

# Applications of Wireless Temperature Measurement Using SAW Resonators

Daniel S. Stevens<sup>1</sup>, Jeffrey C. Andle<sup>2</sup>, Sabah Sabah<sup>1</sup>, Shravan J. Jumani<sup>2</sup>, Bert W.A. Wall<sup>3</sup>,  
 Marcus Baier<sup>4</sup>, Thomas Martens<sup>3</sup>, and Richard Gruenwald<sup>3</sup>

<sup>1</sup>Vectron International, Hudson, NH USA

<sup>2</sup>SenGenuity, Hudson, NH USA

<sup>3</sup>Vectron International, Teltow, Germany

<sup>4</sup>Vectron International, Neckarbischofsheim, Germany

**Abstract**—Surface Acoustic Wave (SAW) resonators can be used to create passive (no batteries, no energy harvesting) sensor elements for wireless temperature measurement systems. This article describes a few applications of such a system and how it can be adapted to meet the requirements of these application areas. With proper design, the systems can operate in harsh environments, require little long term maintenance and lower periodic calibration. Applications for such a system can be found in high voltage electrical environments, rotating or reciprocating equipment, food safety and otherwise difficult to reach or isolated locations.

**Index Terms**— SAW temperature sensors, passive wireless sensors, SAW sensors, wireless temperature sensors, acoustic wave temperature sensors

## I. INTRODUCTION

MONITORING the temperature of moving portions of machinery and other mechanical systems can present challenges where real-time remote data communication is required. Traditional methods of measuring temperature have relied on the temperature dependence of resistance (thermistors or Resistance Temperature Detectors - RTDs), a variety of different types of thermometers, the temperature dependence of a diode junction (silicon), or the emission of infrared radiation from heated objects (IR thermometers). For the applications considered herein, passive devices, e.g. thermocouples, RTD and quartz thermometers, for example, have historically required cabled connections, slip-ring contacts, rotating connections, or battery-powered transmitters to communicate information.

Similarly, measuring the temperature of contacts and connections in high voltage switchboxes and transmission lines presents challenges. A standard requirement for these structures is that there be no metallic or fiber optic cabling from the contact or connection of interest to the supporting structure or frame, as this can cause a dangerous and potentially explosive path to ground. Infrared thermometry is sometimes employed, but this requires direct line of sight to

the area of interest, which should be clean for the best accuracy. IR is usually used for spot checking on a periodic basis and therefore not continuous monitoring. Typically the infrared measurement systems used for this type of monitoring are cost prohibitive.

Battery-powered temperature transmitting systems have drawbacks related to typical physical size and the need for oftentimes rather inconvenient periodic replacement of the battery. In general, batteries are not well suited for high temperature operation, especially above 150 °C.

SAW-based temperature sensing involves electrically inducing an acoustic wave into a piezoelectric material and then reconvertng the energy of the wave (influenced by the temperature to which the sensing element is exposed) back into an electrical signal for temperature measurement. One significant advantage of SAW devices is their passive operation, which makes them very amenable to operation in harsh environments via wireless interrogation. Passive, wireless, SAW-based sensing systems have been described in many publications [1-5] and some systems are now being offered. Some of the available systems utilize SAW resonators and some are SAW delay line based. The interrogation techniques sometimes can include coding schemes [6, 7]. Possibly the simplest and lowest cost techniques use uncoded resonators at multiple frequencies. This limits the number of unique identifiers available, but this can prove sufficient for certain applications, a few of which are discussed in this paper. With any wireless system design, the ambient RF noise environment must be understood and addressed. Each application area presents challenges requiring engineering support for mounting structures and methods, packaging, antenna design, etc., along with local regulations (e.g. FCC, CE, or UL) regarding emissions and safety requirements in hazardous environments. In the systems described herein, enclosures surrounding the SAW sensors may be well-shielded, allowing resonator frequencies that are outside of regulated frequency bands. The SenGenuity system operates from approximately 428 MHz to 439 MHz.

In these types of applications, SAW-based passive wireless temperature sensing technology offers distinct advantages

over these traditional measurement methods, including

- Passive operation, since SAW-based temperature sensors require no batteries or external power-supply. The resulting advantages over actively powered sensing solutions include:
  - Low environmental foot print as passive SAW temperature sensors avoid the adverse environmental impact of batteries.
  - Logistical advantage: The burden of regularly needing to monitor remaining battery life and replace them is eliminated.
- Electrically non-invasive solution: by not requiring wires to power/read sensors, a SAW-based temperature measurement solution can provide an electrically non-invasive solution for high power equipment such as switchgear and other Smart Grid applications.
- Wireless interrogation: SAW-based temperature sensors can be read wirelessly. This makes them well suited for rotating applications and for those applications where sensors are placed in difficult to reach or isolated locations.

