Table 1. Fuzzy if-then rules

If					Then			
	Z	S	M	B		G	D	SD
Ia	✓				CM			✓
Ib	✓				CM			✓
Ic	✓				CM			✓
Ia		✓			CM		✓	
Ib		✓			CM		✓	
Ic		✓			CM		✓	
…								
Ia			✓		CM	✓		
Ib			✓		CM	✓		
Ic			✓		CM	✓		
Ia				✓	CM			✓
Ib				✓	CM			✓
Ic				✓	CM			✓

Table 2. Fuzzy logic fault diagnosis performance

Fault Detection	Diagnosis Accuracy (%)
Good Conditions (healthy motor)	100
Bad Conditions (voltage unbalance	100
Severe Conditions (open phase)	94

rectly processing current signals and inputting them to a fuzzy decision system, excellent diagnosis was achieved. However, future research should improve this approach by using an intelligent means of optimization.

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Advantages of the Instantaneous Reactive Power Definitions in Three Phase System Measurement

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Abstract: The spatial vector concept of the instantaneous apparent power is defined. Some advantages obtained using these definitions in measuring power in a three-phase system and in vector control of electrical machines are discussed. Also, a physical interpretation of these definitions is given based on conventional electromagnetic theory.

Introduction: In a three-phase system, the instantaneous active power p(t) is obtained by the superposition of the instantaneous power in each phase:

$$p(t) = v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c. \tag{1}$$

The conventional definition of the apparent power S, upon which equipment rating is based, is related to the nominal voltage and current handled by the equipment on balanced operation ($\sqrt{3} \cdot V_{line-line} \cdot I_{line}$). The reactive power Q in the three-phase system is defined to match the apparent and real power in the Pitagoras' triangle ($\sqrt{S^2 - P^2}$). These concepts are useful in the evaluation and design of electric systems. However, for unbalanced three-phase systems, some modifications are necessary, and when harmonic voltages or currents are present, the ideas of displacement power factor DPF and total harmonic distortion THD must be introduced [1]. The recent contribution of Kazibwe [2] explains the physical meaning of the reactive power to nonelectrical engineers. In this letter, we introduce a useful new interpretation and definition of instantaneous active and reactive power.

Spatial Vector Definition: A more precise definition of the instantaneous active, reactive, and apparent power in a three-phase system can be obtained using the spatial vectors theory [3]. If we want the instantaneous spatial power to agree with the conventional complex power definitions used in the balanced steady state system, it is necessary to express it as:

$$\vec{s}(t) \equiv \vec{v}(t) \cdot \vec{i}^*(t) = p(t) + jq(t), \tag{2}$$

where $\vec{v}(t)$ and $\vec{i}^*(t)$ are the spatial vectors defined as:

$$\vec{v}(t) \equiv \sqrt{2/3}[1, e^{j2\pi/3}, e^{j4\pi/3}] \cdot [v_a(t), v_b(t), v_c(t)]^t, \tag{3}$$

$$\vec{i}^*(t) \equiv \sqrt{2/3}[1, e^{j4\pi/3}, e^{j2\pi/3}] \cdot [i_a(t), i_b(t), i_c(t)]^t. \tag{4}$$

Using spatial vector definitions in equations 3 and 4 and separating the real and imaginary elements of the resultant expression, the instantaneous real, reactive and apparent power are:

$$\begin{aligned}\vec{s}(t) = p(t) + jq(t) &= [v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c] \\ &+ j\frac{\sqrt{3}}{3}[i_a \cdot v_{bc} + i_b \cdot v_{ca} + i_c \cdot v_{ab}].\end{aligned} \tag{5}$$

The definitions given in equation 5 are valid under any condition, that is, either using three or four wires, in transient or steady state, in balanced or unbalanced condition, or considering sinusoidal or nonsinusoidal waveforms. The real part in equation 5 is equal to the classical instantaneous power definition, but the imaginary part is not so well known, and disagrees in some special cases with the spatial vector definition. In a balanced, steady-state, and sinusoidal three-phase system, the instantaneous active and reactive power are constant, because the spatial voltage vector (equation 3) and the spatial current vector (equation 4) have constant amplitude, and their relative phase is also constant. In this condition, the classical and the spatial vector definitions agree, but in presence of nonsinusoidal waves, or in an unbalanced system the classical and the spatial vector power definitions have some important differences.

Advantages and Differences: Using the equation 5 definition introduces some differences discussed for the following cases:

- Balanced and unbalanced operation
- Harmonics operation
- Transient operation.

