(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 March 2020 (26.03.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/056468 A1

(51) International Patent Classification:
H02J 3/06 (2006.01) *G05F 5/00* (2006.01)
H02J 3/14 (2006.01) *H02M 5/00* (2006.01)
G05F 1/32 (2006.01) *H02M 7/00* (2006.01)

(21) International Application Number:
PCT/AU2019/051019

(22) International Filing Date:
23 September 2019 (23.09.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2018903557 21 September 2018 (21.09.2018) AU

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,

(54) Title: TRANSACTION-BASED ENERGY NETWORK

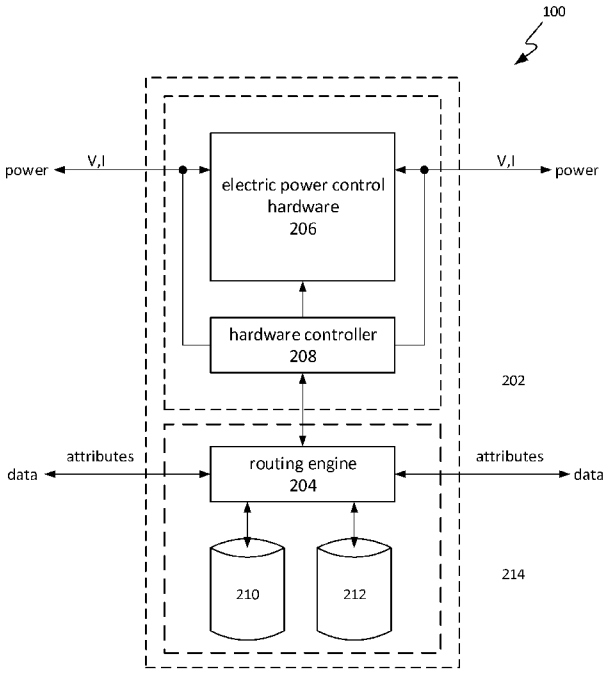


Figure 33

(57) Abstract: An electric power distribution controller configured to be communicatively coupled to other instances of the electric power distribution controller to form a network of electrical power distribution controllers that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation.

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EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

TRANSACTION-BASED ENERGY NETWORK

TECHNICAL FIELD

The present invention relates to the supply of electrical power, and in particular to a transaction-based energy network.

BACKGROUND

The electricity system is undergoing a change of scale not seen for decades. The traditional model of centralised large-scale generation providing electricity and inertia is changing to allow for carbon-free generation technologies such as solar and wind to supply a greater percentage of our electricity needs. This, combined with an increasing uptake in electric vehicles and electrification of heating systems is resulting in a system where the way we generate and use electricity has changed to a more decarbonised, decentralised, digitised and democratised system, but the way we transport it has not evolved and is no longer fit for purpose.

Energy System Challenges

The fundamental design of the electricity grid has not changed in more than 100 years. It is based on a hub and spoke delivery system, with electricity flowing one way from large generators to tranched consumers. The distances travelled are generally quite large, spanning hundreds and sometimes thousands of kilometres, resulting in significant energy losses. The entire system is generator-centric in that generators act to balance the grid by controlling the amount of power that is generated to match the amount of power that is consumed. The traditional generators provide both the real power consumed, as well as other services to the grid to maintain stability such as inertia.

Traditional generation such as coal fire power plants use a spinning turbine to generate electricity. The spinning mechanical inertia stored in the spinning turbine provides immediate acting synchronous power reserves for the system when an imbalance occurs.

Electricity generated from renewable sources such as wind and solar still provide the real power required, however they do not provide any inertia. This is primarily due to the fact that the generating elements are not physically connected to the system. The properties of these renewable generators are also volatile: the voltage, harmonics and phase can change rapidly but the electricity system cannot cope with these rapid changes.

Renewable energy generation is becoming cheaper than traditional generators because the marginal cost of production is very low. In particular, whereas coal power plants require a consumable input of coal to generate power, wind and solar only require the wind and the sun, which are freely available. However, because of the nature of the generation as described above, the electricity grid must be provided with other services in order to maintain the fragile balance of supply and demand in real time to provide a reliable power supply, referred to as balancing services. As the percentage of renewable energy generation increases so does the balancing services requirement. This has led to higher energy prices, for example in the USA the cost of energy is made up of 40% non-wholesale costs, and in some states such as New York this rises to 90% (source EIA). In Germany, the non-wholesale cost of energy accounts for 80.7% of the price of energy (source BDEW 2017).

Energy System Pricing Models

Most electricity systems globally operate in an energy market where generators bid to provide energy at a cost. The market operator then selects the mix of the cheapest generation to supply the predicted demand for a specified period, which is usually 30 minutes.

However, the changes to the electricity system described above significantly affect this practice in a number of ways. First, renewable generation is not dispatchable like traditional generation: it is dependent on the weather which is outside the generators' control. This means the generators at times do not meet their generation requirements, or affect the short-term system stability by immediately starting or stopping generation. Renewable generators often underestimate the amount of energy they will produce in order to avoid undersupply and the associated financial penalties, which means these generators have to curtail excess energy.

Additionally, geographically distributed power generation means that the power flows within the electricity grid are changing, both in quantity and sometimes direction. The grid owner and operator generally have no insight as to what is happening within the system as monitoring instrumentation was not previously required in these locations. This makes it more challenging for the grid to be kept operating effectively and efficiently.

It is desired to overcome or alleviate one or more difficulties of the prior art, or to at least provide a useful alternative.

SUMMARY

In accordance with some embodiments of the present invention, there is provided an electric power distribution controller configured to be communicatively coupled to other instances of the electric power distribution controller to form a network of electrical power distribution controllers that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation.

In some embodiments, the one or more specified electric power attributes include power amount.

In some embodiments, the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and one or more specified electric power attributes selected from: power quality, and attributes of electric power generation.

In some embodiments, the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and one or more specified electric power attributes selected from: power quality, attributes of electric power generation, and pricing.

In some embodiments, the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and pricing, and one or more specified electric power attributes selected from: power quality, and attributes of electric power generation.

In some embodiments, each said electric power distribution controller is communicatively coupled to or is a component of a corresponding electrical power control apparatus including:

one or more signal conversion components receiving electrical power in the form of a corresponding first signal having a corresponding first fundamental frequency and a corresponding first characteristic voltage, and generating a corresponding second signal having a corresponding second fundamental frequency and a corresponding second characteristic voltage;

a signal conversion control component that controls operation of the signal conversion components to determine an output voltage and an output frequency of an output signal of the electrical power control apparatus;

wherein the electric power distribution controller controls operation of the signal conversion control component to satisfy said requests.

In accordance with some embodiments of the present invention, there is provided an electrical power control apparatus including:

one or more signal conversion components receiving electrical power in the form of a corresponding first signal having a corresponding first fundamental frequency and a corresponding first characteristic voltage, and generating a corresponding second signal having a corresponding second fundamental frequency and a corresponding second characteristic voltage;

a signal conversion control component that controls operation of the signal conversion components to determine an output voltage and an output frequency of an output signal of the electrical power control apparatus; and

an electric power distribution controller that controls operation of the signal conversion control components and is configured to be communicatively coupled to other electric power distribution controllers of respective other instances of the electrical power control apparatus to form a network of electrical power control apparatuses that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation.

In some embodiments, each said electrical power control apparatus, includes:

a magnetic core including at least three interconnected limbs defining a

plurality of magnetic circuits, the at least three interconnected limbs including a first limb and second limbs;

a primary winding to receive input electrical power having an input voltage, an input current, and an input power factor, the primary winding being wound around the first limb of the limbs of the magnetic core to generate a corresponding first magnetic flux in the first limb that is divided between the second limbs;

secondary windings to provide output electrical power having an output voltage and an output power factor to a load, the secondary windings being wound around the first and second limbs of the magnetic core to generate the output voltage across the secondary windings from magnetic flux in the first and second limbs of the magnetic core, wherein the secondary windings around the second limbs are wound in opposite polarities; and

control windings wound around the second limbs to modify the magnetic flux in the second limbs and thereby modify the output voltage and the input power factor, wherein the control windings around the second limbs are wound in opposite polarities.

In some embodiments, each said electrical power control apparatus is configured to reduce harmonics such that the output signal has lower distortion than the received first signal.

In some embodiments, each said electrical power control apparatus is configured to correct power factor such that the output signal has an improved power factor relative to the received first signal.

In some embodiments, each said electrical power control apparatus is configured to balance power between phases of the received electric power.

In some embodiments, the electric power distribution controller is configured to:

receive requests for electric power from corresponding downstream electric power distribution controllers specifying one or more corresponding electric power attributes selected from: power amount, stability, noise, reliability, sustainability, and pricing; and

for each request received from a corresponding downstream electric power distribution controller:

(i) process the received request to generate corresponding requests for sending to corresponding upstream electric power distribution controllers in order to determine the abilities of their respective upstream electrical power control apparatuses to individually or collectively supply electric power satisfying the received request;

(ii) receive responses to the generated requests from the corresponding upstream electric power distribution controllers, the responses being indicative of the abilities of the corresponding upstream electrical power control apparatuses to supply electric power satisfying the received request;

(iii) determine whether the indicated abilities indicate that the corresponding upstream electrical power control apparatuses are able, individually or collectively, to supply electric power satisfying the received request;

(iv) select, based on the step of determining and the indicated abilities, one or more of the corresponding upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the electric power distribution controller in order to satisfy the received request;

(v) cause the selected upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the power distribution controller; and

(vi) cause the corresponding electrical power control apparatus to output electric power having attributes satisfying the attributes of the received request to a downstream electrical power control apparatus corresponding to the downstream electric power distribution controller.

In some embodiments, in the event that step (iii) determines that the upstream electric power distribution controllers are unable to satisfy the received request, the electric power distribution controller is configured to cause a corresponding message to be sent to the upstream electric power distribution controllers so as to provide a further opportunity for the upstream electric power distribution controllers to improve their individual or collective ability to satisfy the request.

In some embodiments, steps (i) to (vi) constitute a transaction between the electric power distribution controller, the corresponding downstream electric power distribution controller, and the one or more selected upstream electric power distribution controllers, and each of the electric power distribution controllers participating in the transaction is configured to store data representing the transaction in a corresponding database.

In some embodiments, the attributes specify a cost function that defines pricing for electric power in dependence on the proportions of renewable and non-renewable sources of the electric power.

In some embodiments, the attributes specify a cost function that defines pricing for electric power in dependence on harmonic distortion and/or power factor of the electric power.

In accordance with some embodiments of the present invention, there is provided an electric power distribution process executed by an electric power distribution controller communicatively coupled to other instances of the electric power distribution controller to form a network of electrical power distribution controllers that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation, the process including the steps of:

receiving requests for electric power from corresponding downstream electric power distribution controllers specifying one or more corresponding electric power attributes selected from: power amount, stability, noise, reliability, sustainability, and pricing; and

for each request received from a corresponding downstream electric power distribution controller:

(i) processing the received request to generate corresponding requests for sending to corresponding upstream electric power distribution controllers in order to determine the abilities of their respective upstream electrical power control apparatuses to individually or collectively supply electric power satisfying the received request;

(ii) receiving responses to the generated requests from the corresponding upstream electric power distribution controllers, the

responses being indicative of the abilities of the corresponding upstream electrical power control apparatuses to supply electric power satisfying the received request;

(iii) determining whether the indicated abilities indicate that the corresponding upstream electrical power control apparatuses are able, individually or collectively, to supply electric power satisfying the received request;

(iv) selecting, based on the step of determining and the indicated abilities, one or more of the corresponding upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the electric power distribution controller in order to satisfy the received request;

(v) causing the selected upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the power distribution controller; and

(vi) causing the corresponding electrical power control apparatus to output electric power having attributes satisfying the attributes of the received request to a downstream electrical power control apparatus corresponding to the downstream electric power distribution controller.

In accordance with some embodiments of the present invention, there is provided an electronic storage medium having stored thereon FPGA configuration data representing executable instructions or processor-executable instructions that, when executed by at least one FPGA or processor, cause it to execute the above steps.

Also described herein is an electrical power distribution controller for communicatively coupling to other instances of the electrical power distribution controller to form a network of electrical power distribution controllers that collectively control the flow of electric power in an electrical power distribution network to satisfy requests for electric power with one or more specified attributes selected from: power amount, stability, noise, reliability, sustainability, and pricing.

