Transformer Analysis and Case Studies with Electrical Signature Analysis Part 1

Howard W Penrose, Ph.D., CMRP
President, MotorDoc® LLC
Lombard, Illinois
info@motordoc.com

Abstract: Significant study has been applied to electric machines using electrical and current signature analysis with limited investigation as to the capability of analyzing transformer conditions. In this paper we will discuss the practical application of Electrical Signature Analysis (ESA) in commercial dry-type and industrial/utility oil-filled transformers for the detection and analysis of defects. While it is certain that additional capabilities with ESA and transformers will be identified this paper will focus on connections, impedance balance, and resonance conditions. Several case studies will also be presented including commercial lighting and windpower transformers.

I. INTRODUCTION

With an aging electrical infrastructure including transmission and distribution, and the availability of transformers, complex and traditional methods of monitoring continue to be used limiting maintenance success. Technologies such as ESA, which provide information on electric machinery, driven equipment, and power quality, also provide information on the condition of transformers, which make up part of that electrical circuit.

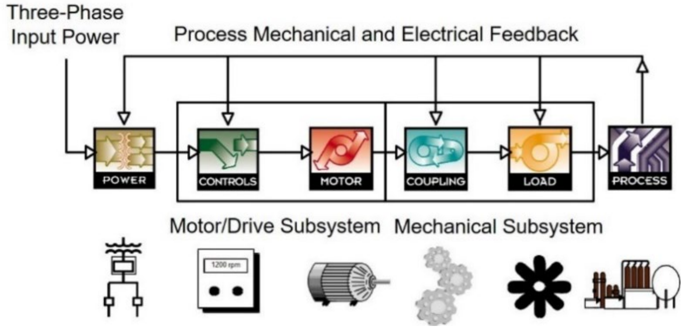


Figure 1: a representation of a typical electric motor system

The original concept behind ESA, sometimes referred to as Motor Current Signature Analysis (MCSA), was the detection of driven equipment in the nuclear power industry such as the mechanical components of motor operated valves.[1] In the original patent application, the ability to look at both incoming power conditions and a focus on the driven equipment was already realized in the early 1980s. In subsequent years the focus of industry and academic research was limited to the electric motors and induction rotors with driven equipment research and transformer research pursued by a handful of organizations and individuals. The lack of pursuit is primarily based upon the limited understanding that the primary transducer of ESA is the magnetic field of an electric machine whether that is an electric motor, generator or transformer.

To date there is some research related to the electrical and mechanical vibration of oil and dry-type transformers that relate to a majority of defects that can be detected. These include:[2]

1) Mechanical (20%)
    a) Bending
    b) Breaking
    c) Displacement
    d) Looseness
    e) Vibration
2) Thermal (11%)
    a) General overheating
    b) Localized hotspots
3) Electrical (16%)
    a) Open circuit
    b) Short circuit
    c) Joint/contact failures

---

[1] Haynes and Eissenberg, “Motor Current Signature Analysis Method for Diagnosing Motor Operated Devices,” US Patent 4,965,513, October 23, 1990

[2] C. Antoun, "High Voltage Circuit Breaker and Power Transformer Failure Modes and Their Detection," 2018 Condition Monitoring and Diagnosis (CMD), 2018, pp. 1-6, doi: 10.1109/CMD.2018.8535655.

4) Chemistry (3%)
    a) Corosion
    b) Contamination
5) Dielectric (37%)
    a) Partial discharge
    b) Tracking and flashover

In accordance with Antoun[2], 73-84% of these defects can be detected with electrical monitoring, depending on the design, when considering ESA in a similar method as vibration analysis and related ESA collected data. The data can further be separated and classified based upon specific vibration or electrical patterns such as thermal, electrical, mechanical, or dielectric degradation.[3,4]

The application of ESA as part of a transformer monitoring and prognostic program can be implemented with the application of data collection or continuous monitoring of an electric motor or generator when the transformer is directly in the circuit without a variable frequency drive or DC drive between the data collection point and test object. This can also include lighting circuit applications where data is collected directly between the panel(s) and transformer including pole transformers. In the case of inverter applications such as solar or commercial/industrial, the data collection point should be either directly at the transformer (best) or at the supply side of the converter or inverter.