Balanced and Unbalanced Operation: As an example, we consider a three-wire system with a balanced sinusoidal voltage source applied to a pair of delta-connected loads: ($1.0 + j\,0.0$ p.u.) and ($0.8 + j\,0.6$ p.u.). For the unbalanced condition, a factor 1.0, 1.05, and 0.95 has been applied in each branch of the load. A comparison between the active and reactive powers obtained from the classical definition, and the exact results obtained using the instantaneous power defined in expression (equation 2) is shown in Figures 1 and 2. The results obtained using the classical definition match the exact calculations in the balanced case, but can only reproduce the active power in an unbalanced case. The spatial vector definition gives an oscillatory response in which the active and reactive powers vary with time. The center of gravity for the oscillation represents the medium value of the active and reactive power.

Harmonics Operation: In this case, the active and reactive power are analyzed using a three-phase inverter without pulse modulation (non-PWM inverter) applied to a delta connected load with an impedance at the fundamental frequency of $0.8 + j\,0.6$ in p.u. The voltage waveform $v_{ab}(t)$ may be described by the Fourier series as:

$$v_{ab}(t) = \sum_{n=1}^{\infty} \frac{4\sqrt{3/2}}{(2n-1)\pi} \cdot \cos\frac{(2n-1)\pi}{6} \cdot \sin((2n-1)(\omega t + \pi/6)). \tag{6}$$

Voltages v_{bc} and v_{ca} are the same as those given in equation 6, but with a relative lag phase of $2\pi/3$ and $4\pi/3$, respectively. Figure 3 shows the values calculated using the classical and spatial vector power definitions. We observe some differences between the classical and the spatial vector power expressions. The average value of the instantaneous active power agrees with the classical definition. However, the average value of the instantaneous reactive power in both expressions is different. The medium value of the spatial vector power is located in the figure's geometric center.

Transient Operation: During transient conditions such as motor startup, transformer energization, or switching process, the applied voltages and the flowing currents have nonsinusoidal waveforms. As an example, we can consider the starting behavior of the squirrel cage motor with full sinusoidal and balanced voltage applied to the stator windings at fundamental frequency, and with nominal load in the mechanical shaft. Figure 4 shows the instantaneous active and reactive power calculated during the transient condition. The classical definition can not be applied under transient conditions because it requires the evaluation of the effective values of the stator voltages and currents. An important advantage of

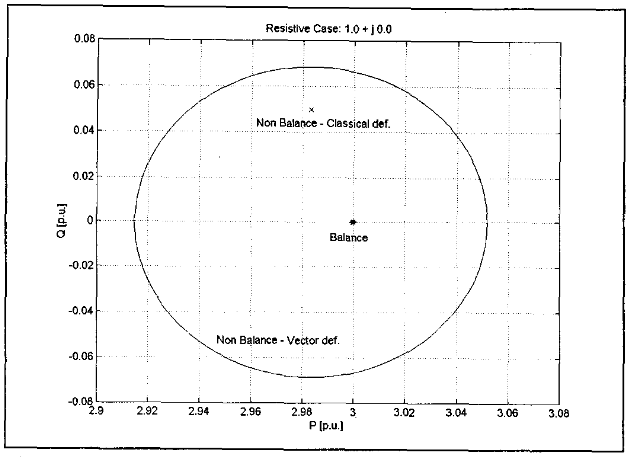

Figure 1. Classical and spatial vector power definitions for a pure resistive balance and nonbalance load

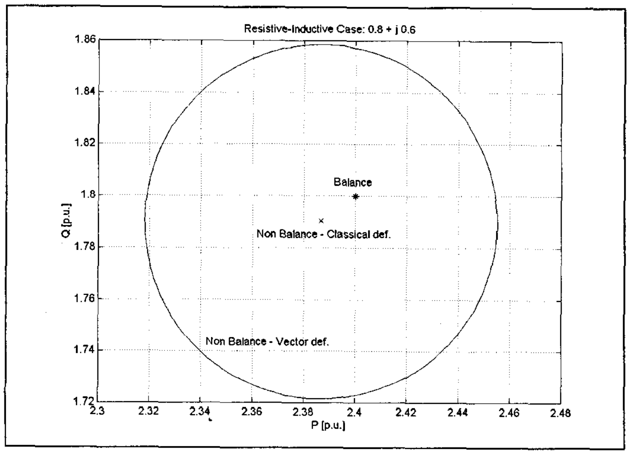

Figure 2. Classical and spatial vector power definitions for a resistive-inductive balance and nonbalance load

