Effect of Motor Voltage Unbalance on Motor Vibration: Test and Evaluation

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***Abstract*—There have been many discussions on the importance of balanced power supply for both best performance and for lower vibration during operation of industrial motors in petrochemical duty and related installations. Results of tests that were conducted on several low-voltage IEEE 841 motors to observe the effect on vibration due to unbalanced power supply will be presented. Various increments of voltage imbalance from 1% up to 10% were tested and monitored on several pole speeds. This paper will present actual test data collected, along with a discussion on how these results relate and impact the various vibration testing and operational conditions provided within industry standards.**

***Index Terms*—Motors, unbalanced current, vibration, voltage imbalance, voltage unbalance.**

I. INTRODUCTION

THE ISSUE of vibration caused by line voltage unbalances is well documented and widely accepted [6]. The objective here is to quantify and expand on the net effect of these unbalances. An issue commonly encountered is that the ideal situation is typically not present, so the question becomes determining what is acceptable and what tradeoffs will be required to meet a given performance expectation. Within this discussion, there will be opportunities to have several conversations that may be illuminating. Motor vibration is a field of study that is at the same time both basic as well as complicated and nuanced. Analyzing a motor with vibration issues is often a process of elimination of "suspects" to arrive at the culprit. One of the usual suspects that flies under the radar is voltage unbalance.

II. DISCUSSION

A. Issues of Concern

The voltage unbalance in a motor is the differences in the magnitude of the voltage on the three phases of supplied voltage. Unbalances in voltage may be caused by many reasons and the effects are serious. When voltages are not balanced, the current in the motor becomes unbalanced as well. Both of these effects have negative consequences and this paper will touch on some of these concerns and concentrate on one, vibration.

The reasons for concern are as varied as the applications in which electric motors are used. The seriousness of one issue or another varies depending on the end user's policies, practices, and the needs and expectations of each site. Unbalanced voltages can lead to several issues that we will discuss in brief, but have been discussed at length in other papers [1]–[3]. Issues that have been found are higher temperatures, lower efficiencies, and higher vibration to name a few examples. This paper will concentrate on the effects of unbalanced voltage on the vibration of motors.

The various effects of unbalanced voltage have negative consequences for motor operation and lifespan. In order to obtain a longer lifespan, end users and industry organizations have taken steps to provide guidance and requirements for motors. Commonly used industry specification such as IEEE 841 and the API 541, API 546, and API 547 standards have been established in order to have a consistent standard for construction and design of motors. Many aspects of motor performance that have a direct effect on the life of motors have been considered and guidance is offered in these specifications.

One potential issue that may occur from operation on unbalance voltage is higher temperatures which stress the insulation system and shorten winding lives dramatically. A popular "rule of thumb" is that motor insulation life decreases by 50% for every 10 s warmer a motor runs [1], [4]

$$\text{Hours of Life} = A \times 0.5^{(T - T_{\text{ref}})/10} \tag{1}$$

where

A expected lifespan at T_{ref};
T actual running temperature;
T_{ref} reference temperature for insulation class.

To provide for a long-lived motor, many specifications have established a limit of NEMA Class B temperature rise on motors that have a NEMA Class F insulation system. It is commonly thought that this restriction will lead to longer motor winding life spans. To provide a quick example (2) if a motor operating at 80eqn2" have est rise has an expected lifespan of 175 thousand hours (roughly twenty years of continuous operation), a similar motor operating at 110 °C temperature rise will have a predicted lifespan on the order of 22 thousand hours (roughly two and a

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half years of continuous operation)

$$\begin{aligned}\text{Hours of Life} &= 175\,000 \times 0.5^{[(110-80/10]}\\ &= 21\,875\text{H}.\end{aligned} \tag{2}$$

The temperature of a motor can exceed the expected design temperature for many reasons such as overloading, air restrictions, and voltage unbalance. The countermeasure for voltage unbalance is that motors should be derated per NEMA MG1 [5, Fig. 14-1]. This effectively reduces the capacity of the motor and may cause lost production.

Unbalanced voltage may also lead to lower motor efficiency. While the time the motor remains in operation, the cost to operate the motor is higher, impacting end-user profit and making it more likely that the motor will be seen as defective and potentially replaced or removed for service.

