

On Field Monitoring Design

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Abstract

Transforming a diagnostic technique into a monitoring product imposes a large number of challenges, both known and unknown. This paper will discuss a number of the known technical challenges that has been encountered in our history, like considerations on system properties, sensors, platform choice and algorithm design. To detect the unknown challenges as early as possible, field prototypes and pilots are needed and considerations on those are discussed.

The paper ends by discussing some aspects of monitoring applications that we have designed in the past in light of the presented challenges.

1. Introduction

Substantial academic and industrial effort is spent on developing valuable diagnostic techniques. With diagnostics, the status of the test object can be manually assessed at selected occasions. The assessment can be made either in a laboratory or at site, on-line or off-line. When enough experience has been gained on a diagnostic method, interest may rise to perform the assessment more frequently and in service. This means that the diagnostic technique should be transformed into monitoring where most of the activity is performed automatically and mainly the final assessment is done by a human.

With monitoring, the measurements can be made more frequently and with a greater stability as the same sensors and acquisition system are used, in contrast to occasional diagnostics performed by different persons and equipment. In this sense, monitoring may be more informative than diagnostics. There are however quite a number of challenges to conquer in transforming a diagnostic method into monitoring and it is the purpose of this paper to present some of the technical ones.

When a monitoring method has been in wide-spread use for sufficient time, methods to make the assessment automatic may be devised. This means that the monitoring is transformed into protection, where the action is much faster. Developing protection requires additional special considerations which are highlighted in the protection key words: dependability and reliability. This means that a protection function should never act when it should not and always act when it should, a quite difficult ambition in reality. Transformation into protection is out of the scope of this paper.

The paper will initially discuss several of items to consider when going from diagnostic to monitoring and then exemplify with two selected monitoring techniques

that we have developed in the past decades to better illustrate the more abstract and general statements made before.

It should however be noted that any presentation with this purpose is limited and biased by the author's own experience and that there are other challenges that may be as important as those mentioned here for some applications.

2. Known challenges

There are a number of more or less obvious obstacles to consider in the transformation from diagnostics to monitoring. This section will discuss some of the technically related ones, starting from the signal source and approaching the core of the monitoring: the application code.

2.1. System properties

For laboratory and off-line field diagnostics, the test voltage can be controlled to the extent required by the test. This is of course not the case for on-line monitoring as there is mainly no other option than using the system voltage. The exception is possibly methods based on injection of a test signal into an energized test object, where the author has experience of a protection application based on a dielectric response approach [1]. Test signal injection requires however additional considerations and will not be discussed here.

Unlike a laboratory test voltage source, the system voltage and frequency are only stable to the extent required for a reliable power delivery. This usually means that they are allowed to vary a few percent's. Examples of voltage and frequency variations in the Nordic grid are shown in fig. 1 and 2.

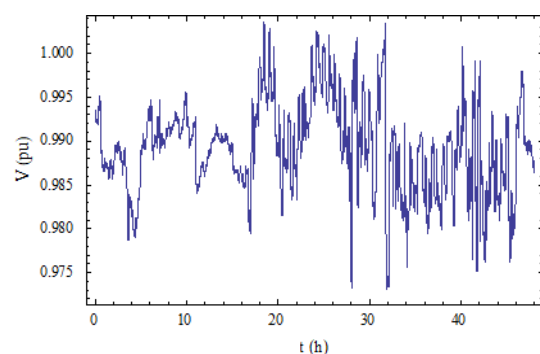


Fig. 1 – Voltage amplitude observed during two days in per unit scale.

It is therefore important to consider how the intended monitoring system will handle voltage and frequency variations of this size. Possibly frequency and voltage

estimation algorithms need to be added to the concept to enable compensation.

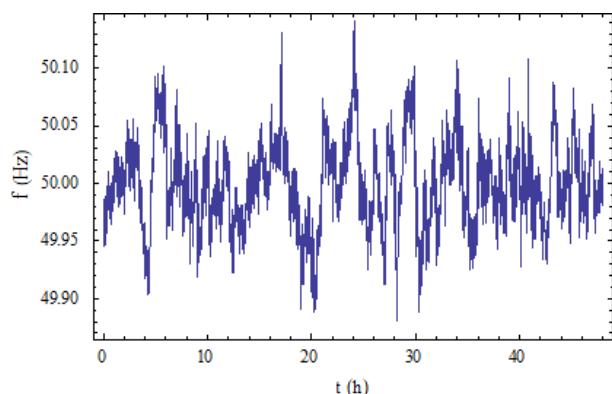


Fig. 2 – Frequency estimates during the same time period as in fig. 1.

