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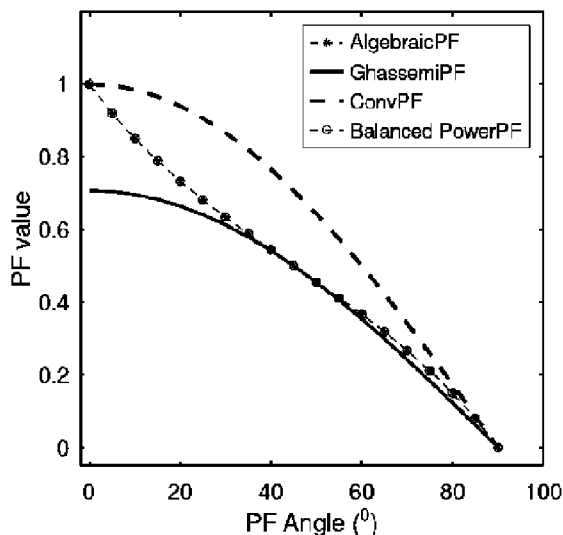


FIG. 5

(57) Abstract: Apparatuses and methods for processing total amount of power injected in alternating current (AC) power systems are disclosed, where the total amount of power consists of both stored reactive, correlative and consumed power. An accurate energy meter is disclosed that computes true power factor as a ratio of cosine of phase shift angle to the sum of both cosine and sine of the phase shift angle between current and voltage waveforms and correlative power factor. The total power adjustment is an algebraic sum of real power and reactive power. Applications of the disclosure are in electrical power industry to determine accurate amount of power generation needed, amount of power stored, amount of power consumed, power system quality and billing and charging rates. Signal correlative modulation in telecommunications, asset management and equipment calibration and insulation.



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Apparatuses and methods for processing power and true power factor (PF) in AC networks

TECHNICAL FIELD

The present disclosure relates generally to systems, processes and applications for determining total electrical power conveyed by power signals, especially alternating current (AC) waveforms. It is useful in power quality and energy analysis through power factor analysis, insulation, calibration and instrumentation management and correlative signal modulation in telecommunications.

BACKGROUND

The invention discloses methods, processes and apparatuses for determining the output power through an energy meter that produces the total power required by an electrical power network. An AC electrical power network consists of voltage and current that flow with sinusoidal amplitude values. The network contains a source generator, wiring, resistive load components and reactive load components. When the current and voltage waveforms are injected into a power network with resistive loads only, then there is no phase shift between them, since the impedance is homogeneous. However, when inductive loads are switched on, they start by lowering the average active power significantly as they store energy in their magnetic fields. The ratio of active power to total power is termed as power factor (PF). The PF corresponds to the value of the reactance in the network.

Normally, capacitors are used as reactors to reduce inductive reactance in order to ensure that maximum power is delivered to the resistive loads. When more inductive loads are randomly injected into the network, power delivered to the resistive load reduces and the power factor is also said to have reduced. When a low power factor is established in the AC power network, power quality is lowered. A poor PF means that heat could damage insulation parts of power equipment, reduction in useful power and an increase in conductor sizes since more current is required to reach the loads in the network.

Power factor correction is performed by adding capacitive reactance to cancel the inductive reactance, and thus improve power factor. However, it is expensive to install the capacitive reactors in the whole network. As a result, power distributors end up in requesting for more reactive power from power producers to provide the sufficient pressure required in order to support the full resistive load [1],[2],[3],[4].

In computing the additional reactive power required, the total power is estimated through energy meters and the active resistive load is deducted appropriately.

However, the method of the prior art overestimates the average active power. The principle applied to derive the active power in the prior art assumes that the impedance between the resistive loads and inductive loads is homogeneous. This way, the average power is computed from algebraically additive power expression instead of a phasor sum.

As a result, an adjustment factor is required to compute the true active power. In order to do so, the total instantaneous power derived using the same biased equation is required to compute the adjustment factor.

Moreover, more accurate principles are applied to show that the average active power is equivalent to the one derived after the adjustment is made.

In summary, a measurement technique for the total amount of instantaneous power injected in an alternating current (AC) power system is presented. It is shown that the power network consisting of reactances and resistances will have covariance elements of voltage and current. A demodulator is used to reduce correlated current and voltage waveforms into singular waveforms and the amount of power is accurately estimated from an analysis of 3-dimensional (3D) complex sinusoids.

Several validation frameworks are disclosed to show that the total instantaneous power, P_T injected in an AC

power network is an algebraic sum function of both the sine and cosine of the power factor (PF) angle, $P_T = f(\cos \theta + \sin \theta)$, where $PF = \cos(\theta)$.

The proposed technique will find use in smart power meters to determine accurate amount of power generation needed, amount of power stored, and amount of power consumed, power system quality and billing rates for different classes of loads. The present disclosure will also find applications in signal analysis, measurements, asset management and insulation systems.

The following table of keywords will be helpful in the succeeding explanations of the present disclosure.

I_{rms}	Value of the root-mean-square of current
V_{rms}	Value of the root-mean-square of voltage
S	Apparent power, $S = \sqrt{P^2 + Q^2}$, [VA]
P	Average active power, $VI \cos(\theta)$ [W]
Q	Phase shift Reactive power stored and returned to source, being at same frequency, [var]
Q_d	Distortion Reactive power stored and returned to source, being at different frequency, [var]
θ^0	Conventional phase shift angle between correlated current and voltage waveforms
PF	Power Factor, $[\cos \theta]$, which is apparent PF with reference to VI , $PF = (P/VI)$
Q_c, P_s	Correlative Reactive power stored and returned to source, [var]
ν_z	Correlative variance factor, $\nu_z = z^2$, $z = \frac{2P_{s,max}}{P} = 2(\tan 45 + 1 - 1/\cos 45) = 2(2 - \sqrt{2})$
PF_c	Correlative power factors, $\sigma_c = \cos\left[\frac{(\theta-45^0)}{\nu_z}\right]$, $\sigma_c^2 = \cos(\theta - 45^0)$
S_t, P_t	Total Apparent power that is able to support P , $P_t = \sigma_c^2 \sqrt{2} VI = \sqrt{2} VI \cos(\theta - 45^0)$, [VA]
PF_T	Total true Power Factor, $PF_T = \frac{\cos(\theta)}{\sigma_c^2 \sqrt{2}} = \frac{\cos(\theta)}{\sqrt{2} \cos(\theta-45^0)} = \frac{\cos(\theta)}{\cos(\theta)+\sin(\theta)} = \frac{1}{1+\tan(\theta)}$
d_{min}^c	Correlative distance detector for θ , $\min_{0 < \theta_t < 90^0} \left(\sqrt{2} \cos^2\left(\frac{\theta_t-45^0}{\nu_z}\right) - \frac{VI}{P_x[\theta]-P_n[\theta]} - V_\theta \right)$
θ_i	True phase shift angle, $\theta_i = \cos^{-1}(PF_T) = \cos^{-1}\left(\frac{\cos(\theta)}{\sqrt{2} \cos(\theta-45)}\right)$
PF_i	True power factor, $\cos(\theta_i)$
P_i	True active power, $VI \cos(\theta_i)$
Q_i	True reactive power, $VI \sin(\theta_i)$
S_i	True apparent power, $S_i = S = \sqrt{P_i^2 + Q_i^2}$

These terms are considered: Power Factor, stored correlative power, correlative variance factor, correlative power factor, Reactive power, Real power, Apparent power, Singular value decomposition (SVD), eigenvalues, demodulation, elliptical flow components and complex sinusoids.

SPECIFIC PROBLEMS AND GAPS

In the conventional method, the total power is estimated as the power that flows in the network without considering correlation ellipses of real and reactive components due to interactive impedance between resistances and reactances. As a result, the average active power value in the prior art is not resolved in the direction of the load. Therefore, the true average power delivered to consumers in the network is not accurately derived in the prior art.

Two principles may be used in power networks to determine active power.

In the first principle, the total current injected into the network is held constant and used to derive the average active power, whereas quadrature reactive and resistive powers are left to vary through a phase shift angle.

If it is assumed that both reactive and resistive loads are algebraically additive, then this method requires an adjustment for the true phase shift angle in order to determine the true power factor that incorporates the changes in the direction of power through the load. In real sense, the power from the two fields should be added phasorially.

65 In the second principle, individual currents for resistive load and reactive loads vary and they are used to derive the power factor. In this second process, the quadrature resistive and reactive powers are balanced and set as equal. The state-of-the-art applies the first principle, but no compensation is done for the average power. As a result, smart meters in the state-of-the-art do not provide correct measurements of power, since they are based on the biased expression for power that overestimates the PF, thus leading to erroneous charging for power delivered and low quality power is delivered.

70 It is understood that based on the incidence of reactances in the power network, correlation occurs. The reactive power is stored and returned to the source. However, the prior art does not incorporate the amount of power stored at different levels of correlation. As a result, correlative reactive power is not considered in the state-of-the-art so as to adjust for the true phase shift angle.

75 For example, when the phase shift angle is $\theta = 45^0$, the power flow has a circular signature, which means both active and reactive power are independent and maximum correlative reactive power will be stored. At other angles, the power signature will be elliptical as will be described later on. The area of the power flow ellipse is given as $A = \pi P \times Q$, which means more reactive power is stored at $\theta = 45^0$. As a result, the average power should be half the apparent power, but the reactive power Q_i should be more at $\theta = 45^0$, where $P = Q$. This is not the case in the prior art.

80 Further still, the prior art shows that in cases of very low PF values, in order to compensate for reactive power in a network that initially delivers current, I to active load, then the new current, I_{new} drawn from the power source approaches infinity i.e. $I_{new} = \frac{I}{\cos(\theta)}$ since $\cos(\theta) \approx 0, \theta \approx 90^0$.

85 Estimation of reactive power involves shifting of the waveform by 90^0 and then integrating over a period. An alternative way of computing the phase shift angle is needed to validate the methods in the prior art.

It was shown in [1], [2] that expressing the apparent power, S in the form $S = P + jQ$, where $P = VI \cos \theta$, refers to the active power and $Q = VI \sin \theta$, refers to reactive power, does not conform to principles of electrical engineering. The prior art holds true only in the case of full correlation between current and voltage, i.e. when $Q = 0$. I refers to the root-mean-square (RMS) value of current waveform and V refers to the RMS value of voltage waveform. θ is the phase-angle between V and I . The equation for S in the prior art satisfies Schwarz inequality, but violates Plancherel's relation [1], [2], which equates the average value of power to the frequency spectrum of power.

MOTIVATION FOR NEW SOLUTIONS

95 Two approaches are presented in the present disclosure: Firstly, the first principle of constant current and varying quadrature powers is applied to derive the average active power. Additionally, an adjustment factor is derived from correlation analysis in order to rectify the bias in the prior art. Secondly, the principle of balanced power with varying quadrature currents is used to derive an equivalent power factor.

100 Instantaneous power can be computed to derive more realistic values of apparent power. The instantaneous values of the product of the voltage waveform and the current waveform have been used to compute power, but underlying theoretical approaches are required to obtain true results.

For example, the voltage waveform was modified in [1],[2] to conform to Plancherel's relation, but the Schwarz inequality was rendered a constant equality. Furthermore, the results in [1] show that the power factor is limited to a maximum of $PF = \frac{1}{\sqrt{2}}$, even in a purely resistive power network and this is effectively similar to the conventional scheme since apparent power in [1],[2] is given as $P_t = \sqrt{2}VI$. The results in [1],[2] were obtained by considering only the voltage signal as a complex sinusoid, while the current signal is treated as a real function. The results for

total power in [1] imply that no correlation was considered.

In the process of deriving the adjustment factor, it is noted when voltage and current waveforms are multiplied, a frequency shift occurs and the output power expression will consist of covariance elements. This scenario is consistent with mixed signals at the output of a modulator. That is, the effective value of power at the input of the modulator is not equal to the power estimated at the output waveforms.

