Transformer Monitoring System for Pole-Mounted Transformers

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***Abstract* — The Transformer Monitoring System is defined as a group of components built together in order to sense and monitor various parameters of a pole-mounted transformer that are vital to its functionality. This system has the capability of monitoring the transformer's voltage, current, and phase angles coming into and out of the lines, as well as, the overall temperature of the transformer. Once all of the data is collected, the information is then processed through an ATMEGA328 processor which analyses the current state of the transformer: normal, warning, or critical. The data then gets transferred through a Zigbee wireless protocol to a MySQL database housed on an external server. An online application retrieves the information about the transformer and displays it to the screen for a user to evaluate.**

***Index Terms* — Analog-digital circuits, condition monitoring, data analysis, distributed databases, electromagnetic induction, preventive maintenance, Zigbee**

I. Introduction

Envision a world where technological breakthroughs have created a systematic, smart grid system where transformers can talk to each other as you or I talk to one another. A world where even the slightest faults and failures of our electric power lines are noticed within a matter of seconds as opposed to hours or even days. This world may seem practical years from now, but with today's technology the future is coming sooner than one might expect. Initiatives from the United States Government to create a smart grid system have already been placed into motion. In 2003, the U.S. Department of Energy, Office of Electric Transmission and Distribution, released a document describing such initiatives.

As the framework behind the Smart Grid begins to mature, the time for individual engineers and engineering companies to construct the devices that will drive this Revolution is now. With our motivation set in stone, we present the Transformer Monitoring System (TMS).

Mounted to the transformer's pole, the monitoring system attaches to the power lines themselves through three nonelectrical contact connectors. One of the connectors uses the method of tapping to the output line in order to power the device. The other two connectors are attached to both the input and output lines in order to measure the voltages and currents. A capacitive coupling is used to sense the voltages; whereas, a current transducer determines the amounts of current. In order to measure the overall temperature of the transformer, a noncontact infrared sensor is used.

After all of the information about the transformer is collected, the data is sent to an ATMEGA328 processor. From here the processor determines if any of the values collected exceed or go under any of the warning or threshold parameters set for that particular transformer. All of the processed data then travels through a Zigbee Xbee wireless adapter which transports it to a central hub computer located away from the transformer. A desktop program, written in Java, receives the data and places it into the MySQL database for future use. Using any computer available, the user will then have access to the data through an internet application created in JavaScript with some PHP. See Fig. 1 for a visual depiction of the overall flow of data.

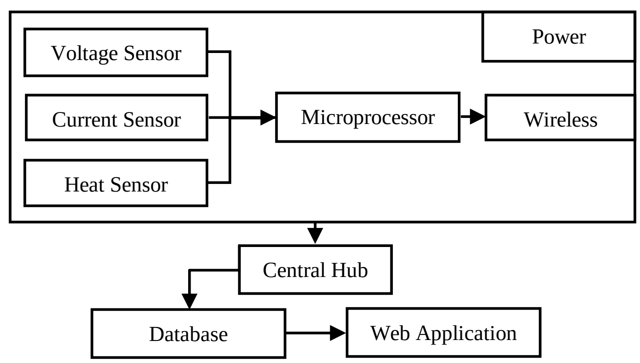

Fig. 1. Flow cycle of data from the pole mounted transformer

II. Power Supply

Since the pole mounted hardware of the monitoring system needs to be self-sufficient, the power supply must be able to adapt to a variety of conditions. The preferred method would be using an inductive coil; this would be to electrically isolate the power in the line and the power to the unit. Due to the small scale of this project and for demonstration purposes, the primary method implemented is tapping the power line.

