A wireless mesh system monitors and controls electrical heater systems.
WIRELESS MESH FOR MONITORING AND CONTROLLING ELECTRICAL
HEATER SYSTEMS

Priority Claim

This present application claims benefit and priority of United States Provisional Patent Application 60/863054 filed October 26, 2006.

The present invention includes a wireless mesh system for monitoring and controlling electrical heater systems.

Background of the Invention

In order to optimally monitor and control an electrical heater system several parameters are measured. These include but are not limited to the temperature of the device or area being heated by the heater, the supply voltage to the heater, the current flowing through the heating device and the ground fault leakage current from the supply circuit to earth ground.

In many existing heater control systems the measurement of these parameters are carried out through sensor devices that are connected to a control or monitoring panel through discrete and dedicated wires. For example, temperature can be monitored by a thermocouple or RTD (Resistance Temperature Device) connected to the control panel
through two (2) special conductor wires for thermocouple devices and two (2) or three (3)
copper wires for the RTD devices.

Total supply current and ground fault leakage current can be measured by current
transformers that generate an AC voltage. For total supply current, a single conductor
can be passed through a current transformer and generate a voltage in proportion to the
magnitude of the supply current flowing through the current transformer. Both supply
and return conductors, e.g., line and neutral, can be passed together through a single
current transformer such that an AC voltage is generated only if there is an imbalance in
the magnitude of the supply current versus the return current; such imbalance being
indicative of a leakage of current to ground. The voltage output of the current
transformers can be connected to the control and monitoring panels using dedicated
copper wires.

Supply voltage can be directly monitored by running dedicated wires to the
monitoring panel at the full supply voltage or through an intervening step down
transformer that reduces the supply voltage by a known ratio in order to avoid high
voltages at the monitoring location. Typically insulated copper wire would be used to
connect the point at which the supply voltage is being monitored to the measurement
circuit in the control room.
There are two disadvantages of systems like those described where copper wire (or thermocouple wire) is used to connect the sensor device and the monitoring or control point. The first disadvantage is that the installed cost of the copper wire (or thermocouple wire) can be quite high. This is particularly true if the wiring circuits are routed through hazardous areas or across physical obstructions such as water features or public or private thoroughfares such as highways or railroads. The second disadvantage is the voltage drop as measurement current passes through long lengths of copper wire. The voltage drop in the measurement circuit must be compensated for with some method such that the measurement made in the control room is a close as possible to that same measurement had it been made at the point of interest in the field. Most compensation circuits have a maximum value of resistance that can be compensated thereby effectively limiting the maximum length of the copper wire or alternatively forcing the use of larger wire gauge, and therefore more expensive copper wire.

**Summary of the Invention**

The present invention includes a system and method for monitoring and controlling heating devices having a heating system for heating a structure, at least one analog sensor attached to the heated structure, a means of converting the analog values measured by the sensors into digital values, a wireless means of conveying the digital values to a control device, the controlling device, to compare the digital values to established set points and action thresholds and an actuating device for initiating control
action. More particularly, the present invention uses a mesh network to monitor and control an electrical heater system.

**Brief Description of the Drawings**

FIG. 1 illustrates an embodiment of the present invention;

FIG. 2 illustrates a second embodiment of the present invention;

FIG. 3 illustrates a third embodiment of the present invention; and,

FIG. 4 illustrates a fourth embodiment of the present invention.

**Detailed Description of the Preferred Embodiment**

The present invention includes a system and method for monitoring and controlling electrical heaters or heating systems. As more detailed below, the system for monitoring and controlling heating devices includes a heating system for heating a structure, at least one analog sensor attached to the heated structure, a means of converting the analog values measured by the sensors into digital values, a wireless means of conveying the digital values to a control device, the controlling device, to compare the digital values to established set points and action thresholds and an actuating device for initiating control action.

The structure that is heated is generally a pipe or tank structure used to transport or store gases or liquids. These structures are present as holding tanks for chemical processes, oil transport lines in cold environments, and other such structures containing
materials requiring the addition of heated, to a general or specific temperature, such as for a particular purpose or environment.