This paper consists of several case studies with details of how the analysis is performed. The studies shall consist of: a lighting panel application and a windpower application.

II. Case Study 1: Lighting Panel Energy Study

An ECMS-1 continuous monitoring system was connected to a 480 Vac, 3-phase with neutral, 125 Amp-rated electrical panel directly fed from three single phase pole-mounted transformers. The circuit is divided into a balanced 277 Vac lighting system with an expected maximum load of 20 Amps per phase. An Onics neutral harmonics filter is attached to the circuit to reduce harmonic-based losses in the neutral. The ECMS-1 is included in the circuit for continuous monitoring and energy monitoring for the study. Two weeks into continuous monitoring it was noted that under specific loading conditions the monitoring system was identifying a loose connection in Phase 3 which prompted an investigation (Figures 2 and 3).

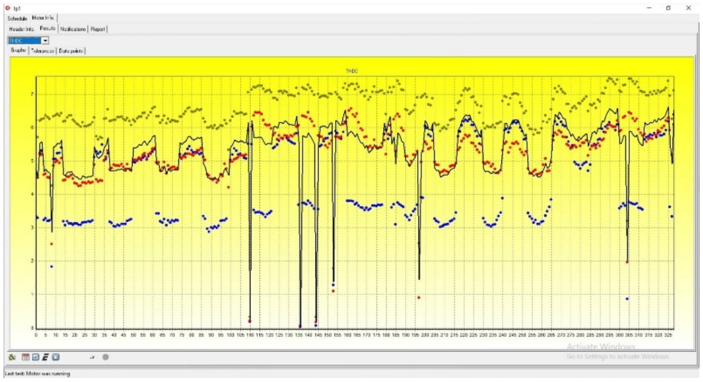
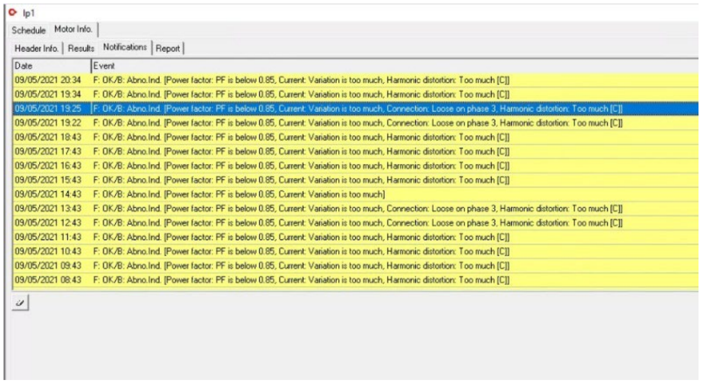


Figure 2: ECMS-1 continuous monitoring total harmonic distortion current



Date	Event
09/05/2021 20:34	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 19:34	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 19:25	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Connection: Loose on phase 3, Harmonic distortion: Too much [C]]
09/05/2021 19:22	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Connection: Loose on phase 3, Harmonic distortion: Too much [C]]
09/05/2021 18:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 17:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 16:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 15:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 14:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much]
09/05/2021 13:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Connection: Loose on phase 3, Harmonic distortion: Too much [C]]
09/05/2021 12:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Connection: Loose on phase 3, Harmonic distortion: Too much [C]]
09/05/2021 11:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 10:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 09:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]
09/05/2021 08:43	F: OK/B: Abno.Ind. [Power factor: PF is below 0.85, Current: Variation is too much, Harmonic distortion: Too much [C]]

Figure 3: ECMS-1 alert screen asssociated with loose connection alerts

The EMPATH data collected by the ECMS-1 was evaluated as shown in Figures 4 and 5 which indicated a signficant unbalance during those times. As shown in Figure 5, the power factor is already low as it represents the 'True Power Factor,' which includes current harmonic distortion.