A. Power Line Tap

Two taps were needed to insure a functional circuit, power and ground. The power is supplied by tapping the low voltage side of the transformer, typically 120V. A fusible link is placed on the line before it runs into the monitoring system box; this is to insure safety and allows for a quick check by service personnel. Ground is connected by tapping the ground line that runs in the 3-phase bundle. The power and ground leads are connected to a 24V step-down transformer mounted on the PCB, this allows for a voltage level that is useable by the system hardware. The 24V output is then passed through a full wave rectifier and smoothing capacitor. The output of the bridge rectifier is then regulated to 15V by a pair of regulators

B. Battery and Charging Circuit

One of the specifications of the monitoring system is the device must rely transformer data even when there is no power present in the transformer. This is accomplished by the use of a standard 12V sealed lead acid battery. The charging circuit for the battery is made by placing two Schottky diodes in parallel in opposite directions between the regulator output and the battery's positive terminal. This simple circuit allows for 100mA charging and a small 10mA top off charge under normal conditions and automatic battery discharge when the regulator output falls below the battery's voltage.

C. Voltage Regulation

A variety of voltages are required for the various components of the system. All voltage regulators use the TO-220 case with appropriate heat sinks. A 12V regulator is used to power the integrator circuits of the current sensors. A pair of 5V regulators is used to supply power to the IR temperature sensor, ATMEGA328 processor, and the 3.3V regulator. The 3.3V regulator is used to supply power to the Zigbee communication device. Lastly, a variable regulator with trim resistor is used to supply power to the DC-offset circuit on the sensors.

III. Voltage Sensor

The method of detecting the voltage on the power line was implemented through the use of a capacitive coupling circuit. This circuit contains three distinct sections of a capacitive plate, low-pass filter, and DC-offset circuits.

A. Capacitive Plate

Solving the equation (1) will give the magnitude of the electric field surrounding the power line.

$$E = \frac{\lambda}{2\pi\varepsilon r} \tag{1}$$

Using the known electric field, the voltage present on the plate can easily be obtained by solving

$$V = Ed\ . \tag{2}$$

Unfortunately, the electric field depends greatly on the electric permeability of the substances between the power lines conducting material and the plate in the sensor. This presents the problem of not being able to accurately calculate the electric field since the permeability of the materials is not known or at best an approximation. The implementation of this sensor now decidedly demands the use of experimentation to create a usable waveform. This was done by crafting a curved piece of aluminum with a surface area that attracted over 2 volts of charge for the given power line was to be used on.

B. Low-pass Filter

The voltage waveform that is received from the capacitive plate is riddled with distortions caused by stray capacitance and transient voltages. This waveform is unusable by the device and necessitates the use of a low pass filter. The low pass filter provides two functions; it creates a more sine wave like output and rejects high frequency noise. A simple low-pass RC filter with a cutoff frequency above 60Hz was implemented due to its low cost and small form factor was easily made to fit inside the sensor body. A resistor(s) was placed at the output of this circuit to make the amplitude of the waveform optimal for processing by the analog to digital converter. This filter is then connected to the DC-offset circuit through a capacitive couple.

C. DC-Offset

The analog to digital converters that are integrated with the ATMEGA328 only read voltages between 0 to 1.1 volts. This creates the need for the DC-offset circuit. Since the ATMEGA328 will be reading the peak to peak voltages of the waveform the need for a precise DC offset is not critical. This is why we used a simple resistive voltage divider circuit, with a dedicated voltage regulator on the power supply. We opted to use resistors in the mega-ohm range to minimize current flow, thus leading to lower power consumption.

D. Construction

The housing method used for the construction of the voltage sensors that was implemented was a clam shell style. The inner wall was made from ¾ inch diameter PVC pipe with a thick wall, the capacitive plate was then affixed to this. The outer wall consists of 2 inch diameter

PVC pipe. The space between these two layers is filled with unsaturated polyester resin to provide structural strength and weather proofing. During prototyping of the capacitive sensors, the need for attention to shielding arose. Since the filter and DC-offset circuits are built into the sensor, stray EMF created a high level of transient voltages. These transient voltages then caused the output of the sensor to be completely unusable. The solution to this problem was to create shielding that protected the circuits on all sides through the use of making the circuit housing out of aluminum. Data transmission was protected through the use of commonly found shielded data cable. Since shielded data cables that are also rated for outside use are not cost-effective for our purposes, the use of water tight conduit was used to protect the data cable from weather.

IV. Current Sensor

The method implemented to detect the amount of current flowing through power line was the use of a Rogowski coil type sensor. The sensor used in this project consists of three parts: a coil, low-pass RC filter, and a DC-offset circuit.