The solution to the problem is to insert a demodulator to shift the frequency back to its original position and the waveforms appear with their singular frequency components. This decomposition is consistent with SVD for principal components.

Two modulated waveforms will exhibit a covariance power matrix of the form $C = [Q_v \lambda_c Q_v]$, whose effective value may be determined through the determinant (*det*) of the matrix C and eigenvalues, $[\lambda_c]$. Here, Q_v refers to the eigenvector matrix. However, the absolute value of matrix C is not always equal to the effective value i.e. $\det[Q_v \lambda_c Q_v] \neq \det | C |$. On the other hand, after the combined signal has been demodulated, it can be shown that the powers of individual waveforms correspond to principal components, where $\det[Q_v \lambda_c Q_v] = \det[\lambda_c] = | \lambda_c |$, which implies that the effective power at the output of the demodulator is equal to the power at the input of the network [5], [6], [7].

The results obtained from the demodulator show that the total power in the network can be implemented through a summer circuit in the energy meter that adds two power factor components and multiplies RMS values of current, I_m peak and RMS value of the voltage peak, V_m . The power factor angle is computed from the phase shift between current and voltage waveforms. The demodulator gives a total power output factor as the sum of the cosine of the PF angle and the sine of the PF angle. It means that additional generator supply must incorporate the extra power due to correlation. The total power factor is given as the ratio of $\cos(\theta)$ to the sum $\cos(\theta) + \sin(\theta)$.

Interestingly, the new approach satisfies both Plancherel's relation that presents only real values for the frequency components and the Schwarz inequality, which shows that the average power is less than or equal to the product of the RMS values of voltage and current.

Moreover, it is shown in the present invention that there is a correlative power factor, which is useful in measuring power of AC signals in a laboratory set-up, without shifting the waveform and integrating over a period. The correlative power factor is given as $PF_c = \sigma_c = \cos\left[\frac{(\theta-45^\circ)}{v_z=z^2}\right]$, where $z = 2(2 - \sqrt{2})$. The measured signal power is given as the product of the square of the correlative power factor and the peak-to-peak amplitude of the effective power signal waveform.

When a current and voltage values in a network are calibrated using input power, an alternative way of measuring the phase shift angle is provided by comparing the received power to the correlative reactive power to compute the angle. The process for computing total power in AC systems is applicable in single-phase and multiple-phase power systems.

The following logic has been applied in the present disclosure:

- a) Using homogeneous power equation in the prior art, incorporate the stored power in computing average active power through an adjustment factor,
- b) Apply total instantaneous power computed from the homogeneous equation to calculate adjustment factor for stored power,
- c) Apply the adjustment factor to adjust the average active power to the true average power value that incorporates stored power.
- d) Use the first principle with inhomogeneous equation to validate the results of the true average active power.

e) Use the second principle to validate the results of the true average active power.

In summary, the teachings of the following arts are studied, where the present invention gives a modified value for active power and reactive power for equal supply of apparent power:

- 150 1. Industrial prior art one: $P_t = VI$, $PF = \cos(\theta)$
 2. Industrial prior art two: $P_t = \sqrt{2}VI$, $PF = \frac{\cos(\theta)}{\sqrt{2}}$
 3. Decorrelated adjustment factors: $P_t = \sigma_c^2 \sqrt{2}VI$, $PF = \frac{\cos(\theta)}{\sigma_c^2 \sqrt{2}} = \cos(\theta_i)$

SUMMARY OF INVENTION

According to one broad aspect of the present invention, an energy meter is proposed that is able to measure the
 155 total energy and total instantaneous power delivered by an AC power network of the homogeneous equation.

According to one broad aspect of the present embodiment, the energy meter consists of a demodulator and algebraic adder circuit devices.

According to one broad aspect of the present invention, the energy meter consists of a demodulator and an algebraic adder processes.

160 According to one broad aspect of the present invention, the energy meter is configured to measure total power in an AC power network.

According to one broad aspect of the present invention, the energy meter is configured to measure phase shift angle between current and voltage waveforms.

According to one broad aspect of the present invention, a meter is configured to measure correlative reactive power,
 165 P_s .

According to one broad aspect of the present invention, a process is provided for experimentally measuring total power, P_t .

According to one broad aspect of the present invention, a process is provided for experimentally measuring reactive power, Q .

170 According to one broad aspect of the present invention, a process is provided for computing correlative variance for instantaneous power.

According to one broad aspect of the present invention, a process is provided for computing phase shift angle by comparing correlative reactive power equation and the received effective total instantaneous power.

According to one broad aspect of the present invention, the energy meter is configured to measure total power
 175 factor as a ratio of cosine of the phase shift angle and the sum of the cosine and sine of the phase shift angle between current and voltage waveforms.

According to one broad aspect of the present invention, true power factor is derived based on varying quadrature currents, while keeping quadrature resistive and inductive power equal in an inhomogeneous impedance network.

According to one broad aspect of the present invention, a process is provided for implementing correlative modulation by mapping bits on different phase shift angles to convey information to a receiver, which then detects the
 180 phase shift angle in order to decode the transmitted bits.

In some embodiments, the applications can be any of energy services in the power industry or signal processing in telecommunication or computer systems.

BRIEF DESCRIPTION OF THE DRAWINGS

185 The invention will be explained in more detail in the following text using one exemplary embodiment and with reference to the drawings, in which

FIG. 1 shows a block diagram illustrating a 3-dimensional AC power flow,

FIG. 2 shows a block diagram illustrating apparatus for the total power energy meter system,
 FIG. 3 shows circuit transforms for AC power source,
 FIG. 4 is an illustration of the results obtained from the total energy meter,
 FIG. 5 is an illustration of comparison of power factor values with the present invention,
 FIG. 6 is an illustration of comparison of total power value of the present invention and that of the prior art,
 FIG. 7 is an illustration of decorrelated AC power signal waveforms,
 FIG. 8 illustrates graphical method for estimating AC signal power,
 FIG. 9 illustrates different methods for estimating AC power,
 FIG. 10 illustrates bit error rates against signal-to-noise ratio for correlative modulation,
 FIG. 11 illustrates a power triangle for decorrelated power system,
 FIG. 12 illustrates correlation effects on shift angle between power and voltage or current waveforms.
 FIG. 13 illustrates variation of adjusted phase shift.

200 DETAILED DESCRIPTION OF EMBODIMENTS

It is an aim of the present invention to overcome the weaknesses of the prior art that neglects variation in residual return power due to correlation within the AC power network, to overcome the weaknesses of the prior art that overestimates the true power factor. The prior art assumes that the network impedance is homogeneous across both the reactances and resistances.

205 It is a further aim of the present invention to overcome the weaknesses of the prior art in computing the total power factor that incorporates correlation between current and voltage signals through singular value decomposition, so as to conform to principles of electrical engineering.

PRINCIPLE OF CONSTANT CURRENT AND VARYING QUADRATURE POWERS

In the first case, the approach of constant current is applied just as is the case in the prior art. However, adjustment factors are subsequently derived in the present disclosure. The adjustment factors are useful in computing the true average power in the network.

Consider an inductor with reactance X_L in series with a resistor, R . The inductor will act to store energy in a given phase period and return it in another phase. This means that the current through the network will consist of the the source power and the storage power on average. If the source voltage is V_s , voltage across the inductor,
 215 V_L , the current drawn by the network is given as,

$$I_R = \left(\frac{V_s - V_L + V_c}{R} \right), \text{ where } V_c \text{ is the effective voltage supplied to } R \text{ from storage.}$$

The power factor is defined as follows, where $I = I_R$, for the series network:

$$PF = \frac{I_R^2 R}{V_s I} = \left(\frac{V_s - \gamma V_L}{V_s} \right)$$

where the quadrature power ratio, $\gamma = \left(\frac{V_L - V_c}{V_L} \right)$, then

220 $PF = 1 - \gamma \frac{V_L}{V_s} = 1 - \gamma \sin(\theta)$

It was a problem of the present disclosure to derive the adjustment factor γ , in order to deduct the effect of stored power from the average active power. In a later description, it is shown that, $\gamma = \frac{1}{\cos(\theta) + \sin(\theta)}$.

HOMOGENEOUS IMPEDANCE APPROACH FOR POWER

The following discussions show the steps taken in computing γ through the approach of instantaneous power of
 225 the homogeneous expression of power.

A complex sinusoid is considered to describe the power flow in the AC network, where $e^{j\Phi} = \cos \Phi + j \sin \Phi$. The flow can be represented as an elliptical motion in the 3D diagram of FIG. 1. Since the quadrature and in-phase components of the complex sinusoids are symmetrical, we use the projection of the components on x -, y - and

z -axis as shown and then apply simple sinusoids in the analysis.

230 Given that the current and voltage in the power network flow with a projected waveform such as $V(t) = V_m \sin(\omega t)$, for the voltage and $I(t) = I_m \sin(\omega t - \theta)$, for the current with a phase shift of θ , frequency ω and peak amplitudes, V_m and I_m , respectively, we write the instantaneous energy, $E(t)$ as,

$$\begin{aligned} E &= V(t)I(t) \times t \\ &= V_m \times t [\sin(\omega t)I_m \sin(\omega t - \theta)] \end{aligned} \quad (1)$$

By the use of the trigonometric identity, $\sin(A - B) = \sin(A)\cos(B) - \cos(A)\sin(B)$, (1) is re-written as,

$$\begin{aligned} E &= V_m \times t [\sin(\omega t)I_m \sin(\omega t - \theta)] \\ &= V_m I_m [\cos(\theta) \sin^2(\omega t) - \sin(\theta) \sin(\omega t) \cos(\omega t)] \end{aligned} \quad (2)$$

Conventionally from (2), the average power is written as

$$\begin{aligned} P_{AV} &= V_m I_m [\cos(\theta) \frac{1}{T} \int_0^T \sin^2(\omega t) dt - \sin(\theta) \frac{1}{T} \int_0^T \sin(\omega t) \cos(\omega t) dt] \\ &= \frac{V_m I_m}{2} \cos(\theta) \\ &= VI \cos(\theta) \end{aligned} \quad (3)$$

where the average value of the second term reduces to zero.

The following is an explanation why the expression in (1) is a biased estimate of power in the reactive network. From the prior art in equation (1), the power can be re-written as follows:

$$\begin{aligned} S &= V_m I_m [\sin(\omega t) \sin(\omega t - \theta)] \\ 230 \quad S &= (V_X I_m + V_R I_m) [\sin(\omega t) \sin(\omega t - \theta)] \end{aligned}$$

where, $V_m = (V_X + V_R)$,

V_X, V_R is the voltage across the inductor and resistor, respectively.

The expression computes the apparent power as an algebraic sum of the real power, $P = V_R I_m$ and reactive power, $Q = V_X I_m$, i.e. $S = P + Q$ instead of the phasor form, where $S = \sqrt{P^2 + Q^2}$.

245 Therefore, if equation (1) is to be properly applied, then it is more accurate to estimate the power factor as the ratio of equation (3) to $S = P + Q$ rather than $S = \sqrt{P^2 + Q^2}$ as is the case in the prior art. This fact will be proved in a later section, where total instantaneous power is derived.

As a result, since $(P + Q) > (\sqrt{P^2 + Q^2})$, a fractional adjustment factor is required to calculate the true power expression. Moreover, the result implies that the average power derived here is higher than the true average active power. It requires an adjustment factor to reduce it to the true value.

It would be necessary to adjust the formula to incorporate the variation of the correlation between the power components by writing the energy as follows,

$$\begin{aligned} E &= V(t)I(t) \times t \\ &= V_m \times t [\sin(\omega t)I_m \sin(\omega t - \theta - \theta_c)] \end{aligned}$$

255 where θ_c accounts for the effects of correlation due to the varying elliptical phasorial direction of current and voltage, while θ is the observed value for the lag or lead.