The passive and wireless functionality offered by SAW based temperature sensors make them ideally suited to a wide variety of applications ranging from electrical switchgear to wireless food temperature probe systems. The following sections describe some system considerations and explore three applications where the benefits of a SAW based temperature measurement system can be used to advantage.

## II. TECHNOLOGY DESCRIPTION

The SenGenuity wireless SAW resonator (SAWR) based temperature sensing solution consists of a reader (RF Transceiver) RF or capacitively linked to one or more SAWR sensing elements as depicted in Figure 1. The system operates in a range from 428 MHz to 439 MHz.

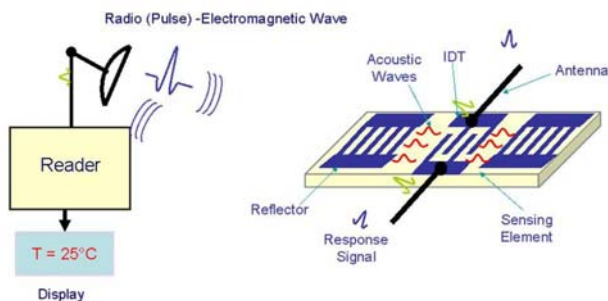


Figure 1: Wireless SAW Temperature Sensing System

Wireless sensors based on changes in resonant frequency require an appropriate reader. Two classes of reader are widely employed for resonant sensors, the most prevalent of which will be referred to as the “frequency domain” method. This method interrogates a specific frequency with a narrow-

band pulse and then measures the returned signal power. Sequentially interrogating a series of frequencies and employing an interpolation fit to the received magnitudes allows the peak resonant frequency of the sensor to be determined with relatively inexpensive electronics requiring no time domain sampling.

The downfalls to this approach are the need to carefully equalize the received signals through automatic level control (ALC) to prevent saturation and the relatively large uncertainty in frequency compared to the interrogation frequency series spacing. While the relationship between the frequency spacing of the individual interrogation pulses is intuitively obvious, the role of saturation of the received signal is less obvious. On the one hand, some degree of saturation is desired to ensure the largest possible receive signal and maximize the read range of the reader. On the other hand, saturation of the received signal causes similar receive amplitudes for multiple interrogation frequencies, making the interpolation less reliable. Furthermore, the spurious signal rejection ratio is degraded as the desired signal saturates. These effects are shown in Figure 2.

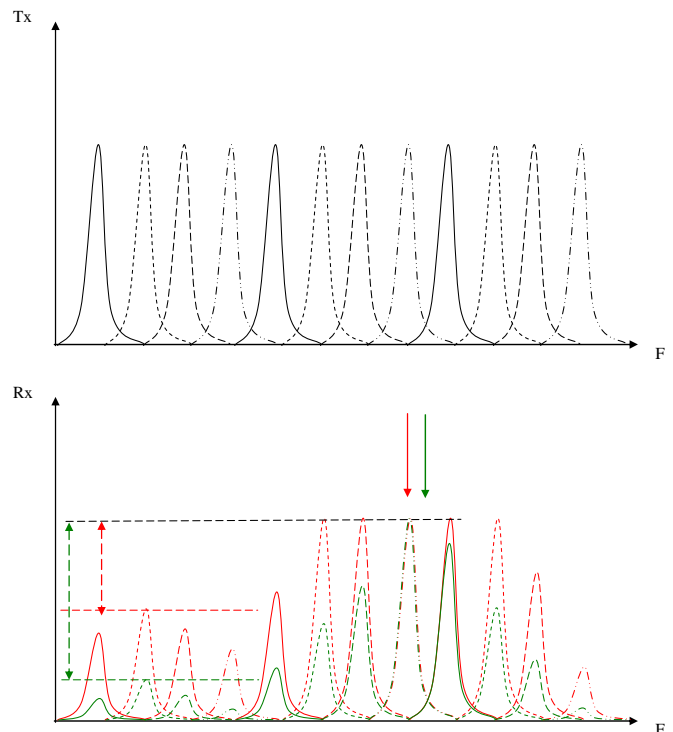


Figure 2. Twelve discrete RF transmissions at discrete interrogation frequencies are shown in the upper plot. The receive power spectral densities are shown in the lower plot. The red traces represent highly saturated signals. The green traces represent properly gain-controlled signals. The figure denotes a decreased rejection of the low side spurious signal and an error in frequency interpolation due to the saturated power spectral density of the responses.