The current is of course changing with load and may vary widely. The load will also affect both the current and voltage waveform, the latter because of the source impedance. Thus, one cannot expect stable and pure sinusoidal voltages and the analysis must be able to handle deformed waveshapes. Even under normal conditions, voltage harmonics of the order of a percent are usually present.

Another aspect of a live power system as test voltage source is that system incidents do happen. Such incidents may lead to corrupted analysis but could also be utilized as a test stimulus on the monitored equipment which may be very informative.

2.2. Sensors

The sensors employed must be very reliable as a monitoring system is intended to increase reliability. Thus, it may be a good idea to include assessment of sensor functionality in a monitoring system, which would at least make it possible to disregard false results caused by sensor problems.

Reliability requires that the design and mounting of additional sensors must be carefully considered. It should not be possible for a monitoring sensor to cause a system trip under any circumstances.

Accuracy is another sensor concern. For example, advanced sensors with control electronics, such as Hall effect sensors, often have a dead band just below the stated accuracy and thus cannot be used if the precision requirements are higher. Further, some common current clamps are found to have a time constant of a minute or so to adjust to the last percent of a sudden change, while voltage dividers may be temperature dependent.

If it is possible to use the existing voltage and current transformers in a substation to obtain the required signals, the reliability is guaranteed by their design and the development work reduced. Instrument transformers have however some limitations:

- The accuracy is usually around 1 %, never better than 0.2 %. Experience shows however that they are stable about an order of magnitude better than the stated accuracy.

- The frequency range of voltage transformers is very limited, about 30 – 800 Hz.
- The frequency range of current transformers is better, about 30 – 100 kHz.
- Current transformers may show a linearity error below some percent of nominal current.

2.3. Platform

The “platform” is the hardware that will perform the monitoring tasks. Thus, it hosts hardware for:

- Signal conditioning and digitalization.
- Digital analysis.
- Logging, communication and presentation.

It is not necessary that all functions are within a single hardware unit which will be exemplified below.

The platform is the main physical item in the monitoring and thus cost critical. Developing a custom platform requires large resources, not the least because of additional demands, such as cybersecurity and environmental compliance.

If the monitoring can be hosted in an existing commercial platform, most of the additional platform concerns have been solved by others and possibly the only contribution is the monitoring code. When total hosting is not possible it is attractive to consider a hybrid solution with some simpler hardware that feeds a commercial host with data.

2.4. Robust algorithm design

The algorithms must be designed to be as immune as possible to system events and sensor deficiencies. A basic approach here is to study differences or ratios rather than absolute values. These may be computed based on the history of the same sensor, a comparison between sensors or a combination. As the stability of instrument transformers usually is ten times better than their accuracy, this will increase the monitoring precision. For comparison of two different sensors, correction factors may be needed to eliminate offset caused by small differences in the sensor’s individual sensitivity.

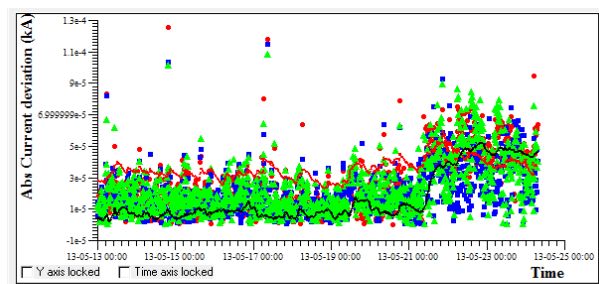


Fig. 3 – Outlier detection example: A graph from transformer performance monitor where the average and standard deviation (lines) are unaffected by up to 2 consecutive outliers.

