Electric Power Systems Research 81 (2011) 1381–1387

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Selection of suitable fuzzy operators for representative power factor evaluation in non-sinusoidal situations

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ARTICLE INFO

Article history:
Received 13 November 2010
Received in revised form 5 February 2011
Accepted 7 February 2011
Available online 22 March 2011

Keywords:
Fuzzy logic
Harmonics
Non-sinusoidal waveforms and power factor

ABSTRACT

Power factor is well defined in sinusoidal situations, however, in the presence of harmonics, different power factors exist and they may provide different values in which case, evaluation becomes problematic. In Morsi and El-Hawary (2008) [1–3], fuzzy systems have been used by the authors to develop a representative index that quantifies the power factor in different operating conditions including sinusoidal and non-sinusoidal situations. However, since different fuzzy operators can be used in the fuzzy system, which will affect the measured output power factor index, this paper investigates the implementation of different fuzzy operators when applied to the developed fuzzy system-based power factor evaluation, in different operating conditions. It is found that the use of the 'algebraic product-sum' operation offers the most suitable connection method, while the 'algebraic product' is the most preferred as an implication method and the 'maximum' operation is best suited for the aggregation operation. These combinations offer the most suitable means for establishing a representative power factor under non-sinusoidal conditions with the least computational burden.

1. Introduction

Power factor is an important index for power quality evaluation, because based on its value, power transmission efficiency can be determined thus motivating the use of power factor correction techniques to counteract the undesired effects of poor power factor electric loads.

In the authors previous work [1–3], a new fuzzy based representative quality power factor (RQPF) was introduced which amalgamates the attributes of the three recommended power factors; the displacement power factor (dPF), the transmission efficiency power factor (TEPF) and oscillation power factor (OSCPF). The motivation for developing the RQPF is to offer a universal single index especially for the cases where the three power factors provide different values which make the power factor evaluation process not straightforward. For example, consider two operating conditions where a reactive load is operating under high and low distortion levels respectively. The displacement, transmission and oscillation power factor values are 0.9, 0.5 and 0.57 for the first case and 0.55, 0.8 and 0.75 for the second case respectively. The first case has high displacement power factor with low transmission efficiency power while the second case has a low displacement power factor and high transmission efficiency power factor. Now if we consider a third case of pure resistive load operating in a highly distorted environment, then the three power factor values are 1, 0.3 and 0.4. In those cases, the three power factors provide controversial results and hence the need for a single universal index becomes necessity. A fuzzy inference system (FIS) was developed using Mamdani's fuzzy inference mechanism, but the following questions arise: What is the appropriate connection method also called ("and" method and "or" method) which should link the input statements in the rules? Which implication method should be applied? Which aggregation operator should be employed for the RQPF module?

The traditional definition of power factor works well only in case of sinusoidal operating conditions. However, due to the increased use of nonlinear loads, power system components have to operate under non-sinusoidal operating condition. As a consequence, alternative power factor definitions based on different apparent power definitions [4–22] have been proposed. The IEEE Working Group [9] recommended the displacement power factor while Willems [17] defined the transmission efficiency power factor and the oscillation power factor. In order to evaluate the power factor index there is a need to represent these power factors by a single value for application to customer billing, setting tariffs and evaluating the service quality. Fuzzy set theory can handle uncertain, imprecision and vague problems in many applications [17–37]. There are many sources of uncertainties and imprecision in the electric power systems [38] which may be caused by voltage and current trans-

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doi:10.1016/j.epsr.2011.02.002

ducer inaccuracies, changing power system operating conditions and imprecise information caused by human involvement in operation management and control of power systems. Therefore, there is a need to use fuzzy systems to evaluate the power factor index in order to evaluate power system quality.

In this paper, many alternative connection methods are considered and applied with different aggregation operators along with the two most popular implication methods; the minimum 'min' and the algebraic product 'prod'. Different combinations of these operators are applied to different case studies; linear and/or nonlinear loads supplied from sinusoidal and/or non-sinusoidal source. The simulation is performed using the fuzzy logic toolbox supported by MATLAB.

The organization of the paper is as follows: Section 2 reviews the power factors definition. In Section 3, the fuzzy-based module used for calculating the RQPF is presented, while explaining the different available connection methods, implication methods and aggregation operators. The results of the application of different connection and implication methods with different aggregation operators are presented in Section 4. Finally conclusions are given in Section 5 while the basic concepts of fuzzy set theory; fuzzy logic and fuzzy inference systems are briefly introduced in the appendix.

