Deployment of InAlN/GaN Hall-effect Sensors for Bucket Transformer Monitoring and Forecasting

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***Abstract*— Every transformer has a core that produces a powerful AC magnetic field while in operation, which can be measured to monitor the health and performance of the transformer in real time. However, the environment inside of a bucket transformer presents several challenges for sensor survival, including magnetic fields with leakage fluxes on the order of 300 mT, the possibility of shorts that can generate fields as high as 2.5 T, a wide range of temperatures from -40 to 140°C, and full submersion in hot mineral oil for extended periods (as long as decades). In an effort to produce magnetic field sensors that can survive within harsh transformer environments, we examined established InAlN/GaN wide bandgap Hall-effect sensors in collaboration with Prolec GE. The sensors proved capable of withstanding numerous environmental conditions inside a transformer. In addition, by integrating InAlN/GaN Hall-effect sensors with an analog-to-digital converter (ADC) and a microcontroller, real-time AC magnetic field signals were measured and stored at a sampling rate of ~1 kHz. This work demonstrates the ability to utilize embedded magnetic field sensor systems to monitor, diagnose, and forecast electric grid system health and performance via Internet-of-Thing (IoT) platforms.**

Keywords—transformer, Hall effect, InAlN/GaN, magnetic field, survival, extreme environment, Internet of Things

I. Introduction

Magnetic field sensors have a variety of useful applications including velocity sensing in vehicles and current sensing in power electronics [1]. Hall-effect sensors have several benefits over other magnetic field sensors such as low cost, ease of integration, and linearity over a wide range of fields [2]. Hall-effect sensors are typically made of silicon (Si), which has a narrow bandgap of 1.1 eV, limiting them to temperatures below 200°C [3], [4]. Wide-bandgap GaN heterostructures do not have this limitation, and have performed well under high temperatures and radiation [5], [6], [7].

In a transformer core, a primary voltage drives an alternating current through the main coil, generating an alternating magnetic field [8]. A bucket transformer presents a unique harsh environment in which sensors must measure fields alternating from < 5 mT to 300 mT, survive magnetic fluxes exceeding 2.5 T, and survive temperatures up to 140°C, all while submerged in mineral oil.

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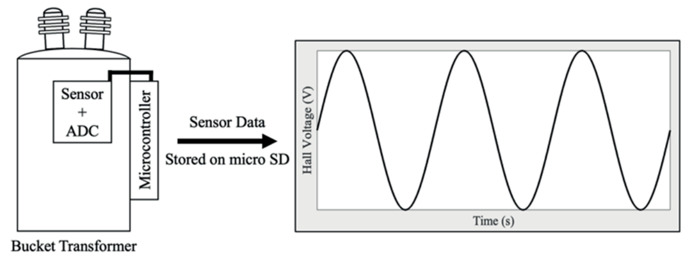

Fig. 1. Hall-effect sensor deployment concept. GaN-based Hall-effect sensors are placed inside of a bucket transformer. Real-time magnetic field strength data is collected onboard the ADC to the microcontroller, where it is then stored on an micro SD card for further analysis.

The ability to measure magnetic field strengths that span several orders of magnitude make Hall-effect sensors ideal for transformer monitoring. InAlN/GaN (indium aluminum nitride/gallium nitride) wide-bandgap Hall-effect sensors have shown promise for extreme-environment and high-temperature operation [2], [9], [10]. More specifically, Alpert et al. demonstrated promising sensitivity recovery of InAlN/GaN sensors up to 600°C for 12 hours [11]. This study focuses on the integration, testing, and deployment of a multi-point hall-sensor prototype capable of monitoring the magnetic field (and current) signatures within a transformer using these wide bandgap sensors.

II. Data Collection

Figure 1 shows the basic design concept for magnetic field data collection inside a transformer. An established microfabricated InAlN/GaN Hall-effect sensor [11] is singulated into a 2.5 × 2.5 mm die. The sensor die is then mounted onto a printed-circuit board (PCB) along with a commercial analog-to-digital converter (ADC) which combined serves as the sensor test board (STB) system. The STB system is coated in a chemically-resistant epoxy and placed inside of the oil-filled transformer. Wires run from the STB to the SAM 32-bit microcontroller (SAM32) that is outside the transformer. The SAM32 is powered by a 3.7 V Lithium Polymer battery. Data is stored on a removable micro SD card mounted on the SAM32.

A. InAlN/GaN Hall-Effect Sensors

The Hall-effect describes the phenomenon in which the path of electrons in a current is bent by the perpendicular component of an applied magnetic field of unknown strength, described by the Lorentz law. With a known current running perpendicular to the unknown magnetic field, the strength of field can be determined by measuring the mutually perpendicular voltage difference [12].

The microfabrication and response of the InAlN/GaN Hall-effect sensor used in this bucket transformer deployment study is described in [11]. While this specific transformer application did not require operation above 200°C, InAlN/GaN was selected as the sensor material platform for this design concept because of their success in other extreme environments as shown in our prior experience with these sensors [11].

