Energy and Power Measurements on a Nonsinusoidal 345 kV System Using Three-Phase Megahertz Time-Series Data

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***Abstract*—Measuring energy exchange in a power system with distorted signals requires analysis beyond using filtered fundamental waveform techniques that may fail to capture energy transfer when dynamics are shorter than a cycle. Time-domain metering on networks with distortion caused by sources, such as inverters, measures subcycle phenomena and electric energy flow under all system conditions.**

This paper investigates time-domain metering approaches and references measurements of a 345 kV transmission line. A new power quality metric, "electric energy factor" is introduced as an alternative to power factor utilization measurement under distorted conditions.

I. Introduction

Power quality meters with 1 megasample per second (Msps) sampling rates have existed since the 1980s and are used for capturing information and detection of high-frequency transients [1]. In the past 30 years, megahertz data have primarily focused on harmonic calculations and voltage transient detection within the power quality community. Many papers have focused on voltage transient detection, arcing detection, traveling-wave (TW)-based fault locating and, in the last decade, TW-based protection.

Analyzing time-series waveform data from both terminals of a 345 kV transmission line shows several new observations not seen in measurements filtered to a narrow bandwidth around the fundamental. For example, Fig. 1 depicts a three-phase instantaneous power signal from Lone Star Transmission with ripple in the waveform. Fig. 2 shows a similar phenomenon in the three-phase instantaneous power signal, but at the slightly higher loading level of the line. The ripple shown in Fig. 1 and Fig. 2 would not be visible if the signal was filtered. This paper does not investigate the cause of signals such as shown in Fig. 1 and Fig. 2. These waveforms are shown simply to demonstrate one example of a signal that is not well-represented if filtered.

Lone Star is a transmission owner and operator in North Texas. Since March 2013, the Lone Star 345 kV transmission network corridor has transmitted primarily wind-generated electric power from remote western Texas to northeastern Texas. These two lines are partially parallel on double-circuit towers with 50 percent series compensation. The lines run from West Shackelford (WS), northwest of Abilene, Texas, to just south of the Dallas–Fort Worth metropolitan area. A one-line diagram of the Lone Star transmission line is shown in Fig. 3.

In 2022, Tennessee Valley Authority engineers in [2] and [3] highlighted the reality of increasing transmission voltage unbalance, the variance of phase magnitudes and angles, and the application of solar inverter-based resource (IBR) generation. The power system is trending towards being more unbalanced and more nonsinusoidal. Better intelligent electronic devices (IEDs), algorithms, and methods to monitor, detect, measure, and report the unbalance and distortion are needed. The three-phase instantaneous power in Fig. 1 and Fig. 2 include two visible phenomena: an amplitude-modulated ripple and high-frequency distortion. In common with most power measurement devices, one-cycle average power averages these two distortions and represents the signal as a nearly flat line.

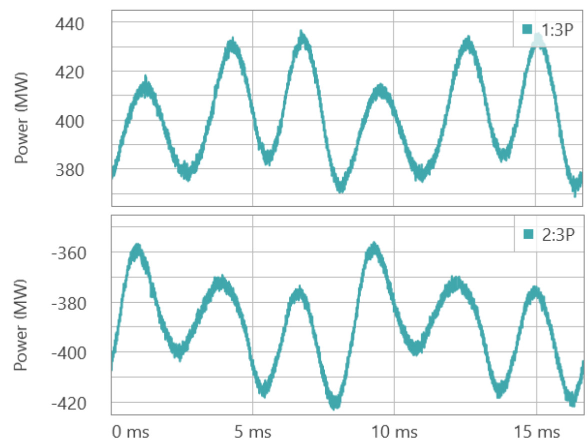

Fig. 1 17:39:44.564 UTC (1) WS and (2) Navarro (NAV) three-phase instantaneous power.