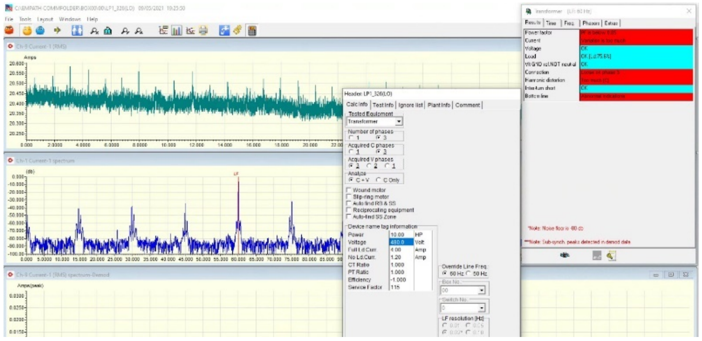
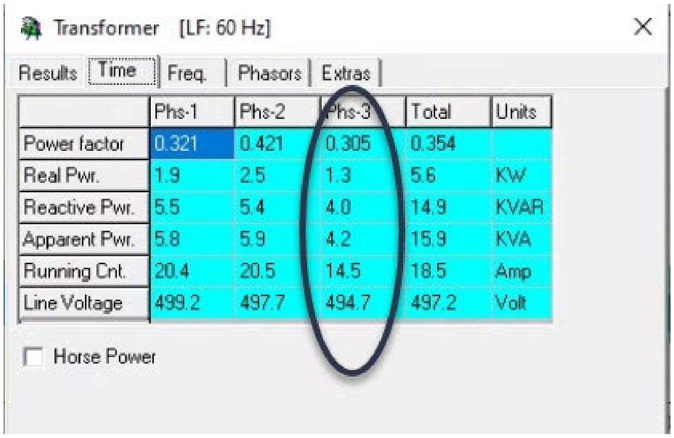


Figure 4: EMPATH analysis screens low frequency and RMS (in current)

---

[3] M. Beltle and S. Tenbohlen, "Vibration Analysis of Power Transformers," 18th International Symposium on High Voltage Engineering, Seoul, Korea, August 25-30, 2013.

[4] Mehdi Nafar, Bahman Bahmanifirouzi, Masoud Jabbari, "Transformer Monitoring by using Vibration Analysis," Australian Journal of Basic and Applied Sciences, p. 984-990, 2011



	Phs-1	Phs-2	Phs-3	Total	Units
Power factor	0.321	0.421	0.305	0.354	
Real Pwr.	1.9	2.5	1.3	5.6	KW
Reactive Pwr.	5.5	5.4	4.0	14.9	KVAR
Apparent Pwr.	5.8	5.9	4.2	15.9	KVA
Running Cnt.	20.4	20.5	14.5	18.5	Amp
Line Voltage	499.2	497.7	494.7	497.2	Volt

☐ Horse Power

Figure 5: power data capture including all readings low on Phase 3 under the full lighting load for the facility.

A review of the voltage and current waveforms in Figure 6 shows that Phase 3 is shifted and has a much lower peak to peak amplitude.

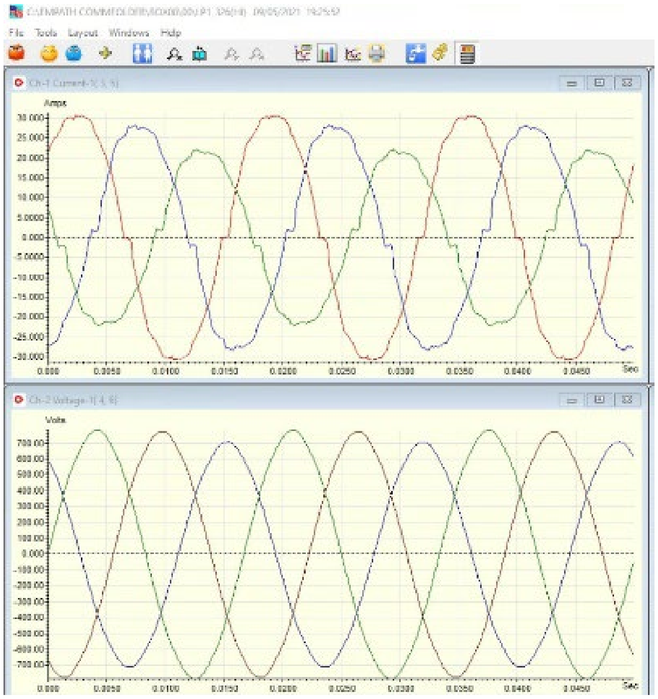


Figure 6: blue is Phase 1, red is Phase 2, and green is Phase 3, top is current in amps p-p and bottom is voltage p-p. Poor power factor results in a dramatically out of phase voltage and current.