The analog sensors of the present invention are preferably temperature sensors, current sensors, ground-fault current sensors, voltage sensors, resistance sensors and/or combinations thereof. For example, three or more sensors may be monitored where two, or all of them, are within the same class of sensor. Preferably, these sensors produce a voltage signal in proportion to an analog value of interest, such as for example, resistance temperature devices wherein the resistance of the device changes in direct relationship to the temperature of the device allowing a controlled current passing through the device to generate a voltage drop in proportion to the resistance of the device and thus in proportion to the temperature of the device; a voltage dividing device wherein the output voltage of the device is directly proportional to a larger unknown voltage typically used to energize the heater device; a current sensing device such as a current transformer that produces a voltage proportional to the current flowing into or out of the heater device; or a ground fault sensing device that produces a voltage proportional to the imbalance between the current flowing into a heater device and the current flowing out of the heater device.

In one preferred embodiment, the output value of multiple, e.g., three, sensors are independently, and more preferably simultaneously, measured and converted into digital values. In another embodiment the output values of the multiple sensors are measured and converted within an interval of less than about three seconds.

The system preferably monitors and controls specific parameters related to the operational health and performance of a heater circuit. Preferably, these parameters
include the total current, supply voltage, ambient temperature, surface temperature of the pipe or tank being heated and ground fault leakage current.

The total current is the magnitude of the current flowing into and out of the heater. For a fixed resistance heater, it is a direct proxy for the power being generated by the heater governed by Ohms Law of \( P = I^2R \). If resistance of the heater, \( R \), is fixed then measuring the current, \( I \), provides a direct means to calculate the heating power, \( P \), being generated by the heater at the moment of measurement. Comparing the surface temperature, the ambient temperature and the power, operational efficiency of the system performance may be determined including, for example, whether the system is operating to its design efficiency, whether insulation materials are behaving as expected, and whether some portion or all of the heater circuit has been disconnected or damaged.

Supply voltage is a measurement of the line voltage being applied to the heater. Given Ohms Law as \( P = VI \), in cases where the heaters’ resistance is variable or unknown, e.g., self-regulating heaters, it is desirable to measure both total current and supply voltage for proper analysis. In addition, by monitoring the supply voltage certain degradation of the heater power supply system may be detected including, for example, conditions such as voltage sag due to transformer overload, general drop in plant voltage, or excessive loss of voltage in the cold leads. These cold leads are the conductor used to connect the heater to the electrical distribution panel or control panel. Ideally they are
much lower in resistance than the heater to minimize power, i.e., heat, dissipation in non-heater areas.

Measuring the air temperature in the vicinity, or ambient temperature, of the pipe or tank structure being heated provides a measure of the heat lost to the atmosphere through the insulation. By measuring both the surface temperature of the pipe or tank and the ambient temperature, and calculating the difference, or ΔT (delta T), comparison with a value representing the type and thickness of the insulation being used provides a theoretical heat loss through the insulation. This theoretical heat loss provides an indicator for the amount of heat that must be supplied from the heater system to offset this heat loss and maintain a steady temperature at the pipe or tank. Additional calculations may include the effect of fluid flow through the heated pipe. Knowing the theoretical power required for maintaining the temperature and the actual power being dissipated by the heater, and comparing this with the changes in surface temperature, can be instructive regarding the condition of the insulation. Ambient temperature is also required for certain group control algorithms wherein the decision is made to turn a group of heaters off or on without specific pipe-by-pipe feedback. Freeze protection heating and PASC algorithm heaters systems are examples of group control based on ambient temperature measurement.
Generally, pipe or tank surface temperature is the primary control parameter used
to determine when to turn the heater current off or on. In addition knowing the surface
temperature in comparison to the ambient temperature, it is possible to calculate the $\Delta T$
across the insulation and perform various aspects of system performance analysis.

