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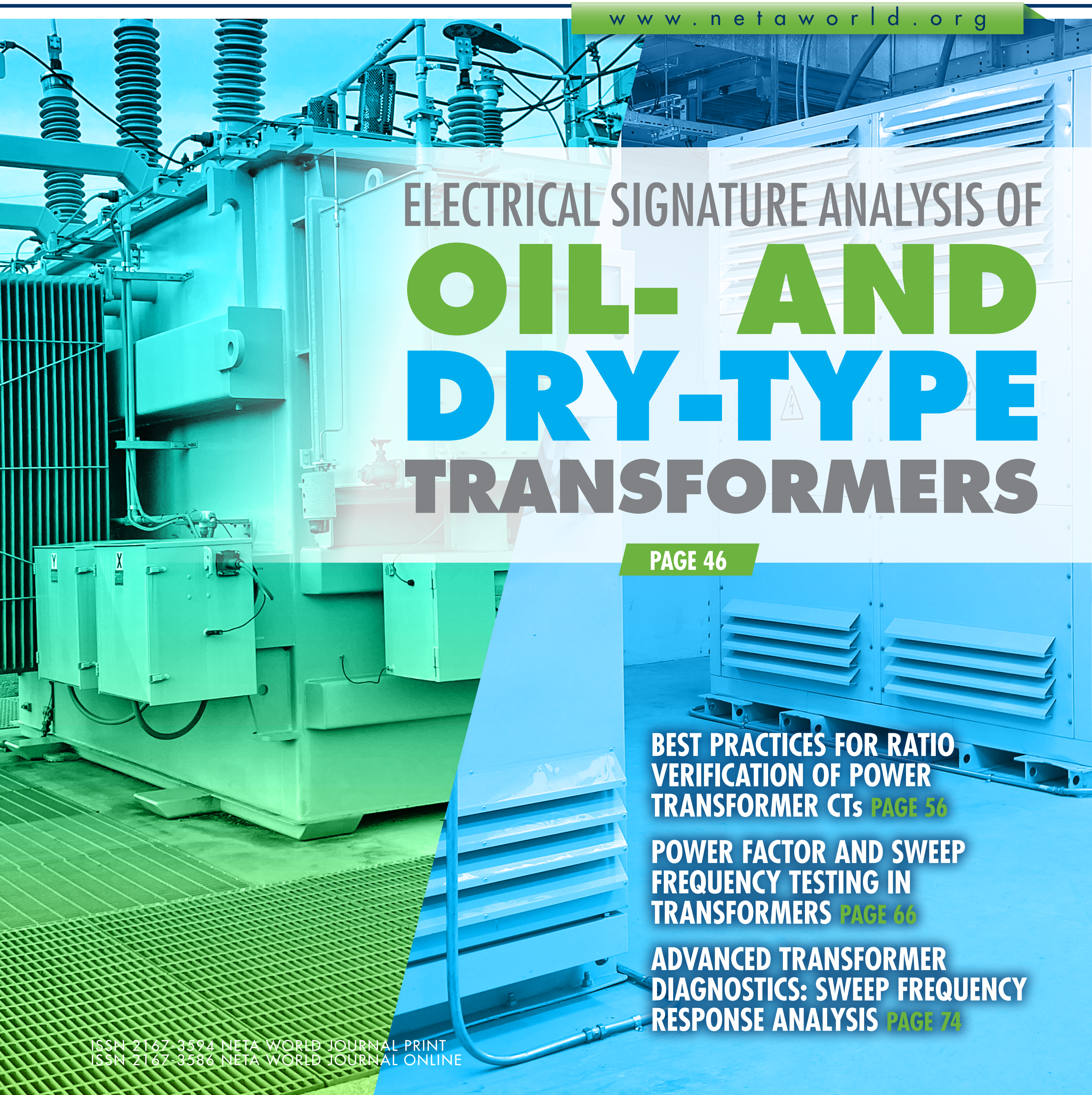

