Evaluation of the Impact of Harmonics on Electric Machine Reliability

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Power, magnetic and ground harmonics have a negative impact on the reliability of your electric motors both electrically and mechanically. We often focus just on the power harmonics when reviewing information on power quality, but rarely view the self-generated electric machine harmonics and the harmonic content present in grounds and neutrals. Over the past several years I've become more aware of the non-power harmonic issues as the problems we have identified that are tied directly to ground, neutral and machine slot harmonics are on the rise. We often see these issues in terms of: problems with 'nuisance tripping' of protective devices; the rapidly increasing number of bearing defects that appear as electrical discharge, even when a machine is operating across the line; failure of electronic systems; insulation defects and power electronic failures; increased lightbulb replacements; and, even a lack of savings following the installation of energy savings devices.

For this brief overview of the harmonic impact on electric machine reliability we will first break up each type of harmonic issue and then will discuss real-world impacts from our field work and fault investigations.

POWER HARMONICS

Look up the term electrical harmonics and you will receive no end in references, papers, presentations and tutorials. As such we will limit our time on this particular subject other than an overview. High power harmonic issues will impact the other harmonic considerations in neutral, ground, and exacerbate electric motor stator slot and rotor harmonics. Present marketing information used to represent one power device over another, as well as energy efficiency, often blinds us to the overall impact on our power system and the results can be terrifying. However, once the salesperson has sold their wares and moved on you are stuck with unusual system problems that may or may not appear to have any relationship to the device(s) you installed that were sold as 'low harmonic' or 'clean' systems.

There are FOUR types of power harmonic issues that we deal with. The first three are the common 3^{rd} harmonic, which is often associated with single phase systems, the 5^{th} harmonic, which is described as a 'counter-rotating harmonic,' and the 7^{th} harmonic, which is described as a 'pro-rotating harmonic.' The final type that is often overlooked, or we are sometimes told by people who are ignorant of how power systems work, is that even harmonics (2^{nd}, 4^{th}, 6^{th}…) don't exist. However, they very much do, often at very low levels in modern power systems. An even harmonic can occur due to standard non-linear loads such as power harmonics and are often not easily measurable until the system has a large number of non-linear loads. They also are caused by asymmetrical waveforms such as faults (loose connections, for instance), arcing, partial discharge and corona, and significant voltage and/or current unbalances. Finally, they are caused by magnetic core saturation, such as when a motor or transformer (most often) is over-saturated (overloaded). Figures 1-4 show different examples of the types of power harmonics that are found.[1]

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[1] Penrose, Howard, Practical Electrical and Current Signature Analysis of Electrical Machinery and Systems, Success by Design Publishing, Lombard, IL, 2022.

Figure 1: Relatively clean voltage waveform with less than 1% THD voltage.