INHOMOGENEOUS IMPEDANCE APPROACH FOR POWER

Alternatively, the power across the resistor, which is the active load can be written directly from a resolved voltage value (which takes care of changes in both voltage and current), i.e. $\tan(\theta) = \frac{X_L}{R}$, $I = \frac{V_R}{R} = \frac{V_X}{X_L}$, $V_R = V_m - V_X$

$$260 \quad V_R = V_m - V_R \tan(\theta), \quad V_R = \frac{V_m}{1+\tan\theta}$$

$$P_R = V_R \sin(\omega t) I_m \sin(\omega t) = \left(\frac{V_m}{1+\tan\theta}\right) \sin(\omega t) I_m \sin(\omega t)$$

The average active power then becomes,

$$P = \frac{1}{T} \int_0^T P_R dt = \frac{1}{2} \left(\frac{V_m I_m}{1+\tan(\theta)}\right) = \frac{VI}{1+\tan(\theta)}$$

The power factor becomes,

$$265 \quad PF = \frac{P}{VI} = \frac{1}{1+\tan(\theta)}$$

In order to derive parameters of measurement as observed from sensors of power waveforms, an estimation of the shift angle, θ and direction angle θ_c , is required. The following, objective methods are disclosed in the teachings of the present invention through decorrelation to compute these adjustment factors and the parameters of power measurements.

270 INSTANTANEOUS POWER AT THE MODULATOR OUTPUT

We note that from (1), using $\cos(A - B) = (\cos A \cos B + \sin A \sin B)$, an alternative form of the energy flow can be given as,

$$E(t) = \frac{V_m I_m \times t}{2} [\cos(\theta) - \cos(2\omega t - \theta)]$$

$$= \frac{V_m I_m \times t}{2} [\cos(\theta) - \cos(2\omega t) \cos(\theta) - \sin(2\omega t) \sin(\theta)] \quad (4)$$

The result in (4) consists of two waveforms and a constant power, namely a constant term proportional to the phase angle, θ , a second term of P and the third term of Q , which depict correlated components of power. It shows that part of average power P is transferred to reactive component, Q as additional stored power.

Performing the average power computation at this point, as is the case in the prior art, means that the component of P that is stored as reactive power has not been accounted for, since $\cos(2\omega t)$ is equated to zero value.

The correlated form of the waveforms is analogous to signals present at the output of a modulator. The modulator is characterized by a mixed signal output.

280 Taking the RMS values of the carrier waveforms, we can write

$$E(t) = \frac{V_m I_m \times t}{2} \left[\cos(\theta) + \frac{1}{\sqrt{2}} \cos(\theta) + \frac{1}{\sqrt{2}} \sin(\theta) \right] \quad (5)$$

However, note that taking the RMS values at the output of the modulator will give a wrong power value because of the frequency shift. This is because the sinusoidal waveforms at the output are covariance waveforms for power and are not independent voltage and current waveforms.

285 Actually, (4) can be re-written as $t \cdot [P + P \cos(2\omega t) + Q \sin(2\omega t)]$, when the current is resolved onto the voltage, where the voltage is the reference. They possess covariance parameters between the two waveforms. In order to evaluate power from independent signals, the energy equation is transformed into independent values that are similar to SVD performed by a demodulator.

DEMULATOR OUTPUT

290 We now apply the identities, $\sin(2A) = 2 \sin(A) \cos(A)$ and $\cos(2A) = 2 \cos^2(A) - 1$, to perform SVD on the carrier waves in order to obtain the singular waveforms such that,

$$E(t) = \frac{V_m I_m \times t}{2} [\cos(\theta) - \cos(2\omega t) \cos(\theta) - \sin(2\omega t) \sin(\theta)]$$

$$= \frac{V_m I_m \times t}{2} [\cos(\theta) - 2 \cos(\omega t) \cos(\omega t) \cos(\theta) + \cos(\theta) - 2 \sin(\omega t) \cos(\omega t) \sin(\theta)]$$

$$E(t) = \frac{V_m I_m \times t}{2} [[2 - 2 \cos(\omega t) \cos(\omega t)] \cos(\theta) - 2 \sin(\omega t) \cos(\omega t) \sin(\theta)] \quad (6)$$

It is now observed that the elements of the demodulator consist of singular decorrelated values in (6) that move at the same frequency, ω . Since the magnitudes of the powers of these waveforms are equal to the power at the input generator in (1), the RMS values are estimated algebraically such that from (6), we write,

$$E(t) = \frac{V_m I_m \times t}{2} \left[\left[2 - 2 \times \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} \right] \cos(\theta) + 2 \times \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} \sin(\theta) \right] \quad (7)$$

The total output power is given as $P_T = E/t$, which measures the total injected power into the system within one second, thus total power, P_T is written as,

$$\begin{aligned} P_T &= \frac{V_m I_m}{2} \left[[2 - 1] \cos(\theta) + \sin(\theta) \right] \\ &= \frac{V_m I_m}{\sqrt{2} \sqrt{2}} [\cos(\theta) + \sin(\theta)] \\ &= VI [\cos(\theta) + \sin(\theta)] = (P + Q) \end{aligned} \quad (8)$$

This result implies that in order to support an active load of $P = VI \cos(\theta)$ [W], then the total apparent power required to be delivered at source will be equal to $S = (P + Q)$.

That is, $S = VI$ will support an active load $P_i = VI \cos(\theta_i)$ which is less than P .

This is because correlation will reduce the actual phase shift angle from θ_i to θ . The total power is useful in adjusting the true power factor as $PF = \cos(\theta_i)$.

From (8), an adjustment factor of $\frac{S}{P_T} = \left(\frac{1}{\cos\theta + \sin\theta} \right)$ is needed to adjust the power factor so as to incorporate the effects of correlation, where the stored power acts as a source of to the load.

INTERPRETATION OF RESULTS OF THE PRESENT DISCLOSURE

Several interpretations can be produced from the power equation in (8). In order to retain conventional definition of apparent power, then we consider FIG. 1, and write, $P_T = S + S_s = \sqrt{P^2 + Q^2} + S_s$, where S denotes the apparent power, $P = VI \cos(\theta)$ is the active power dissipated and $Q = VI \sin(\theta)$ is the reactive power, when S_S is best defined as the excess power projected on the z -axis due to the assumption of a constant maximum current I , at the location that contains the circle of FIG. 1 and FIG. 11 as additional stored correlative power that is required to support full load P , thus

$$\begin{aligned} S_s &= VI [\cos(\theta) + \sin(\theta)] - VI \\ &= VI [\cos(\theta) + \sin(\theta) - 1] \end{aligned} \quad (9)$$

It is noted here that the power factor is well defined as $PF = \cos(\phi)$, where, ϕ denotes the observed angle by which the current and voltage leads or lags each other in their phases.

However, we introduce a new adjustment for total power factor, (PF_T) being the fraction of real average power and total power,

$$PF_T = \frac{VI \cos \theta}{VI(\cos \theta + \sin \theta)} = \frac{\cos \theta}{(\cos \theta + \sin \theta)} \quad (10)$$

Further discussions on the newly proposed values of total power and PF_T are presented later on in this disclosure. What follows is a discussion on the non-violation of the principles of electrical engineering by the new value of power as provided in this disclosure.

SCHWARZ INEQUALITY AND PLANCHEREL'S RELATION

Here, Schwarz's inequality and Plancherel's relations are used to show that the result obtained for total power

satisfies both of these theoretical principles.

Schwarz's inequality for any two signals $y(t)$ and $x(t)$, is expressed as follows [1],

$$\left| \int_a^b x(t)y(t)dt \right|^2 \leq \int_a^b |x(t)|^2 dt \cdot \int_a^b |y(t)|^2 dt \quad (11)$$

325 The LHS of (11) is equivalent to the square of the average value of power in a period on $T = 1[s]$, which is shown in (3). Therefore, the LHS of (11) is given as $[VI \cos(\theta)]^2$.

The RHS of (11) is equivalent to the product of individual square of RMS values. From the SVD approach used in this disclosure, from (8), the RMS value of the voltage may be written as $V\sqrt{\cos(\theta) + \sin(\theta)}$, while that of the current is given as $I\sqrt{\cos(\theta) + \sin(\theta)}$. As a result, the Schwarz inequality equivalent to one in (11) is given as,

$$\begin{aligned} VI \cos(\theta) &\leq V\sqrt{\cos(\theta) + \sin(\theta)} \cdot I\sqrt{\cos(\theta) + \sin(\theta)} \\ VI \cos(\theta) &\leq VI[\cos(\theta) + \sin(\theta)] \end{aligned} \quad (12)$$

330 It is evident from (12) that equality exists only when $\theta = 0^0$, otherwise the RHS is always greater than the LHS. For the Plancherel's relation, if a signal $x_p(t)$ is a square integrable function over one period, then the power in the signal can be found in either a time or frequency description based on Parseval's theorem. For two arbitrary periodic signals, $x_p(t)$ and $y(t)$, the relation is written as [1],

$$\frac{1}{T} \int_0^T x_p(t)y_p^*(t)dt = \sum_{-\infty}^{\infty} X(f)Y^*(f) \quad (13)$$

where $(*)$ denotes the phasor conjugate.

335 Evidently, the LHS of (13) denotes the average power, while the RHS of (13) is given as,

$$\sum_{f=-\infty}^{\infty} V(f)I^*(f) = \sum_{-f_1}^{f_1} V(f)I^*(f) \quad (14)$$

It has been shown in [1] that the frequency spectrum of (14) results in real values of the components power, which is similar to (8), where $V(t)$ and $I(t)$ are given according to (1). We note that in the prior art, the apparent power is normally given as a complex value, i.e. $S = P + jQ$, which does not satisfy (13). It is observed that the proposed function for total power as expressed in this disclosure satisfy both the Schwarz inequality and Plancherel's relation.

340 The results of total power and total power factor are used to implement an energy meter. FIG. 2 is an illustration of the apparatus for the total energy meter.

The supply power from the generator is passed through a bus (1) into an AC power network (2). A connector (3) is used to connect an energy meter (4). The meter consists of a power factor demodulator (5), and an algebraic adder (8). Device (5) computes the phase shift angle between current and voltage. The phase shift angle is then

345 used to compute two values of cosine and sine of angle theta. These values are passed on to the algebraic adder (8) through outputs (6) and (7). The output (9) of the algebraic adder is used to calibrate the total power from the product of the RMS value of voltage amplitude and current amplitude. The meter is configured to show newly defined values for correlative power factor, correlative reactive power and display resultant power waveforms.

The following discussion is on the theoretical circuit analysis, which is exploited in order to provide further validation

350 of the results.

VALIDATION VIA CIRCUIT TRANSFORMATION

Consider a system where a resistive load and a reactive load exist in an electrical network supplied by an alternating current. Based on FIG. 3, the reactive load may be reduced to a voltage source since in the first half of the sinusoid; power is returned to the source and delivered to the reactance in the subsequent duration of the wavelength. Let's
 355 express the current through the resistive load in a network that consists of two voltage sources; in the analysis, we treat each voltage as short circuit, while the other source supplies the network:

Case (a): During power delivery to the reactance: (negative voltage source from reactance), we short-circuit the generator source: $V = 0, I_1 = (-V_x)/R$, then short-circuit the reactance voltage source : $I_2 = V_R/R$.

Case (b): During power return: (positive voltage source from reactance), we place a short-circuit to the generator
 360 source: $V = 0, I_3 = V_x/R$, then we short-circuit the reactance voltage source : $I_4 = V_R/R$.

Taking the average instantaneous powers for case (a) and (b), we have

$$\begin{aligned} P_T &= \frac{1}{2} \left[\frac{-V_x \times (-V)}{R} + \frac{V_R \times V}{R} + \frac{V_x \times V}{R} + \frac{V_R \times V}{R} \right] \\ &= \frac{V}{2R} [2V_x + 2V_R] = \frac{V}{R} [V_x + V_R] \\ &= VI[\cos(\theta) + \sin(\theta)] \end{aligned} \quad (15)$$

The result here in (15) underpins the validity of the algebraic sum and in fact, other graphical methods can also be used to show that the total power in the network consists of the return power stored and the power delivered in the form as presented in this disclosure. This analysis includes the supply from storage and it is equal to instantaneous
 365 power derived in (8).