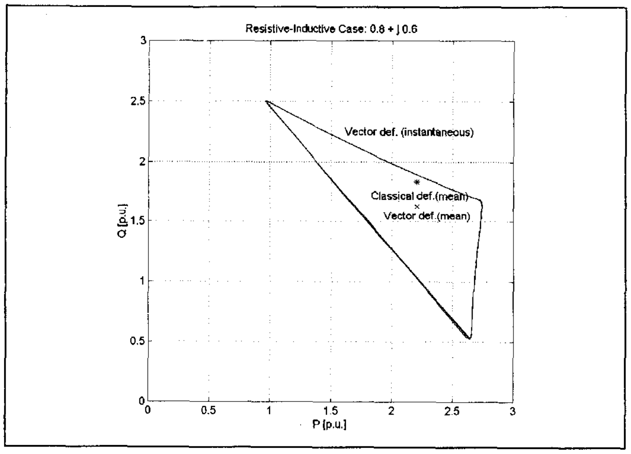

Figure 3. Classical and vector power definitions for a resistive-inductive load with a three phase inverter source without modulation applied

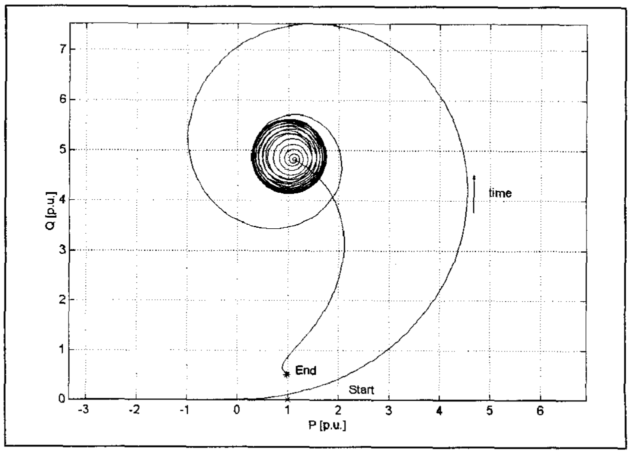

Figure 4. Spatial vector power during a squirrel cage motor startup

the spatial vector definition is the possibility of using it in the dynamic estimation of the machine model parameters [4].

Physical Interpretation: To offer a physical interpretation of the definition presented in equation 2, remember the relationship between the electromotive force e, and the electrical field intensity $\mathbf{E}$ on the one hand, and between the magnetic field intensity $\mathbf{H}$ and the current i for the other. The vector multiplication of the electrical field intensity $\mathbf{E}$ and the magnetic field intensity $\mathbf{H}$ is defined as the Poynting vector $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ [5]. This space-time vector represents the power flow by unit area of the electromagnetic field. For example, in a given point of the air-gap on the rotating electric machine, the Poynting Vector $\mathbf{S}$ has two components, one in the radial direction that determines the active power flow, and the other is the tangential component that maintains the rotating electromagnetic field required during operation. In a three phase transmission line the phenomenon is similar, but the instantaneous active power $p(t)$ corresponds to the longitudinal component of the Poynting vector and the reactive power $q(t)$ is related with the tangential or rotational component of this vector. As the current i and the magnetic field intensity $\mathbf{H}$ are related through Ampère's law, and the electromotive force e is obtained by the integration of the electric field intensity $\mathbf{E}$, it is reasonable to think that the instantaneous active power $p(t)$ is narrowly related to the radial component of the Poynting Vector $\mathbf{S}$, and the instantaneous reactive power $q(t)$ depends on the imaginary part of this vector.

Conclusions: The vector definition of the instantaneous electric power in three-phase systems simplifies the reactive and apparent power measurement. The physical meaning of these variables through Poynting's vector $\mathbf{S}$ gives a better interpretation of these definitions. The instantaneous reactive power is a useful concept in vector control of electrical machines, in three-phase measurement including harmonic flow, unbalanced conditions and also in the transient analysis of the system behavior.

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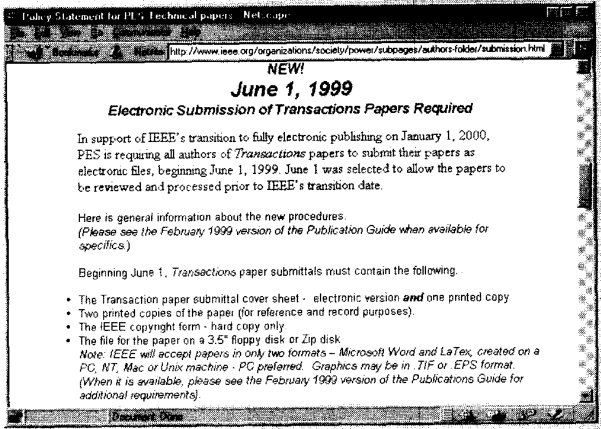

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