Motors that run on unbalanced power will have higher vibration than motors that are run on balanced power. Higher vibration levels impose additional stress on mechanical components such as frames, shafts, and bearings. The desire of customers to purchase a motor with a long lifespan has led many to establish vibration monitoring programs; these programs are designed to monitor the vibration of various motors throughout a facility. Interpretation of vibration information is a key factor in proper evaluation of data produced as part of a monitoring program. Without accurate interpretation of collected data, decisions will be made that may allow a motor to run in an undesired state for an extended time span. A key factor of a monitoring program is that the information collected provides reliable, accurate, and timely determination of motor health.

Once a motor is determined to have high vibration, analysis of the available data will commence. Evaluation of vibration data is a topic of much discussion and interest as the analysis has a significant influence on the direction of further investigations and recommendations. Inaccurate analysis may lead one down a path of inquiry that is fruitless and distracting, ultimately consuming resources and time that are typically in scarce supply. Accurate evaluation of vibration is as much an art as it is a science. When evaluating motor vibration, experience greatly assists the evaluator. Learning the science of vibration analysis will provide a good framework for experience to grow upon. Experience and ingrained knowledge should not be disregarded in favor of strict adherence to "book learning."

A key factor in vibration analysis is the use of spectrum data. Spectrum data provide a deeper insight into the potential suspects of motor vibration. Specific frequencies will lead the evaluating engineer to a short list of potential suspects. A typical spectrum is provided in Fig. 1. This spectrum shows speed in units of CPM, this is cycles per minute, another way of expressing revolutions per minute or r/min. As can be seen, this motor is showing a high influence at 3600 r/min, the motor running speed, and 7200 r/min, two times the running speed, as well as 21 000–22 000 CPM range. As this is a 2-pole motor and was run without load, at 60 Hz, there are fewer suspects that could provide this frequency signature. Each peak seen may have one or more causes and the analysis must include combinations of factors. This particular motor happened to be tested with a relatively large voltage unbalance, leading to an elevated 7200 r/min (two times line frequency) vibration level. Once a set of suspects is identified, additional information can be incorporated into the analysis to either eliminate suspects or confirm the inclusion of the suspected cause.

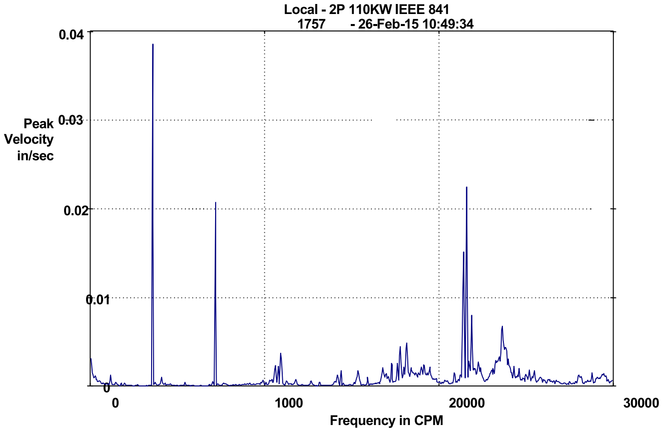

Fig. 1. Data label: ODE vertical uncoupled test 6.

Analysis of two times line frequency (2f) will traditionally point to a short list of suspects [6]. Most of these potential causes indicate imbalances in the magnetic field of the motor.

Typical causes that would be suspected are an eccentric air gap, soft foot, loose stator core; thermal bowing of the rotor, interphase and ground faults; unbalanced voltages, and loose top cover fits [6]. Each of these potential causes has additional aspects that can be evaluated such as phase angle effects, and the reaction of the vibration data when power is interrupted. Of the potential causes listed above, only thermal bowing of the rotor can be eliminated if the motor vibration drops to zero when power is interrupted. When the magnetic fields have collapsed and the motor continues to vibrate, it is indicative of a mechanical issue. A sudden decrease in vibration level when power is cut will indicate that there is an electrical component to the observed vibration.