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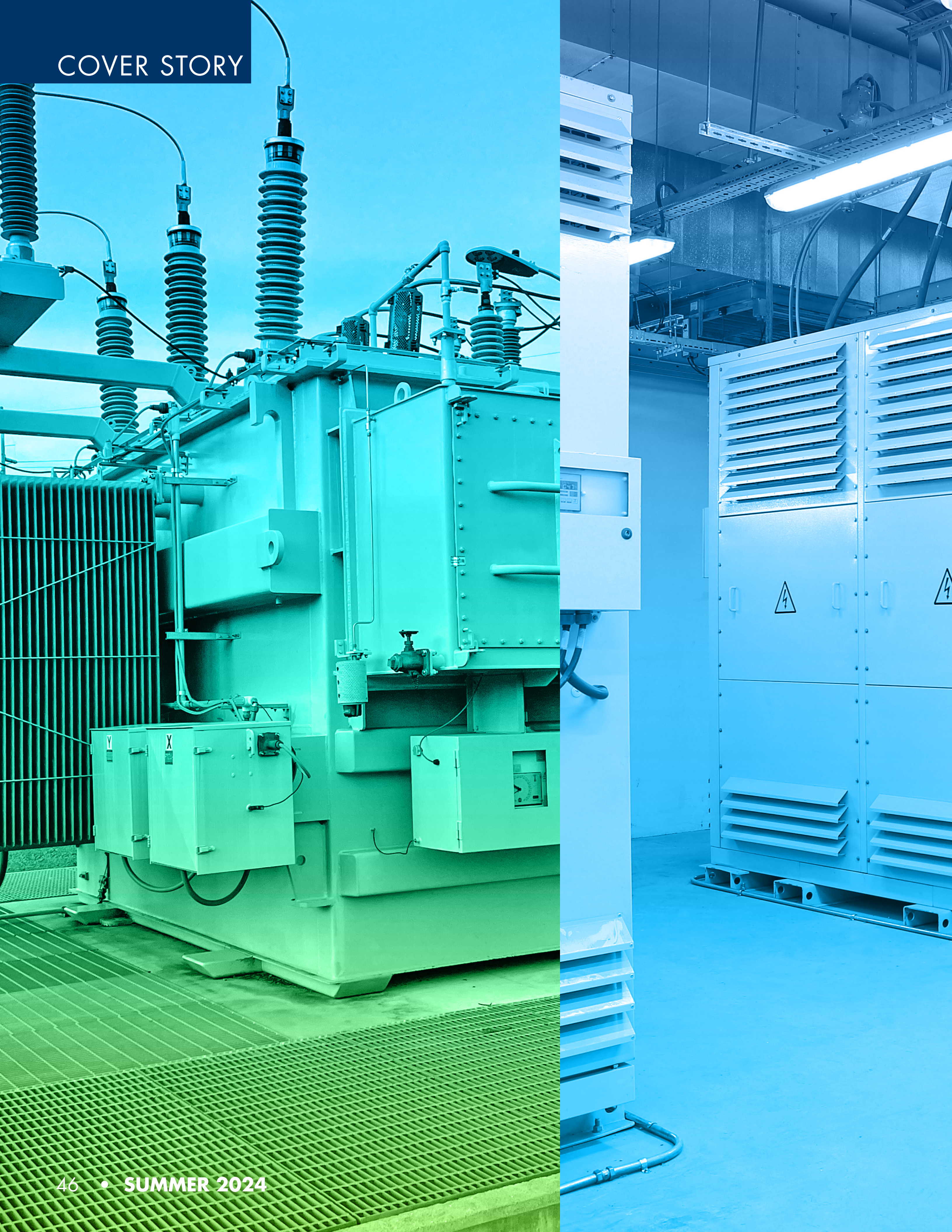

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ELECTRICAL SIGNATURE ANALYSIS OF OIL- AND DRY-TYPE TRANSFORMERS

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Periodic and continuous electrical signature analysis can be used to evaluate the general condition and power quality that affects oil- and dry-type transformers. This article discusses how conditions such as loose connections, resonance, component looseness, and failing electrical components can be detected. Case studies from several applications including wind power, solar, and industrial dry- and oil-type transformers are presented.

ELECTRICAL SIGNATURE ANALYSIS

The purpose of electrical signature analysis (ESA) is to use the magnetic field in the air gap of an electrical machine to evaluate power quality — the condition of the electrical and mechanical components in the electric motor or generator and driven equipment. The analysis is performed using measured voltage and current data with the line frequency acting as the amplitude-modulated carrier frequency. Sample rates, FMAX, bin size, and Nyquist are similar to that of vibration analysis with a Nyquist value of 2 and the data being analyzed in an FFT spectrum in either linear data or decibels. Decibel levels are read down from the peak voltage or current to associated peaks and are presented as -dB (or dB down). Unlike in vibration, where a value such as stator conditions is the number of stator slots times the running speed, ESA is the number of stator slots times the RPM +/- of the line frequency.

In the case of electric machines, most conditions and the forcing functions associated with them are interpreted directly from the supplied data. This means that a defect in a bearing, rotor, or stator is explicit, while the use of the technology and measurements of a transformer signature are implicit and infer conditions associated with condition and reliability. With transformers, we review phase impedance, power factor, phase balance, harmonics, and variations in the magnetic field between primary and secondary.

In oil-filled transformers, the pass-through connections go through insulated seals referred to as bushings that seal the oil in. These are often oil-filled and hold the external connections away from the transformer frame, as shown in Figure 1. The fins on the sides are radiators for cooling the transformer oil, which normally relies upon thermal flow. Fans may be applied to extend the operating range of the transformer. Large sealed transformers may also include an expansion tank for excess oil as it expands thermally. There may also be pressurized nitrogen and nitrogen bottles to keep dissolved gases in the transformer oil and protect the insulation system and oil from water. Transmission and distribution systems, as well as some large substation transformers, may also have auto-taps that adjust for voltage to keep the output within an acceptable range.

The primary difference between an oil-type and dry-type transformer is the cooling medium and resulting size. Dry-type transformers (Figure 2) use air as the cooling medium. Both require slightly different maintenance tasks and have slightly different failure modes. In oil-type transformers, the cooling medium can accelerate reliability issues through degradation from soluble gasses generated from age, contamination, heat, and operation. Dry-type transformers are subject to contamination and problems with airflow.

Dry and oil transformer types are subject to problems associated with power quality, loose connections, cooling medium issues, and other conditions associated with loads and environment. Several existing technologies are used for different voltage levels and fault

Figure 1: *Oil-Filled Transformers with Bushings (top), Fins, and Fans*

Figure 2: *Dry-Type Transformer with Vents at Top and Bottom*
Internal fans operate to cool the transformer.

types. These are normally passive or injected technologies such as turn-to-turn ratio testing, oil analysis, ultrasound, vibration analysis, partial discharge testing, insulation resistance, and others. Many papers and articles associated with using electrical signature analysis and power quality testing are available. This article will focus on the types of issues associated with ESA fault detection in transformers.

