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Mathematical Tools for the Analysis of Periodic and Aperiodic Grid Signals

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Abstract –Numerous *sensing techniques and instrumentation are used in determining the state of the electric grid. Coupled with such measurements are the methods and analysis tools used. The parameters of interest result in both periodic and aperiodic signals. An examination of appropriate analysis tools is presented.*

Key Words: electric grid, aperiodic signals, analytics

1. INTRODUCTION

A periodic function is defined as a function that repeats its values at regular intervals. The typical example of such a function is that a function f is said to be periodic if, for some nonzero constant P, it is the case that

$$f(x) = f(x + nP)$$

for all values of x in the domain. where n=1,2,... The classic examples of periodicity are trigonometric functions such as the sine wave depicted in Figure 1.

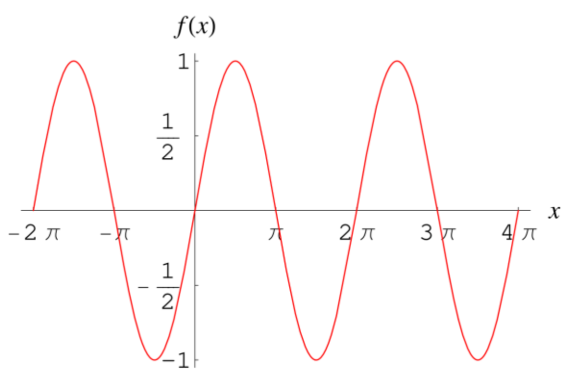

Figure 1. Classic periodic function.

This specific definition of a periodic function sets the conditions to define an aperiodic function: *An aperiodic (or non periodic function) is any function that isn't periodic, and as such, any measured signal can be described in terms of being periodic or aperiodic.* A variant on this definition is one provided by Adams [1]: *Although an aperiodic function isn't not periodic in nature, there is a very close relationship: mathematically, you can think of them as periodic functions with a period of infinity*. Note that there are (at least) two subclasses of aperiodic functions, those being: (1) *Almost-periodic* function which, although not periodic themselves, can be represented by a sum of two or more periodic functions; and (2) *Quasiperiodic* functions which are a combination of periodic functions of different frequencies that never completely match up. These classes of aperiodic functions are illustrated in Figure 2.

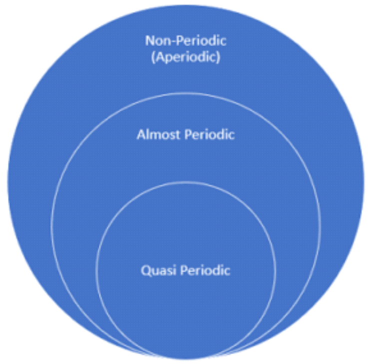

Figure 2. Classes of aperiodic functions.

2. A REVIEW OF ELECTRICAL GRID SENSING: ASSETS AND MEASUREMENT NEEDS

Electrical grid assets require monitoring to ensure that they are adequately performing their designed function and to properly maintain the asset to avoid unanticipated failure while in operation. A number of practical, operational benefits can be derived from increased measurement capabilities including:

(1) Increased reliability and resilience through prevention of catastrophic failures of critical assets;

(2) Delayed build-out of new transmission and other grid assets through more effective asset utilization;

(3) More rapid detection and correction of critical fault conditions, and

(4) Implementation of condition-based maintenance programs as a substitute for run-to-failure or time-based maintenance.

Capacity for Measurement of Assets: A wide range of sensing and measurement technologies are currently employed for the purpose of monitoring grid assets, Table 1. One prominent example is dissolved gas analysis (DGA) techniques, which are commonly employed for diagnosing the operational health and condition of power transformers.

Transformer bushings also represent a major source of catastrophic failure in transmission substations, and measurements of electrical parameters may be used to assess bushing health. Circuit breaker monitoring is another area in which existing technology solutions can be identified and can include gas temperature, pressure, and leak rate as well as mechanical systems.