Of the remaining suspects, eccentric air gap, soft foot conditions, loose stator core, interphase and ground faults, unbalanced voltages, and loose top covers each have a set of specific tests that can be performed on the motor to either confirm or dismiss a suspected cause. Air gap eccentricity is best checked by measuring the air gap directly with feeler gauges or other equivalent devices. Soft foot conditions can be measured using dial indicators and a detailed evaluation of the motor mounting. Loose stator cores are more difficult to diagnose, but it can be accomplished by using a series of bump testing of the frame and stator core. Phase ground faults can be evaluated with disassembly and observation of the physical condition of the winding. Typically, ground faults will also be locatable by looking for the copper missing out of the winding. Top cover fit issues can be discovered by loosening or tightening cover hold down bolts and observing the effect on the motor vibration. A bump test or other equivalent tests may be used on top covers in order to determine their resonating frequencies.

Motor voltage unbalance is difficult to diagnose without data of the motor voltage condition during running conditions. Data must be collected with the motor in operation and in its installation. Without having the vibration data collected concurrently with data regarding the voltage on each leg of the motor, analysis of vibration caused by voltage unbalance will be difficult to accomplish. By observing and reviewing the data collected, it is easier to evaluate the unbalance of the voltages supplied, and make a determination about whether the power supply is a contributing factor.

Removal of the motor from service and sending to a repair shop may, in the instance of voltage unbalance, mask the issue. Moving the motor to a different mounting base on a different power supply may produce a vibration unlike that of the end-user installation, further complicating the analysis.

B. *Industry Vibration Limits*

Industrial electric motors have many standards and specifications that may be imposed with a series of expectations on motor performance. In the North American market, the primary motor standard is NEMA MG-1. Petrochemical specifications that are commonly cited are IEEE 841 for low- and medium-voltage motors, and API 547 and API 541 for medium-voltage motors.

NEMA MG-1 [5] part 7, for 2-, 4-, and 6-pole standard machines calls for vibration levels to be below 0.15 in/s for a motor tested on a balanced voltage, on a resilient mounting. On rigid mounting, the overall allowable vibration drops to 80% of the resilient vibration level. Vibration levels for slower speeds are reduced. NEMA MG-1 also provides guidance for the collection and evaluation of shaft probe based displacement values.

Other industry standards impose different, and in many cases, tighter restrictions on vibration levels. The objective of many of these standards is to provide a more reliable motor that exhibits a longer operational lifespan. The standards have been a reliable and effective route to an improved product for end users. The efforts of these standards to achieve the lower vibrations levels can be completely countered by a poorly balanced voltage supply. In order to reach these low vibration levels in practice, it is important to allow every motor a proper opportunity for success by providing a motor friendly environment during operation.

Among these industry specifications is IEEE 841, the IEEE Standards for Petroleum and Chemical industry motors [7]. This standard applies to Totally Enclosed Fan Cooled (TEFC) motors 1–500 HP, and voltages up to and including 4160 V. Section 6.9 of the standard contains the relevant specification on motor vibration. Motors of 2-, 4-, and 6-pole speeds are limited to an unfiltered radial peak vibration velocity level of 0.08 in/s, 8-pole motors are limited a peak vibration velocity of 0.06 in/s. For all speeds, the unfiltered axial vibration shall not exceed 0.06 in/s peak vibration velocity. There is a specification to limit the vibration of the motor examined at two times the line frequency, or two times the motor rotor speed. These vibration frequencies are limited to no more than 0.05 in/s.

Similar to IEEE 841, the American Petroleum Institute has offered two specifications that are relevant to form wound squirrel cage motors. API 547 is designated for medium-voltage motors 250 HP and larger [8]. API 541 [9] is specified for motors 500 HP and above. API 547 has a limit on motor vibration velocity of 0.1 in/s for all pole speeds. When shaft probes are installed, the relevant sections of the API 541 specification shall be applied.

API 541 [9] is one of the most stringent motors standards and has an extensive set of vibration limitations and expectations. Motors with speeds above 1200 r/min are limited to 0.10 in/s for both filtered and unfiltered vibration velocities. Displacement values shall not exceed 1.5 mils peak-to-peak for motors up to 5000 r/min. Vibration displacements at frequencies below the running speed are limited to 0.1 mil, or 20% of the unfiltered measurement. Running speed frequency is limited to no more than 80% of the unfiltered limit. Above the running speed frequency, the vibration is limited to no more than 0.5 mils.