Using ESA for transformers provides an additional level of fault detection, especially when used for continuous monitoring. Conditions covered in this include:

- Power quality, including power factor and harmonics
- Core excitation in wind power applications
- Load balancing in solar applications
- 13.8 kV to 480 V transformer overload due to ground/neutral harmonic content
- Loose connections on transformer bushing

During an electrical reliability evaluation of a food processing site, it was noted that the main transformer supplying the facility (Figure 3) had a tinny ring to it. Evaluation of the subs fed from the transformer, observation of

Figure 3: *125 kV to 13.8 kV Transformer with Low Power Factor and High Harmonic Loads*

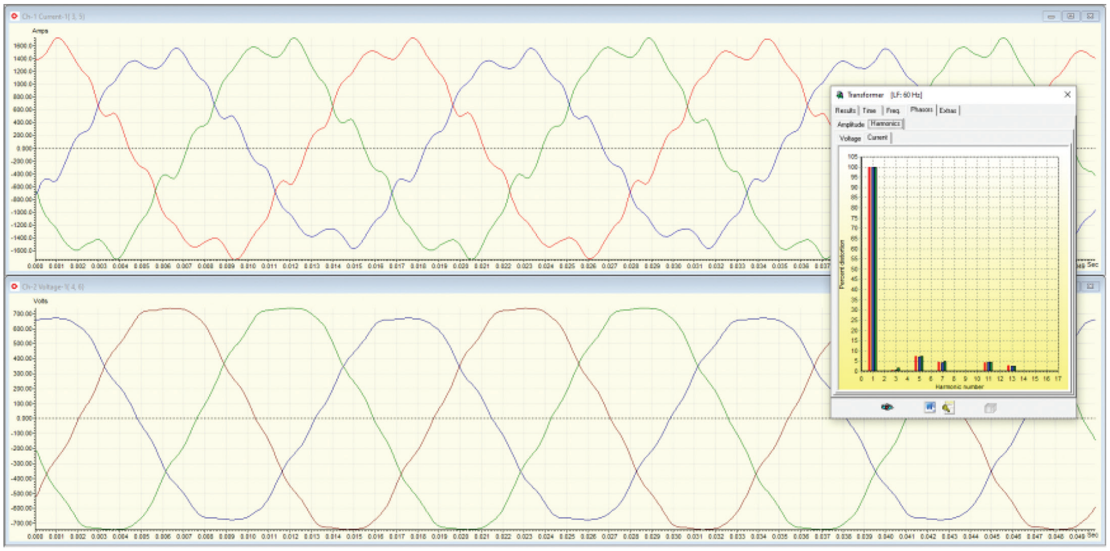

Figure 4: *Secondary of Subtransformer with Primarily 5th and 7th Harmonic and Multiples in Voltage and Current*

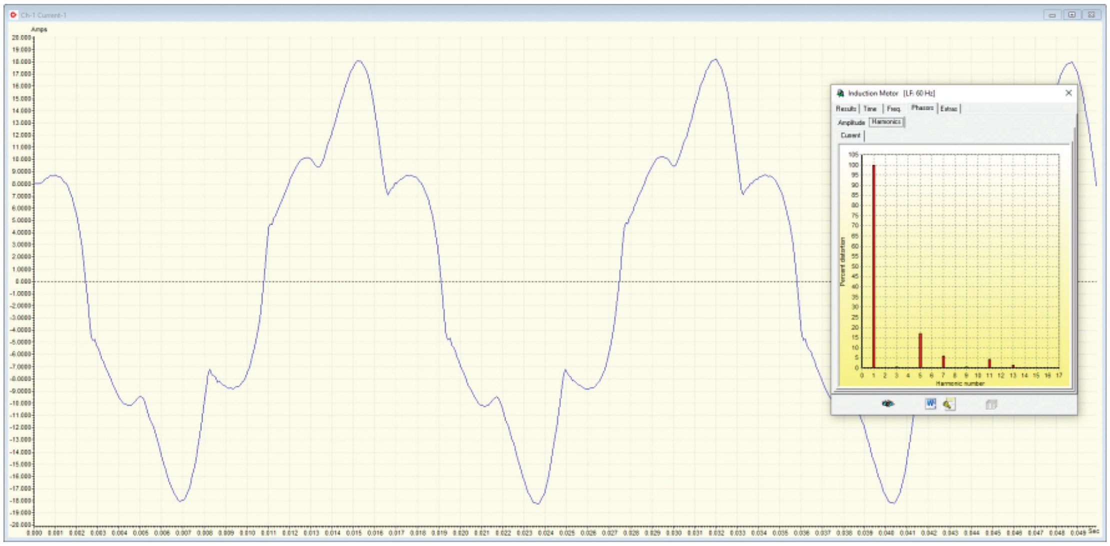

Figure 5: *Ground Current at Subtransformer*
Note: This value should be in milliamps.

the transformer heating on a 34°F day while operating at a measured 70% load, and a plant power factor under 0.8 indicated that the transformer was overloaded, and the harmonic and power factor were outside of the operating capabilities of the transformer.

