On Ambient Temperature of Transformer Substations in Desert Climates

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***Abstract*—Ambient temperatures used as inputs for transformer prediction, monitoring, or aging algorithms are normally obtained from the atmospheric data available from local and international meteorological agencies. While easy to obtain and certainly useful, this data source may lead to erroneous readings as the ambient temperature, such as the proposed in the standard IEEE C57.91-2011, should be based on the air temperature in contact with the radiator of the transformer, which might divert considerably from the atmospheric temperature measured by a weather station on the vicinity. Differences can be attributed to several factors such as the distance to the meteorological stations, architectural constraints, reduced ventilation, and/or exposure to direct sunlight. These variations could affect the outcome and accuracy of algorithms used for aging prediction, maintenance, and planning. This matter is of additional importance in regions with extremely high temperatures, as transformers ratings are based on the assumption of an ambient temperature of 30 °C. To investigate this effect, this paper studied the difference between the recorded atmospheric and substation temperatures under extreme hot climates. Measurements were performed at a standard outdoor transformer station in the middle east for a year, including the summer months' harsh meteorological conditions and the milder winter, to capture significant temperature fluctuations. The data presented can provide insights for more accurate equipment aging modeling and maintenance planning.**

***Index Terms*—Transformer temperature monitoring, RFID wireless sensing, smart grids, substation maintenance.**

I. Introduction

Transformer failures have fatal consequences for the electrical grid and are therefore among the main assets monitored by network operators. During their lifetime, different stresses such as electrical disturbances, overloading, short circuits or harsh environment may lead to degradation and speed up the transformer ageing [1], [2]. Asset management determines the status and performance of transformers with the use of maintenance plans, health and end-of-life assessments [3]. A more active approach, namely condition monitoring, is based on the detection and analysis of the transformer parameters, utilizing data obtained during planned maintenance activities or using a monitoring system and sensors. Transformer monitoring coupled with solid maintenance programs have proven to have technical and economic benefits [4].

The transformer life expectancy depends mainly on hot spot temperature (playing a pivotal role in transformer insulation aging) affected by loading and ambient temperature [5]–[7]. It has to be noted that, in hot areas, the transformer loading is typically influenced by the ambient temperature due to the highly dominant thermostatically controlled loads (such as air conditioning systems), especially during summer. This pinpoints ambient temperature as an essential parameter in anticipating/identifying the transformer decay. The effect of ambient temperature on transformer life has been addressed in literature [5]–[8]. An important observation made in the aforementioned literature is that the transformer life is shorter in hot areas than in cold regions.

Standards such as the IEEE C57.91-2011 [9], quantify the effect of overloading transformers and characterize the influence of ambient temperature on accelerated aging. Under the assumption that typical air-cooled distributions transformers are engineered to work under a baseline average temperature of 30 °C [10], the standard suggests, for quick approximations, that a decrease of 1.5% of the transformer KVA rating is introduced for each degree increase of the ambient temperature. Clause 7 of the standard offers a more precise model to thermal aging [7].

Particularly, condition monitoring of transformers relies on the correctness of the input data. Temperature monitoring is generally based on three main inputs: the load, transformer internal temperatures and the ambient temperature. While data for the first two inputs are captured through sensors with a certain accuracy, the ambient temperature is normally derived from the atmospheric data available from local and international meteorological agencies [10]–[12]. Standards such as IEEE C57.91-2011 [9] define ambient temperature as "*the air in contact with its radiators or heat exchangers*", which may experience considerable variation with the meteorological temperature recorded by weather stations. Studies, such as [13], quantify that 66% of errors from field data originate from database quantization, remote ambient temperature monitoring, and an insufficient sampling rate. The research also emphasizes the unreliability of the ambient data given the distance between the temperature sensor and the transformer being monitored, which can account for as much as 6 °C. Besides the error due to location, the type of substation, weather outdoor or indoor, and architectural barriers that may impede the air circulation and add extra deviation to the ambient temperature.

