METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.pg.gda.pl

A SINGLE-POINT APPROACH BASED ON IEEE 1459-2000 FOR THE IDENTIFICATION OF DETECTION OF PREVAILING HARMONIC SOURCES IN DISTORTED THREE PHASE POWER SYSTEMS

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Abstract

This paper deals with a novel single-point strategy for the detection of prevailing harmonic sources downstream or upstream the metering section in three-phase power systems. It is an enhancement of a previous strategy, already developed by the authors and it is based on the comparison of three non-active power quantities which are based on the IEEE Std. 1459-2000 approach. The method does not require any spectral analysis of voltages and currents because it is based only on the separation of the fundamental components from the harmonic content of voltage and current. In the paper, the effectiveness of the strategy is investigated by means of simulation tests which were carried out on a IEEE standard three-phase test power system used by other authors as a benchmark to test harmonic sources detection methods. The analysis is carried out considering also the presence of the measurement transducers.

Keywords: power measurements, harmonic distortion, reactive power, power quality, IEEE Std. 1459.

1. Introduction

The identification of harmonic-producing loads in power systems has become a very important issue for the assurance of power quality and the attribution of responsibility between customers and utilities for disturbances caused in power systems. In power networks there are a several non-linear and/or time-variant loads which inject harmonics in the line currents, causing disturbances also on the supply voltage; these disturbances can be conducted through the power system also to the other loads, which can absorb a distorted current, even if they are linear and time-invariant. The traditional quantities used for the evaluation of the harmonic pollution level are not able to provide a meaningful information for the detection of harmonic sources.

In literature, various methods have been presented for the detection of the harmonic sources, both single-point and multi-point [1-6]; the first strategies are based on measurements performed in one metering section and, in some conditions, they can report inaccurate information about the harmonic state of the system; the second strategies are based on distributed synchronous measurements performed in different metering sections; even if these methods are more reliable than the first ones, they are generally difficult to implement and require complex and expensive measurement instrumentation.

A large part of the aforesaid methods make use of the evaluation of the harmonic active power flow at the metering section. However, it is known that in some practical situations this approach gives an incorrect information about the location of the harmonic sources [7-10]. In these cases, some useful information can be obtained from the “nonactive” components of the apparent power. It is known that several power theories have been formulated in literature in order to give a meaningful interpretation to the terms of the instantaneous power that do not contribute to the net transfer of energy.

Starting from the analysis of the above mentioned power theories, the authors proposed a novel strategy for the identification of polluting sources in power systems [10-11]. It was based on the simultaneous evaluation of three different nonactive power quantities, already proposed in literature, at the same metering section. It was shown that this strategy was able to give some useful information on the location of the dominant harmonic source. However, it required to perform a spectral analysis of voltage and current.

In this paper the authors present an enhancement of the approach of [10-11], by substituting one of the nonactive powers previously used with a new parameter [12] which is obtained from the IEEE Std. 1459-2000 approach [13]. The new strategy is easier to be implemented than the previous one, because it is based only on the separation of the fundamental components from the harmonic content of voltage and current. Thus the measurement system can be significantly simplified; the new strategy was implemented in the time domain by using a technique already developed by the authors for the detection of fundamental and harmonic components of voltages and currents [3, 14].

In this paper, firstly, the theoretical formulation of the proposed strategy is briefly summarized. Secondly, some simulation tests are presented, which were carried out on a IEEE standard test power system [15]. The effectiveness of the proposed technique is investigated both in absence and in presence of the measurement transducers.

2. The proposed strategy

The proposed single-point strategy for the detection of the dominant harmonic source, upstream or downstream the metering section, is based on the comparison of the following nonactive power quantities derived from the IEEE 1459-2000 approach

$$Q_1 = V_1 I_1 \sin\theta_1 , \tag{1}$$

$$N = \sqrt{S^2 - P^2} , \tag{2}$$

$$Q_X^2 = V^2\left(I_1^2 \sin^2\theta_1 + I_H^2 \sin^2\theta_H\right) = V^2\left[I_1^2 \sin^2\theta_1 + \frac{D_H^2}{V_H^2}\right], \tag{3}$$

where Q_1 is the fundamental reactive power, N is the nonactive power, defined in the IEEE Std. 1459-2000 [13] and Q_X is a “fictitious” reactive power, which was introduced in [12], starting from the approach of the aforesaid standard. In the previous equations: V_1 and I_1 are the RMS values of the fundamental components of voltage and current and θ_1 is their displacement; S is the apparent power and P is the active power; V is the RMS value of the whole voltage, I_H and V_H are the RMS values of the whole harmonic current and voltage respectively and D_H is the harmonic nonactive power [13].

