Innovative Sensory Concepts for Power Systems

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Abstract: **This paper addresses the use of innovative and unconventional instrumentation technologies for power systems. The main focus is on: giant magnetoresistance, Faraday and Poeckels and other optical effect devices, Hall effect devices, satellite measurement technologies, mechanical measurements, lab on a chip / chemical sensing, and video technologies. It is suggested to utilize overhead conductor mechanical and thermal measurements to provide corrections for state estimation applications.**

***Index Terms*: sensors, instrumentation, power system measurements, voltage, current, power.**

I. POWER SYSTEM INSTRUMENTATION

POWER system instrumentation is used to provide information to operators (e.g., alarms), for protective relaying, for revenue metering, control, and other operating functions. Instruments in general are described in a quantified way by a bandwidth (BW) and a dynamic range (DR),

$$BW = \omega_a - \omega_b$$
$$DR = M_{\max} / M_{\min}, \qquad (1)$$

where ω_a and ω_b refer to the upper and lower radian / second frequencies of the three decibel points of the instrument frequency response curve (see Fig. 1) and M_{max} and M_{min} refer to the maximum and minimum discernable (measurable) levels of a generalized instrument. Fig. 2 depicts some commonly used instrumentation technologies for power systems from the point of view of their BW and DR.

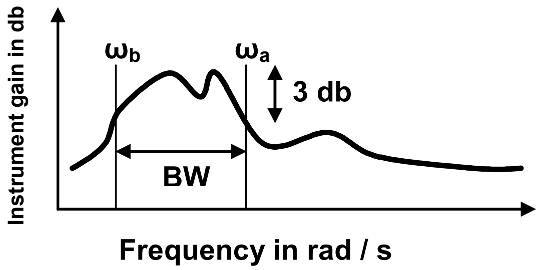

Fig. 1. Frequency response curve of a generalized instrument showing the instrument bandwidth

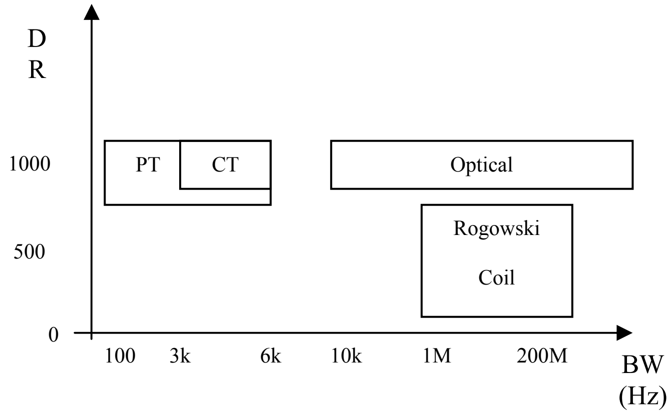

Fig. 2. Dynamic range (DR) and bandwidth of commonly used power system instrumentation technologies

Power systems are operated largely on the basis of information received from the field via sensors and communications channels (e.g., existing SCADA systems). Table I shows some sensory signals and an indication of their application.

TABLE I
SENSOR APPLICATIONS FOR POWER SYSTEMS

Quantity	*Transmission Lines*	*Substations*	*Transformers*	*Circuit Breakers*
Acceleration	X			
Vibration	X	X	X	
Stress/Strain	X			
Tension	X			
Shock	X	X		
Pressure			X	
Temperature	X	X	X	X
Inclination/Tilt	X	X	X	
Position				X
Protection Relay Output	X	X	X	X

A significant cost of sensory systems lies in the communications systems required. Also, the sensor packaging, considering the often hostile operational environment, contributes significantly to cost. These concepts stress processing at the point of measurement and minimizing the transmission of data to the next communication level. For some signals, time tagging may be important, and GPS based timing signals may be used. Data compression methods can be taken from digital signal processing technology to implement systems with effectively wide dynamic range because this dynamic range is often encountered in power system instrumentation. Similarly,

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methods of bandwidth compression shall be used to accommodate a large number of frequency multiplexed instrumentation channels. For the communications channel between hierarchy levels, the following should be considered: local storage and processing (i.e., no transmission to next hierarchy, but store in flash memory); pilot wire and carrier current; dedicated channels; radio; microwave; fiber optic; and satellite (where this list is approximately ordered in terms of priority and importance).