A number of sensing and measurement technology platforms are currently under development to address needs in the area of asset monitoring. For example, the Electric Power Research Institute (EPRI) has developed a robust set of programs seeking to address sensing and measurement needs for transmission and substation applications. Examples of sensing technologies currently under development include:

(1) RF sensors to monitor a broad range of relevant parameters for conductors including disconnections, fault currents associated with lightning, geomagnetic induced currents, temperature and inclination, motion and vibration, and proximity and tampering for security;

(2) Optical diagnostic methods to monitor vibration and information about gas phase composition such as acetylene species surrounding high-temperature bushings;

(3) Local hydrogen and other chemical composition sensors for power transformers; and

(4) Unmanned aerial vehicle and robotic systems for inspection of overhead and underground transmission lines.

States/Parameters	Directly measured or calculated from measurements	Sensors/meters required	Description and Note
Visual inspection	Direct observation	Photography, video monitoring, ultraviolet imaging	Deployed by drones, robots, manual
Tempera-ture	Measured	Thermocouples and other point temperature sensors, IR imaging techniques	Point sensors identify single temperature locations while imaging tools such as IR imaging can also identify component hot spots while quantifying local temperature
Chemical analysis	Measured	DGA	Presence of N_2, O_2, H_2, CO_2, CO, CH_4, H_2, C_2H_6, C_2H_4, C_2H_2 in transformer insulating liquid or above the transformer oil in the gas phase
Tension	Calculated and Measured	Strain sensor, level or height monitoring	Can be inferred from direct strain sensors or indirect measurements such as line sag for transmission lines
Motion	Calculated	Vibration sensor, strain sensor, imaging based techniques	Camera imaging based methods with associated data analytics and motion proxies such as vibration or strain sensors.
Electrical equipment parameters	Calculated and Measured	Voltage and Current Transducers	Volt, current, phase angle, see previous sections on power flow and electrical grid state
Electrical discharge and corona	Calculated and Measured	Direct or calculated leakage current, local RF and static electric fields	Important for medium and high voltage energized assets including transformer bushings, transmission lines, etc.
Load tap changer position	Measured	Mechanical relay switch position	
Insulation oil level monitoring	Measured	Direct imaging or level indicator measurements	

Table 1. Key States and Parameters Relevant for Electrical Transmission and Distribution System Asset Monitoring and Fault Diagnosis.

A key challenge associated with new and emerging sensing and measurement technologies required for asset monitoring applications is the need for compatibility with electrically energized components. In the case of applications within the distribution system, cost is also a key factor that will drive new technology development for new lower cost sensing solutions.

For geographically dispersed grid assets ranging from components to transmission and distribution lines, deployment of unmanned aerial vehicles instrumented with on-board sensing, imaging, or diagnostic capabilities or even with interrogation and data storage and management capabilities for interrogation of localized sensors show significant potential for wide area infrastructure monitoring. Similarly, application of satellite and wide area monitoring electromagnetic techniques, such as lidar and others, is anticipated to see increasing deployment moving into the future.

The monitoring requirements such sensor system may address can be grouped into two logical categories: "Functional Performance" and "Health Condition" of the assets.

Functional Performance of Assets: As illustrated for a large electrical transformer, Figure 3, the parameters to be monitored for function performance are largely electrical properties such as voltage, current, phase angle, and frequency. These parameters are used to calculate other power parameters such as real power, reactive power, harmonics, and power quality. Requirements for the accuracy, precision, and frequency of measurements is driven by how the information will be used for operation and maintenance of the power system. In some cases, the usefulness of the measurement depends on how quickly the sensing and measurement data can be produced, integrated with other data, and converted to actionable knowledge. In other cases, the technical precision and accuracy of the measurement will be dominant. In all cases, particularly for distribution assets, the cost of the sensor will play a critical role in dictating the potential for widespread deployment and hence the ultimate impact.