The stored power supplies the load as well. Therefore, the observed angle θ , consists of current derived from the stored energy. In order to calculate the true average power, the amount of current from storage should be deducted from the average power derived from θ .

VALIDATION AT THE MODULATOR OUTPUT

370 The covariance elements of power at the output of the modulator are considered, where (4) is re-written as,

$$P_T = [P + P \cos(2\omega t) + Q \sin(2\omega t)] \quad (16)$$

where P_T contains the covariance elements of real and reactive power, thus correlated components.

From FIG. 1, it can be seen that a complex sinusoid can be resolved into x -axis and y -axis of waveform components that move in the direction of z -axis. Therefore, equation (16) implies that P is in the z -direction, while S' is the resultant RMS value of power as shown in FIG. 1. In order to obtain the Q -element of power in the z -direction,
 375 then $S' = P' + jQ'$, must be resolved back to the y -component of power, as $S' \sin(\theta)$.

Equation (16) is now written as follows,

$$\begin{aligned} P_T &= P + S' \sin(\theta) \\ &= P + |(P' + jQ')| \sin(\theta) \\ &= P + |(P' + jQ')| \cdot \frac{|Q'|}{|(P' + jQ')|} = P + Q \end{aligned} \quad (17)$$

The result in (17) is the same as that in (8) and (15). It is evident that Q is resolved as a power element that is already in the z -direction and the previous result of $P_T = P + jQ$ does not hold true when the complex sinusoid is considered for both current and voltage waveforms.

380 Furthermore, we apply $\sin 2A = 2 \sin A \cos A$, to demodulate the power signal, such that $P_T = P + P \cos 2\omega t +$

$Q \sin 2\omega t$ is modified such that $P_T = P + P(2 \cos \omega t \cos \omega t - 1) + 2Q \sin \omega t \cos \omega t$. This simplifies as $P_T = 2P \cos \omega t \cos \omega t + 2Q \sin \omega t \cos \omega t$. By taking the RMS values of the same frequent signals, we have $P_T = 2[P \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} + Q \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}}]$, which simplifies as, $P_T = P + Q$.

CORRELATION SYNTHESIS

385 Consider V and I to be two random variables, with mean V_μ and I_μ , and standard deviation, $\sigma_0 V$ and $\sigma_c I$, respectively. Then, [6], [7],

Covariance, $\text{Cov}_{VI} = \sigma_0 V I = E[(V - V_\mu)(I - I_\mu)]$

Correlation, $\text{Corr}_{VI} = \rho = \frac{\text{Cov}_{VI}}{\sigma_0 V \sigma_0 I}$

In the case of inductive reactance, X_L , let the current lag the voltage ($V_\mu = 0$), so we have

$$\begin{aligned} \rho_p &= \frac{E[(V - V_\mu)(I - I_\mu)]}{\sigma_0 V \sigma_c I} = \frac{E[(V - 0)(I - I_\mu)]}{\sigma_0 V \sigma_0 I} \\ &= \frac{E[(VI - VI_\mu)]}{\sigma_0 V \sigma_0 I} = \frac{P - Q}{P} \\ Q &= P(1 - \rho_p) \end{aligned} \quad (18)$$

390 The total power delivered in the presence of $Q(> 0)$ -component is given as,

$$P_T = P + Q = P + P(1 - \rho_p) \quad (19)$$

From FIG. 1, an ellipse is the z -component of the 3D waveform. It follows from (18) that, $\rho_p = 1 - \tan(\theta)$. When $\rho_p = 0$, then there is no correlation and the z -component of power is circular as shown in FIG. 1. This means that $P = Q$, and $R = X_L, \theta = 45^\circ$ (resistance equals reactance). In this condition, maximum power is delivered independently such that,

$$\begin{aligned} P_{T_{max}} &= P_T(\rho_p = 0) = P + Q = P + P(1 - \rho_p) = 2P \\ &= 2VI \cos(\theta) = VI[\cos(\theta) + \sin(\theta)] = \sqrt{2}VI \end{aligned} \quad (20)$$

395 Maximum correlation occurs when $\rho = 1$, which implies that only one of the power components exists. In this case, $P_T = P + P(1 - \rho_p) = P$. The ellipse projected on the z -axis will form a straight line. Other correlation values, ($0 \leq \rho_p \leq 1$), will result in power values that fall between P and $2P$.

A function is derived that relates instantaneous power P and $2P$ under correlation conditions. The same function is then applied to relate the average active power observed and the true active power dissipated under correlation conditions over all values of θ .

ANALYTICS FOR POWER PRODUCTION AND DISTRIBUTION

An example of an initially resistive load with current I and voltage, V is considered. Let a reactive element be switched on in the network. Then, an additional reactive power must be requested from the generator to overcome the reactive power in the network in order to fully support the resistive load. Let, the new total power required from the generator to supply the resistive load and overcome the reactive power be P_{GEN} .

The illustrations in FIG. 4 are best understood when it is assumed that all the compensation efforts have been undertaken by adding the capacitive reactors in the network. The legend $genV A_{Phasor}$ refers to the total amount of generation that will be required to maintain the same voltage in the network when the current increases, which is given as

$$P_{GEN}^P = \frac{VI}{\cos(\theta)} \quad (21)$$

410 The result of (21) means that there is a very high current demand from the power generator. However, (21) also shows that if the reactive elements in the network increase to lower the power factor, then the current tends to infinity. In the real sense, if the initial resistive load was supported by power that is equal to $P = VI$, and the reactive load increases to power equivalent to P , then the generator should supply an additional power of P . This means that the total power from the generator that will fully support the initial resistive load, plus the reactive load
415 is given as $P_{new} = 2VI$.

$genVA_{proposedAL}$ refers to the total amount of generation required, as calculated from the algebraic meter, which is given as

$$P_{GEN}^A = VI[1 + \sin(\theta)] \quad (22)$$

In this case, the amount of power generation required follows the requirements of the resistive load. When the reactance drops power equal to (VI) , no power exists across the resistive load, where the phase shift is 90° , then the
420 power required at the generator will only double to support the total wattage (VI) , i.e. $P_{GEN}^A = 2VI$, as depicted in FIG. 4.

VA_{phasor} refers to the power initially delivered to the network through the conventional energy meter, $S = P + jQ$. It is a constant with a value equal to (VI) , throughout the range of the PF angles.

$VA_{proposedAL}$ refers to the power initially delivered to the network through the proposed energy meter. It varies as
425 an arc over the range of PF angles. The power delivered shows a curve that starts at (VI) but rises to a peak of $(\sqrt{2}VI)$ when reactance, X equals the resistive load, R and falls back to (VI) at maximum reactance when the phase shift is 90° .

Resistive Load refers to the variation of the dissipative load as it varies with the phase shift in the network. The maximum load is supported when the phase shift between current and voltage waveforms is zero.

430 *Reactive Load* refers to the variation of the reactive load as it varies with the phase shift in the network. The maximum reactance occurs when the phase shift between current and voltage waveforms is 90° . *Extra demand* (watts) refers to variation of the resistive load required to be supported when there is reactance in the network. It is determined as,

$$P_R = VI[1 - \cos(\theta)] \quad (23)$$

FIG. 5 shows comparisons for the proposed algebraic PF and that proposed by Ghassemi [1] and the one used in
435 the present industry, ConvPF, which always overestimates PF. It is observed that Ghassemi model has a maximum PF value of ≈ 0.7071 , even when the network is purely resistive. However, the proposed algebraic PF one has a maximum of unity at 0° of PF angle and a minimum of zero. In addition, there exists a point of inflexion that portrays the behaviour of PF when there is a change in a more resistive network into a more inductive network. It is noted that both the balanced power principle and balanced current principles lead to the same amount of PF as
440 depicted in FIG. 5.

INDUSTRIAL IMPLICATIONS

Table 1 compares the results of the new generation requirement to reduce the power factor to zero in the network using the conventional phasor method and the proposed algebraic adder method.

445 The table shows that the phasor method, which is the industrial standard underestimates the total power required, when the power factor is high, while it overshoots the requirement when the power factor is low. The underestimation leads to delivery of low quality electrical power at lower prices to consumers with inductive loads. Normally, operation at very low PF is avoided through the implementation of reactors that increase the PF by reducing the

TABLE I
NEW POWER GENERATION REQUIREMENTS

PF Angle, ($^{\circ}$)	Phasor Meter	Algebraic Meter
$\theta = 0$	VI	VI
$\theta = 30$	$1.155VI$	$1.5VI$
$\theta = 45$	$1.414VI$	$1.707VI$
$\theta = 60$	$2VI$	$1.866VI$
$\theta = 80$	$5.759VI$	$1.99VI$
$\theta = 90$	∞	$2VI$

total reactance in the network.

450 With the proposed meter, power producers will be required to provide more power to power distributors than that of the current practice.

Furthermore, consumers with inductive loads will be correctly monitored and exact billing costs will be charged. The demand charge will be accurately estimated for consumers at the correct power quality.

Adequate reactors will be implemented in the network since the prior art underestimates the total number of capacitors required in the network.

455 Accurate energy loggers and energy analyzers will be produced for power system analysis.

More accurate insulation and shielding devices will be designed using the meter of the present invention.

FIG. 6 illustrates how the total power in the electrical power network is influenced by the power factor angle, θ . As the reactance increases, θ increases and the total power is given by the sum of the three components of power, i.e. P , Q and P_s , where $P_T = \sqrt{P^2 + Q^2} + P_s = P + Q$.

460 At maximum power,

$$S = P\sqrt{2}, P_T = VI(\cos \theta + \sin \theta) = \sqrt{2}VI,$$

$$P_{s_{max}} = \sqrt{2}VI - VI = 0.414VI.$$

Similarly,

$$P_{s_{max}} = P + Q - S = 2P - P\sqrt{2} = 0.586P.$$

465 In this disclosure, new parameters have been described that are useful in producing a new and smart energy meter that is able to measure total power and new power delivery requirements. The variation of total power, generation demand and billing requirements are key parameters that are used to bill consumers of power and must be determined with accuracy.

470 A new theoretical PF model has been presented and it has been validated from various theoretical approaches through an analysis of a complex sinusoid for both current and voltage waveforms. Thus, the total power injected, P_T in an AC power network is an algebraic sum function of both the sine and cosine of the power factor (PF) angle, $P_T = f(\cos \theta + \sin \theta)$. As a result, the 3D power will be equal to or more than the product of RMS values of the 2D, V and I .

CORRELATIVE PROCESS FOR DETERMINING PHASE SHIFT ANGLE

475 The expression for correlative reactive power in (9) can be used to compute the phase shift angle when the supply power $S = VI$ is known, and P_t^e is evaluated from the waveforms. The correlative reactive power is given as,

$$P_s = S[\cos(\theta) + \sin(\theta) - 1],$$

$$P_s = P_t^e - S,$$

Equating the two, we obtain the following,

$$\frac{2 \cos^2 \left(\frac{\theta-45^0}{\nu_z} \right)}{\sqrt{2}} (P_x - P_n) = VI [\cos(\theta) + \sin(\theta)]$$

$$\cos^2 \left(\frac{\theta-45^0}{\nu_z} \right) = \frac{\sqrt{2}}{2} \frac{VI}{(P_x - P_n)} [\cos(\theta) + \sin(\theta)]$$

Then the following correlative distance detector is designed, where a minimum correlative distance is determined over various angles from,

$$d_{min\theta_t} = \min_{0 < \theta_t < 90^0} \left(\sqrt{2} \cos^2 \left(\frac{\theta_t-45^0}{\nu_z} \right) - \frac{VI}{\sqrt{(P_x - P_n)}} [\cos(\theta_t) + \sin(\theta_t)] \right)$$

as follows,

$$d_{min\theta_t} = \min_{0 < \theta_t < 90^0} \left(\sqrt{2} \cos^2 \left(\frac{\theta_t-45^0}{\nu_z} \right) - \frac{VI}{\sqrt{(P_x - P_n)}} - V_\theta \right)$$

where θ_t is the test angle and angle threshold factor, V_θ is obtained as,

$$V_\theta = \sqrt{2} \cos^2 \left(\frac{\theta-45^0}{\nu_z} \right) - \frac{VI}{\sqrt{(P_x - P_n)}}, \text{ when } \theta = \theta_t.$$

E.g., at $\theta = \theta_t = 45^0$, $\sqrt{2} = 0.7071$, $d_{min} = 0$, since $V_\theta = -7.117e^{-4}$.