The following technologies have been identified for purposes of illustration of innovative power system instrumentation:

- Giant magnetoresistance
- Faraday and Poeckels and other optical effect devices
- Hall effect devices
- Satellite measurement technologies
- Mechanical measurements
- Lab on a Chip/ Chemical sensing
- Video technologies.

II. GIANT MAGNETORESISTANCE

The giant magnetoresistance effect (GMR) is a property of certain materials to exhibit a decrease of resistance when present in a magnetic field. These materials are actually structures composed of ferromagnetic and nonmagnetic metal layers and the resistance of the structure depends on the alignment of the magnetization of the adjacent layers. A magnetic field sensor can thus be developed. In power systems, GMR can be an alternative to current sensing. Since current flow in a transmission line induces a magnetic field around it, a GMR material can be used to find the current in the line through the intensity of the magnetic field.

Fig. 3 shows a simple illustration of how GMR can be applied. The magnetic field due to the presence of current in the conductor causes the resistance in the GMR material to change. An induced voltage across the GMR material allows current to flow through the GMR material. The resistance of the GMR material can thus be calculated by measuring the induced voltage across and the current through it. Using these measurements and information about the GMR material, a processor can calculate the current flow in the conductor. Currently GMR technology is primarily used in the data storage industry but other existing applications of GMR exist as automotive sensors and solid-state compasses.

GMR technology has not been applied in power engineering. In order to apply this technology, temperature compensation is needed, and a sensitive method of measuring the GMR material resistance is needed. Fig. 4 shows a Kelvin or double bridge which has the capability of sensitive measurement without complications due to terminal resistance. Table 2 defines the several resistances shown in Fig. 4. The switch shown in Fig. 4 is used to calibrate the Kelvin bridge. Details on calibrating the Kelvin bridge can be found in [18].

The essence of the use of the double bridge appears in four steps listed in Table 3. It is possible to automate the switch closures/openings listed in Table 3. If the voltage sensor in Fig. 4 employs A/D conversion with b bit technology, the number of decimal places of accuracy in attaining a bridge balance is N_{10},

$$N_{10} = b \log_{10} 2 .$$

Once a Kelvin bridge is calibrated, the resistance of the GMR material can be found by