Such monitoring and analysis is costly and time-consuming because it requires manual sampling and laboratory analysis techniques, but the benefits can still outweigh the costs for large power transformers, which are in operation for decades and represent major social, economic, and opportunity costs if they must be replaced due to unanticipated and often catastrophic failures. In the case of particularly critical transformer assets, real-time diagnostic methods have been developed, such as on-lineDGA, but are far too expensive for widespread deployment. For lower voltage and power rated transformers such as distribution transformers, even conventional DGA analysis techniques become cost-prohibitive. As such, lower cost and robust sensing device solutions are of interest for real-time monitoring of the most important parameters associated with the dissolved gases, including species such as H_2, CH_4, acetylene, ethane, ethylene, N_2, O_2 CO, CO_2, and others. In addition to DGA analysis, other sensors commonly employed for transmission transformers include bushings sensors, oil temperature and level, and tap electrical grid infrastructure. In addition to electrical parameters, physical parameters such as position (open or closed) of switches, reclosers, breakers, fuses, etc., can also be considered related to functional performance of assets.

Health Condition of Assets: In some cases, the electrical parameters monitored for function performance can also provide useful information about the health condition of the asset. However, electrical parameters are often “lagging indicators” of the on-set of conditions for which asset maintenance is required. For this reason, monitoring alternative types of parameters can be more valuable for providing an early indicator of conditions for which timely maintenance can avoid impacts on function performance and extend the operational lifetime of assets. Examples of such measurements include chemical, mechanical, and thermal measurements and their changes with time, either abruptly or over extended time durations, which can reveal potential health issues of assets to enable condition-based maintenance programs. Prominent examples of parameters that fall within this category and their associated applications include the chemical changes that occur in the gases above and dissolved within the insulating oil for large power transformers as well as strain, temperature, and sag measurements on conductors as they stretch and contract with changes in weather and electrical loading conditions.

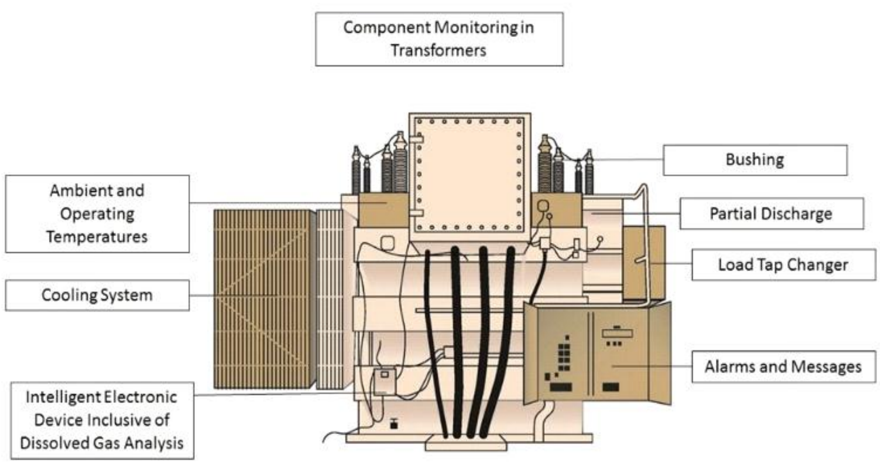

Figure 3. Power transformer component monitoring schematic showing examples of instrumentation and measurements of interest.

Techniques, such as lidar and others, is anticipated to see increasing deployment moving into the future.

3. GRID SIGNALS IN AN INTEGRATED SYSTEM

An example of an envisioned smart grid communication network design [2] presented a view of the grid elements, components and applications – along with information transfer requirements – in a sequence of diagrams, here as Figures 4 and 5.