A. Current Transducer

As current passes through the power line it creates magnetic field, the strength of this field is given by

$$\beta = \frac{\mu_0 I}{2\pi r}. \quad (3)$$

Once the magnetic field is known, the magnetic flux can be easily determined by solving

$$\phi = \frac{\Delta\beta}{\Delta t}. \quad (4)$$

Using the magnetic flux, finding the voltage induced on the coils can be attained by solving

$$V_{coil} = NA\Phi. \quad (5)$$

Because the amount of voltage induced on the coils is relative to the magnetic permeability of the materials between the power line and the magnet wire of the coils. Solving the equations can only serve as bases of finding a starting point for a coil prototype, this is due to the fact that the permeability of the materials used is not known and can only be estimated. The consequences of this estimation lead to the design of the coil being based on the physical diameter and length needed and not the desired voltage. The implementation of a current transducer is fairly simple and straight forward. Laminated transformer core material of 2 inch diameter was used to create a structure for the coils, 29 AWG magnet wire was then wound tightly around the core. Both ends of the wire were then soldered to the circuit board located within the sensor housing. Rubber electrical tape was then wrapped around the coil to protect the fragile magnet wire during final construction.

B. Low Pass Filter

Since the coil acts as an AC current source, we connected the output across a voltage sensing resistor to create a voltage sine wave output. This output was riddled with significant voltage spikes. To correct this, a low pass RC filter was used. The filter not only brought the output closer to a perfect sine wave, it also effectively blocked all high frequency noise.

C. DC-Offset

Since the analog to digital converters only accept voltages between 0 to 1.1 volts, there is a need for the DC-offset circuit. Since only peak to peak voltages will be read, the need for a precise DC offset is not critical. This is why we implemented a simple resistive voltage divider circuit, with the same dedicated voltage regulator as the voltage sensors on the power supply. We opted to use resistors in the mega-ohm range to minimize current flow, thus leading to lower power consumption. A coupling capacitor was used at the input to prevent DC flowing to the integrator circuit output. The output was smoothed further more by using a smoothing capacitor.

D. Construction

The construction of the current sensor housing is very similar to the housing used for the voltage sensors. This is due the desire for the voltage and current sensor to be in the same body if it was to be installed on an actual power line. The housing method used for the construction of the current sensors is again of a clam shell design. The inner wall was made from ¾ inch diameter PVC pipe with a thick wall, the Rogowski coil is then attached to inner core material. The outer wall consists of 2 inch diameter PVC pipe. The space between these two layers is filled with unsaturated polyester resin to provide structural strength and weather proofing. As in the voltage sensor prototyping, the need for shielding arose. Since the integrator, filter, and DC-offset circuits are built into the sensor, stray EMF created a high level of transient voltages. These transient voltages then caused the output of the sensor to be completely unusable. The solution to this problem was to once again, build an aluminum cage around the circuit board. Data transmission was protected through the use of commonly found shielded data cable and the use of watertight conduit.

V. TEMPERATURE SENSOR

The sensor chosen to take in temperature is the Melexis MLX90614ESF-AAA. It is an infrared sensor with memory, and it communicates to the microprocessor using PWM. The device measures the surface temperatures of objects placed in front of it. The component has a measurement resolution of 0.02°C and is factory calibrated for a wide -70°C to 380°C object temperature range. There are four pins on the device, and they are as follows: 3.3V supply, ground, clock, and PWM output. The temperature is reported in Kelvin, and converted to Fahrenheit on the ATMEGA328.

VI. ATMEL ATMEGA328 MICROPROCESSOR

The Atmel ATMEGA328 microprocessor will detect information from the sensors, process that information, and relay the information to the central hub. There will be five sensors that will be connected to the microprocessor. These sensors monitor the input voltage and input current of the transformer, the output voltage and output current of the transformer, and the surface temperature of the transformer. The three parameters that will be monitored are the peak-to-peak voltage from each line sensor, the phase difference between the voltage and current sinusoidal waveforms, and transformer surface temperature.

