Verification of Electrical Disturbance Measurement Data to Be Used for Wind Turbine Model Validation

Sanna Uski
VTT Technical Research Centre of Finland
Espoo, Finland
sanna.uski@vtt.fi

Abstract—**In order to verify that a simulation model operation corresponds to the real-life system operation, the models are validated against measurement data of a real system or system component. The procedure naturally presumes that the used measurement data is accurate and correct. This paper discusses the possible problems in the data interpretation and errors concealed in the measurement data of three-phase electrical quantities. Also a check-list is suggested for the measurement data verification. The emphasis is especially on disturbance measurement data of wind turbines to be used for a wind turbine model validation. Use of erroneous data could lead into a false conclusion of a wind turbine behavior or incorrect validation of a wind turbine model. Potential problems and errors in the measurement data are illustrated through actual experiences of measurement data that initially seemed feasible but in fact contained errors. These experiences also demonstrate the usability of the presented check-list for data verification. Discovering the errors enables the correction of the data and increases the data reliability.**

Index Terms—**Disturbance, data verification, measurement data**

I. Introduction

The simulation models must be validated against measurement data in order to guarantee the model accuracy. The validation should be done against a representative selection of measurement incidents, e.g., of test cases with incident created on purpose, or recordings captured of accidental occurrences in the system. Typically the interest is in the wind turbine response to a voltage dip. In the model validation, the model should show similar behavior—and particularly its main characteristics—as that of the real-life system that was measured.

On contrary to the theoretical context, in real-life there are no measurements that would give absolutely perfect values and precision. Also the human error possibility is always present, e.g., in the physical measurement set-up, measurement software coding, and data post-processing. Overall, it is highly important to verify the obtained measurement data.

The practical problems faced and human errors are rarely mentioned or discussed in publications dealing with the use of measurement data. It is rather taken granted that there are no errors in the data, it is evident what has been measured, and data is described correctly. There are only few publications that deal with issues even partly related to the topic of this paper. [1] deals with the measurement validation and data quality related to Fieldbuses. In [2] is discussed about the measurement accuracy of the unbalanced three-phase quantities.

This paper deals with the problems faced in some measurement campaigns as well as digs into deep in the data analysis to point out the importance of data verification. Data verification was found important by experience, as even a data sanity check[1] may not guarantee the data validity.

Electrical measurements are generally discussed in chapter 2 and disturbance measurements of the demonstration sites are described in chapter 3. The main part of the paper, i.e., potential errors and data validation means are approached in chapter 4, and the practical examples of disturbance measurement data validation are given in chapter 5.

II. Measured and Calculated Electrical Quantities

The voltages and currents are clearly the primary electrical quantities possible to be measured. Power is the product of the voltage and current, and its “measurement” is generally based on the voltage and current measurements.

Faults and disturbances involve quite fast and possibly unbalanced phenomena. The measurements have to be correspondingly fast and with high enough frequency sampling in order to capture the phenomena correctly and in sufficient detail. Some general requirements for disturbance data are given, e.g., in [3].

Many of the numerous calculation methods of active and reactive power rely on symmetry and/or averaging (over a period), which does not give correct results during unsymmetrical fault situations and transients. Especially in the case of unsymmetrical faults, the reactive power value may deviate significantly when calculated by different methods. In the data analysis discussed in this paper, the positive sequence

[1] Definition for sanity check is doing a quick check for completely stupid and evident mistakes, and that the data looks reasonable and makes sense.

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fundamental method for calculating active and reactive power according to Niiranen's recommendation in [4] is used. The positive sequence fundamental method requires data series of phase voltages and phase or line currents preferably in sampling frequency of 5 kHz or higher according to [4].

Phase-to-phase voltages can be calculated with measured phase-to-ground voltages, but calculating the phase-to-ground voltages of the measured phase-to-phase voltages is difficult, especially if the neutral voltage is not measured. Thus it would be reasonable to measure voltages as phase-to-ground values.