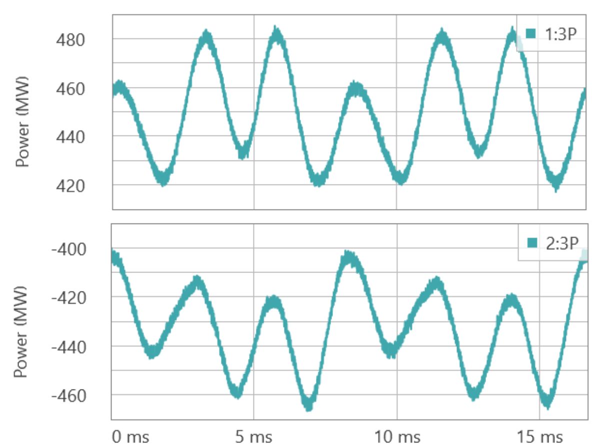

Fig. 2 18:38:20.683 UTC (1) WS and (2) NAV three-phase instantaneous power.

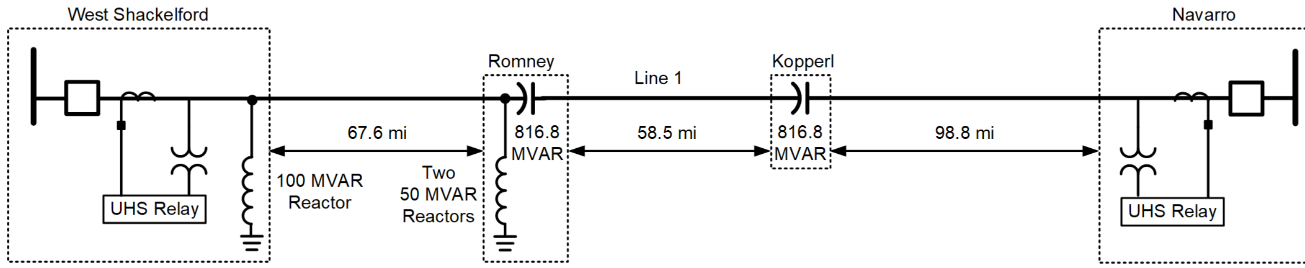

Fig. 3 Simplified ultra-high-speed (UHS) relays metering one-line diagram for WS to NAV (Line 1) series-compensated line.

Presently, metering rms calculations of voltage, current, and power are computed over integer units of power system signal periods. Measuring the system within the time domain without narrow band filtering allows calculations over any window, independent of system frequency. Sample rates of 1 Msps help identify higher-frequency content such as power line carrier communication signals.

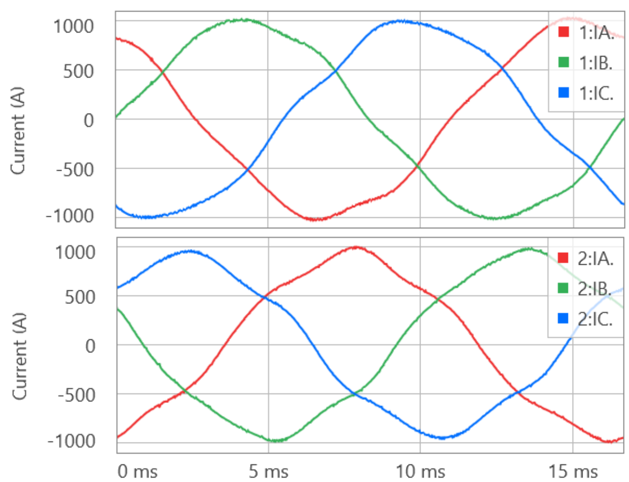

Fig. 4 17:39:44.564 UTC (1) WS and (2) NAV phase currents.