Also described herein is an electrical power distribution network, including:

a plurality of electrical power control apparatuses, each of the electrical power control apparatuses including:

one or more signal conversion components receiving electrical power in the form of a corresponding first signal having a corresponding first fundamental frequency and a corresponding first characteristic voltage, and generating a corresponding second signal having a corresponding second fundamental frequency and a corresponding second characteristic voltage;

a signal conversion controller that controls operation of the signal conversion components to determine an output voltage and an output frequency of an output signal of the electrical power control apparatus; and

an electrical power distribution controller as described above;

electrical power generation components acting as sources of electrical power to at least some of the electrical power control apparatuses; and

electrical power consumption components acting as sinks of electrical power from at least some of the electrical power control apparatuses;

wherein the electrical power control apparatuses operate autonomously but are interconnected such that an output of each of the electrical power control apparatuses is connected to an input of at least one corresponding other of the electrical power control apparatuses and to one or more of the sinks and/or sources of electrical power so that the electrical power control apparatuses collectively maintain the voltages and frequencies of electrical power signals flowing through the electrical power distribution network at target values to compensate for variations in the sinks and/or sources of electrical power.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the present invention are hereinafter described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 is a functional block diagram of an electrical power control apparatus/process in accordance with some embodiments of the present invention;

Figure 2 is a block diagram of an electrical power control apparatus in accordance with some embodiments of the present invention, including a magnetic core having multiple magnetic circuits and a control system to control the modulation of magnetic flux in those magnetic circuits;

Figure 3 is a circuit diagram with a rectifier circuit, a DC link and two bridge circuits to provide pulse width modulation of a control winding of the electrical power control apparatus;

Figure 4 is a schematic diagram of a single-phase magnetic core of a single-phase embodiment of the electrical power control apparatus, showing the configurations and connections of the primary, secondary, and control windings;

Figure 5 is a graph showing the B-H curve of electrical steel used in the described embodiments of the electrical power control apparatus;

Figure 6 is a functional block diagram of an embodiment of the control system of the electrical power control apparatus;

Figure 7 is a block diagram of a phase lock loop (PLL) component of the control system;

Figure 8 is a block diagram of a vector signal generator component of the control system;

Figure 9 is a block diagram of a half park transform component of the control system;

Figure 10 is a block diagram of a reference voltage generator component of the control system;

Figure 11 is a block diagram of a voltage controller component of the control system;

Figure 12 is a block diagram of a reactive power estimator component of the control system;

Figure 13 is a block diagram of a reactive power regulator component of the control system;

Figure 14 is a wire frame representation of a three-phase magnetic core of a three-phase embodiment of the electrical power control apparatus, which is able to control voltage waveform, RMS voltage, power factor, and balance power across the three phases;

Figure 15 is a Nichols plot of the response of the phase lock loop component of Figure 7;

Figure 16 is a Nichols plot of the response of the voltage controller component of Figure 11 for different power factors;

Figure 17 is a Nichols plot of the response of the reactive power components of Figures 13 for different power factors;

Figures 18 to 21 are three-dimensional surface plots of respectively the output to input voltage ratio (Figure 18), the output power (Figure 19), the control power (Figure 20), and the power factor (Figure 21), each of these being plotted as a function of input voltage amplitude and phase for different control voltages;

Figure 22 is a screen capture image showing actual measured waveforms of input signals provided to the apparatus and corresponding output signals generated by the apparatus, including the input voltage waveform (top left), RMS voltage (middle left) and power factor (lower left), and the output voltage waveform (top right), RMS voltage (middle right) and power factor (lower right);

Figure 23 is a graph of a measured input voltage waveform, and the corresponding control signal voltage and output voltage waveforms, demonstrating removal of 3^{rd}, 5^{th} and 7^{th} harmonics present on the input waveform from the output generated by the electrical power control apparatus;

Figure 24 is a plot of a physical voltage dip test completed to IEC standard 610000-4-11, showing the reduction in voltage dip in the output generated by the electrical power control apparatus;

Figure 25 is a magnetic circuit diagram of an embodiment of the electrical power control apparatus, showing the configuration of primary, secondary, control, and rectifier windings/coils;

Figure 26 is a schematic diagram showing the configuration of the magnetic core and windings/coils of an embodiment of the electrical power control apparatus;

Figure 27 is a cross-sectional side view of the magnetic core of an embodiment of the electrical power control apparatus as shown in Figure 26 showing the arrangement of the copper turns in the coils, and the locations of thermocouple sensors;

Figure 28 is a three-dimensional wire frame view showing the three-dimensional spatial arrangement of the windings/coils shown in Figure 26, together with a structural frame to support and move the apparatus;

Figure 29 is a block diagram of power electronics used to drive the control windings and rectifier winding of the apparatus of Figure 25;

Figure 30 is a circuit diagram of the power electronics shown in Figure 29, including a rectifier circuit, a DC link and two bridge circuits to provide pulse width modulation (PWM) of the control windings and rectifier winding;

Figure 31 is a schematic wireframe representation of a three-phase configuration of a magnetic core for an electrical power control apparatus to control voltage waveform, RMS voltage, power factor, and balance power across the three phases through the magnetic core;

Figures 32 and 33 are schematic diagrams of an electrical power device or system in accordance with embodiments of the present invention;

Figure 34 is a flow diagram of a power control process executed by a transaction or routing engine of the system of Figure 33;

Figures 35 to 42 are block diagrams illustrating energy transactions between transaction or routing engines of electricity distribution networks; and

Figure 43 is a flow diagram of an energy transaction process executed by a transaction or routing engine of the system.

DETAILED DESCRIPTION

"Faraday Exchanger" power control components

The described embodiments of the present invention include an electrical power control apparatus and process that involve receiving input electrical energy in the form of an input signal having some voltage waveform and root-mean-square (RMS) voltage, and converting that input electrical energy to output electrical energy in the form of an output signal having a desired or 'target' voltage waveform and a desired or 'target' output RMS voltage. The input electrical energy will typically vary over time (that is, its voltage waveform and/or RMS voltage is time-dependent), and thus the apparatus and process operate to dynamically control the conversion so that the output electrical energy has the desired target voltage waveform and target RMS voltage, which themselves may also vary over time. Additionally and simultaneously, the output electrical energy of the apparatus will have a power factor determined by the downstream load drawing power from the apparatus. The apparatus determines that power factor on its output and provides a unity power factor on its input, such that (the input of) the apparatus appears as an ideal (purely resistive) load.

The electrical power control apparatus and process are thus able to provide voltage waveform and RMS voltage conversion while simultaneously providing power factor correction, utilising high-speed electromagnetic path modulation instead of electronic circuit switching (used in power electronics devices) to deliver improved efficiency and performance (as well as electrically isolating the two systems).

Although the electrical power control apparatus and process are primarily described herein in the context of mains power distribution, it will be apparent to those skilled in the art that the electrical power control apparatus and process may be used in essentially any electrical system application that requires control of output power factor and/or voltage waveform and/or RMS voltage, including, transformers, power factor compensation, harmonic filters, and other applications, for example. Many other applications of the electrical power supply system and process described herein will be apparent to those skilled in the art in light of this disclosure.

In this specification, unless the context indicates otherwise, the term "signal" is used for convenience of reference, and is to be construed broadly as referring to a form of electrical energy characterised by a voltage, current, and at least one fundamental frequency (which could be zero in the case of a DC voltage), and does not necessarily require that any form of information is represented by or conveyed by the signal, notwithstanding that some embodiments of the invention may involve the communication of information encoded in the signal.

As shown in Figure 1, an electrical power control apparatus 100 (also referred to herein as a "Faraday exchanger") includes a voltage control component 104, a power factor control component 108, and a controller 106. As described above, the voltage control component 104 receives an input signal of some characteristic input voltage, and provides a corresponding output signal having a selected or desired output voltage, regardless of the input voltage. Similarly, the power factor control component 108 receives an input signal of some output power factor, and provides a corresponding signal having a selected or desired input power factor, regardless of the input signal power factor. In combination, the voltage control component 104 and the power factor control component 108 act in concert so that the apparatus 100 receives an input signal having some (typically time-varying) characteristic voltage V_{in} and power factor PF_{in} and

generates a corresponding output signal having a selected voltage V_{out} and a selected power factor PF_{out}, where the output voltage V_{out} *is* maintained substantially at a desired value and the input power factor PF_{in} is maintained substantially at unity.

For example, where the electrical power control apparatus 100 is used as part of a mains electricity distribution system, the apparatus 100 can be configured so that the output voltage V_{out} is constant and equal to the required voltage level independent of V_{in}, and the output waveform is maintained as a perfect (or at least improved) sine wave independent of the input waveform, and the power factor on the input side is maintained at 1 independent of the output power factor being determined by the load on the apparatus 100. Waveform harmonics and voltage deviations are a major source of losses and instability within an electricity grid.

The controller 106 uses step down devices (*e.g.*, buck converters in the described embodiments) to monitor the input voltage, and generates corresponding voltage control and power factor control signals that are respectively used to control the operation of the voltage control component 104, and the power factor control component 108.

The same result can be delivered by changing the voltage control component to a current control component. In this configuration, the current is measured instead of the voltage at the same location, but using current sensors instead of voltage sensors.

Similarly, the same result can also be delivered by changing the voltage or current control component to a flux control component. In this configuration, the magnetic flux is measured instead of the voltage or current, at the same location but using flux sensors instead of voltage or current sensors.

As known by those skilled in the art, a transformer is an electromagnetic device that transfers electric energy from one circuit to another circuit via mutual inductance, and is typically made up of a primary winding, a magnetic core and a secondary winding. When an alternating voltage is applied to the primary winding, an alternating current flows through the primary winding. This magnetizing current produces an alternating magnetic flux. The flux is mostly constrained within the magnetic core, and induces a

corresponding voltage in the linked secondary winding, which if connected to an electrical load produces an alternating current. This secondary load current then produces its own alternating magnetic flux which links back with the primary winding.

The secondary voltage is determined by the product of the primary voltage and the ratio of the number of turns in the secondary winding and the number of turns in the primary winding. Transformers are commonly used to convert between high and low voltages, but they are bulky by necessity at distribution frequencies. They offer high efficiency, simplicity of design, and bidirectional power transfer. However their passive nature affords limited regulation of the power transferred, requiring the introduction of inefficient power factor control and voltage regulation. The physics of operation at mains supply frequencies also makes them comparatively large for a given power rating, increasing costs of materials, fabrication and insulation management.

Body of Device

As shown in Figure 4, in the described embodiment, a device includes a magnetic core in the form of an EI core (of single phase shell configuration) where the primary and secondary coils or windings (these terms being equivalent in this specification) are located on the centre limb of EI the core; however, unlike a conventional transformer, the secondary is connected in series to an additional pair of coils on the two outer limbs, one wound with the same polarity or sense as the centre secondary coil, and the other wound with the opposite polarity or sense. A corresponding pair of control coils are also wound around the outer pair of limbs, with the two control coils wound in opposite polarities or senses on each limb. This geometry, combined with selection of the magnetic core material (being an M400-50A non grain oriented soft electrical steel in the described embodiments), results in good magnetic coupling between the primary coils and secondary coils, good magnetic coupling between the secondary coils and control coils, but poor magnetic coupling between the primary coils and the control coils, this general arrangement providing the best performance.

The primary winding on the centre arm has N_1 turns, and the secondary winding is split across all 3 limbs, with the centre limb having N_2 turns, and the outer limbs having xN_2 and $-xN_2$ turns, meaning that they are wound in opposite directions. The control windings have an equal number of turns wound in opposite directions.

When the control windings are turned off (have no power flowing through them), the flux flowing in the core is evenly split between the two outer flux paths (*i.e.*, defined by the outer limbs) because the geometry is symmetrical. As the two outer secondary windings are wound in opposite directions, they effectively cancel each other out in the magnetic circuit, and do not affect the magnetic field in the central limb, and consequently the voltage transformation between the primary and secondary windings is N_1 to N_2, as would be the case for a normal transformer. A consequence of this configuration is that if there is no control of the device (for example if the control component fails for any reason), the device operates as though it is a normal transformer.

