B=70 amps 0-p. Using equation (8), the current pulsation is therefore 60%.

B. Hilbert Transform

It would be beneficial to have an automated method for evaluating the current pulsation. The primary author has applied the Hilbert Transform [13] to determine the envelope using SciPy [14] in the Python programming language [15].

Figure 2 shows the current with pulsation (dashed blue line). The envelope (red line) was calculated using the Hilbert Transform. Note that the absolute value of the current can be superimposed on the plot (solid green line) and will still have the same calculated envelope. This would be a good feature to add to digital meters used for monitoring motors at the plant.

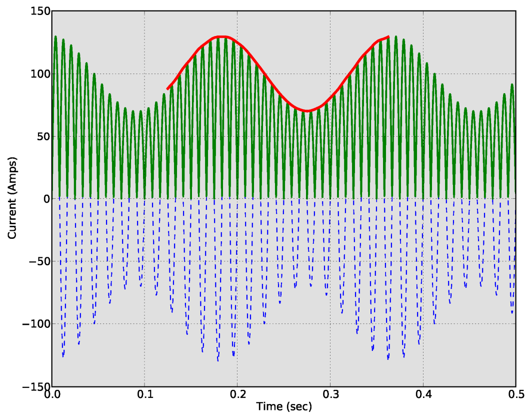

Fig. 2 Hilbert Example with Absolute Value

C. *Frequency Analysis*

Frequency analysis techniques can also be used to evaluate the motor current. Figure 3 shows the frequency spectrum of the motor current plotted on a logarithmic scale to accentuate and identify any side-bands of the electrical frequency (60 Hz).

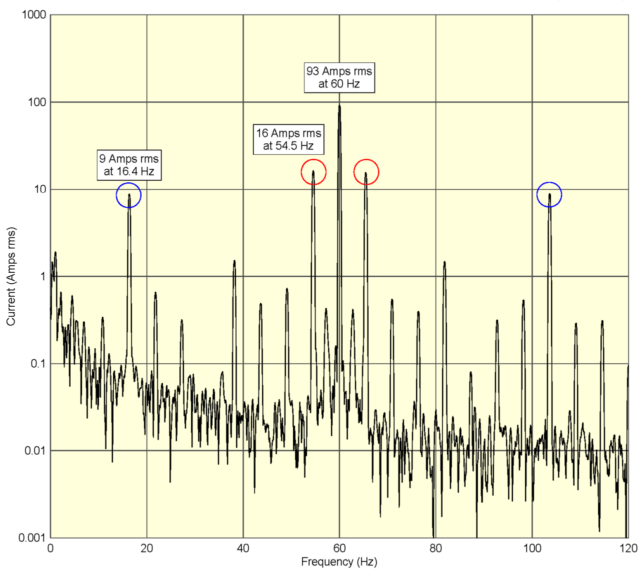

Fig. 3 Frequency Analysis of Current

In this example, the motor was operating at 327 RPM (5.45 Hz). The electrical frequency is shown in the center of the graph. The side-bands at 54.5 Hz and 65.5 Hz (circled in red) have spacing of ±1× operating speed. This is typically the low-frequency producing the highest current pulsation due to the rigid-body torsional mode associated with f_n.

As noted in Figure 3 there are also significant side-bands at 16.4 Hz and 103.6 Hz (circled in blue) with spacing of ±8× operating speed. This is somewhat unusual, and it was later determined with strain gage measurements on the motor shaft that the first TNF was coincident with the 8× compressor harmonic causing high alternating torque in the system.

VII. Case 1: 17,500 HP Motor & 6-Throw Compressor

Although the compressor system in this case study had acceptable current pulsation (less than 66%), it still provides an opportunity to compare measured torsional vibration of the motor with resulting current pulsation at various compressor loads. A description of the system is shown in Table 3.