Figure 4 is an example of the primary side of one of the sub transformers, and Figure 5 is the current on ground leading back from the sub. Each of the subs adds to the power factor, harmonic, and ground/neutral loads at the utility feed.

The harmonic content is found in power and ground being fed back to the transformer. Poor power factor adds to core heating and the overall transformer effective load. The 70% load quoted from the utility is based upon the apparent load and does not include derating and core resonance due to poor power factor and harmonic content.

Due to access restrictions, smartphone audio was obtained and processed to show power loss (Figure 6) and decibel patterns (Figure 7). The purple squares in Figure 6 are related to loose components, and the red arrow points to core vibration due to harmonics and high ground currents. Figure 7 shows the power factor and core vibration (refer to IEEE Std. C57.136-2000, *IEEE Guide for Sound Level Abatement and Determination for Liquid-Immersed Power Transformers and Shunt Reactors Rated over 500 kVA).* The power quality conditions will reduce the life of the transformer.

CORE EXCITATION IN WIND POWER

A common problem in the wind industry is overheating transformers due to a combination of factors including the firing frequency of rotor inverters in doubly-fed induction generators (DFIG). The factors that generate this issue are outside of the scope of this paper. However, the conditions are easily detectable with ESA including detection of the inverter frequency and a transformer excitation frequency that falls between the first and second inverter harmonic.

The frequencies present in Figure 8 generate heating in the transformer core and will generally increase thermal gassing, depending on the dielectric oil, which primarily consists of hydrogen. Thermal and chemical degradation of the insulating materials inside the transformer

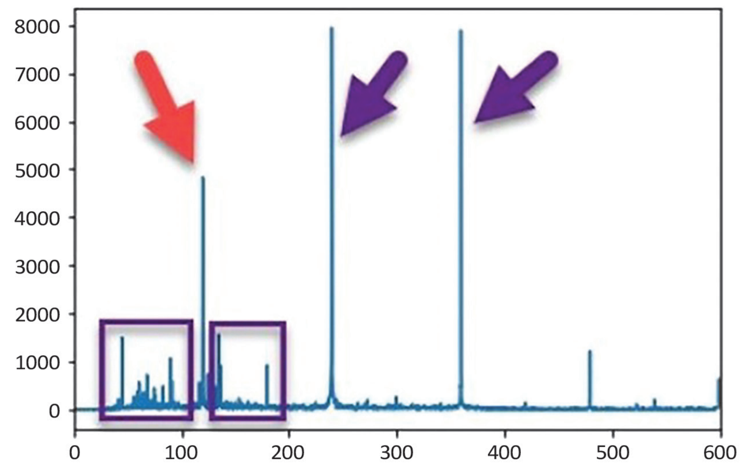

Figure 6: *Power Analysis of Audio Related to Transformer Sound*

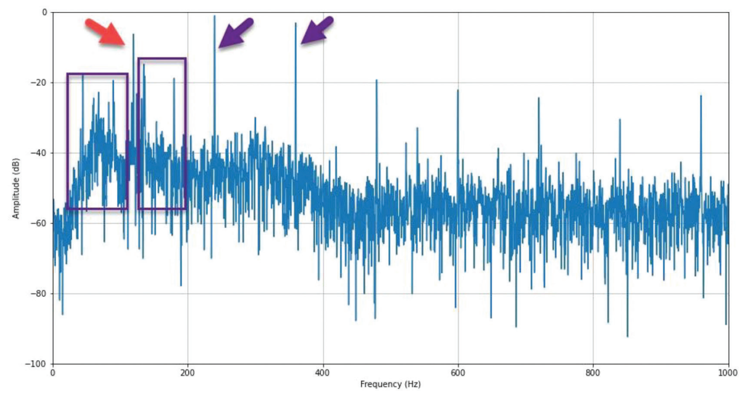

Figure 7: *Decibel Analysis of Transformer Audio*
120 Hz and related harmonics are directly related to power factor and harmonic content.