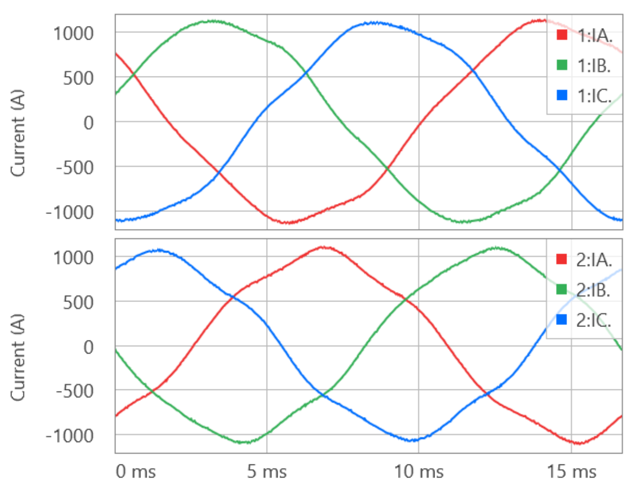

Fig. 5 18:38:20.683 UTC (1) WS and (2) NAV phase currents.

Two GPS time-synchronized ultra-high speed (UHS) relays [4], Fig. 3, at the terminals of the 345 kV 224.9 mile WS to NAV line (Line 1), captured and stored the data sets as event records. These two nonsinusoidal three-phase megahertz time-series data sets are the initial (predisturbance) records from May 11, 2021, that were examined in a previous technical paper [5].

The current waveforms are depicted in Fig. 4 and Fig. 5. The voltage waveforms are depicted in Fig. 6 and Fig. 7. Note that the signals are nonsinusoidal and slightly unbalanced.

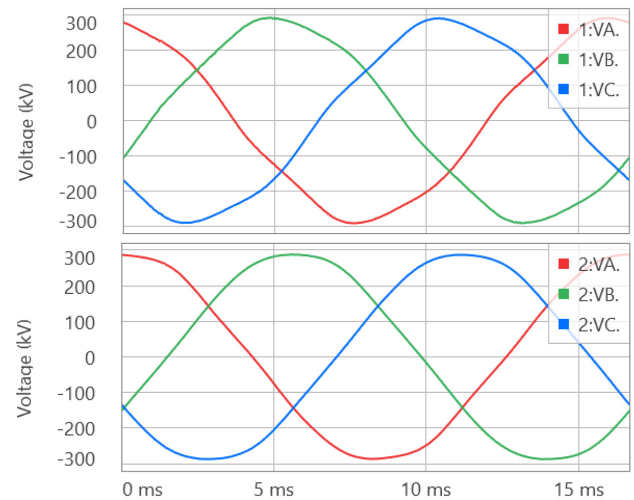

Fig. 6 17:39:44.564 UTC (1) WS and (2) NAV phase voltages.

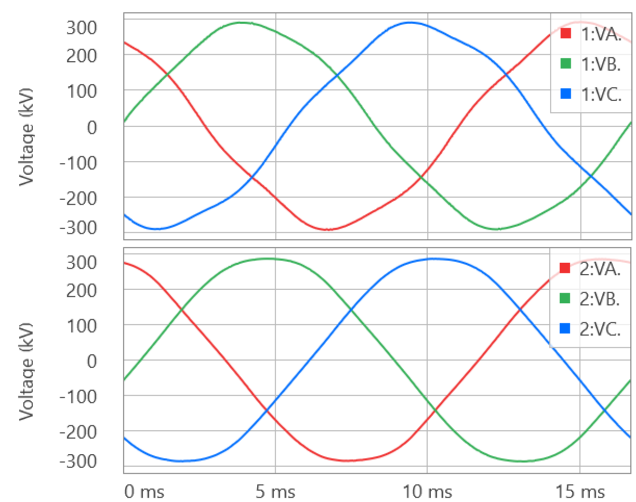

Fig. 7 18:38:20.683 UTC (1) WS and (2) NAV phase voltages.

This paper summarizes how to perform time-domain energy and power calculations, which can be useful for power systems with distorted signals, as shown in the previous figures.

