WHY NETWORK COHERENT DATA IS SMART

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ABSTRACT
Voltage and current data time stamped within sufficient time-uncertainty allow smart opportunities in network operation. The usefulness of network coherent data is demonstrated by means of two case studies. It is shown that synchrophasors could further additional network performance information on renewable sources of energy integrated at distribution voltage levels. On-line modelling is an additional smart opportunity made possible by PQ instrumentation if designed according to the latest draft of the IEC 61000-4-30 Class requirements.

INTRODUCTION
The IEEE stated a vision of the smart grid as “The smart grid is an electrical network from the generation of electrical energy until the delivery to end-users, which make use of the latest advances in wireless and other communications technology and intelligent information management systems to ameliorate the robustness, reliability, energy efficiency and security of such network”.

Energy metering manufacturers has exploited the entrepreneurial opportunity to an extent that “smart” during the past few years have been claimed by collecting revenue and to some extent, controlling load by employing two-way communication in billing instruments.

The IEEE envisioned much more. One opportunity to the realisation of the smart operation of an electrical network is in network coherent data.

Agreement on an engineering benchmark of “coherent” exists. GPS and other IEEE standard time-stamping methodologies are well known with straightforward implementation. It allows integrating the features of a Phasor Measurement Unit (PMU) and a Power Quality (PQ) instrument, inclusive of current. With every parameter time-stamped, this set of network coherent data resulting is useful for smart grid operation.

The latest draft version of the IEC 61000-4-30 Power Quality (PQ) document includes the requirement on time stamping. Simultaneous (to the PQ parameters) recording of energy can be based on the power definitions set by the IEEE 1459-2010. It is an opportunity for agreement on how power should be measured and should be considered for possible incorporation into the IEC 61000-4-30 Class A PQ measurement requirements. A number of opportunities result:

a) PQ parameters can now qualify and quantify both supply and loading conditions coherently at different points in the network.

b) PQ instrumentation, which record network coherent data, can at the same time record synchrophasor data.

c) Network coherent data can be used to do on-line modelling and validation of network components.

d) Network coherent data is required in the proper monitoring and assessment of emission such as when sources of renewable energy have to be integrated into distribution systems.

e) The IEEE 1459-2010 can be used as the standard in measuring energy to support PQ analysis.

PQ REQUIRES BOTH SUPPLY AND LOADING CONDITIONS
The latest draft version of the IEC 61000-4-30 makes provision for the inclusion of current parameters and a referenced approach to time-stamping. This allows different PQ instruments geographically separated, to produce coherent network data.

The basic measurement principle of the IEC 61000-4-30 [2] is based on digital samples representing 10 or 12 fundamental cycles of the voltage waveform for 50 or 60 Hz respectively to attain a 200 ms window of data and referred to as the 10/12 cycle block principle.

Frequency analysis is based on 1280 samples per 10/12-cycle block of data. It includes possible changes in instantaneous frequency of the voltage signal (zero crosses can change cycle by cycle). Calculation of harmonic phasors per phase for voltage and current is set by the IEC 61000-4-30, but with proper time-stamping it is now also synchronised phasors. The simultaneous calculation of effective 3-phase voltage, current and other IEEE 1459-2010 values [1] per 10/12-cycle block follows with minimal additional computational and storage effort.

A summary of the parameters proposed (in addition to the IEC 61000-4-30 and shown for the 3-wire case only) is listed in Table I.

HOW NETWORK COHERENT DATA WAS OBTAINED
The latest draft version of the IEC61000-4-30 Class A requirements was implemented in the design of a new PQ instrument by a South African company. Time-stamping uncertainty of better than 100 ns was achieved and the ability to record synchrophasor data was included, and at
Observe the incident in the network operator in terms of voltage stability. The network was designed for voltage drops and such an incident was noted during the peak hours due to clouds moving over the installation. Injection of energy is at a point where the network was designed for voltage drops and such a significant variation in production could be of interest to the network operator in terms of voltage stability. Observe the incident indicated by the black oval. An A significant variation in the production of PV energy is noted during the peak hours due to clouds moving over the installation. Injection of energy is at a point where the network was designed for voltage drops and such a significant variation in production could be of interest to the network operator in terms of voltage stability. Observe the incident indicated by the black oval. An instantaneous and also significant change in production occurred. A focus on this incident as shown in Fig. 3 indicates a strong correlation between the phase angle and the production of PV energy. The power changed from around 20 MVA to 30 MVA within 2 minutes whilst the phase angle changed from 0.4° to 1.6°.

**CASE STUDY 1: USING THE SYNCHROPHASOR AT DISTRIBUTION VOLTAGE LEVEL**

The principle of the micro-synchrophasor was introduced by Alex McEachern and is currently researched by the California Institute for Energy and Environment [5] for usefulness at distribution voltage levels. But, it should be possible to do more than stability control and monitoring as what is done with the traditional application of the 50/60 Hz voltage synchrophasor. Simultaneous recording of current synchrophasors allow the analysis of the interaction of energy production with the voltage phase angle at for example between the Point of Connection (PoC) and at the Point of Common Coupling (PCC). The impedance in-between has to be sufficient to cause a detectable change in voltage phase angles, but that is what the micro-synchrophasor attempts, “micro” variations in the phase angle.

