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# (54) Title: VARIABLE VOLTAGE LOAD TAP CHANGING TRANSFORMER

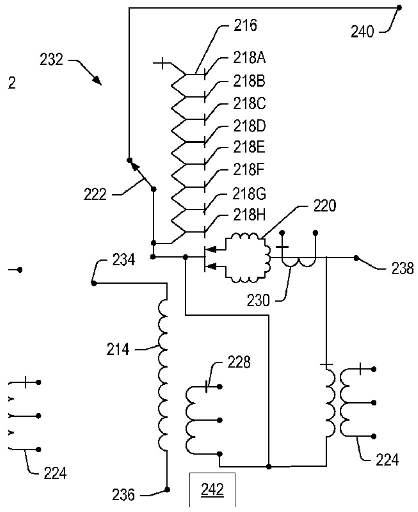

*FIG. 3*

**(57) Abstract:** Power supply systems for subsurface heaters are described herein. The power supply system includes a variable voltage, load tap changing transformer. Systems and methods for supplying electrical power to subsurface heaters using the variable voltage transformers are also described herein.

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# VARIABLE VOLTAGE LOAD TAP CHANGING TRANSFORMER

## BACKGROUND

### 1. Field of the Invention

**[0001]** The present invention relates to power supply systems for subsurface heaters. More particularly, the invention relates to variable voltage transformers used for supplying electrical power to subsurface heaters.

### 2. Description of Related Art

**[0002]** Single-phase load tap changing voltage regulators have been a reliable utility staple since their creation in the 1930's. Load tap changing voltage regulators were deployed at the far end of utility distribution systems to stabilize customer voltages in locations distant from power sources. The voltage regulators provided reliable adjustment for stabilizing voltages (for example, plus or minus 10 %). Voltage regulators are autotransformers with typical nominal voltage ratings ranging from 7200 V to 19,900 V. Associated 10% load tap changers have adjustment ranges of + or – 10% of the input line voltage. For example, a voltage regulator with an input voltage rating of 13,200 V would have an adjustment capability of 1320 V above 13,200 V (or up to 14,520 V) and have an adjustment capability of 1320 V below 13,200 V (or down to 11,880 V).

**[0003]** Modern utility voltage regulators have microprocessor controllers that monitor output voltage and adjust taps up or down to match a desired setting. Typical controllers include current monitoring and may be equipped with remote communications capabilities. The controller firmware may be modified for current based control (for example, control desired for maintaining constant wattage as heater resistances vary with temperature). Load resistance monitoring as well as other electrical analysis based evaluation are a possibility because of the availability of both current and voltage sensing by the controller. Typical tap changers have a 200% of nominal, short time current rating. Thus, the regulator controller may be programmed to respond to overload currents by means of tap changer operation.

**[0004]** Electronic heater controls such as silicon-controlled rectifiers (SCRs) may be used to provide power to and control subsurface heaters. SCRs may be expensive to use and may waste electrical energy in the power circuit. SCRs may also produce harmonic distortions during power control of the subsurface heaters. Harmonic distortion may put noise on the power line and stress heaters. In addition, SCRs may overly stress heaters by switching the power between being full on and full off rather than regulating the power at or near the ideal current setting. As a result, there may be significant overshooting and/or undershooting at the target current for temperature limited heaters (for example, heaters using ferromagnetic materials for self-limiting temperature control). Thus, there is a need for smoother and less distorted control of current provided to electrical resistance heaters, especially temperature limited heaters that are used to heat subsurface hydrocarbon containing formations.

**[0005]** A variable voltage, load tap changing transformer, which is based on a load tap changing regulator design, may be used to provide power to and control subsurface heaters more simply and without the harmonic distortion associated with electronic heater control. The variable voltage transformer may be connected to power distribution systems by simple, inexpensive fused cutouts. The variable voltage transformer may provide a cost effective, stand alone, full function heater controller and isolation transformer.

## SUMMARY

**[0006]** Embodiments described herein generally relate to power supply systems for subsurface heaters. Certain embodiments relate to variable voltage transformers used for supplying electrical power to subsurface heaters.

**[0007]** In certain embodiments, a variable voltage transformer comprises a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding; a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage; a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage; and wherein an electrical load is configured to be coupled to the multistep load tap changer to provide electrical power to the load with a selected voltage, the multistep load tap changer is configured to tap a selected voltage step in order to provide the selected voltage to the electrical load.

**[0008]** In some embodiments, a variable voltage transformer system for providing power to a three-phase electrical load includes a first variable voltage transformer coupled to a first leg of three-phase electrical load; a second variable voltage transformer coupled to a second leg of three-phase electrical load; a third variable voltage transformer coupled to a third leg of three-phase electrical load. Each of the first, second, and third variable voltage transformers include a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding; a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage; a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage. The corresponding leg of the three-phase electrical load is configured to be coupled to the multistep load tap changer to provide electrical power to the load with a selected voltage. The multistep load tap changer is configured to tap a selected voltage step in order to provide the selected voltage to the corresponding leg.

**[0009]** In some embodiments, a method of controlling voltage provided to one or more electric heaters comprises providing electrical power to the first heater with a selected voltage using a variable voltage transformer, wherein the variable voltage transformer comprises: a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding; a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage; a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage, the multistep load tap changer tapping a selected voltage step in order to provide the selected voltage to the first heater; assessing change in electrical resistance of the first heater over a selected period of time; and adjusting the selected voltage provided to the first heater by changing the selected voltage step tapped by the multistep load tap changer, wherein the selected voltage is changed in response to the change in the electrical resistance of the first heater.

**[0010]** In some embodiments, a method of controlling voltage provided to one or more electric heaters comprises providing electrical power to the first heater with a selected voltage using a variable voltage transformer, wherein the variable voltage transformer comprises: a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding; a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage; a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage, the multistep load tap changer tapping a selected voltage step in order to provide the selected voltage to the first heater; assessing an electrical resistance of the first heater; providing electrical power at the first selected voltage until the electrical resistance of the first heater reaches a selected value; assessing the electrical resistance of the first heater over a selected period of time, and assessing if there is a change in the electrical resistance of the first heater at the second selected voltage over the selected period of time; and adjusting the second selected voltage provided to the first heater by changing the selected voltage step tapped by the multistep load tap changer, wherein the second selected voltage is changed in response to the change in the electrical resistance of the first heater.

**[0011]** In some embodiments, a method of controlling voltage provided to one or more electric heaters comprises providing electrical power to the first heater with a selected voltage using a variable voltage transformer, wherein the variable voltage transformer comprises: a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding; a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage; a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage, the multistep load tap changer tapping a selected voltage step in order to provide the selected voltage to the first heater; assessing an electrical resistance of the first heater at the selected voltage; and cycling the selected voltage provided to the first heater by switching the selected voltage step tapped by the multistep load tap changer between at least two voltage steps such that the selected voltage is cycled between at least two voltages after a selected amount of time at each of the at least two voltages.