$$R_{GMR} = R_X = \frac{R_A}{R_B} R_R .$$

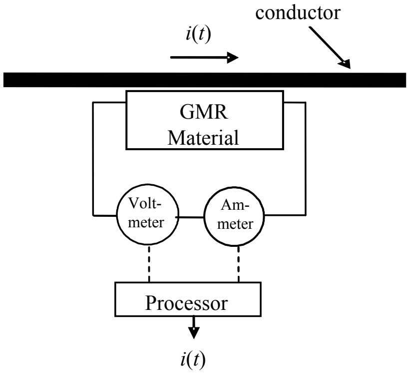

Fig. 3. GMR sensor in a power system

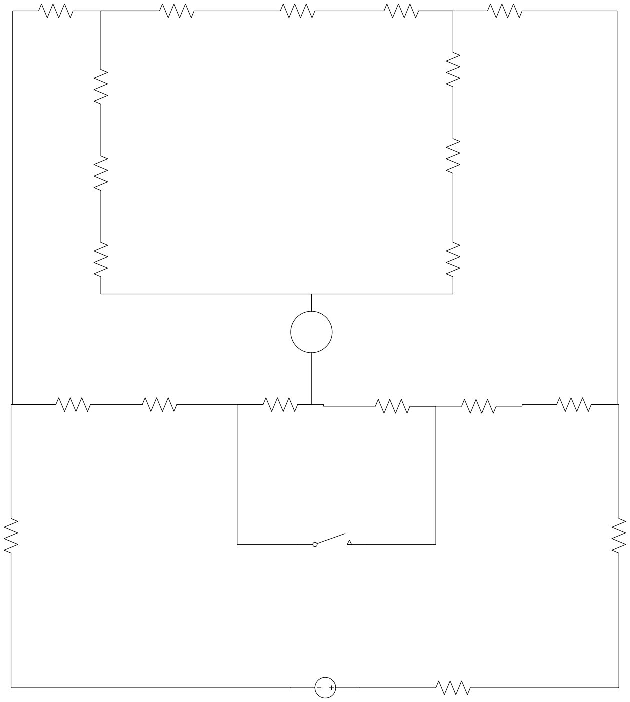

Fig. 4. Kelvin Bridge

TABLE II
RESISTANCES IN A KELVIN BRIDGE

R_A, R_B	Ratio Arms
R_{C1}, R_{C2}, R_{C3},R_{C4}	Terminal resistances
R_{P1}, R_{P2}, R_{P3}, R_{P4}	Lead resistances
R_1, R_2, R_3, R_4	Resistance between the conductor and the lead
R_X	GMR resistance to be deter-

	mined
R_R	Resistor in which R_X is compared to
R_D	Link resistance

TABLE III
FOUR STEPS TO BALANCE A KELVIN BRIDGE

Step	Link *d*	P	Vary	Objective
1	On	Off	A, a, or B, b	A/B=a/b
2	On	On	A', B'	G=0
3	Off	Off	A', b'	G=0
4	Off	Off	A, a	G=0

III. OPTICAL INSTRUMENTATION

The basic optical instrumentation techniques are shown in Table 4. The use of optical sensors in power engineering, while becoming more common, is regarded by most power engineers as an exotic methodology. The main attractions of optical instruments are: high voltage isolation, and very wide (often virtually infinite) bandwidth. Optical instruments generally fall into three broad classes: those that depend on the rotation of the plane of polarization as in the Faraday effect; those that depend on interference as in Fresnel lens technology; and those that depend on the speed of light and its timing. The main existing successful power instruments -- including power quality instruments -- have largely fallen into the first category. There is some activity in the development of new optical sensors, and the attention is mainly concentrated in the second category, although the first category continues to attract attention.

TABLE IV
BASIC OPTICAL INSTRUMENTATION METHODS

Phenomenon	Instrumented quantity	Applications
Kerr effect	Electric field	Optical instrumentation of high voltage overhead power lines
Poeckels effect	Electric field	Optical instrumentation of high voltage overhead power lines
Faraday effect	Magnetic field	Optical instrumentation of high voltage overhead power lines
Fresnel effect	Luminous intensity	Laboratory applications Dielectric oil testing
Lasers	Luminous intensity	Surveying Laboratory applications Polarizer technologies
Polarization / reflection	Luminous intensity, mechanical motion	Experimental
Interference patterns	Luminous intensity, mechanical motion	Experimental

Perhaps the greatest attraction of optical instrumentation is the simplicity of the devices. These devices offer the long range potential of reducing sensor costs by more than an order of magnitude. If one accepts that the greatest hobble of contemporary power system instrumentation is the cost of the primary sensors, optical sensors are the natural selection as alternatives for low cost sensors. Note, however, that optical sensors often require light sources which have to be specially designed. These sources, unfortunately, add to cost.

The main commercially available power instrumentation that uses optical technology is the Faraday rotation effect 'power donut.' This is a device for the measurement of current by causing the plane of polarization of linearly polarized light to rotate by $\Delta\Theta$. The rotation $\Delta\Theta$ is given by,

$$\Delta\Theta = K_v B l \,, \tag{2}$$

where K_v is the Verdet constant in radians per meter per (weber per square meter), B is the flux density in weber per square meter, and l is the length of the path of the light beam in the medium. The usual configuration is for a fiber optic cable to be wound around the conductor to be instrumented (current I is measured). Fig. 5 shows a pictorial of this configuration. Crown glass is often used as the medium. Note that B is the flux density in the direction perpendicular to the path l. Because K_v is very small, it is necessary to make the path length l very long. Values of l are normally in the 100 - 1000 meter range. The flux density B is proportional to the current I (virtually an exact proportionality in the absence of ferromagnetic materials). This type of device gives exceptionally wide bandwidth and linearity. With the proper selection of path length, the dynamic range is nearly unlimited -- or at least limited only by the transducer that measures the plane of polarization rotation.