Outlier detection is an important method to handle system events, large or small. An outlier detection method can however discard important fast changes in the monitored object if not properly designed. To avoid such algorithm failures, a useful practice is to only

classify a limited number of consecutive measurements as outliers; if more occur, a change is detected. A simple approach to outlier detection is to calculate average and standard deviation of the measured or derived quantities, an example is shown in fig. 3.

2.5. Coding

While the coding of diagnostic measurements may be simple and non-critical, coding monitoring is much more demanding and should not be done by temporary resources, like students or consultants. If the monitoring application is successful and becomes widely spread, revisions and modifications are sure to be needed many times. Therefore, detailed knowledge of the code must be preserved.

To simplify maintenance, the code structure, the “architecture”, is of high importance. Primarily this means that the code should be divided into well-defined sub-tasks for reusability and clarity. Thus, signal acquisition tasks should be separated from other tasks as the acquisition device may change. It is highly recommended to separate analysis calculation from presentation, as the analysis results are also needed for logging and possible communication to high-level asset management systems. Many product companies and utilities are presently developing their own asset management systems and would require data from all monitoring applications. There is however no real standardized interface for such communications, thus the best that can be done in the first stage is to have the monitoring results available for any kind of communication added later.

Another important architectural consideration is to be able to trace back the analysis result to the original data. This is important during development but also when problems are seen during the actual monitoring.

Log files are an important end result. These should contain enough information to recalculate the analysis for problem solving. Open, preferably text, file formats are highly recommended.

The programming language and environment is of less importance, often the best choice is the coder’s favorite. For product prototypes or hosted applications, the host platform decides. Nevertheless, arrangements for testing and debugging with realistic data during development must be arranged.

3. Unknown challenges

Despite the rather extensive list of known challenges above, surprises will occur. The best method to find surprises early is to have realistic data available during the method development, this section will discuss a few options to acquire such data. The author never attempts any serious monitoring design without access to field recordings of data similar to what the intended application will see.

A key point is to get a realistic estimate of the noise level, as this is one of the primary limitations. Noise

levels are almost impossible to estimate without field measurements; even an increase of a factor two in the noise level may change an application from promising to impossible.

3.1. Pre-information from field

It is clear from the above and the requirement on test data for code development that realistic field data is needed early in the development. This may require a temporary field acquisition campaign that just records and performs no analysis. How such campaigns can be arranged is discussed below.

An interesting option is if the application requirements are such that standard disturbance recorders, abundant in most sub-stations, can be utilized. If so, no special campaign is needed, you need only to ask a friendly utility for some records. Disturbance recorders are generally characterized by:

- Sample rates in the range 1 – 10 kS/s and 16-bit precision, recording time 2 – 10 s. Records are stored in standard COMTRADE [2] format.
- Usually, disturbance recorders are set to only record at large system events. These are (fortunately) rare and it may not be relevant for your application to analyze such data. There is however usually an option to manually trigger disturbance records.
- Disturbance records are typically intended to analyze protection performance. Thus, they may only record signals that are important for protection, which may mean that mainly currents are recorded and maybe only one voltage. Check that your important signals are recorded.

3.2. Laboratory equipment in field

A field recording campaign using laboratory equipment is required if disturbance records are not an option. Such campaigns need to be carefully prepared as it may be more or less difficult to modify them once installed.



Fig. 4 – Current clamps mounted on current transformers secondary circuit.

If the standard instrument transformers can be utilized, installation can be made without an outage if secondary sensors are employed as shown in figs. 4 and 5. All

utilities prefer to avoid outages and therefore such a solution is attractive.

The output level of instrument transformers is standardized, most often 110 V and 5 A, and one can use resistive dividers and current clamps to adapt the signal level to the data acquisition unit employed. A standard laptop is often sufficient to control the acquisition and save captured signals. Remote control of the computer can be arranged by a cell phone modem but take caution with cybersecurity risks. We have had such field stations running for many years, the oldest has been running for about 8 years.