A comparison among Q_1, Q_X and N, calculated in the same metering section and in the same working condition, can give some information on the presence of disturbing loads [12]. In fact, in a given distorted working condition, Q_1 can be considered as a minimum reference value, since it is the only nonactive power component in the sinusoidal condition. N is a maximum reference value since it groups all the nonactive components of the apparent power. It can be demonstrated that $Q_1 \le Q_X \le N$, since Q_X includes Q_1 but it is not the only component of nonactive power (the three quantities are equal in sinusoidal conditions). The differences among the values of the three considered quantities depend on the supply and load conditions. For example, in the case of a nonsinusoidal supply and a linear load, the amount of current distortion is low and it is due to the distortion of the supply voltage; thus the difference between Q_I and N is not much significant (*i.e.* the contribution of the harmonics is small, as generally happens in the practical cases) and Q_X is closer to Q_I than to N (*i.e.* the contribution of the current harmonics is reduced mainly to the fundamental). On the contrary, when a non linear load is present, the amount of current distortion is higher compared with the previous case, and Q_I and N assume values that are significantly different, because the total amount of distortion becomes more relevant; also the contribution of the harmonics to the value of Q_X increases, with Q_X closer to N than to Q_I. Finally, when both the load and the supply are responsible for the harmonic distortion, an intermediate situation occurs where the differences among the three quantities are relevant and Q_X assumes an intermediate value between Q_I and N.

For the sake of completeness it has to be observed that the aforesaid considerations are true for resistive and inductive loads; on the other hand, in the presence of capacitors different situations can occur. In fact, even if such components do not introduce new harmonics in the network, they can amplify the already existing distortion. This aspect should be taken into account in practical situations, for example when capacitors are used for the power-factor correction at fundamental frequency (see next section).

The proposed approach was extended to the three-phase balanced case, by evaluating the three nonactive power quantities as the sum of the respective phase (a, b, c) quantities

$$Q_{I(abc)} = Q_{Ia} + Q_{Ib} + Q_{Ic}, \tag{4}$$

$$N_{(abc)} = N_a + N_b + N_{c},, \tag{5}$$

$$Q_{X(abc)} = Q_{Xa} + Q_{Xb} + Q_{Xc} \;. \tag{6}$$

On the other hand, the validity of the proposed approach was investigated also in the unbalanced case, showing that some meaningful results could be obtained also in this case, even if the separation of the effects of the unbalance and nonlinearity is not directly achievable (the strategy is sensitive to harmonic distortion and not to unbalance).

In [12], a preliminary validation of the proposed strategy was carried out in both the single-phase and the three-phase case, showing its effectiveness in different working conditions and also in some critical cases, where other methods could give incorrect results (such as the method based on harmonic active power).

3. Simulation results in the absence of transducers

The simulations were carried out on the IEEE Test System n. 2 A 13 Bus Utility Distribution System [15]. This system is based on the IEEE 13 bus radial distribution test feeder and it serves as a benchmark for unbalanced harmonic propagation studies. In this system, loads are modelled as constant RL impedances and the motor was assumed to be out of service. Thus, the application of IEEE test system no. 2 is a simplification in the case of voltage unbalance. It was also proposed as a harmonics test system, with some modifications detailed in [15] and it was already used by other authors as a benchmark system for the analysis of multi-point measurement techniques for harmonic pollution monitoring [5-6]. Furthermore, the system was already used by the authors for the validation of the previous strategy proposed in [10-11]; thus a direct comparison could be made between the enhanced strategy and the previous one.

In brief, the test system contains three-phase, single-phase and phase-phase line configurations, shunt capacitors, spot and distributed loads. The conventional loads are modeled with constant impedance, current or power at fundamental frequency. The loads producing harmonics (fluorescent light banks, adjustable speed drives and composite residential loads) are modeled with their linear equivalent section in parallel with current sources. The complete data of the system are detailed in [15].