III. DISTURBANCE MEASUREMENTS—EXAMPLE CASES

The data used as example in this paper is from two separate measurement campaigns. Both campaigns are related to wind turbine and wind power plant measurements, and the data was recorded for wind turbine model validation purposes. At both disturbance measurement sites, there were coinciding measurement campaigns of different type at the same wind turbines. The measurement data of these other measurement campaigns has been available to be used as help for the disturbance measurement data analysis.

There were many entities involved in the measurement campaigns and thus not a single party may have a full comprehension of all the possible related issues of the wind power plants, nor the measurements. Generally, the obtained disturbance measurement data is not ready to be used for, e.g., wind turbine model verification as-is. The data must be processed, checked and analyzed first by the user of the data.

A. Site A Measurements

The disturbance measurement campaign carried out at the Site A consisted of measurements in two locations, the wind power plant and the connection substation. The wind power plant consisted of five Type 1 wind turbines (i.e. fixed speed wind turbines) of the nominal power of 600 kW. These measurements were also described and data used in [5]. The measurements in the wind power plant were recorded of a single wind turbine and the whole wind power plant.

The measured quantities were line currents and phase-to-ground voltages of all three phases, neutral current and neutral voltage (see Fig. 1). There were six aged disturbance recorders per site and the length of the recorded data was limited to 1250 data samples. A sufficient period of data before the triggering incident was included in the measurement data sets. Due to the limitation in the number of data samples, the measurements were taken in double:

- by 3.7 kHz sampling frequency to capture the transients with better accuracy at the initiation of and during the disturbance (about 0.338 s period), and
- by 500 Hz sampling to capture a longer period of time (2.5 s) to see the wind turbine response and behavior after the disturbance and the fault clearance.

The recordings at the two locations, the wind power plant and the substation, were triggered independently from each other. At each location all the recordings were triggered simultaneously. In both locations the neutral voltage

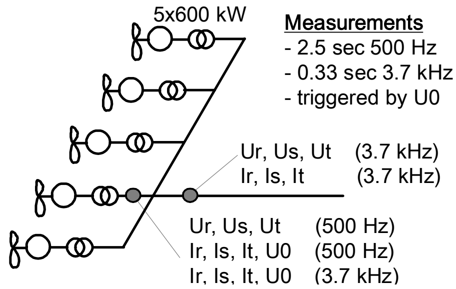

Figure 1. The measurement set-up at the wind power plant collector station in the Site A. Recorders for the quantities and their sampling frequencies for the measurements of a single wind turbine and the whole wind power plant.

exceeding 3% of phase voltage was to be used as the triggering quantity. Due to the triggering logic for the measurements, it was likely to obtain measurements both at the wind power plant and substation of the same incidents.

During the measurement campaign, data of 274 incidents was obtained. Most of the data was of different kinds of fault incidents, single-phase-to-ground, phase-to-phase, two-phase-to-ground, three-phase, and varying fault type faults. The majority of the faults took place somewhere else in the grid, and not on the wind power plant feeder connection.

B. Site B Measurements

The disturbance measurement campaign carried out at the Site B consisted of measurements in two locations, a single wind turbine and the wind power plant collector station. The wind power plant consisted of three Type 4 wind turbines (i.e., full power converter equipped variable speed wind turbines) of the nominal power of 2 MW.

The line currents and phase-to-ground voltages were planned to be measured. The measurement was at 2 kHz sampling for 1.54 s period of time, with 0.5 s of pre-fault data. The measurements were triggered independently in the two locations, i.e. at the wind turbine and the collector station of the wind power plant. It was expected to obtain measurements at both locations of the same incidents. During the measurement campaign, data of 316 incidents was obtained from the wind turbine and 15 incidents from the wind power plant collector station. Due to difficulties in adjusting the triggering logic most ideally, most of the data was of normal operation or wind turbine start-up. However, 14 wind turbine measurement data cases contained voltage dip incidents that are more interesting for further analysis in terms of wind turbine behavior due to disturbances. Simultaneous measurement data from the wind turbine and the whole wind power plant was obtained only in two voltage dip cases. In the end, it is not clear which triggering logic was used.

