The Assessment of the Measurement of the Poynting Vector for Power System Instrumentation

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***Abstract*— The concept of using the Poynting vector to measure power system quantities is examined critically. The properties of this vector are described and a potential value in the area of instrumentation of losses is discussed. The main difficulties are highlighted. Potential application areas lie in the instrumentation of high voltage insulator losses and transmission class reactor losses.**

***Index Terms*— Pointing vector, sensors, power system instrumentation.**

I. The Poynting Vector

The objective of this paper is to describe the findings of the researchers on a study of the potential for instrumentation of the Poynting vector in electric power systems. The Poynting vector at a given point in space is $\vec{S}$ given by

$$\vec{S} = \vec{E} \times \vec{H} \tag{1}$$

where $\vec{E}$ is the electric field and $\vec{H}$ is the magnetic field intensity at a point. In (1), all quantities are vectors and the X notation refers to the vector cross-product. The basic idea investigated is to directly measure $\vec{S}$ and use this sensory information for power engineering supervision and control.

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II. Historical background and properties of the Poynting vector

The Poynting vector is named after its inventor, the physicist John Henry Poynting in the 1880s. The magnitude of $\vec{S}$ has the units of watts per square meter and represents the power flux (or energy/time flux) through a given area. The vector $\vec{S}$ is a measure of both electric and magnetic fields. In an AC configuration, $\vec{S}$ is time varying and generally consists of a double frequency term and a constant term (in each of the ordinal directions in space). Thus, for a 60 Hz power system, in the vicinity of a current carrying conductor that is energized above ground, $\vec{S}$ has a 120 Hz term and a DC term. These remarks are a consequence of the fact that the E field is a 60 Hz vector which may be chosen as a reference phasor in each of the ordinal directions, and the corresponding H components are also 60 Hz phasors which generally have a phase displacement from E. Therefore $\vec{E} \times \vec{H}$ will generally have a 120 Hz component as well as a DC component (i.e., sum and differences of 60 and 60). The direction of the vector $\vec{S}$ is the direction of the propagation of the energy that is producing the electric and magnetic fields. Basic references relating to the Poynting vector and its properties appear in [1-3].

III. Power and the Poynting vector

The integral of the Poynting vector over a closed surface is the power that emanates from that closed surface. Thus, a plane region R will have a power crossing perpendicularly with a magnitude of $\vec{S}$ integrated over that plane. In 60 Hz AC circuits, this will be instantaneous power $p(t)$, and this will generally contain a 120 Hz component as well as a DC component. The DC component is the average value of $p(t)$ over time. Therefore $p(t)$ is the active or real power. The amplitude of the 120 Hz component is proportional to the reactive power Q.

If $|\vec{S}|$ is integrated (e.g., averaged) over a plane surface, and this signal is applied to a low pass filter (e.g., cutoff below 120 Hz), one would expect that the resulting signal is a measure of the active power which moves perpendicular to the

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given plane. In the case of a 60 Hz, three phase high voltage transmission line, the low passed signal Av{$|\vec{S}|$} (where Av{.} refers to the time average) will be proportional to the active power transmitted in the line in phase A in Figure 1. In the case of high power factor, v(t) and i(t) will be nearly in phase, and this results in a large average value of $|\vec{S}|$ in the direction of the line (i.e., axially, as shown in Figure 1). If the power factor is low, $|\vec{S}|$ will be mainly a 120 Hz signal proportional to the reactive power flow in the line.

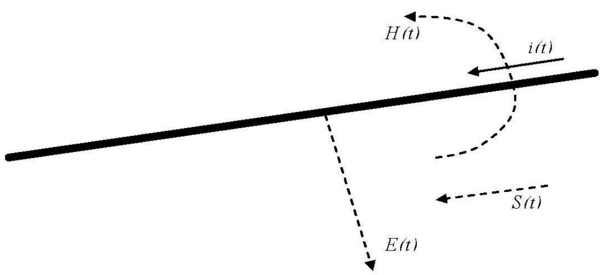

Fig. 1 High voltage transmission line with Phase A shown, directions of vectors *E*, *H*, and *S* shown

Further, [27] demonstrates that the Poynting vector cannot distinguish between purely resistive and resistive-inductive loads in a three-phase connection. Thus the Poynting vector cannot be used in a measurement framework where reactive power is a consideration. This is a significant drawback for power engineering applications.