Data for this study have been acquired in Qatar, which is categorized by the Köppen Climate Classification as Bwh, tropical and subtropical desert climate [14]. Similar to most locations in the Arabian Desert, during the summer, the country experiences no rainfall and extreme average temperatures of around 42 °C, reaching a maximum of 50 °C. The winter months are milder but still relatively hot, with averages of around 23 °C [15]–[17]. This study was performed on a typical outdoor transformer station across twelve months. All temperature readings were obtained by our developed wireless thermal monitoring system that is cost-efficient and noninvasive. The collected data was analyzed against the recorded average atmospheric temperature in the location and the load of the transformer. This study's main finding is that temperature data from meteorological agencies and the ambient temperature in transformer substations (air temperature in contact with the transformer's radiators) might divert significantly in desert climates. This difference can have a considerable impact on the thermal analysis used in condition monitoring systems and, consequently, in the power distribution equipment's maintenance and life expectancy.

II. Wireless Sensing System Setup

To characterize the substation temperature and its effects in the transformer radiators and body under different loading and atmospheric temperatures, a battery-less wireless temperature logging system was developed in this work. This system utilizes the passive radio-frequency identification (RFID) tag developed in [18] as the core thermal sensing device. Based on our preliminary testing, the sensing resolution (0.17 °C) and precision (±2.5 °C) of the tag satisfy the grid monitoring standards. The designed wireless thermal monitoring system is shown in Fig. 1, which consists of the thermal sensing tag, an RFID reader, a laptop for data storage, and other supporting components. For long-term testing in the desert environment, the data collection devices (commercial grade) were placed under air conditioning to avoid malfunctions. Fig. 2 shows the collected temperature data and transmission protocol between each device. Specifically, the wireless link used a back-scattering communication scheme with a carrier frequency of 900 MHz for contact-less sensing, while the wired interfaces were based on serial communication. To track the transformer thermal behavior under varied loading, the system operated at a speed of 4 samples/minute/tag.

As shown in Fig. 1, three sensor tags were deployed on the transformer in different locations using thermal glue for heat conduction and covered with a thin polyurethane foam for heat insulation from the ambient. One extra tag was used to track the temperature of the substation. Also worth noting is that the same wireless setup can be used to characterize other grid equipment operating conditions such as those proposed in [19]. Long-term measurement data can be utilized to collect insights and guide the actual equipment deployment and maintenance.

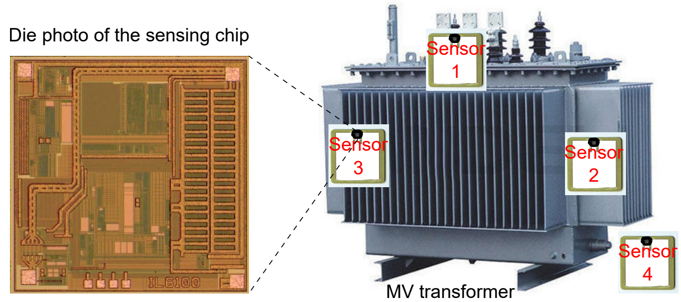

Fig. 1. System block diagram showing the deployment of the sensors (sensor 1: top surface, sensor 2: left radiator, sensor 3: right radiator, sensor 4: hang in the air).

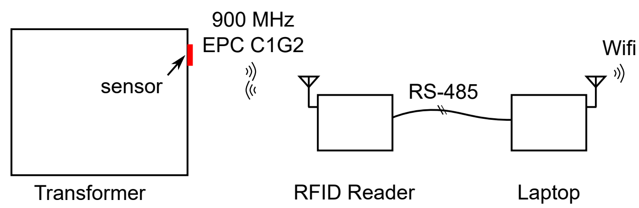

Fig. 2. Illustration of data transmission between different system components.

