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True power factor metering for m-wire systems with distortion, unbalance and direct current components

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ABSTRACT

Two companion papers describe an internally consistent general power theory valid for instantaneous and average power for systems with any number of wires, under conditions of unbalance, distortion or dc components. Measuring apparent power and power factor under non-ideal conditions, even in typical three-phase four wire systems, needs the resistances of the wires, particularly the neutral wire, to be defined, and without this detail all conventional power theory approaches are inadequate and give misleading measurement results. This paper illustrates the practicality of measurement of distorted power supplies, and describes laboratory tests showing the differences between measurements using the new approach and a conventional instrument. Applications of the new approach in real power systems are described, including hybrid ac/dc systems and smart grids, and in measuring quality of supply affected by disturbing loads, and the non-active power in transformers subjected to geomagnetically induced currents. The nature of changes required in international standards and the implications for further practical research and development are identified.

1. Introduction

Building on two companion papers [1,2], an approach to multi-phase power system measurement based on the general power theory has been implemented in practice and the results illustrate the practical feasibility and significance of the approach. The key concepts and some implications are presented here in five sections.

First, in Section 2, a specification for power meters is defined in the context of the need for accurate measurement and the practical problems encountered by others. The specification is not an exploration of conventional metrology, which is covered in other papers and standard specifications, but identifies the conditions for which the meters must be appropriate and the parameters needed as inputs to the meter for apparent and non-active power to be measured under non-ideal conditions. In Section 3, a prototype hardware and digital signal processor (DSP)-based true power factor meter that uses the general power theory is described. The concept of the prototype was extended to a computer based measurement system based on the transducers and processes of a conventional power meter, so Section 4 describes laboratory tests that demonstrate practically the differences between measurements with a conventional standard-compliant instrument and using the new approach. In Section 5 the benefits of the new methods of measurement are discussed in four practical application areas. Finally, in Section 6 a possible approach to future standards for measurement of apparent power and power factor is proposed.

2. Specification of meters for accurate apparent power measurement

The IEEE standard 1459–2010 [3] clearly identifies various reasons why accurate measurement of distorted and unbalanced power is needed. Briefly, loads on modern power systems have the potential to disturb the delivery networks and the equipment being used by customers, and there is a need to maintain supplies of acceptable quality and apportion the costs of doing so to those causing the disturbances. In addition, meters and instruments are needed for energy billing, energy quality evaluation, detection of the sources of distortion, and design of filters and compensators. The purpose of the standard is to provide "criteria for designing and using metering instrumentation". Similarly, many authors have addressed the need for compensation of voltage unbalance and distortion, although, in practice, all proposed solutions have been inadequate in coping with combined distortion, unbalance and zero sequence or dc components.

Jeon [4] identified applications that require a theory suitable for m-wire systems with wires of any resistance, including a multi-path transmission system and a three phase four-wire system in which the neutral conductor is of different resistance to the phase

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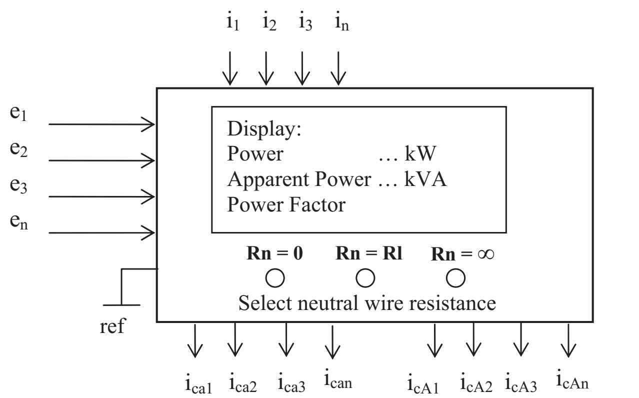

Fig. 1. The TPF meter with input and output signals, display and selection buttons.

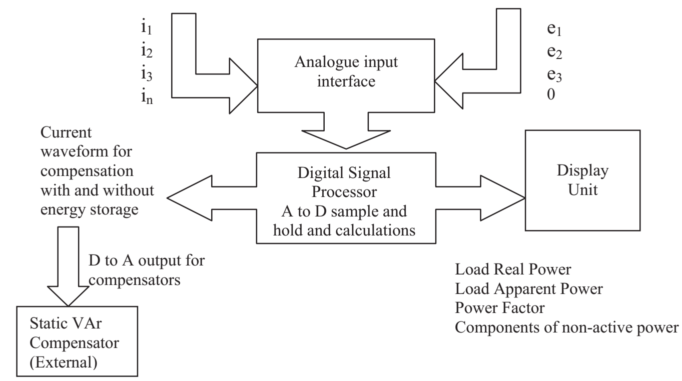

Fig. 2. Processor block diagram for the TPF meter.

conductors. However, his solution for distortion due to harmonics was only valid for a balanced load. Similarly, Mishra et al. [5] described the short-comings of load compensation approaches in power electronics proposed by other authors and formulated another compensation technique, and they too found their scheme was inadequate, in this case working for unbalanced but not distorted voltages.