IV. INSTRUMENTATION

Unfortunately, a literature search of the Poynting vector does not reveal any known sensor that can measure $\vec{S}$ directly. The existing literature suggests that three components of $\vec{E}$ are measured (e.g., three sensors, with blinds of shields in all directions except the one ordinal direction to be measured); and similarly the three components of $\vec{H}$ are measured. Then (1) is used to obtain $\vec{S}$. Note that the cross product is a vector product given by

$$u \times v = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ u_x & u_y & u_z \\ v_x & v_y & v_z \end{vmatrix}, \qquad (2)$$

where $\hat{x}$, $\hat{y}$, $\hat{z}$ are the unit vectors in the *x, y*, and *z* directions. In cylindrical coordinates, the cross product is

$$u \times v = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ u_r\, cos(u_\theta) & u_r\, sin(u_\theta) & u_z \\ v_r\, cos(v_\theta) & v_r\, sin(v_\theta) & v_z \end{vmatrix} = \begin{vmatrix} \hat{r} & \hat{\theta} & \hat{z} \\ u_r & u_\theta & u_z \\ v_r & v_\theta & v_z \end{vmatrix} \qquad (3)$$

where $\hat{r}$, $\hat{\theta}$, and $\hat{z}$ are the unit vectors in the cylindrical coordinate directions *r, θ* and *z*. The six measurements of electric and magnetic field are then converted to digital form and passed to a microprocessor to calculate (2) or (3). There appears to be no direct way to measure $\vec{S}$.

In view of the foregoing, there appears to be no reasonable advantage of working with $\vec{S}$ in place of measurement simply of active and reactive power in AC circuits.

V. POTENTIAL APPLICATIONS IN ENGINEERING IN GENERAL: A PRACTICAL ASSESSMENT

A literature search on applications of the Poynting vector and instrumentation of the Poynting vector produced approximately 113 references of which about 25 seemed to be most near to the application stage. Of the remaining, most are related to high frequency phenomena, mainly in antennas, waveguides, strip lines, and other ultra high frequency devices. The application areas identified are:

- Antennas and high frequency phenomena [3 – 12]
- Superconductivity [13]
- Circuit theory [14]
- Education and electromagnetic field theory [15-24]
- Power engineering [25-27].

The applications in power engineering appear to center on low or near zero power factor cases. As an example, losses in a high voltage post type insulator occur due to surface conduction along the insulator. Displacement current also occurs due to the capacitance from the conductor to the insulator base. This is a very low power factor phenomenon, and the currents involved are very low. Therefore the tangential component of the magnetic field around the post type insulator is very low. The electric field will be essentially axial to the insulator. This means that the Poynting vector along a cylindrical plane enclosing the insulator will be radial (mainly at 120 Hz due to the low power factor). There will be a small DC component of $\vec{S}$. The literature found in this area is mainly centered on measurement of electric and magnetic field separately, and multiplication using (2) via a microprocessor. In [25-26] there is an implication that this is feasible in a laboratory environment, however no one has implemented this technology in actual field conditions.

The practical assessment of the study reveals the following observations relating to applications in power engineering:

- There appears to be no direct measurement instrument or sensor for $\vec{S}$.
- The measurement of $\vec{S}$ appears to be relegated to similar technologies form the measurement of voltage and current for the purpose of obtaining average power and reactive power.