By energising the control windings (putting AC or DC power through them) the balance of the flux between the two magnetic pathways is altered. This results in the two outer secondary windings each having a different amount of flux flowing through them. As they are wound with opposite polarities this results in the effect of adding or subtracting turns from the secondary winding via a proportion of N2 + xN2 or a proportion N2 + -xN2, depending on the % of flux passing in each limb. This changes the voltage transformation ratio N1 to N2 of the device, with no moving parts or power electronics in the power flow path.

Furthermore, as they do not interact with the primary coil, a phase shift in the control coil voltage will produce a phase shift between the primary and secondary coils. This allows the input and output power factors to be adjusted independently.

For the transformer to operate optimally, it is advantageous to have good magnetic coupling between the primary and the secondary windings, and between the secondary and the control windings, but little or (ideally) no coupling between the primary and the control windings. When in operation, uniquely, flux circulates around the outer shell of the core, not passing through the centre limb. This flux is stored magnetic energy that allows the apparatus 100 to provide power factor control by absorbing or injecting energy The amount of magnetic energy that can be stored within the core is dependent on the physical size of the core, because more magnetic material is required to store a larger amount of magnetic energy without the material becoming magnetically saturated. As the core becomes larger, the efficiency of the voltage transform will reduce due to the increased iron losses associated with a larger core. There is therefore a design

trade off between efficiency and magnetic energy storage which can be optimised for the specific design requirements for each device.
In some embodiments, an additional coil is added to the centre arm of the core and is connected to a rectifier, as shown in Figure 26. This rectifier forms part of the controller as shown in Figure 29 and is connected to an inverter through a DC link with a capacitor.

In the described embodiments, the device operates in a different section of the core material B-H curve to a normal transformer. A material with linear properties in the operating area of the B-H curve is desirable to enable the device to be controlled to deliver voltage waveform, RMS voltage and power factor control.. Similarly, the core material should have a permeability curve which has a soft increase (i.e. does not rapidly change from one value to another) in the magnetic field up to material saturation to enable the device to be controlled to deliver voltage waveform, RMS voltage and power factor control.

The core of the device can be composed of any electromagnetic material that will allow magnetic flux to be transferred between windings. In the described device, this is a non grain-oriented electrical grade steel. The windings of the device can be made with any electrical conductor, in the described device this is high conductivity copper.

The specific configuration of a device (including winding and core materials and configurations, laminations, dimensions, core size and shape, number of phases and face configurations, et cetera) can be determined using standard electromagnetic design methods known to those skilled in the art.

One such core material that could be used is M400-50A electrical steel. This material is described in the table below, and its flux density against field strength (B-H curve) is shown in Figure 5.

Parameter	Symbol	Value	Units	Comment
Material	--	--	--	Non-grain oriented electrical steel
Manufacturer	--	--	--	Cogent Power
Grade	--	--	--	M400-50A
Thermal conductivity	k	45	W/m·K	@20 °C
Conventional density		7700	kg/m^3	Density
Relative permeability at 1.5 T	μ_r	1050	NA	
Resistivity	ρ	42	μΩcm	
Specific losses at 50Hz				

at 1.0 T	--	1.49	W/kg	
at 1.5 T	--	3.57	W/kg	
Magnetic polarisation at 50Hz				
at 2500 A/m	J	1.63	T	
at 5000 A/m	J	1.76	T	
at 10000 A/m	J	1.97	T	

The sizing of the magnetic core is dependent on the amount of energy passing through the device, in the same way that the core of a transformer is dependent on its power rating.

The number of windings in the primary, secondary and control coils is dependent on the performance of the device required, such as the standard voltage transformation as well as the range of voltage control performance. The configuration and dimensions of one embodiment of the device are shown in Figure 26, with each coil having the following number of turns: A 113, B 54, C 13, D13, E 14, F 14, G 79. A cross section of these windings is shown in Figure 27.

3 phase device

The electrical power control apparatus can be expanded from a single phase to a 3 phase device in multiple ways. Firstly, 3 single phase devices can be used individually on each phase of a 3 phase connection. This arrangement successfully controls voltage and power factor in the same way as a single phase device does. The control of the device will consist of power electronics, which will also have the capability to balance power across the 3 phases.

In another embodiment, a more advanced core arrangement can be utilised where all 3 phases pass through a single electromagnetic core, as shown in Figure 14. This works using the same principles as a single phase device, however power can be balanced between the phases within the magnetic core as they are magnetically coupled.

The arrangement shown in Figure 14 has multiple control windings which, using the same control scheme expanded to 3 phases, can control the voltage, frequency and power factor, as well as balance power across the phases. This requires a geometry which is symmetrical between all 3 phases. Any geometry which meets this requirement whilst allowing the placement of control windings on both flux paths for each phase, and splitting of the secondary coils as per the single phase device will achieve the desired

result. This may include for example a geometry of a tube (rather than a triangular prism as shown in the diagram), with a ring at the top and bottom of the device joining the 3 arms of the core.

Figure 31 shows another 3 phase geometry, with each rectangular face of the triangular prism consisting of a single phase shell type core. The primary coil is wound around the middle horizontal arm, the secondary coil wound around all three horizontal arms, the control windings wound around the top and bottom horizontal arm.

Additionally, a rectifier coil can be wound around the centre horizontal arm. This constitutes 7 coils on each phase, or 21 coils for the three phase device.

Additionally, on each vertical axis of the prism, two additional control coils are added to enable balancing of power between the phases, to total six phase balancing coils per device. This results in 29 coils per device in total.

Device Performance Relationships

The performance of the energy exchange device is dependent on several parameters such as the mutual and self inductances of the primary, secondary and control coils, as well as a number of variables such as the input, output and control voltages, power throughput and load power factor.

Let **L** (H) and **R** (Ω) denote the inductance and resistance matrices between the device primary (1), secondary (2) and control (3) coils. Define $\omega = 2\pi f$ (rad/s) as the angular frequency of the supply voltage, $\mathbf{i} = [i_1 , i_2 , i_3]$ (A) as the current through the coils and $\mathbf{v} = [v_1 , v_2 , v_3]$ (V) as the voltage across them. The relationship between current and voltage across the device is given by:

$$[\mathbf{R} - j\omega\mathbf{L}]\,\mathbf{i} = \mathbf{v}$$

If the load impedance $Z = R\,(1 + j\,(1 - p^2)^{1/2} / p)$ where R (Ω) is the load resistance and p the power factor then $v_2 = Z\,i_2$ and the above equation can be solved explicitly if v_1 and v_3 are specified. In the following sections, input to output relationships are plotted as a function of the control voltage v_3 for the parameter values listed in the table in order to demonstrate the characteristics of the apparatus 100.

Parameter	Symbol	Value	Units
Base frequency	f	60	Hz
Primary voltage	V_1	115	Vrms

Secondary voltage	V_2	55	Vrms
Coil Inductance	**L**	*	H
Coil Resistance	**R**	*	Ω
Load resistance	R	4	Ω
Load power factor	Z	0.8	-

With respect to the described embodiment, Figure 18 shows the voltage ratio V1 / V2 x |v2|/ |v1| x 100% as a function of the control voltage magnitude and phase relative to the primary voltage signal. The voltage ratio clearly varies with the control voltage and in fact the relationship is almost linear when the control is in phase with the primary voltage. This implies that ratio across the device can be altered and, since the variation is monotonic, it can be controlled.

With respect to the described embodiment, Figure 19 shows the output power as a function of the control voltage magnitude and phase relative to the primary voltage signal. The output power varies as the output voltage squared hence the profile of output power is very similar to that of output voltage. In practice the output power will be determined by the behaviour of the electrical load.

With respect to the described embodiment, Figure 20 shows the control power as a function of the control voltage magnitude and phase relative to the primary voltage signal. Control power can clearly be either positive or negative depending on the magnitude and phasing of the applied control voltage and the power electronics needed to drive the control coils must be able to inject and absorb power from the device.

With respect to the described embodiment, Figure 21 shows the input power factor as a function of the control voltage magnitude and phase relative to the primary voltage signal. Power factor is clearly influenced by the control voltage, particularly its phase. As the power factor relationship with respect to control voltage phase is monotonic, and that of the voltage ratio with respect control voltage amplitude is also monotonic, then it is possible to control both voltage ratio and input power factor simultaneously.

Control System

As shown in Figure 2, the control system monitors the apparatus output voltage and input current and voltage, with the objective of ensuring that the output voltage waveform is a sinusoid of the correct amplitude and the input power factor is unity. Those skilled in the art will know there are many ways to achieve the desired control, of various algorithms and configurations, using a variety of different hardware

implementation types. One such implementation is described below, implemented as a discrete process on digital processors, as described below.

Control Architecture

The overall structure of the control system is shown in Figure 6. The phase lock loop (PLL) monitors the input voltage and synchronizes the output frequency and phase angle of the reference voltage generator to the input waveform. The voltage controller monitors the error between this reference and the measured output voltage and generates the control demand needed to drive the voltage error to zero.

The phase of the reference voltage signal is augmented by the reactive power controller. This drives the estimated input reactive power to zero and hence the input power factor to unity. Reactive power is estimated by monitoring input current and voltage over an entire cycle.

The 3 closed loops that operate in the control system are the PLL, VCL and RPL. Their control performance is assessed within the following paragraphs.

Phase lock loop (PLL)

The components in the phase lock loop are shown in Figure 7, 8, and 9. The input voltage is first scaled approximately to generate a signal that has a maximum value around unity. The scaling doesn't have to be precise as the PLL is relatively insensitive to input amplitude. A vector consisting of the input signal phase shifted by 90 deg is produced by the AB vector generator shown below. This is then Park transformed into the DQ frame using the phase angle generated by the PLL. Only the Q component is needed.

Parameter	Symbol	Value	Units
Sample frequency	fp	fs/10	kHz
Input scaling	Vs	$1/V1_{max}$	V
Base frequency	f0	f0	Hz
LP filter bandwidth	Wf	100π	rad/s
LP filter bandwidth	Wo	20π	rad/s
Proportional gain	K_p	20	rad/s
Integral gain	K_i	50	rad/s^2
Feedforward frequency	f0	f0	Hz
Frequency upper limit	W_{max}	2π 1.1 f0	rad/s

lower limit	W_{min}	2π 0.9 f0	rad/s

The Q component is zero when the PLL phase is synchronised to the input signal. The PI control law increases or lowers the estimated frequency (and hence its phase) in order to drive the Q error to zero. LP (low pass) filters are included to remove any unwanted noise from the voltage signal. The feedforward reduces feedback requirements allowing the bandwidth of the closed loop to be made as low as possible, this reduces the sensitivity signal noise even further. Parameters for the PLL are defined in the table below.

In the described embodiment, the PLL provides the phase synchronisation needed by the other 2 control loops, but its operation is virtually independent. The loop is deliberately made as low bandwidth as possible to enhance suppression. The open loop characteristics are shown in the Nichols plot in Figure 15 and key control parameters summarised in the table below.

Parameter	Symbol	Value	Units
Loop bandwidth		3	Hz
Gain margin		+Inf	db
Phase margin		+80	deg
Peak sensitivity		+0.8	db

Reference voltage generator

The purpose of the reference voltage generator is to produce a voltage demand for the voltage control loop to track. This is shown in Figure 10. The amplitude input is set to the desired output voltage, and the phase is set by the PLL and reactive power regulator. As such, no parameters are needed.

High bandwidth voltage control

The voltage control law shown in Figure 11 is a high gain integral action control law equipped with low bandwidth feedback to wash out unwanted DC signal. Parameters for the control law are defined in the table below.

Parameter	Symbol	Value	Units
Sanple frequency	fs	fs	kHz
Control gain	Kv	20×10^3	V/s
Washout frequency	Wv	$200\ \pi$	rad/s
Output limit	V_L	+/-200	V

In the described embodiment, the voltage control loop requires to track the voltage reference signal precisely which requires a high bandwidth to attenuate harmonics. A Nichols plot of the voltage open loop is shown in Figure 16, and the key control parameters summarised in the table below. Note that the open loop transfer function (OLTF) is relatively independent of the load power factor due to careful selection of the core magnetic material to minimise core flux dispersion (leakage) and primary to control coil cross coupling inductance. The low frequency roll-off of the control system is required to avoid saturating the control amplifier input with a DC signal.