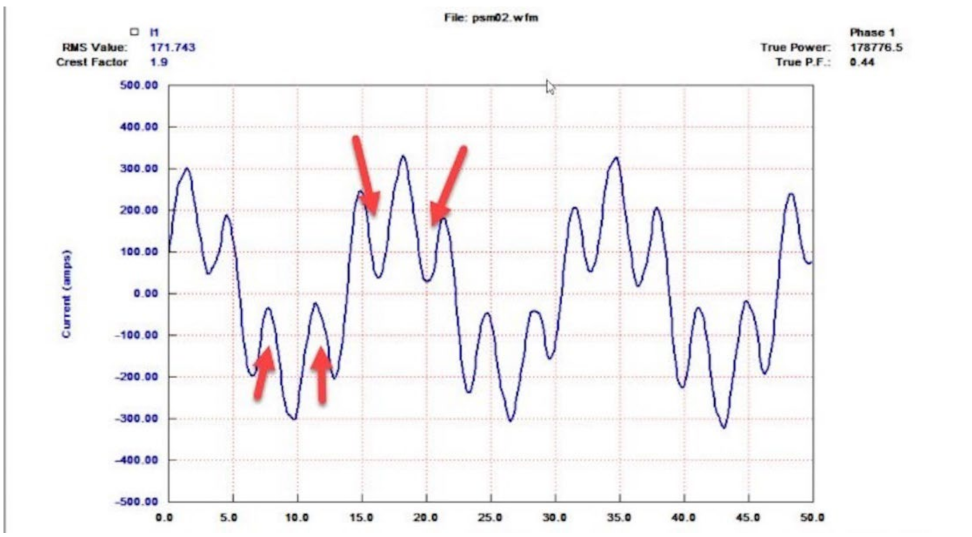

Figure 2: 5th harmonic example.

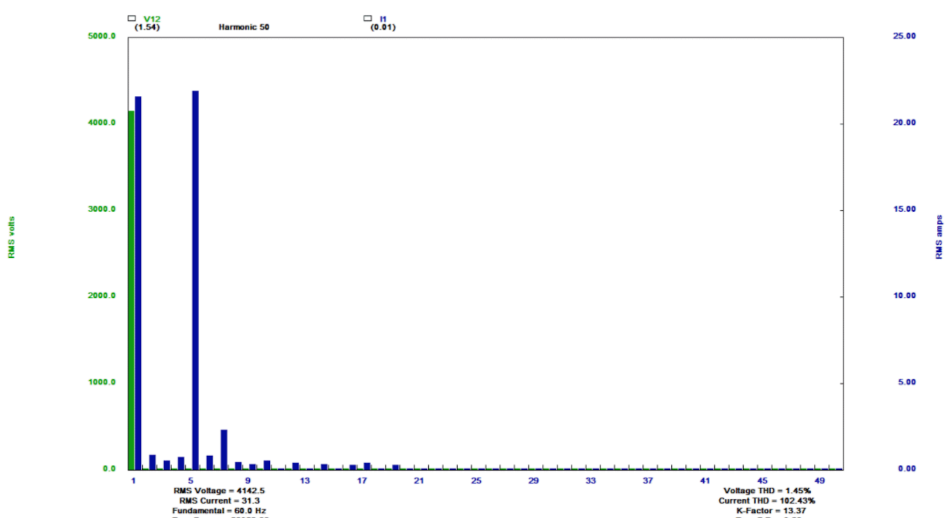

Figure 3: Harmonic content associated with Figure 2.

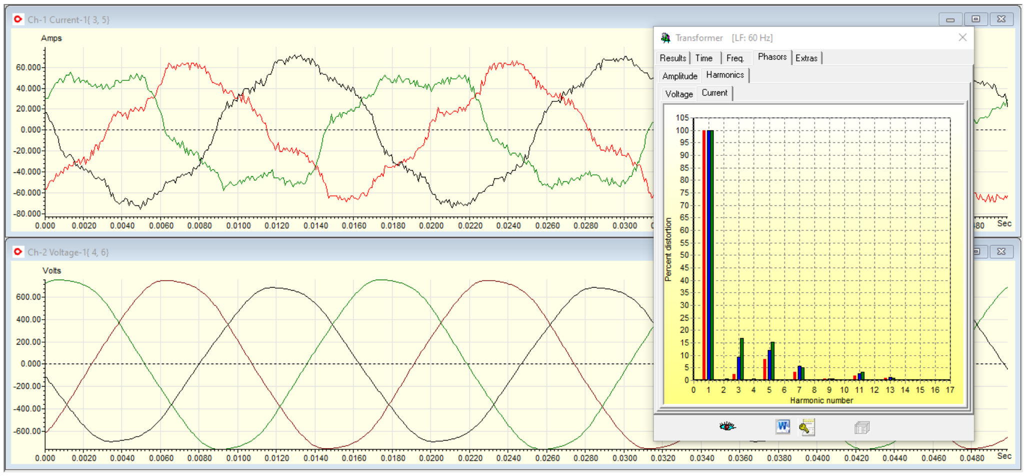

Figure 4: Typical power quality and harmonics on the secondary of a manufacturing transformer including current harmonics. Voltage harmonics are at less than 2% in the 5th.