C. *Industry Experience*

There exists an industry standard for system voltages. This standard is ANSI C84.1, and the latest version was issued in 2011. This standard points out that 2% of industrial customers experience a voltage unbalance above 3%. Of the remaining 98% of industrial customers, 66% experienced less than 1% voltage unbalance [10]. Based on these numbers, it is reasonable to expect that 1/3 of industrial users will be operating their facilities, and their electric motors at a level of voltage unbalance above 1%. Therefore, it is reasonable to expect that the motors at these facilities will be running at vibration levels above those that were tested at the manufacturer's site.

Additionally, it is important to note that while the voltage supplied to the site may be balanced, that does not ensure that the voltage supplied to each motor is balanced. When diagnosing a suspect motor, it is important to know the specific voltage applied to its terminals.

III. THEORY ON 2F VIBRATION

Motors experiencing 2f vibration are typically diagnosed with an electrical unbalance, typically expressed as a magnetic field unbalance. There are many common causes as listed above, but the common thread in each is the lack of electromagnetic balance. Air gap distortions cause a differing amount of side pull on the rotor depending on the air gap length. Soft foot conditions will create a distortion of the air gap as well. Interphase and ground faults will affect the voltage and current available to create each electromagnetic pole pair along with other effects.

Each of the above-mentioned conditions will exhibit elevated levels of vibration; typically the issues are centered on the two times line frequency region when looking at a motor vibration spectrum results. Distortions to the air gap and effects on pole pair creation will lead to a motor that operates under an unbalanced condition.

Voltage unbalance conditions can be evaluated using symmetrical components. The motor can be evaluated by looking at the positive sequence, negative sequence, and zero sequence networks. One of the key factors in this style of evaluation is the direction of phase sequencing. The negative sequence rotates at the rated frequency, but in an opposite direction from the positive sequence network.

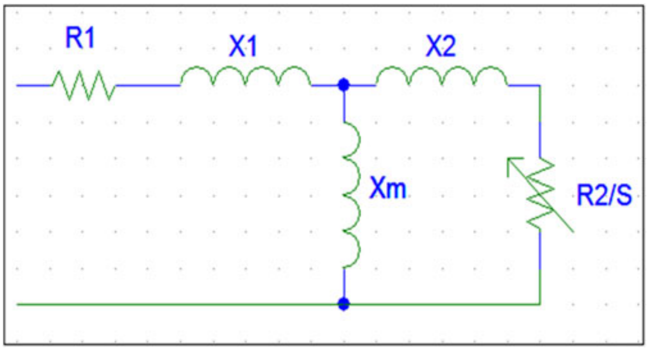

Fig. 2. Equivalent circuit diagram.

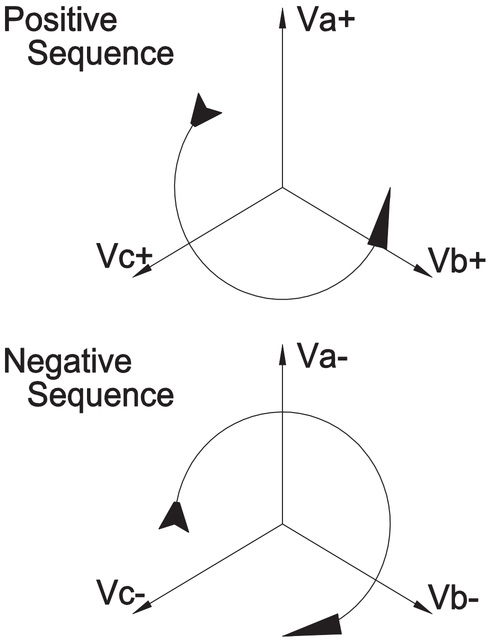

Fig. 3. Positive versus negative sequence voltage supply.

When attempting to understand a motor's reactions, a good tool is to evaluate an electric motor based on an equivalent circuit diagram. In the simplified diagram provided in Fig. 2, the circuit elements are identified as R_1 and R_2 being the stator and rotor resistances, X_1 and X_2 are the terms for the stator and rotor reactance, X_m is mutual Inductance, and the slip is shown by the value of "*S*."