II. Time-Series Method

A. Background and Context

An electric utility prefers that customers have three-phase balanced fundamental frequency at unity power factor (PF) load with no distortion. This ideal load condition has the least electricity service equipment capacity requirement and, hence, maximizes the efficiency of distribution and transmission level equipment.

Monthly reading of electricity consumption and demand is the basis of the monthly bill for the end user. For commercial and industrial end users, additional penalty charges may also be billed, such as a PF penalty, to encourage customers to improve their load PF and offset the cost impact to the utility. In the U.S., significant load distortion is addressed through requiring the end user to mitigate and reduce the current distortion to the acceptable level stated in IEEE Std 519 [6].

Metering IEDs employ signal processing to provide measurements that represent the magnitude and angle of the fundamental component for current and voltage measurements. These measurements are inherently of limited bandwidth and are of restricted use for measurement, analysis, and control when grid voltages and currents are distorted.

B. Time-Domain Measurements

Frequency, phase angle, and PF are unreliable measurement quantities when voltage and current signals in an electric power system are not single-frequency sinusoids. Additionally, reactive power is not well defined for non-single-frequency sinusoidal electricity measurement and the calculation methods vary between models of IEDs, which makes it difficult to compare measurement between multiple metering points [7].

The time-domain devices in this paper use a common precise time reference that provides time-stamped measurements that synchronize measurements from multiple points across the system.

A 1 Msps, precise time-based time-domain IED measures sampled voltage and current signals with T_S = 1 µs. These µs time-stamped signals are inputs to instantaneous power and energy calculations for quantifying the energy consumption and bidirectional energy flow in the line.

The metering IED receiving the energy data can aggregate energy for a duration of 1 µs to one month or more for metering, control, billing, power quality (PQ), compensation, and historic record purposes.

Instantaneous power (1) quantifies energy transfer over a given time interval. Energy (2) is the time integral of instantaneous power (2).

$$p(t) = v(t) \cdot i(t) \tag{1}$$

$$e(t) = \int p(t) \cdot d(t) \tag{2}$$

Equations (1) and (2) are written in discrete-time notation as instantaneous power $p[k]$ (3) and instantaneous energy $e[k]$ (4):

$$p[k] = v[k] \cdot i[k] \tag{3}$$

$$e[k] = p[k] \cdot T_S \tag{4}$$

Equation (3) can be separated further into two components: positive instantaneous power, $p^{POS}[k]$ (5), and negative instantaneous power, $p^{NEG}[k]$ (6):

$$p^{POS}[k] = \begin{cases} p[k], p[k] > 0 \\ 0, otherwise \end{cases} \tag{5}$$

$$p^{NEG}[k] = \begin{cases} p[k], p[k] < 0 \\ 0, otherwise \end{cases} \tag{6}$$

Using instantaneous power (3), energy is measured in the time domain using the energy packet-based method for energy metering, (7):

$$E^{NET}[n] = T_S \sum_{k=M(n-1)+1}^{k=Mn} p[k] \tag{7}$$

where:

T_S is the fixed IED sample rate.

M is the number of samples in the energy packet.

Energy packets divide into positive and negative, based on the direction of power flow. These equations are applied later in the paper.

$$E^{POS}[n] = T_S \sum_{k=M(n-1)+1}^{k=Mn} p^{POS}[k] \tag{8}$$

$$E^{NEG}[n] = T_S \sum_{k=M(n-1)+1}^{k=Mn} p^{NEG}[k] \tag{9}$$

The energy packet-based method produces a measurement of the electric power system at fast, discrete-time intervals and sums the results. The energy packet measurement is reported at a fixed rate. Switching from a frequency-based energy calculation to a fixed time-based energy calculation has two advantages [8]:

1. Processing latency is deterministic.
2. The need to track and measure system frequency is eliminated.

III. Applications

Previously in this paper, plots showed how higher rate sampling enables seeing power system dynamics not visible when using heavily averaged signals. In this section, two applications of energy-based calculations are introduced.