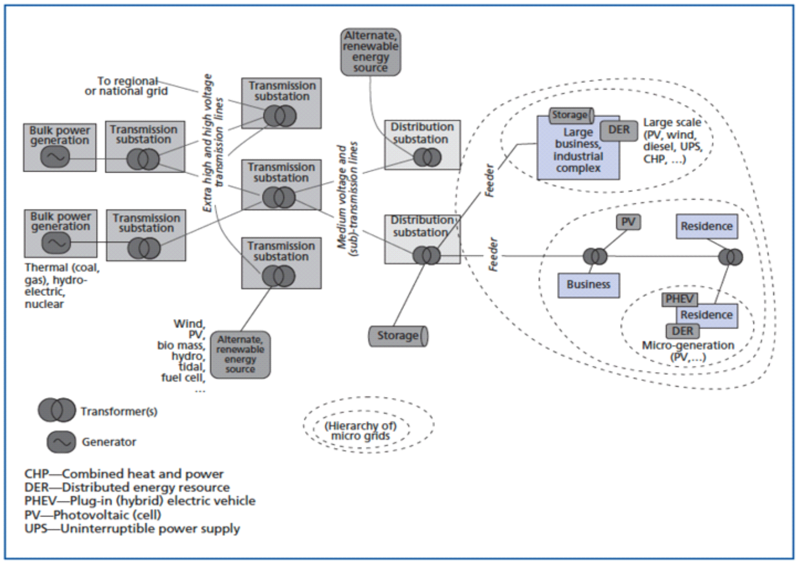

Figure 4. Generation, transmission and distribution elements comprising the smart grid.

Application	Scope HS or P2P	Data Rate/ Data Volume (at Endpoint)	(One Way) Latency Allowance	Reliability	Security
Smart metering	HS	Low/v. low	High	Medium	High
Inter-site rapid response (e.g., teleprotection)	P2P	High/low	Very low	Very high	Very high
SCADA	P2P, HS	Medium/low	Low	High	High
Operations data	HS	Medium/low	Low	High	High
Distribution automation	HS, P2P	Low/low	Low	High	High
Distributed energy management and control (including ADR, storage, PEV, PHEV)	HS, P2P	Medium/low	Low	High	High
Video surveillance	HS	High/medium	Medium	High	High
Mobile workforce (push-to-X)	HS	Low/low	Low	High	High
Enterprise (corporate) data	HS	Medium/low	Medium	Medium	Medium
Enterprise (corporate) voice	P2P	Low/v. low	Low	High	Medium
Micro grid management (between EMSs)	HS, P2P	High/low	Low	High	High

ADR—Automated demand response
EMS—Energy management system
HS—Hub-spoke
P2P—Peer-to-peer
P(H)EV—Plug-in (hybrid) electric vehicle
SCADA—Supervisory control and data acquisition

Figure 5. The communications requirements for the logical application elements comprising the smart grid are presented along with "recommended" network topologies.

Coupled with the network topology and communications requirements of Figure 5 are the companion latency requirements for a variety of central smart grid applications, presented as Figure 6.

Application (only a few example applications considered)	Application setting		Latency allowance (assumed, unverified)	Comments
Teleprotection	All	↓ In the order of decreasing priority	8 ms, 10 ms	For 60 Hz and 50 Hz, respectively
Phase measurement unit	Class A data service		16 ms	60 messages per second stipulated for Class A data service in [14]
Push-to-talk signaling	Incident-related		100 ms	
Smart meter	Connect to many meters in a short time		200 ms	Example: ADR within 1 minute for up to 300 meters connected over a shared medium
SCADA data: poll response			200 ms	See [8].
VoIP bearer			175–200 ms	Includes P2P and all PTT
VoIP signaling			200 ms	Includes non-incident-related PTT
Phase measurement unit	Class C data service		500 ms	Post event (latency value assumed). See [14].
On demand SCADA			1 second	See [8].
Smart meter	Periodic meter reading		≥ 1 second	Say, once an hour or lower frequency of reading

ADR—Automated demand response
P2P—Peer-to-peer
PTT—Push-to-talk
SCADA—Supervisory control and data acquisition
VoIP—Voice over IP

Figure 6. Smart grid application latency requirements.