The processor will make calculations based on inputs from the sensors. The voltage and current sensors on the input and output side of the transformer will provide an AC waveform at 60Hz to the 10 bit analog to digital converters within the microprocessor.. The low and high values of the sinusoidal waveform will be within the range of 0mV to1000mV. The microprocessor will calculate the peak-to-peak voltage, the phase shift between the two line sensors on both the input and output sides of the transformer. The infrared temperature sensor will be pointed at the surface of the transformer and will provide serial temperature data to the microprocessor.

The microprocessor will calculate the peak-to-peak voltage of the sinusoidal waveform from each of the four line sensors. It will take three voltage readings from the analog to digital converters. These readings will be value between 0 and 1023 where 1023 represents the reference voltage and 0 represents ground. Each reading will be 1 millisecond apart. To measure the maximum voltage of the waveform it will continue to take readings until the second reading is greater than the first and third reading. To measure the minimum voltage of the waveform it will continue to take readings until the second reading is less than the first and third reading. It will then subtract the minimum reading from the maximum reading. It will multiply that value by the 1.1 reference voltage and divide it by 1023. The result is the peak-to-peak voltage of the waveform.

The phase shift between the voltage and current sinusoidal waveforms will be calculated by the microprocessor. When a maximum value is realized on a voltage waveform the microprocessor will record a timestamp in milliseconds. Then it will wait until a maximum value is detected on the current waveform and record another timestamp in microseconds. The processor will then compute the phase shift by multiplying the time elapsed between the peaks by the frequency and multiply the result by 360. In case the processor fails to detect the peak on the current waveform that immediately follows the voltage waveform, the processor will divide the result by 360 and use the remainder as the phase shift value. Also, phase shift will be recorded as values between -180 and +180. If a phase shift value is greater than 180 the processor will subtract 180 from the value and multiply it by -1.

The microprocessor will determine the state of each monitored parameter and the overall state of the transformer. Three states will be defined in order of severity as normal, warning, and critical. The peak-to-peak voltage and current parameters that are monitored on the input and output sides of the transformer will have both low and high threshold values for warning and critical states. Threshold values will also be assigned to the phase angles between the voltage and current waveforms and the temperature parameter. These parameters will consist of both a warning and critical threshold value. A detailed explanation of the threshold values affect the states can be seen in Fig 2.

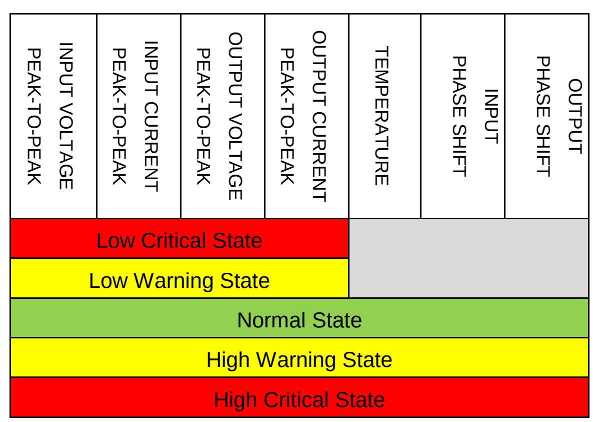

Fig. 2. Visualization of the threshold values affected states.

The threshold values that will be used to determine the states can be updated by the central hub through the XBEE network. These values will be sent in a predefined format so that the microprocessor will be able to read in the data and assign each value to the proper threshold variable. The format of the data that the microprocessor will be monitoring is as follows:

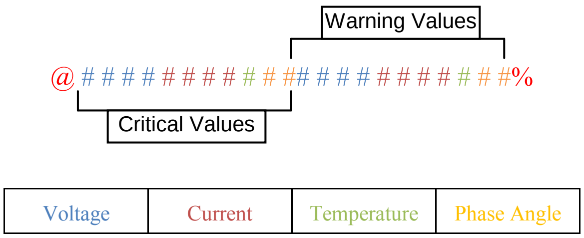

Fig. 3. Visualization of the formatted string received by the microprocessor. The color key below the string shows which sections are delegated for the various transformer parameters.