B. Sensor Test Board (STB) System

The Hall-effect STB system functions as a sensor device driver and data acquisition board [13]. The STB has an onboard analog-to-digital converter (ADC) to transform analog voltage data from the InAlN/GaN Hall-effect sensor into digital data that is sent to the SAM32 microcontroller. This onboard ADC was an ADS124S08 with 24 bit resolution. STBs were constructed from a high glass transition temperature (180°C) PCB in order to survive the highest temperatures found in a transformer.

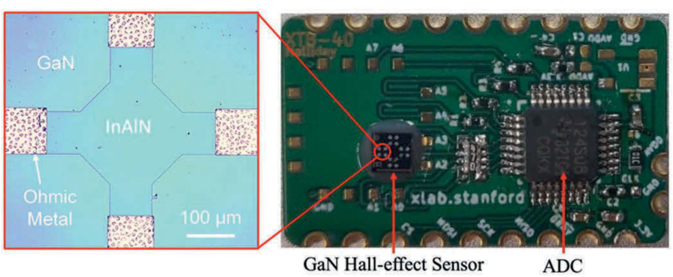

Fig. 2. GaN Hall-effect sensor mounted on sensor test board. Analog voltage data is collected by the sensor, and converted to digital data at the ADC [14].

III. Experimental Methods

To demonstrate operation in a transformer environment, the Hall-effect STB system aimed to record data in 300 mT fields with resolution better than 5 mT, operate at temperatures as high as 140°C, and survive 2.5 T fields for as long as 3 seconds. Sensors would ideally sample at 10 times the operating frequency of the transformer (60 Hz), but this preliminary study used a general purpose SAM32 microcontroller that was unable to achieve this sampling rate.

A. Operating Range Survival (0 – 300 mT)

To test the operating range and resolution, ta Lakeshore 8404 Hall Measurement System was used to expose the sensors to a range of temperatures and magnetic fields. This tool is capable of generating a DC magnetic field as high as 1.67 T at room temperature. The InAlN/GaN Hall-effect sensors were first exposed to a sweep of magnetic fields from -500 to 500 mT, with a step size of 5 mT at room temperature. Hall voltage data was not averaged, and represents the sensor's raw output. As expected, the measured Hall-effect voltage had a perfectly linear relationship with exposed B-field, indicating that the sensor had a resolution better than 5 mT. The same sensor was then exposed to a sweep of fields from -20 to 20 mT, with a step size of 0.1 mT at room temperature (Figure 3). The Hall-effect voltage plotted against the exposed magnetic field maintained nearly the same linearity and the same offset as the first sweep. From these tests, it was concluded that these sensors have a resolution better than 5.0 mT in high fields, and better than 0.1 mT in low fields.

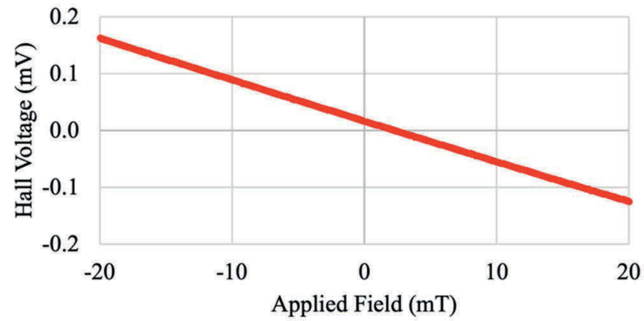

Fig. 3. Measured Hall-effect voltage versus applied magnetic field of Hall-sensor, sweeping field strengths from -20 to 20 mT with a 0.1 mT step size.

B. Maximum Flux Density (2.5 T)

When a bucket transformer shorts, it can generate a large magnetic field as high as 2.5 T for roughly three seconds. To test whether the Hall-effect STB system would survive, one sensor chip mounted on a PCB was exposed to a 3 T field for five seconds using magnetic resonance imaging (MRI).

TABLE I. Sensitivity and Offset Before and After 3 T Exposure

	Sensitivity (V/A/T)	Offset (mT)
Before Exposure	33.05	30.8
1 Hour After Exposure	32.94	30.2
1 Day After Exposure	32.68	31.7

To observe the influence of high magnetic fields on sensor performance, the current biased sensitivity and offset for a single sensor were measured before 3 T exposure, one hour after exposure, and one day after exposure (Table I). There is negligible variation in both sensitivity and offset, indicating sensor survival under maximum flux density for 5 s. Each measurement was made by sweeping the magnetic field from -20 to 20 mT with a 1.0 mT step size.

C. Variable Temperature (30 – 140°C)

A Lakeshore 8404 Hall Measurement System was also used to expose the sensors to a range of temperatures and precise magnetic fields. For each temperature from 30 to 140°C, in steps of 30°C, a sensitivity and offset measurement was collected by sweeping magnetic fields from -20 to 20 mT with a 1.0 mT step size (Figure 4). Negligible changes (less than 2%) in sensitivity and offset were observed over this temperature range.