TABLE 3
SYSTEM DESCRIPTION FOR CASE STUDY 1

Synchronous Motor	Single-Bearing Design Rated 17,500 HP at 327 RPM 22 Poles, 13,200 Volts, 652 Amps, 60 Hz
Reciprocating Compressor	Hydrogen Service 6-Throw, 3- Stage Variable Capacity Control (1% - 100%)
Total Inertia (Wk^2) of Motor, Flywheel & Compressor	734,600 lb-ft^2
Synchronizing Power, P_r	36,500 kW/rad (from motor manufacturer)
TNF of Oscillation, f_n	186 CPM or 3.1 Hz (calculated)
Compressor Factor, C	29 (calculated)

This reciprocating compressor had six throws and three stages of compression. Compressor cylinders 1 – 4 are recycle (3rd stage). Cylinder 5 is 2nd stage make-up and cylinder 6 is 1st stage make-up (oil pump end of the compressor). This hydrogen compressor was continuously controlled (without load steps), using hydraulic power and electronic time control to delay closing of the suction valves. The variable capacity control system was installed on all cylinders in place of conventional unloaders and/or pockets.

The gas volume compressed per stroke could be regulated with the actuator. By keeping the suction valve open, part of the gas in the cylinder flows back into the suction chamber. After the suction valve is closed, the remaining gas in the cylinder can be compressed. Compressor capacity is defined by the closing time, which is set electronically via a fast-switching solenoid valve.

For this system, the undamped TNF of oscillation, f_n, was computed to be 186 CPM or 3.1 Hz, which was 43% below the running speed of 327 RPM. This met the 20% SM recommended by API.

NEMA does not provide a recommended compressor factor, C, for 6-throw compressors. For this system, the C value was computed to be 29. Since the measured motor current had less than 10% pulsation, it was concluded that a C value of 29 is acceptable for a 6-throw compressor in this type of service.

Field testing was performed, which included measuring: motor oscillation using a rotational laser vibrometer, motor shaft torque (mean and alternating) using a strain gage telemetry system, and motor current. Figure 4 shows frequency spectra plots of the measured oscillation and alternating torque in the motor shaft. The maximum angular oscillation occurred at 1× operating speed, whereas the alternating torques were highest at the 6×, 8× and 10× compressor harmonics. This shows that the current pulsation occurring at 1× speed was mostly related to angular oscillation of the motor rotor and not the alternating torque in the motor shaft.

In general, the current pulsation was related to the rigid-body torsional mode (zero mode). The alternating torque at the higher harmonics was influenced by the twisting in the shaft (first torsional mode). Figure 5 shows that the maximum current pulsation was less than 10%, which is considered low level.