Every pound sign (#) represents the quantity of the measured variable. Look at Fig. 3 for example, blue are all of the voltage threshold values for that particular transformer. The first four are the critical ranges for both the low and high side of the power lines connecting to the transformer, whereas, the second four are the warning ranges. A color key was added to show the overall break down of the formatted string. In order to start or end the string a "@" or "%" must be used in that exact order. This allows the Zigbee a chance to stop sending a string and/or start a new string in the middle of a current transmission if need be.

The microprocessor will also transmit the data and calculations that it has made to the central hub. It will transmit upon request from the central hub, or by a transmit timer every 30, 1, or 1/2 minute(s) depending upon whether it is in a normal, warning, or critical state respectively. Whenever the microprocessor transmits data by request of the central hub the transmit timer will restart. The central hub will transmit the character "*" to request an update from the microprocessor. The microprocessor will transmit the data as follows:

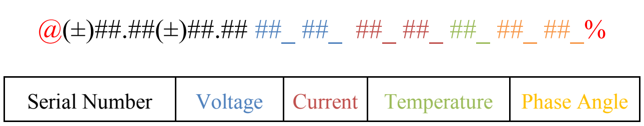

Fig. 4. Visualization of the formatted string transmitted by the microprocessor. The color key below the string shows which sections are delegated for the various transformer parameters.

Just like the receiving string format in Fig. 3, every pound sign (#) represents the quantity of the measured variable. Unlike the last format, Fig. 4 includes the states for every variable that is monitored on the transformer as denoted by the "_". There, one of three characters will be place to represent if that variable exceeded or fell under any of the threshold values: a "$" represents the variable having a normal state, "?" represents the variable falling within the warning ranges, and a "!" represents the variable passing any of the critical values. Not only is the processor sending the quality of the variables but also the serial number associated with those values. This number is explained later on in section VI.

The pins on the microprocessor will be connected to the components on the transformer monitoring system through a printed circuit board. The components will connect to the pins as listed in Table 1.

TABLE 1
Pin Assignments

PIN	PIN NAME	ASSIGNMENT
23	PC0	INPUT VOLTAGE SINOSOIDAL WAVEFORM PEAK-TO-PEAK
24	PC1	INPUT CURRENT SINOSOIDAL WAVEFORM PEAK-TO-PEAK
25	PC2	OUTPUT VOLTAGE SINOSOIDAL WAVEFORM PEAK-TO-PEAK
26	PC3	OUTPUT CURRENT SINOSOIDAL WAVEFORM PEAK-TO-PEAK
27	PC4	TEMPERATURE MONITOR SCL
28	PC5	TEMPEATURE MONITOR SDA
2	PD0	RECEIVE SERIAL DATA FROM XBEE
3	PD1	TRANSMIT SERIAL DATA TO XBEE
7	VCC	5 VOLT SUPPLY
8	GND	GROUND

V. Communications

The requirements of the project were to produce a device not only capable of monitoring a power transformer, but also of making sure that the information can be transmitted to and interpreted by a central hub station. The hub station is able to communicate with multiple monitoring boxes, and the network is able to self-heal nodes that are no longer functioning. The monitoring boxes are expected to be about a mile apart from each other. An example of our mesh network with all possible connections is shown in Fig. 5.

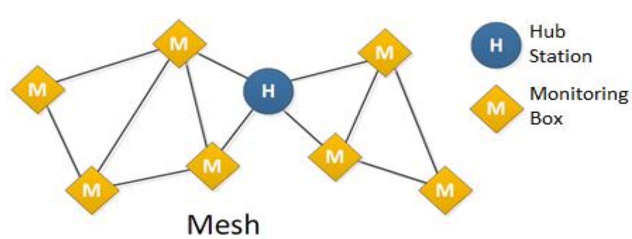

Fig. 5. Example of Mesh Network used for the Transformer Monitoring System. This takes into consideration all connections, so some lines shown here are redundant. The actual system would not use all of the shown paths.

Each monitoring box is able to accept communication that changes certain values such as the threshold voltage, current, and temperature variables. There also exists the ability for a hub station to change the identification number of the transformer for reporting purposes.