IV. POTENTIAL DISTURBANCE MEASUREMENT DATA ERRORS AND DATA VERIFICATION

There is always a possibility of human errors as well as a lack of information, and deficiencies and misunderstandings in the communication between people involved in a measurement campaign. In three-phase voltage and current measurements there are several possibilities for errors, both in the measurement implementation and data analysis, e.g.:

- phase-to-ground voltages were measured instead of intended phase-to-phase voltages, or vice versa;
- mixing the voltage and current pairs (i.e., the naming of the phase, or line, currents and voltages);
- the direction of the current measurement;
- using wrong data scaling coefficients or units;
- errors in the synchronization of the measurement data
  - slight delays in the data samples, e.g. due to consecutive triggering of the different quantity samples instead of simultaneous sampling of all the quantities, seen as asymmetry (although in the real-life systems there may occur actual asymmetry) or
  - different recording initiation of the data sets (e.g., three voltage sets and three current sets are not synchronized with each other).

Especially combinations of the above listed errors in the data can be deceitful and make the data seem correct without thorough and systematic data check. Most of the above listed errors could be possible to be corrected retrospectively in the data analysis phase, provided that the errors are identified first.

Often the errors are systematical in the whole measurement data set instead of concerning only a single measurement case. An error that cannot be detected in one measurement data case could be detected in another, and thus corrected in all the cases. Sometimes an error is discovered through an analysis of a large number of data cases, and could not be discovered only in an individual measurement case.

There is no clear, straight forward and universal procedure for data checking, as the measurement data and available information are very case-specific. The following sections describe several issues to be checked in the data validation. The validation steps may not be possible to be done independently and in the order they are presented. Several points may need to be considered simultaneously, especially in the case there appears to be something wrong in the data and it is difficult to pinpoint the exact error.

A. A Visual Data Check of Three-Phase Data

Plotting the three-phase data in figures, with or without the data scaling, could roughly ascertain several things, e.g.:

- the quantities are of the same three-phase system;
- appropriate symmetry of three-phase quantities;
- appropriate amplitude of three-phase quantities;
- naming/pairs of measured three-phase quantities (i.e. current–voltage data pairs, and current–current or voltage–voltage data pairs in simultaneous measurements, e.g., in different locations or by different sampling frequency);
- the voltage and current behavior during the fault period in the data (unexpected behavior could signal potential problems and the nature of these problems, although definite conclusions cannot be made).

B. Basic Calculations of Measured Data

The raw data is scaled with given data scaling coefficients, and the magnitudes are checked. Also the RMS-values of current and voltage data, as well as active and reactive power values are to be calculated and evaluated for reasonability.

The current data direction depends on the installation of the current transformers, and is basically a matter of selecting signs. In the case of sinusoidal instant current measurements, it is quite easy to check the current data sign(s), so that power is flowing from the network towards the loads and from generating units to the network.

With multiple errors in the data, the error detection may be complex. The calculated active and reactive power can be used to check the current measurement direction, provided that the data otherwise is correct.

Calculating the phasor representation of the three-phase data in normal operation period can be used for assessing the symmetry or asymmetry of the data.

C. Data Synchronism

The different three-phase quantity data sets, e.g. line currents and phase voltages, should be checked for synchronism. Also the measurements from separate locations could be checked for synchronism. The check for synchronism could be done by detecting discontinuity or transition points that can be clearly identified in the data.

In the case there are no clear discontinuity points in the relevant data series, calculating the active and reactive power could be used to evaluate current and voltage data synchronism. The phase shift between the current and voltage directly affects the active and reactive power magnitudes. The shift could be real and correct, or due to data asynchronism.

The active and reactive power magnitudes during the measurement case may be known, e.g., from other measurements, or due to the known operation range and characteristics of the turbine. In case there is uncertainty in the absolute values (or the data scaling coefficients), the ratio of reactive and active power can be calculated and assessed.

D. Phase-to-Phase or Phase-to-Ground Voltage Data

In the case of phase-to-phase voltage data, the sum of two voltage series should be equal to the inverse of the third voltage series at all times, as in

$$(u_1-u_2)+(u_2-u_3)=-(u_3-u_1) \quad (1)$$

with $u_n - u_m$ signifying a (measured) phase-to-phase voltage, and u_n and u_m signifying phase (to-ground) voltages.