The notching in current shown in Figure 6 is related to power harmonics and also an indicator of the sidebands noted around line frequency, harmonics and subharmonics as show in Figure 7. The subharmonics are in ¼ line frequency increments (15Hz, 30Hz, 45Hz) with sidebands of 0.536 Hz.

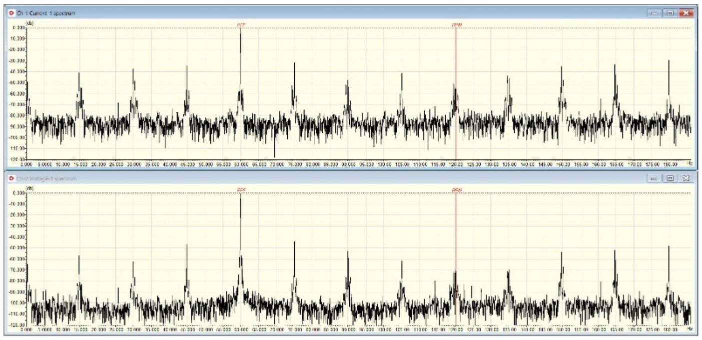


Figure 7: current top and voltage bottom low frequency data set. 15 Hz, 30 Hz, and 45Hz sub-harmonics.

The loading was evaluated in Figure 8 and it was found that the 'loose connection' finding would appear under the heavier loads. A review of the current and voltage harmonics, as shown in Figure 9, indicate that Phase 2 and 3 have even harmonic content while Phase 1 is generally lower. It is also noted that even-numbered harmonics are present, an indicator of an issue within the transformer.

Figure 8: load profile in % of full load as set in the software header. Phase 3 issue shows during peak loads only.

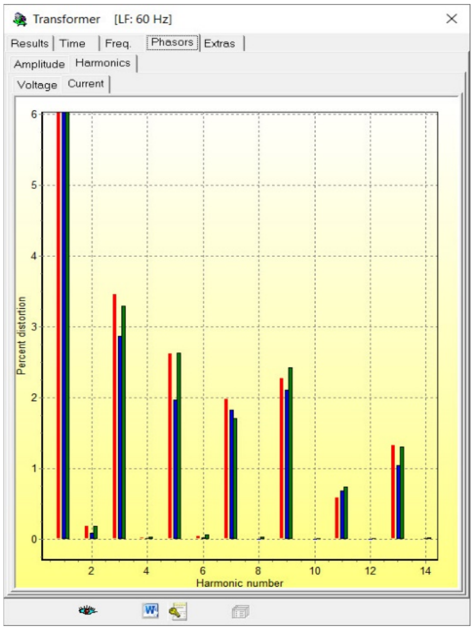


Figure 9: harmonic content. Phase 1 blue, Phase 2 red and Phase 3 green.

An infrared analysis was performed on the lighting panel to identify if a loose connection did exist at that point. As shown in Figure 10, a loose connection was detected and tightened with small improvement to the data collected.