Alternatively, a “time domain” approach to determining resonant frequency is employed [8,9]. This approach typically employs double heterodyne down-conversion with in-phase and quadrature sample streams at baseband. Direct down-

conversion and single heterodyne conversion are possible although the susceptibility to possible out-of-band spurious signals is worse. Discrete Fourier Transform (DFT) analysis of the in-phase and quadrature samples to obtain power spectral density (PSD) and curve fit interpolation of the PSD values are employed. While these extra steps incur additional electronics complexity and computational burden, they overcome the limitations of the purely “frequency domain” method. The spacing of the interrogation frequencies is primarily limited by the bandwidth of the resonator response of the sensor and the bandwidth of the pulse’s power spectral density. Saturation of the receiver is desired in the time domain samples since frequency information is not lost through saturation. The effects of saturation in frequency domain and time domain readers is analogous to the same effect in amplitude modulated (AM) versus frequency modulated (FM) radio receivers.

In the time domain, saturation tends to make the ring-down of the resonator appear longer and more uniform, resulting in better apparent accuracy, as seen in Figure 3. The degree of saturation should still be somewhat limited to prevent deterioration of the spurious signal rejection ratio.

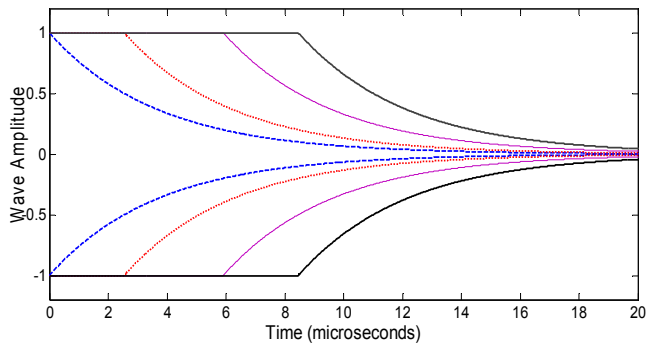


Figure 3. The decay envelope is shown for a resonator with a Q of 10,000. The blue lines indicate the received signal with no saturation. Red, purple and black indicate 2x, 5x, and 10x amplitude saturation resulting in 2.5, 6, and 8.5  $\mu$ s of apparent increase in the decay time of the digitized waveform.

The Q of the SAW resonator is a critical parameter, both as the unloaded Q and as the loaded Q determined by the radiation resistance and loss resistances of the antenna. Figure 4 illustrates that the resonator, with an unloaded Q of nearly 12,000, requires a loaded Q of at least 6,000 for high received signal strengths. A low-Q resonator of similar design is also shown with an unloaded Q of approximately 7,500. The diminished pulse width is seen to reduce the received power by 3 dB. These values of Q are readily achievable with SAW resonators.

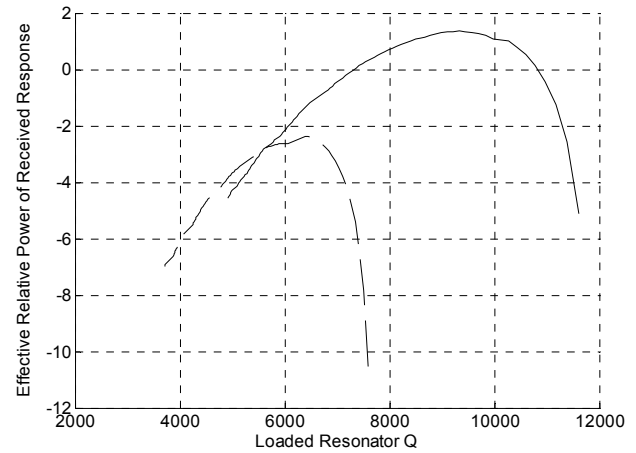


Figure 4. A SAW response with high Q (TFSS432, solid) is analyzed assuming a 1 $\mu$ s switching time between interrogation pulse and receiving and a 22  $\mu$ s receive gate time. The roll-off at very high loaded Q’s result because the wave is not sufficiently reradiated by the antenna. The roll-off at low loaded Q’s result because the pulse decays too rapidly. A resonator with unloaded Q of  $\sim$ 7,500 was also analyzed and shown to have 3 dB worse receive power.