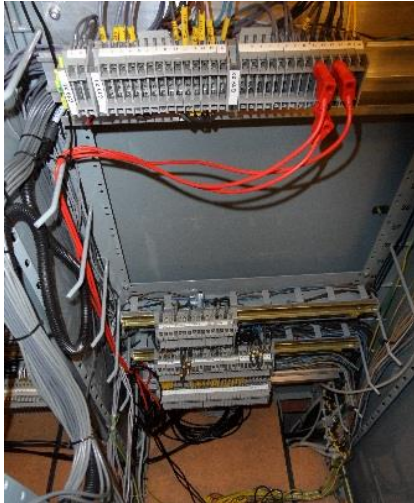


Fig. 5 – Voltage dividers on voltage transformers secondary circuits.

If a wider frequency range than offered by instrument transformers is required, special sensors and more advanced data acquisition must be employed. In such situations, consider the notes on sensor reliability above. In addition, special sensors, such as voltage sensing from a bushing tap, may need an outage to be installed. Furthermore, it may become necessary to place all equipment outdoors which implies further efforts to arrange a proper weather shielding.

3.3. Pilots

Pilot installations are the final step before a wider deployment of the monitoring solution and the main item is to certify that all functionalities perform as intended. Nevertheless, it is important to have log files that enable tracing the analysis chain from raw data to end results. Surprises are not uncommon, even at this stage, and could be caused by that the pilot site is different from the previous sites in an important aspect.

An additional use of pilots is to evaluate end-user reactions regarding installation, user interface and result interpretation. Will a user from a common utility be able to interpret the results correctly or is there a need for special assistance?

As the pilot should be connected to the utility's internal network, communication may become an issue depending on the utility's security policy. Remote control will probably not be allowed, and it may become necessary to arrange for regular transmission of logs.

4. Examples

To further illustrate the general statements above, this section will present two example applications designed by the author and co-workers. The presentation will focus on aspects related to the paper's topic, avoiding a more complete and lengthy description.

4.1. Filter capacitor monitoring

In this case, the task is to monitor capacitors in a harmonic filter for any sign of degradation. The classical approach is to employ methods based on dielectric response and monitor the capacitance and loss.

This approach is also used here but the requirements may seem impossible as the loss of the filter capacitors is about 2×10^{-4} . From the section on system and sensor properties, we recall that the accuracy of instrument transformers and the stability of frequency is only about 1%. In addition, the components of the filter are only accurate to the same level. Clearly this calls for a careful design and only changes can possibly be detected with the required accuracy.

The development was initiated with obtaining a number of disturbance records from a relevant site. These records contained bus voltages, filter currents and load currents for the three phases. A large number of fundamental-frequency phasors were extracted from these records for the further study. A "phasor" is a notation for a sinusoidal oscillation's frequency, amplitude and phase.

The filter circuit diagram, fig. 6, reveals that it connects the 5th harmonic to ground while providing negative (capacitive) reactive power at fundamental frequency.

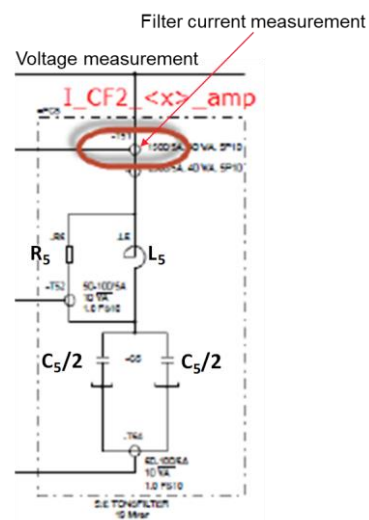


Fig. 6 – Harmonic filter circuit with voltage and current measurement points indicated.

An expression for the filter impedance can be derived from the circuit in fig. 6 and with the component values inserted, this gives an impedance of $0.015 - 5.713 j \Omega$ at 50 Hz, while the capacitor alone provides an impedance of $-5.951 j \Omega$. The impedance at fundamental frequency is thus very much dominated by the capacitor. An

estimate of the sensitivity to changes in the filter components further reveals that capacitor changes will be totally reflected in the filter impedance at fundamental frequency while changes in the inductor or resistor will only affect the impedance on the percent level.

There is a large load variation in the test data set and it is clear that individual sensors are not identical. Further the frequency varies about 0.25 %.

The impedances are simply calculated by $Z = U/I$ and the result for the test set is shown in figs. 7 and 8. There is a rather large difference between the phases due both to sensor and component offset from nominal values. In addition, each phase impedance varies about 0.3 %, probably due to varying load and other conditions.