E. Data Scaling Coefficients

Usually the measured raw data is not in the absolute values, but generally there are some scaling coefficients to be used to transform the data in correct magnitude in intended units. The scaling of the raw data and provided data scaling coefficient should be checked. The calculations mentioned in section B could be used for the reasonability of the given scaling coefficients. The precision of the scaling factors could be evaluated, e.g., by comparing the data to other synchronous measurements or operation range limits of the wind turbine.

F. Pairing Up the Three-Phase Quantities

The naming (e.g., R-S-T or a-b-c or 1-2-3) or pairing up the phase voltage and current measurements is of quite general nature and easy to detect when all other issues are correct. However, combined with some other errors in the data, detecting the errors in pairing up the three-phase quantities may become more complex.

V. Verification of Disturbance Measurement Data—Practical Experiences

The following illustrates how some of the errors in the data could be, and were, detected in the demonstration cases.

A. Visual Data Check of Three-Phase Data

After the initial measurement equipment installation on the Site B, the test data of normal operation was not reasonable. The voltages were not three (phase-to-ground or phase-to-phase) voltages of the same symmetrical system neither in the wind turbine nor wind power plant measurements. The measurements were corrected so that three sinusoidal data series of 50 Hz system, with approximately 120° phase shift and equal amplitude, were obtained of normal operation both in wind turbine and wind power plant measurement locations.

B. Data Synchronism

Quite ample amount of data was available from the Site A. E.g., the currents were measured at two sampling frequencies and there was data of the individual wind turbine as well as the whole wind power plant. In data plots the data seemed over all feasible. I.e., it was synchronous three-phase data with credible magnitudes and matching phase names.

A single representative case to start with, was selected to be used for wind turbine model validation. A part of the measured phase voltage and current (original, unsynchronized) data sets are presented in Fig. 2 and 3 respectively. This data case consists of a varying fault. It begins as a 2-phase short-circuit, changes to 2-phase-to-ground fault and finally to 3-phase short-circuit, after which the fault is cleared by automatic disconnection of the parallel faulted feeder line. (For the comparison of the data plots of incorrect and corrected data, the corrected synchronized current data is shown now in the Fig. 4.)

The 3.7 kHz and 500 Hz voltage data in Fig. 2 were easy to synchronize with each other for plotting. The current data sets in Fig. 3 were synchronized using the same time axis as in the voltage data. For this, it was assumed that the 500 Hz current measurement was to the opposite direction of the 3.7 kHz measurement, and the positive direction being from the grid towards the turbine. These current data seem to be quite well corresponding to each other, except for about half a cycle in the beginning of the fault. In the normal operation period the correspondence is good.

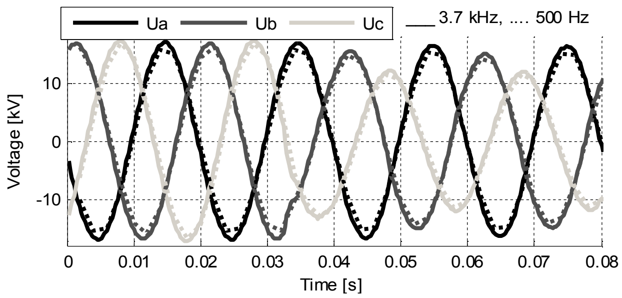

Figure 2. An excerpt of the phase voltages plotted of the 3.7 kHz and 500 Hz measurement data. A two-phase short-circuit begins right after 0.03 s.

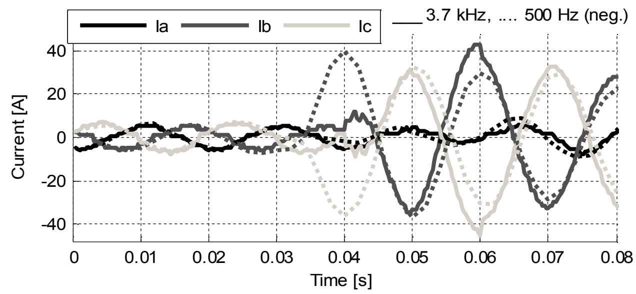

Figure 3. An excerpt of the phase currents plotted of the 3.7 kHz and 500 Hz original measurement data using the same time axis as in the voltage plot above. The 500 Hz current measurement data seems to be inverse, i.e. the positive direction is from the grid towards the turbine. The direction of 3.7 kHz measurement current data seems to be from the turbine towards the grid.