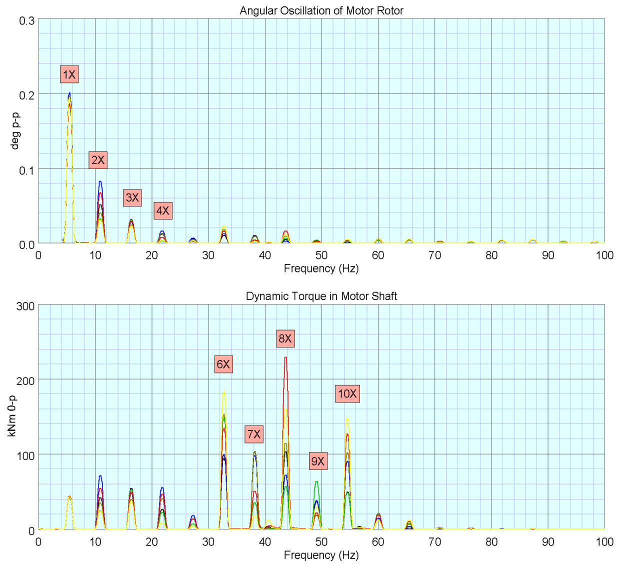

Fig. 4 Motor Oscillation and Alternating Torque

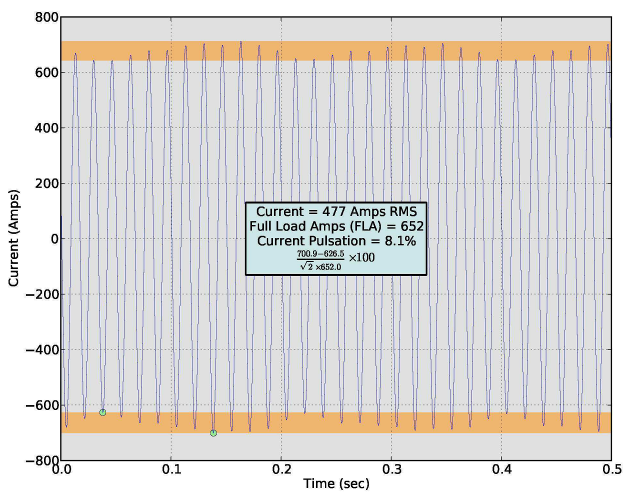

Fig. 5 Motor Current with Low Pulsation

The hydrogen make-up and recycle stages can be adjusted independently according to the process requirements. As shown in Table 4, various percentages of compressor load were tested to relate current pulsation and angular oscillation. For this motor, it was estimated that 1 deg p-p of angular oscillation would create approximately 30% of current pulsation.

TABLE 4
SUMMARY OF MEASURED AMPLITUDES

Load Steps		**Ang. Osc. (deg p-p)**		**Current**	**Ratio of**
Make-Up	**Recycle**	**1×**	**Overall**	**Pulsation**	**Puls. / Osc.**
60%	70%	0.19	0.22	6.8%	31% per deg
	100%	0.19	0.24	7.6%	32% per deg
80%	70%	0.20	0.25	6.8%	27% per deg
	100%	0.19	0.20	6.1%	31% per deg
100%	70%	0.20	0.29	8.2%	28% per deg
	100%	0.19	0.27	8.1%	30% per deg
				AVERAGE	**30% per deg**

VIII. Case 2: 4,000 HP Motor & 6-Throw Compressor

For this application, atmospheric air was being compressed to 6000 psi final discharge pressure and stored in high-pressure vessels to be used in a specialized test of space equipment. The reciprocating compressor had a single load step (fixed clearance) and all cylinders were double-acting. The synchronous motor used slip rings for static field excitation. A description of the system is shown in Table 5.

TABLE 5
SYSTEM DESCRIPTION FOR CASE STUDY 2

Synchronous Motor	Single-Bearing Design Rated 4,000 HP at 277 RPM 26 Poles, 6,600 Volts, 269 Amps, 60 Hz Exciter = 125 VDC, 146.5 Amps
Reciprocating Compressor	Air Service 6-Throw, 6-Stage
Total Inertia (Wk^2) of Motor, Flywheel & Compressor	147,000 lb-ft^2
Synchronizing Power, P_r	5,400 to 7,200 kW/rad (estimated)
TNF of Oscillation, f_n	189 – 218 CPM 3.1 – 3.6 Hz (estimated)
Compressor Factor, C	15 – 20 (calculated)

The machinery had been in service for over 20 years, but after an upgrade of the switch gear, high current pulsation was detected causing the motor to trip. To avoid unexpected shutdowns, the averaging time for the current was extended.

The compressor manufacturer had performed calculations to determine the required system inertia to prevent excessive oscillation. The worst case for current pulsation was predicted when operating at 4,500 psi discharge pressure. To limit the speed variation to 2% or less, the total system inertia would need to be at least 111,000 lb-ft^2. To limit the speed variation to 1.5% or less, a total inertia of 149,000 lb-ft^2 would be required. Note that the actual system inertia was 147,000 lb-ft^2, which was very close to the required value for 1.5% speed variation.

A rotational laser vibrometer was used to measure angular oscillation of the motor shaft. Figure 6 shows the primary oscillation frequency was at 1× operating speed. With the compressor loaded, the oscillation increased to 1.7 deg p-p, which corresponds to 3% p-p speed fluctuation. This was double the predicted value when neglecting EM stiffness in the TVA.

