Intelligent, sensor-based condition monitoring of transformer stations in the distribution network

Christina Nicolaou*†, Ahmad Mansour*, Philipp Jung*, Max Schellenberg*, Andre Würde‡, Alexander Walukiewicz§, Jannis Nikolas Kahlen¶, Marius Shekow¶, Kristof Van Laerhoven†

*Corporate Sector Research and Advance Engineering, Robert Bosch GmbH, Renningen, Germany
Email: {christina.nicolaou2, ahmad.mansour, philipp.jung, max.schellenberg}@de.bosch.com

†Department of Electrical Engineering and Computer Science, University of Siegen, Siegen, Germany, Email: kvl@uni-siegen.de

‡ IAEW at RWTH Aachen University, Aachen, Germany, Email: a.wuerde@iaew.rwth-aachen.de

§ Messko GmbH, Oberursel, Germany, Email: a.walukiewicz@messko.com

¶Fraunhofer FIT, Cooperation Systems & Digital Energy, Sankt Augustin, Germany,
Email: {jannis.kahlen, marius.shekow}@fit.fraunhofer.de

2021 Smart Systems Integration (SSI) | 978-1-6654-4092-9/20/$31.00 ©2021 IEEE | DOI: 10.1109/SSI52265.2021.9466985

***Abstract*— Today's maintenance and renewal planning in transformer stations of energy distribution networks is mainly based on expert knowledge, experience gained from historical data as well as the knowledge gathered from regular on-site inspections. This approach is already reaching its limits due to insufficient databases and almost no information about the stations' condition being gathered between inspection intervals. A condition-based strategy that requires more maintenance for equipment with a high probability of failure is needed. Great potential is promised by intelligent sensor-based diagnostics, where objective comparability can be achieved by condition monitoring of the station fleet. Cost-effective micro-electro-mechanical (MEMS)-bases sensor systems promise to provide a suitable solution for network operators and enable a widespread use. In our paper, we present a MEMS-based sensor system, that can be used to gain information about network transparency, station safety as well as maintenance and renewal planning. Moreover, we propose an intelligent measurement scheme which adaptively selects relevant data and avoids unneeded redundancy (Smart Data instead of Big Data).**

Keywords—condition monitoring, distribution network, smart data, diagnostic

I. Introduction

Transformer substations are key components of the power grid. Their maintenance and renewal are essential for providing a safe network and ensuring a reliable power supply of consumers. This is especially the case since power transformers are often in use for decades and are therefore inevitably affected by aging and wear effects. In the high and extra-high voltage networks, a large amount of maintenance work as well as individual considerations including the use of extensive measurement technology, complex monitoring systems and diagnostic procedures are justified. The relatively small amount of transmission substations has high acquisition costs and an outage of one of them has considerable effects on the grid including high financial loss of the utility [1]. In comparison, transformer stations in the distribution network cost only a fraction of the high-power units and the consequences of a failure are less far-reaching. From an economic point of view, extensive condition assessment with cost-intensive monitoring systems such as those used at the high-voltage level is not reasonable, since the costs for online monitoring equipment are of a similar order of magnitude as those of the equipment under investigation [1]. For this reason, onsite inspections at regular intervals (every 3-4 years) using checklists were established as the standard for evaluating the condition of distribution substations. Missing data on the station condition between these intervals as well as a lack of experience with new equipment types and the impact of renewable energy feeds, complicates maintenance and renewal planning for the utilities. The devices installed today are classically operated at low load, leaving a high residual life reserve. Accelerated aging of standard equipment is expected from the effects of the reverse load flow direction and the resulting additional load caused by more decentralized feed-in systems in the classic unidirectional network [2]. A significant number of the installations already shows an increased age and is approaching the end of its calculated service life, which is why efficient and targeted maintenance is becoming increasingly important [1]. Moreover, there is an increasing pressure on utility companies to achieve a higher return of investment with lower maintenance budgets and expenses in countries with liberalized and deregulated energy markets [1].

For the evolution of the classical to an intelligent distribution grid, a condition-based strategy as well as continuous sensor-based monitoring and diagnostics are needed. Cost-effective Micro-Electro-Mechanical Systems (MEMS)-based sensor systems ensure continuous, online condition monitoring and objective comparability of the station fleet and thus reduce the subjectivity of checklists [3]. In addition to plain measurement technology, intelligent data processing as well as a comprehensible representation of the station's condition are required. One of the main challenges thereby is the distinction between significant and unnecessary data that generate no added value. The transmission of the right amount of data (Smart Data instead of Big Data) is therefore as important as the right choice of sensors and the setup of the measurement system.