**[0012]** In further embodiments, features from specific embodiments may be combined with features from other embodiments. For example, features from one embodiment may be combined with features from any of the other embodiments.

**[0013]** In further embodiments, treating a subsurface formation is performed using any of the methods, systems, power supplies, or heaters described herein.

**[0014]** In further embodiments, additional features may be added to the specific embodiments described herein.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0015]** Advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description and upon reference to the accompanying drawings in which:

**[0016]** FIG. 1 shows a schematic view of an embodiment of a portion of an in situ heat treatment system for treating a hydrocarbon containing formation.

**[0017]** FIG. 2 depicts a schematic for a conventional design of a tap changing voltage regulator.

**[0018]** FIG. 3 depicts a schematic for a variable voltage, load tap changing transformer.

**[0019]** FIG. 4 depicts a representation of an embodiment of a transformer and a controller.

**[0020]** While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. The drawings may not be to scale. It should be understood that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but to the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

## DETAILED DESCRIPTION OF EMBODIMENTS

**[0021]** “Alternating current (AC)” refers to a time-varying current that reverses direction substantially sinusoidally. AC produces skin effect electricity flow in a ferromagnetic conductor.

**[0022]** “Curie temperature” is the temperature above which a ferromagnetic material loses all of its ferromagnetic properties. In addition to losing all of its ferromagnetic properties above the Curie temperature, the ferromagnetic material begins to lose its ferromagnetic properties when an increasing electrical current is passed through the ferromagnetic material.

**[0023]** A “formation” includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. “Hydrocarbon layers” refer to layers in the formation that contain hydrocarbons. The hydrocarbon layers may contain non-hydrocarbon material and hydrocarbon material. The “overburden” and/or the “underburden” include one or more different types of impermeable materials. For example, the overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate. In some embodiments of in situ heat treatment processes, the overburden and/or the underburden may include a hydrocarbon containing layer or hydrocarbon containing layers that are relatively impermeable and are not subjected to temperatures during in situ heat treatment processing that result in significant characteristic changes of the hydrocarbon containing layers of the overburden and/or the underburden. For example, the underburden may contain shale or mudstone, but the underburden is not allowed to heat to pyrolysis temperatures during the in situ heat treatment process. In some cases, the overburden and/or the underburden may be somewhat permeable.

**[0024]** “Formation fluids” refer to fluids present in a formation and may include pyrolyzation fluid, synthesis gas, mobilized hydrocarbons, and water (steam). Formation fluids may include hydrocarbon fluids as well as non-hydrocarbon fluids. The term “mobilized fluid” refers to fluids in a hydrocarbon containing formation that are able to flow as a result of thermal treatment of the formation. “Produced fluids” refer to fluids removed from the formation.

**[0025]** A “heat source” is any system for providing heat to at least a portion of a formation substantially by conductive and/or radiative heat transfer. For example, a heat source may include electric heaters such as an insulated conductor, an elongated member, and/or a conductor disposed in a conduit. A heat source may also include systems that generate heat by burning a fuel external to or in a formation. The systems may be surface burners, downhole gas burners, flameless distributed combustors, and natural distributed combustors. In some embodiments, heat provided to or generated in one or more heat sources may be supplied by other sources of energy. The other sources of energy may directly heat a formation, or the energy may be applied to a transfer medium that directly or indirectly heats the formation. It is to be understood that one or more heat sources that are applying heat to a formation may use different sources of energy. Thus, for example, for a given formation some heat sources may supply heat from electric resistance heaters, some heat sources may provide heat from combustion, and some heat sources may provide heat from one or more other energy sources (for example, chemical reactions, solar energy, wind energy, biomass, or other sources of renewable energy). A chemical reaction may include an exothermic reaction (for example, an oxidation reaction). A heat source may also include a heater that provides heat to a zone proximate and/or surrounding a heating location such as a heater well.

**[0026]** A “heater” is any system or heat source for generating heat in a well or a near wellbore region. Heaters may be, but are not limited to, electric heaters, burners, combustors that react with material in or produced from a formation, and/or combinations thereof.

**[0027]** “Hydrocarbons” are generally defined as molecules formed primarily by carbon and hydrogen atoms. Hydrocarbons may also include other elements such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. Hydrocarbons may be, but are not limited to, kerogen, bitumen, pyrobitumen, oils, natural mineral waxes, and asphaltites. Hydrocarbons may be located in or adjacent to mineral matrices in the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilytes, carbonates, diatomites, and other porous media. “Hydrocarbon fluids” are fluids that include hydrocarbons. Hydrocarbon fluids may include, entrain, or be entrained in non-hydrocarbon fluids such as hydrogen, nitrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, water, and ammonia.

**[0028]** An “in situ heat treatment process” refers to a process of heating a hydrocarbon containing formation with heat sources to raise the temperature of at least a portion of the formation above a temperature that results in mobilized fluid, visbreaking, and/or pyrolysis of hydrocarbon containing material so that mobilized fluids, visbroken fluids, and/or pyrolyzation fluids are produced in the formation.

**[0029]** “Temperature limited heater” generally refers to a heater that regulates heat output (for example, reduces heat output) above a specified temperature without the use of external controls such as temperature controllers, power regulators, rectifiers, or other devices. Temperature limited heaters may be AC (alternating current) or modulated (for example, “chopped”) DC (direct current) powered electrical resistance heaters.

**[0030]** The term “wellbore” refers to a hole in a formation made by drilling or insertion of a conduit into the formation. A wellbore may have a substantially circular cross section, or another cross-sectional shape. As used herein, the terms “well” and “opening,” when referring to an opening in the formation may be used interchangeably with the term “wellbore.”

**[0031]** A formation may be treated in various ways to produce many different products. Different stages or processes may be used to treat the formation during an in situ heat treatment process. In some embodiments, one or more sections of the formation are solution mined to remove soluble minerals from the sections. Solution mining minerals may be performed before, during, and/or after the in situ heat treatment process. In some embodiments, the average temperature of one or more sections being solution mined may be maintained below about 120 °C.

**[0032]** In some embodiments, one or more sections of the formation are heated to remove water from the sections and/or to remove methane and other volatile hydrocarbons from the sections. In some embodiments, the average temperature may be raised from ambient temperature to temperatures below about 220 °C during removal of water and volatile hydrocarbons.