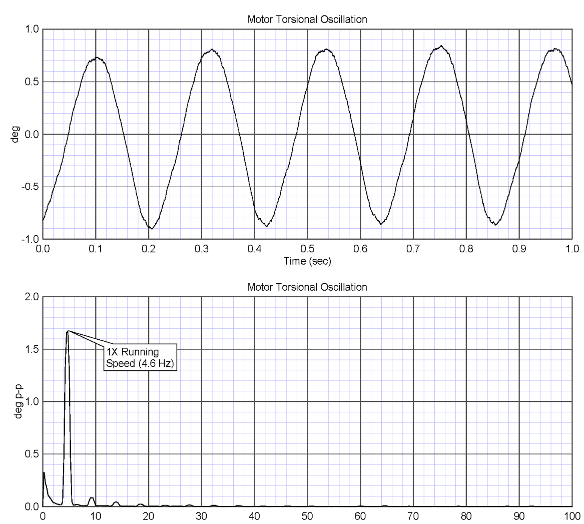

Fig. 6 Angular Oscillation of Motor

Torsional measurements were correlated with electrical measurements, which included stator voltage, stator current, field voltage, and field current. As shown in Figure 7, when the compressor was unloaded (blue traces), the current pulsation was low; however, when the compressor was loaded (red traces) the current pulsation increased dramatically.

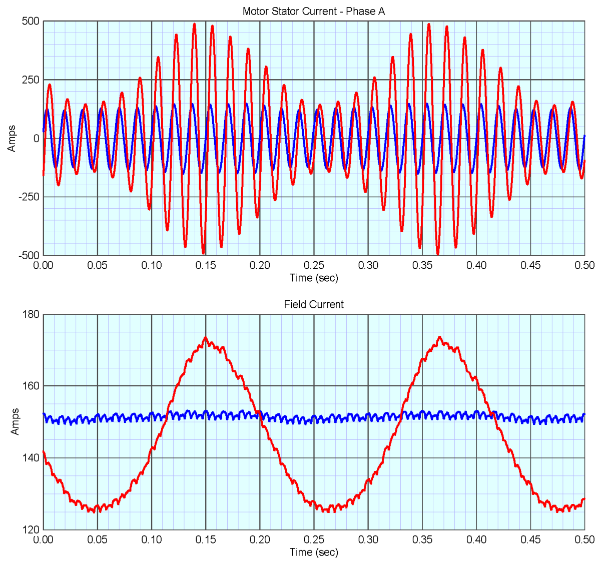

Fig. 7 Measured Stator and Field Currents

The peak stator current varied from 150 to 500 amps. The percent current pulsation was found using equation (8) where $(500 - 150) / \sqrt{2} / 269 = 0.92$ or 92% of FLA. This amount of current pulsation exceeded the 66% limit. For this motor, the current pulsation divided by oscillation was 54% per 1 deg p-p.

It was noticed that the field current also had variation at 1× operating speed when the compressor was loaded. A test was performed where the field excitation was decreased, resulting in a lagging PF. Correlation was found between the field excitation and the angular oscillation at 1× operating speed. No parameters were changed on the compressor during this test.

As shown, current pulsation was due to excessive angular oscillation at 1× running speed (4.6 Hz) and was related to the rigid-body mode (zero mode), not the first torsional mode. Current pulsation was 132%, which is much higher than normal 20% to 40%, and the 66% limit set by NEMA. This was causing problems with flickering of lights and motor insulation damage due to excessive heat.

High current pulsation was unexpected because original calculations by the compressor manufacturer predicted that the motor and flywheel had sufficient inertia to prevent a problem. Yet the measured angular oscillation was approximately double the predicted amplitude.