- In 60 Hz applications, the main signal obtained in calculating $\vec{S}$ is a 'DC average' as well as a 120 Hz signal. Active and reactive power are readily derived from these components.
- Measurement of $\vec{S}$ in very low power factor conditions (e.g., power delivered to a post type insulator; power delivered to a shunt reactor) may offer some specialized advantages – especially in laboratory conditions.
- Without a breakthrough in the direct measurement of $\vec{S}$, there appears to be no salient advantage over current transformer and potential transformer technology to obtain *i(t)* and *v(t)*, and subsequently *p(t)* and average power.
- If the area of Poynting vector instrumentation is pursued, a prerequisite would be a well equipped electromagnetic fields laboratory, especially with the capability of measurement of low electric and magnetic fields.
- In power engineering environments, electric and magnetic field strengths may well be confounded by stray fields from unexpected and unwanted sources. This confounding will degrade accuracy in using the Poynting vector.
- The instrumentation of the Poynting vector for electric power applications is a high risk venture.
- It has been proposed to use the Poynting vector to identify active power losses in reactors and partial discharge in insulators. The main issue is that using present technology, it is difficult to distinguish between high power levels associated with power transfer and the very low active power levels associated with losses.

VI. Possible applications in Power Engineering

It appears that the Poynting vector may capture power density with precision, and if the direction of the power flow is compared to the desired direction, there is the potential to measure power losses. As an example, in a high voltage post-type ceramic insulator, as depicted in Fig. 2. A high current passes through the conductor, and the direction of the Poynting vector for the high power would be left and right in the diagram. Resistive losses occur due to current flowing in the z-direction in the diagram. The electric field is oriented in the z-direction. Therefore the cross product of the electric and magnetic fields due only to the resistive losses will be in the θ-direction. If a Poynting vector sensor could be developed with a 'blind' in the z- and r-directions, then it would be possible to identify the resistive losses attributed to insulator current. Note in Figure 2 that all electromagnetic fields are 60 Hz AC fields and the Poynting vector has a DC as well as 120 Hz component. Only the DC component is used to identify active power loss in the insulator.

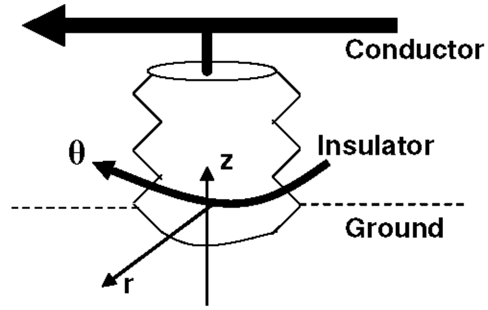

Fig. 2 Post-type insulator showing coordinate system

Another application of the Poynting vector in power engineering is the measurement of active power shunt reactor losses as shown in Fig. 3. In this application, the high power is passed through the conductor at the top of the figure. The inductive current in the shunt reactor is indicated as I_r in Figure 3. The purpose of shunt reactors is to consume reactive power for power factor correction in leading power factor cases. If a Poynting vector sensor could be developed with a 'blind' from the magnetic and electric fields of the phase conductor, then it would be possible to identify the active power losses attributed to current in the reactor.

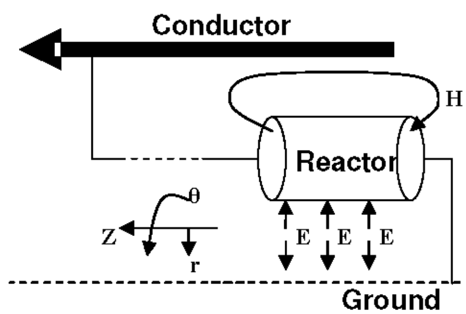

Fig. 3 Shunt reactor showing coordinate system and location of electric and magnetic fields

Note that I_r lags the conductor voltage by nearly 90 degrees. Thus the reactive power in the reactor is much greater numerically than the active power losses. Fig. 4 shows the instantaneous *v(t)* and *i(t)* in the reactor. The product *v(t)i(t)* is the instantaneous power applied to the reactor. If *i(t)* lags v(t) by 90 degrees, *p(t)* = *v(t)i(t)* will have a zero average value. That is, as v(t) and i(t) go through one cycle, energy is first stored and then recovered in the reactor. If there are active power losses in the reactor, *i(t)* will lag *v(t)* by somewhat less than 90 degrees and *p(t)* will have a positive average value as depicted in Fig. 4. Because $\vec{S}$ is $\vec{E}\times\vec{H}$, in cylindrical coordinates (see Fig. 3), using (3) one finds mainly a tangential component of $\vec{S}$ in the physical vicinity of the shunt reactor. The instrumentation challenge is to find the time average value of the θ component (i.e., tangential component) of $\vec{S}(t)$. Note in Figure 3 that the vector labeled *E* is the electric field resulting from the voltage applied to the reactor. This voltage is graded from the energized ungrounded side of the reactor where E is strong, to the grounded terminal of the reactor where $E = 0$.. The high level electric field from the power conductor itself is not shown in Fig. 3. The measurement of $S_\theta(t)$ near the reactor would need to be shielded from the electric field of the phase conductor. An important instrumentation challenge is the distinction between reactor reactive power at very a high level versus the low level real power which represents the reactor losses. Note that $p(t)$ is a 'double frequency' sinusoidal wave.