One PQ instrument was installed at the Point of Connection (PoC) where the 75 MW PV plant feed into a 132 kV distribution system. The second instrument was installed 102 km further at the 132 kV Point of Common Coupling (PCC). The loading at the PCC reflects both the PV plant production and the loading of the system downstream from the PoC. Observe the results shown in Fig. 2.

A significant variation in the production of PV energy is noted during the peak hours due to clouds moving over the installation. Injection of energy is at a point where the network was designed for voltage drops and such a significant variation in production could be of interest to the network operator in terms of voltage stability. Observe the incident indicated by the black oval. An
distribution network with sources of renewable energy all over, can further smart opportunities to the enhancement of network operation and control.

**CASE STUDY 2: ONLINE MODELLING OF NETWORK COMPONENTS**

With voltage and current phasors at all harmonic frequencies measured against a referenced time-base, with sufficient resolution and at different points of interest in the network, additional understanding of network performance should be possible. Coherent measurements across a transmission line allow the direct determination of the impedance values. It can be expected that the line parameters will be time independent. Changes in loading, temperature, sag depth; wind speed, insulator pollution and others can cause a variation with time. The on-line verification of the line parameters can be used to confirm the validity of the line model in the network simulator, which make use of fixed values.

One PQ instrument was installed at the center node of a 330 kV transmission system of a Southern African country with the second instrument installed at the other end 550 km away as shown in Fig. 4, a hydro-generating station feeding only into this transmission line. No loading or injection of energy exist in-between the two points of measurement.

For the purpose of this case study, the variation in the 50 Hz positive sequence resistance ($R_1$), inductance ($L_1$) and capacitance ($C_1$) was calculated against time and is presented for a typical 24-hour period. Climatic conditions over the length of this line are significantly different. Soil conditions and geographical features are also diverse.

The theoretical values for the line parameters were calculated from the physical geometry of the line and the conductors as used. Results obtained for a typical summer day is shown in Fig. 5, 6 and 7.

Minimal difference between the theoretical values and the derived values for inductance and capacitance were found. A minimal variation with time is also noted.

The challenge is to understand why the resistance changes significantly during a day. Step changes were confirmed to correlate to step changes in energy flow. A hydropower source is dictating the flow of energy in this transmission line and fast changes in operational conditions occurs daily.

A network operator has to schedule load flow (for example) based on a network model. Continuous verification of the line parameters can be useful in validating the operational procedures by compensating for the deficiency in a theoretical model. With network coherent data available, continuous and on-line measurement of line parameters are straight-forward.
THE POWER OF ENERGY IS IN THE IEEE 1459-2010

Many scientifically sound publications [5] exist on why agreement is needed on the measurement of electrical energy in a power system with non-sinusoidal voltage and/or current waveforms under unbalanced loading and/or asymmetrical voltages supplied. A historic paper on this topic was published in 1927 already by Budeanu [3].

The IEEE Working Group on nonsinusoidal, asymmetrical and unbalanced conditions in power systems chaired by Alexander Emanuel published in 2010 a practical approach to the definition of power in a modern 3-phase power system, the IEEE 1459-2010 [1]. Widespread application is not yet seen, but the usefulness as a practical engineering approach to the measurement of energy is clear. The resolution of power proposed by this IEEE standard is depicted in Figure 8.

This approach is based on the “effective” apparent power (S_e) [4], which makes use of effective 3-phase voltage and current parameters, listed and explained in Table 1. The contribution to S_e due to waveform distortion (harmonics), asymmetrical supply voltages and unbalanced loading is segregated into different power components. Each can be related to the root cause.