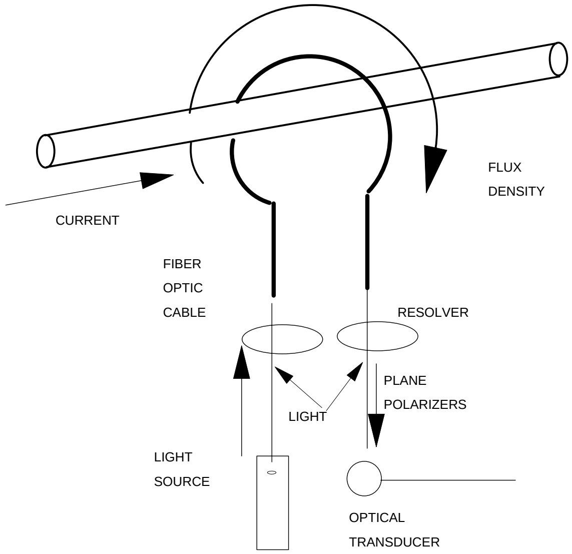

Fig. 5. Measurement of current using the Faraday rotation effect

Several optical instrumentation technologies are implemented using an optical Rogowski coil. This device is an optical coil (e.g., of fiber optic cable) that allows the interaction of B and H fields with the optical beam to be at great length (i.e., lengthen l in Equation (2) so that $\Delta\Theta$ is large enough to reliably measure).

The signal strength at the optical transducer in Figure 4 is given by

$$V_{sig} = K\cos(\theta_{polarizer} - \Delta\theta)$$

where $\theta_{polarizer}$ models the fixed plane of polarization of the resolver. The angle $\theta_{polarizer}$ may be taken as zero with no loss of generality. Then

$$V_{sig} = K\cos(\Delta\theta) = K\cos(K_v B l)$$

For example, for Jana Flint glass with Verdet constant 88.8 10^-3 min m/Wb, and 1000 A current measurement with the fiber optic cable located 3 cm from the conductor, if $\Delta\theta = 5^o$ can be resolved, one finds that the length of the fiber optic doil (l in (2)) is about 0.6 m. If 1 A is to be instrumeneted under the same conditions, the fiber optic coil must be 640 m long as shown as follows

$$l = \frac{(5^o)(60\frac{\min}{\deg})(2\pi)(3)(10^{-2})}{(88.8)(10^{-3})(1A)} = 640 \quad m\cdot$$

Infrared instrumentation has been used extensively in identifying heat. References [9]-[11] document some applications in power distribution. Ultraviolet radiation occurs in electrical discharges, and this may be useful in identifying partial discharge and incipient breakdown.

IV. HALL EFFECT

Hall effect devices are semiconductor devices that have effective resistance that is variable dependent on the incident magnetic field. These devices are bulk semiconductor devices, and as such have very high bandwidth. The main factor that limits their bandwidth is the stray capacitance and the terminal - to - terminal capacitance. Bandwidths of at least 10 MHz are common, and extensions to the 100 MHz range may be possible. For power quality and most other power engineering applications, the bandwidth is nearly infinite.

Hall effect devices are limited in their current handling capability -- usually limiting the upper end of the device dynamic range. The lower end is virtually unlimited -- or limited by the ability to detect small changes in voltage and current.

V. SATELLITE MEASUREMENT TECHNOLOGIES

Satellites have been proposed in the use of the measurement of sag in power systems [4],[5]. The physical measurement of sag is important in determining the real-time rating of a conductor. The configuration of a conductor sag satellite measurement is shown in Fig. 6. The differential global positioning system (DGPS) method can be used to measure the overhead conductor position. Only the conductor of the critical span is used to find the sag, and on this conductor is a remote locator called a rover. The rover location gathers information about the conductor position from satellites and sends that information to a nearby base station.

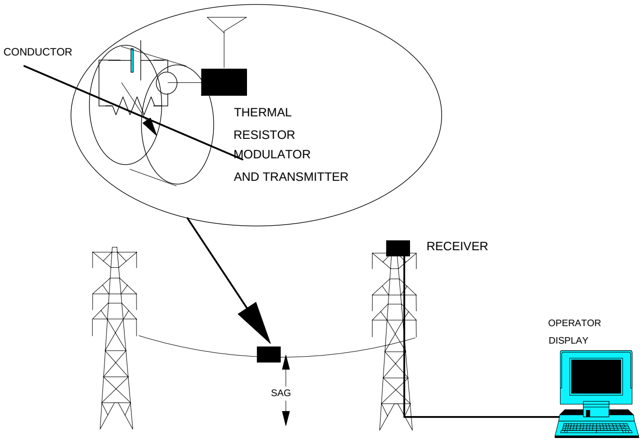

Fig. 6. DGPS conductor sag measurement illustration. The use of a resistive element to measure conductor temperature is also shown.