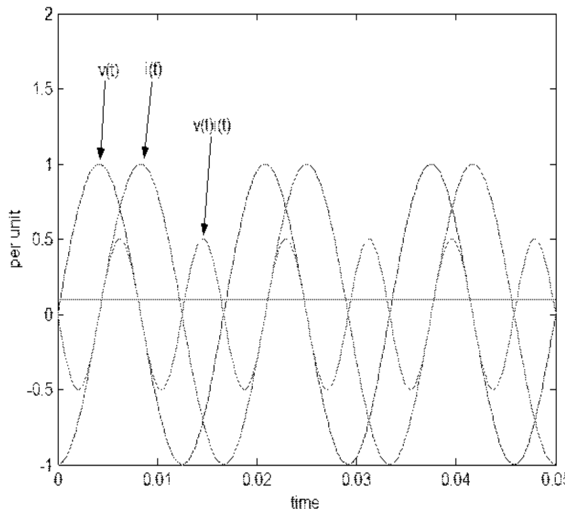

Fig. 4 Instantaneous voltage and current in a reactor. The instantaneous power is $p(t) = v(t)i(t)$.

The foregoing discussion is based mainly on power frequency, sinusoidal steady state instrumentation. It is interesting to speculate on:

- Transient instrumentation
- Nonsinusoidal steady state cases (i.e., harmonics)

In the case of transients, note that the Poynting vector is capable of developing a signal that is proportional to the instantaneous power, $p(t)$. The limitation in this regard is the primary instrumentation used, and the speed with which the complex real-time multiply can be done (as in Eq. (1)). Further, there seems to be no known application for this measurement. In the case of harmonic instrumentation, for example in distribution circuits, the advantage of the use of Poynting technology is, again., limited by the bandwidth of the primary instrumentation. At present, IEEE Standard 519 suggests a 5 kHz instrumentation bandwidth, and many instruments capable of capturing harmonic signals in power distribution systems are designed to this limit. Depending on how fast Eq. (1) could be implemented in real time, the bandwidth of the instrumentation of $p(t)$ in the presence of harmonics could be implemented. Note that since the Poynting vector captures the product of v(t) and $i(t)$, without knowing either $v(t)$ or $i(t)$, there would be no way to recover either harmonic voltage or current without knowledge of the other. For this reason, the use of Poynting technology for capturing distribution system harmonics seems infeasible.

VII. Conclusions

If the prospect of Poynting vector instrumentation is pursued for power system instrumentation, a prerequisite would be a well equipped electromagnetic fields laboratory, especially with the capability of measurement of low electric and magnetic fields. The main issues to be addressed are the shielding of the sensor to reveal specific components of $\vec{S}$. In power engineering environments, electric and magnetic field strengths may well be confounded by stray fields from unexpected and unwanted sources, and this is a further difficulty. Confounding by stray fields will degrade accuracy in using the Poynting vector. In the instrumentation of sites in which low level losses are to be captured, an instrumentation and signal processing challenge is present in that high level active power in $p(t)$ must be distinguished from low level average values of $p(t)$. The instrumentation of the Poynting vector for electric power applications is a high risk venture.

It has been proposed to use the Poynting vector to identify active power losses in shunt reactors and partial discharge in insulators. The main issue is that using present technology, it is difficult to distinguish between high power levels associated with power transfer and reactive power dissipation and the very low active power levels associated with losses.

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IX. Biographies

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