The following code is an example showing various values of V_θ , where $\sqrt{2} = 1$,

$$d_{min39} = 2/\text{sqrt}(2) * (\text{cosd}((39 - 45)/1.3726))^2 - \frac{VI}{\sqrt{(P_x - P_n)}} - 0.4046$$

$$d_{min40} = 2/\text{sqrt}(2) * (\text{cosd}((40 - 45)/1.3726))^2 - \frac{VI}{\sqrt{(P_x - P_n)}} - 0.4069$$

$$d_{min41} = 2/\text{sqrt}(2) * (\text{cosd}((41 - 45)/1.3726))^2 - \frac{VI}{\sqrt{(P_x - P_n)}} - 0.4098$$

$$d_{min41} = 2/\text{sqrt}(2) * (\text{cosd}(41 - 45)) - \frac{VI}{\sqrt{(P_x - P_n)}} - 0.4098$$

If $d_{min\theta_t}$ is minimum, then $\theta = \theta_t$.

In the case where $\theta = 45^0$, the correlative distance detector for the phase shift angle is set as follows,

$$d_{min}^c = \min_{0 < \theta_t < 90^0} \left(\frac{2}{\sqrt{2}} \cos^2 \left(\frac{\theta_t-45^0}{\nu_z} \right) - \frac{VI}{(P_x - P_n)} \right)$$

then, find θ for which,

$$d_{min}^c(\theta + \mathcal{U}) = d_{min}^c(\theta - \mathcal{U}).$$

INSTRUMENTATION, SIGNAL MEASUREMENTS AND ANALYSIS

It is easy to visualize a graph of power waveform when the value of voltage, current and the shift angle are known. These measurements can be found in the prior art. The power waveform is represented by equation (1). However, it is not easy to visualize the two components of power from the power waveform. A process of transforming equation (1) into equation (6) will enable the measurement of power in an experimental set up. An example of these waveforms are provided in FIG. 7. In order to perform a laboratory power measurement, the following steps are provided in the present disclosure:

1. Compute the phase shift angle from current and voltage waveform to obtain the angle θ or obtain the shift angle through correlative reactive power, P_s
2. Determine the maximum peak value of the received power sinusoid, P_r as P_x
3. Determine the minimum peak value of the received power sinusoid, P_r as P_n
4. The average active power, $P = P_a$ is written as $P_a = (P_x - P_n) \cos(\theta)$
5. Decorrelated total power, P_t through peak RMS value as, $P_t = \frac{-2}{\sqrt{2}}(P_x - P_n) = (P_{t,x} - P_{t,n})$
6. Compute the correlative power factor, $\sigma_c = \cos\left(\frac{\theta-\mu_\theta}{\nu_z}\right)$, $\nu_z = \left(\frac{2P_{smax}}{P}\right)^2$, $\mu_\theta = 45^0$, $0 \leq \theta \leq 90^0$
7. By variance, the total effective power is: $P_t^e = (P + Q)$, $P_t^a = \frac{-2\sigma_c^2}{\sqrt{2}}(P_x - P_n) = \sigma_c^2(P_{t,x} - P_{t,n})$
Or, by scalar difference, power estimate is given as, $P_t^b = (P_{t,x} - P_{t,n}) - 2(1 - \sigma_c)(P_{t,x} - P_{t,n})$
Or, graphical power estimate is given as, $P_t^c = (P_{t,x} - P_{t,n}) - 2(1 - \sigma_c)(Q_e + P)$
Or vectorially by vector difference, $P_t^d = [\sigma_c \times (P_{t,x}) - [1 + (1 - \sigma_c)] \times P_{t,n}]$

It is observed from the steps that the reactive power is expressed as follows: $Q = P_t^e - P_a$. This can be further expressed as, $Q = (P_x - P_n) \left[\frac{2\sigma_c^2}{\sqrt{2}} - \cos(\theta) \right]$.

510 The proof is to show the following, $[\frac{2\sigma_c^2}{\sqrt{2}} - \cos(\theta)] = \sin(\theta)$,

Then, $\left(\frac{2\cos^2(\frac{\theta-45^\circ}{\nu_z})}{\sqrt{2}} - \cos(\theta)\right) = \sin(\theta)$, which holds true, for which $\nu_z = (2[2 - \sqrt{2}])^2$.

The power measurement equations of the present disclosure are now presented:

$$P_t^e = (P + Q), P_t^a = \frac{-2\cos^2(\frac{\theta-45^\circ}{\nu_z})}{\sqrt{2}}(P_x - P_n) = \cos^2(\frac{\theta-45^\circ}{\nu_z})(P_{t,x} - P_{t,n})$$

$P_a = (P_x - P_n) \cos(\theta)$, active power

515 $Q = (P_x - P_n)[\frac{2\sigma_c^2}{\sqrt{2}} - \cos(\theta)] = (P_x - P_n) \left(\frac{2\cos^2(\frac{\theta-45^\circ}{\nu_z})}{\sqrt{2}} - \cos(\theta)\right) = (P_x - P_n) \sin(\theta)$

$P_s = P_t^e - S = (P + Q) - \sqrt{(P^2 + Q^2)}$, correlative reactive power.

We note that $\sigma_c^2 = \cos(\theta - 45^\circ)$ as well.

GRAPHICAL PROCESS FOR EVALUATING TOTAL POWER

The graphical process is estimated using FIG. 8 as follows:

520 $Q_e^2 = h_Q^2 + b_Q^2 - 2b_Q h_Q \cos(\Omega)$

$$l_\Phi = \frac{l \cos(45^\circ)}{\cos(\theta)}$$

$$\hat{l}_\Phi = \frac{l_\Phi}{\cos(\Phi)} = \frac{l \cos(45^\circ)}{\cos(\Phi) \cos(\theta)}$$

$$\Omega = (90 + \Phi)^0$$

$$h_Q = \hat{l}_\Phi \sin(\Phi) = \frac{l \cos(45^\circ)}{\cos(\Phi) \cos(\theta)} \sin(\Phi)$$

525 $b_Q = l - \hat{l}_\Phi, l = V \times I$

In order to further validate the experimental results, the following is a description on how to use a power waveform to estimate the total power injected in a network, by plotting the analytical expression in (16) in Q and P .

1. Subtract the average value, P from the power waveform, to obtain P_d
2. Estimate the RMS value of P_d through a division by $\frac{1}{\sqrt{2}}$
3. Add P to P_d to form P_t
4. Determine the maximum peak value of the sinusoid of P_t as P_x
5. Determine the minimum peak value of the sinusoid of P_t as P_n
6. Compute the correlative power factor, $\sigma_c = \cos(\frac{\theta-\mu_\theta}{\nu_z}), \nu_z = (\frac{2P_{s,max}}{P})^2, \mu_\theta = 45^\circ, 0 \leq \theta \leq 90^\circ$
7. Total power is more accurately given as, $P_t^a = \sigma_c^2 \times (P_x - P_n)$

Or, power estimate is given as, $P_t^b = (P_x - P_n) - 2(1 - \sigma_c)(P_x - P_n)$

Or, graphical power estimate is given as, $P_t^c = (P_x - P_n) - 2(1 - \sigma_c)(Q_e + P)$

Or vectorially as, $P_t^d = [\sigma_c \times (P_x) - [1 + (1 - \sigma_c)] \times P_n]$

530 The results from analytical expressions confirm that the experimental results are correct and give the exact estimation of power when the most accurate statistical error elimination is selected. These results are shown in FIG. 9. The scalar variance estimation is the most accurate process for the experimental measurements, followed by the scalar difference process even for the analytical estimation. The total power processed from the correlative variance show very close match to the decorrelated value of total instantaneous power i.e. $P_t = \sigma_c^2 \sqrt{2} VI$.

APPLICATIONS IN SIGNAL PROCESSING

535 The present disclosure further presents a method of signal processing, where different phase shift angles are used as sources of information bits. This kind of modulation scheme is referred to as correlative phase modulation or power factor modulation, where a sets of PFs are used as sources of information. A preferable detector is used at the receiver to detect the information conveyed by the received signal. Signals can be images or current or voltage waveforms.

540 In a classic example of the present disclosure in signal processing, the following steps are used:

Mapping: An example mapper is the following:

bit 0: $x_1 = \sin(\omega t - \theta_1)$, (this has single frequency, F)

bit 1: $x_2 = \sin(\omega t) \sin(\omega t - \theta_2)$, (this has double frequency, $2F$)

The received signal with additive noise is written as $y = x_i + n$.

545 Fast Fourier transform is applied on y for form frequency-dependent values, $Y(F) = \text{fft}(y)$

For the detector, twice the product of the absolute value of $Y(F)$ is checked if more than a threshold, δ at respective frequencies.

bit 0 : is decoded if $2|Y(F_1)| > \delta, 2|Y(F_2)| < \delta/2$

bit 1 : is decoded if $2|Y(F_1)| < \delta, 2|Y(F_2)| > \delta/2$

550 FIG. 10 is an illustration for bit error rates (BER) against signal to noise ratio (SNR). It shows that different thresholds lead to different BER values. The signal with $\theta_1 = \theta_2$ leads to similar BER rates. In the example disclosed here, a threshold of 0.4 presents the best performance for the detector.

Several forms may be used for the detection of phase shift modulation. For example, minimum noise distance among various RMS values of the received signal are detected in the following way:

555 $dist_i = rms(y) - rms(y(\theta_i))$

$y(\theta_i) = V \sin \omega t \times I \sin(\omega t - \theta_i)$

The illustration in FIG. 11 shows that in order to support an average power equal to $P = VI \cos \theta$, then additional reactive power is needed to adjust Q to Q_f . This means that an additional apparent power is required to provide enough pressure to support such a load. The initial apparent power $S = VI$, can only support an average power

560 of $P_i = VI \cos \theta_i$, where $\theta < \theta_i$, and computed through the adjustment factors disclosed in the present invention.

VALIDATION FROM PRINCIPLE OF CONSTANT POWER AND VARYING QUADRATURE CURRENTS

The second principle of constant quadrature power is now used to confirm the results obtained through the adjusted power coefficients of the first principle. A network of parallel reactance and resistance is considered, where the total current, I is split into the current, I_R through the resistive load and the current I_X through the reactance as

565 follows,

$$I = (I_R + I_X)$$

The voltage across the two elements, R and X_L will be equal i.e. $V_R = V_X$,

$$I_R R = I_X X_L,$$

$$I_R = I_X \tan(\theta), \quad I = [I_X + I_X \tan(\theta)]$$

570 Now, deriving the power factor as a ratio of power dissipated to the total apparent power,

$$PF = \frac{I_R^2 R}{VI} = \frac{I_R^2 R}{V[I_X + I_X \tan(\theta)]}$$

Then, in order to exclude the stored power, apply equal quadrature powers such that, ($I_R^2 R = VI_X$),

$$PF = \frac{I_R^2 R}{VI_X(1 + \tan(\theta))} = \frac{1}{1 + \tan(\theta)}$$

It is easy to see that this value for PF can be expressed as follows,

575 $\frac{1}{1 + \tan(\theta)} = \left(\frac{\cos \theta}{\cos \theta + \sin \theta} \right)$

The present disclosure can have several interpretations. For example, the inductive network becomes the power supply such that,

$$PF = \frac{V_m I_X}{V_m I} = \frac{(I - I_R)}{I} = \left(1 - \frac{1}{1 + \cot(\theta)} \right) = \frac{1}{1 + \tan(\theta)}.$$

580 The validation framework shows that the true average power delivered is half of apparent power at $\theta = 45^\circ$, when the resistance is equal to the reactance in the network. This result is quite representative of the fact that there is no correlation at $\theta = 45^\circ$, and a half of the total power will be delivered to the resistive load before storage begins.