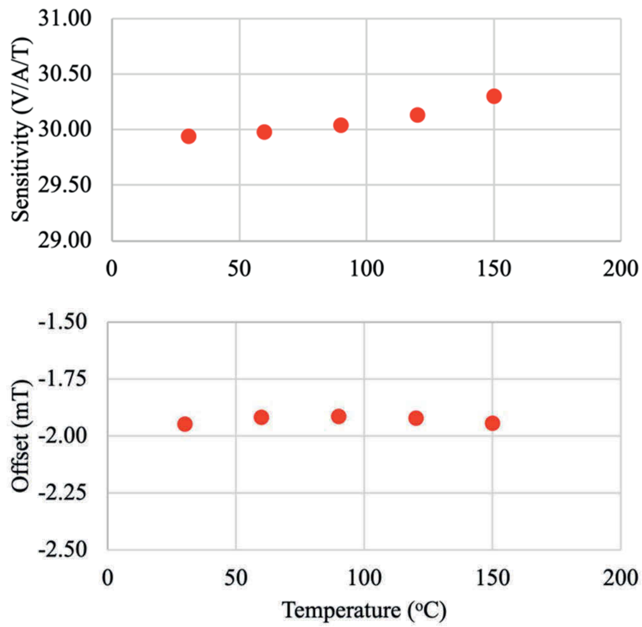

Fig. 4. Sensitivity and offset variation of InAlN/GaN Hall-effect sensor as a function of temperature from 30 to 150°C. Each data point represents a sweep of magnetic fields from -20 to 20 mT with a 1.0 mT step size.

D. *Packaging for Oil Compatibility*

To become a useful addition to existing in-field transformers, the STB system must be able to survive fully submerged in mineral oil for decades [15]. For this deployment study, EP41S-5 Chemically Resistant Epoxy from Masterbond was chosen to coat the STB and mounted sensor to prevent any deterioration. This epoxy exhibits good flow properties, good electrical insulation, and minimal volume changes during the cure process. This epoxy passed American Society for Testing and Materials (ASTM) compatibility tests. The STBs were dipped into a pool of epoxy to ensure a thick, uniform coating. Data from a single sensor indicated a 1% sensitivity increase and a 7% offset increase after epoxy coating.

IV. Sensor Network Prototype

After confirming that individual sensors can survive within the harsh environment of a transformer, a multi-point sensor prototype was developed. The prototype design goal was to independently run six STB nodes from a single SAM32, with all data being saved onto the micro SD card. This would allow the arrangement of multiple sensors around a transformer core to gain a comprehensive understanding of the core's behavior.

A. *Construction*

The prototype is a rectangle of protoboard that links the microcontroller to up to six STBs. The top of the board functions as a front end, where the user can plug in the SAM32, as well as six bundles of seven wires, with each bundle attaching to an individual STB. The underside of the board is the back end, where the shared SPI lines are daisy chained appropriately. Digital data from each STB is sent to the microcontroller and stored as a .txt file in the micro SD card.

B. *Performance in Transformer*

Numerous AC field tests were performed on a dry transformer core (Figure 5). The SAM32 was programmed to record data at the highest possible sampling rate from each STB. A small sample of data collected after several minutes is shown in Figure 5. This data was gathered when two STB systems were being run simultaneously from the prototype. Prolec GE has continued to test this prototype running six STB systems, simultaneously.

The InAlN/GaN Hall-effect sensors were able to survive the condition in commercial bucket transformers. However, the existing STB + SAM32 microcontroller are not ideal for data collection from multiple sensors. Most of the technical issues encountered were with data collection (e.g. sampling rate) rather than sensor performance.

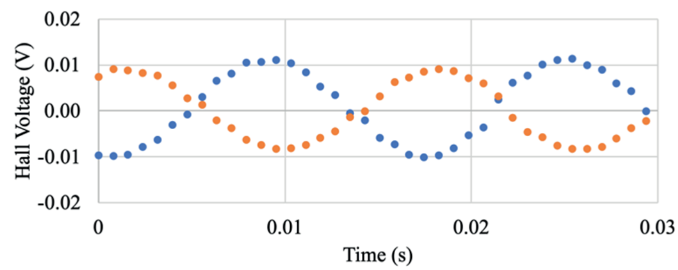

Fig. 5. Data collected from a dry bucket transformer by two sensors at 1.3 kHz sampling rate. Offset was removed from each sensor, centering their oscillations around 0 V. The difference in amplitude comes from the slight difference in sensitivities between the two sensors.

V. Conclusion

The ability of InAlN/GaN Hall-effect sensors to operate in the unique environment found within bucket transformers was demonstrated. These established sensors were integrated a commercial ADC on a high-temperature PCB and microcontrollers to develop a modular, battery-powered system that could measure and record magnetic fields. Using these sensor networks within the existing electrical grid has the potential to reduce upkeep costs in the industrial power sector.

In the prototype that was created, the daisy chaining is done outside the transformer, and forty-two wires need to go through the wall of the bucket. It is likely more advantageous to do the daisy chaining inside the transformer so that far fewer wires need to penetrate the bucket.

Similar sensor networks using wide-bandgap Hall-effect sensors can help integrate the aging electrical grid into the Internet of Things. This multi-point sensor transformer monitoring system could change the way power electronics companies conduct maintenance on their transformers, and help to build a smarter, more reliable electric grid.

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