For the purposes of the paper, some simplifying assumptions were made, thus the IEEE network essentially consisted of a power source (at node 50), a transformer (between nodes 50 and 31) and the following five loads:

- L1 at node 33, including the single-phase load 34 (the motor and shunt capacitors at node 34 were assumed to be out of service);
- L2 aggregated load at node 32, consisting of the single-phase load 45, the phase-phase load 46, and half the distributed load between nodes 32 and 71 (this last load was modeled as a spot load connected to node 32);
- L3 aggregated load at node 71, consisting of half the distributed load between nodes 32 and 71 (modeled as a spot load connected to node 71), the phase-phase load 92 and the single-phase loads 52 and 911, with shunt capacitors;
- L4 at node 71, consisting of a three-phase load;
- L5 at node 75, consisting of a three-phase load, with shunt capacitors.

A schematic representation of the simplified network is reported in Fig. 1. Table 1 shows the THD factors and the unbalance degrees for the five loads, in the original configuration of the network.

The IEEE network was implemented by means of the PSCAD/EMTDC software. Five metering sections, one for each considered load, were defined. Different working conditions were simulated, by considering the original configuration of the network, or by substituting some of the original nonlinear and/or unbalanced loads with equivalent linear and balanced loads having the same power characteristics of the original ones [10-11]. All the equivalent loads consisted of RL elements, with the exception of L5, which consisted of RLC elements (even if load L3 included also shunt capacitors, the equivalent aggregated load was modeled with RL elements).

In each test, the simulation in the PSCAD/EMTDC environment was run and the instantaneous values of voltages and currents were measured at the five metering sections. The obtained data were saved in a MATLAB file and they were used as input data for the evaluation of Q_I, Q_X and N; also the THD factors and the unbalance degree were evaluated. The measurement of the aforesaid quantities was implemented in MATLAB environment, by using a time-domain technique already proposed by the authors for the detection of the fundamental components of voltages and currents [4, 14]. This technique makes use of double time-domain coordinate transformations; the first one is the Park transformation, which transforms the voltages (or currents) into their alpha, beta and zero components; the second one transforms the Park components on a rotating coordinate system, which is synchronized with the fundamental power supply frequency, by means of an internal software PLL [16-17].

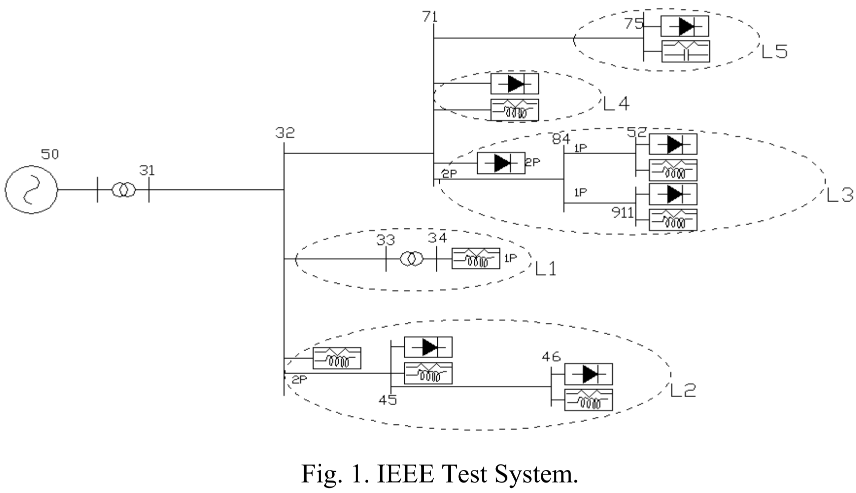


Fig. 1. IEEE Test System.

Table 1. THD factors and unbalance degrees - All nonlinear loads (original network configuration).