Parameter	Symbol	Value	Units
Loop bandwidth		>2	kHz
Gain margin	GM	+13	db
Phase margin	PM	+70	deg
Peak sensitivity		<0	db

Reactive power estimator

An estimate of reactive power is needed to control the power factor. Reactive power is computed by multiplying the quadrature component of input voltage by current and averaging this over a complete cycle. The reactive power estimator is shown in block diagram form in Figure 12. Note that ¼ (quadrature) and full cycle delays are approximated to the nearest sample time using the z-d operator.

Parameter	Symbol	Value	Units
Sample frequency	fq	fs/10	kHz

Reactive power regulator

The reactive power regulator is a low gain limited integrator as shown in Figure 13. The limiter is used to curtail the degree of control action used to avoid saturating the magnetic core of the FE with unrealistic power factor compensation demands. Parameters for the regulator are defined in the table below.

Parameter	Symbol	Value	Units
Sample frequency	fq	fs/10	kHz
Gain	Kq	0.025	rad/s/VA
Output upper limit		$\pi/2$	rad
lower limit		0	rad

The reactive power regulator is required to hold the input power factor at unity. The control loop is inherently nonlinear by virtue of the product of voltage and the quadrature current used in the reactive power estimation algorithm. Stability and performance should therefore be evaluated using a nonlinear method of analysis such as phase plane. The Nichol's plot in Figure 17 shows the OLTF of the loop when linearised about a primary voltage. The key parameters are summarised in the table below.

Parameter	Symbol	Value	Units
Loop bandwidth		5 to 12	Hz
Gain margin		+12	db
Phase margin		+70	deg
Peak sensitivity		-1	db

Figure 22 is a screenshot showing the actual measured input and outputs of the described embodiment device in operation. The left column includes three plots of values measured on the primary winding, and the right column includes plots of respective values measured on the secondary winding.

The top row shows the primary AC voltage waveform, with significant random noise. The output waveform on the secondary is a relatively clean AC waveform. In the described embodiments the device is able to reduce the total harmonic distortion (calculated as the harmonics energy divided by the total energy) from 35% on the input to less than 2% on the output.

The middle row includes plots of RMS voltage, with random noise and a step function on the primary windings, and a stable output voltage on the secondary winding.

The bottom row includes a plot showing a load power factor varying on the secondary winding. However, this is not passed upstream to the primary winding, as can be seen by the stable unity power factor of the primary winding shown in the left-hand plot.
The harmonic suppression is further shown in Figure 23. Figure 64 shows the apparatus performance for a voltage dip.

The power flow through the apparatus is regulated by controlling its control windings shown in Figure 4. As the input power and output power draw can be constantly changing, the control windings are correspondingly adjusted by changing the DC or AC

control current to provide a selected level of reluctance. The control current can be either a direct analog signal, where the current level is changed directly, or can take the form of a digital signal using pulse width modulation (PWM) to provide an equivalent average current. PWM uses a digital signal switched at a rate much higher than will affect the load to control the power supplied. Switching the voltage to a load with the appropriate duty cycle approximates the desired voltage level. In the same manner, the duty cycle can be varied to deliver an approximation of an analog waveform using digital sources. Modern semiconductors are able to provide this switching in microseconds, meaning that power loss is very low, but the imperfect waveform produce can cause significant harmonics and losses in some applications.

PWM of the current through the control winding is achieved through a control circuit consisting of a rectifier, a DC link, and two bridges, as shown in Figure 3. The two bridges are made up of four diodes and four insulated-gate bipolar transistors (IGBT). The four IGBT's are switched on and off by controller 106 in order to provide the correct current level in the control winding 202 to deliver the target signal output. It will be apparent to those skilled in the art that this can be achieved in a number of various circuit topologies. A control circuitry topology utilising step down converters (buck converters) allows a greatly reduced power usage to achieve the desired magnitude and range of virtual air gap control.

By controlling the PWM at a speed of 50kHz, the waveform of the output signal is modulated using the control windings in order to smooth out harmonics, as shown in Figure 23. Faster control speeds better compensate and correct harmonics.

Additionally, in some embodiments the rectifier is connected to the magnetic core of the device through a winding on the centre limb, as shown in Figure 25. The rectifier is actively controlled by the control system in order to regulate DC link voltage and input reactive power. The inverter is able to control output voltage and also input reactive power. The combined control of both the rectifier and inverter is therefore able to regulate output voltage and input power factor. Balancing reactive power injection between the control coil and the rectifier to hold unity power factor should reduce the size of both the rectifier and the inverter.

In some embodiments, an energy recovery circuit is used to store the excess energy that would be otherwise lost. This energy can be stored within a capacitor, inductor or

other energy storage device, and subsequently reinjected into the main power flow through the device directly, or directly from the capacitive, inductive or other storage.

Frequency Stability

As the frequency of the coupled electrical system is dependent on the frequency of the generated electricity and balanced with the load, as this balance between generation and load varies, the frequency of the system will vary. Therefore changing the control winding current, the reluctance of the circuit will change and energy will be injected into or taken from the power flow as described above. This can provide short term frequency stability for an electrical system.

A large number of possible configurations for the electrical power supply system described herein will be apparent to those skilled in the art in light of this disclosure. In one such configuration a core type transformer is manufactured using standard core cutting and stacking techniques (see, for example, http://sites.ieee.org/gms-pes/files/2014/11/Transformer-Manufacturing-Processes.pdf).

The control winding is powered by an electronic circuit switching control circuit, utilising pulse width modulation of an AC control signal, as shown in Figure 3. A high speed microprocessor (such as the 100MHz Texas Instruments device described at http://www.ti.com/product/TMS320F2808) has sensor inputs from the input and output (the circuit directly before the primary and directly after the secondary windings) to measure voltage.

The microprocessor executes a control process to PWM the four IGBT devices in the bridge circuits shown in Figure 3. This varies the flow through the control coils in order to maintain the correct level of flux at each monitored location, which in combination with the measured voltage and current input and output, delivers the target setpoint at the output. The flux control feedback loop operates at 1MHz, and the phase lock loop at 100kHz.

An energy recovery circuit is included to capture and store the energy diverted as a result of the virtual air gap. This recovery circuit includes a capacitor to allow short term storage and smoothing of the energy flow.

Energy Storage

As described above, energy is stored in the magnetic core within an internal loop. In Figure 4, energy injected into the core through the primary winding can circulate in the outer shell of the core This effect allows out of phase reactive power (both capacitive and inductive reactive power) from the input to be phase shifted within the magnetic core, reducing reactive power on the output. This then achieves the power factor control required. This ability is available for both capacitive and inductive power factor.

In some embodiments, an electrical energy supply system includes a additional form of energy storage which can absorb and inject energy directly into the magnetic flux of the core. This can consist of capacitors or any other fast responding energy storage to increase the available stored energy. For instance this would increase the total available stored energy within the outer shell of Figure 4.

Controller

As described above, the controller 106 receives a signal representative of the frequency and voltage of a corresponding input signal applied to the system, generates corresponding frequency, power factor and voltage control signals that are respectively provided to the frequency control components 102 and the voltage control component 104 and power factor control component 108 in order to control the operation of each of these components to ensure that the corresponding output signal has the desired target output frequency and output voltage and input power factor.

In the described embodiments, Hall effect flux sensors are utilised located at the specific points where the control winding(s) interact and affect the flux in the magnetic core. These measurements are used in conjunction with the input and output voltage and frequency to determine the control signal required. However, it will be apparent to those skilled in the art that other measurement sensors and techniques can be used to monitor the flux, such as a winding around the magnetic core that will have a current induced based on the flux.

The operational speed of the controller 106 is dependent on the frequency of the power flow being controlled by the system. Given this can be in the kHz range, high speed control can be utilised if required by the application requirements in use within a system.

Within an electricity grid of 50Hz or 60Hz, microprocessors with relative low clock frequencies in the MHz range are sufficient.

The controller 106 constantly measures the voltage and frequency of the input signal and, in some embodiments, also the voltage and frequency of the output signal to directly control the control windings by way of the voltage and frequency and power factor control signals in order to maintain a target setpoints.

In situations where the input in providing more power than the output requires at that instant, the controller reduces the power flow through the device by increasing the reluctance of the magnetic circuit. Increasing the reluctance of the device means that additional power is stored in the magnetic field of the device.

In situations where the input is providing less power than the output requires at that instant, the controller determines this by monitoring the input and output signals, and generates corresponding control signals to increase the power flow through the device by decreasing the control current in its control winding(s). This decreases the reluctance and increases the flux in the device, discharging stored magnetic energy within the device to the output, thereby delivering an essentially instantaneous power output that is greater than the power input to the device. If the device is already at a minimum level of reluctance (*i.e.*, the control current is already zero and thus cannot be decreased further), in some embodiments the energy stored within additional energy storage devices such as capacitors can be used to compensate for this lack of power in the short term.

An alternative control methodology for the electrical power supply system is a lagging control (rather than a leading control as described above). In this configuration, the system acts in a synchronous manner, with the input and output injecting and sucking energy out of the magnetic field as required and based on the instantaneous input and output power levels. This then changes the reluctance of the magnetic circuit and the balance of efficiency of energy transfer between the primary and secondary windings. The controller monitors the input and output, and then reacts to the effect of this imbalance to bring the system back to balance.

In the described embodiments, the controller 106 is implemented as a field programmable gate array (FPGA), powered from the power flow through the device, and the electrical power supply processes are implemented as configuration data stored in non-volatile memory. However, it will be apparent to those skilled in the art that in other embodiments the controller 106 could be implemented as an application-specific integrated circuit (ASIC), or as a microprocessor (for example, an Intel™ Architecture IA-64 Core i7 multi-core processor) programmed to execute instructions stored in non-volatile memory. It will also be apparent to those skilled in the art that in other embodiments the controller may be powered by a separate local power supply where available, such as local control power from a distribution board.

Extending upon the PWM control implementation described above, the measured flux is used for a control feedback loop with the FPGA (or other controller device, where applicable) as shown in Figure 6. The reference signal for this control is provided by a phase lock loop (PLL) driven by the measured flux. The phase lock loop uses a phase detector, filter and voltage control oscillator with a feedback loop to lock the input and output frequency to each other, as shown in Figure 7. In the described embodiments, the phase lock loop is controlled at a frequency of 1kHz; however, it will be apparent to those skilled in the art that a different control frequency can be used in other embodiments.

The same process applies for reverse power flow by interchanging the primary and secondary inputs, outputs and setpoints. The same process can be used for 3 phase power by applying the process to each phase.

It will be apparent that the electrical power supply system and process described above are particularly advantageous as they are able to dynamically and rapidly respond to changes in the input energy received by the system in order to generate corresponding output energy having a target voltage and a target frequency. In particular, this ability allows the described system and process to match the output energy to the energy required by the loads on the system. Moreover, the system and process are bi-directional, meaning that they are able to do this for energy supplied from an energy grid and flowing in one direction, for example, and also for energy supplied from renewable energy sources, which may be flowing through the system in the opposite direction. For example, changes in local energy generation arising from changes in wind

and/or changes in available sunlight are able to be mitigated by the system and process to provide a relatively constant output for a fixed load. Similarly, changes in the load on the system can be compensated for within the ability of the corresponding devices.

"Faraday Grid" electricity network

Multiple instances of the electrical power control apparatus or Faraday Exchanger described above can be interconnected with sources and sinks of electric power to provide an improved form of electricity distribution network referred to herein as a "Faraday Grid". Details of the Faraday Grid are described in International Patent Application No. PCT/AU2017/050997, the entirety of which is expressly incorporated herein by reference.

A Faraday grid electrical power distribution network includes electrical power control apparatuses in the form of Faraday exchangers that are typically distributed throughout the network and that collectively maintain the corresponding voltages and frequencies of electrical power signals flowing through the electrical power distribution network at corresponding target values to compensate for variations in the sinks and/or sources of electrical power, including the variability of renewable energy sources such as wind and solar power, for example.