5  Heater systems having ideal electrical insulation prevent any current leakage to
ground. Errors made during installation, damage to the heater system during operation or
maintenance, and component degradation allowing water to come into contact with
connector blocks or electrical splices can lead to an increase in the leakage of electrical
current to ground, or ground fault leakage current. In general, it is desirable to measure
and track the ground fault leakage current over time to detect any trends or sudden
increases. Gradual trends or sudden changes can indicate incipient or already occurring
system faults. Above well defined thresholds, ground fault leakage currents are
considered excessive and a safety risk. Electrical/mechanical devices such as ground
fault circuit breakers or ground fault interruption devices may be activated to cause the
circuit to be isolated. Recognition of a developing trend or an existing fault that is
beneath an automatic shut-down threshold can be very beneficial in planning preventive
maintenance with minimal system disruption.

10  Measurement of as many of the above parameters as possible for optimal control
and maintenance is preferred. As such, the present invention may include devices that
measure as many of these operational parameters as possible, accurately digitize these measurements without the need to compensate for voltage drop over long lead wires and transmit the values to control room monitoring equipment using the most cost effective telemetry method.

The system measures three inputs per field node, such as for example, three temperatures; three currents; a temperature, a ground fault leakage current and a total current; a supply voltage, a current and a ground fault current; or any combination of similar or dissimilar parameters. Preferably, the measurement of more than one of the above parameters is provided by a multiple input device. The three inputs may be selected, for example, by considering the space constraints of the desired enclosure size and the frequent need to measure three current phases at the same location. Representative examples of three parameter measurements of the present invention include, for example without limitation, (1) primary current, secondary current and temperature of the step-down or isolation transformer supplying a heater system; (2) supply voltage, total current, surface temperature of a heated pipe or tank; (3) three independent temperatures from nearby pipes; (4) total current, ground fault current and surface temperature for an individual heater circuit; (5) ambient temperature, surface temperature and total current for a specific heated structure; or (6) individual phase current in a three phase power feeder.
The present invention is further directed to the use of a wireless mesh as the wireless means of conveying the digital values. The wireless mesh includes a node system for relaying the digitized inputs. In the mesh network individual sensing devices are capable of relaying measured values from other nearby sensing devices such that the individual devices are relieved of the need to transmit their digital values directly to the controlling device. Mesh radio nodes need only be powerful enough to send information to preferably two or more immediate neighboring nodes. The transmitter does not have to be powerful to reach the control room. Neighbor nodes intelligently relay measurement data through the network of nodes in short, low power transmission from neighbor to neighbor until the message reaches the control device, generally located in a control room. Preferably, the node operates at less than 3.7 VDC, as supplied from a lithium thionyl battery. In some cases a node may have less than three inputs if, for instance, only one temperature input is required or only supply voltage and total current are desired. Additionally, a node may operate without any inputs, in which case its sole function would be to operate as a packet relay node for other information generating nodes in the nearby mesh.

The mesh networking form of wireless data transmission provides a platform that is particularly well suited for the industrial environment of refineries, tank farms, petrochemical plants and similar process industries. These environments are characterized by large steel structures that interfere with conventional line-of-sight wireless systems. The ability of a mesh network to select from multiple possible signal routing paths allows a mesh system to be deployed in a target environment without the
need to pre-engineer line of site antenna alignments. Further, as facilities evolve and more steel is added and potentially more nodes, the mesh software has the capability to find alternate routing paths on a dynamic basis assuring reliable communications from the field node to the control room equipment.

In a preferred embodiment of the present invention of mesh networking is a low power and intermittent operation. In target operating environments having explosive vapors present from time to time, it is desirable to have a node that can operate at sufficiently low power to qualify as intrinsically safe under regulatory and safety standards definitions. Mesh network wireless systems offer several advantages over conventional point-to-point or master/slave wireless systems in that lower power transmitters can be used intermittently allowing long term battery powered operation. In addition the formation of the mesh and routing paths is adaptive and does not require a direct line of sight from control room to remote measurement devices. Companies engaged in the development and commercialization of mesh systems include an alliance of companies involved in the development of generic and specific mesh networking solutions, such as those operating under the name "Zigbee Alliance", provided for example at www.zigbee.org. Zigbee specifications are herein incorporated by reference.