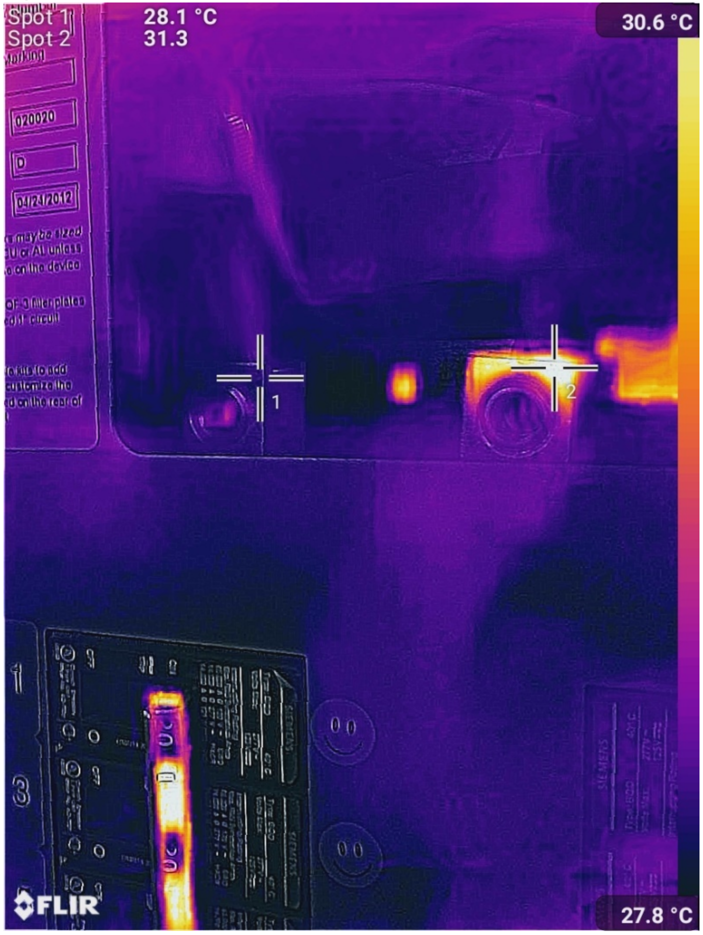


Figure 10: 3C hotspot found at the top of one lug. Lug tightened and unbalance dropped to 1C.

The disconnect for the lighting panel was tested and found to be in excellent health. The lighting panel is fed directly from a set of three pole-mount transformers, so the feeders were traced back. Originally thought to be a different set of pole-mounts directly behind the facility, the trace showed that the transformers were actually almost a block away. The finding resulted when it was discovered that the transformers also fed an adjoining facility and the Phase 3 transformer was different than Phase 1 and 2.

Figure 11: IR of line coming to the outside disconnect of the facility.

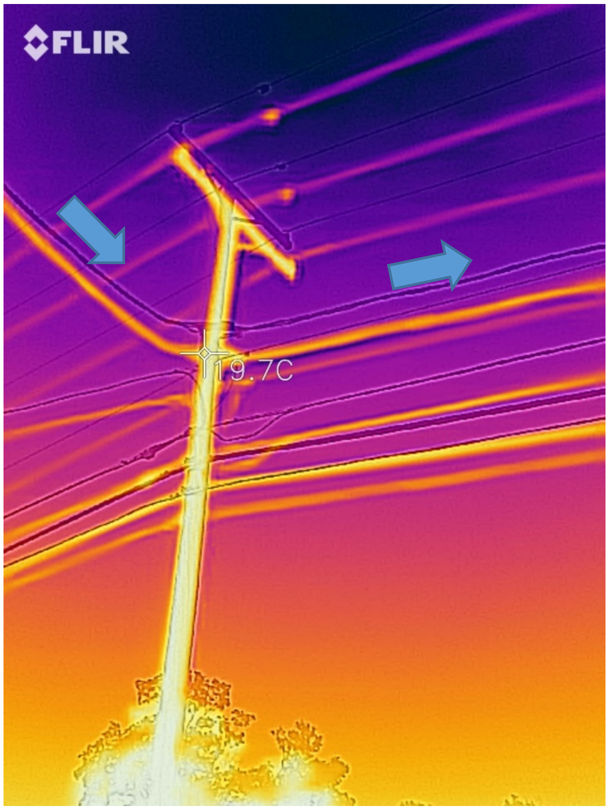


Figure 12: originally expected the cable to go left instead of right.