One of the challenges with the waveforms and larger power current harmonics is the impact on True Power Factor (PFt) versus Apparent Power Factor (PFa). PFa involves the line frequency voltage and current in order to determine the lag in relation to the voltage, for total current and kVA. In the case of Figure 3, this value was 0.92. PFt includes adding all of the current values for each harmonic and adding them to the power factor calculation. The result in Figure 3 is 0.38, which accounts for additional current in the circuit and, in the case of the condition in Figure 3, results in such conditions as slow starting of electric machines and damage to electronic systems, in addition to loading of the transformer. The solution included filtering and increasing the size of the transformer and supply cables. Unfortunately, the way that standards, such as IEEE 519[2], are written, the impression is given that low level voltage harmonics and higher level current total harmonic distortion have a limited effect.

Power harmonics are known to have a large impact on the electrical system in the plant as well as being tied to utility penalties. Power harmonics are also tied to increased energy usage, damage to equipment, and reduced reliability of electrical and electronic systems including IoT devices.[3]

GROUND AND NEUTRAL HARMONICS

Losses to ground and neutral also count in terms of harmonic losses. In this case, ground and neutral voltage, current and harmonics are due to:[4]

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[2] IEEE Std. 519, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE, 2014 Edition.

[3] J. M. Tabora et al., "Assessing Energy Efficiency and Power Quality Impacts Due to High-Efficiency Motors Operating Under Nonideal Energy Supply," in IEEE Access, vol. 9, pp. 121871-121882, 2021, doi: 10.1109/ACCESS.2021.3109622.

[4] R. Apolonio, J. C. Oliveira, A. B. de Vasconcellos and R. Szczypior, "Experimental and computational analysis of effects caused by voltage variations on ground return single-phase distribution systems: zero sequence harmonics and impacts," 2004 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (IEEE Cat. No. 04EX956), Sao Paulo, Brazil, 2004, pp. 511-516, doi: 10.1109/TDC.2004.1432432.

- Induced currents from power cabling running in parallel to the ground/neutral leads;
- Equipment references such as variable frequency drives, single phase systems, and unbalanced loads;
- Insulator leakage to ground or neutral;
- Improper connections in grounding and neutral;
- System unbalances;
- Capacitive coupling; and,
- Fault conditions.

As ground is a reference for electrical and electronic systems, high levels of ground or neutral energy in voltage and current have a negative effect on protective relays, PLCs, VFDs, bearing currents, and other conditions where equipment is ground referenced. Both ground and neutral feed back to the distribution or sub transformer and can saturate the transformer core without being measured or identified by relay protection.[5]

Electric motor bearing electrical failures are not just caused by shaft currents but also ground voltage and current issues.[6] Extraordinary high potential, in particular, when fast rise time and harmonics are present in ground (noise), the results are the same as high shaft voltage/current. Bearing heating and electrical discharge, including rapid overheating of lubricants, will occur. This can also occur in applications where variable frequency drives are not used as control for the motor and can be found as severe in soft starts but also in across-the-line controls.