**[0033]** In some embodiments, one or more sections of the formation are heated to temperatures that allow for movement and/or visbreaking of hydrocarbons in the formation. In some embodiments, the average temperature of one or more sections of the formation are raised to mobilization temperatures of hydrocarbons in the sections (for example, to temperatures ranging from 100 °C to 250 °C, from 120 °C to 240 °C, or from 150 °C to 230 °C).

**[0034]** In some embodiments, one or more sections are heated to temperatures that allow for pyrolysis reactions in the formation. In some embodiments, the average temperature of one or more sections of the formation may be raised to pyrolysis temperatures of hydrocarbons in the sections (for example, temperatures ranging from 230 °C to 900 °C, from 240 °C to 400 °C or from 250 °C to 350 °C).

**[0035]** Heating the hydrocarbon containing formation with a plurality of heat sources may establish thermal gradients around the heat sources that raise the temperature of hydrocarbons in the formation to desired temperatures at desired heating rates. The rate of temperature increase through mobilization temperature range and/or pyrolysis temperature range for desired products may affect the quality and quantity of the formation fluids produced from the hydrocarbon containing formation. Slowly raising the temperature of the formation through the mobilization temperature range and/or pyrolysis temperature range may allow for the production of high quality, high API gravity hydrocarbons from the formation. Slowly raising the temperature of the formation through the mobilization temperature range and/or pyrolysis temperature range may allow for the removal of a large amount of the hydrocarbons present in the formation as hydrocarbon product.

**[0036]** In some in situ heat treatment embodiments, a portion of the formation is heated to a desired temperature instead of slowly heating the temperature through a temperature range. In some embodiments, the desired temperature is 300 °C, 325 °C, or 350 °C. Other temperatures may be selected as the desired temperature.

**[0037]** Superposition of heat from heat sources allows the desired temperature to be relatively quickly and efficiently established in the formation. Energy input into the formation from the heat sources may be adjusted to maintain the temperature in the formation substantially at a desired temperature.

**[0038]** Mobilization and/or pyrolysis products may be produced from the formation through production wells. In some embodiments, the average temperature of one or more sections is raised to mobilization temperatures and hydrocarbons are produced from the production wells. The average temperature of one or more of the sections may be raised to pyrolysis temperatures after production due to mobilization decreases below a selected value. In some embodiments, the average temperature of one or more sections may be raised to pyrolysis temperatures without significant production before reaching pyrolysis temperatures. Formation fluids including pyrolysis products may be produced through the production wells.

**[0039]** In some embodiments, the average temperature of one or more sections may be raised to temperatures sufficient to allow synthesis gas production after mobilization and/or pyrolysis. In some embodiments, hydrocarbons may be raised to temperatures sufficient to allow synthesis gas production without significant production before reaching the temperatures sufficient to allow synthesis gas production. For example, synthesis gas may be produced in a temperature range from about 400 °C to about 1200 °C, about 500 °C to about 1100 °C, or about 550 °C to about 1000 °C. A synthesis gas generating fluid (for example, steam and/or water) may be introduced into the sections to generate synthesis gas. Synthesis gas may be produced from production wells.

**[0040]** Solution mining, removal of volatile hydrocarbons and water, mobilizing hydrocarbons, pyrolyzing hydrocarbons, generating synthesis gas, and/or other processes may be performed during the in situ heat treatment process. In some embodiments, some processes may be performed after the in situ heat treatment process. Such processes may include, but are not limited to, recovering heat from treated sections, storing fluids (for example, water and/or hydrocarbons) in previously treated sections, and/or sequestering carbon dioxide in previously treated sections.

**[0041]** FIG. 1 depicts a schematic view of an embodiment of a portion of the in situ heat treatment system for treating the hydrocarbon containing formation. The in situ heat treatment system may include barrier wells 200. Barrier wells are used to form a barrier around a treatment area. The barrier inhibits fluid flow into and/or out of the treatment area. Barrier wells include, but are not limited to, dewatering wells, vacuum wells, capture wells, injection wells, grout wells, freeze wells, or combinations thereof. In some embodiments, barrier wells 200 are dewatering wells. Dewatering wells may remove liquid water and/or inhibit liquid water from entering a portion of the formation to be heated, or to the formation being heated. In the embodiment depicted in FIG. 1, the barrier wells 200 are shown extending only along one side of heat sources 202, but the barrier wells may encircle all heat sources 202 used, or to be used, to heat a treatment area of the formation.

**[0042]** Heat sources 202 are placed in at least a portion of the formation. Heat sources 202 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 202 may also include other types of heaters. Heat sources 202 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 202 through supply lines 204. Supply lines 204 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 204 for heat sources may transmit electricity for electric heaters, may transport fuel for combustors, or may transport heat exchange fluid that is circulated in the formation. In some embodiments, electricity for an in situ heat treatment process may be provided by a nuclear power plant or nuclear power plants. The use of nuclear power may allow for reduction or elimination of carbon dioxide emissions from the in situ heat treatment process.

**[0043]** Production wells 206 are used to remove formation fluid from the formation. In some embodiments, production well 206 includes a heat source. The heat source in the production well may heat one or more portions of the formation at or near the production well. In some in situ heat treatment process embodiments, the amount of heat supplied to the formation from the production well per meter of the production well is less than the amount of heat applied to the formation from a heat source that heats the formation per meter of the heat source.

**[0044]** In some embodiments, the heat source in production well 206 allows for vapor phase removal of formation fluids from the formation. Providing heating at or through the production well may: (1) inhibit condensation and/or refluxing of production fluid when such production fluid is moving in the production well proximate the overburden, (2) increase heat input into the formation, (3) increase production rate from the production well as compared to a production well without a heat source, (4) inhibit condensation of high carbon number compounds ($C_6$ and above) in the production well, and/or (5) increase formation permeability at or proximate the production well.

**[0045]** Subsurface pressure in the formation may correspond to the fluid pressure generated in the formation. As temperatures in the heated portion of the formation increase, the pressure in the heated portion may increase as a result of thermal expansion of fluids, increased fluid generation, and vaporization of water. Controlling rate of fluid removal from the formation may allow for control of pressure in the formation. Pressure in the formation may be determined at a number of different locations, such as near or at production wells, near or at heat sources, or at monitor wells.

**[0046]** In some hydrocarbon containing formations, production of hydrocarbons from the formation is inhibited until at least some hydrocarbons in the formation have been mobilized and/or pyrolyzed. Formation fluid may be produced from the formation when the formation fluid is of a selected quality. In some embodiments, the selected quality includes an API gravity of at least about 15°, 20°, 25°, 30°, or 40°. Inhibiting production until at least some hydrocarbons are mobilized and/or pyrolyzed may increase conversion of heavy hydrocarbons to light hydrocarbons. Inhibiting initial production may minimize the production of heavy hydrocarbons from the formation. Production of substantial amounts of heavy hydrocarbons may require expensive equipment and/or reduce the life of production equipment.