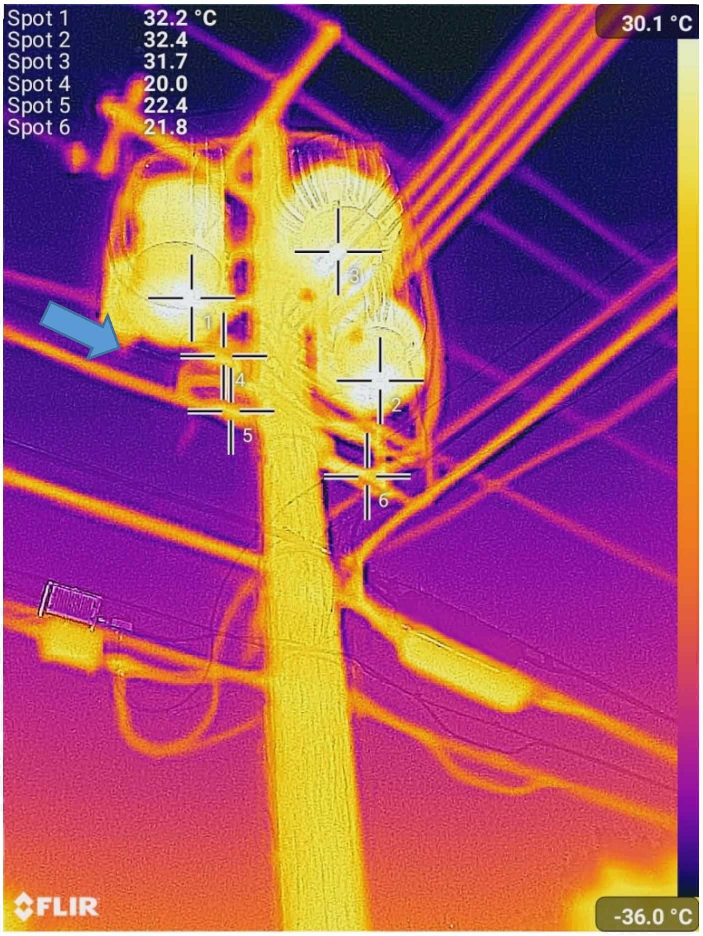


Figure 13: Blue arrow is parallel to feeder towards pole mount transformers.

Figure 14: pole mount transformers. The one on the left is Phase 3, middle is Phase 2 and right is Phase 1. Different transformers and resulting unbalanced circuit impedance plus possible loading at the neighboring facility.

As noted in Figure 14, there are two of one design transformer and Phase 3 is a different design transformer. It can be assumed until additional information is forthcoming from the utility that they are different designs and impedances. The neighboring facility has additional 12 roof-top air conditioning units and is three times the size and related lighting as the facility being monitored. However, their operating hours are dramatically different, primarily being weekend afternoons and evenings and limited weekday evenings. Their operating hours and the findings did not coincide indicating that the balance issue is most likely related to the circuit impedance from mis-matched transformers.

III. Windpower Transformer Resonance and SSR

Improper sizing of transformers can be perilous. Low loading with certain capacitive conditions either in long distance transmission lines or drive circuits can result in an effect referred to as ferroresonance. This is similar to mechanical natural frequencies in that the transformer core and circuit resonate and voltage control can be lost. Wind turbines will often operate on the lower end of their power curve resulting in frequently lightly-loaded transformers. When conditions exist which include power factor correction at low loads, voltage correction using in-line or shunt capacitors in long distance transmission lines, and variable wind speeds, two conditions occur in many wind turbine designs. The first is a transformer resonance that will occur at about 2000 Hz in 50Hz environments or 2800-3000 Hz in 60Hz environments.[5] In some cases, repeated starts and stops in low wind conditions or an event in the transmission line can start the resonance, which may also result in two additional conditions: SSCI – Sub-Synchronous Control Interaction; and, SSTI – Sub-Synchronous Torsional Interaction. These two effects are primarily found in Singly- and Doubly-Fed Induction Generators (SFIG or DFIG).

With close to 3000 wind turbines evaluated, primarily SFIG and DFIG, the test results are similar as in this case study with a majority of the turbines analyzed. This case was performed with the intention to gather specific operating data on a series of wind turbines that were experiencing defects in the rotors, gearboxes and transformers in which the solutions were elusive. The EMPATH system has been used within the windpower industry since 2003 to investigate these and similar defects in the complete system.

---

[5] K.R.M. Nair, "Power & Distribution Transformers Practical Design Guide", CRC Press, New York, 2021

Using an EMPATH data collector, the connections are usually made at the base of most towers. In this case it was determined that testing performed at the generator terminals on the 1.5 MW, 690 Volt generator would provide improved results as shown in Figure 15.