It is unlikely that power line conductors would interfere with the satellite signals [6]. The accuracy of the measurements depends on the configuration of the receivers, parameters that influence error in measurements, and the digital signal processing of the GPS measurements [7].

In a different venue, satellite visual and non-visual photography can be used to identify and prioritize tree trimming along transmission rights of way. The trees and growing vegetation frequently endanger the operation of a high voltage transmission line. A potential scenario is that during a storm, wind drives overgrown tress close to the line. This may cause flashover between the conductor and tree. The effect of this flashover is unforeseeable. In most cases, protective systems de-energize the line to extinguish the arc. After 3 to 6 cycles, the re-energization of the line is possible. However, in some cases the short circuit persists and may trigger wide area outages. An example is the August 2003 blackout in the US Northeast and adjacent Canada which resulted in the loss of power for millions of households and significant industrial and commercial financial losses.

Presently, power companies regularly survey the lines by helicopter to locate the trees that may endanger the lines. One of the most common technologies used is LiDAR which results in airborne images of rights of way (see Fig. 7). This is a laser, visual spectrum technology that is based on timing the reflection of light from airborne sensors to the trees. The expected vegetation growth can be calculated using appropriate models. The correlation of the survey and vegetation growth calculation results in a tree trimming schedule. This technology is expensive because relatively small areas are surveyed thus requiring a considerable number of airborne surveys. Sometimes LiDAR technology is inaccurate. As an example, inaccuracies may result from inaccurate prediction of tree growth due to unexpected rainfall.

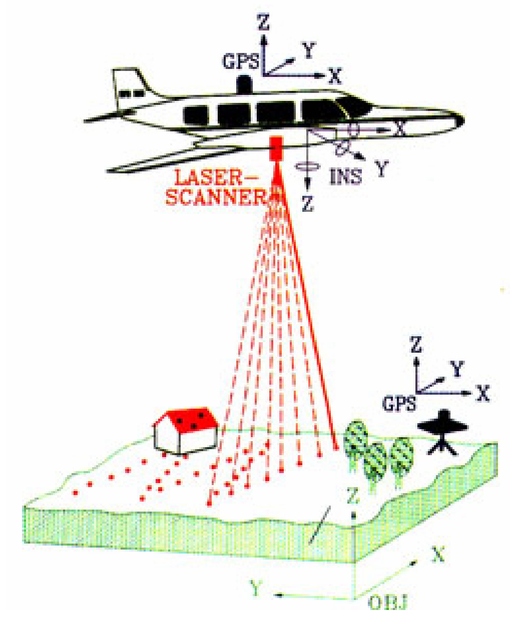

Fig. 7. Pictorial of LiDAR technology

The United States is regularly (yearly, or in some wavelengths much more frequently) surveyed by satellite. The satellite images of large areas, including transmission rights of way can be purchased. The availability of satellite images is a motivation to develop a satellite image based low cost method that identifies location of trees that endanger transmission line operation. The National Electric Safety Code limits the location of trees or objects that are penetrating in a safety envelope (e.g., 20 ft radius) surrounding the conductors. The satellite photography technology utilizes input data such as the satellite images of the line and the GPS coordinates of the towers. In order to utilize satellite imagery to identify tree interference with overhead lines, a three dimensional 'stereo' image is needed. Satellite stereo image pairs are readily available, and potentially useable for this application. The main issue appears to be the cost of purchasing the stereo pairs.