Montero et al. [6] compared four widely used strategies for controlling shunt active power filters in 3-phase 4-wire systems and reported that only what they called the 'perfect harmonic cancellation' strategy "was capable of correct action under any conditions of use" under the power definitions of IEEE Standard 1459, but it still did not achieve complete compensation to unity PF.

More recently, Ustariz et al. [7] identified a significantly distorted 3-phase supply to a 6-phase, 12-pulse rectifier as a practical installation requiring accurately calculated compensation, but their solution did not allow for the supply wires to have different resistances. By contrast, Atefi and Sanaye-Pasand [8] studied the power factor of a supply to an arc furnace with a neutral wire of negligible resistance, which they found "has significant effect in the physical meaning of the apparent power". While their solution provides rigorous analysis it does not propose how compensation will be controlled.

Clearly, practical combinations lead to measurement problems underlying any compensation control, apportionment of costs or understanding of "undesired losses, voltage drop and EMC problems" [9]. The generalised theory contributes to an improved understanding of all these practical problems and offers complete compensation, providing practical measurement of apparent and non-active power and power factor that is strictly accurate taking into account the wire resistances, is able to display the measured quantities, and generates the inputs needed by compensators.

3. Initial true power factor meter for three-phase systems

The first meter conceived was for three equal resistance phase wires and a neutral wire with an assumed resistance of value zero, infinite or equal to the phase conductors. This was termed a true power factor (TPF) meter and a provisional patent was registered. A prototype TPF meter was assembled around the Texas Instrument DSP TMS320F240 and used to measure unbalanced and distorted 3-phase supplies, comparing results with conventional meters, without relying only on simulations. The meter displayed power, apparent power and power factor according to the selected resistance of the neutral wire, and provided two signals suitable for input into two compensators without and with energy storage.

Fig. 1 illustrates the TPF meter in a block diagram showing the sequence of sensing the input parameters, processing the data according to the relative wire resistance values, and outputting a result. The meter inputs consist of four currents and voltages derived from transducers on the lines supplying the load. (Subsequently only m-1 currents were sensed as the m-th current is defined by the others by Kirchhoff's law.) The labels of the inputs correspond to the load and compensators in the circuit connection diagram in the companion paper [2], without the apostrophe representing resistance weight or the (t) representing that they are a function of time.

Fig. 2 illustrates how the instantaneous values of line currents and voltages are processed by the DSP. The user of the instrument can select three conditions depending on the nature of the neutral wire. The instrument output is calculated according to the value attributed to the neutral wire, assuming the resistances of all the phase wires are equal.

Clearly, this prototype instrument had the shortcomings of assuming all phase wires had equal resistance and the limitation of the neutral resistance to only three values, but it demonstrated the practical possibilities of the approach to metering and compensation.

The exercise also clarified an important issue distinguishing instrument design and construction from the broader topic of understanding the performance of power systems. It was still necessary, however, to assess the effects of the general power theory approach on practical power measurements and compare them with the measurements made by conventional power instruments.

4. Experimental laboratory measurements

Instrument design and manufacture is a specialised area and the risk of error in construction and calibration of a physical meter make it difficult to obtain strictly comparable results using a laboratory prototype TPF meter. Instead, a laboratory proof-of-concept demonstration was implemented by taking voltage and current samples with a good quality conventional (commercial) 3-phase power meter. By adopting the sensing systems of a conventional power meter compliant with industry standards, all the conventional issues of metrology are removed from comparison by making them common to the conventional and novel approaches, and the effect and practicality of the proposed new approach to measuring apparent power are demonstrated. The calculations can be made by computer using the sampled signal data, and enable a direct comparison of the algorithms using a common base of physical measurements for the conventional and new methods. This computer-calculation approach has an advantage of flexibility in demonstrating the practicality of the new method for different conditions because alternative calculations can be carried out more easily by computer than by programming a physical DSP, but in a practical instrument the calculations would be carried out in a DSP.