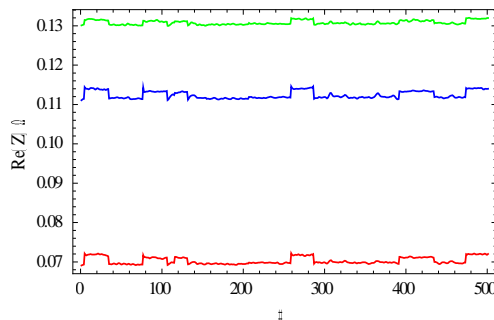


Fig. 7 – Real part of filter impedance at fundamental frequency for the three phases. Nominal value is 0.015 Ω . The x-axis indicate phasor number, which is roughly the time with some intervals.

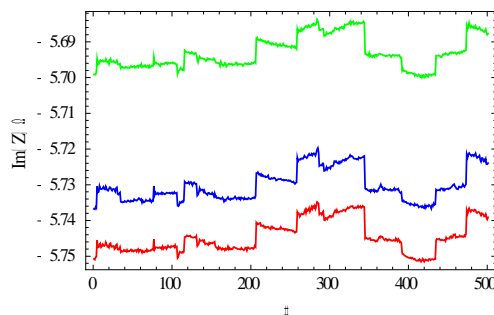


Fig. 8 – Imaginary part of filter impedance at fundamental frequency for the three phases. Nominal value is -5.713 Ω .

Frequency variations are easily accounted for but this gives here only a minor improvement. It can be observed, however, that all phases have a quite similar variation if the offset is disregarded. This becomes more apparent if the average impedance of each phase is subtracted, as shown in fig. 9. If further the common variation, indicated by a black line in fig. 9, is subtracted, a quite small variation is seen, about 1 m Ω or 2×10^{-4} , as shown in fig. 10. This is close to the requirements and probably the best that can be obtained with this data.

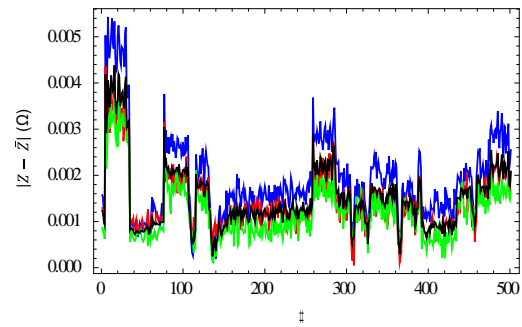


Fig. 9 – Difference to phase average for the impedances of the three phase filters. The average of the differences is indicated by a black line.

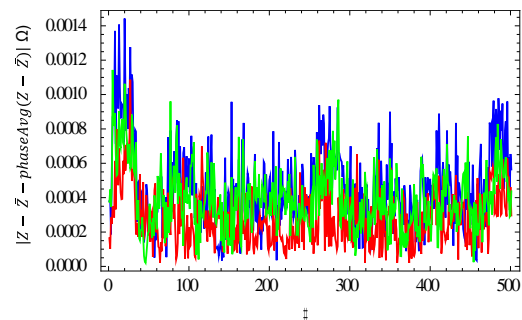


Fig. 10 – The average difference in fig. 9 is subtracted from the difference to phase average.

Thus, the analysis technique is established and a prototype implementation need to be designed. As these filters are used in FACTS and HVDC applications there is a control system with disturbance recording facilities available. The final result should be sent to a database for presentation.

The monitoring prototype design then becomes quite simple:

1. The control system regularly triggers disturbance records.
2. A custom application in the control system hardware detects new disturbance records and analyzes them.
3. The analysis result is written to a file which is read by the database controller and added to the database.

This monitoring task exemplifies many of the challenges mentioned above and we are eagerly waiting for the first pilot results.

4.2. Transformer performance monitoring

Performance monitoring implies that the normal service performance of the equipment is monitored, in contrast to most other monitoring approaches which are focused on detecting incipient faults. Performance monitoring can detect equipment problems that may not lead to faults but degraded performance or risk for faults.