TABLE I. IEEE 1459-2010 PARAMETERS TO COMPLIMENT PQ AND ENERGY PARAMETERS [1]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_s</td>
<td>$V_s = \sqrt{\frac{\sum_s (V_{s_{ab}}^2 + V_{s_{bc}}^2 + V_{s_{ca}}^2)}{9}}$</td>
</tr>
<tr>
<td>V_e</td>
<td>$V_e = \frac{\sqrt{V_{e_{ab}}^2 + V_{e_{bc}}^2 + V_{e_{ca}}^2}}{\sqrt{2}}$</td>
</tr>
<tr>
<td>V_e'</td>
<td>Positive sequence voltage and current phasor of the 50/60 Hz 3-phase voltage and current phasors</td>
</tr>
<tr>
<td>V_c</td>
<td>$V_{eh} = \sqrt{V_{c}^2 - V_{c1}^2}$</td>
</tr>
<tr>
<td>I_e</td>
<td>$I_{e} = \frac{\sqrt{\sum_s (I_{s_{ab}}^2 + I_{s_{bc}}^2 + I_{s_{ca}}^2) + \sum_s I_{s_{ab}}}}{3}$</td>
</tr>
<tr>
<td>I_c</td>
<td>$I_{eh} = \sqrt{I_{e}^2 - I_{c1}^2}$</td>
</tr>
<tr>
<td>THD_v</td>
<td>$THD_v = \frac{V_{eh}}{V_{c}}$</td>
</tr>
<tr>
<td>THD_i</td>
<td>$THD_i = \frac{I_{eh}}{I_{c1}}$</td>
</tr>
<tr>
<td>S_e</td>
<td>$S_e = 3\sqrt{V_{e}I_{e}}$</td>
</tr>
<tr>
<td>S_c</td>
<td>$S_c = 3\sqrt{V_{c}I_{c}}$</td>
</tr>
<tr>
<td>S_d</td>
<td>$S_d = S_{eh} - S_{c1}^2$</td>
</tr>
<tr>
<td>D_v</td>
<td>$D_v = THD_v S_e$</td>
</tr>
<tr>
<td>D_i</td>
<td>$D_i = THD_i S_c$</td>
</tr>
<tr>
<td>S^2</td>
<td>$S^2 = V^2 I^2 = P^2 + Q^2$</td>
</tr>
<tr>
<td>PF_e</td>
<td>$PF_e = \frac{P_e}{S_e}$</td>
</tr>
<tr>
<td>PF_c</td>
<td>$PF_c = \frac{P_c}{S_c}$</td>
</tr>
<tr>
<td>S_c1</td>
<td>$S_{c1} = S_c^2 - (S_1^2)^2$</td>
</tr>
</tbody>
</table>

PQ is mostly a subject for engineers solving practical concerns in power systems. The academic debate on how power should be defined in a modern power system, was solved by the publication of the IEEE 1459-2010 [1]. Ongoing research is being done to validate the additional understanding brought about by coherent measurement of both the IEEE 1459-2010 and the IEC 61000-4-30 parameters at different points in the network when for example the interaction of renewable energy sources with distribution systems are studied. Some cause and effect information can be enhanced by these parameters; a high level demonstration is presented below.

In Case study 1 the phase angle across a 132 kV line was shown to reflect the sudden variation in PV production to an extent to be measured with sufficient certainty with most modern PQ instrumentation if designed to the latest IEC 61000-4-30 Class A requirement. Minimal additional resources in the instrument are needed to simultaneously measure power as defined to the IEEE 1459-2010. The distortion power in voltage and current at both the PV plant and the PCC is then shown in Fig. 9.

Fig. 8. IEEE 1459-2010 resolution of three-phase effective apparent power [1]

Fundamental frequency positive sequence active (P_e) and reactive power (Q_e) in the components is regarded as the only useful power components in a power system. Unbalanced loading and asymmetrical supply voltages manifest in (Q_e).

The contribution to effective apparent power (S_e) by frequency components above the fundamental frequency is termed the non-fundamental apparent power (S_n). Distortion power due to current harmonics (D_i), distortion power due to voltage harmonics (D_v) and the harmonic apparent power (S_h) due to the interaction of both voltage and current harmonics can now be segregated and analysed separately to better understand the root cause and the effect onto the performance of the power system, such as when grid compliance studies have to be done at sources of renewable energy.
Distortion power in voltage and current at the PV plant is not correlated all of the time, but commensurate with the production. It increases the useless power in the distribution system and because it is only detectable as a function of production at the PV plant and not at the PCC, it is conclusive as to the source of some of the useless power observed at both. Other contributors to useless power will be due to unbalanced loading and asymmetrical supply voltages, quantified by the unbalance power $S_{ul}$ in Table 1, and lastly the interaction between voltage and current harmonics quantified by the harmonic apparent power, $S_{NH}$.

Such approach to the definition of power could be useful to better understand the integration of sources of renewable energy feeding into a distribution network at different points. With on-line access to data at the different sources, continuous assessment of emission will be a powerful tool to network operators.

**CONCLUSION**

The application of the synchrophasor at distribution voltage levels seems to further additional understanding of how sources of renewable generation interact with the network. Detectable changes in phase angle, both from a meteorological and a network point of view, exist in a relative short 132 kV line. Investigations as at what lower voltage levels measurement results with sufficient uncertainty can be obtained, is on-going. Uncertainty in phase angle measurement results from the digitisation resolution, the sampling frequency, the accuracy in time-stamping and the subsequent signal processing.

Network coherent data can be generated by general power system instrumentation such as the PQ recorders used on this paper, if designed to the latest draft of the IEC 61000-4-30 Class A requirement. This coherent network data was traditionally only used in the management of PQ from a voltage quality perspective. It can now add additional value to network operators, such as in the direct and on-line determination of line parameters.

PQ parameters which also reflects loading (current) and with the simultaneous analysis of energy based on the IEEE 1459-2010 approach to the definition of power, and measured coherently with sufficient uncertainty, can allow innovative applications towards the IEEE vision of what a smart grid is about.

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**REFERENCES**