**[0047]** After mobilization or pyrolysis temperatures are reached and production from the formation is allowed, pressure in the formation may be varied to alter and/or control a composition of formation fluid produced, to control a percentage of condensable fluid as compared to non-condensable fluid in the formation fluid, and/or to control an API gravity of formation fluid being produced. For example, decreasing pressure may result in production of a larger condensable fluid component. The condensable fluid component may contain a larger percentage of olefins.

**[0048]** In some in situ heat treatment process embodiments, pressure in the formation may be maintained high enough to promote production of formation fluid with an API gravity of greater than 20°. Maintaining increased pressure in the formation may inhibit formation subsidence during in situ heat treatment. Maintaining increased pressure may reduce or eliminate the need to compress formation fluids at the surface to transport the fluids in collection conduits to treatment facilities.

**[0049]** Maintaining increased pressure in a heated portion of the formation may surprisingly allow for production of large quantities of hydrocarbons of increased quality and of relatively low molecular weight. Pressure may be maintained so that formation fluid produced has a minimal amount of compounds above a selected carbon number. The selected carbon number may be at most 25, at most 20, at most 12, or at most 8. Some high carbon number compounds may be entrained in vapor in the formation and may be removed from the formation with the vapor. Maintaining increased pressure in the formation may inhibit entrainment of high carbon number compounds and/or multi-ring hydrocarbon compounds in the vapor. High carbon number compounds and/or multi-ring hydrocarbon compounds may remain in a liquid phase in the formation for significant time periods. The significant time periods may provide sufficient time for the compounds to pyrolyze to form lower carbon number compounds.

**[0050]** Formation fluid produced from production wells 206 may be transported through collection piping 208 to treatment facilities 210. Formation fluids may also be produced from heat sources 202. For example, fluid may be produced from heat sources 202 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 202 may be transported through tubing or piping to collection piping 208 or the produced fluid may be transported through tubing or piping directly to treatment facilities 210. Treatment facilities 210 may include separation units, reaction units, upgrading units, fuel cells, turbines, storage vessels, and/or other systems and units for processing produced formation fluids. The treatment facilities may form transportation fuel from at least a portion of the hydrocarbons produced from the formation. In some embodiments, the transportation fuel may be jet fuel.

**[0051]** Modern utility voltage regulators have microprocessor controllers that monitor output voltage and adjust taps up or down to match a desired setting. Typical controllers include current monitoring and may be equipped with remote communications capabilities. The controller firmware may be modified for current based control (for example, control desired for maintaining constant wattage as heater resistances vary with temperature). Load resistance monitoring as well as other electrical analysis based evaluation and control are a possibility because of the availability of both current and voltage sensing by the controller. In addition to current, sensed electrical properties including, but not limited to power, voltage, power factor, resistance or harmonics may be used as control parameters. Typical tap changers have a 200% of nominal, short time current rating. Thus, the regulator controller may be programmed to respond to overload currents by means of tap changer operation.

**[0052]** Electronic heater controls such as silicon-controlled rectifiers (SCRs) may be used to provide power to and control subsurface heaters. SCRs may be expensive to use and may waste electrical energy in the power circuit. SCRs may also produce harmonic distortions during power control of the subsurface heaters. Harmonic distortion may put noise on the power line and stress heaters. In addition, SCRs may overly stress heaters by switching the power between being full on and full off rather than regulating the power at or near the ideal current setting. Thus, there may be significant overshooting and/or undershooting at the target current for temperature limited heaters (for example, heaters using ferromagnetic materials for self-limiting temperature control).

**[0053]** A variable voltage, load tap changing transformer, which is based on a load tap changing regulator design, may be used to provide power to and control subsurface heaters more simply and without the harmonic distortion associated with electronic heater control. The variable voltage transformer may be connected to power distribution systems by simple, inexpensive fused cutouts. The variable voltage transformer may provide a cost effective, stand alone, full function heater controller and isolation transformer.

**[0054]** FIG. 2 depicts a schematic for a conventional design of tap changing voltage regulator 212. Regulator 212 provides plus or minus 10% adjustment of the input or line voltage. Regulator 212 includes primary winding 214 and tap changer section 216, which includes the secondary winding of the regulator. Primary winding 214 is a series winding electrically coupled to the secondary winding of tap changer section 216. Tap changer section 216 includes eight taps 218A-H that separate the voltage on the secondary winding into voltage steps. Moveable tap changer 220 is a moveable preventive autotransformer with a balance winding. Tap changer 220 may be a sliding tap changer that moves between taps 218A-H in tap changer section 216. Tap changer 220 may be capable of carrying high currents up to, for example, 668 A or more.

**[0055]** Tap changer 220 contacts either one tap 218 or bridges between two taps to provide a midpoint between the two tap voltages. Thus, 16 equivalent voltage steps are created for tap changer 220 to couple to in tap changer section 216. The voltage steps divide the 10% range of regulation equally (5/8% per step). Switch 222 changes the voltage adjustment between plus and minus adjustment. Thus, voltage can be regulated plus 10% or minus 10% from the input voltage.

**[0056]** Voltage transformer 224 senses the potential at bushing 226. The potential at bushing 226 may be used for evaluation by a microprocessor controller. The controller adjusts the tap position to match a preset value. Control power transformer 228 provides power to operate the controller and the tap changer motor. Current transformer 230 is used to sense current in the regulator.

**[0057]** FIG. 3 depicts a schematic for variable voltage, load tap changing transformer 232. The schematic for transformer 232 is based on the load tap changing regulator schematic depicted in FIG. 2. Primary winding 214 is isolated from the secondary winding of tap changer section 216 to create distinct primary and secondary windings. Primary winding 214 may be coupled to a voltage source using bushings 234, 236. The voltage source may provide a first voltage across primary winding 214. The first voltage may be a high voltage such as voltages of at least 5 kV, at least 10 kV, at least 25kV, or at least 35kV up to about 50kV. The secondary winding in tap changer section 216 may be coupled to an electrical load (for example, one or more subsurface heaters) using bushings 238, 240. The electrical load may include, but not be limited to, an insulated conductor heater (for example, mineral insulated conductor heater), a conductor-in-conduit heater, a temperature limited heater, a dual leg heater, or one heater leg of a three-phase heater configuration. The electrical load may be other than a heater (for example, a bottom hole assembly for forming a wellbore).