Of particular interest to our discussion here is the effect this will have on the magnetic field that is generated in the stator. As the negative sequence phase rotation is opposite, the positive sequence the resulting magnetic fields will be rotating in opposite directions, shown graphically in Fig. 3 both at the rated line frequency [3].

As the two sequences are opposing one another, this interaction leads to the two times line frequency vibration phenomenon associated with unbalanced voltage operation. This interaction also appears in the interaction of other vibration phenomena that are related to electromagnetic unbalances, faults, and air gap eccentricities.

As can be seen in Fig. 2, the resistance of the rotor is viewed as a variable resistor. This resistance is controlled by the slip of the motor. At low slip (running speed), this value is quite low, typically below 0.05 per unit (p.u.) speed, sometimes referred to as percent slip. When a motor experiences an unbalanced voltage situation, the sequence networks come into play. In this situation, the resistance of the rotor for the negative sequence will be exceedingly low as the effective slip value is close to 2 p.u. The effective resistance of the rotor is more than 35 times smaller in the negative sequence network. This difference illustrates how even a small voltage unbalance can result in a large current unbalance and will cause motor performance issues.

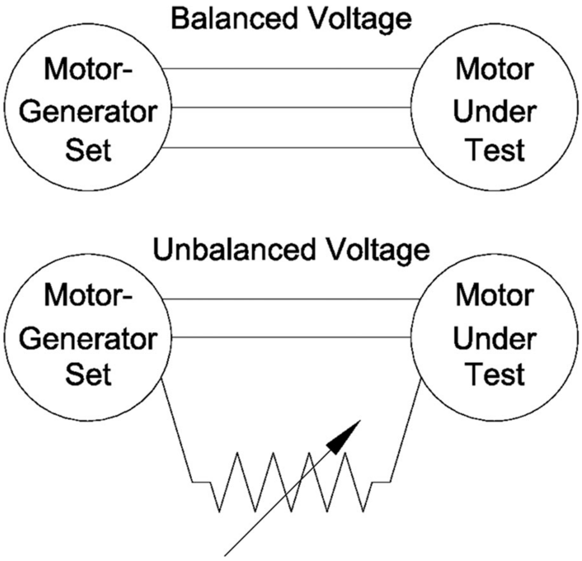

Fig. 4. Simple schematic of test setup.

IV. EXPERIMENTAL SETUP AND DATA

A. *Test Setup*

In order to test the motors, a method was needed to create unbalanced three-phase voltages which maintained correct phase progression and phase angle between each phase of voltage. In order to accomplish this task, a series of stainless steel resistors were inserted in a single phase of the motor generator set power supply to the motor under test (see Fig. 4). The value of the inserted resistance was affected by altering the number of resistors in series and parallel arrangements. This allowed motors to be tested at various levels of motor voltage unbalance. The range of resistances available ranged from 0.25 up to 9 Ω. At each test point, an estimated voltage drop was calculated and the approximate resistance was applied. Specific combinations of series and parallel connections were used to obtain the closest possible resistance to the prediction.

When reviewing the data, the motor voltage unbalance was calculated as follows:

$$\%\ \text{Imbalance} = 100\% \left(\frac{\text{Maximum voltage deviataion from average voltage}}{\text{Average voltage}}\right). \tag{3}$$

Fig. 5. Actualized test setup.

TABLE I
LISTING OF TEST MOTORS

Test Number (Table)	Horsepower	Pole Speed	Voltage (V)	Frame Size	Average Radial Vibration, Balanced Voltage (in/s)
2	200	4	460	440	0.033
3	200	2	460	440	0.044
4	75	4	460	320	0.035
5	200	2	460	440	0.053
6	50	2	460	320	0.061
7	100	4	460	440	0.025
8	100	2	460	440	0.063

At each level of voltage unbalance, the motors were run without a load on the motor shaft. The vibration was measured in 5 axes as recommended by NEMA MG-1 and is reported in units of in/s.