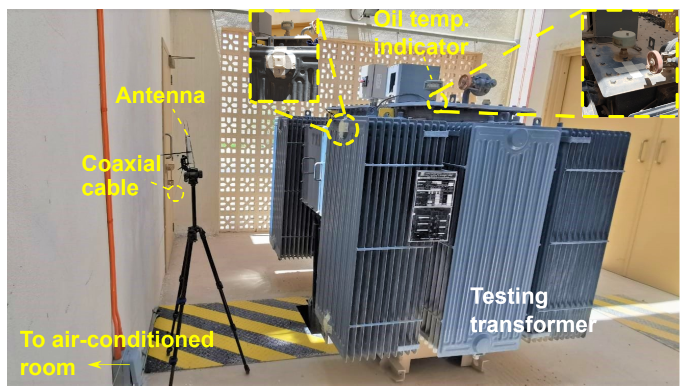

Fig. 3. Test setup with antenna mounted on a tripod and facing transformer and lattice wall

III. Experiment and Analysis

A. Field Testing

This study was performed over a complete year from July 2019 to July 2020 in a transformer substation in Qatar, with the aim of comparing the difference between the atmospheric temperature recorded and the actual temperature at the substation. Atmospheric data were obtained from the NASA Prediction Of Worldwide Energy Resources, using the temperature at 2 meters as a parameter [20]. The selected dates also allowed the capture of temperature variation in the transformer between the extreme heat summers and the mild winters of the region. Despite analyzing the load and thermal behavior of the transformer not being the testing objective,

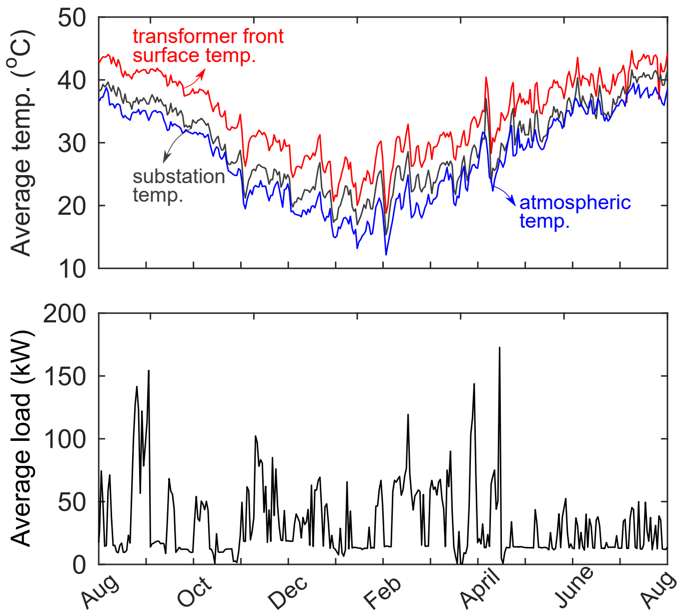

Fig. 4. General overview of recorded data.

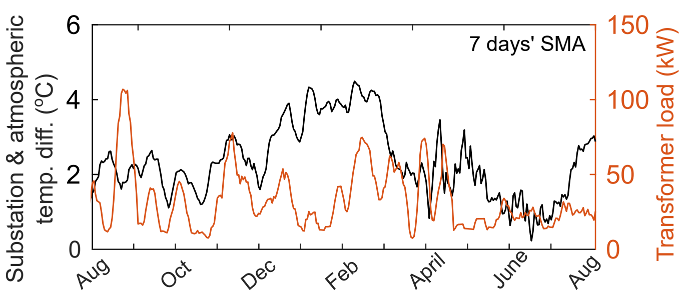

Fig. 5. Difference between the substation and atmospheric temperature vs. different load conditions (average of 7 days' data for a clearer view).

the results are shown and used as an indirect indicator of the performance of the measurement system. The transformer station selected is an outdoor, foundation-mounted substation completely surrounded by walls, except on one side where a concrete lattice wall offers some extra ventilation beside the open roof. The substation mounts two 1600 kVA oil filled transformers cooled by Oil Natural Air Natural (ONAN) means. Fig. 3 shows the simplified testing setup, including the antenna and the tag deployment. Sensors were deployed on the transformer top surface and two side radiators. An extra sensor was used to capture the ambient temperature of the substation.