A. Energy Flow

The Sankey diagram is a flow diagram where the width of a line represents the magnitude of flow [9]. Using this approach, the energy flow through a two-terminal transmission line is shown in Fig. 8. $E_X^{POS}[n]$ is the total energy into the line over interval M·T_S seconds and $E_X^{NEG}[n]$ is the total energy out of the line over the same interval. The energy into the line is computed as the summation of instantaneous energy samples, when the associated instantaneous power measurements are positive. Similarly, the energy out of the line is computed when the power measurements are negative. In this example, the value X can be either WS or NAV.

Input energy is either moved through the transmission line to the output, is stored by some device within the line, or is dissipated by transfer of heat energy out of the power system. Delays within the transmission line are a result of charge storage from phenomena such as capacitance, inductance, and energy storage.

Fig. 8 depicts how energy packets can model energy flows. Future work can develop this technique and apply it to additional power system problems.

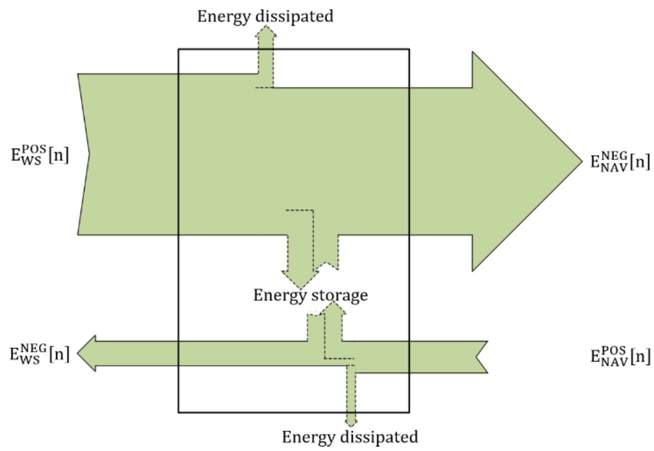

Fig. 8 Electric energy flow through a two-terminal transmission line.

B. Electric Energy Factor Metric

The electric power industry uses PF as a metric of the degree of effectiveness of energy flow in the power system. Power purchasers causing low PF frequently pay a PF penalty to offset the seller's added cost for capacity and capacitive support the utility provides. It is well understood in [7], [10], [11], [12], and [13] that under nonsinusoidal distorted conditions, PF has limitations.

A corresponding energy-based measurement for revenue and PQ applications is electric energy factor (EEF), which is a time-domain metric related to PF. The equation for EEF is (10):

$$EEF[n] = {E^{NET}[n]} / {E^{ABS}[n]} \tag{10}$$

In (10):

$$E^{ABS}[n] = T_S \sum_{k=M(n-1)+1}^{k=Mn} |p\,[k]| \tag{11}$$

EEF is a ratio of the net energy to the absolute energy over the duration $M \cdot T_S$ seconds. Note that EEF calculated in this paper is subject to edge effects and dependent on the integration window length. An alternative is to low-pass filter the EEF value before use.

Conceptually, the numerator of (10) is proportional to average power and the denominator is related to the energy that could be transmitted under ideal conditions. In this sense, the denominator serves a similar role as apparent power. Therefore, the EEF equation is similar to the PF equation, hence the proposal to consider EEF as a potential alternative to PF. It is anticipated that future work will develop this technique and apply it to more power system problems.

IV. Conclusion

Time-domain field measurement of three-phase electric power energy transfer across a nonsinusoidal 345 kV transmission line using time-based and synchronized IED processed and captured megahertz time-series metering data was discussed. The authors explored the use of time-domain metering for distorted nonsinusoidal systems, the application of which should be explored further.