Fig. 5 shows a photograph of the test setup with the motor under test. In this case, the resistor bank is set up with three resistors in series, creating 4.5 Ω of resistance in one single phase of the motor's power supply. For this test, the voltage unbalance was 4.4% with a current unbalance of 36%. This test setup offered the advantage of a quick and easy conversion from one test setup to another. This sped up the testing of the motors; however, the drawback was that the test setup did not allow for very small incremental unbalance changes to be evaluated.

B. *Test Motors*

Several motors of various sizes were tested. The motors were sourced from multiple leading manufacturers. The test motors were selected to be of 2-pole and 4-pole speeds, and sizes of commonly used horsepower ratings. The motors tested are listed in Table I, showing the horsepower, pole speed, voltage, frame size, and the basis for the per unit vibration (no-load, balanced voltage vibration).

Two other motors were tested in addition to the ones listed in Table I; however, there were issues with the vibration data outside the scope of this paper; therefore, they were excluded. Additionally, it was desired to investigate increased noise as a function of the voltage unbalance. Due to other activities during the timeframe of the tests, no valid noise data were collected.

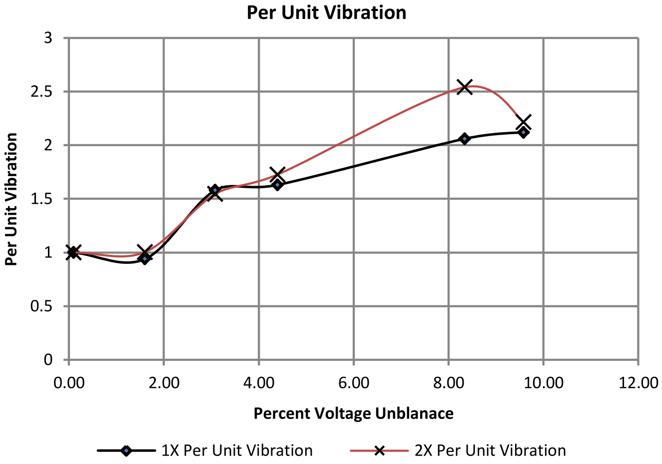

Fig. 6. 4-Pole 200 HP 447TS frame.

TABLE II
4-POLE 200 HP 460 V 447TS FRAME

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.047%	0.033	1	1
1.545%	0.031	0.94	1.0046
3.054%	0.053	1.58	1.5459
4.611%	0.055	1.63	1.7271
8.344%	0.070	2.06	2.5401
9.582%	0.071	2.12	2.2144

C. *Test Data and Analysis*

Each motor was tested at levels of voltage unbalance up to the limits of safe operation of the generator. The various levels of vibration were measured at radial points on the drive end and on the nondrive end of the motors. Axial vibration was measured on the drive end of the motor. As the motors, all presented a different level of vibration under balanced voltage conditions, it was decided that the best analysis would be viewing the results on a per unit basis.

As can be seen in Fig. 6 and Table II, the vibration of the motor in question doubled. This did not result in an unacceptable average vibration level for this motor, in this particular mounting situation, without load. However, the IEEE 841 standard does not call for average vibration but defines the vibration requirements at any position. This motor exhibited a vibration level at 0.1471 in/s on the nondrive end horizontal position. This is well above the IEEE 841 limit for vibration. On a motor that runs at or near the IEEE 841 vibration limit of 0.08 in/s, this motor would exhibit more than 0.169 in/s. It is quite easy to show that the motor run on unbalanced voltage will rapidly increase vibration levels and may quickly exhibit unacceptable performance.

TABLE III
2-Pole 200 HP 460 V 447TS Frame

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.016%	0.04410	1.000	1.0000
1.136%	0.06393	1.449	1.1543
2.920%	0.05013	1.137	0.7232
3.720%	0.04423	1.003	0.7290
5.596%	0.04405	0.999	0.5526

TABLE IV
4-Pole 75 HP 460 V 360TS Frame

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.104%	0.0345	1.000	1.0000
0.836%	0.0313	0.906	0.9450
2.854%	0.0320	0.928	0.7018
3.955%	0.0558	1.617	1.0814
5.537%	0.0500	1.448	1.4312
6.781%	0.0655	1.898	2.0803