2. Review of power factors definitions

In the literature, there are three power factor definitions; displacement power factor, transmission efficiency power factor and oscillation power factor. The displacement power factor (dPF) provides quantitative information of the active power amount that can be transmitted out of the maximum power at the fundamental frequency (60 Hz). Mathematically the displacement power factor can be expressed as the ratio [6]:

$$\mathrm{dPF} = \frac{P_1}{S_1} \tag{1}$$

where the index '1' stands for the fundamental frequency component while P_1 and S_1 are the active and apparent power at the fundamental frequency respectively and they are defined according to [9] as:

$$P_1 = V_1 \cdot I_1 \cos\ \phi_1, \quad S_1 = V_1 \cdot I_1 \tag{2}$$

Such that V_1, I_1 are the root mean square (rms) values of the voltage and current respectively while ϕ_1 is the phase angle between the voltage and current at the fundamental frequency. On the other hand, the transmission efficiency power factor (TEPF) is defined as the ratio between the total active power (including the fundamental and harmonic components) with respect to the total apparent power. Ref. [17] defined the transmission efficiency power factor as:

$$\mathrm{TEPF} = \frac{P}{S} \tag{3}$$

where the total active power and the total apparent power are defined according to [39] as:

$$P = V \cdot I\ \cos\phi = \frac{1}{T}\int_0^T v(t)\cdot i(t)dt, \quad S = V \cdot I \tag{4}$$

Willems [17] introduced a quantity called rms power that is equal to the sum of the instantaneous power and another new apparent power called the oscillating power:

$$S_{\mathrm{rms}} = \sqrt{P^2 + \left(\frac{1}{2}\right)S^2}, \quad S_{\mathrm{OSC}} = \left(\frac{1}{\sqrt{2}}\right)S \tag{5}$$

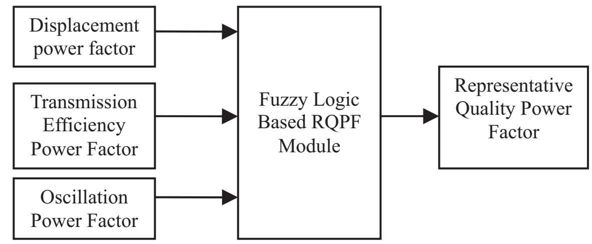

Fig. 1. Schematic diagram of the representative quality power factor (RQPF) module.

Based on these quantities, Willems defined the oscillation power factor to evaluate the oscillation associated with the power transmitted as follows:

$$\mathrm{OSCPF} = \frac{P}{S_{\mathrm{rms}}} = \frac{P}{\sqrt{P^2 + S_{\mathrm{OSC}}^2}} = \frac{\mathrm{TEPF}}{\sqrt{(1/2) + \mathrm{TEPF}^2}} \tag{6}$$

Willems showed that in single-phase systems the maximum value of the oscillation power factor is 0.816 and occurs in case of pure resistive circuits supplied from sinusoidal voltage source.

3. Fuzzy based representative quality power factor module

This section explains the fuzzy based representative quality power factor (RQPF) module used to evaluate the power factors by representing them by a single value. Fig. 1 shows a schematic diagram for the RQPF module proposed where it has three inputs and one output. The three recommended power factors namely displacement, transmission efficiency and oscillation power factors represent the input to the fuzzy representative quality power factor module while the output is the universal representative quality power factor index. The RQPF module is designed using the fuzzy logic toolbox built-in MATLAB, the design procedure is as follows:

3.1. Fuzzy based representative quality power factor module

Using triangular membership functions and linguistic variables, each crisp value of the three power factors that represents the input to the RQPF module and the representative quality power factor at the output of the RQPF module can be transformed into fuzzy values. The reason for favoring triangular membership functions to

Table 1
Typical dual pairs of non-parametric t-norms and t-conorms.

	T-norm		T-conorm
Minimum	$\min\{a,b\}$	Maximum	$\max\{a,b\}$
Algebraic product	$a \cdot b$	Algebraic sum	$a+b-a\cdot b$
Hamacher product	$\frac{a\cdot b}{a+b-a\cdot b}$	Hamacher sum	$\frac{a+b-2a\cdot b}{1-a\cdot b}$
Einsten product	$\frac{a\cdot b}{2-[a+b-a\cdot b]}$	Einsten sum	$\frac{a+b}{1+a\cdot b}$
Bounded difference	$\max\{0,a+b-1\}$	Bounded sum	$\min\{1,a+b\}$

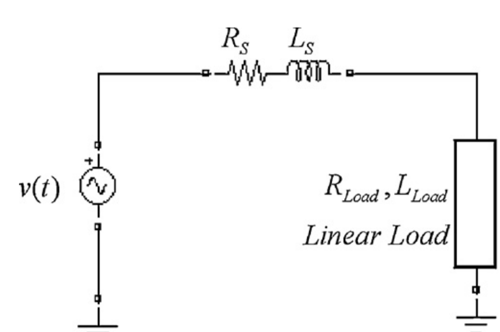

Fig. 2. Linear load supplied from a voltage source.