In the first part of this paper, the proposed measurement system is introduced. The system requirements and the intended application scenarios as well as the selected sensors and the measurement setup to address the use cases are presented. In the second part, an intelligent measurement scheme which adaptively selects relevant data and avoids unneeded redundancy is explained.

II. Measurement System

The aim of the proposed measurement system is to monitor the general condition of distribution substations and their components online. Several automated online systems for high-voltage substations are already available on the market, especially for monitoring the key component – the power transformer. However, these do not meet all the utilities' requirements.

978-1-6654-4092-9/20/$31.00 ©2021 IEEE

A. Station Condition Monitoring Systems

Standard methods of the high-voltage level include oil ageing investigations, partial discharge detection, bushing, load and temperature monitoring as well as vibration analysis [3, 4, 5]. Such systems are only installed in strategically important or difficult to access distribution substations and are not suitable for a broad application in the distribution network. Low-cost systems on the market usually consider only single aspects of monitoring, focusing especially on network transparency, which covers consideration of the power flow and the load of individual components. Only few systems consider parameters beyond current and voltage measurements. Nelson et al. proposed a remote condition monitoring system, which continuously observes transformer loading, oil level, transformer temperature and humming sound [6]. Due to the invasive installation of temperature and oil level sensors in the transformer tank, the system is not universally applicable as a retrofit solution. With the *Netztrafo-Node* (NTN), the municipal utilities of Munich began to roll out a non-invasive online system in their distribution substations. The NTN includes the monitoring of load on low voltage side, ambient temperature and door surveillance and transmits the data via LoRaWAN to the utility [7]. Most of the mentioned systems are mainly used to monitor network transparency or do not fulfill all necessary requirements in order to achieve the greatest added value for utility operators.

B. Use Cases

In addition to the importance of network transparency and the associated load detection of the transformer as basic information of the operating condition, the guarantee of operating safe stations is important. Especially the detection of unauthorized intrusion into the stations is needed. In addition, the condition and aging of the transformer as well as of the switchgear are valuable information for the maintenance and renewal planning. Based on the ambient environment, the general condition of the station can be evaluated. Temperature and humidity values are of special interest in order to estimate the tendency to corrosion and partial discharge or to indirectly detect leakage. In addition to an advantageous selection of use cases, several requirements for the monitoring system must be fulfilled for a preferably universal implementation.

C. Requirements

Medium and especially low-voltage networks are characterized by a large collection of similar components [1]. Thereby, the individual distribution stations mainly consist of the primary technology (transformer, medium-voltage switchgear and low-voltage distribution), the optional secondary technology components (including energy meters, power system protection, communication, automation and control equipment) as well as the necessary infrastructure. Although all substations are quite similar in their functionality, there is a high diversity in their setups. This includes the building type, the different asset configurations and operating parameters, various manufacturers as well as a heterogeneous age distribution of the units. To cope with these variances, a high compatibility of the measurement system as well as generalizable data processing models are needed. This includes examining possible sensor positions for the most universal use. In addition, online capability for continuous condition assessment and a non-invasive, simple and fast installation of the system are important. For the acceptance on field level, the additional effort for the use of the system must be as low as possible and an easy handling solution must be provided. To get a meaningful picture of their station fleet for planning purposes, a retrofit solution is preferable for both new stations and especially for existing ones. Furthermore, a high availability of the system must be ensured. Shortening of intervals between inspections due to measurement systems failures must be avoided, especially since the electrical units are designed for high reliability and long-time operation. Product cycles of electronic components are much shorter compared to the typical service lifetime of transformers, which lies within a range of 30 years [4]. To overcome this obstacle, modular systems concepts are suitable, where individual components can be exchanged easily. The use of standardized hardware interfaces further provides a high degree of flexibility of the system [4]. Since most of the local network stations are not yet remotely accessible, an appropriate communication technology for a stable data transmission must be considered as well. The transmitted data must then be processed into a comprehensible visualization of the status of the utilities' transformer fleet including alarms, failure events and locations as well as measured values.