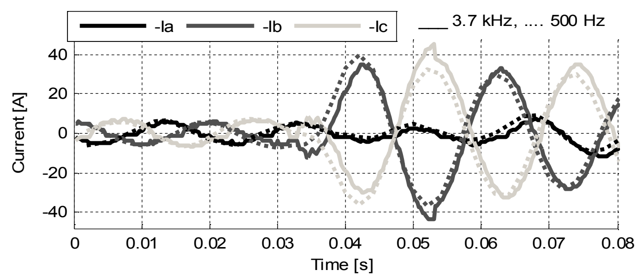

Figure 4. An excerpt of the phase currents plotted of the 3.7 kHz and 500 Hz corrected, synchronized, measurement data. The positive direction of the current measurement in both data sets is from the grid towards the turbine and thus both are plotted inverse. The 3.7 kHz current data is moved 26 data points, i.e. approximately 1/3 of a cycle to the left, and the 500 Hz data is moved 1 data point, i.e. 1/10 of a cycle, to the right on the time axis.

The active and reactive power before the fault, calculated of the original (incorrectly synchronized) 500 Hz data, were in the level of 60 kW and -140 kVar and seem somewhat reasonable.

The measured voltage (of 3.7 kHz data, seen partly in Fig. 2) at the wind turbine connection point (see Fig. 1) was used as input for EMT simulation in PSCAD/EMTDC software for wind turbine model validation. However, the model line current response did not correspond to the measured line currents. The model could be incorrect, but in this case it was discovered that the measurement data in fact had errors.

The operating points of the wind turbine can be calculated from a period of pre-fault normal operation data. The operating points of the wind turbine in all the measurement cases were calculated of the 500 Hz data, and all the PQ-operating points were plotted in Fig. 5.

The plot of PQ-data points should correspond to wind turbine PQ-operation characteristics. In this case the combined generator and capacitor bank features determine the PQ-operation. The 600 kW nominal power wind turbine reactive power operation range is down to approximately -110 kVar when considering the capacitor bank and -273 kVar without the capacitor bank in operation. In the unsynchronized, original, data the active power operating range is too narrow and reactive power operating range too wide, and the PQ-operating points are systematically unreasonable.

Based on a comparison of the Site A 500 Hz data measured at the substation and wind power plant—basically at the two ends of a line—the line current measurements at the substation were discovered having been recorded one data point later than the corresponding voltages. This is noticed also by comparing the substation 500 Hz current data to the corresponding voltage data and considering the discontinuity points in the data (i.e. the disturbance transition points).

In the 500 Hz data, even a single data point error in the data synchronism makes a huge error—of magnitude of 1/10, i.e. 36 degrees shift—in the data if not resynchronized. This error in the sinusoidal data synchronism results in significant errors as used for calculating the active and reactive power.

The original (asynchronous) and synchronized data differences are seen in the Fig. 5 with the PQ-operating points calculated of the original and synchronized, correct, data.

The PQ-operating points calculated of the synchronized data in Fig. 5 form the characteristic curve of the wind turbine. The nominal capacity of the wind turbine is 600 kW and the operating points seem to be lying within the operating range, and covering it quite well. Also the reactive power of the turbine is within the correct and reasonable range, considering that occasionally some of the capacitor bank steps (50 + 50 + 62.5 kVar) were not in operation.