**[0058]** The secondary winding in tap changer section 216 steps down the first voltage across primary winding 214 to a second voltage (for example, voltage lower than the first voltage or a second voltage). In certain embodiments, the secondary winding in tap changer section 216 steps down the voltage from primary winding 214 to the second voltage that is between 5% and 20% of the first voltage across the primary winding. In some embodiments, the secondary winding in tap changer section 216 steps down the voltage from primary winding 214 to the second voltage that is between 1% and 30% or between 3% and 25% of the first voltage across the primary winding. In one embodiment, the secondary winding in tap changer section 216 steps down the voltage from primary winding 214 to the second voltage that is 10% of the first voltage across the primary winding. For example, a first voltage of 7200 V across the primary winding may be stepped down to a second voltage of 720 V across the secondary winding in tap changer section 216.

**[0059]** In some embodiments, the step down percentage in tap changer section 216 is preset. In some embodiments, the step down percentage in tap changer section 216 may be adjusted as needed for desired operation of a load coupled to transformer 232.

**[0060]** Taps 218A-H (or any other number of taps) divide the second voltage on the secondary winding in tap changer section 216 into voltage steps. The second voltage is divided into voltage steps from a selected minimum percentage of the second voltage up to the full value of the second voltage. In certain embodiments, the second voltage is divided into equivalent voltage steps between the selected minimum percentage and the full second voltage value. In some embodiments, the selected minimum percentage is 0% of the second voltage. For example, the second voltage may be equally divided by the taps in voltage steps ranging between 0 V and 720 V. In some embodiments, the selected minimum percentage is 25% or 50% of the second voltage.

**[0061]** Transformer 232 includes tap changer 220 that contacts either one tap 218 or bridges between two taps to provide a midpoint between the two tap voltages. The position of tap changer 220 on the taps determines the voltage provided to an electrical load coupled to bushings 238, 240. As an example, an arrangement with 8 taps in tap changer section 216 provides 16 voltage steps for tap changer 220 to couple to in tap changer section 216. Thus, the electrical load may be provided with 16 different voltages varying between the selected minimum percentage and the second voltage.

**[0062]** In certain embodiments of transformer 232, the voltage steps divide the range between the selected minimum percentage and the second voltage equally (the voltage steps are equivalent). For example, eight taps may divide a second voltage of 720 V into 16 voltage steps between 0 V and 720 V so that each tap increments the voltage provided to the electrical load by 45V. In some embodiments, the voltage steps divide the range between the selected minimum percentage and the second voltage in non-equal increments (the voltage steps are not equivalent). For example, voltage steps in the top half of the tap changer section may be larger than voltage steps in the bottom half of the tap changer section.

**[0063]** Switch 222 may be used to electrically disconnect bushing 240 from the secondary winding and taps 218. Electrically isolating bushing 240 from the secondary winding turns off the power (voltage) provided to the electrical load coupled to bushings 238, 240. Thus, switch 222 provides an internal disconnect in transformer 232 to electrically isolate and turn off power (voltage) to the electrical load coupled to the transformer.

**[0064]** In transformer 232, voltage transformer 224, control power transformer 228, and current transformer 230 are electrically isolated from primary winding 214. Electrical isolation protects voltage transformer 224, control power transformer 228, and current transformer 230 from current and/or voltage overloads caused by primary winding 214.

**[0065]** In certain embodiments, transformer 232 is used to provide power to a variable electrical load (for example, a subsurface heater such as, but not limited to, a temperature limited heater using ferromagnetic material that self-limits at the Curie temperature or a phase transition temperature range). Transformer 232 allows power to the electrical load to be adjusted in small voltage increments (voltage steps) by moving tap changer 220 between taps 218. Thus, the voltage supplied to the electrical load may be adjusted incrementally to provide substantially constant current to the electrical load in response to changes in the electrical load (for example, changes in resistance of the electrical load). Voltage to the electrical load may be controlled from a minimum voltage (the selected minimum percentage) up to full potential (the second voltage) in increments. The increments may be equal increments or non-equal increments. Thus, power to the electrical load does not have to be turned full on or off to control the electrical load such as is done with a SCR controller. Using small increments may reduce cycling stress on the electrical load and may increase the lifetime of the device that is the electrical load. Transformer 232 changes the voltage using mechanical operation instead of the electrical switching used in SCRs. Electrical switching can add harmonics and/or noise to the voltage signal provided to the electrical load. The mechanical switching of transformer 232 provides clean, noise free, incrementally adjustable control of the voltage provided to the electrical load.

**[0066]** Transformer 232 may be controlled by controller 242. Controller 242 may be a microprocessor controller. Controller 242 may be powered by control power transformer 228. Controller 242 may assess properties of transformer 232, including tap changer section 216, and/or the electrical load coupled to the transformer. Examples of properties that may be assessed by controller 242 include, but are not limited to, voltage, current, power, power factor, harmonics, tap change operation count, maximum and minimum value recordings, wear of the tap changer contacts, and electrical load resistance.

**[0067]** In certain embodiments, controller 242 is coupled to the electrical load to assess properties of the electrical load. For example, controller 242 may be coupled to the electrical load using an optical fiber. The optical fiber allows measurement of properties of the electrical load such as, but not limited to, electrical resistance, impedance, capacitance, and/or temperature. In some embodiments, controller 242 is coupled to voltage transformer 224 and/or current transformer 230 to assess the voltage and/or current output of transformer 232. In some embodiments, the voltage and current are used to assess a resistance of the electrical load over one or more selected time periods. In some embodiments, the voltage and current are used to assess or diagnose other properties of the electrical load (for example, temperature).

**[0068]** In certain embodiments, controller 242 adjusts the voltage output of transformer 232 in response to changes in the electrical load coupled to the transformer or other changes in the power distribution system such as, but not limited to, input voltage to the primary winding or other power supply changes. For example, controller 242 may adjust the voltage output of transformer 232 in response to changes in the electrical resistance of the electrical load. Controller 242 may adjust the output voltage by controlling the movement of control tap changer 220 between taps 218 to adjust the voltage output of transformer 232. In some embodiments, controller 242 adjusts the voltage output of transformer 232 so that the electrical load (for example, a subsurface heater) is operated at a relatively constant current. In some embodiments, controller 242 may adjust the voltage output of transformer 232 by moving tap changer 220 to a new tap, assess the resistance and/or power at the new tap, and move the tap changer to another new tap if needed.

**[0069]** In some embodiments, controller 242 assesses the electrical resistance of the load (for example, by measuring the voltage and current using the voltage and current transformers or by measuring the resistance of the electrical load using the optical fiber) and compares the assessed electrical resistance to a theoretical resistance. Controller 242 may adjust the voltage output of transformer 232 in response to differences between the assessed resistance and the theoretical resistance. In some embodiments, the theoretical resistance is an ideal resistance for operation of the electrical load. In some embodiments, the theoretical resistance varies over time due to other changes in the electrical load (for example, temperature of the electrical load).