The SAW resonators employed must, of course, be designed for the temperature range of interest, the frequency vs. temperature excursion limits which can be of both sensitivity and regulatory concerns, the accuracy required, etc. When the system relies on a single resonator’s frequency to indicate and correlate to temperature, calibration of the sensor element may be required, depending on the accuracy required. As well it is quite desirable, especially for high temperature environments, to have a low aging process that offers accuracy over prolonged periods between calibrations. Typical aging curves of specially processed SAW resonators are shown in Figure 5, which shows a very small drift of frequency with time. Use of differential measurements of two resonators with different frequency-temperature characteristics can reduce some of the error terms further.

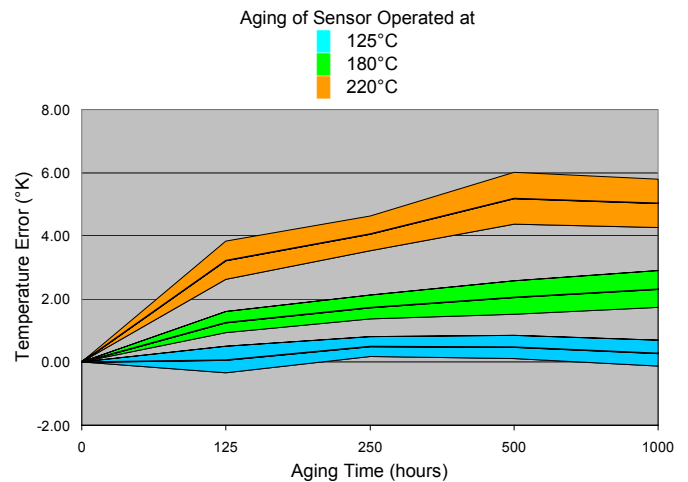


Figure 5. Typical aging curves of 433 MHz SAW resonator sensor elements at three operating temperatures show that the aging stability of the devices is suitable for accuracy requirements of a few degrees.

### III. LOW AND MEDIUM VOLTAGE SWITCHGEAR TEMPERATURE MONITORING

Thermal signatures of substation equipment, such as switchgear, can provide valuable equipment state information. Traditionally, the thermal health of electrical transmission and distribution equipment has been measured by making use of thermal imaging cameras on an audit basis, where thermal images are acquired only a few times per year. With an increasing push towards a Smart Grid, greater system reliability and wide area situational awareness, monitoring the thermal health of electrical equipment on a continuous, real-time basis is advantageous.

Switchgear, which serve as important points of control within power distribution systems, transformers and other transmission and distribution (T&D) components, are susceptible to failure if not closely monitored and controlled. Increased loads can greatly stress switchgear. The resulting increases in temperatures of critical switchgear components can cause significant degradation of metal contacts and insulation. In turn, this increases the probability of internal short-circuits or increases in contact resistance, which, if unchecked can lead to system failure and even switchbox explosions. The problem is especially relevant in emerging economies like India and China where the burgeoning need for power greatly stresses outdated legacy electric power infrastructure. Conventional methods of monitoring switchgear temperature are expensive and not entirely effective. Surface Acoustic Wave (SAW) technology can provide a passive (no battery or energy harvesting), wirelessly interrogated temperature measurement solution that is ideally suited for switchgear.

A SAW-based system for switchgear, as shown in Figure 5, includes SAW temperature sensors mounted on critical switchgear components and an antenna (not shown) which is used to establish a wireless link between the sensors and an externally mounted wireless reader.

A SAW-based temperature measurement solution for switchgear includes SAW temperature sensors mounted in different locations within the switchgear box, as shown in Figure 6, and a reader capable of interrogating multiple SAW temperature sensors in rapid sequence. The reader antenna is mounted within the box, offering good radio frequency shielding of the interrogation process by the box itself, while the interrogator is mounted outside the box, allowing all active electronics to be serviced without requiring a shutdown of power. The locally powered reader sends short RF pulses into the switchgear and, if the pulses are at the frequency of the sensor, the sensor receives, modifies and passively returns the pulses. Returned pulses contain information related to sensor temperature. Data can be transmitted to a central office over wire/fiber or can be transmitted wirelessly.