B. Analysis and Discussion

An overall snapshot of the results is shown in Fig. 4, which presents the data obtained from the transformer, the temperature in the substation, the atmospheric temperature, and the load profile in kW. As reflected in the data, the selected transformer was working intermittently, alternating idle periods with peaks of 150 kW. A first glance at the data shows no clear correlation between the temperature rise in

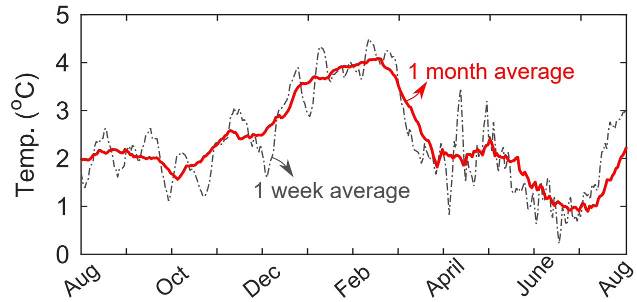

Fig. 6. Temperature difference between the substation and atmospheric temperature.

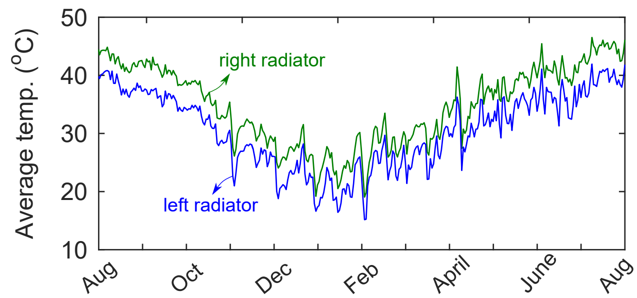

Fig. 7. Temperature profiles of the right and left radiator of the transformer.

the transformer, represented by the load peaks due to the lack of recordings from the oil temperature, and the transformer's body temperature. This result could be anticipated as surface temperature thermal modeling does not only depend on the heat transfer between the oil, inside walls, and the outer surfaces but is heavily influenced by external factors such as wind speeds and ambient temperature. Summer periods will see an ambient temperature rise and a deterioration of the cooling conditions, making the transformer's mismatch between internal and external temperatures less evident. Fig 5, reflects more accurately this point by comparing the weekly moving average of the load to the difference between the substation and atmospheric temperature. The results indicate that, as expected, the relation is more evident in milder seasons than in hot periods.

The temperature recording of Fig. 6 shows the difference between the substation and atmospheric temperature. The simple moving average indicates a 2 °C average difference during the hot season. The cooler season, with ranging temperatures from 14 °C to 22 °C represents a higher difference of approximately 4 °C. Applying the C57.91 standard, this 3 °C difference in the annual mean temperature would represent a considerable loss of life of about 1.7% per year [5], [6], [9], which was not identified nor considered in most existing age-prediction algorithms.

Since our testing was performed in the transformer closest to the lattice wall, which explains the 5 °C difference between the sensors located at opposite radiator fins shown in Fig. 7. The left radiator sensor was directly exposed to the wall with openings, while the right radiator was facing a second transformer beside it followed by a wall. The air circulation dissipation effect can also be noted in the recordings of the front top surface, one of the hot spots of the transformer, when compared with the right radiator fin, which is usually higher in all the series. This lack of symmetry emphasizes the value of standards such as IEC 62271-202 [21] based on the use of natural convection combined with the reduction of the irradiance provided by the air flow generated by the heat it produces.

IV. Conclusion

Condition monitoring systems provide reliable detection algorithms but depend highly on the accuracy of the input data. Ambient temperature is a critical parameter in transformer thermal analysis but is usually obtained from atmospheric data available from local and international meteorological agencies. Our results indicate that the differences between the atmospheric temperature and the recorded in a transformer station can vary significantly. The difference can range between 2 °C to 4 °C, depending on the season in desert climates. This disparity could have a significant impact on the operational reliability and life estimation of distribution transformers. The asymmetry in the temperature of the body of the transformer highlights the importance of following the natural ventilation recommendations for substations, especially in harsh environments. The data presented can serve as a guide for the monitoring and planning engineers employ in these regions to better estimate the maximum load of transformers and ultimately to increase their life expectancy, reduce maintenance costs and generally enhance the network reliability as a whole.

Further research in this area can provide a more dynamic understanding of the thermal behavior of transformers and help guide field engineers in performing efficient cooling and transformer load distribution. A large scale measurement program is recommended to extend the work presented and improve the transformer temperature algorithms.

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