A transaction-based electricity network

A Faraday grid network as described above can be enhanced by the addition of a further control layer wherein each electrical power control apparatus has an additional control component referred to herein as a 'transaction engine' or 'routing engine'. As described below, the routing engines of the electrical power distribution network communicate with one another to make collective decisions as to which of the associated electrical power control apparatuses will supply electrical power in order to satisfy a request or demand for electric power with one or more specified attributes of the requested electric power, including at least a value for the amount of power requested (e.g., in kW). In some embodiments, these attributes are selected from power quality (which can include quality attributes such as specified acceptable amounts of noise/distortion, power factor, frequency stability, reliability), and attributes of electric power generation (including proportion of renewable power generation and geographical locality of that generation), and pricing, but other attributes and combinations thereof can be provided in other

embodiments. In this context, the provision of electric power beyond bare supply (by providing electric power with one or more requested attributes or characteristics, which may require improving the quality of the supplied electric power by, for example, reducing harmonics, correcting power factor, and the like) is regarded as an additional service, and can be charged for accordingly.

In the described embodiments, the one or more specified electric power attributes include power amount and optionally one or more further specified electric power attributes. In some embodiments, the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and one or more specified electric power attributes selected from: stability, noise, reliability, and sustainability. In some embodiments, the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and pricing, and one or more specified electric power attributes selected from: stability, noise, reliability, and sustainability.

As shown in Figures 32 and 33, an electrical power device or apparatus 100 autonomously requests and supplies electrical power sourced from other ('downstream' in the sense of power flow at any given time, although that flow can change direction) instances of the electrical power device or apparatus in accordance with requests for electric power from yet other ('upstream' in the sense of power flow at any given time) instances of the electrical power device or apparatus, where each request includes data representing attributes of the requested electrical power and the electrical power device or apparatus 100 selects one or more of the upstream electrical power devices to supply that power based on their ability to do so. Instances of the electrical power device 100 can be interconnected as described below, together with sources and/or sinks of electrical power, to form an electrical power distribution network or power grid that autonomously manages the supply of electric power throughout the network or grid to meet power supply requirements (insofar as it is possible for the network to do so) specified by attributes of the electric power including power amount, and optionally one or more additional attributes, which in some embodiments are selected from (but are not limited to) stability, noise, reliability, sustainability, and pricing. Other electric power attributes may be apparent to those skilled in the art in light of this disclosure.

When connected as part of an electrical distribution network or grid, each electrical power device 100 has power and data inputs and outputs, but is completely agnostic as to what it is connected to: it can be connected to one or more generation, consumption, transmission, or distribution components, or combination thereof, or any other such component of an electricity system. However, for the purpose of description, a power input of an electrical power device is described herein as being connected to multiple sources or suppliers of electric power, including one or more other instances of the electrical power device, and optionally one or more generators of electric power, and optionally one or more sinks of electrical power. The generators of electric power can include renewable generators of electric power such as solar power generators, wind power generators, hydro-electric power generators, and the like, and/or one or more non-renewable generators of electric power, such as coal or gas fired turbine generators, for example.

A data input receives data from other instances of the electrical power device representing attributes of the electrical power that is available to be supplied by those electrical power devices, which for the purposes of description can be thought of as being topologically upstream of the electrical power device, although the device can operate in either direction. Moreover, it will be apparent to those skilled in the art that the data input and output of each device can, and typically are, implemented as a single bidirectional communications port. The electrical power device 100 has its power input connected to one or multiple generators and/or one or multiple suppliers of electric power, including other instances of the electric power device, and optionally one or more sinks of electrical power which can also be other instances of the electrical power device.

Similarly, each electrical power device 100 has a power output connected to multiple consumers of electric power (which for the purposes of description can be thought of as being topologically downstream of the device), including one or more other instances of the electric power device, and optionally one or more generators of electric power and optionally one or more sinks of electrical power, which can also include instances of the electrical power device.

Each electrical power device 100 can be thought of as a type of router of electrical power within an electrical distribution network or grid. Briefly, the device 100 receives one or more requests for electric power satisfying one or more corresponding attributes, and

selects one or more suppliers or sources of electric power that are able to satisfy the received requests. In some embodiments, the attributes of a demand or request define at least the amount of power (*e.g.*, in kW) required and the price (*e.g.*, per kW) that the requestor is willing to pay. In response to receiving such a request, a device 100 able to supply electric power with the requested attributes issues an offer to supply the requested electric power. In the embodiments under discussion, the attributes of an offer define at least the amount of power (*e.g.*, in kW) that the supplier has available, and the price (*e.g.*, per kW) that the supplier is willing to sell that power for.

In the simplest such scenario, an electrical power device 100 can select a supplier that is able to supply at least the requested power at a price that is no higher than the requester's price. However, it may be that no one supplier is able to supply sufficient power to satisfy the request, and the electrical power device 100 has to select multiple suppliers that collectively are able to supply the requested amount of power. Similarly, it may be that the available suppliers are not willing to sell power at the requested price, and the electrical power device 100 mediates a negotiation between the upstream suppliers and the downstream requester, as described below.

Moreover, attributes other than price can also play a role in the selection of suppliers. For example, a requester may specify that at least 50% of the supplied power is generated from renewable energy sources. Additionally, a requester may specify that the supplied power has to meet certain quality attributes, such as stability and/or noise, for example.

The provision of the described electric power devices 100 in an electric energy distribution network or grid addresses the issues of intermittence and volatility that plague existing energy networks, as described above. Additionally, the electrical power devices 100 operate autonomously to automatically provide sufficient electric power with the required attributes at the lowest available cost at any given time. Additionally, each electrical power device 100 includes short-term electrical energy storage. Consequently, the provision of electrical power devices 100 throughout the network provides distributed autonomous inertial services that at least improve and potentially ensure grid stability without need for external inputs.

As shown in Figure 33, each electric power device or system 100 includes a power control component 202 and a routing engine 204. In the described embodiments, the power control component 202 includes electric power control hardware 206 and a hardware controller 208. The electric power control hardware 206 operates under control of the hardware controller 208 to receive electric power having certain (and usually unknown in advance) input characteristics, and to output corresponding electrical power having certain desired output characteristics. Characteristics of the input electric power received by the power control hardware 206 are measured by corresponding measurement components (not shown) known to those skilled in the art and the measured characteristics are provided in the form of signals or data to the hardware controller 208. Based on these measured characteristics such as voltage, current, phase angle, power factor, active power, reactive power, and harmonics, for example, the hardware controller 208 generates control signals for the electric power control hardware 206 that cause the latter to dynamically modify the received electric power in order to generate output power having the desired values of the measured characteristics. Most typically, the power control component 202 is used to control the RMS voltage, voltage waveform (to remove harmonics), and power factor, and to balance power across all three phases. In some embodiments, deviations of these attributes from target values are measured and used to control the power control component 202 to restore those attributes to as close to the target values as practical. In other embodiments, the electric power control hardware 206 only has the ability to transmit the electric power directly through the device without modification.

In the described embodiments, the power control component 202 is based on the electric power control apparatus referred to as a "Faraday Exchanger" (abbreviated as "FE"), and described in international patent application No. PCT/ AU2019/050246, entitled *An Electrical Power Control Apparatus And Process*, as described further below. However, in other embodiments, the electric power control component 202 may take other forms and perform different operations on the electric power flowing through it. For example, the electric power control hardware 206 can be any one or more instances of a standard electric power device or apparatus known to those skilled in the art, such as an inverter, a transformer, a rectifier, a voltage booster, a static synchronous compensator (STATCOM), a static VAR compensator (STATVAR), or even a simple capacitor bank, or any practical combination of these and/or other power devices or apparatuses. Many other such power devices, apparatuses and combinations thereof

will be apparent to those skilled in the art in light of this disclosure. Additionally, the hardware controller 208 can be incorporated into the routing engine 204 such that the latter directly controls the operation of the electric power control hardware 206 in addition to the routing and other functions described herein. This can be achieved, for example, by tightly coupling the two (virtual or physical) components 204, 208 and having them communicate with each other directly using a standard communications protocol such as Modbus or Direct I/O, or alternatively by providing a single control system that performs the functions of both components 204, 208 described herein. Many other possible combinations and configurations will be apparent to those skilled in the art in light of this disclosure, such as incorporation of the routing engine 204 into the hardware controller 208, for example.

Finally, a routing engine 204 can also be directly coupled to a generator of electric power (such as wind, hydro, or solar generator, for example) or a sink of electric power (such as a factory or a residence, for example), instead of a power control component 202.

Regardless, the routing engine 204 handles the data communications between other (upstream and downstream) instances of the electric power device 100 to determine which of these is/are to provide electric power to the corresponding electric power control hardware 206. This allows the combination of power flows from the corresponding electric power devices 100 to be monitored and recorded at the most granular level possible (*i.e.*, by individual electric power devices 100) to provide better reconciliation of power flows and transactions. Power will flow within the electricity grid based on the behaviour of the electric power devices 100, with each electric power control hardware 206 and corresponding hardware controller 208 affecting the flow through control of voltage and current, power factor, and phase balancing.

The routing engine 204 receives requests for electric power (representing demand) from downstream components of the electricity grid (typically, but not necessarily, being other instances of the electric power device 100, possibly in combination with one or more direct sinks for (or consumers of) electric power, as described above, and issues corresponding requests to components of the electricity grid that supply electric power (referred to for convenience as "suppliers", and typically, but not necessarily, being other instances of the electric power device 100, possibly in combination with one or more suppliers of (generators of) electric power and, if required, negotiates with those

suppliers and the requestors in order to reach agreement between these components to supply electric power satisfying the required attributes at an agreed price.

In some embodiments, the routing engine 204 also receives sensing data representing one or more operating parameters of the electric power control hardware 206. This includes the voltage and current of the input and output power flows through the power control component 202 of the device 100. This information is stored locally, and is used by the routing engine 204 to calculate the electric power flowing into and out of the device 100, and therefore the amount of energy that has been transferred as part of the corresponding energy transaction between itself and its corresponding upstream and downstream devices. In embodiments of the device 100 in which the electric power control hardware 206 has the abilities of a FE, there may be differences in the power flow from the input to the output, including one or more of voltage correction, power factor (reactive power), phase balances, and a reduction in harmonics. This information is also stored locally, enabling the device 100 to calculate the amount of electricity system 'service' it is providing, such as frequency stability, power conditioning, and others within regulatory energy markets, such as those described at https://www.nationalgrid.com/uk/electricity/balancing-services/frequency-response-services, for example.

In particular, in the described embodiments where the electric power control hardware 206 includes switchable magnetic circuits, these operating parameters can include one or more of: the voltage(s) on the control winding(s) of the magnetic circuits, the temperature(s) of these and any other primary, secondary, or any other windings, and vibration of the power control hardware 202. This information is stored locally and can be utilised to identify changes in operating conditions and responses which may indicate device performance degradation, and/or maintenance requirements. This information can be retrieved automatically, or manually by the device operator or owner by way of an external communications protocol with the device.

The routing engine 206 stores two sets of data representing its operations. In the described embodiments, the sets of data are respectively stored in a transactions database 210 and an operations database 212. In Figure 33, the databases 210, 212 are represented as being coupled directly to the routing engine 204, and may be physically incorporated as part of the same device or apparatus 214. However, it should

be understood that either or both of the databases 210, 212 may be networked databases distributed in one or more other locations, which may be geographically remote from the routing engine 204. Databases 210 and 212 may also be a single database with the information combined.

The transactions database 210 stores data representing each agreed energy supply transaction, and the operations database 210 stores details on the operation of the electric power control hardware 202 for each transaction. The operation details include: (i) operating parameters such as voltage, current, temperature, and vibration, and (ii) details on the electric power operations that were performed by the electric power control hardware 206 for a corresponding power transaction in order to improve the quality of the electric power it supplied relative to the quality of the received electric power. Typically, these operations include voltage control, phase balancing, reduction of harmonics, and power factor correction. These can be regarded as services provided to the energy consumer in order to improve the quality of the supply. In some embodiments, these services are charged for accordingly by applying a services cost function to the power services that were provided for that supply period and that supply.

Figure 34 is a flow diagram of a power control process executed by each routing engine 204 of the network.

As described above, routing engines 204 of respective electrical power devices 100 negotiate with one another in order to determine electrical power transactions in which a demand for electric power (with one or more required attributes) communicated by an electrical power device 100 is met by a supply of electric power from one or more other electrical power devices 100.