Figure 15: Voltage and current connections at generator. CT ratio used is 3:1 with one clamp around 1/3rd of cables per phase.

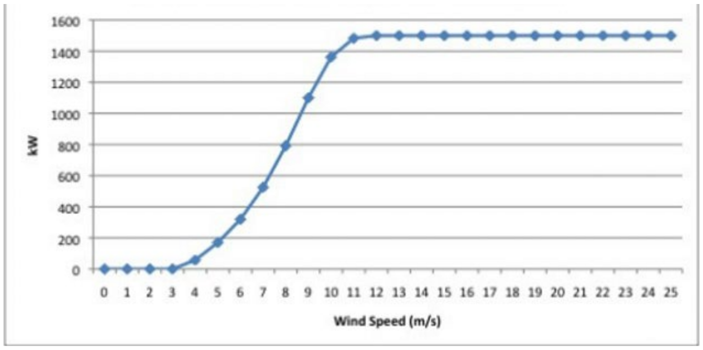


Figure 16: during study wind was 5.8m/s with gusts to 8m/s at 13C.

The wind speed was noted, as shown in Figure 16, to understand the operating point on the power curve. It was also noted that there were frequent gusts and the wind direction changed rapidly which we expected would cause additional oscillation.

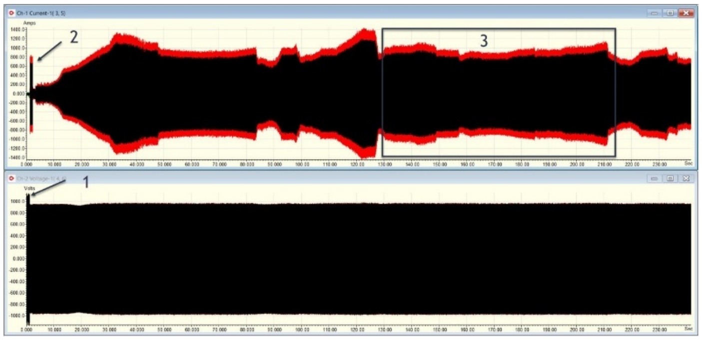


Figure 17: startup with voltage present (1), breaker closed when wind speed and blade speed were acceptable to the turbine software (2), and a point of low oscillation (3).

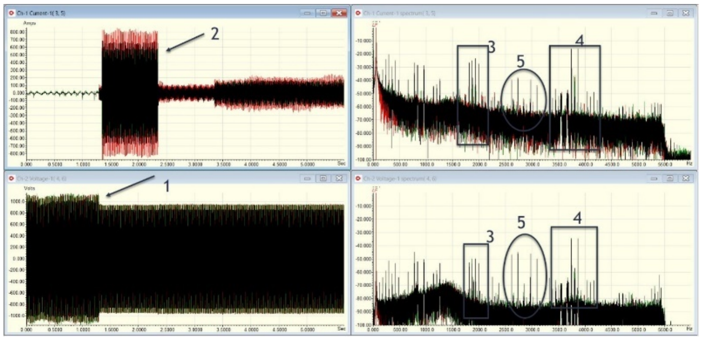


Figure 18: close up of when the circuit closes and the impact on frequencies shown. Transformer resonance (5) and tank circuit rotor inverter frequency with 2nd harmonic (3), (4).

In the operation of the turbines, the complete powertrain is brought up to speed which ranges from 14-20 RPM for the blades and main shaft. This enters a gearbox in which the main shaft is connected to a planetary gear set, then a low speed, mid-speed, and high-speed gear set. Depending on the generator design, the output speed is above 1200 or 1800 RPM (asynchronous generators). When the circuit closes to the grid there is a definitive current spike (Figures 17 and 18 item (2)) which generates an oscillation that will fall between 1.5 to 3 seconds for most turbines.

It is noted in Figures 17 and 18 at point (5) that the center of the peaks is 2880 Hz with two times line frequency sidebands. Items (3) and (4) are the firing frequency of the rotor inverter (3) and it's harmonic (4). In a well set up turbine at heavier loads and with less capacitance due to long distance transmission lines, the resonance (5) will have much lower peaks.