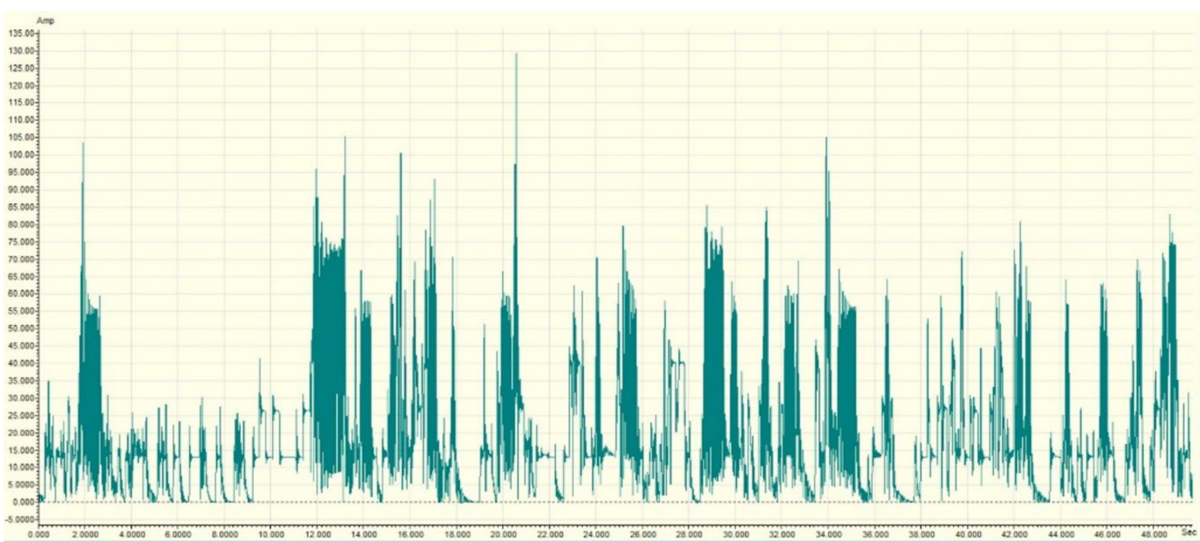

Figure 5: Ground noise during startup of a 300 hp motor on a soft start. Ground noise resulted in frequent bearing failures.

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[5] D. R. Carpenter and J. Willingham, "Objectionable currents associated with shock, fire and destruction of equipment," 2015 IEEE IAS Electrical Safety Workshop, Louisville, KY, USA, 2015, pp. 1-11, doi: 10.1109/ESW.2015.7094952.

[6] J. Kalaiselvi and S. Srinivas, "Passive common mode filter for reducing shaft voltage, ground current, bearing current in dual two level inverter fed open end winding induction motor," 2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Bran, Romania, 2014, pp. 595-600, doi: 10.1109/OPTIM.2014.6850977.

Figure 6: Bearing ball damage from the ground currents in Figure 5.

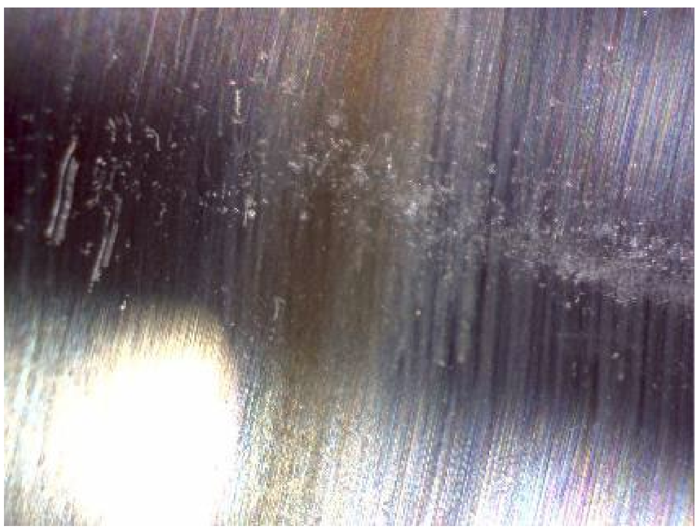

Figure 7: Outer race damage from ground currents.