**[0070]** In some embodiments, controller 242 is programmable to cycle tap changer 220 between two or more taps 218 to achieve intermediate voltage outputs (for example, a voltage output between two tap voltage outputs). Controller 242 may adjust the time tap changer 220 is on each of the taps cycled between to obtain an average voltage at or near the desired intermediate voltage output. For example, controller 242 may keep tap changer 220 at two taps approximately 50% of the time each to maintain an average voltage approximately midway between the voltages at the two taps.

**[0071]** In some embodiments, controller 242 is programmable to limit the numbers of voltage changes (movement of tap changer 220 between taps 218 or cycles of tap changes) over a period of time. For example, controller 242 may only allow 1 tap change every 30 minutes or 2 tap changes per hour. Limiting the number of tap changes over the period of time reduces the stress on the electrical load (for example, a heater) from changes in voltage to the load. Reducing the stresses applied to the electrical load may increase the lifetime of the electrical load. Limiting the number of tap changes may also increase the lifetime of the tap changer apparatus. In some embodiments, the number of tap changes over the period of time is adjustable using the controller. For example, a user may be allowed to adjust the cycle limit for tap changes on transformer 232.

**[0072]** In some embodiments, controller 242 is programmable to power the electrical load in a start up sequence. For example, subsurface heaters may require a certain start up protocol (such as high current during early times of heating and lower current as the temperature of the heater reaches a set point). Ramping up power to the heaters in a desired procedure may reduce mechanical stresses on the heaters from materials expanding at different rates. In some embodiments, controller 242 ramps up power to the electrical load with controlled increases in voltage steps over time. In some embodiments, controller 242 ramps up power to the electrical load with controlled increases in watts per hour. Controller 242 may be programmed to automatically start up the electrical load according to a user input start up procedure or a pre-programmed start up procedure.

**[0073]** In some embodiments, controller 242 is programmable to turn off power to the electrical load in a shut down sequence. For example, subsurface heaters may require a certain shut down protocol to inhibit the heaters from cooling to quickly. Controller 242 may be programmed to automatically shut down the electrical load according to a user input shut down procedure or a pre-programmed shut down procedure.

**[0074]** In some embodiments, controller 242 is programmable to power the electrical load in a moisture removal sequence. For example, subsurface heaters or motors may require start up at second voltages to remove moisture from the system before application of higher voltages. In some embodiments, controller 242 inhibits increases in voltage until required electrical load resistance values are met. Limiting increases in voltage may inhibit transformer 232 from applying voltages that cause shorting due to moisture in the system. Controller 242 may be programmed to automatically start up the electrical load according to a user input moisture removal sequence or a pre-programmed moisture removal procedure.

**[0075]** In some embodiments, controller 242 is programmable to reduce power to the electrical load based on changes in the voltage input to primary winding 214. For example, the power to the electrical load may be reduced during brownouts or other power supply shortages. Reducing the power to the electrical load may compensate for the reduced power supply.

**[0076]** In some embodiments, controller 242 is programmable to protect the electrical load from being overloaded. Controller 242 may be programmed to automatically and immediately reduce the voltage output if the current to the electrical load increases above a selected value. The voltage output may be stepped down as fast as possible while sensing the current. Sensing of the current occurs on a faster time scale than the step downs in voltage so the voltage may be stepped down as fast as possible until the current drops below a selected level. In some embodiments, tap changes (voltage steps) may be inhibited above higher current levels. At the higher current levels, secondary fusing may be used to limit the current. Reducing the tap setting in response to the higher current levels may allow for continued operation of the transformer even after partial failure or quenching of electrical loads such as heaters.

**[0077]** In some embodiments, controller 242 records or tracks data from the operation of the electrical load and/or transformer 232. For example, controller 242 may record changes in the resistance or other properties of the electrical load or transformer 232. In some embodiments, controller 242 records faults in operation of transformer 232 (for example, missed step changes).

**[0078]** In certain embodiments, controller 242 includes communication modules. The communication modules may be programmed to provide status, data, and/or diagnostics for any device or system coupled to the controller such as the electrical load or transformer 232. The communication modules may communicate using RS485 serial communication, Ethernet, fiber, wireless, and/or other communication technologies known in the art. The communication modules may be used to transmit information remotely to another site so that controller 242 and transformer 232 are operated in a self-contained or automatic manner but are able to report to another location (for example, a central monitoring location). The central monitoring location may monitor several controllers and transformers (for example, controllers and transformers located in a hydrocarbon processing field). In some embodiments, users or equipment at the central monitoring location are able to remotely operate one or more of the controllers using the communications modules.

**[0079]** FIG. 4 depicts a representation of an embodiment of transformer 232 and controller 242. In certain embodiments, transformer 232 is enclosed in enclosure 244. Enclosure 244 may be a cylindrical can. Enclosure 244 may be any other suitable enclosure known in the art (for example, a substation style rectangular enclosure). Controller 242 may be mounted to the outside of enclosure 244. Bushings 234, 236, 238, and 240 may be open air, high voltage bushings located on the outside of enclosure 244 for coupling transformer 232 to the power supply and the electrical load.

**[0080]** In certain embodiments, enclosure 244 is mounted on a pole or otherwise supported off the ground. In some embodiments, one or more enclosures 244 are mounted on an elevated platform supported by a pole or elevated mounting support. Mounting enclosure 244 on a pole or mounting support increases air circulation around and in the enclosure and transformer 232. Increasing air circulation decreases operating temperatures and increases efficiency of the transformer. In certain embodiments, components of transformer 232 are coupled to the top of enclosure 244 so that the components are removed as a single unit from the enclosure by removing the top of the enclosure.

**[0081]** In certain embodiments, three transformers 232 are used to operate three, or multiples of three, electrical loads in a three-phase configuration. The three transformers may be monitored to assess if the tap positions in each transformer are in sync (at the same tap position). In some embodiments, one controller 242 is used to control the three transformers. The controller may monitor the transformers to ensure that the transformers are in sync.

**[0082]** It is to be understood the invention is not limited to particular systems described which may, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting. As used in this specification, the singular forms “a”, “an” and “the” include plural referents unless the content clearly indicates otherwise. Thus, for example, reference to “a bolt” includes a combination of two or more bolts and reference to “a fluid” includes mixtures of fluids.

**[0083]** Further modifications and alternative embodiments of various aspects of the invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as the presently preferred embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims.

# CLAIMS

1. A variable voltage transformer, comprising:

a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding;

a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage;

a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage; and

wherein an electrical load is configured to be coupled to the multistep load tap changer to provide electrical power to the load with a selected voltage, the multistep load tap changer being configured to tap a selected voltage step in order to provide the selected voltage to the electrical load.