For transformers, we have devised a performance monitoring method based on a simple equivalent circuit, shown in fig. 11 [3, 4]. It follows from this model how the voltage drop, ΔV , and the secondary current, I_2 , depend on the primary current, I_1 , through the magnetizing impedance and the winding impedance.

A linear fit of observed voltage drop and secondary current against primary current will thus enable on-line estimation of winding impedance, magnetizing current as well as the transformation ratio. In addition, the power loss can be estimated by comparing the power in and out of the transformer.

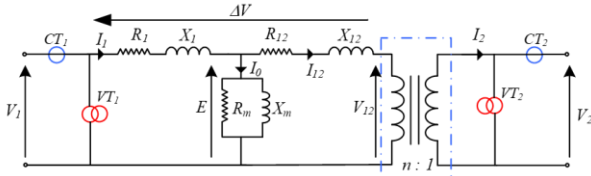


Fig. 11 – Simple equivalent circuit for a transformer including magnetization losses and winding impedance. Voltage measurement are performed at VT₁ and VT₂, while current measurements are at CT₁ and CT₂.

This approach has been extensively tested using laboratory equipment on a number of transformers during several years. Tables 1 and 2 compares some results to nominal values given on the transformer nameplate.

Table 1 – Turns ratio estimates compared to nominal values for one tested transformer.

		Tap 6	Tap 7	Tap 8	Tap 9
Turns ratio	Phase 1	4.261-0.016i	4.192-0.014i	4.122-0.01i	4.051-0.008i
	Phase 2	4.27-0.018i	4.2-0.017i	4.13-0.012i	4.057-0.009i
	Phase 3	4.264-0.025i	4.193-0.022i	4.124-0.018i	4.054-0.014i
	Nominal	4.267	4.200	4.133	4.067

Table 2 – Winding impedance estimates compared to nominal values for the same transformer.

		Tap 6	Tap 7	Tap 8	Tap 9
Impedance	Phase 1	1.36+41.02i	1.34+39.64i	1.16+38.14i	1.26+36.29i
	Phase 2	1.79+41.25i	1.68+39.79i	1.50+38.27i	1.48+36.28i
	Phase 3	1.71+41.24i	1.59+39.94i	1.38+38.39i	1.33+36.46i
	Nominal	1.44+40.05i	1.42+38.81i	1.40+37.58i	1.37+36.38i

Some surprises were of course encountered, such as higher losses during certain periods as shown in fig. 12. About 25 kW more losses were observed in these periods, to be compared to the factory measured loss of 36 kW.

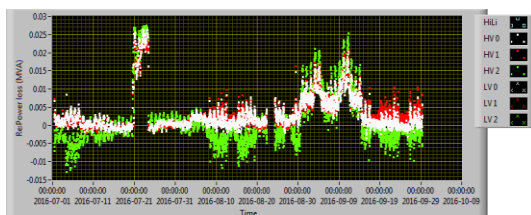


Fig. 12 – Power loss during three months of monitoring. Note the two periods with clearly higher losses.

When looking for a reason for these high losses, it was found that the times correlated perfectly with activity in a hydro-power station on the secondary side. There was thus no problems with the transformer, the losses were due to system settings. The summer before, this transformer had caused some concerns as it had gotten very hot and that summer the hydro-power station had been much more active.

Having established the value of performance monitoring, a prototype with commercial equipment was built. This system uses instrument transformers and a standard protection relay for signal acquisition. The relay communicates with a SCADA system, which hosts the analysis and presentation functions [5].

A SCADA system seems ideal for presentation of monitoring results as its purpose is to supervise all relevant parameters of a substation or an entire grid. The product version of the performance monitor is to be included in the next release.

5. Final words

The aim of this paper is to prepare the reader for the obstacles encountered in monitoring design. Quite some effort has obviously to be spent and much experience gained before a monitoring method can be offered commercially. Therefore, it is beneficial if at least some of the items discussed here are considered already when diagnostic methods are conceived.

6. Acknowledgement

The experience presented here could not have been obtained without the help of many present and former colleagues at the research facility in Västerås. In particular Nilanga Abeywickrama should be mentioned as he will continue this line of work after the authors retirement.

7. References

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