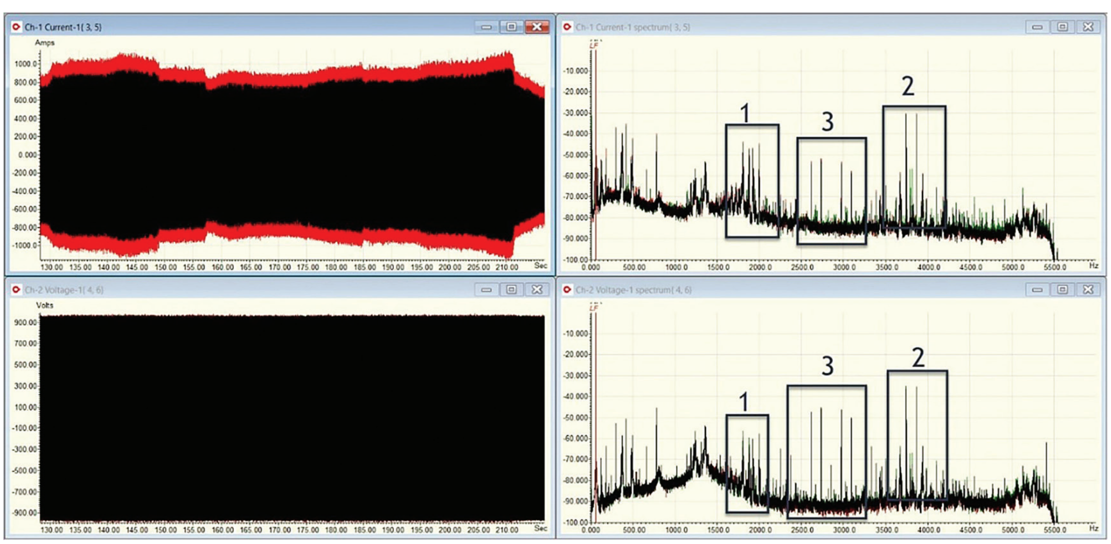

Figure 8: *ESA Voltage and Current Data on a Wind Generator*
Legend: 1 is the rotor inverter frequency; 2 is the second harmonic of the rotor inverter frequency; 3 is related to transformer core resonance.

may result. In dry-type transformers, resonance will also affect connections.

LOAD BALANCING IN SOLAR APPLICATIONS

One of the primary concerns in solar applications is balancing the load between the two lower voltage primaries and the secondary. Figure 9 is a solar transformer with unbalanced primary and inverter harmonics that convert the solar DC power to AC at the transformer. The primaries are often phase-shifted to reduce output harmonics in the distribution system as shown in the simple transformer sketch in Figure 10.

When unbalances exist, the firing frequencies and transformer core resonance will show similarly as with wind turbines as shown in Figure 11 and Figure 12.

Figure 9: *Solar Transformer Being Tested and Evaluated between Primaries from the Output of the Solar Inverter*

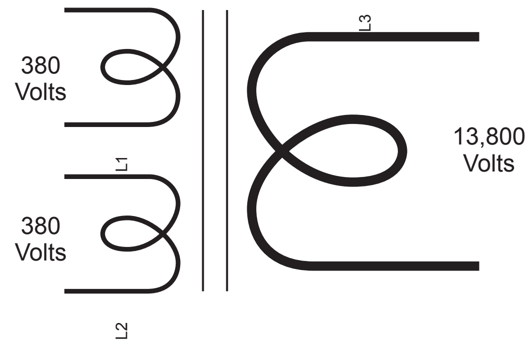

Figure 10: *Rough Circuit Sketch of a Solar Step-Up Transformer*

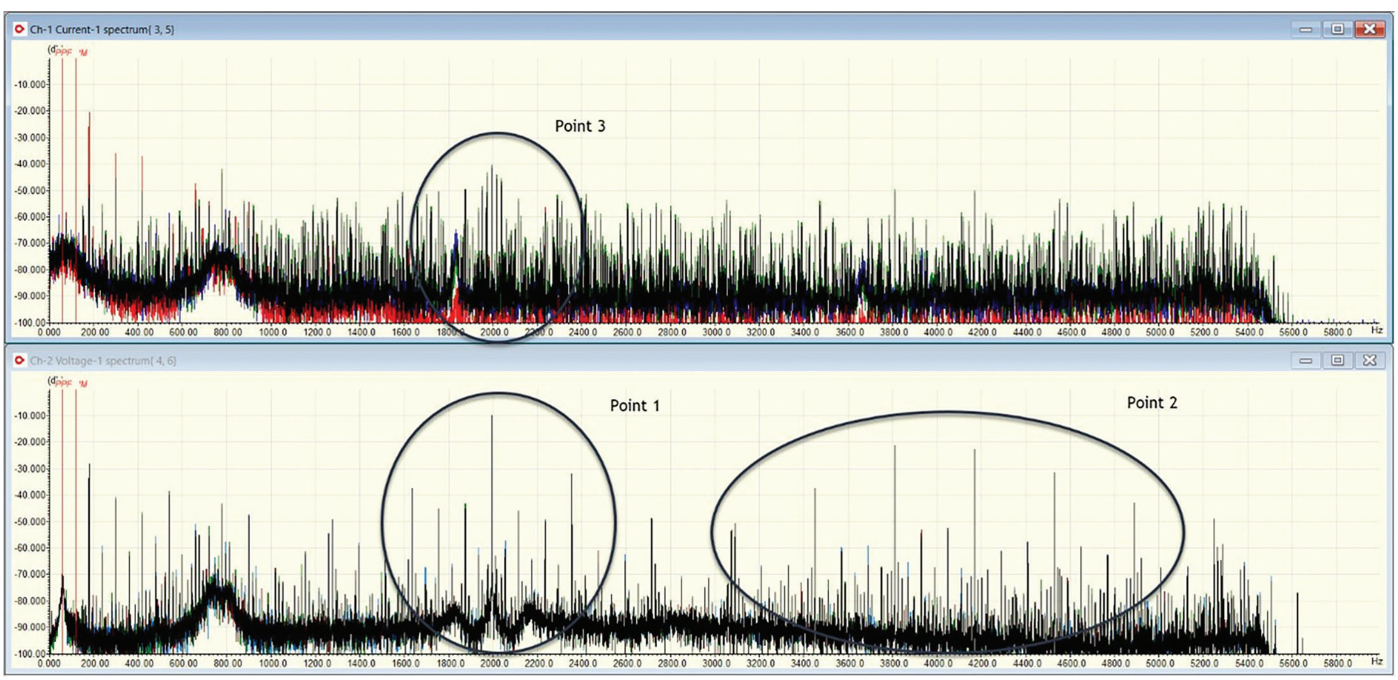

Figure 11: *Spectral Analysis of One Primary of a Solar Transformer*
Point 1 and Point 3 represent the inverter frequency; point 2 represents the resonance present in the transformer.