Figure 5. The interrogation unit (reader) and three typical SAW temperature sensor modules. The sensor elements are 3.8mm x 3.8mm ceramic-packaged resonators embedded in the PCB package. The coil antenna shown has been designed for operation in the vicinity of 433 MHz with a desirable radiation pattern.

Figures 6 and 7 show early prototype installations into a test switchbox. This was used to debug some of the noise issues as well as mounting concerns.

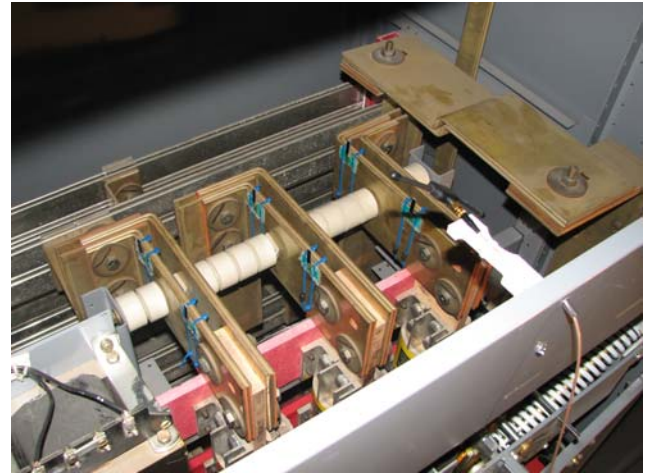


Figure 6. Installation in a low voltage switchbox. The upper picture shows installation on or near the switch contacts, using high temperature cable ties to secure the temperature sensing elements. The lower picture shows sensor modules incorporating small monopole antennas, which are adhesively mounted near bolted connections.





Figure 7: This picture shows the low voltage (408V) switchbox that was used for studying system installation issues.

The measurement systems are also deployed in medium voltage (10kV) switchboxes. The interior of the switchbox of one installation is shown in Figure 8. For this installation, a dipole antenna was selected to connect to the reader unit. Six SAWR temperature sensors are monitored, as shown in the display of Figure 9. The display shows that some of the parameters that are monitored include transmit and receive power, along with the frequency of the SAWR and the temperature. Field installations usually deploy banks of switchboxes; an example is shown in Figure 10.

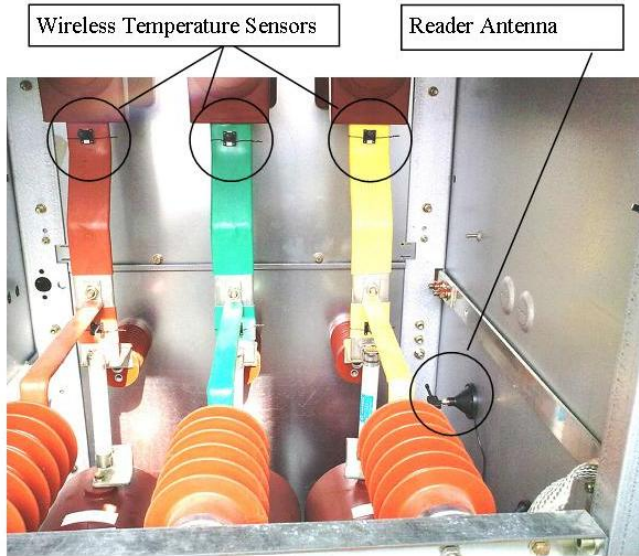


Figure 8. Installation into a medium-voltage (10-15kV) switchbox.

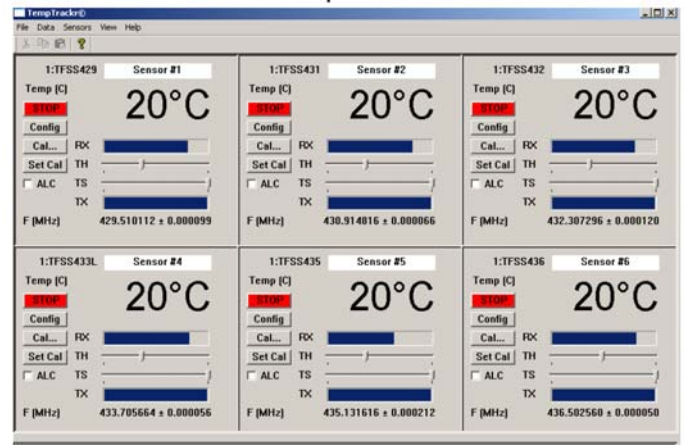


Figure 9. In standalone applications, the temperatures can be displayed as shown on this PC screen image. Typical installations embed the reader electronics into the overall system monitoring electronics.