FIG. 12 shows that in an elliptical network e.g. when $\theta = 7^\circ$, then the curves for V, I, S do not coincide on one another. These are points of high correlation. However, correlation is lowered as the angle increases towards $\theta = 45^\circ, \rho = 0$, and the power curve for S coincides with either V or I . The adjusted shift angle shows a reduction in the average active power. To compute the shifts between S and I , the difference in amplitudes of the two curves is calculated at a point on the x -axis. Same is done for the shift between S and V curves as the shift angle is varied. The effects of the changes in the coincidence of these curves of S, V, I are depicted in FIG. 13, where it is observed that the shape of the product of the shifts is similar to the shape of the adjusted phase shift angle, θ_i .

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CLAIMS:

1. A method for processing total instantaneous electrical power as a sum of consumed resistive power, reactive power and stored correlative reactive power, in an alternating current waveform of an electrical power network, which consists of resistive loads, reactive loads and apparent power, wherein;
 - (a) a demodulation process is performed on current and voltage waveforms to obtain a phase shift angle between current and voltage waveforms followed by determining a cosine function of the phase shift angle and a sine function of the phase shift angle;
 - (b) an addition process is carried out after the demodulation process has been completed to give an output sum value of the cosine and sine functions;
 - (c) the output sum value is used to multiply root-mean-square of peak voltage and peak current amplitudes as a product, which results in the value of the total instantaneous electrical power; and
 - (d) the total instantaneous electrical power is an algebraic sum of resistive power derived from the resistive loads and reactive power derived from the reactive loads, while stored correlative reactive power is a difference between the total instantaneous electrical power and the well-known apparent power.
2. The method of claim 1, further comprising computing additional reactive power needed to be generated in order to deliver full power to the resistive load in an electrical power network whenever reactive loads increase in the electrical power network, wherein
 - (a) the additional reactive power needed to be generated is determined as a difference between required generator power and the whole resistive load in the electrical power network; and
 - (b) required power from generator is the sum of the total instantaneous electrical power and a resistive load balance remaining to reach the full resistive load in the electrical power network.
3. The method of claim 1, further comprises computing correlative reactive power, wherein the correlative reactive power is determined as the difference between the total instantaneous electrical power and the well-known apparent power in the network, where the maximum correlative reactive power is determined when there is no correlation, in which the angle of the phase shift degree is forty five degrees.

4. A method of computing a true power factor value as a ratio of cosine function of phase shift angle to the sum of cosine function of the phase shift angle and sine function of the phase shift angle, wherein the true power factor value is a ratio of average active power to total instantaneous electrical power.
5. A method for experimentally determining total instantaneous electrical power from a received power waveform as a difference between maximum peak value and minimum peak value multiplied by an effective correlative power factor variance, in steps where;
 - a) twice the amplitude of received power waveform is divided by a negative of the square-root of two to form a reactive waveform;
 - b) twice average active power is subsequently added to the reactive waveform to form total power waveform;
 - c) a maximum peak value of the total power waveform is multiplied by the effective correlative power factor variance to form effective maximum peak value;
 - d) a minimum peak value of the total power waveform is multiplied by the effective correlative power factor variance to form effective minimum peak value;
 - e) the total instantaneous electrical power is given as the difference between the effective maximum peak value and the effective minimum peak value; and
 - f) the effective correlative power factor variance is a square of cosine of a deviation of the phase shift angle from the angle where there is no correlation, which is forty five degrees, where the deviation is divided by a correlative variance factor, and the correlative variance factor is given as the square of twice the ratio of maximum correlative reactive power to the well-known average active power.
6. A method for experimentally processing phase shift angle through a correlative distance detector, where correlative distances are determined at various phase shift angles, and a minimum distance is used to select the phase shift angle, given that apparent power and received power waveform are known, wherein
 - a) the received power waveform is used to determine peak-to-peak power amplitude as a difference between maximum amplitude and minimum amplitude; and
 - b) the correlative distance for each angle is determined as a difference between square-root of two times correlative power factor variance and angle threshold factor.

7. A method of signal processing where different phase shift angles are used as a source of information to be conveyed to a receiver in a communications system through a transmitter, wherein a detector at the receiver computes frequency of the received signal and compares it with different frequencies according to a reciprocal mapper at the transmitter, then a threshold value is used to decode information conveyed by different angles of the phase shift degree using correlative power information.
8. A method of signal processing where different phase shift angles are used as a source of information to be conveyed to a receiver in a communications system through a transmitter, wherein a detector at the receiver computes phase shift degree of the received signal according to a correlative distance detector and compares it with different phase shift degrees according to a reciprocal mapper at the transmitter, then a threshold value is used to decode information conveyed by different angles of the phase shift degree.
9. A system consisting of;
 - (a) a demodulator processor that measures a phase shift angle between current waveforms and voltage waveforms in an alternating current electrical power system, which consists of resistive loads and reactive loads, then applies singular waveform value decomposition such that power of the waveforms is represented in terms of a cosine function of the angle of the phase shift degree and a sine function of the angle of the degree of the phase shift;
 - (b) an adder processor that determines total value of instantaneous electrical power as a product of root-mean-square values of peak current and voltage amplitudes and the sum of the cosine function of the phase shift angle and a sine function of the phase shift angle; and
 - (c) an energy meter device that reads an amount of total instantaneous electrical power delivered in electrical power network as a sum of power stored and returned to power source due to reactance and power dissipated by the resistive loads in the electrical power network, as an algebraic sum of cosine function of phase shift angle and sine function of the phase shift angle times root-mean-square of peak voltage and peak current amplitudes.
10. The system of claim 9, further comprising computing true power factor value as the ratio of the cosine function of phase shift angle and the sum of cosine function of phase shift angle and sine function of phase shift angle, wherein the true power factor value is the ratio of average active power and the total instantaneous electrical power.

11. The system of claim 9, displays values for the true power factor, total instantaneous electrical power, phase shift angle, the active power, the correlative reactive power, the reactive power and apparent power.
12. An instrument for measuring total instantaneous electrical power from a power waveform in a resistive and reactive power network as a difference between maximum peak value and minimum peak value multiplied by an effective correlative power factor variance, in steps where:
 - g) twice the average active power is subtracted from the power waveform and twice the resultant waveform is divided by a negative of the square-root of two to form a reactive waveform;
 - h) twice the average active power is subsequently added to the reactive waveform to form total power waveform;
 - i) maximum peak value of the total power waveform is multiplied by the effective correlative power factor to form effective maximum peak value;
 - j) minimum peak value of the total power waveform is multiplied by the effective correlative power factor to form effective minimum peak value; and
 - k) the total instantaneous electrical power is given as the difference between the effective maximum peak value and the effective minimum peak value.
13. A system for signal processing comprising a mapper at a transmitter and a detector at a receiver, wherein the mapper is used to assign different phase shift angles is used as a source of information to be conveyed to a receiver in a communications system through a transmitter, wherein a detector at the receiver computes frequency of the received signal and compares it with different frequencies according to the mapper at the transmitter, then a threshold value is used to decode information conveyed by different angles of the phase shift degree using correlative power information.
14. A system for signal processing comprising a mapper at a transmitter and a detector at a receiver, wherein the mapper is used to assign different phase shift angles is used as a source of information to be conveyed to a receiver in a communications system through a transmitter, wherein a detector at the receiver computes phase shift degree of the received signal according to a correlative distance detector and compares it with different phase shift degrees according to a reciprocal mapper at the transmitter, then a threshold value is used to decode information conveyed by different angles of the phase shift degree using correlative power information.