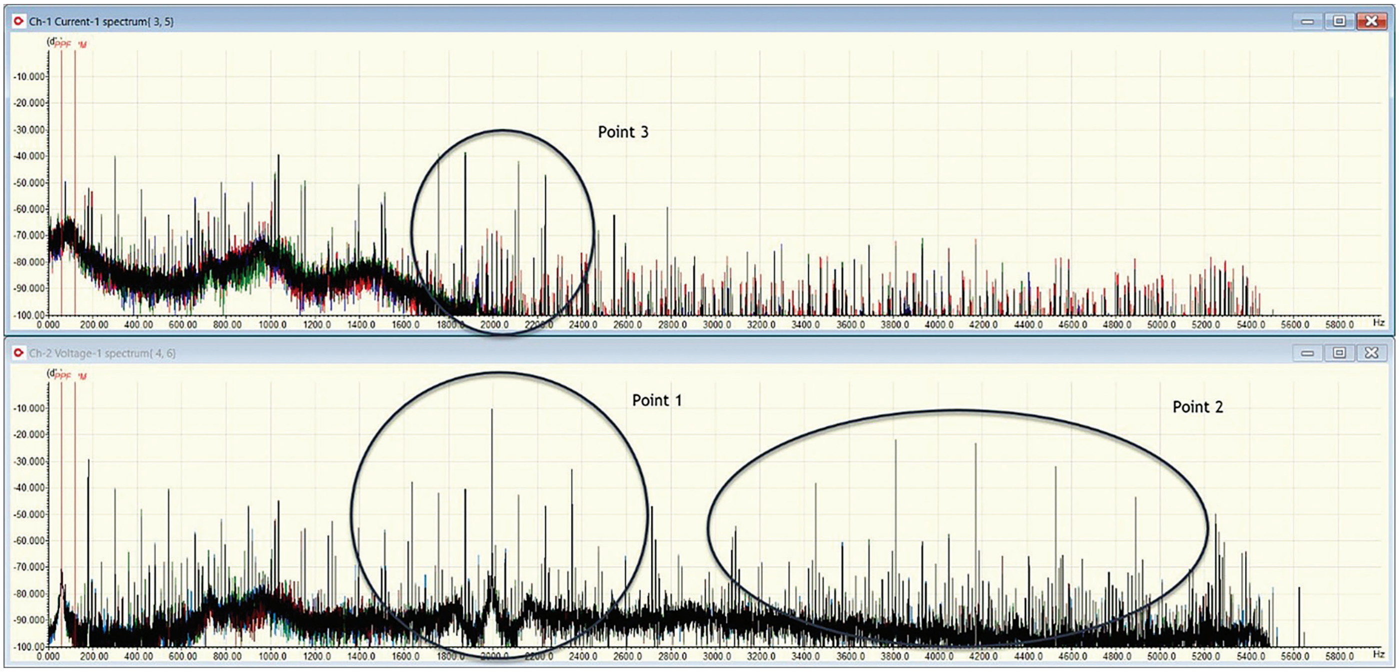

Figure 12: *Spectral Analysis of the Other Primary in the Same Transformer*

Figure 13 and Figure 14 show the electrical and power data associated with the solar transformer. As is observed, the transformers are heavily unbalanced between the sides. In cases where the transformer primaries are balanced, resonance rarely appears to occur. This condition results in heating and gassing with reduced insulation and oil life.

Transformer [LF: 60 Hz]

Results | Time | Freq. | Phasors | Extras

	Phs-1	Phs-2	Phs-3	Total	Units
Power factor	0.997	-0.427	-0.438	0.630	
Real Pwr.	27.1	9.1	12.9	49.1	KW
Reactive Pwr.	2.0	19.2	26.5	47.7	KVAF
Apparent Pwr.	27.2	21.2	29.4	77.9	KVA
Running Cnt.	111.2	87.0	121.3	106.5	Amp
Line Voltage	397.8	395.8	397.3	396.9	Volt

☐ Horse Power

Figure 13: *Electrical Data from One of the Primaries Note the 49.1-kW and current values.*

13.8 KV TO 480 V OVERLOAD DUE TO GROUND/NEUTRAL HARMONIC CONTENT

The ground and neutral feedback to the transformer will generate heating and increase the loading on the transformer in cases where voltage and current are present, in particular where there are harmonics over the fundamental.

Note the changes between Figure 15 and Figure 16 where neutral and ground harmonic correction was implemented. The noise in the current waveform decreases and the even harmonics are eliminated due to a reduction in load on the transformer core. The comparison is at a similar load current.