D. Sensor Selection

To cope with the described use cases and requirements, a monitoring system consisting of modular sensor systems is presented. All sensor systems feature integrated A/D conversion, amplification and correction factors, thus providing processed digital values. The first sensor system is a central sensor node for environmental parameter monitoring. For the general station status, ambient temperature, pressure and humidity measurements are considered. By means of the latter, conclusions about the susceptibility to leakages or partial discharge (PD) are to be drawn. Furthermore, unauthorized intrusion can be detected by UV- or time-of-flight sensors. Integrated are also a volatile organic compound (VOC) sensor with cross-sensitivity to ozone and a MEMS-based microphone with a frequency range up to 80kHz (ultrasound) for general PD detection. The microphone as well as an additional accelerometer can also be used for station context information. This includes the detection of switchgear actuation, vibrations acting on the station (e.g. by heavy passing traffic) and the interpretation of background noise. In addition to the measured values, a weather database is included in order to correctly classify the measured environmental parameters.

The second sensor system consists of two MEMS-based vibration sensors; a high-sensitive 3-axis sensor with a bandwidth of 3 kHz and a single-axis sensor with a high bandwidth of 20 kHz. This sensor system is used for drawing conclusions on the transformer load and aging. For the transformer aging, the tank temperature (measured by a PT100) is also considered. Temperature measurements give good information about overloading or local overheating, which has a big effect on the transformer life due to the thermal aging of the insulation.

Additionally, a network analyzer on the low voltage side is used in the development phase to label the data with load values. In further versions, cost-effective current sensors can be used as in [7]. The system can be extended with further modules such as vibration sensors on the switchgear for actuation detection or PD detection modules on bushings.

E. System Architecture

The various sensor nodes are connected via Power over Ethernet (PoE), or via Ethernet in case of the analyser, to a gateway, from where measurement data are transmitted via LTE to a server and stored in a database (see Fig. 1). The gateway itself consists of a housing, which integrates an LTE Router, a PoE switch, a power supply unit and an industrial embedded controller based on Raspberry Pi modules. The controller enables the use of "learning on the edge", since data processing functions such as feature extraction cannot only be implemented on sever side, but also on gateway side. Since sending unlimited amounts of data is not possible, the data can either be sent in fixed intervals or a gateway-side logic must be implemented. The data are made available to the operators via a dashboard.

III. Data Evaluation

In order to evaluate the monitoring system in relation to the desired use cases and especially concerning the transformer aging, the data obtained from the field must first be examined in more detail.

A. Measurement Correlations

Fig. 2 shows an example of gathered measurement data at a transformer in one distribution substation. Since temperature, load and the 100 Hz component of transformer vibrations are good indicators for transformer failures and aging effects [8], the correlation between these values is evaluated. The recognition of unambiguous conclusions in this case on transformer aging and failures is made more difficult by several factors. With a global transformer failure rate of 1-2 %, field failures are very rare [3]. It is therefore very unlikely that any type of error is detected during an evaluation phase, where only a few systems are deployed. Great variations of installed assets as well as the lack of labels in the field make it even harder to clearly identify correlations due to too many influencing factors. This is the reason why generalizable models are needed. In order to cope with these restrictions, knowledge from the context of the sensors must be incorporated (such as the relationship between load, tank temperature and vibrations). Instead of learning fingerprints of the error cases, a fingerprint of the normal state can be learned from correlations in field and laboratory data with the help of sensor- and data fusion and from reproduced error cases from laboratory experiments. Drift effects of the normal state (e.g. slowly increasing vibrations at same temperature

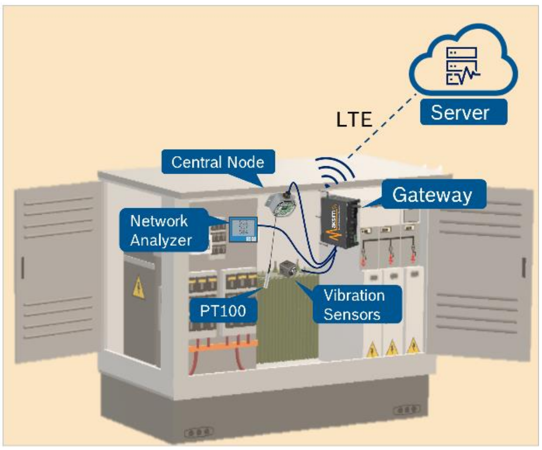

Fig. 1 Schematic illustration of the MEMS-based sensor system for condition monitoring of distribution substations