The airgap torque resulting from this starting process is outlined in Figure 19. In this case it is noted that there is a signficant initial torsional impulse followed by a valley and then the airgap torque increases. Of particular interest is the increasing oscillation (peak to peak) of the air gap torque as the machine comes up to full power.

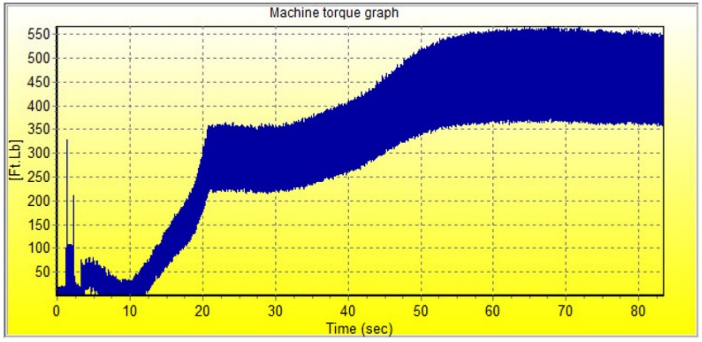


Figure 19: air gap torque as wind turbine comes up to load.

This oscillation occurs at 24 Hz and 48 Hz as predicted by Mohammadpour and Santi for SSTI and SSCI.[6] While relatively low, the torsional impulses at speed have a long-term impact on the powertrain, in particular the gearbox gears and bearings, and the rotor circuit.

Figure 20: high speed wind turbine gear fracture.

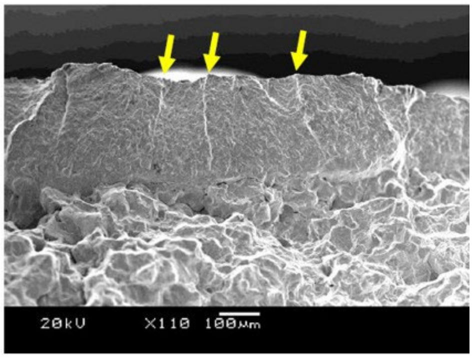


Figure 21: fatigue fractures in wind generator rotor wye ring prior to failure

The most common failure types in all SFIG/DFIG wind turbine generators include rotor wye ring failures, gearbox wear and failures, and transformer heating. Transformer heating is identifyable enough that windpower transformers are excluded from utility, industrial and commercial gassing standards as they normally operate in an equivalent alert state. Present theory is that internal resonance, arcing and other conditions are causing the gassing conditions. These show, primarily, in ESA as resonance, SSTI, SSCI, and related signatures.

IV. Considerations and Conclusion

EMPATH ESA provides the ability to perform either data collection or continuous monitoring of your system including the ability to analyze the transformer. As we continue this white paper series we will add to the base history associated with transformer findings and how they relate to other technologies.

The first case study and type of defect noted in this white paper was the detection of a transformer 'loose connection' which is an impedance unbalance. In this case study that unbalance was due to a mis-matched pole-mount transformer that would otherwise have gone undetected. The defect was noted in the automated analysis and defect report.

The second case study and type of defect noted was a resonance issue in a utility wind turbine generator transformer and the impact across the average system of this type. In this case, the resonance and resulting SSCI and SSTI conditions, in addition to starting torques, impact the reliability of the transformer, generator and powertrain. These conditions and their effects are easily detectible with properly configured ESA systems, at which time the only one on the market that meets the required sample rate and resolution is the EMPATH and ECMS.

For more information contact MotorDoc LLC at info@motordoc.com.

Bio: Howard W Penrose, Ph.D., CMRP, is the president of MotorDoc® LLC, a past chair of SMRP, a member of the IEEE PES Materials Subcommittee standards group, IEEE DEIS standards committee, and vice chair of the American Clean Power Association technical standards committee. He has over 35 years in the electric machinery and industrial/electrical reliability industry. MotorDoc LLC is a Veteran Owned Small Business.

---

[6] Mohammadpour and Santi, "Analysis of Sub-Synchronous Resonance (SSR) in Doubly-Fed Induction Generator (DFIG)-Based Wind Farms," Synthesis Lectures on Power Electronics, Morgan & Claypool Publishers, University of Nebraska, Lincoln, 2015.