		Load L1	Load L2	Load L3	Load L4	Load L5
THD_V [%]	Phase A	4,71		7,85		
	Phase B	4,10		6,77		
	Phase C	4,40		7,45		
THD_I [%]	Phase A	2,11	4,40	5,97	7,48	22,8
	Phase B	2,12	6,90	5,78	6,99	38,9
	Phase C	2,24	7,98	11,85	7,56	29,4
Vi/Vd [%]		0,33	0,33	0,91	0,91	0,91
Ii/Id [%]		84,6	95,6	74,3	3,24	29,7

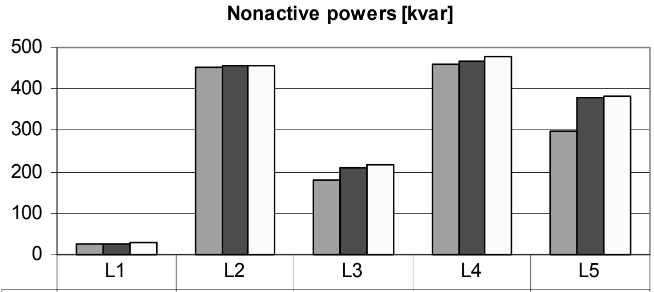
In the Figs 2a-2c there are reported some of the results obtained for the nonactive powers Q_I, Q_X and N.

Fig. 2a refers to the original configuration of the IEEE network with all nonlinear loads. In all cases the proposed strategy based on nonactive powers led to the identification of the disturbing loads. In fact, at each metering section, the three power quantities Q_I, Q_X and N are different and Q_X is closer to N than to Q_I, thus indicating the presence of a disturbing load. Obviously, the values assumed by the considered power quantities and the size of their differences depend on the harmonic state of the power system and the nature of each load. For example, for the loads L3, L4 and L5 the distortion levels in both voltages and currents are higher than those of the loads L1 and L2 while, for these last two loads, the contribution of unbalance is more significant. As a consequence, the differences among the considered power quantities are more relevant for L3, L4 and L5, while these differences are less significant for L1 and L2. This means that the proposed method is more sensitive to harmonic distortion than to unbalance. Moreover, the difference among the three power quantities is greater for load L5 than for the other loads, because of the effect of the shunt capacitors, which amplify the distortion both due to the nonlinear load itself and coming from the supply side.

Fig. 2b refers to the network configuration with loads L1, L2, L3, L5 linear and load L4 nonlinear. It can be observed that for the loads L1, L2 and L3 the values of Q_I, Q_X and N are very close, while for L4 the differences between them are more significant and Q_X is close to N. From this result it can be deduced that L1, L2, L3 have a linear behaviour and the dominant harmonic source is upstream each metering section, *i.e.* the distortion is due to the supply; on the contrary, L4 has a nonlinear behavior and the dominant harmonic source is downstream the metering section, *i.e.* the distortion is due to the load L4 itself. Thus, the analysis of the nonactive powers led to the correct identification of the dominant harmonic source at each metering section. For the load L5, even if it is linear, there is a difference among the values of Q_I, Q_X and N, because of the presence of the shunt capacitors (this difference is smaller than the one obtained in the previous case, where the load L5 was nonlinear). Thus, particular attention should be paid when capacitors are present.

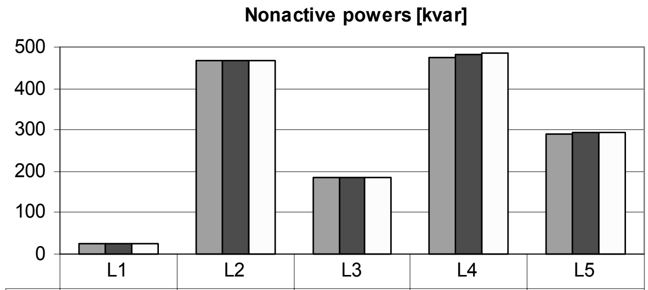
Fig. 2c refers to the network configuration with loads L1, L3 and L5 linear and loads L2 and L4 nonlinear. Also in this case the analysis of the nonactive powers led to the correct identification of the disturbing loads. In fact, for example, the values of Q_I, Q_X and N are very close for the loads L1 and L3; on the contrary, for L2 and L4 the difference between the considered nonactive powers is more significant and Q_X is closer to N than to Q_I. From these values, it can be deduced that L1, L3 have a linear behaviour and the dominant harmonic source is upstream each metering section, *i.e.* the distortion is due to the supply; on the other hand, L2 and L4 have a nonlinear behaviour and the dominant harmonic sources are downstream each metering section, *i.e.* the distortion is due to the loads themselves. Also in this case, the difference among the considered power quantities depend on the nature of the load (*i.e*. the differences are more significant for L4 than for L2). Moreover, the load L5 shows the same behaviour of the previous case.