In the simplest example, as shown in Figure 35, two electrical power devices 100 communicate and transact directly with each other. For example, Device B communicates a demand for electric power to device A, whilst Device A communicates to B its capacity to supply electric power. As described above, a demand for electric power takes the form of an electronic message representing a request for electric power with one or more required attributes, these attributes specifying at least a required amount of power (*e.g.*, in kW), and typically (but not necessarily) one or more additional attributes (such as total amount of energy or the expected duration of the supply, for

example). In some embodiments, these additional attributes include at least a cost function that is used to calculate a numeric score or 'cost' that provides a basis on which one energy supplier is selected in preference over another energy supplier. Typically (but not necessarily), the cost function includes a price of the electric power demand or supply (*e.g.*, in $/kW), either alone or in combination with one or more other quantitative parameters. For example, a cost function can define one price for energy from renewable sources, and a different price for energy from non-renewable sources, or a linear combination thereof with different weighting factors. Other examples of variations in cost functions are the quality of power, the average (or RMS – root mean square) voltage value, and the total harmonic distortion (defined as the ratio of total harmonic amplitudes to the amplitude at the fundamental frequency). This can be in addition to one or more Boolean requirements, such as a demand requiring that the supplied energy be entirely from renewable sources, for example.

In a request for power, price (if used in a cost function as a transaction attribute) represents the maximum price that the requestor is willing to pay. In an offer to supply power, price represents the actual price at which the supplier wishes to sell power. If the cost values (determined by their respective cost functions) of the demand and supply are mismatched, then it is open for either entity to adjust its cost values in order to seek a matching cost value from another transacting party. Once a match is found, the entities agree to complete a transaction. Each entity stores the transaction data in its corresponding transaction database 210, and the supplier supplies electric power in accordance with the agreed transaction parameters.

During the supply of power, each routing engine 204 records its own operational data for the power being sent or received (as the case may be) in its corresponding operations database 212. At the completion of the transaction, both routing engines 204 maintain a record of what they believe the total transaction was, typically including at least the parties involved in the transaction, a timestamp and duration of supply, total energy transferred (*e.g.*, in kW.h), price**,** a cost function that was applied (for example this could be a simple 1 to 1 function with price, or a surge pricing function based on constraints within the network), a services cost, a services cost function that was applied (for example this can be a variable price for a voltage correction service, based on the constraints within the network and the total amount of correction provided), and the total transaction cost.

The total price of supply is determined by applying the cost function to the amount of energy supplied (the total energy transferred multiplied by the price per unit energy) and adding the total value of the services provided (the service cost function multiplied by the services cost) upon reconciliation of the transaction, based upon any requested services provided by the electrical power device 100. The services provided typically include one or more of voltage control, phase balancing, harmonics reduction, and power factor correction.

For each transaction, the records stored in the transaction database 210 associated with the two devices are the inverse of each other (A:B = -(B:A)). These can be verified against each other to ensure that each transaction is correct and mutually agreed. Each routing engine 204 can check its transactions by comparing its records to all the other routing engines 204 it has transacted with. For example, in a transaction between three of the devices 100, as illustrated in Figure 36, device X verifies its records against those of both device Y and device Z.

In some embodiments, the amount of power for a demand does not need to be specified, as it is inherent to the price. If a device 100 is buying energy, then its price will be greater than zero, and this fact is equated to having a demand. Conversely, if a device 100 does not require power and therefore has no demand, its price will be zero and it will not transact. When a device 100 has a large amount of power available, then it can lower its price initially, and then increase it again as the amount of power it has to sell decreases. If a device has no available power to sell, then it can set its price to an (effectively) infinitely high value so that no device 100 would ever agree to transact with it.

In Figure 36, device X has access to view the transaction lists (databases 210) of both Y and Z. This allows X to verify its transactions with both parties, but also to check that it is not being misled by either party, bearing in mind that the devices 100 can be operated by different organisations with potentially competing interests. In some embodiments, device X is also able to view the operations database 212 of both Y and Z, allowing X to verify that the inputs and outputs from devices Y and Z are aligned with the transactional values (such as services costs) being applied. Because Y and Z transaction lists include both their consumer and supplier transactions, X is able to

determine whether either party is falsifying its price or demand data. Because devices Y and Z can review all transactions that X has completed between them, a complete backup of X transactions is already maintained. Copies of Y and Z transaction lists can optionally be stored on X for additional data redundancy.

As a further illustrative example, Figure 37 shows four devices 100 in a linear transaction. In this example, device A is directly coupled to or includes a wind turbine generating power, and device D is directly coupled to a residential home consuming that power. Devices B and C are devices 100 within the electricity grid that allow the power to be transported between the two end locations. Within the electricity grid, some appliances at residence D are turned on, and start to draw power from the grid, causing power (electric current) to flow through A – B – C – D.

In this example, a trivial cost function that is simply the price is used, with no additional parameters. Accordingly, device A pushes a data update of a price to B. This type of push update will occur every time there is a change in value, as well as after a set amount of time since the last push notification to ensure communications health and data validity. This can be achieved using any of many different communications protocols and standards, as known by those skilled in the art. B then has a price it can buy (from A) and sell power at, which it communicates to C. C then has a price it can buy (from B) and sell power at, which it communicates to D. D determines that it would like to purchase the electricity at this price and communicates that price to C. C accepts the price from D, and sends its price to B. B accepts the price from C, and sends a price to A. A accepts the price from B. Thus A does not directly transact with D. In summary:

(i) A is selling to B;

(ii) B is buying from A and selling to C;

(iii) C is buying from B and selling to D; and

(iv) D is buying from C.

This device-centric approach, where devices 100 transact only with devices they are connected to, is completely scalable and expandable to any grid size and configuration.

In a further example, as shown in Figure 38, devices D and E are generators, B and C are consumers, and A is a transportation point between them.

B has a requirement for power, so:

(i) D sends a price (Dp) to A;
(ii) E sends a price (Ep) to A;
(iii) A now has a price it can sell power at (Ap = min (Dp and Ep)), which it communicates to B and C (in this hypothetical example, Dp is lower);
(iv) B sends a price (Bp) to A that (in this example) equals Ap;
(v) A now has a valid transaction with B, and sets its buy price which D and E see. As Dp is lower, A chooses to transact with D; and
(vi) A and D confirm the transaction between them.

C now also has a demand for power:

(i) C can see that A has power available at price Ap, and set its price to Cp = Ap;
(ii) A now has a valid transaction with C, and sets its buy price which D and E both see. As Dp is lower, A chooses to continue to transact with D.
(iii) The load at B becomes higher than the supply D:
(iv) B will notice the voltage dropping on its supply, and A will notice its voltage dropping on its output.
(v) A increases its price to the next lowest price available, in this case Ap = Ep.
(vi) B accepts this price and updates Bp= Ap, creating a valid transaction.
(vii) A now has a valid transaction with B, and sets its buy price which D and E see. Dp has no capability to supply left, and has set its price to an (effectively) infinitely high value, so A chooses to transact with E at Ep.
(viii) A and E confirm their mutual transaction.

As D and E can both see the transaction list of A, they will know the price of the other generator, the amount it can supply, and the total demand that is coming from B and C. This means they can act intelligently to set their own prices. Acting together, the devices 100 described herein allow an open market for buying and selling electricity, price collusion is prevented unless every single operator works together. It is expected that like other markets there is external oversight and regulation to prevent such collusion events occurring.

It is also possible for a device 100 to have other devices 100 with both positive and negative demands on the same side. For example, in Figure 39, device A is an electricity

grid device 100, devices B and D are consumers, and devices C and E are prosumers able to both consume and generate power.

Device A receives a price from B, C, D, and E. This allows A to, for example, transact with C to buy power, and then sell that same power to B, following the standard operating principles described above. Transacting through A (rather than C to B directly) allows the utility that owns A and the wires connecting B and C to earn revenue against its assets that are providing an energy transportation service between C and B. This is a unique feature of the devices described herein when compared to existing energy grids.

Energy Market

The routing engines 204 of the power control devices 100 described herein constitute an open and agnostic platform that allows all participants/agents within an entire electricity grid to interact as a marketplace for energy distribution. The resultant system provides autonomous decentralised control of the electricity network, resolving issues of volatility (such as voltage management, harmonics management, inertial requirements for balancing, and the like). The ability of the routing engines 204 to trade in an efficient and price driven manner resolves the network issues of intermittence, allowing an open free market to deliver energy at the lowest cost.

By combining a routing engine 204 with a Faraday Exchanger as the electric power control hardware 206 in a single device or apparatus 100 as shown in Figure 33, several additional features are unlocked when multiple devices are within a single network, including:

(i) The device 100 can control the power flow through the magnetic core to control power flow, both for the network and for itself, taking into consideration:

- network constraints such as network capacity and voltage levels, and
- attributes requested by agents within the system, such as requests for power quality level or renewable energy sources, and price;

(ii) determine price for the consumer taking into account both generation and transportation costs in real time, dependent on network operating conditions ,

(iii) The hardware required for data monitoring, processing, and storage is all provided at zero marginal cost through the roll out of Faraday Exchangers to resolve network operational constraints.

(iv) The operational structure of the electricity grid as described herein allows it to operate as an autonomous marketplace without additional communications infrastructure, and incremental roll out of participants without upfront capital expenditure in networks or control systems. In some embodiments, data communication technologies such as 4G and/or Ethernet, for example, can be used to communicate between devices.

Properties of Energy Trades

Energy traded within the grid can have one or more associated attributes that are taken into consideration when establishing trades. These attributes act as metadata, and allow users to have further control over their energy usage and can include at least the following:

- Generation Type – the source of the energy generation, such as environmentally friendly or fossil fuel, for example allowing users to prioritise 'green' energy within certain quality, price, and percentage parameters.
- Location – the location of the energy generation, for example allowing users to prioritise local generation in a microgrid environment.
- Quality Parameters – the power quality RMS voltage and harmonics profiles, for example allowing users who are sensitive to voltage fluctuations (such as large industrial motors) to maximise productivity of the asset.
- Energy Security – the security of supply, for example allowing users with critical energy requirements to ensure that their supply is maintained in preference to other users (this is primarily achieved through real time pricing response).

Within these parameters, the devices 100 will seek to optimise the transaction cost for their corresponding agents.

Device Operating Modes

Every power control device 100 utilises the same basic component parts and functionality, allowing it to fill any roles within the system. The devices 100 have operating modes which can be selected by the user in order to ensure that the device 100 operates in the desired manner. This can be selected directly by the users (as described below), or determined autonomously by the device 100.

In the described embodiments, the basic operating modes of each device 100 are:

- Generation – the device is connected to a generation source upstream and will only see one-way power flow.
- Transportation – the device is only directly connected to other FGM devices, which can be of any type.
- Consumption – the device is connected to a consumption device downstream and will only see one-way power flow.
- Prosumer – the device is connected to a downstream component which is able to use and generate power but has no additional downstream devices.

When a single operator operates multiple devices, the fees between devices will create a net zero cost transaction. For example, an electricity grid owner may have thousands of instances of the device 100 within their network in order to provide the functionality described herein. As the electricity is accounted for through multiple devices 100, the cost functions and total cost added by each device 100 for its operation will be income on one side of the transaction and an expense on the other. During reconciliation, these will negate each other, and the cost differential between the input transaction on one side of the transaction chain and the output transaction on the other side of the transaction chain will be the income generated by the network owner for providing the corresponding service(s).

Another example is that a single household residence, with a power control component 202 in the form of a Faraday Exchanger connecting the household to the electricity grid, and multiple consumption devices within the residence with transactional capabilities provided by 214, or in combination with 202, or device 100. Within the household, all devices will be registered to the same owner, and transaction fees between the devices will negate each other. This is desirable as the household also owns the wires conducting

the electricity, so a third party does not need to generate revenue for providing the energy transportation service.

User Interaction

The electricity grid described herein can operate automatically, based on the parameters selected by the user, and does not require constant monitoring or control action. Users can interact with their devices 100 through an interactive interface accessed via a standard web browser or smart phone application and a web server executed by at least one processor of the routing engine 204.

In the described embodiments, the routing engine 204 is implemented as a field programmable gate array (FPGA), and the described energy transaction processes are implemented as configuration data stored in non-volatile memory. However, it will be apparent to those skilled in the art that in other embodiments the routing engine 204 could be implemented as an application-specific integrated circuit (ASIC), or as a microprocessor (for example, an Intel™ Architecture IA-64 Core i7 multi-core processor) programmed to execute instructions stored in non-volatile memory. It will also be apparent to those skilled in the art that in other embodiments the routing engine 204 and controller 106 can be implemented as respective control layers in the same FPGA (or ASIC or software components executed by one or more processors).