VI. Mechanical Measurements

The sag of the transmission line is an important element of the transmission line dynamic rating. If the transmission line sag is accurately measured in real time, system operators can determine the real time line ratings of the transmission line. Having real time line ratings of the system allow operators to push the transfer of power to the limits of the transmission line and could alter the behavior of the trade of power across that line. A further application of overhead conductor sag is in 'correcting' resistance and reactance data for transmission lines. In the well known application of state estimation in power system operation (the plethora of literature in the area is exemplified by [12]), measurements of active and reactive power are assembled in a measurement vector z, and these measurements are assumed to be linearly related to a state vector x consisting of bus voltage phase angles and bus voltage magnitudes,

$$Hx = z, \tag{3}$$

where H is the process matrix. The matrix H contains the line impedance data, and entries of H depend on conductor temperature (e.g., line resistance) and conductor sag (both inductance and resistance of the line). A mechanical measurement of overhead line tension could provide information on corrections to database entries for line impedances. Hence, these corrected entries could be used to 'correct' H.

One method of measuring sag of a transmission line is to use load cells placed between the conductor and a tension tower. Calculations methods can be used onsite and the measurement data can be transferred. One device that utilizes load cells and onsite calculation is a Cat-1 transmission line monitoring system [7].

The CAT-1 transmission line monitoring system performs a thermal line rating study by monitoring actual conditions. By installing the CAT-1 system, 15-30% additional capacity on transmission lines can typically be made available. The CAT-1 system utilizes a tension monitoring system as shown in Fig. 8. The load cells are installed between the cross arm and the dead-end insulators at both sides of a dead-end structure. An ambient temperature sensor reads the real time temperature in the vicinity of the transmission line. Wind speed sensors are also placed to measure wind speed in the vicinity of the transmission line. Cables carry signals from the load cells, wind speed sensors, and ambient temperature sensors to a CPU and data logger placed in the vicinity of the tower. Communications to the CAT-1 unit can be preformed remotely. Once a CAT-1 system is installed and calibrated, the sag of the conductor is calculated in real time by measuring the tension on the line via the load cells, ambient temperature readings, and wind speed readings. The sag is then compared to clearance limits of the conductor. The real time line thermal rating is calculated using the sag and clearance limits and can be accessed remotely by system operators.

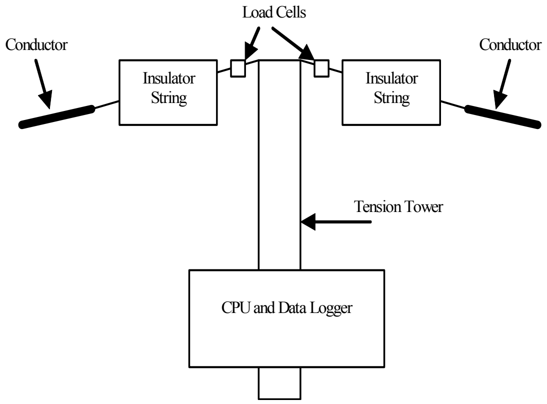

Fig. 8. Typical CAT-1 System Installation

As an example of how conductor tension might be used in an innovative application, consider the state estimation problem applied to the system of Fig. 9. Consider bus 0 as a reference bus with voltage 1 + j0 per unit. The system has 10 lines and 4 states. Consider only the active power flow between busses, and consider all ten lines to be instrumented for real power P. Then (3) consistos of the process matrix H which is 10 by 4, measurement vector z which has 10 entries, and the state vector X with dimension 4. If all line reactances are j0.01 per unit, and

$$z = [10,10,5,-15,-10,20,25,0,10,-15]^t$$

this gives (no noise)

$$\hat{x} = [-0.10,-0.20,-0.25,-0.10]^t \text{ radian.}$$

If line reactance 0-1 changes by -10% (which could be measured by instrumenting tension) H changes, and the estimate produces

$$\hat{x} = [-0.10,-0.20,-0.25,-0.10]^t \text{ radian.}$$

This illustrates how $\hat{x}$ can vary (nearly 4% in $\hat{x}_1$ in this case) albeit in a system specific case.