Overall, the combination of power and ground/neutral harmonic currents, such as those shown in Figure 8, have a very large impact on plant energy and reliability.[7] The overall losses associated with ground and current harmonic content can be found in Figure 9 and, depending on the conditions of the plant, can result in safety issues up to and including arc flash and fires.[8]

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[7] Penrose, Howard W, Practical Electrical and Current Signature Analysis of Electrical Machinery and Systems, Success by Design Publishing, Lombard, IL, 2022.
[8] D. R. Carpenter and J. Willingham, "Objectionable currents associated with shock, fire and destruction of equipment," 2015 IEEE IAS Electrical Safety Workshop, Louisville, KY, USA, 2015, pp. 1-11, doi: 10.1109/ESW.2015.7094952.

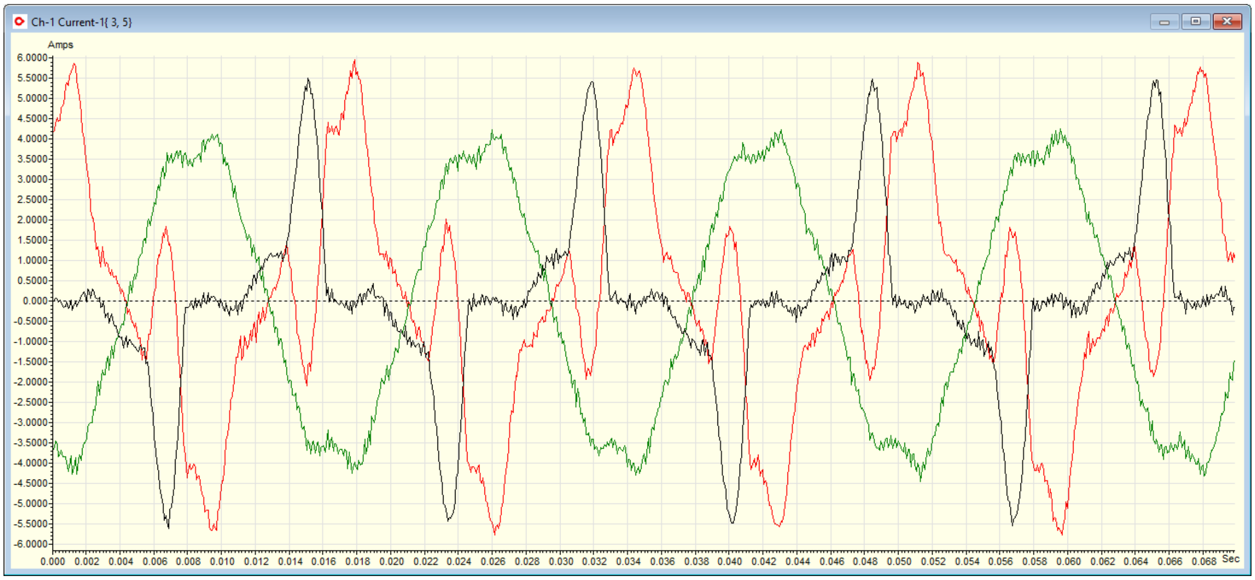

Figure 8: Current on each of three ground leads at the utility meter. The results are not uncommon.