Figure 10. A small bank of medium voltage switchboxes.

The absence of wires (to power and read the sensors) greatly reduces the potential for arc-flashing and short-circuits. Temperature measurements are obtained on a continuous, real-time basis and are used to trigger alarms based on preset threshold values. By monitoring the thermal health of switchgear, system operators can obtain early warning signs of adverse events, which can be addressed before they occur. Similar solutions can be developed for circuit-breakers, overhead transmission lines and other electrical transmission and distribution equipment.

#### IV. WIRELESS FOOD PROBE

Undercooked food can carry dangerous pathogens like *Clostridium perfringens*, *Salmonella* and *E coli*, which can cause serious illness. These pathogens can be easily eradicated from food by ensuring that it is cooked at

prescribed temperatures for prescribed amounts of time. In order to fulfill food safety requirements, commercial oven users are sometimes required to collect and maintain food temperature data for future inspection by regulatory authorities. As a result, commercial oven manufacturers (and several residential oven manufacturers) are increasingly providing food temperature probes along with their ovens. A typical food temperature probe, shown in Figure 11, consists of an RTD that is placed close to the tip of a hollow metal spike (that gets inserted into the food) and an electric cable that is used to transmit temperature data to embedded oven electronics.



Figure 11: Typical Wired Temperature Probe

While a wired food probe serves its intended function well, it has a few distinct disadvantages associated with it. Very often the cable of the wired food probe breaks if the user fails to secure it before closing the oven door. Wired probes can be difficult to clean and maintain. Some probes do not come with detachable connectors as shown above, requiring the user to clean the probes within the oven cavity. Food particles and oil can often lodge themselves into cable insulation making them look aesthetically unappealing, if not unsafe, after extended use. Commercial oven manufacturers have to accommodate specially designed manifolds and conduits within the oven to allow for the cabling required by wired food probes. This adds to the cost and complexity of manufacturing operations.

SAWR-based wireless temperature sensing technology can be used to make a wireless food temperature probe that addresses the disadvantages of wired probes. A wireless food temperature probe, shown schematically in Figure 12, consists of a SAWR temperature sensor embedded close to the tip of the probe and attached to an antenna that is contained at the end of the probe in the exposed handle. The sensor is powered and read electromagnetically by an interrogation antenna (appropriately placed within the oven cavity) connected to embedded interrogation electronics.

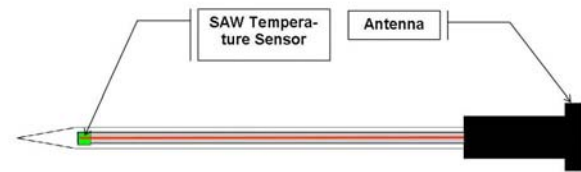


Figure 12. Schematic representation of a wireless food temperature probe

A wireless food temperature probe does away with accidental cable breakage. Further, since a wireless food temperature probe is not tethered to the oven, it can be easily cleaned, as any kitchen utensil, in a dishwasher. Lastly, a wired food temperature probe system requires no manifolds and conduits required for cabling and therefore greatly reduces manufacturing complexity and cost. Wireless food temperature probes can meet the standards of food regulatory authorities, including measurement accuracy and choice of materials used in probe construction.

## V. TEMPERATURE MONITORING IN ROTATING OR RECIPROCATING SYSTEMS

Temperatures of rotating surfaces can be measured either by making use of thermal imaging cameras or complex mechanisms like slip rings, which establish a link between the sensor (e.g. thermocouples) placed on the rotating surface and the measuring instrument. Slip rings can accommodate multiple sensors and can therefore enable the identification of hot spots and other thermal differentials on the rotating surface. However, slip rings, by virtue of being mechanical devices with sliding friction contacts, often have poor reliability and can be difficult to install and retrofit. Thermal imaging cameras can provide for a simpler, non-invasive, albeit sometimes more expensive temperature measurement solution. However, their ability to pin-point hot-spots is greatly limited by the speed of the rotating surface. The faster it rotates, the lower the ability of the camera to identify thermal differentials. Oil and grease is often found in moving mechanical systems and can easily be thrown or sprayed onto the surfaces that are to be measured. Contamination of the surfaces makes thermal measurement difficult, inaccurate, or even impossible.