Because of the potential for wired systems to go down during storms or emergencies, we ruled out wired communication, and we chose to go with XBee Zigbee PRO Series 2 Modules. Zigbee is a wireless mesh networking protocol that is based on the IEEE 802.15.4 standard. It handles the organization of the mesh network and the addressing methods. The protocol is able to self-heal if a node is missing. Zigbee networks contain three nodes. These nodes are coordinator, router, and end device nodes as shown in Fig. 6.

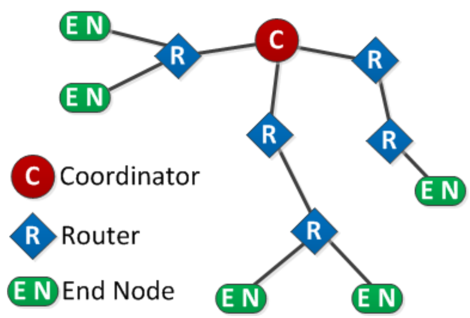

Fig. 6. A model of the different node types in a Zigbee network. Notice how the end nodes do not route information to other nodes.

From Fig.6 we will use two nodes. One node will be the coordinator type, and one will be the router type. This ensures that there no lack of service in case a node is no longer functioning. A router is able to reorganize the network to send data around the no longer functioning node. The main reason why the End Device node does not fit the requirements of the Transformer Monitoring System is that it is unable to route information; it can only receive and send to one other node.

One of the largest off-the-shelf suppliers of the Zigbee devices is Digi, and they come in the form of XBee modules. From recommendations and other proven examples that we have seen, the team has chosen to use XBee devices because of reliability and ease of use. All XBee Zigbee devices found during research operate on a 2.4Ghz frequency. The devices used for this project are advertised to have a line-of-sight transmit distance of 2 miles. The antennas approved by the FCC for XBee Zigbee devices are omni-directional antennas. The omni-directional single element antenna we have chosen has 9dBi gain.

XBee devices can act as wireless serial ports. For example, if two XBee devices are properly connected to two different personal computers, they will show up as COM ports, and they data entered on one computer over the COM port will show up as received data on the COM port of the other computer. XBee devices have four primary pins for communication. They are as follows: Clear To Send, Ready To Send, Transmit, and Receive. From testing, it has been demonstrated unnecssary to utilize the Clear To Send and Ready To Send pins. The transmit and receive pins are able to be connected directly to the Atmel ATMEGA328 microprocessor, because it is also powered on 3.3V, which is what the XBee also uses. The XBee module used by the coordinator is connected to the hub station through a USB port. The main adjustment needed to communicate through the USB port is to convert all the 5V signals to 3.3V, and vice-versa.

VI. Central Hub Computer

After the data has been passed along to the USB port a desktop program, the Daemon, then parses the information and stores the valuable information into the database. Recall that the user is able to view the information through an internet application that gains access to the database. From the USB port to the user's computer screen, it is critical that the flow of data does not get interrupted or stopped for a prolonged period of time. This will lead to loss in accuracy since data would not be logged properly.

A. Daemon Program

The Daemon program is given its name due to the fact that it handles the connection between the USB port and the database while running in the background without the user's control. Made to be fault retardant, the Daemon program is coded in Java and can restart itself if errors cause it to crash. In case of system malfunctions the program is totally isolated from the web application for safety measures. It is important for the two programs to be separated so that even if one of the two programs crashes there will always be a way for the data to get logged into the database.

B. MySQL Database

After the data is parsed it is sent to a MySQL database for storage. Inside of the database there are eleven fields for every transformer with a fixed allocation of bits as shown in Table 2.

TABLE 2
Transformer Parameters

Transformer Parameters	Parameter Types	Allocation of Bits
Serial Number	Value(22)	22
Longitude	Value(11)	11
Latitude	Value(11)	11
Time Stamp	Time	-
Voltage In	Int	5
Voltage Out	Int	5
Current In	Int	5
Current Out	Int	5
Temperature	Int	3
Phase Angle In	Int	3
Phase Angle Out	Int	3

Basically every transformer has its own serial number associated to it. This serial number is the concatenation of its longitude and latitude decimal representation. Since no two objects can occupy the same location at the same time, we felt like this serial number is adequate enough to call it unique. This is important since the database sorts and keeps tracks of every log based on the serial number. If any transformers were to share the same serial number then the information within the database could become unusable.