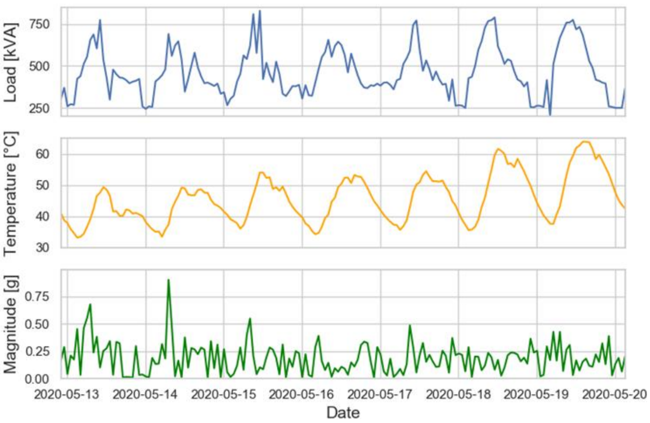

Fig. 2 Timeseries plot depicting the load, tank temperature and vibration (100 Hz component) measurements at one transformer over one week.

and load) indicate slow changes such as aging effects, while sudden changes or anomalies (e.g. suddenly increasing vibration due to loosening of the transformer's coil windings) indicate a fault.

A major challenge in learning the normal condition of the station is the limited data rate. Data cannot be sent continuously, and a lot of unprocessed data do not bring any added value to the operator. One way to deal with this problem is to send data in fixed intervals. The problem here is that if the intervals are chosen too short, unnecessarily large amounts of data are sent and if the intervals are too large, important data points are missed. To avoid this, we propose an intelligent measurement scheme, called adaptive triggering, which adaptively selects relevant data on the gateway-side and avoids unneeded redundancy (Smart Data instead of Big Data).

B. Adaptive Triggering

In case of the transformer, known relationships between the vibrations and the load exist. The 100 Hz component of core vibrations is quadratically dependent on the voltage, while the 100 Hz component of the winding vibrations are quadratically dependent on the current. To be able to prove this relationship for the different stations, a high range of different load values is preferable. When transmitting in fixed large intervals (e.g. once an hour), the chance of missing special load conditions is high (see Fig. 3, load conditions above 200 kVA are missed). Short intervals, in contrast, lead to a lot of redundant data and very high data rates. The data rate is critical, since not only load measurements are of interest, but also the corresponding vibration measurements. Only measuring the vibration every 10 s for 250 ms leads to approximately 345 Mbyte/day/sensor, which are more than 10 GB/sensor per month and therefore also a cost factor. With an algorithm that takes care of an equal distribution of data points (measurements of each load condition occur equally often), no load states are missed, while at the same time unnecessary redundancy is avoided.

The basis of this algorithm, called adaptive triggering, is the histogram representation of a measured variable, which is stored as a matrix. In the initial phase, data are recorded in a fixed interval and the histogram is initially filled. Based on the initial data, the histogram is divided into a fixed number of bins of equal width and in each case the bins' edges as well as the bins' heights are retained in the matrix. The individual measured values no longer need to be stored. In the next step, the histogram is replenished evenly (equally high bins), with

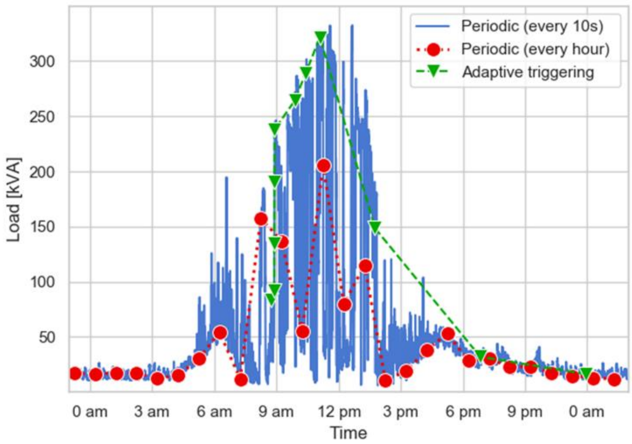

Fig. 3 Comparison of load values measured over one day in intervals of 10 s (blue) and one hour (red) and with the adaptive triggering (green).

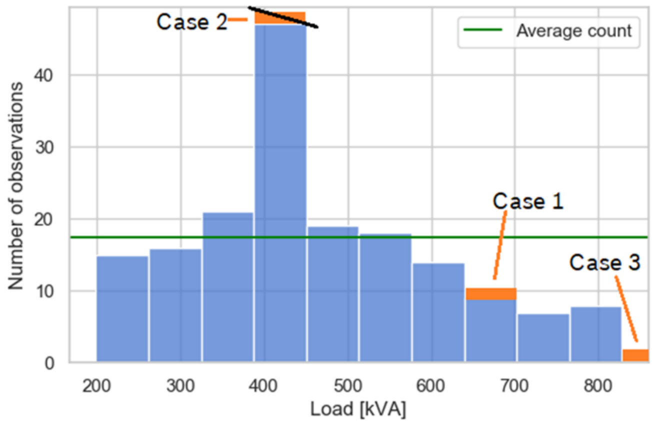

Fig. 4 Histogram and average count of the load measurements presented in Fig. 2. The different cases for a new arriving data point are marked in orange. The data points are accepted only in Case 1 and 3 and the histogram is adapted correspondingly.