In another preferred embodiment of the present invention, intermittent packet transmission is used. When the heater systems have operational time constants that are
long, ambient and surface temperatures, most particularly, have values that do not change rapidly under typical conditions. This allows the measurements to be made on an intermittent basis, for example, once every five (5) minutes, and transmitted back to the control room at those relatively infrequent intervals. Allowing the node to go into a partial sleep mode for most of the five (5) minutes and only awaken when it is necessary to relay data for a neighbor node or make and transmit local measurements allows the battery life to be considerable extended, such as conserved for many years. As such, using currently available lithium thionyl batteries, operations may last between 7 and 10 years.

One preferred embodiment of the present invention includes a battery powered mesh node using 3.6 VDC 19 Amp Hour Lithium Thionyl Primary Battery, three inputs configurable by dip switch for current, ground fault current, voltage, pipe temperature or ambient temperature, a mesh networking at fixed frequency in North American, European and Asian ISM frequency bands, and an internal antenna.

The system may measure the total current flowing on each of three individual phases into a multiple phase heater or values of the total current flowing in a single phase heater.

The system may measure values for the surface temperature of a structure, the ambient temperature in the air surrounding the structure and the current flowing into the heater.
In one embodiment measurement includes three values of the total current flowing on each of three individual phases into a multiple phase heater such that the phase balance can be monitored and adjusted to provide a balanced loading on all three electrical phase.

In another embodiment three values consisting of the total current flowing in a single phase heater, the voltage being used to drive the current into and out of the heater and the imbalance, if any, between the current flowing into the heater and out of the heater such that any abnormality in the heaters electrical performance such as increasing imbalance of current flowing into and out of the heater can be used as a means to detect unsafe operation and as a criteria to disconnect voltage to the heater, or such that a disproportionate change in the current flowing into the heater without a corresponding change in applied voltage can be used to infer that the heater has suffered physical damage, or such that gradual shifts in the relationship between current and applied voltage can be used to deduce changes to the efficiency of the heater.

Additionally, the three values may include the surface temperature of the heated and insulated structure, the ambient temperature in the surrounding air and the current flowing into the heater, allowing the controller to determine if the heater is operating in the expected range of operation given the prevailing thermal conditions or to determine that the temperature difference between the heated and insulated structure is less than anticipated for the amount of current flowing into the heater thereby allowing the controller to infer that the thermal insulation has reduced efficiency and may be missing, damaged or wet.

Other combinations of three simultaneous measurements made from the identified classes of analog sensors, in light of the disclosure herein, also allow the controller to
make informed deductions about the state of the heater, insulation, electrical supply, and/or temperature of a mechanical structure heated by the heater device.

Referring to the figures, as seen in FIG. 1, three input wireless mesh nodes monitor a structure's surface temperature, total heater current and supply voltage. This configuration is useful to control the heater, compute heater power output with a variable resistance heater and to monitor maintained temperature, heat up and cool down rates. In FIG. 2, three input wireless mesh nodes monitor a structure's surface temperature, total heater current and ambient temperature. This configuration is useful to control the heater, monitor heater output with a constant resistance heater, and to assess the thermal insulation efficiency by measuring the ΔT across the insulation material. FIG. 3 illustrates three input wireless mesh nodes monitoring a structure's surface temperature, total heater current and ground fault leakage current. This configuration is preferred for mineral insulated (MI) heater cables when the user needs to control the heater based on structure surface temperature, monitor the heater operation via total current and monitor the circuit condition of the heater power feeder and connection points through the ground fault leakage current. As seen in FIG. 4, three input wireless mesh nodes monitor total current in each of three phases providing current to a three phase heater. This configuration is useful to check for balanced phase loading, useful in power management, and to monitor the condition of the heater as it ages through normal use.
Example 1

Three RTDs (Resistance Temperature Devices) are attached to a structure being heated. The three RTDs are connected to the input terminals by three conductor copper wire cables. The length of these RTD connection cables may be several hundred feet, if necessary, but typically will be less than 50 feet in order to maximize the benefits of the wireless topology. Transmitting nodes of the wireless mesh are physically attached to the pipe or other structure using standard mounting hardware used for the same purpose with non-wireless junction boxes. The RTD cables are routed through the mounting mast of the nodes and connected to three terminal blocks on the circuit board of the device.