By reducing the field excitation, it was demonstrated that the angular oscillation of the motor could be decreased. Figure 8 shows the 1× harmonic decreasing from 1.75 to 1.3 deg p-p. The effective torsional spring to ground (EM) was reduced with a weaker field. This agrees with NEMA which states that the motor characteristic, P_r, increases with an increase in line voltage or the excitation current, and decreases with a reduction in these parameters.

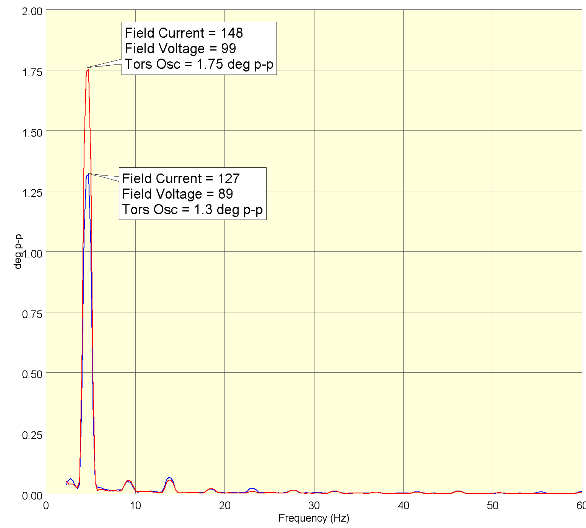

Fig. 8 Angular Oscillation of Motor with Reduced Excitation

It was reported that the automatic PF control was disabled. The possibility of exciting the motor with an external power supply was discussed. Had time allowed, this would have been an interesting experiment to determine if the angular oscillation could be further reduced. Since sensitivity to motor electrical parameters was demonstrated, it was recommended to review the one-line diagram to see what other electrical equipment may share the power supply and if perhaps the power supply could be considered “soft.”

It was also recommended to check for failed compressor valves, which could affect the torque effort and possibly increase alternating torque levels at 1× running speed. For comparison, the adjacent compressor unit was tested which was operating at slightly higher speed of 300 RPM. It was found that the angular oscillation was only 0.5 deg p-p or less when operating the same type of compressor fully loaded.

IX. Case 3: 4,000 HP Motor & 4-Throw Compressor

After commissioning this compressor unit, the motor had difficulty starting and exciter components experienced premature failures. The measured current pulsation was high (≈ 100%) and exceeded the NEMA specification of 66%. A general description of the original system is shown in Table 6.

TABLE 6
SYSTEM DESCRIPTION FOR CASE STUDY 3

Synchronous Motor	Single-Bearing Design Rated 4,000 HP at 327 RPM 22 Poles, 4,000 Volts, 444 Amps, 60 Hz
Reciprocating Compressor	Hydrogen Service 4-Throw, 2-Stage
Total Inertia (Wk^2) of Motor, Flywheel & Compressor	64,000 lb-ft^2
Synchronizing Power, P_r	5400 to 7200 kW/rad (estimated)
TNF of Oscillation, f_n	242 – 280 CPM 4.0 – 4.7 Hz (estimated)
Compressor Factor, C	13 – 17 (computed)

The compressor manufacturer had originally performed a study, which predicted acceptable current pulsation in the motor electrical system based on the expected torque effort from the compressor. An application review revealed that the motor manufacturer was unaware that the motor was being used for a reciprocating compressor with unsteady torque, and that the field current control logic was not designed to handle pulsation.

Synchronizing power, P_r, was not provided for this motor, but was estimated to be 5,400 to 7,200 kW/rad by multiplying the rated power of 4000 HP by 1.35 or 1.8. Using equation (5), the TNF of oscillation, f_n, was 242 - 280 CPM, which is less than 20% from the operating speed of 327 RPM. The compressor factor, C, was estimated to be 13 to 17. For several 4-throw compressor applications listed in NEMA, the C value should ideally be ≥12.5 for 66%, ≥16 for 40%, and ≥21.5 for 20% current pulsation. As shown, the calculated C value for this system was near the minimum recommendation from NEMA.