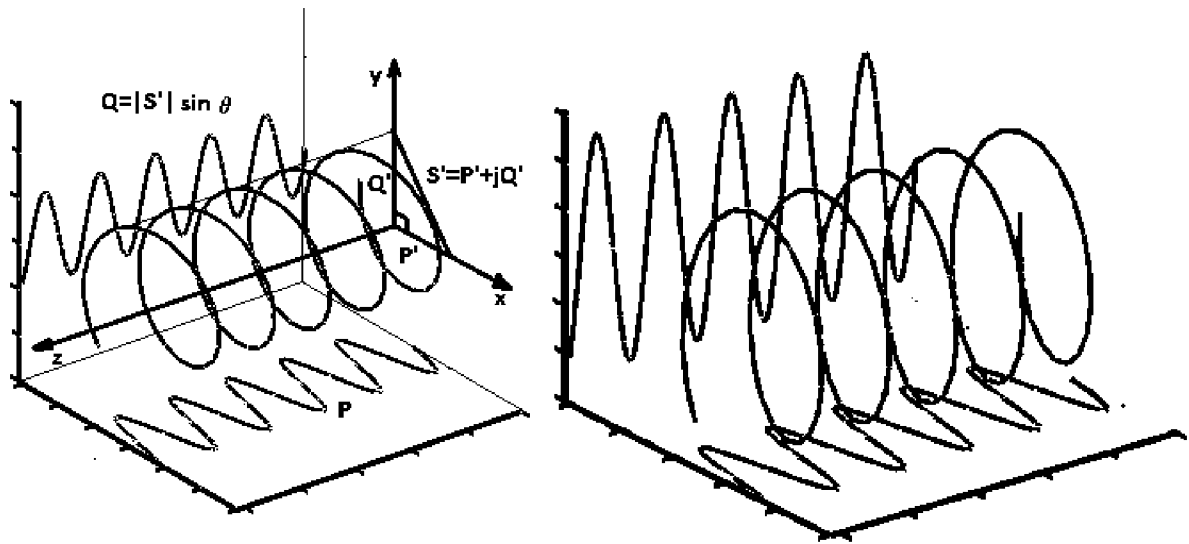


FIG. 1

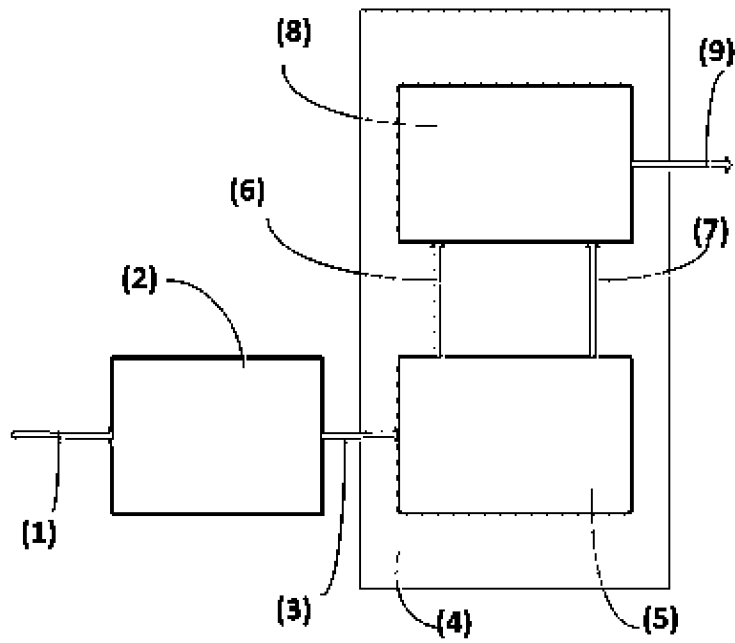


FIG. 2

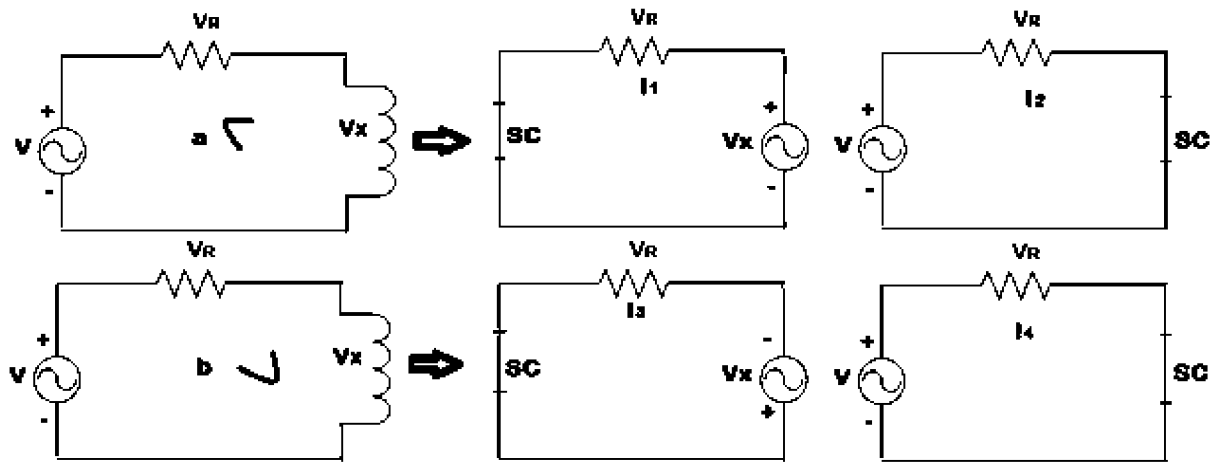


FIG. 3

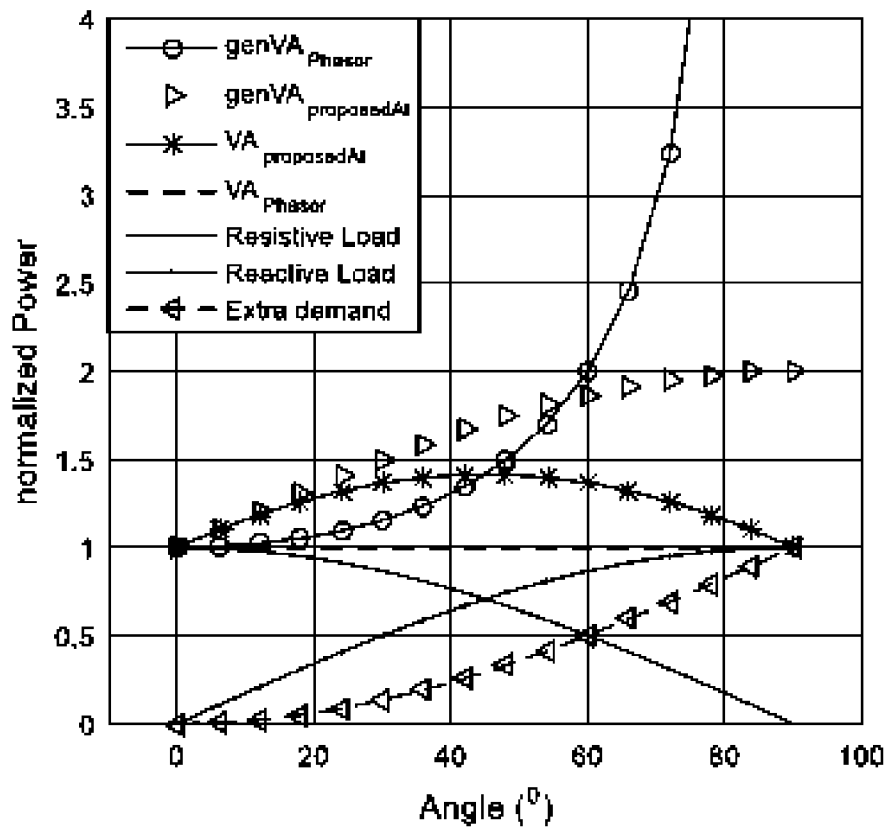


FIG. 4

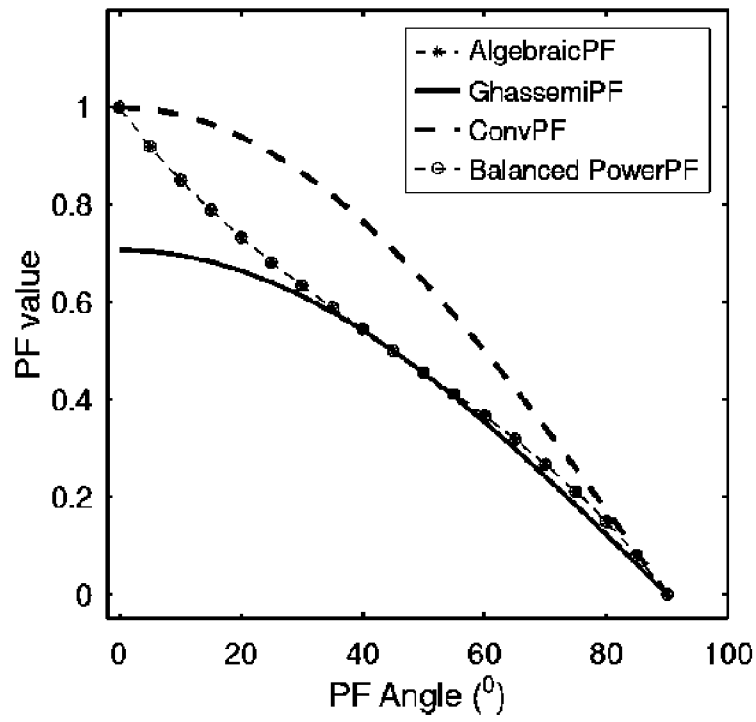


FIG. 5

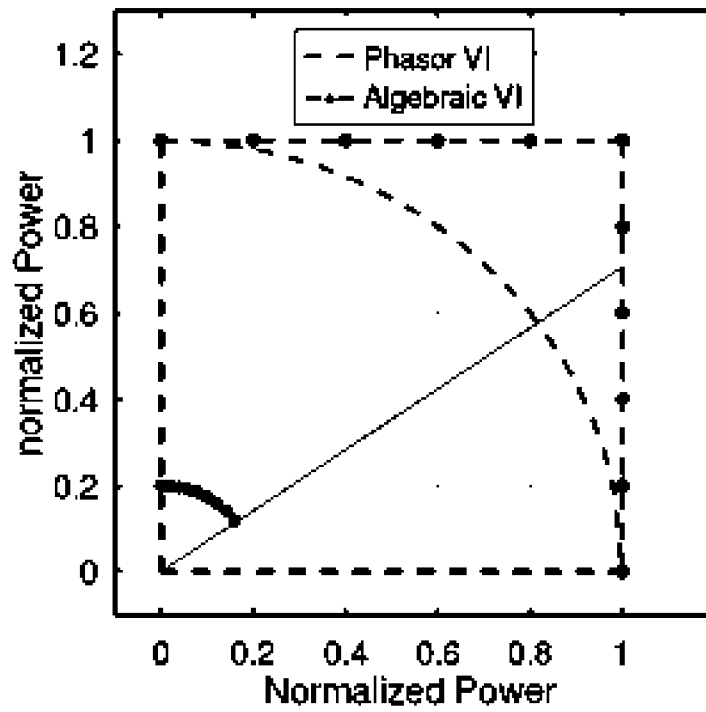


FIG. 6

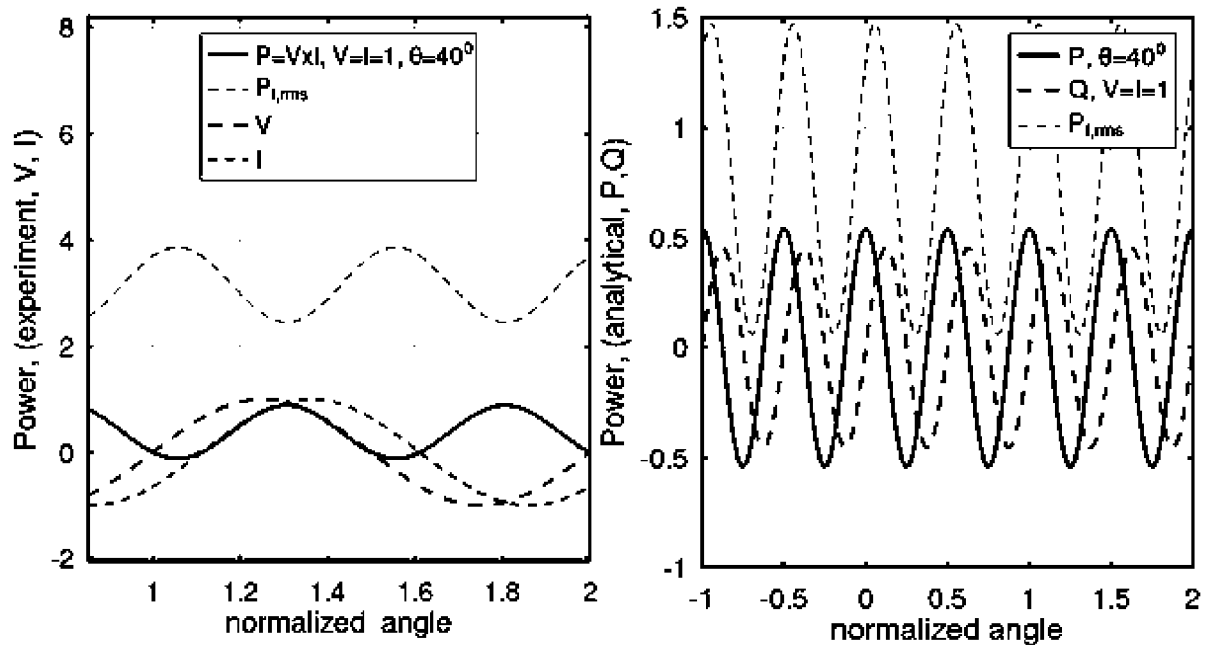


FIG. 7

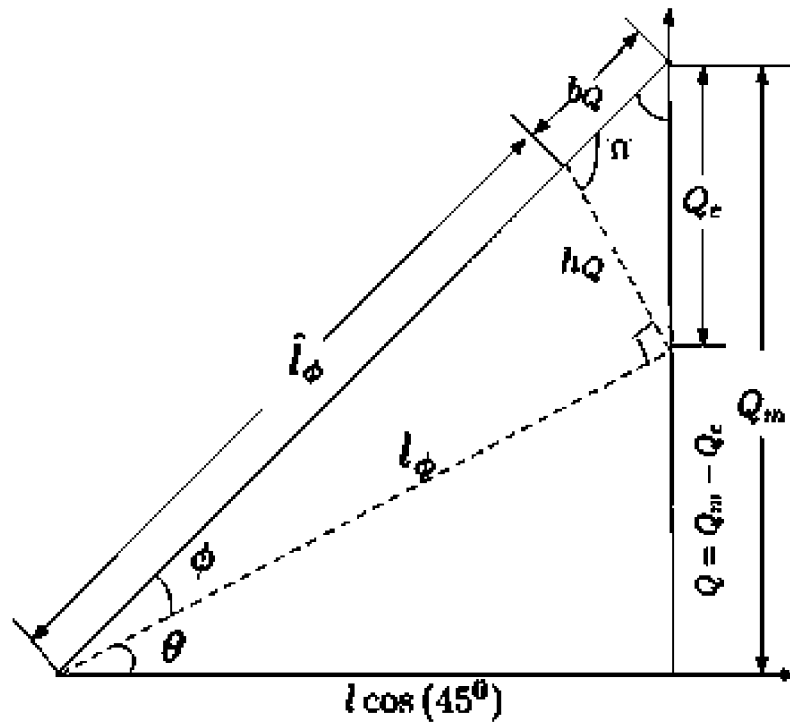


FIG. 8

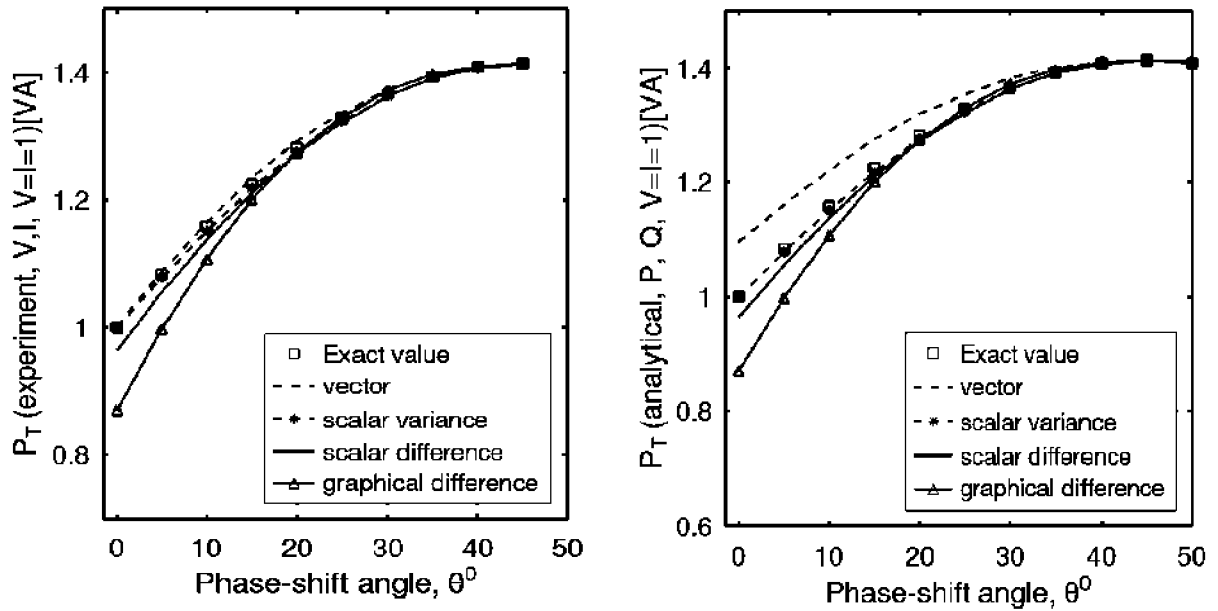


FIG. 9

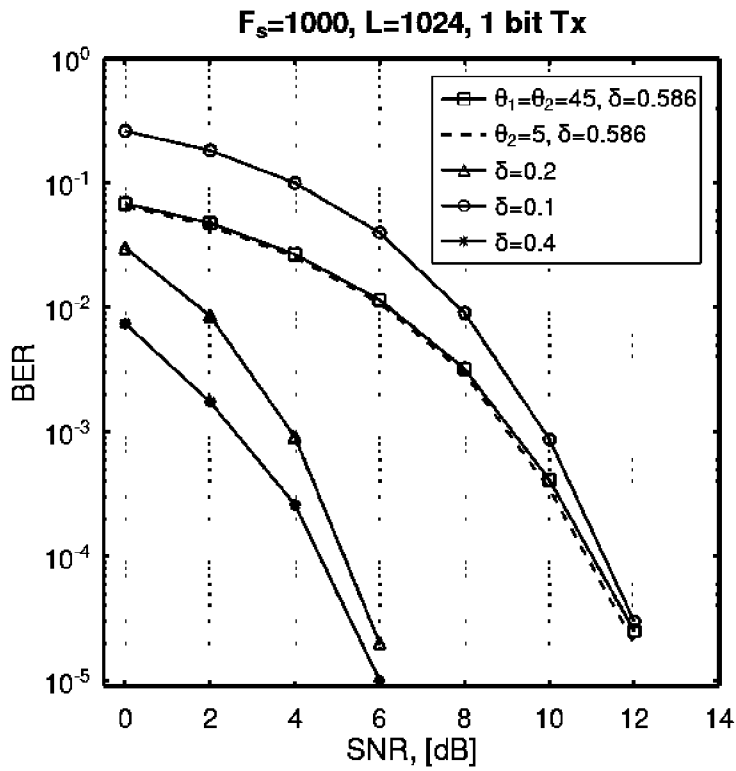


FIG. 10

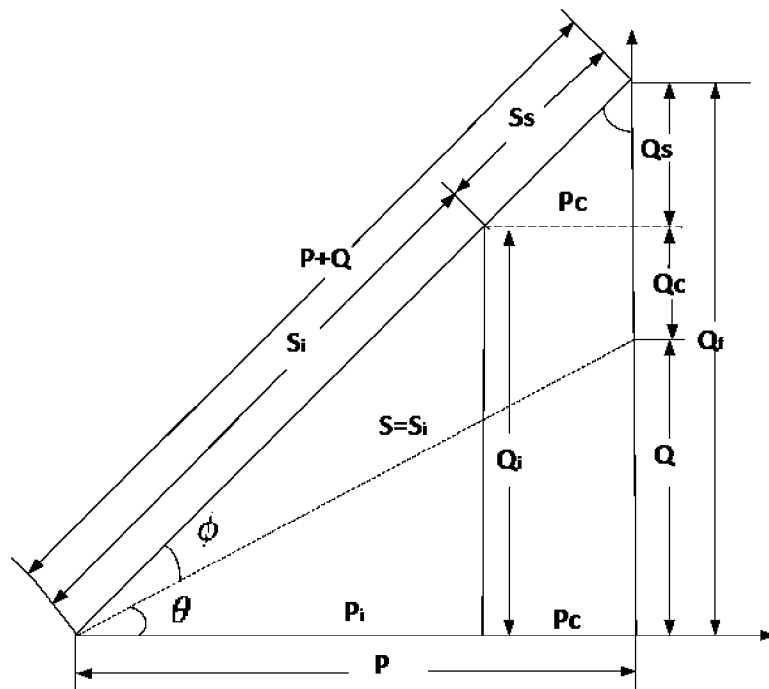


FIG. 11

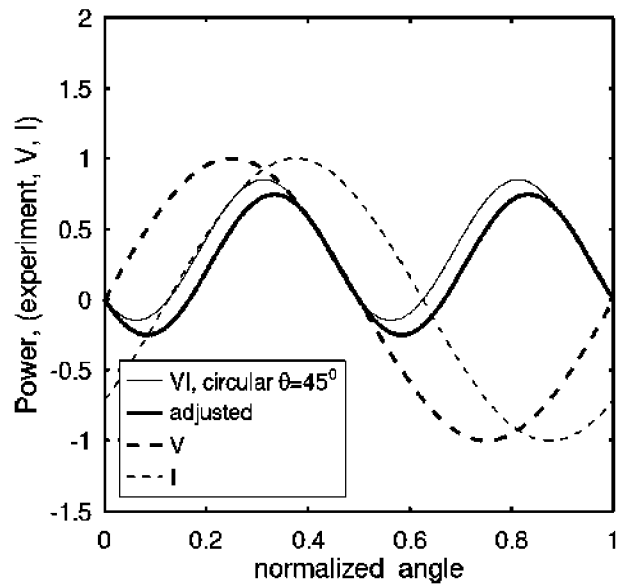
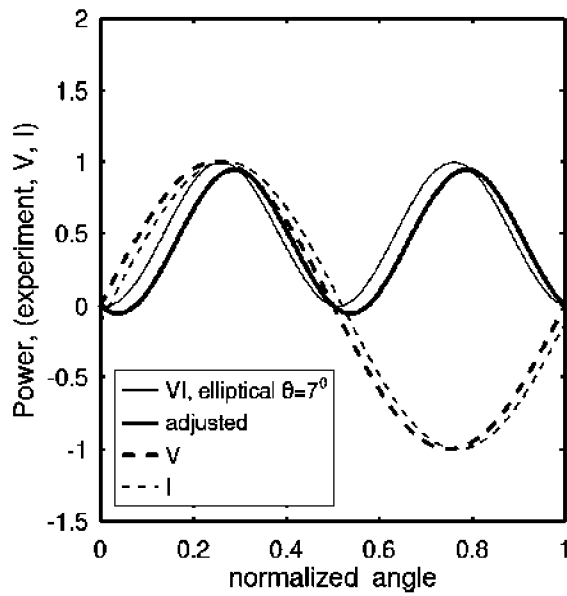


FIG. 12

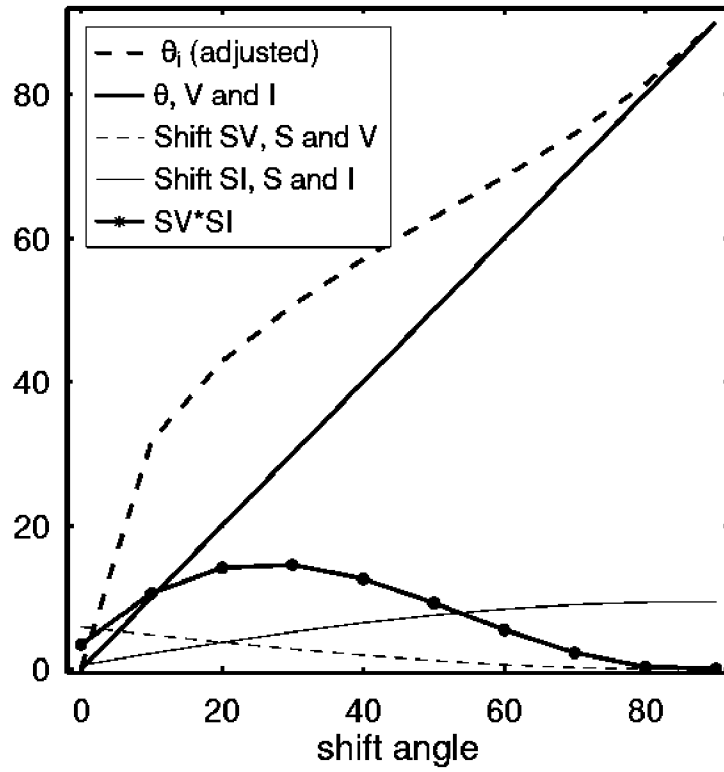


FIG.13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB2021/055349

A. CLASSIFICATION OF SUBJECT MATTER G01R 21/06(2006.01)j According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) G01R;G06F Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) CNKI;CNPAT;WPI;EPODOC;IEEE: power, electr+, factor, PF, sine, cosine, phase, shift, angle, degree, frequency, active, reactive, apparent, resist+, load, demodulat+, decod+, voltage, current, AC, square, root, peak, total, sum, correlative distance, difference, ratio, average, map+		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 106610450 A (SHANGHAI BELLING CO., LTD.) 03 May 2017 (2017-05-03) description, paragraphs 0045-0077	4