In thorough inspection, the 3.7 kHz current measurement data turned out to be approximately 1/3 cycle (26 data samples) ahead of the whole wind power plant current and

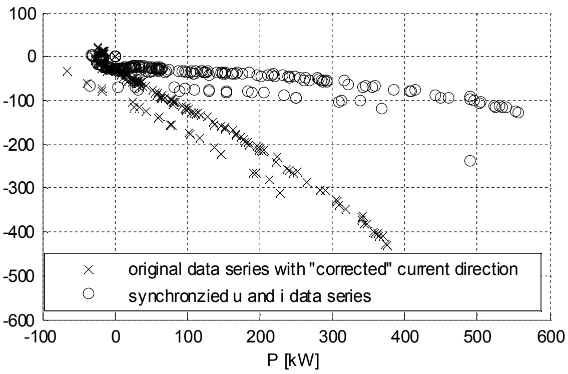

Figure 5. Comparison of the wind turbine initial operating points—the reactive power as a function of the active power. The active and reactive power were calculated assuming synchronized current and voltage data in the original data series and assuming reverse current measurement direction ("corrected"). Actually the 500 Hz sampling current recording was a single measurement step too early, and the Q(P) plots of the corrected synchronized voltage and current data series are quite different from the original data.

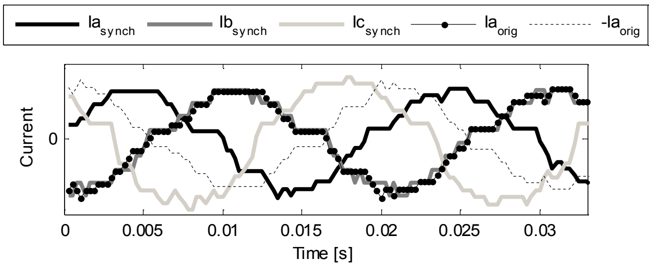

Figure 6. The initial asynchronous 3.7 kHz current measurement data of phase 'a' is compared to the synchronized current data of all three phases during normal operation. The 1/3 cycle too early started phase 'a' measurement overlaps with the synchronized phase 'b' current. The inverse of the original current data is closer to the synchronized phase 'a' current in terms of the phase shift—that could be assumed as a matter of current measurement direction and selecting sign when analyzing the initial data.

inverse (i.e., the positive direction of the current was from the network towards the wind turbine). The corrected synchronized current data are depicted in Fig. 4. Fig. 6 shows a comparison of the original unsynchronized and the corrected synchronized current data. This illustrates the difficulty of synchronization error detection in the normal operation period and instead assuming, e.g., the current data direction error.

The error of approximately 1/3 cycle shift (advancing), and inversed sign in the data can be easily left unnoticed as the initial three-phase sinusoidal data resembles quite closely the correct data especially in the normal operation. See, e.g., the normal operation period in Fig. 4. In addition, even tens of degrees error in the sine wave forms is quite unnoticeable in visual assessment of the phase voltage and current pairs (see, e.g., voltages in Fig 2 and incorrect and correct currents in Fig. 3 and 4), but in reality the error is quite significant.

With the correct synchronized data, the active and reactive power of the measurement data case in question are in the level of 130 kW and -76 kVar (compared to 60 kW and -140 kVar with 1/10 of a cycle, i.e. 36 degrees', error in the phase shift due to asynchronism of the data sets).

The data series were initially not inspected in terms of the transition points, because the data otherwise seemed feasible, rather well synchronized and reasonable. The measurement data of a real-life system naturally contain small errors, inaccuracies, slight unbalance, slight asynchronism etc., but significant errors in data synchronism were not expected.

C. Phase-to-Phase Voltage Measurements Instead of Phase-to-Ground Measurements

Considering the specified measurement set-up and the actual wind turbine characteristics, the Site B measurement data was not reasonable. The measured and scaled voltage data magnitude was totally wrong. Also the calculated active and reactive power data magnitude was wrong, as well as the QP-ratio (i.e. Q/P) was not reasonable in many measurement cases.

The Type 4 wind turbines are capable of controlling the reactive power flexibly on a wider range than many other power production units. Without exact knowledge of the used reactive power control logic, it may be difficult to assess the reasonability of the calculated reactive power. However, the reactive power control is likely to compensate the voltage rise caused by active power production.