These tables provide targets for communications operation and performance that are valid for supporting sensor telemetry today (2022) – having not changed substantially in the ten years since being described in [3]. Such a communication system is thereby able to transport the measurements from the wide array of periodic and aperiodic grid signals just described.

4. Analysis tools

With respect to the electrical grid, the vast majority of transmission, generation and distribution of energy is in the form of a sine wave operating at 50 or 60 Hz. The voltage level varies depending on utility needs relying on transformers to change the actual level. Analysis of this oscillatory periodic signal - sine wave - amplitude, frequency and phase follows traditional signal transforms, most notably a *Fourier Transform* (and the variants such as *least-squares spectral analysis*).

The applications and measurement "needs" outlined in the previously presented Tables and Figures are mostly involved in determining the status and performance of the utility's components and systems used to generate, transmit and distribute the electricity (aka, control). In essentially all electric utility measurements, the parameter of interest relies on some form of transduction to be converted into an electrical signal. A synopsis of such parameters is presented in Table 2 [4].

For this more broad scope of signals, the parameters of interest align more with aperiodic signals or perhaps the quasi- or almost- periodic signals. The transform analysis tools may still be applied to such signals – given certain functional requirements such as using Fourier integrals rather than Fourier series. Additional classic techniques including *wavelet analysis [5]* and *nonlinear dynamic analysis [6]*, used preferentially for acoustic characterization of aperiodic voices, may be applied to the analysis of aperiodic electrical grid measurements. Applying *Time History Analysis [7]* – a technique that is frequently used in the analysis of buildings – may be appropriate for aperiodic electrical grid signals.

Phenomena	Sensor	Electrical Output
Megnetic	Hall Effect	Voltage
	Magneto-Resistive	Resistance
Temperature	Thermocouple	Voltage
	RTD	Resistance
	Thermistor	Resistance
	IC	Voltage
	Infrared	Current
	Thermopile	Voltage
Humidity	Capacitive	Capacitance
	Infrared	Current
Force, Weight, Torque, Pressure	Strain Gauge	Resistance/Voltage
	Load Cell	Resistance
	Piezo-electric	Voltage or Charge
	Mechanical Transducer	Resistance, Voltage, Capacitance
Motion and Vibration	LVDT	AC Voltage
	Piezo-electric	Voltage or Charge
	Microphone	Voltage
	Ultrasonic	Voltage, Resistive, Current
	Accelerometer	Voltage
Flow	Megnetic Flowmeter	Voltage
	Mass Flowmeter	Resistance/Voltage
	Ultrasound/Doppler	Frequency
	How-wire Anemometer	Resistance
	Mechanical Transducer (turbine)	Voltage
Fluid Level and Volume	Ultrasound	Time Delay
	Mechanical Transducer	Resistance, Voltage
	Capacitor	Capacitance
	Switch	On/Off
	Thermal	Voltage
Light	Photodiode	Current
Chemical	pH Electrode	Voltage
	Solution Conductivity	Resistance/Current
	CO Sensor	Voltage or Charge
	Photodiode (turbidity, colorimeter)	Current

Table 2. Measurement parameters relevant to electric utility operations [4].

4. SUMMARY

With respect to AC electric grid voltage and related measurements, the analysis tools to be used are simple: the signal is periodic therefore the transform-based mathematics are appropriate for use. Similarly, for analysis of the signals associated with the systems and components which operate the grid, the array of mathematical processes available for aperiodic signal analysis are to be used. It is worthwhile to repeat that a fundamental difference between periodic and aperiodic signals is that an aperiodic signal cannot be represented by any singular mathematical equation. Within this context, an aperiodic signal is a random signal which never repeats, which allows for a variety of other classical mathematical analysis techniques but eliminates the potential use of the types of Fourier analysis that is of use for periodic signals As may be expected, a complex system such as a system of assets within the electrical grid will require measurement of signals with a variety of structures, and no signal analysis techniques will be most applicable for every requirement.

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