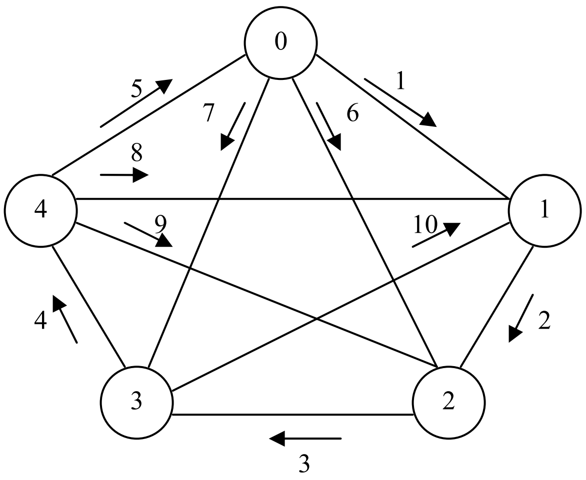

Fig. 9. Illustrative State Estimation Example

There may be an application of mechanical sensors in the measurement of audio noise in distribution transformers that are subject to nonsinusoidal load currents. For example, field engineers frequently describe how distribution transformers ‘whine’ and ‘sing’ when heavy load currents are taken from the unit (for the nonsinusoidal case). For example, arc furnace transformers frequently emit considerable audio noise, a buzzing sound, in the 120 - 360 Hz range, that is plainly audible. Theoretically, 60 Hz currents give rise to 120 Hz audio because vibration in the positive and negative part of the current cycle individually create audio vibration, thereby doubling the frequency of audio energy. Likewise, third harmonic currents cause 360 Hz audio, and fifth harmonic currents cause 600 Hz audio. These sounds indicate physical motion of windings and laminations in the transformer. The motion of windings can degrade the transformer life. The motion of laminations can also degrade the core of the unit and ultimately increase losses and decrease life.

VII. LAB ON A CHIP, CHEMICAL SENSING

One innovative way to enhance sensor technology in power systems is to introduce labs on a chip. This technology would integrate microprocessors on sensors to calculate other variables that would be available for data collection.

Ozone detection is important in determining the state of insulators in power systems. The presence of ozone in the air can enhance corona discharges in power systems. There are a variety of sensors that can be used to detect the presence of ozone. Ozone measurements have been carried out mostly by the use of analytical instruments which are based on photometric, chemiluminescence and fluorescence techniques, iodide methods, passive sampling, mass spectrometry and remote monitoring techniques [17]. These sensing techniques can be fairly accurate, but have a large cost and a high difficulty of operation. Low cost easy to use sensors have been proposed which use sensitive semi-conducting oxide thin films of In2O3, SnO2 or CuPc [15,16].

A method that has not been developed in power systems that can be used to estimate the severity of impurities in various devices is electron spin resonance (ESR). ESR is currently used for a number of different applications such as:

- to identify and quantify radicals
- to identify reaction pathways
- in biological applications.

ESR is spectroscopic technique that can detect materials that have free radicals in them. The basic theory behind ESR is that when an electron is placed in an external magnetic field, the magnetic moment of the electron can align itself parallel or anti-parallel to the field. To move the electron between the two different alignments, the electron has to move between two energy fields, which is governed by,

$$\Delta E = g_e u_B B_0 , \tag{4}$$

where g_e is the gyromagnetic ration of the electron, u_B is the magnetic moment of the electron, and B_0 is the external magnetic field strength. The electron placed in the magnetic field is forced to resonance between the two different alignments in which the energy absorbed becomes the ESR spectrum of the electron.

The ESR technology can be of some use in the area of insulator management in power systems. ESR could be used as a technique to estimate the number of free radicals in composite type insulators which cause breakdown and flashovers.

VIII. VIDEO TECHNOLOGIES

Applications of video technologies can have a variety of applications in power systems. Video technologies in power systems can range from closed-circuit TV motoring of substations to cameras placed inside of transformers to estimate the loss of life. Applications of video technologies can impact power systems in several areas:

- Improved maintenance
- Decreased maintenance costs
- Reduced loss of large equipment
- Reduced number of outages.

The addition of video technologies on transmission towers can help improve and decrease the cost of maintenance. Video feeds of existing transmission towers can help improve maintenance in a number of ways. One way is the maintenance of insulators on transmission towers. A high resolution video camera could be placed such that a number of insulators can be visually inspected. This application of video technology can have a low cost to benefit ratio as well as it can improve maintenance. Normally, insulators are visually inspected by driving by or flying around on a helicopter. This can cost companies large sums of money just to inspect them. Also the time between inspections can be in the order of months. Having video technologies on site allows for companies to visually inspect insulators virtually at any time, with a one time installation cost.