Although the database groups the data by transformer serial number, it also keeps the most recent up-to-date information lying on top of the stack. As mentioned earlier, the Transformer Monitoring System will send in data to the central hub every 30 minutes and possibly every 5 seconds. Though it is important to keep old information, the users generally would like to know what the current status of their transformers are. This is the reason why the database stores the transformer's time stamp as it is read in. Grouping like this becomes extremely important later on when trying to visually show the user what is going on in with their transformer.

C. Web Application Program

In order to display the contents of the database for the user to see and interpret, a Google Maps API was integrated into the JavaScript code that we wrote. With Google's technology at our disposal, we were able to create a state of the art way of keeping track of every transformer's location and status in a nice, neat, organized visual manner. How it works is simple. Every transformer's longitude and latitude gets marked on the map by a little transformer icon. Once all of the transformers inside of the database are loaded, the user then has the capability to either change the viewing area or analyze any transformers currently on the screen.

The ability to change the viewing area is exactly like that of the actual website maps.Google. Since the API utilizes the same basics, users have the options to enter in a country, state, city, address, zip code, etc. Once the user presses enter however, a new filter is created for that particular place. To remove the hassle of always having to enter in the place, filters are saved to the database for future use. As the user adds more transformers to their grid system around the state or country, the user has the potential of monitoring more than one region in a fast and effortless manner through the use of filter tabs. Every time the user opens up the web application the previous tabs are loaded until the user manually deletes them.

One interesting aspect of the web application is its way of showing the user which transformers are normal, warning, or critical. As mentioned before, when the program loads the locations of the transformers are marked with little transform icons. Those icons change color based upon which state the transformer is in. If the transformer is normal then the color of the icon is green, in a warning state yellow and if it is in a critical state red. At any time the user can double click on that icon to view a much more detail look into what is cause those errors. This is also the place where the user has the capability to change any of the threshold values that might be tripping the alarms.

The final aspect of the web application is the safety protocol that is put in place. Every time the user travels to the web application, a user login will be displayed to the screen prompting for a user name and password. This ensures that no outsiders are able to gain easy access to information the user has collected. Due to user login names being stored into the database, each user will have his/her own set of filters.

VI. Conclusion

The Transformer Monitoring System is capable of keeping track of power transformers. Each monitoring box has five sensors as follows: two current sensors, two voltage sensors, and one temperature sensor from Melexis. The custom built sensors and the temperature sensor values are received by the microprocessor, which compares them to programmed to threshold values. The surpassed threshold values determine how often the microprocessor transmits information using the XBee device over the mesh network. The transmitted values are received by the central hub station, which maps the monitoring boxes to locations using Google maps.

The two-semester senior design course has been beneficial to all the members of this team. We have learned about the power grid, power transformers, and different techniques on how to measure voltage and current, more about microprocessors, and the basics of how to transmit information over a mesh network

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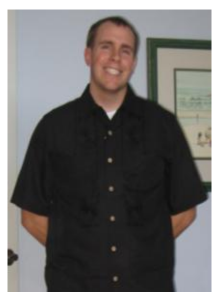
Bradley Tanner, a senior student of the electrical engineering department at University of Central Florida, will graduate in the summer of 2011. He is planning on moving overseas to the Middle East in hopes to work in the power field.

Jonathan Rowe, a senior student of the electrical engineering department at University of Central Florida, will graduate in the fall of 2011. He is currently working with Lockheed Martin and will continue in the fall.

Charles Payne, a senior student of the electrical engineering department at University of Central Florida, will graduate in the summer of 2011. He is planning on starting his full time carrier with Lockheed Martin come graduation.



Robert Howard, a senior student of the electrical engineering department at University of Central Florida, will graduate in the fall of 2011. He is currently looking for an internship for the fall with hopes of a full time job offer in the spring