Knowing that the provided data scaling factors were not correct, the calculated magnitudes of the data were not useful. Thus the QP-ratio was examined. In the measurement cases with a voltage dip, and the current level also varying from a case to case, the QP-ratio varied in the range of -0.5…0.3. In the cases with largest current values of all measurement cases, (i.e. larger power production) the calculated QP-ratio was approximately 0.3 (note the positive sign). The wind turbine loading measurement data have shown the wind turbine reactive power control logic in fact attempting to compensate the active power production impact on the voltage rise.

Checking the measured voltage data with equation (1) confirmed that the measured voltage data was in fact phase-to-phase voltages instead of phase-to-ground voltages. In this measurement campaign it was specifically emphasized—and even double checked afterwards from the installation staff—that the measured voltages should be phase (to-ground) voltages. Evidently there has been communication problems between people involved or/and human errors.

It is difficult to calculate accurately the phase voltages of the phase-to-phase voltages in the case when the neutral voltage has not been measured. The phase voltages are needed for the active and reactive power calculation with the earlier referred positive sequence fundamental frequency method.

However, without the neutral voltage (and assuming it now zero in the calculations) the phase voltages can be calculated of the phase-to-phase voltages. The calculated power values are fairly accurate under normal operation (i.e. symmetric three-phase quantities) and depict the wind turbine operation state with reasonable accuracy. During the unsymmetrical periods in the data, e.g., during faults, the absolute calculated power values are not accurate. If model validation is the ultimate purpose for using the measured data, and not studying the absolute power values, the mentioned method can be used as long as the same method is used for the model simulation data. This was stated and done, e.g., in [5] with even less accurate reactive power calculation method.

After transforming the measured voltage data to phase-to-ground voltages and calculating active and reactive power, the QP-ratios as well as the sign of reactive power of the measured wind turbine were reasonable (see Fig. 7).

D. Data Scaling Coefficients

The data scaling coefficients needed to be corrected for the Site B data. For this, the measurement data from the loading measurements and wind turbine controller was used. The sampling was 1 Hz in both, the continuous loading measurement, and wind turbine controller data. Thus a short-duration voltage dip may not be seen at all in the 1 Hz data as it may occur between the data samples (data sample being truly instantaneous quantity measurement, or an average over a short period). In one such case, the data sampling apparently occurred during a voltage dip. Thus the measured phase voltages and line currents as well as the active and reactive power right before the voltage dip are known. Thus the scaling

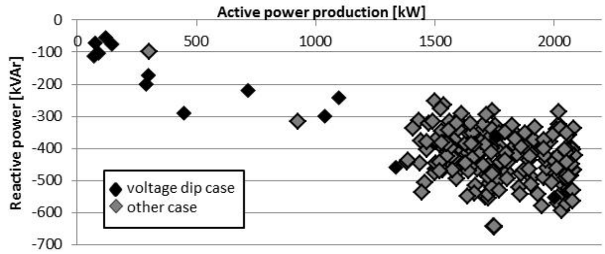

Figure 7. The measurement cases' active and reactive power in the initial (pre-fault) state. Only a few measurement cases contained a voltage dip and other cases were e.g. of normal operation and triggered for other reasons. I.e., the triggering logic for the measurements was not set quite appropriately.

coefficients were determined for the disturbance measurement voltage and current data. The determined data scaling coefficients, 1.576 for the voltage data and 3.6 for the current data, do not seem like self-explanatory values.

Based on the active and reactive power calculated with scaled and corrected voltage and current data, it was confirmed that the disturbance measurement voltages were in fact phase-to-phase voltages. The pre-fault wind turbine PQ-operating points in the measurement cases are shown in Fig. 7. These values are in a reasonable wind turbine operating range.

VI. CONCLUSIONS

This paper highlights potential problems faced in disturbance measurement campaigns, and in the measurement data. The problems, problem detection and possible solutions are illustrated by experiences of two measurement campaigns.

The measurement data must be verified and analyzed before being used, e.g., for wind turbine model validation purposes. Otherwise there is a possibility of false conclusions of actual system operation and incorrect modelling. The measurement data may seem to be correct and feasible, although the data, the assumptions of the data, or measurement setup in fact contain errors.

Over all, it ought to be remembered that the data must be analyzed as a whole and may contain multiple easy to detect and correct errors that together can disguise each other.

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