IX. PHASOR MEASUREMENT UNITS

Phasor measurement units (PMUs) are relatively new sensory devices for power systems that operate on the principles of phasor identification and time stamping using the Global Positioning Satellite (GPS). The essence of the PMU is the reading of an analog signal, digitizing the signal using a sampling rate s_1 (in samples / s), and the utilization of several of the samples of the signal correlated with a GPS time measurement (i.e., time stamped). The data provided by a PMU are synchronized phasor measurements. The correlated samples are made to fit a cosine wave in the mean square sense, and thereby obtain a magnitude and phase angle within the accuracy of the mean square fit. In the three phase case, the signals are then converted to symmetrical components, e.g. ($\alpha = 1\angle 120^o$),

$$\begin{bmatrix} V_+ \\ V_- \\ V_o \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} . \qquad (5)$$

Generally, the positive sequence values are reported back to control centers for operator displays. Although few electric utility companies are now utilizing PMUs beyond simple measurement, there is a considerable potential for real time measurement and control. For example, if only the positive sequence information is used, the full complex power measured in a line or at a bus, namely $P + jQ$, is,

$$P + jQ = V_{an}I_a{}^* + V_{bn}I_b{}^* + V_{cn}I_c{}^* = V_+I_+^* + V\_I_-^* + V_oI_o^* . \qquad (6)$$

If only the positive sequence signal is used, the complex power $V\_I_-^* + V_oI_o^*$ is lost (unaccounted for). In many power systems, the zero sequence voltage is negligible, and therefore the correction term $V\_I_-^*$ could be applied to the conventional PMU report to obtain a better estimate of $P + jQ$. Further, estimates of the voltage and current unbalance factors,

$$U_V = V\_/V_+ \qquad U_I = I\_/I_+ , \qquad (7)$$

could be used to preprocess PMU data before further use.

It is possible to estimate the bandwidth and dynamic range required to use PMU data. For the presently commonly used configuration of ‘positive sequence only’ signals, voltage and current measured to ten decimal places, at an ultimate sampling rate of 100 per second requires $\log_2(10^{10})/0.010$ or about 3.4 kb/s. Let C denote the channel capacity in bits / s, then,

$$C = BW \log_2(1 + \frac{S}{N}) , \qquad (8)$$

connects C with the required bandwidth (BW in Hz) and signal to noise ratio S/N. For the indicated example, for a signal to noise ratio of 50, one finds a required bandwidth of about 587 Hz. If four voltages and four currents are transmitted, the minimum bandwidth required is about 5 kHz. The required bandwidth increases linearly with the sampling rate – for example, in the cited example, if the sampling rate were 1000 per second, the required bandwidth would multiply by ten and be about 50 kHz. The dynamic range (ratio of largest analog signal to smallest analog signal) in this example is 10^{10}.

X. INTELLIGENT SENSORS

A majority of sensors that are in general use today are analog sensors. Analog sensors are attractive since they may be more rugged and less costly than digital sensors. One major drawback of analog sensing is the lack of intelligence they can provide to the sensing network compared to digital sensors. Calibrating analog sensor measurements to real world conditions is also major problem. A new IEEE standard 1451.4 promotes analog sensors [13].

Calibrating analog sensors is preformed using sensor data sheets. Once the sensors are calibrated, they are placed into the system where output voltage of the sensor is monitored and mapped into whatever the sensor is measuring. Standard 1451.4 changes how sensor data are read. Standard 1451.4 require analog sensors to have a Transducer Electronic Data Sheet (TEDS) to provide calibration information to the data acquisition system. TEDS can be stored on a ROM chip and transmitted. The 1451.4 compatible analog sensors, along with IEEE standards that describe how data should be transmitted over wired and wireless networks, allow networked sensors of different proprietary networks to communicate [14].

XI. CONCLUSIONS

The generic conclusion of this study is that unconventional instrumentation may offer power engineering new, useful information about the operating state of the power system. Concepts in electrical, chemical, mechanical, optical, and electromagnetic sensing have been discussed, and new potentially low cost and potentially valuable sources of information have been identified. Some potential areas of improvement include:

- State estimation accuracy enhancement (e.g., through the utilization
- Information to operators on the physical integrity of transmission circuits
- Measurements that may ultimately allow the estimation of loss of life of key transmission equipment.

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