A. Field Measurements of Original System

Field tests were performed to identify the source of the current pulsation. This included measuring angular oscillation of the motor, motor current, and motor shaft torque as shown in Figure 9. The motor oscillation reached nearly 3 deg p-p at full load, which is considered high. This angular oscillation primarily occurred at 1× running speed and created excessive current pulsation, but not excessive stresses in the motor shaft.

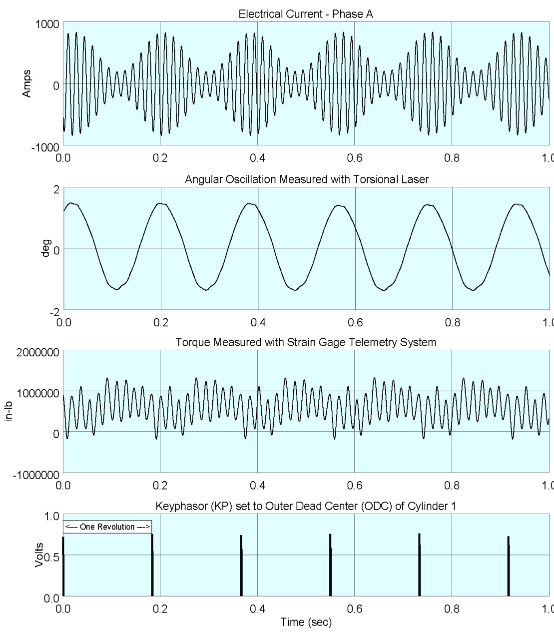

Fig. 9 Measured Current and Torsional Response

Table 7 summarizes the measured angular oscillation and current pulsation for various compressor load steps. For this motor, the ratio was approximately 35% to 38% current pulsation per 1 deg p-p.

TABLE 7
MEASURED RESPONSE FOR CASE STUDY 3

Compressor Load Step	Transmitted Torque	Torsional Oscillation	Current Pulsation
50% Load	39%	0.9 deg p-p	32%
75% Load	60%	2.2 deg p-p	80%
Full Load	80%	2.9 deg p-p	105%

The first TNF was measured at 54.5 - 55.0 Hz, and the second TNF was 91 Hz. Because the first TNF was coincident with 10× operating speed (54.5 Hz), the alternating torque was marginal, but a separate issue from the high current pulsation. Since the angular oscillation occurred at 5.45 Hz, which was well below the first TNF of the system, it was not being mechanically amplified.

Pressure-volume (PV) cards were measured in all compressor cylinders. Torque effort curves were developed for each load step by applying pressure and including the reciprocating masses. Figure 10 shows example torque effort curves for the entire compressor at full load. Note that the sign convention is negative for load torque.

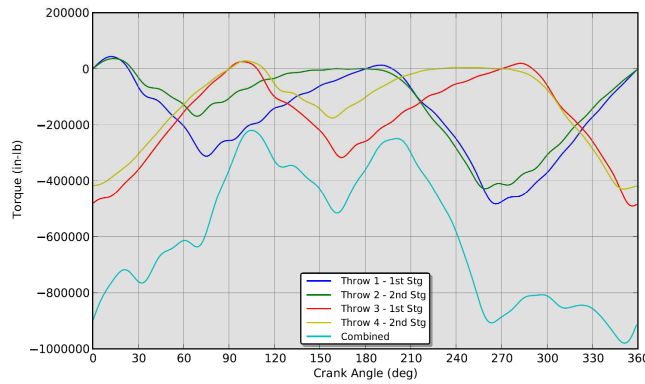

Fig. 10 Torque Effort Curves for Compressor at Full Load

B. Torsional Vibration Analysis

Based on the original TVA, it appeared that the compressor system should have had sufficiently large inertia. However, as shown in Table 8, those predicted values using the mass-elastic model without EM were approximately half of the measured angular oscillation. The higher measured values are due to an amplification from the electrical system that was omitted from the original TVA.