The microprocessor installed on the nodes is programmed to obtain temperature from the three RTD devices at a user determined interval typically in the range of 1 to 15 minutes, but preferable about 5 minutes for the range of pipes and structures typically heated by electrical cables in an industrial setting. The specific time interval is selected based on the trade-off between the desire to know the current surface temperature of the structure with the least latency period and the shortened battery life imposed by too frequent temperature updates.

Upon obtaining a set of temperature measurements, the nodes transmit the current values through the wireless mesh to a base station near the heater control equipment. The interface from the base station to the heater control panels is typically hard wired RS-232
or RS-485 serial communications in the range of 9600 to 38,400 baud but may be slower or faster if conditions warrant. The temperature data is made available to the heater control equipment in the form of Modbus registers, each containing a temperature value corresponding to one of the RTD inputs at the device. The Modbus register map may contain sufficient registers for a large number of temperature values corresponding to the temperatures being reported by a number of field nodes monitoring various pipes and tank throughout the facility. The structure of the Modbus registers is designed to emulate the data as it would be presented in a traditional hard wired hub and spoke type data multiplexing arrangement. This implementation minimizes the need to re-program existing control room equipment.

Example 2

In a second example of use, the nodes are connected to current transformers and current-to-voltage transducers instead of to RTDs. DIP switches on the device allow the inputs to be reconfigured to accept voltage signals proportional to current instead of measuring resistance values proportional to temperature. The nodes can be installed in the field in the proximity of the conductors carrying current to electrical heaters. Two varieties of current transformer are particularly useful. A split core transformer can be slipped over an existing conductor and clamped shut without disconnecting the primary conductor. A continuous ring transformer has the primary conductor threaded through
its core (which requires disconnecting one end of the primary conductor). The later style offers somewhat better measurement accuracy at the cost of a more difficult installation.

In both cases the output signal of the current transformer is an AC current that is proportional to the AC current flowing through the primary conductor but typically at a much smaller value. For example a 0 - 1000 ampere primary current is monitored with a 1000:5 step down transformer such that with a 1000 ampere current in the primary conductor a 5 ampere current is produced in the current transformer secondary. The reduced current is more easily converted to a DC voltage at a safer level of energy. The output of the current-to-DC voltage transducer is connected to one of the (up to) three inputs on the device. With the DIP switch in the CT position, the micro-controller is programmed to periodically measure the magnitude of the DC voltage, digitize the value, and send the information back to the base station via the mesh network. At the control room a dedicated computer is programmed with commercial monitoring software so that the current measured values can be extracted from the base station via Modbus protocol and displayed on the user interface screen of the monitoring software package.

**Example 3**

In a third example of the use, the nodes are installed on a pipe at the point where the heater cable is connected to the power supply cable. The nodes can be set up to monitor temperature with one input using an RTD, total supply current using a current
transformer and current-to-DC voltage transducer as the second input and ground fault leakage current measured by a current transformer and a current-to-DC voltage transducer as the third input. Again the nodes are programmed to make periodic measurements of all three values and report the digitized value of the readings to the base station via the wireless mesh. Existing heater control panels or specially programmed monitoring software running on personal computers in the control room can then extract the "near real time" information from the Modbus array of data maintained in the base station. The values are then used for control and monitoring purposes for the heater system or trended over long periods of time to determine the overall condition of the heater system.

Other examples include combinations of ambient temperature, supply voltage, total current, ground fault leakage current and surface temperature may be accomplished in light of the disclosure herein.

Convenient access to these control and monitoring parameters from a single data array is particularly useful for monitoring and controlling electrical heater system. Collecting the measurements in groups of three inputs, each of which can be user configured for the desired type of measurement, and having these measurements relayed to the control room eliminates the need of installing and maintaining hard wired systems that are costly to install and repair.
The foregoing summary, description, examples and drawings of the invention are not intended to be limiting, but are only exemplary of the inventive features which are defined in the claims.
What is claimed is:

1. A system for monitoring and controlling heating devices, comprising:
   a heating system for heating a structure;
   at least one analog sensor associated with an electric heater or the heated structure;
   a means of converting the analog values measured by the sensors into digital values;
   a wireless means of conveying the digital values to a control device;
   the controlling device, to compare the digital values to established set points and action thresholds; and,
   an actuating device for initiating control action.