A user can interact with their device 100 and select pre-defined profiles; for example, to prioritise green energy, optimised price, local energy, and the like. An appropriately authorised user can also select an operating mode (prosumer, transportation, et al); however, the device 100 is also able to detect its directly connected devices 100 and autonomously decide its own operating mode. This is done through an initial communications ping to any devices 100 (also referred to herein as nodes) it is directly connected to within the network. The nodes respond by identifying their own operating mode, providing context to the requesting device 100. A device 100 is always configured for the profile that the end user is likely to have. For example, an electricity utility is provided with default Transportation mode devices 100, unless specified otherwise. The ability for user to interact with a device 100 can be removed after an initial configuration (or at any time) by manual physical adjustment of the communications hardware within the device, thus preventing (or at least inhibiting) cyber tampering. The service(s) provided by the device 100 can then be apportioned to the upstream or downstream connected devices, as determined by the operational measured data. The service cost will always be apportioned in respect to the benefit received. For example, voltage

control and harmonic suppression benefits will have their cost passed downstream, whilst power factor control will have cost passed upstream with respect to the electricity flow.

Energy as a Service

Each device 100 monitors its own performance on both its input and output. By measuring the instantaneous voltage and current at each interface, it is able to calculate and record the amount of energy transported (i.e. the transportation service).

In the case of a device 100 that includes a Faraday Exchanger (or a similarly capable component), it is also able to record and quantify the services provided in terms of voltage control, power factor control, phase balancing and/or harmonics removal. As each Faraday Exchanger is able to control RMS voltage, remove harmonics, control power factor, balance power across phases, and store energy, a significant service can be provided to the electricity system to maintain stability and efficiency as described above. These services can be measured by monitoring the input and output of the device, recording and quantifying the measurements (or metrics thereof) in real time, thereby capturing and determining the value for remuneration. This enables an electricity system where Faraday Exchangers are not bought and owned by the grid, but are rented or provided free to the grid, with a fee for service model being used.

Revenue model

In some embodiments, each device 100 charges a small fee on the buy and sell sides of each transaction it participates in. In the described embodiments, this charge is calculated as a percentage of the value of the transaction that is taking place. The fees on the buy and sell side are identical to prevent participants from attempting to game the system.

The fees include charges for the following:

- Transportation – a fee for providing the ability to move the energy. This is a fixed percentage of the value of the total energy transported.
- Services – a fee for variable services provided during the energy transport, depending on the operational mode of the device and the services provided, which can

include one or more of: grid balancing, voltage control, harmonic suppression, and power factor control. The values of these individual services are set by the market on a per unit basis, and are calculated upon reconciliation.

For example, in the simple linear transaction system shown in Figure 40, the following revenue is generated the devices 100:

Device A

- Buy Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Sell Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Services Fee: (Voltage Control + Harmonic Suppression + Power Factor Control) * services cost function

(Services fee calculated as required through measuring the input and the output of the device)

Device B

- Buy Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Sell Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Services Fee: (Grid Balancing + Harmonic Suppression + Power Factor Control) * services cost function

(Services fee calculated as required through measuring the input and the output of the device)

Device C

- Buy Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Sell Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Services Fee: (Grid Balancing + Harmonic Suppression + Power Factor Control) * services cost function

(Services fee calculated as required through measuring the input and the output of the device)

Device D

- Buy Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Sell Fee Transportation: %_Fee * Qty_Power(V*I*time) * Price * cost function
- Services Fee: (Voltage Control + Harmonic Suppression + Power Factor Control) * services cost function

(Services fee calculated as required through measuring the input and the output of the device)

Data ownership and privacy

The electricity grid described herein is based on a private chain model with a distributed ledger, an example of which can be found at https://energyweb.org/. This means that there is no central repository of information, with only participants that are authorised with the system allowed to access it, as opposed to a public chain model that is open to anyone. The system described herein allows only permissioned agents (such as a device 100) within the system to access and store information for other agents that it is in direct communication with. Second degree connections (defined as a device 100 that can trade with another device 100 that is capable of trading with the participant) within the grid has visibility of current transactions, but not the full history of transactions or usage.

It will be apparent to those skilled in the art that various permissioned models including a central shared ledger can be used in the described electricity grid, as well as implementations of a public chain model. The private chain with limited connections as described above is desired to limit the quantity of transactions as the value of the commodity (i.e. electricity) is comparatively low compared to the computational cost of the system. The energy grid described herein will work equally as well with any distributed ledger model.

Redundant Data Model

There is no single point of failure within the private chain model described herein. In Figure 36, Device X has a local copy of all transactions it has completed in its ledger. It also has access to the ledger of both devices Y and Z. As such, device X can review the transactions that Y and Z have completed and have had verified by their other transaction partners. This chain of trust ensures that a single device 100 cannot fraudulently act within the network. If device X were to fail, the ledger information that would have existed with device X can be reconstituted through the combination of the other ledgers that it had transacted with, in this case Y and Z.

It is possible for a device 100 to operate in a data redundant mode, whereby each device maintains a copy of their transactions on another single device 100, on multiple devices 100, or on all of the directly connected devices 100 that they directly trade with. This allows the grid to have complete data redundancy, securing data in the event of any device failure. If a failure does occur, the failed device 100 can be repaired or replaced, and the data can be automatically replicated and the new device 100 seamlessly integrated with the grid.

This can be especially useful for participants who own multiple devices 100 within the grid, such a network operators. The data privacy mode can be chosen by the device 100 owner and is changeable.

Use Cases

Prosumer

A residential home has a device 100 (a routing engine 204) as the connection for the home to the electricity grid. These can be packaged as part of a new installation, or as upgrades undertaken by existing companies operating in this space. For example, the home may have solar panels connected to battery storage, with both the solar generation and the battery storage connected to the device 100.

The device 100 makes decisions based on price signals within the grid market and the current situation within the home to determine how to act. For example, to determine whether to store current solar power generation and use grid power, or to use the solar power as it is generated.

Connected Home

Within a connected home, multiple devices 100 can be connected through a power control adapter plug (a smart adapter to send and receive information through the power outlet) or a device 100 or routing engine 204 within the consumer device itself, and each device 100 / routing engine 204 is able to make real time decisions about purchasing energy and modifying its behaviour appropriately. For example, a heater can let the temperature drift if power is expensive, or can temporarily overheat is power is cheap. These devices can all act within a single grid account to optimise the position of the owner against a set of configurable rules. This layer of energy management can improve systemic demand management.

As the devices are all connected to the same electricity grid market as described herein, they can trade with the upstream device they are directly connected to, whether that be a Device 100 connecting the solar panels, battery, and home to the electricity distribution grid, or a device 100 within the distribution grid.

Domestic precinct

A number of residential and/or commercial properties can form a microgrid that is connected to the main electricity grid, with multiple small scale renewable generation

and storage devices within the microgrid. Once each distribution level transformer within the microgrid is replaced with a Faraday Exchanger (e.g., the 7200V / 240V transformer) a peer to peer transactional grid can operate.

This arrangement allows users within the microgrid to buy and sell energy from other users whilst remaining connected to the main electricity grid. No additional specialized smart grid infrastructure is required to be installed or maintained for this solution.

University or Military Campus

A large-scale campus with the potential for larger amounts of local energy generation (including renewables), storage and larger consumption items. These can form a microgrid with a single input from the main electricity grid.

By using the described devices 100, energy can most efficiently be distributed from different sources to maximize its value. As an example, battery power would not be used whilst there is sufficient solar and wind generation to meet demand.

Connection of Multiple Microgrids

Multiple microgrids can be operating together or remotely to form a single market. Each microgrid operates as a transactional grid with the appropriate hardware installed internally to the microgrid. When adjacent to each other, the transactional connection can occur directly to expand the scope of the two microgrids. Where they are geographically separated, but connected through a distribution or transmission network that has Faraday Exchangers, the transactional connection can still operate over the third party network.

By connecting two microgrids with no grid connection through an external system, the transactional layer of the grid can reconcile itself between multiple grids, with the actual energy being traded indirectly through the main electricity grid. This allows microgrids to most effectively and efficiently purchase and sell renewable electricity between each other.

Energy Market Effect

Residential users have a fixed price today that is significantly higher than the spot price for energy through retailers to minimise their downside risk in a wholesale energy market. Having a device 100 or routing engine 204 for a house allows the household to automatically buy and sell directly within the grid marketplace and within determined parameters that are configurable in real time will reduce the total cost of energy for users. When a device 100 has battery storage (with or without behind the meter generation) two significant outcomes are delivered:

- If the energy price is too high from the electricity grid supply, the household can use its stored energy (or energy being directly generated behind the meter) rather than buying expensive energy. This means that the average price of electricity being purchased from the grid is a much lower wholesale price, with exposure to the market spikes removed.
- With significantly more smaller scale prosumers (residential, industrial, commercial, etc) in the market, a new high side price cap is effectively put in place. If prices rise to a certain threshold from generators based on supply and demand, not only will prosumers reduce energy usage from the grid and switch to their stored energy, they can also enter the market to sell their stored energy. This effect simultaneously increases supply and reduces demand in the market. This is analogous to the massive deflationary effect that shale oil had in global hydrocarbon markets.

The transactional electric power apparatus/device and processes described herein allow for the efficient routing of electric power through an energy distribution network or grid to meet the requirements of energy producers, consumers and distribution network operators, while also improving the quality of the electric power to meet consumer requirements, and the desired sourcing of that power (for example, in terms of the proportion of renewable power and its locality of generation). The matching of energy producers and suppliers to consumers improves the performance of the energy distribution network and consumer and producer outcomes.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention.

CLAIMS:

1. An electric power distribution controller configured to be communicatively coupled to other instances of the electric power distribution controller to form a network of electrical power distribution controllers that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation.

2. The electrical power distribution controller of claim 1, wherein the one or more specified electric power attributes include power amount.

3. The electrical power distribution controller of claim 1, wherein the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and one or more specified electric power attributes selected from: power quality, and attributes of electric power generation.

4. The electrical power distribution controller of claim 1, wherein the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and one or more specified electric power attributes selected from: power quality, attributes of electric power generation, and pricing.

5. The electrical power distribution controller of claim 1, wherein the one or more specified electric power attributes are a plurality of specified electric power attributes including power amount and pricing, and one or more specified electric power attributes selected from: power quality, and attributes of electric power generation.

6. The electric power distribution controller of any one of claims 1 to 5, wherein each said electric power distribution controller is communicatively coupled to or is a component of a corresponding electrical power control apparatus including:

one or more signal conversion components receiving electrical power in the form of a corresponding first signal having a corresponding first fundamental frequency and a corresponding first characteristic voltage, and generating a corresponding second signal having a corresponding second fundamental frequency and a corresponding second characteristic voltage;

a signal conversion control component that controls operation of the signal

conversion components to determine an output voltage and an output frequency of an output signal of the electrical power control apparatus;

wherein the electric power distribution controller controls operation of the signal conversion control component to satisfy said requests.

7. An electrical power control apparatus including:

one or more signal conversion components receiving electrical power in the form of a corresponding first signal having a corresponding first fundamental frequency and a corresponding first characteristic voltage, and generating a corresponding second signal having a corresponding second fundamental frequency and a corresponding second characteristic voltage;

a signal conversion control component that controls operation of the signal conversion components to determine an output voltage and an output frequency of an output signal of the electrical power control apparatus; and

an electric power distribution controller that controls operation of the signal conversion control components and is configured to be communicatively coupled to other electric power distribution controllers of respective other instances of the electrical power control apparatus to form a network of electrical power control apparatuses that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation.

8. The electric power distribution controller of claim 6 or 7, wherein each said electrical power control apparatus, includes:

a magnetic core including at least three interconnected limbs defining a plurality of magnetic circuits, the at least three interconnected limbs including a first limb and second limbs;

a primary winding to receive input electrical power having an input voltage, an input current, and an input power factor, the primary winding being wound around the first limb of the limbs of the magnetic core to generate a corresponding first magnetic flux in the first limb that is divided between the second limbs;

secondary windings to provide output electrical power having an output voltage and an output power factor to a load, the secondary windings being wound around the first and second limbs of the magnetic core to generate the output

voltage across the secondary windings from magnetic flux in the first and second limbs of the magnetic core, wherein the secondary windings around the second limbs are wound in opposite polarities; and

control windings wound around the second limbs to modify the magnetic flux in the second limbs and thereby modify the output voltage and the input power factor, wherein the control windings around the second limbs are wound in opposite polarities.