TABLE 8
ANGULAR OSCILLATION – PREDICTED VS MEASURED

Compressor Load Step	Predicted w/o EM	Predicted w/ EM	Measured
50% Load	0.4 deg p-p	0.9 deg p-p	0.9 deg p-p
75% Load	1.0 deg p-p	2.2 deg p-p	2.2 deg p-p
Full Load	1.3 deg p-p	2.9 deg p-p	2.9 deg p-p

A torsional stiffness of 16×10^6 in-lb/rad was applied between the motor rotor and stator (ground) to simulate EM effects. Once the torsional model was updated and the EM spring was included, the predicted motor oscillations matched field measurements for all load cases as shown in Table 8.

Increasing the flywheel inertia by a factor of four was analyzed. This would result in an f_n of 204 CPM, and maximum oscillation of 1.4 deg p-p at full load. The estimated current pulsation would be 50%, which is below the NEMA limit of 66%. However, such a large flywheel was impractical. Therefore, the refinery decided to purchase a new motor with larger inertia.

The TVA was updated to evaluate the new motor design. The steady-state alternating stresses/torques and angular oscillations were evaluated over the range of compressor load conditions. With the increased inertia of the new motor, the NEMA compressor factor was estimated to be 22. The natural frequency was predicted to be 213 CPM, which is 35% below running speed including the EM effects. The results of the study indicated that with the new larger motor, the electrical current pulsation should be reduced to an acceptable level.

The transient startup of the new synchronous motor was also analyzed. Peak torque values were provided to the motor manufacturer for further evaluation of their motor design and the bolted flange connection. For reference GMRC [9] states that a motor driving a 4-throw compressor should normally be able to withstand a mean torque of 100% rated torque ± cyclic torque of 200% rated torque. This equates to an allowable peak torque of 300% rated torque.

C. Follow-up Field Measurements with New Motor

Torque in the motor shaft was measured during startup with the compressor valves installed. The peak torque was 720,000 in-lb, which is lower than the predicted value of 900,000 in-lb. Therefore, no fatigue damage should occur in the shafts during startup.

The 75% load and full load compressor steps no longer produced reversing torque in the motor shaft. In addition, angular oscillation and current pulsation were greatly reduced. The results are summarized in Table 9 for all load steps.

TABLE 9
RESULTS WITH NEW MOTOR

	Angular Oscillation		Current Pulsation	
Compressor Load Step	**Original Motor**	**New Motor**	**Original Motor**	**New Motor**
Unloaded	2.0 deg p-p	1.0 deg p-p	72%	10%
50% Load	0.9 deg p-p	0.5 deg p-p	32%	10%
75% Load	2.2 deg p-p	1.1 deg p-p	80%	30%
Full Load	2.9 deg p-p	1.4 deg p-p	105%	48%

As shown in Figure 11, the current pulsation was reduced from 105% to 48% while operating with full compressor load. The system with the new motor now meets the NEMA limit of 66%. This was accomplished by increasing the total system inertia (motor + flywheel + compressor) from 64,000 to 108,000 lb-ft^2. The new motor design also offered better cooling and other benefits besides the significant reduction in torsional vibration and current pulsation. After completing these modifications, the unit has been operating satisfactorily for several years.