2. The system of claim 1, wherein the at least one analog sensor includes a class of sensor selected from the group consisting of temperature sensor, current sensor, ground-fault current sensor, voltage sensor, resistance sensor and combinations thereof.

3. The system of claim 2, wherein the at least one analog sensor produces a voltage signal in proportion to an analog value of interest.

4. The system of claim 3, wherein the at least one sensor node independently measures and converts the output value of three analog sensors simultaneously to digital values.
5. The system of claim 4, wherein at least two of the three sensors are the same class of sensor.

6. The system of claim 3, wherein the at least one sensor node measures and converts the output values of the at least two analog sensors within an interval of less than about three seconds.

7. The system of claim 6, wherein at least two of the three sensors are the same class of sensor.

8. The system of claim 1, wherein the wireless means of conveying the digital values includes a mesh network.

9. The system of claim 4, wherein the three sensors include measurement of the total current flowing on each of three individual phases into a multiple phase heater.

10. The system of claim 9, wherein the three sensors measure values of the total current flowing in a single phase heater.

11. The system of claim 10, wherein the relationship between current and applied voltage can be used to deduce changes to the efficiency of the heater.
12. The system of claim 1, wherein the at least one sensor node includes analog sensors to measure values for the surface temperature of a structure, the ambient temperature in the air surrounding the structure and the current flowing into the heater.

13. A method for monitoring and controlling heating devices, comprising:

activating a heating system for heating a structure;
associating at least one analog sensor with an electrical heater or the heated structure;
converting the analog values measured by the sensors into digital values;
wirelessly conveying the digital values to a control device;
comparing the digital values to established set points and action thresholds; and,
initiating control action in response to the compared values.
FIG. 1

Measuring Device and Mesh Node

A/D #1
A/D #2
A/D #3

Voltage Signal #3 (proportional to applied voltage)

Network Control and Radio Transceiver

Rectifier and filter circuit

Voltage Signal #2 (proportional to total current)

Voltage Signal #1 (proportional to surface temperature)

Constant current source and voltage divider network with resistance-temperature-device that changes resistance as a function of temperature

Heater

Heated Structure

Insulation

Voltage divider resistor network

Current transformer with output voltage proportional to total current

Rectifier and filter circuit

Wireless communication via direct or relayed through multiple other mesh nodes
FIG. 3

- Measuring Device and Mesh Node
  - A/D #1: Digital Packet Forming
  - A/D #2
  - A/D #3
  - Network Control and Radio Transceiver
  - Voltage Signal #3 (proportional to applied voltage)
  - Voltage Signal #2 (proportional to total current)
  - Voltage Signal #1 (proportional to surface temperature)

- Controlling Device and Mesh Node
- Rectifier and filter circuit
- Insulation
- Heated Structure
- Constant current source and voltage divider network with resistance-temperature-device that changes resistance as a function of temperature
- Wireless communication via direct or relaying through multiple other mesh nodes
- Current transformer with output voltage proportional to ground fault leakage current
- Current transformer with output voltage proportional to total current
FIG. 4

Rectifier and filter circuit (3 places)

A/D #1
A/D #2
A/D #3

Digital Packet Forming

Voltage Signal #3 (proportional to Phase A current)
Voltage Signal #3 (proportional to Phase B current)
Voltage Signal #3 (proportional to Phase C current)

Network Control and Radio Transceiver

Measuring Device and Mesh Node

Insulation

3 Phase Heater

Heated Structure

Wireless communication via direct or relayed through multiple other mesh nodes

Current transformer with output voltage proportional to Phase A current
Current transformer with output voltage proportional to Phase B current
Current transformer with output voltage proportional to Phase C current

Controlling Device and Mesh Node