A	US 10750587 B2 (ECOSENSE LIGHTING INC.) 18 August 2020 (2020-08-18) the whole document	1-14
A	CN 110879311 A (BEIJING SIFANG AUTOMATION CORPORATION et al.) 13 March 2020 (2020-03-13) the whole document	1-14
A	US 2020293627 A1 (GEN ELECTRIC) 17 September 2020 (2020-09-17) the whole document	1-14
A	US 2018198512 A1 (UNIVERSITY OF KWAZULU-NATAL) 12 July 2018 (2018-07-12) the whole document	1-14
A	MICHEL MALENGRET et al. "Active Currents, Power Factor, and Apparent Power for Practical Power Delivery Systems" <i>IEEE</i> , Vol. 8, 31 August 2020 (2020-08-31), the whole document	1-14
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 05 August 2021		Date of mailing of the international search report 28 September 2021
Name and mailing address of the ISA/CN National Intellectual Property Administration, PRC 6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088 China Facsimile No. (86-10)62019451		Authorized officer WANG, Dechuang Telephone No. 86-(10)-53961791

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/IB2021/055349

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				US	10306724	B2	28 May 2019
				CN	110463348	A	15 November 2019
				US	2018279437	A1	27 September 2018
				WO	2018132110	A1	19 July 2018
CN	110879311	A	13 March 2020	None			
US	2020293627	A1	17 September 2020	WO	2020185990	A1	17 September 2020
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