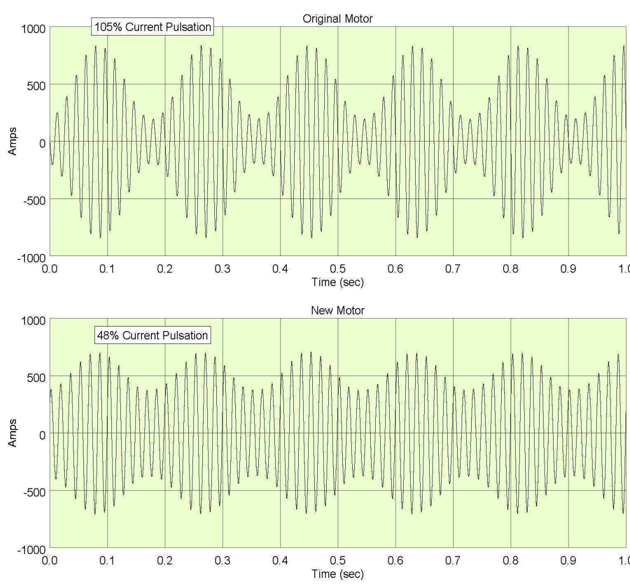

Fig. 11 Comparison of Current – Original vs New Motor

X. CONCLUSIONS AND RECOMMENDATIONS

This paper summarizes the NEMA and API requirements for synchronous motors driving slow-speed reciprocating compressors. These standards produce similar outcomes but approach the calculations from different viewpoints.

For the NEMA method, a similar compressor is found in the available table and a C value selected for the amount of current pulsation. The lookup table is problematic when a similar compressor cannot be found. The total inertia of the system is adjusted until the computed C value meets the selected value from the NEMA table. The formula for C includes P_r.

For the API method, a SM of 20% is specified for rigid-body mode regardless of the type of compressor. Also, a SM of 10% is specified for higher compressor harmonics. The EM spring should be included into the torsional model and can be estimated using equation (7). The motor and flywheel inertias should then be adjusted until all separation margins are met. In addition to providing guidance on allowable speed fluctuation and current pulsation, API also requires that a complete TVA by performed.

The case studies presented in this paper show that when designing the motor and flywheel it is important to understand the unsteady loads produced by the reciprocating compressor. The torque effort of the compressor can change depending on how it is loaded, which will affect the current pulsation. The torsional response can also be amplified if there is insufficient SM from the TNFs of the complete motor – compressor train.

Motor excitation can affect the current pulsation. It is important that the automatic PF control not react to and amplify angular oscillation of the motor rotor. However, using constant excitation could be inefficient when the compressor is operating at reduced load. Therefore, the plant should verify that the PF is near unity.

Field measurements can be performed to evaluate the current pulsation for all compressor load steps, and to help identify any potential problems related to torsional vibration. Some plants require testing during startup of a new motor – compressor unit.

It would be beneficial to have continuous monitoring of the current pulsation. As shown in this paper, the envelope can be automatically determined using the Hilbert Transform. Perhaps this function could then be included in the motor protection relay.

XI. NOMENCLATURE

A	Amperes.
API	American Petroleum Institute.
C	Compressor factor from NEMA.
CPM	Cycles per minute, used for frequency of vibration.
C_s	Coefficient of speed fluctuation.
DC	Direct current.
EM	Electromagnetic.
f	Electrical line frequency (cycles-per-second or Hz).
f_n	Natural frequency of rigid-body torsional mode (cycles per minute or CPM).
FLA	Full load amperage.
GMRC	Gas Machinery Research Council.
Hz	Hertz or cycles-per-second.
IEC	International Electrotechnical Commission.
K_{em}	Torsional stiffness due to EM effects (in-lb/rad).

n Synchronous speed (RPM).
NEMA National Electrical Manufacturers Association.
P_d Damping torque coefficient (kW/rad/sec).
PF Power factor.
p-p Peak-to-peak.
P_r Synchronizing torque coefficient (kW / electrical rad).
PV Pressure-volume in compressor cylinder.
RMS Root mean squared.
RPM Revolutions per minute, used for speed of machine.
SDOF Single-degree of freedom.
SM Separation margin.
TNF Torsional natural frequency.
TVA Torsional vibration analysis.
V Volts.
VAR Volts Amperes Reactive.
Wk^2 Polar mass moment of inertia (lb-ft^2).
ω_{avg} Average speed.
ω_{max} Maximum speed.
ω_{min} Minimum speed.
0-p Zero-peak amplitude.

XII. ACKNOWLEDGEMENTS

The authors would like to thank Donald R. Smith (retired EDI President) for his time and review of this paper.

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