Transformer [LF: 60 Hz]

Results | Time | Freq. | Phasors | Extras

	Phs-1	Phs-2	Phs-3	Total	Units
Power factor	1.000	-0.494	-0.347	0.631	
Real Pwr.	208.6	91.6	62.8	363.1	KW
Reactive Pwr.	1.9	161.2	170.0	333.1	KVAF
Apparent Pwr.	208.6	185.4	181.2	575.3	KVA
Running Cnt.	869.1	771.2	759.6	800.0	Amp
Line Voltage	393.8	392.7	392.7	393.1	Volt

☐ Horse Power

Figure 14: *Electrical Data Associated with the Other Primary Note the 363.1 kW and operating current.*

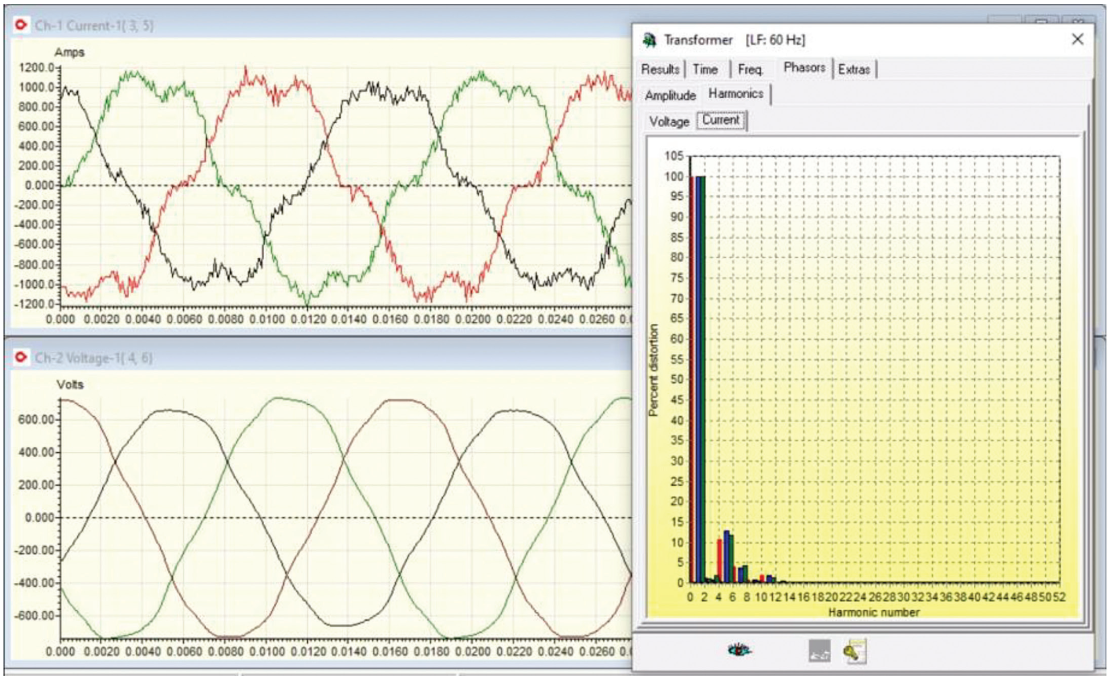

Figure 15: *Before Neutral and Ground Harmonic Correction*
Note the even and odd harmonics.

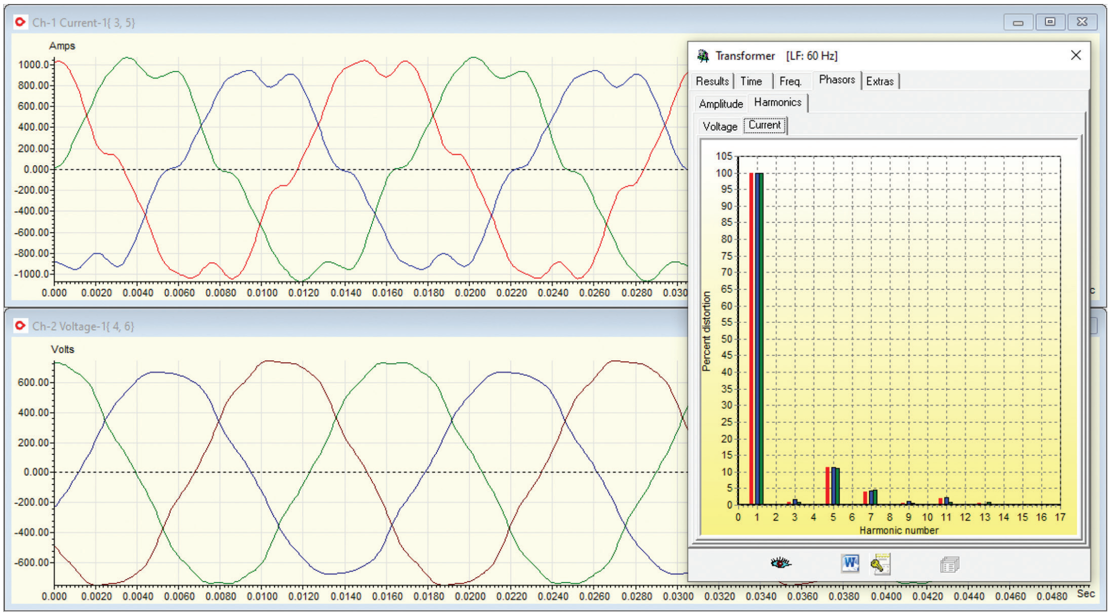

Figure 16: *After Installation of Neutral and Ground Harmonic Correction*

LOOSE CONNECTION ON TRANSFORMER BUSHING

Loose connections (Figure 17) are found through a combination of impedance unbalance; even harmonics will often be present. The impedance unbalance (Figure 18) distinguishes between harmonic loading and the loose connection.