The insight gained regarding line energy flow using time-domain measurements can be applied in PQ metering and revenue metering applications throughout the electric power system from energy source to the utilization load.

High sample rate energy and demand metering allow seeing distortion and unbalance, plus measuring it. All signals, regardless of their shape, distortion, or period, resolve into a measurable quantity.

V. Acknowledgments

In memory of Steve J. Szablya (1961–2023), 2016 IEEE Outstanding Engineer Award recipient. In 2021, he recruited and inspired Richard D. Kirby to investigate non-disturbance electric power signals in the time domain by focusing on the "dots." We are thankful for his critical thinking perspective, coaching, and aid in the development of the analysis documented in this paper and the submission of the original abstract to Georgia Tech FDA conference. He contributed to a preliminary version of this paper.

The authors also thank Dr. Ellery Blood of Schweitzer Engineering Laboratories, Inc., for his assistance during the authoring of this paper.

VI. References

[1] IEEE Std 1159-2019, *IEEE Recommended Practice for Monitoring Electric Power Quality*.

[2] D. C. Deloach, J. D. Kuhlers, A. M. Murphy, and G. E. Piercy, "Voltage Unbalance in a Changing Grid," proceedings of the Annual Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, GA, May 2022.

[3] D. C. Deloach, D. N. Hooker, and A. M. Murphy, "Case Studies for Utility Scale Solar Facility Performance and Power Quality Issues," proceedings of the Annual Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, GA, May 2022.

[4] SEL-T400L *Time-Domain Line Protection Instruction Manual*. Available: selinc.com.

[5] M. Lewis, F. Elhaj, and R. Kirby, "UHS Relay Testing for Optimal Protection of a Long 345 kV Line With Series Compensation," proceedings of the Annual Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, GA, May 2022.

[6] IEEE Std 519-2014, *Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*.

[7] H. Kirkham, D. Strickland, A. J. Berrisford, A Riepnieks, J. Voisine, and J. Britton, "Overview of IEEE Standard 1459 Revision," 2022 IEEE Power & Energy Society General Meeting (PESGM).

[8] E. O. Schweitzer, III, D. E. Whitehead, G. Zweigle, V. Skendzic, and S. V. Achanta, "Millisecond, Microsecond, Nanosecond: What Can We Do With More Precise Time?" proceedings of the 42nd Annual Western Protective Relay Conference, Spokane, WA, October 2015.

[9] A. B. W. Kennedy and H. R. Sankey, "The Thermal Efficiency of Steam-Engines," *Minutes of the Proceedings of the Institution of Civil Engineers*, 1896, pp. 278–312.

[10] L. S. Czarnecki, ”Do Energy Oscillations Degrade Energy Transfer in Electrical Systems?” *IEEE Transactions on Industry Applications*, Vol. 57, Issue 2, March–April 2021, pp. 1314–1324.

[11] P. S Filipski, “Apparent Power – A Misleading Quantity in the Non-Sinusoidal Power Theory: Are all Non-Sinusoidal Power Theories Doomed to Fail?” *ETEP*, Vol. 3, No. 1, Jan/Feb 1993.

[12] H. Kirkham, A. Emanuel, M. Albu, and D. Laverty, “Resolving the Reactive Power Question,” IEEE, 2019.

[13] H. Kirkham, D. White, and A Riepnieks, “Power Factor Revisited,” IEEE, 2020.

VII. Biographies

Matthew J. Lewis is a senior protection and control engineer at Lone Star Transmission, LLC, in Mansfield, Texas. His current focus is maintenance and engineering of new generation interconnect projects. He is a registered Professional Engineer in Florida and Texas. He has 16 years of experience in electrical engineering with 11 of those years in electric power engineering. He received a BS in electrical engineering from Florida Atlantic University in Boca Raton, Florida, in 2008, and in 2016, he earned his Master of Engineering in electrical engineering, with emphasis on Industrial Power Systems, from the University of Houston in Houston, Texas.

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