a)



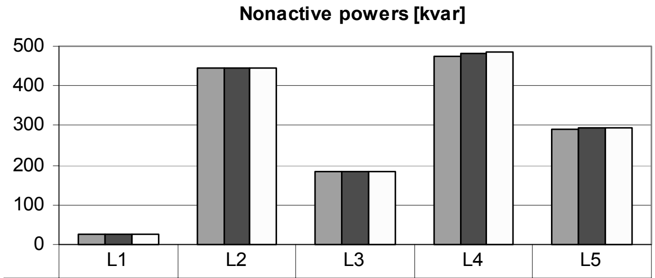
	L1	L2	L3	L4	L5
Q1	26.80	452.7	180.6	459.9	297.9
Qx	27.12	454.3	208.2	468.7	378.2
N	27.69	454.6	216.9	478.5	383.6

b)



	L1	L2	L3	L4	L5
Q1	27.130	466.000	183.200	475.300	290.900
Qx	27.130	466.000	183.300	481.600	292.600
N	27.130	466.000	183.300	484.600	292.600

c)



	L1	L2	L3	L4	L5
Q1	27.170	444.600	183.500	476.000	291.300
Qx	27.170	446.400	183.600	482.200	293.200
N	27.170	446.400	183.600	485.800	293.200

Fig. 2. a). Simulation results of the proposed strategy in the absence of measurement transducers. All non linear loads (original configuration). b). Simulation results of the proposed strategy in the absence of measurement transducers. L1, L2, L3 and L5 linear loads, L4 non linear load. c). Simulation results of the proposed strategy in the absence of measurement transducers. L1, L3 and L5 linear loads, L2 and L4 non linear loads.

4. Uncertainty discussion

With respect to the proposed method, its uncertainty depends on:

- digital signal processing and software implementation of the time-domain strategy which mainly depends on the PLL software used for the synchronization of the rotating

coordinate system and the filters used for the extraction of the fundamental components of voltages and currents;
- analog-to-digital conversion;
- transducers and signal conditioning accessories (transformers, attenuators and amplifiers, anti-aliasing filter, and so on).

In [18] the accuracy of the time-domain method for the extraction of fundamental components and the measurement of the IEEE Std. 1459-2000 power quantities was carried out by means of simulations according to test conditions chosen taking into account the requirements of IEC standards for power quality and harmonics measurements. The uncertainties due to analogue-to-digital conversion were taken into account (the uncertainties introduced by a 12-bit A/D converter were considered). In all cases, the method locked the input voltage frequency with an uncertainty lower than ± 0,01%. Both the fundamental and harmonic components of voltages and currents were measured with an uncertainty lower than ± 0,05% while the related power measurements were measured with an uncertainty lower than limits reported in IEC Standard 61000-4-7 [19].

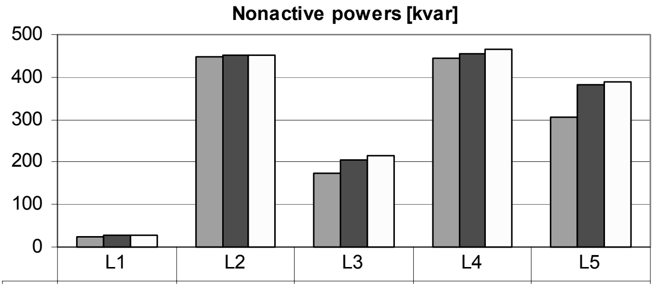
On the other hand, it is well known that one of the predominant contributions to influence to the uncertainty in the measurement chain is often due to the measurement transducers and conditioning accessories. The assessment of their influence on the accuracy of a generic instrument is not a simple issue, because there are many types of transducers available on the market, with different accuracy characteristics. Moreover, in the presence of harmonic distortion, the problem is to evaluate the behaviour of the transducers, in order to take into account their contribution to the uncertainty in a correct way [20-21].