TABLE V
2-Pole 200 HP 460 V 447TS Frame

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.058%	0.0539	1.000	1.0000
1.013%	0.0340	0.631	0.8544
3.597%	0.0534	0.990	0.9628
5.381%	0.0624	1.157	0.9447
6.565%	0.0641	1.189	1.0034
7.687%	0.0680	1.263	0.9526

TABLE VI
2-Pole 50 HP 460 V 320TS Frame

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.102%	0.0608	1.000	1.0000
1.485%	0.0605	0.995	0.9680
3.048%	0.0620	1.019	0.9693
4.420%	0.0664	1.091	0.9782
5.241%	0.0754	1.240	1.0702
5.698%	0.0874	1.437	1.1111

The test data in Table III do not exhibit values that are consistent with the balance of data collected from other motors. It is possible that the motor characteristics and the resulting performance were affected by the running of the motor. The data collected at the lower unbalance levels are consistent, and there appears to be a change in the motor, mounting or other aspect that affected the data collected.

The data for the next motor tested, as seen in Table IV, show that the motor performs very similar to the test data collected for the motor shown in Table II. The vibration level increased significantly as the voltage unbalance increased.

TABLE VII
4-Pole 100 HP 460 V 440 Frame

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.047%	0.0228	1.000	1.0000
0.679%	0.0238	1.042	8.0000
2.098%	0.0338	1.487	4.2800
3.086%	0.0363	1.592	4.0000
4.125%	0.0373	1.635	4.2800
4.881%	0.0407	1.786	2.5700
5.846%	0.0383	1.681	3.1400

TABLE VIII
2-Pole 100 HP 460 V 440 Frame

Percent Voltage Unbalance	Average Radial Vibration (in/s)	Overall Vibration (p.u.)	2× Vibration (p.u.)
0.103%	0.0634	1.000	1.0000
0.690%	0.0648	1.022	1.0160
2.117%	0.0636	1.003	1.0054
3.128%	0.0640	1.009	1.0101
3.755%	0.0641	1.011	1.0214
4.658%	0.0663	1.046	1.0613

The motor tested in Table VII is in line with the balance of the 4-pole motors tested and shows a similar increase in overall vibration level.

The motor shown in Table VIII was later found to have a slightly misaligned bearing. This resulted in data that while the motor was run with a voltage unbalance, the effect was low as compared to the reactions from the mechanically induced vibrations. This motor, had it been repaired, would have still shown a higher vibration at 2f; however, for a completely different reason that what was corrected.

The 2-pole motors presented in Tables V and VI show a similar increase in vibration, however not to the same degree as the 4-pole motors shown in Tables II, IV, and VII . A potential explanation for the differences between the 4-pole motors and the 2-pole motors is that the 2-pole motors typically have a larger air-gap. The cause for the differences in vibration is an area for future research and investigation.

V. Potential Remedial Actions

Correcting the unbalance in the voltage supplied to the motor will be beneficial to provide a longer life motor, and improve reliability and profit. The allowable level of vibration when in operation will be determined by each end user. Some factors that might influence this decision are the size of a motor, spare stock on hand, mission criticality, and many other criteria. A careful inspection of a motor and the connections to the rest of the system as installed should be conducted when a motor is found to have an unbalanced voltage. The cause may be as simple as a poor connection or high resistance joint that is easily corrected. Another potential remedial action is to rebalance the power system of a facility if there is an identified imbalance in loads. An additional remedial action that can cause a smaller disruption to service and provide other benefits would be the addition of an adjustable-speed drive (ASD). An ASD is not without drawbacks including, cost, space, and complexity of integration; however, it does provide many beneficial capabilities, one of which is the balancing of voltage supplied to a motor.

VI. CONCLUSION

As has been shown, electric motor performance is influenced by power supply. It is evident that motors operated in environments that do not provide a well-balanced power supply will be adversely affected. Motors supplied with an unbalanced voltage have been shown to have elevated vibration levels, levels that may cause an undesirable operational condition for the motor and the driven equipment. It is recommended that voltage balance be validated as part of any investigation, and if voltage unbalance is viewed as a contributing factor to motor vibration, remedial action should be taken. Working with the local utility and with electrical distribution at the facility are two ways to improve the voltage balance. If issues persist, an adjustable speed drive may be used to eliminate the voltage unbalance to the motor.

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