CONCLUSION

ESA is an excellent tool for direct or incidental detection of major defects in transformers by

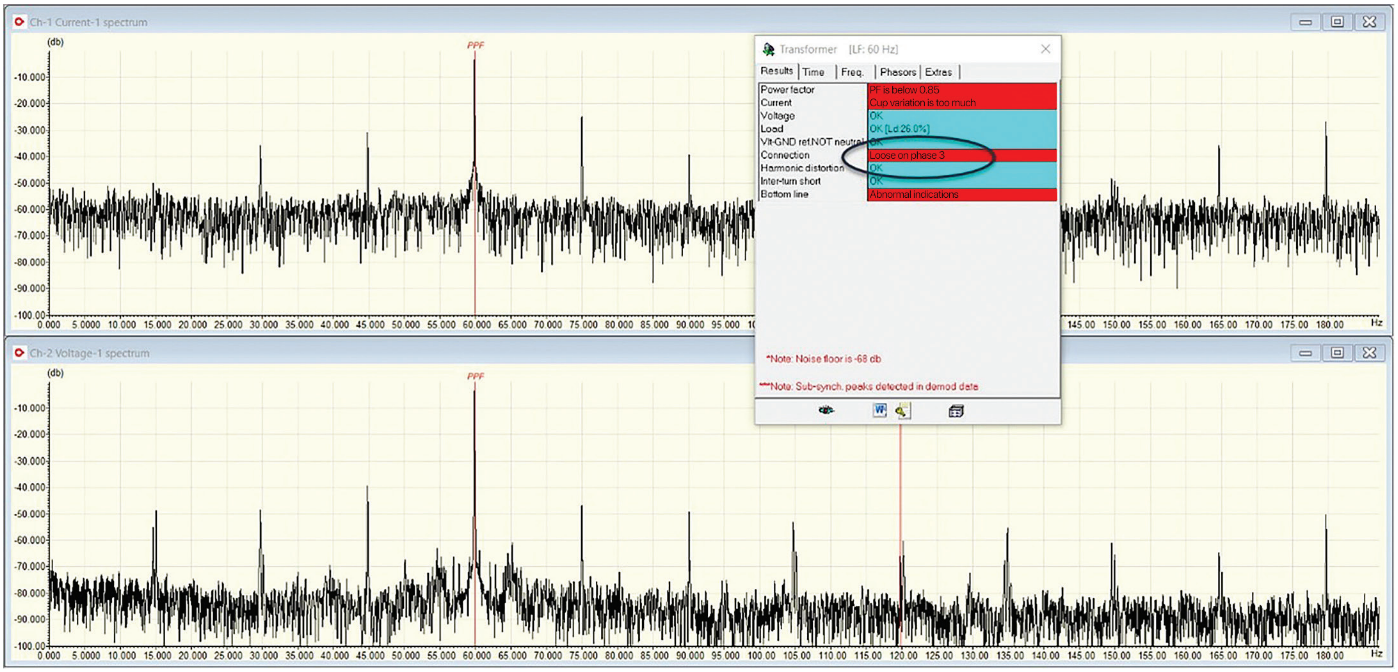

Figure 17: *Loose Connection Found on Lighting Transformer*

evaluating the power quality, phase impedance, and impact of loads. In these examples, we have detected loose connections, overloading, neutral and ground impacts, power factor problems, and a few others. When used as part of continuous monitoring, these conditions can be found early enough to mitigate the defects. NW

Transformer [LF: 60 Hz]

Results | Time | Freq. | Phasors | Extras

	Phs-1	Phs-2	Phs-3	Total	Units
Power factor	0.787	0.652	0.784	0.739	
Real Pwr.	49.3	39.1	39.8	128.2	KW
Reactive Pwr.	38.7	45.6	31.5	115.8	KVAR
Apparent Pwr.	62.6	60.1	50.8	173.5	KVA
Running Cnt.	9.2	8.8	7.4	8.4	Amp
Line Voltage	11890	11904	11827	11873	Volt

☐ Horse Power

Figure 18: *Impedance Unbalance Found on Phase C*

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Howard W. Penrose, PhD, CMRP, CEM® *is President of MotorDoc® LLC, a veteran-owned small business. He was a U.S. Navy electric machine repair/rewind journeyman (NEC 4619/4621) and is the 2022-2025 Chair of Standards Development at American Clean Power. Penrose is the past chair of the Society for Maintenance & Reliability Professionals (SMRP); past chair of Chicago Section IEEE; an active member of IEEE standards committee(s); past Senior Research Engineer at the University of Chicago Energy Resources Center; chair of the committee for wind/solar/energy storage standards for the USA through American Clean Power (formerly AWEA); and the U.S. appointee to CIGRE Working Group A1 Electrical Machines for those topics. He is a five-time recipient of the UAW-GM People Make Quality Happen Award; a leading researcher of ESA/MCSA applications; and has worked with diverse design teams including the GM hybrid Tahoe and Volt, John Deere 644 and 944 hybrid construction tractors, LVAD heart pump, flywheel generators, and high temperature/low atmosphere electric machines. He serves on the SMRP government affairs team for workforce, smart grid, cybersecurity, and infrastructure, among numerous other energy/environment/ workforce programs. Penrose received his PhD in industrial-general engineering and is certified in data science and machine learning from Kansas Western University, Stanford University, the University of Michigan, IBM, and AWS.*