5. Simulation results in the presence of transducers

The simulation tests were repeated considering also the presence of the transducers. This was made by introducing to the measured voltages and currents the amplitude and phase errors due to current and voltage transformers (CTs and VTs) of different classes of accuracy. As regard this, the Standards EN 60044-1 [22] and EN 60044-2 [23] provide information regarding CTs and VTs accuracy and specifications only for sinusoidal conditions. No specific requirements and standardized test procedures are available for the characterization of the transducers in distorted conditions, so that in such condition their behaviour could be different from sinusoidal conditions. In literature different approaches have been proposed for the characterization of CTs and VTs in the presence of harmonics. For example, in [20] the behaviour of CTs and VTs under distorted conditions was analysed by evaluating the frequency response, as suggested from the Standards IEC 61000-4-30 [21] and IEC 61000-4-7 [19].

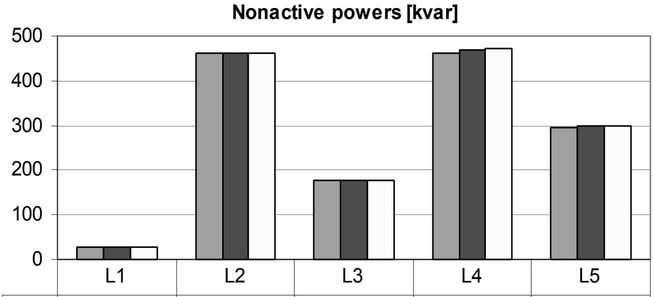
For the simulations, transducers of class 1 accuracy were considered; the amplitudes and phase errors for the fundamental components of voltages and currents were chosen in accordance with the Standards [22-23], while the amplitudes and phase errors for the harmonic components were chosen in accordance with the results of frequency response [20]. Moreover, the errors due to analogue-to-digital conversion were taken into account [24]. As an example, in the Figs 3a, 3b and 3c there are reported the results obtained for IEEE Test System configurations of the Figs 2a, 2b and 2c respectively. It can be observed that even if the numeric results were different from the previous cases, the proposed approach maintained its validity, detecting the disturbing loads, as made in the absence of the transducers.

a)



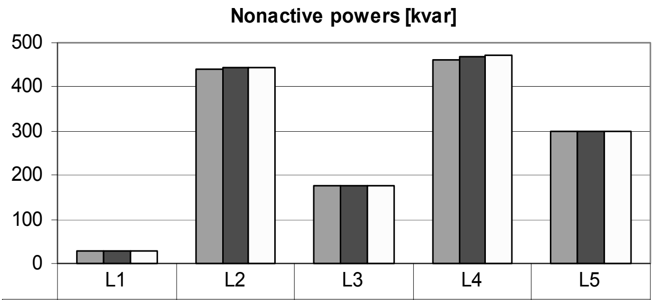
	L1	L2	L3	L4	L5
Q1	25.48	448.8	174.3	446.1	304.4
Qx	26.67	450.5	204.8	455.1	382.8
N	27.17	450.7	213.8	465.3	388.3

b)



	L1	L2	L3	L4	L5
Q1	26.44	461.6	176.9	463.2	295.5
Qx	26.44	461.7	176.9	469.6	300.2
N	26.44	461.7	176.9	472.7	300.2

c)



	L1	L2	L3	L4	L5
Q1	26.47	441.2	177.1	462.2	299.1
Qx	26.48	443.4	177.2	468.4	300.8
N	26.48	443.4	177.2	472.1	300.8

Fig. 3. a) Simulation results of the proposed strategy in the presence of measurement transducers. All non linear loads (original configuration). b) Simulation results of the proposed strategy in the presence of measurement transducers. L1, L2, L3 and L5 linear loads, L4 non linear load. c) Simulation results of the proposed strategy in the presence of measurement transducers.L1, L3 and L5 linear loads, L2 and L4 non linear loads.

6. Conclusions

This paper deals with a new strategy for the detection of harmonic sources in power systems, which is based on the simultaneous measurement of three nonactive power quantities, derived from the approach of the IEEE Std. 1459-2000. The proposed method is an enhancement of a previous approach, already developed by the authors. The main advantage of the novel method is that is based only on the separation of the fundamental components from the harmonic content of voltage and current. Thus, it can be entirely implemented in the time domain, simplifying the measurement system. The simulation tests, which were carried out on an IEEE standard test three-phase power system, show that the proposed method can give useful indications for the detection of the dominant harmonic source, upstream of downstream the metering section both in the absence and in the presence of the measurement transducers.

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