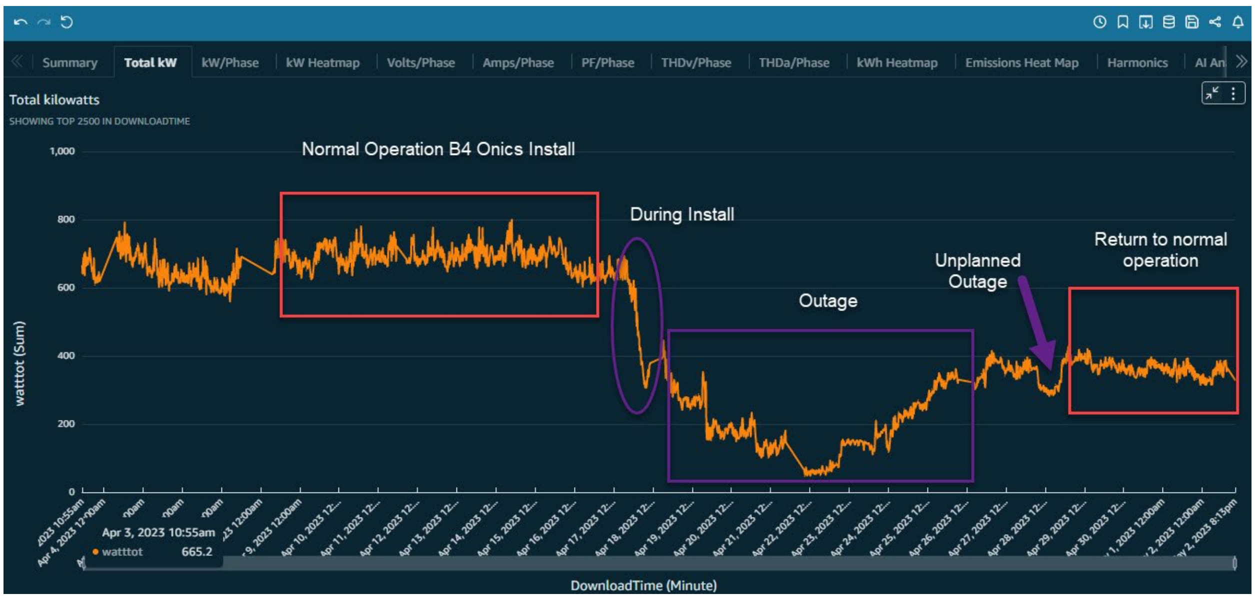

Figure 9: Before, during and after installation of ground and neutral filters in a plant. Production is constant.

STATOR AND ROTOR HARMONICS

In the past the impact of rotor harmonics came from the output of variable frequency drives and the power 5th and 7th harmonic content that would generate heating in the rotor of an electric motor.[9] With higher ground and power harmonics present in the system, such conditions are not unusual. For instance, in Figure 10 the rotor has discolored slightly, but it had not operated on a VFD. The cause of failure in this instance was also the bearings due to a combination of heat and electrical fluting.

[9] Chuck Yung, "Effects of Harmonics on Squirrel Cage Rotors," EASA Currents, May 2023 issue, EASA, 2023.

Figure 10: Induction rotor undergoing rotor 'growler' testing following overheating of the rotor (discoloration) from high power and ground harmonics.

The heating factor of a rotor is based on the operating frequency (slip frequency) of the rotor and the 5th harmonic content, as a rule of thumb (it is even more complex), resulting in an increase in eddy-current surface heating. If the above motor was operating at 1785 RPM, the motor would have a slip frequency (operating frequency) of [((1800 RPM-1785 RPM)/1800 RPM) * 60Hz = 0.5 Hz. This would result in the 5th harmonic (5 * 60Hz = 300 Hz) divided by the rotor frequency with the results to the 1.5 power: (300Hz/0.5Hz)^1.5 = ~14,700 times the surface eddy current heating due to high frequency currents on the rotor. In the case of the above rotor, it takes a temperature approaching 430C (~800F) to 'blue' the rotor laminations.

Harmonic content in ground has the following additional effects:

- Overheating of grounding conductors and equipment;
- Interference with electronic equipment including VFDs, servo amplifiers, lighting, IoT devices, and PLCs;
- Increased risk of electrical shock due to elevated voltage and current on metal surfaces; and,
- Negative impacts on protective devices such as relays.

An additional type of harmonic we deal with in electric motors includes the slot and rotor harmonics due to design. The stator is the most susceptible both from mis designs in original manufacturing to improper electric motor repair redesign.[10]

[10] Chuck Yung, "Coil Pitch and Search for the Perfect (Sine) Wave," EASA Currents, EASA, Jan. 2004.