SAW-based solutions provide an alternative approach to the temperature measurement of rotating surfaces. Passive SAW wireless temperature sensors are mounted on the circumference of the rotating surface and pass by a fixed, capacitive plate linked to a wireless reader, as schematically shown in Figure 13. The capacitive plate, which is coupled to the sensor directly in front of it, excites the sensing element within the sensor and carries the response signal generated by the sensor to a wireless reader unit, where it is processed for generating temperature measurements.

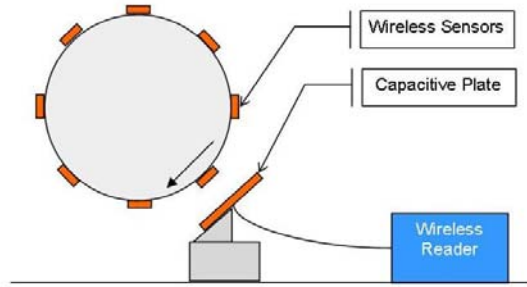


Figure 13: Wireless Rotating Temperature Solution

This SAW-based temperature measurement solution addresses the disadvantages associated with slip rings or rotating contacts and thermal imaging based solutions. Multiple temperature sensors can be mounted on the rotating surface to enable the precise identification of hot spots, providing a significant advantage over thermal imaging cameras. The wireless link established between the sensors and wireless reader, via the capacitive plate, effectively does away with the need for complex connections to the sensors. An antenna-based system can also be used, provided the appropriate numbers of individual SAW frequency resonators are employed.

## VI. CONCLUSION

SAW-based technology offers unique advantages over traditional temperature measurement methods. The passive, wireless functionality offered by SAW-based sensors make them ideal for high power applications, rotating applications and those applications where sensors need to be placed in isolated or difficult to reach locations. The applications described in this article are by no means exhaustive. They do, however, serve to illustrate the diverse application footprint that can be achieved with a SAW-based temperature measurement system.

## REFERENCES

- [1] L.M. Reindl, A. Pohl, G. Scholl, and R. Weigel, "SAW-based radio sensor systems," *IEEE Sensors Journal*, vol. 1, no. 1, pp.69–78, June 2001.
- [2] G. Scholl, C. Korden, E. Riha, C.C.W. Ruppel, U. Wolff, G. Riha, L. Reindl and R. Weigel, "SAW-based radio sensor systems for short-range applications," *IEEE Microwave Magazine*, vol.4, no.4, pp. 68-76, Dec.2003.
- [3] F. Seifert and R. Weigel, "SAW-based Radio Sensor and Communication Techniques," *27th European Microwave Conference and Exhibition*, vol. 2, no. 8-12, pp. 1323 – 1346, 1997.
- [4] R. Fachberger, G. Bruckner, R. Hauser and L. Reindl, "Wireless SAW based high-temperature measurement systems," *2006 International Frequency Control Symposium and Exposition*, pp. 358–367, 2006.
- [5] C. Hausleitner and R. Steindl, "Low cost radio interrogation system for passive SAW sensors and transponders," *Proc. 2000 Asia-Pacific Microwave Conf.e*, pp. 1589 – 1592, 2000.
- [6] D.R. Gallagher, M.W. Gallagher, N. Saldanha, J.M. Pavlina, and D.C. Malocha, "Spread spectrum orthogonal frequency coded SAW Tags and sensors using harmonic operation," *Microwave Symposium Digest*, 2009.
- [7] C.S. Hartmann, "A global SAW ID tag with large data capacity," *Proc. 2002 IEEE Ultrason. Symp.*, vol.1, pp. 65-69, 2002.
- [8] V. Kalinin, "Pulsed interrogation of the SAW torque sensor for electrical power assisted steering," *Proc. 2004 IEEE Int. Ultrason., Ferroelectrics and Freq. Control 50<sup>th</sup> Anniv. Conf.*, pp.1577-1580, 2004.
- [9] V. Kalinin, "Influence of receiver noise properties on resolution of passive wireless resonant SAW sensors," *Proc. 2005 IEEE Int. Ultrason. Symp.*, pp.1452-1455, 2005.