the aim that only unseen or rarely taken data are included in the histogram and are also transmitted. Four different cases can be distinguished when a new data point arrives (see Fig. 4):

- Case 1 – The data point lies in a bin, in which only few data points are recorded: The data point is transmitted, and the corresponding bin height of the histogram is incremented.
- Case 2 – The height of the corresponding bin is already high (more than the average height): The data point is redundant and is therefore discarded.
- Case 3 – The data point lies outside the histograms range (lowest or highest recorded value): The data point is transmitted, and the histograms' edges and bin heights are updated (number of bins is constant).
- Case 4 – The histogram is evenly filled up: A buffer is added to the average height of the bins so that the continuous transmitting of data points is guaranteed.

The results of using the adaptive triggering for load measurements on a transformer are shown in Fig. 3. With the approach, a data reduction of a factor greater than 500 can be achieved.

IV. Conclusion

In this paper, we present a MEMS-based sensor system for condition monitoring of substations in the distribution network. In contrast to existing low-cost systems, it cannot only be used for network transparency on low voltage side, but also for evaluating the general condition and safety of the station via a central sensor node and to detect load and aging effects via temperature and vibration sensors on the transformer tank. By monitoring the condition of the station, transformer and switchgear, an improved maintenance and renewable planning on the utilities' side is possible. The monitoring system is rolled out to the first stations of the associated project partners. Open challenges include the evaluation of the presented use cases, the associated assessment of the individual sensors and the implementation of a comprehensive view on the fleet condition.

Furthermore, an intelligent measurement scheme, called adaptive triggering, is introduced, which adaptively selects relevant data to be transmitted to the utilities and avoids unneeded redundancy. This new approach promises high potential also in other applications where the amount of data must be reduced significantly.

Acknowledgment

The project (MAKSIM - Measurement, information and communication technology to digitalize the asset management of electrical distribution networks) on which this report is based was funded by the Federal Ministry for Economic Affairs and Energy under the funding code 0350035A-D. The authors are responsible for the content of this publication. They contributed to this paper as follows: C. Nicolaou, P. Jung, M. Schellenberg, A. Würde, A. Walukiewicz, J. Kahlen and M. Shekow elaborated the use cases, the sensor selection and the system architecture. C. Nicolaou and A. Mansour designed and implemented the algorithms and analyzed the data, while K. Van Laerhoven supervised the findings of this work. C. Nicolaou designed the figures and wrote the manuscript with input from A. Mansour and K. Van Laerhoven. Associated partners of the project are N-Ergie Netz GmbH, Rheinische NETZGesellschaft mbH, Regionetz GmbH and Fritz Driescher KG.

References

[1] D. Beerboom, "Objektive Zustandsbewertung von Mittelspannungsnetzen als Grundlage der Asset-Optimierung," epubli, 2017.

[2] W. Horenkamp et al., "VDE-Studie Dezentrale Energieversorgung 2020 - Gesamttext," Stresemannallee 15 60596 Frankfurt, 2007.

[3] M. Wang, A. J. Vandermaar and K. D. Srivastava, "Review of condition assessment of power transformers in service," IEEE Electrical Insulation Magazine, vol. 18, pp. 12-25, 2002.

[4] T. Leibfried, "Online monitors keep transformers in service," IEEE Computer Applications in Power, vol. 11, p. 36–42, 7 1998.

[5] S. Tenbohlen, M. Heindl, M. Jovalekic, A. Mueller and M. Siegel, "Trends of the diagnosis of high voltage equipment," in Diagnostische Elektrische Betriebsmittel, Fulda, Germany, 2012.

[6] A. A. Nelson, G. C. Jaiswal, M. S. Ballal and D. R. Tutakne, "Remote condition monitoring system for distribution transformer," in 2014 Eighteenth National Power Systems Conference (NPSC), 2014.

[7] Stadtwerke München, "Smarte Ortsnetz-Trafos durch moderne Funktechnik," Smarter World, pp. 7-10, 5/2019.

[8] A. Secic, M. Krpan and I. Kuzle, "Vibro-acoustic methods in the condition assessment of power transformers: a survey," IEEE Access, vol. 7, p. 83915–83931, 2019