Figure 11 shows a recent field finding on a new design electric motor. The high stator slot harmonics, which show as a stator mechanical signature in ESA, also result in significant 'ripple' in the motor operating current. This adds unnecessary load to the motor (it operates >5% loaded over another motor in the same application) and, as a result, impacts the efficiency of the motor.

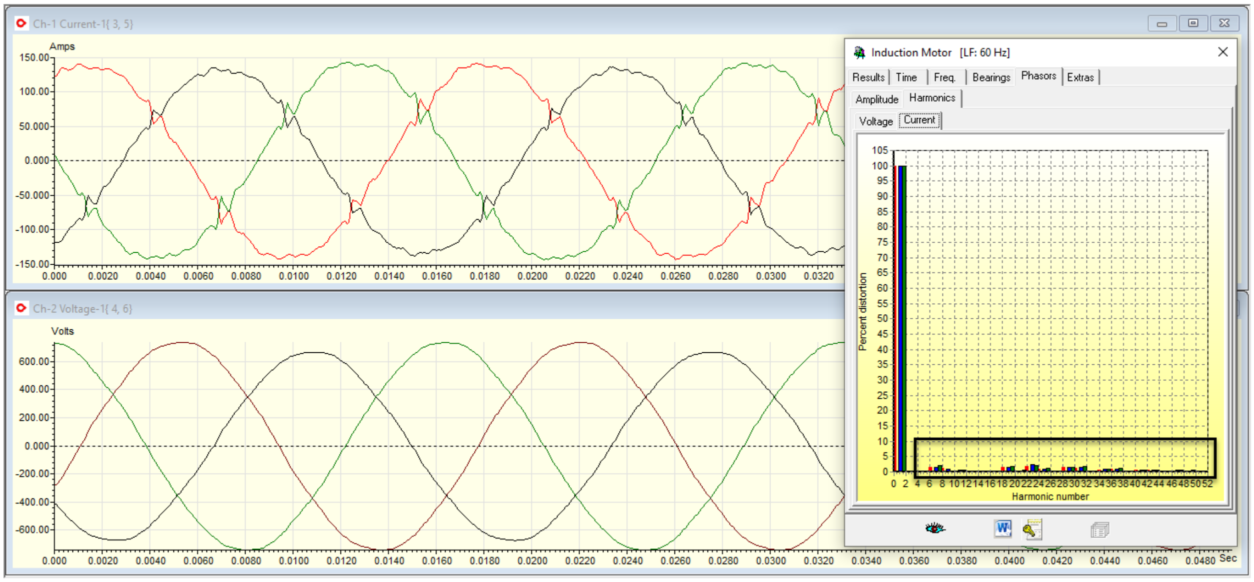

Figure 11: Stator slot harmonics results in unusual motor current and high order harmonics which generate higher rotor temperatures, reduced bearing life, and loading on the motor.

CONCLUSION

When we begin to bring together this aspect of power quality's impact on electric motors, the combination can have unusual effects. These are often seen as repetitive mystery failures of bearings and windings, but can also spread to other components in the system. For instance, when we use insulated bearings on the motor and a brush on the drive end, we can end up with ground noise currents flowing through the coupling to load. When these conditions are discovered, the next step is often isolating the load by insulating the coupling. Now we end up with high potential associated with the motor and rotating components while smaller levels of current are still present through the rest of the system. Technicians often do not evaluate shaft current failures in driven equipment as the common literature points strictly to the electric machine. However, we have investigated numerous instances where gearbox, fan, and pump bearings have electrical discharge damage even when isolated from an electric motor.

There are many ways to correct for all of these conditions ranging from filtering power actively or passively, filtering ground, and ensuring proper redesigns and inspections of motors when installing them. The defect found in the Figure 11 motor started as a test on an efficiency claim only to discover that a unique winding design puts the motor into a signature that motor design and repair companies carefully avoid.

In addition to the electric motor, transformers and other electrical and electronic systems are impacted by high harmonic conditions. These instances will be covered in additional articles.

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