2. The transformer of claim 1, wherein the multistep load tap changer is configured to switch the selected voltage step to change the selected voltage provided to the electrical load.

3. The transformer of claim 1, wherein the multistep load tap changer is configured to switch the selected voltage step to change the selected voltage provided to the electrical load in response to a change in the electrical load so that the electrical load is provided with relatively constant current.

4. The transformer of claim 1, further comprising a control system coupled to the transformer, the control system configured to control the multistep load tap changer so that the multistep load tap changer switches the selected voltage step in response to a change in the electrical load.

5. The transformer of claim 1, further comprising a voltage measurement transformer coupled to the secondary winding, wherein the voltage measurement transformer is configured to assess the selected voltage provided to the electrical load.

6. The transformer of claim 1, further comprising a switch coupled to the secondary winding, wherein the switch is configured to electrically isolate the electrical load from the transformer.

7. The transformer of claim 1, further comprising a control power transformer coupled to the secondary winding, wherein the control power transformer is used to provide power to one or more controllers configured to operate the transformer.

8. The transformer of claim 1, further comprising a current transformer coupled to the secondary winding, wherein the current transformer is configured to assess electrical current passing through the secondary winding.

9. The transformer of claim 1, wherein the voltage steps comprise equally partitioned voltage steps.

10. The transformer of claim 1, wherein the voltage steps comprise non-equally partitioned voltage steps.

11. The transformer of claim 1, wherein the electrical load comprises one or more subsurface heaters.

12. A method for controlling voltage provided to one or more electrical heaters, comprising:

providing electrical power to a first heater with a selected voltage using a variable voltage transformer, wherein the variable voltage transformer comprises:

a primary winding configured to be coupled to a voltage power source that provides a first voltage across the primary winding;

a secondary winding electrically isolated from the primary winding, wherein the secondary winding is configured to step down the first voltage to a second voltage that is a preset percentage of the first voltage;

a multistep load tap changer coupled to the secondary winding, wherein the load tap changer divides the second voltage into a selected number of voltage steps, the voltage steps incremented from a selected minimum percentage of the second voltage to a selected maximum percentage of the second voltage, the multistep load tap changer tapping a selected voltage step in order to provide the selected voltage to the first heater;

assessing change in electrical resistance of the first heater over a selected period of time; and adjusting the selected voltage provided to the first heater by changing the selected voltage step tapped by the multistep load tap changer, wherein the selected voltage is changed in response to the change in the electrical resistance of the first heater.

13. The method of claim 12, wherein the selected voltage is changed in response to the change in the electrical resistance of the first heater such that the electrical current provided to the first heater is relatively constant.

14. The method of claim 12, wherein the change in electrical resistance of the first heater is assessed by using a current transformer coupled to the secondary winding and a voltage transformer coupled to the secondary winding, wherein the electrical resistance is calculated by dividing a voltage assessed from the voltage transformer by a current assessed from the current transformer.

15. The method of claim 12, wherein the voltage steps comprise equally partitioned voltage steps.

16. The method of claim 12, wherein the voltage steps comprise non-equally partitioned voltage steps.

17. The method of claim 12, wherein the first heater comprises a subsurface heater.

18. The method of claim 12, further comprising assessing an electrical resistance of the first heater by comparing the assessed electrical resistance to a theoretical electrical resistance of the first heater; and changing the selected voltage provided to the first heater if there is a substantial difference between the assessed electrical resistance and the theoretical electrical resistance.

19. The method of claim 12, further comprising limiting the number of changes in the selected voltage for a set period of time.

20. The method of claim 12, further comprising cycling the selected voltage provided to the first heater so that the electrical current provided to the first heater remains relatively constant.

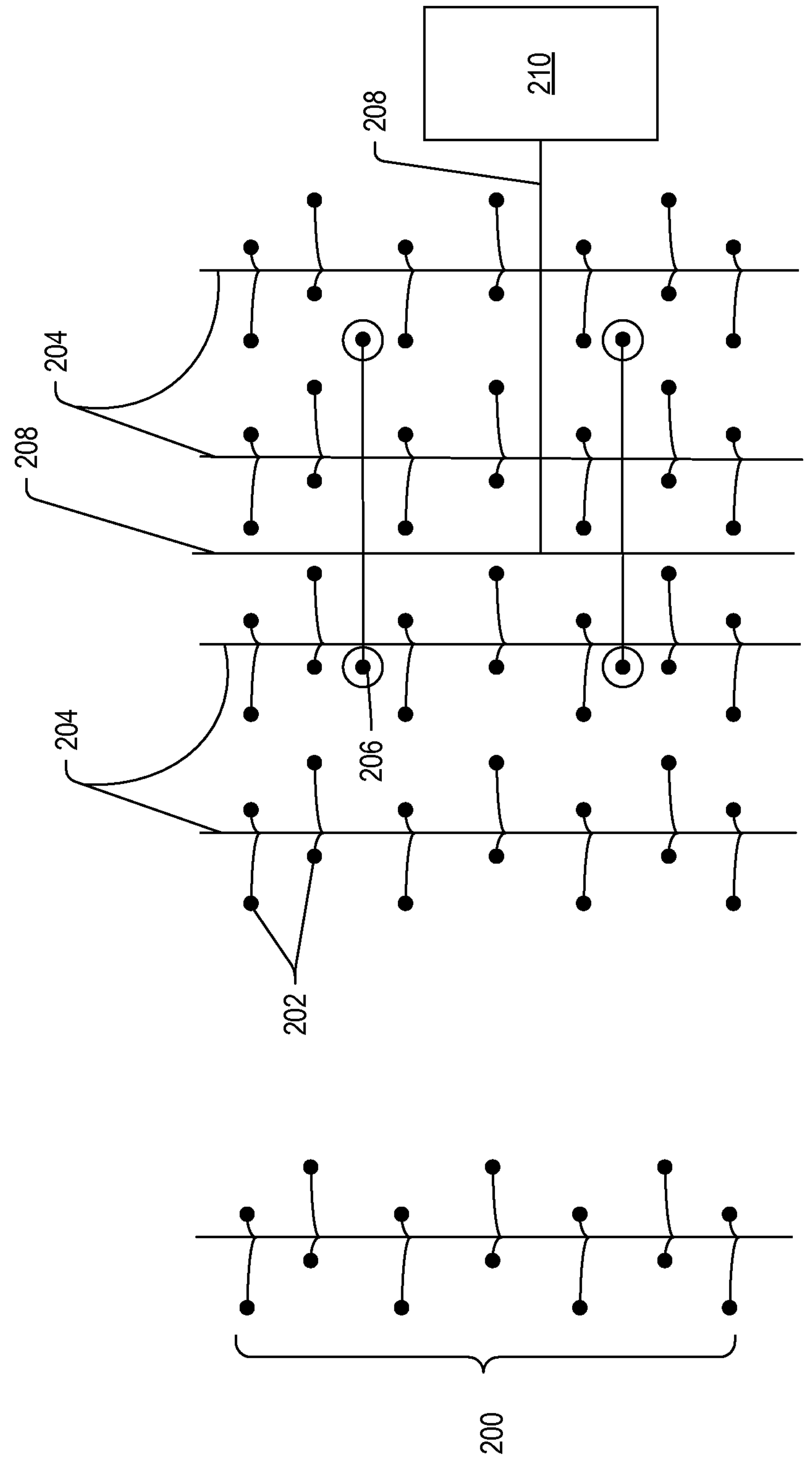

FIG. 1

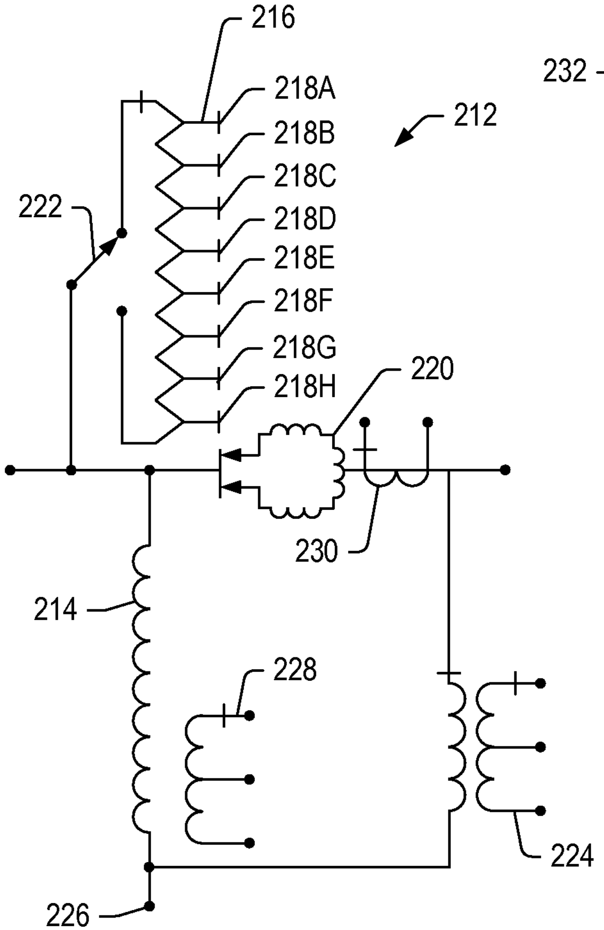

FIG. 2

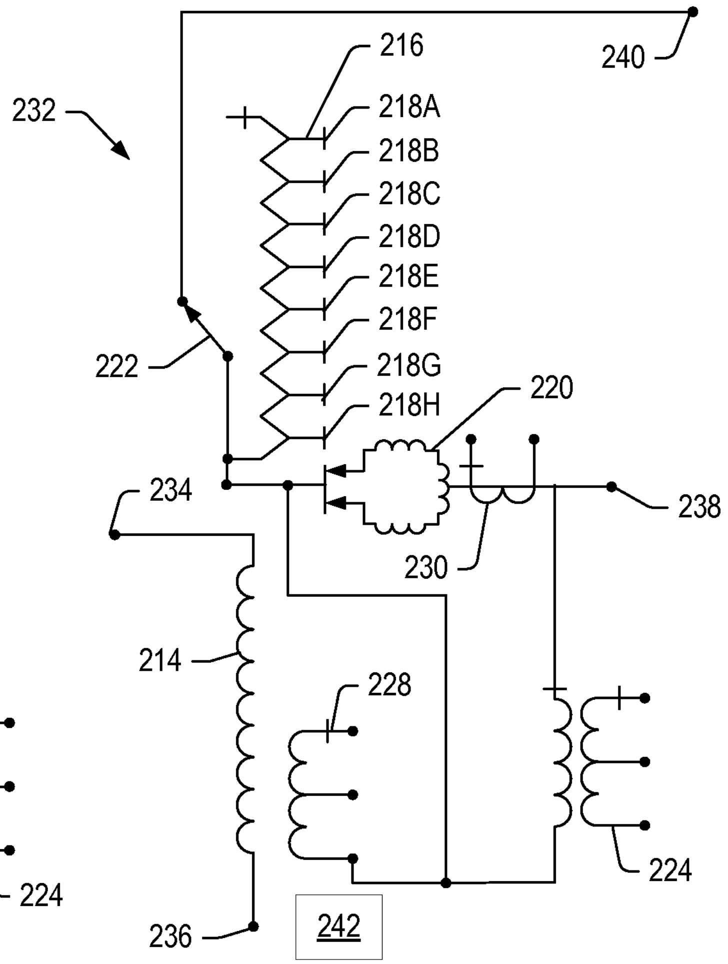

FIG. 3

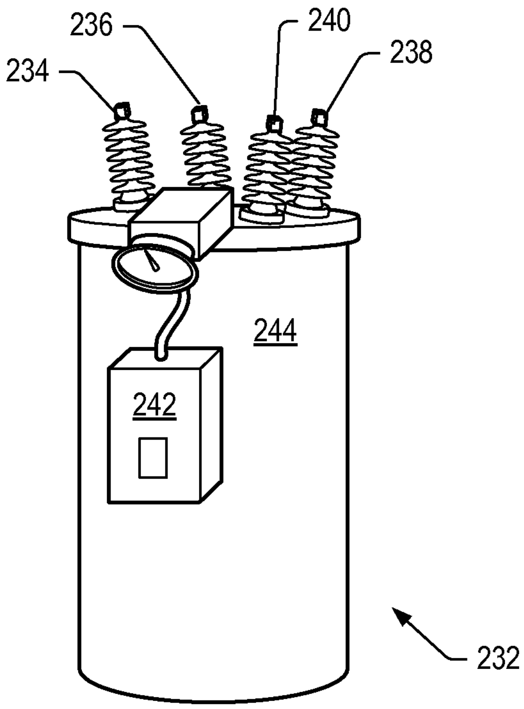

FIG. 4

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2008/079699

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G05D 11/00 (2008.04)
USPC - 700/286
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - G05D 11/00; H01F 29/00, 27/32 (2008.04)
USPC - 700/286

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | WO 98/34249 A1 (FROMM et al) 06 August 1998 (06.08.1998) entire document | 1-20 |
| Y | US 2006/0052905 A1 (PFINGSTEN et al) 09 March 2006 (09.03.2006) entire document | 1-20 |

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
01 December 2008

Date of mailing of the international search report
15 DEC 2008

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