9. The electric power distribution controller of any one of claims 6 to 8, wherein each said electrical power control apparatus is configured to reduce harmonics such that the output signal has lower distortion than the received first signal.

10. The electric power distribution controller of any one of claims 6 to 9, wherein each said electrical power control apparatus is configured to correct power factor such that the output signal has an improved power factor relative to the received first signal.

11. The electric power distribution controller of any one of claims 6 to 10, wherein each said electrical power control apparatus is configured to balance power between phases of the received electric power.

12. The electric power distribution controller of any one of claims 6 to 11, wherein the electric power distribution controller is configured to:

receive requests for electric power from corresponding downstream electric power distribution controllers specifying one or more corresponding electric power attributes selected from: power amount, stability, noise, reliability, sustainability, and pricing; and

for each request received from a corresponding downstream electric power distribution controller:

(i) process the received request to generate corresponding requests for sending to corresponding upstream electric power distribution controllers in order to determine the abilities of their respective upstream electrical power control apparatuses to individually or collectively supply electric power satisfying the received request;

(ii) receive responses to the generated requests from the corresponding upstream electric power distribution controllers, the

responses being indicative of the abilities of the corresponding upstream electrical power control apparatuses to supply electric power satisfying the received request;

(iii) determine whether the indicated abilities indicate that the corresponding upstream electrical power control apparatuses are able, individually or collectively, to supply electric power satisfying the received request;

(iv) select, based on the step of determining and the indicated abilities, one or more of the corresponding upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the electric power distribution controller in order to satisfy the received request;

(v) cause the selected upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the power distribution controller; and

(vi) cause the corresponding electrical power control apparatus to output electric power having attributes satisfying the attributes of the received request to a downstream electrical power control apparatus corresponding to the downstream electric power distribution controller.

13. The electric power distribution controller of claim 12, wherein, in the event that step (iii) determines that the upstream electric power distribution controllers are unable to satisfy the received request, the electric power distribution controller is configured to cause a corresponding message to be sent to the upstream electric power distribution controllers so as to provide a further opportunity for the upstream electric power distribution controllers to improve their individual or collective ability to satisfy the request.

14. The electric power distribution controller of claim 12 or 13, wherein steps (i) to (vi) constitute a transaction between the electric power distribution controller, the corresponding downstream electric power distribution controller, and the one or more selected upstream electric power distribution controllers, and each of the electric power distribution controllers participating in the transaction is configured to store data representing the transaction in a corresponding database.

15. The electric power distribution controller of any one of claims 1 to 14, wherein the attributes specify a cost function that defines pricing for electric power in dependence on the proportions of renewable and non-renewable sources of the electric power.

16. The electric power distribution controller of any one of claims 1 to 15, wherein the attributes specify a cost function that defines pricing for electric power in dependence on harmonic distortion and/or power factor of the electric power.

17. An electric power distribution process executed by an electric power distribution controller communicatively coupled to other instances of the electric power distribution controller to form a network of electrical power distribution controllers that collectively control the flow of electric power in an electric power distribution network to satisfy requests for electric power with one or more specified electric power attributes selected from: power amount, power quality, and attributes of electric power generation, the process including the steps of:

receiving requests for electric power from corresponding downstream electric power distribution controllers specifying one or more corresponding electric power attributes selected from: power amount, stability, noise, reliability, sustainability, and pricing; and

for each request received from a corresponding downstream electric power distribution controller:

(i) processing the received request to generate corresponding requests for sending to corresponding upstream electric power distribution controllers in order to determine the abilities of their respective upstream electrical power control apparatuses to individually or collectively supply electric power satisfying the received request;

(ii) receiving responses to the generated requests from the corresponding upstream electric power distribution controllers, the responses being indicative of the abilities of the corresponding upstream electrical power control apparatuses to supply electric power satisfying the received request;

(iii) determining whether the indicated abilities indicate that the corresponding upstream electrical power control apparatuses are

able, individually or collectively, to supply electric power satisfying the received request;

(iv) selecting, based on the step of determining and the indicated abilities, one or more of the corresponding upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the electric power distribution controller in order to satisfy the received request;

(v) causing the selected upstream electrical power control apparatuses to supply electric power to the electrical power control apparatus corresponding to the power distribution controller; and

(vi) causing the corresponding electrical power control apparatus to output electric power having attributes satisfying the attributes of the received request to a downstream electrical power control apparatus corresponding to the downstream electric power distribution controller.

18. An electronic storage medium having stored thereon FPGA configuration data representing executable instructions or processor-executable instructions that, when executed by at least one FPGA or processor, cause it to execute the steps of claim 17.

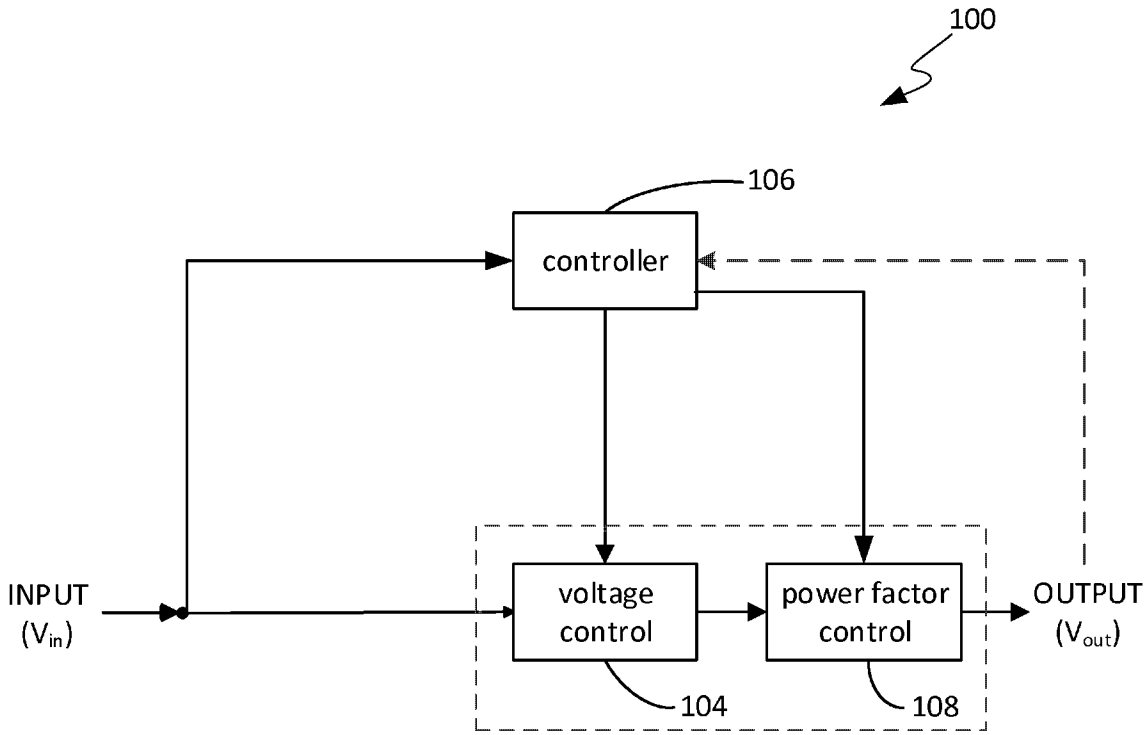


Figure 1

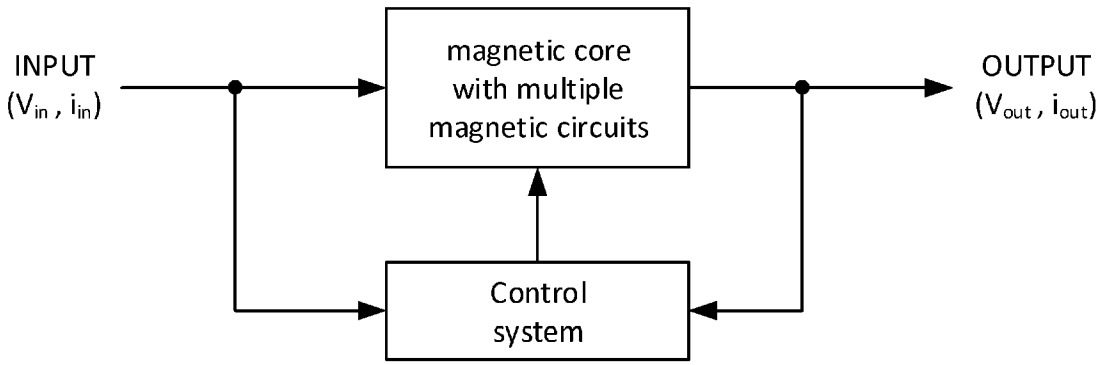


Figure 2

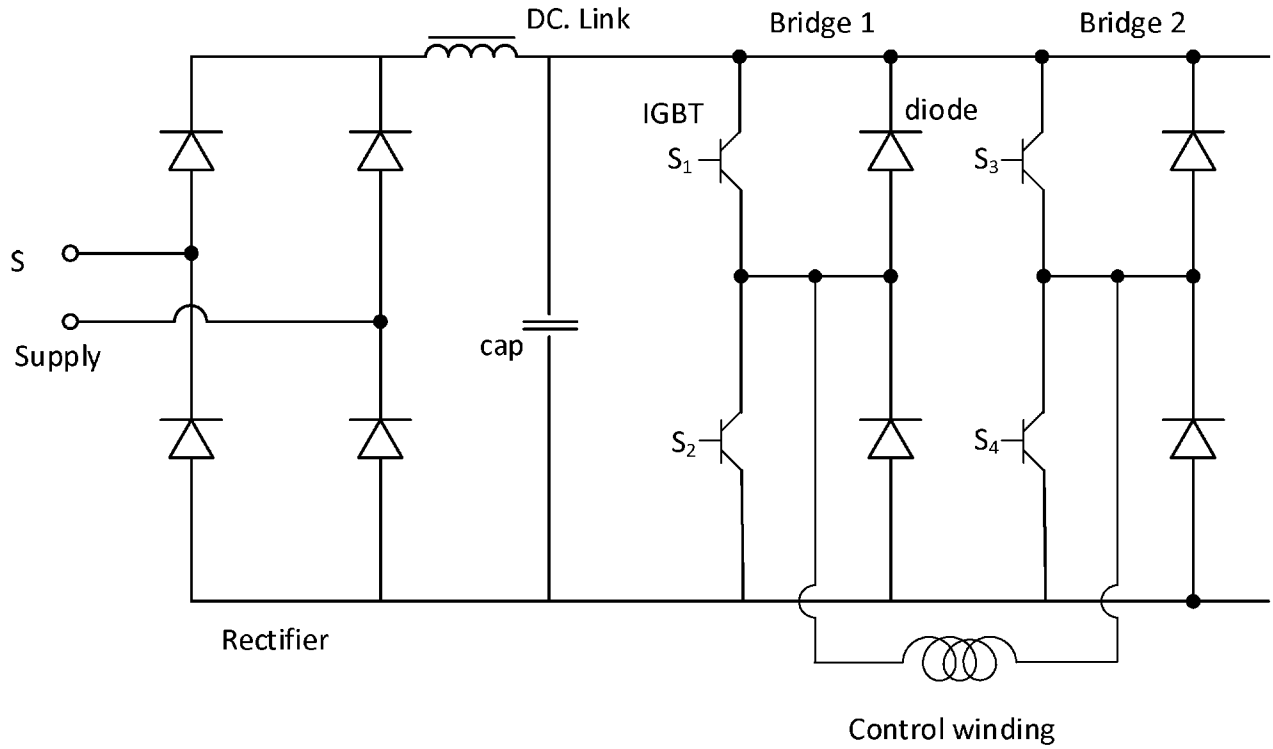

DC. Link
Bridge 1
Bridge 2
IGBT
diode
S_1
S_3
S
Supply
cap
S_2
S_4
Rectifier
Control winding

Figure 3

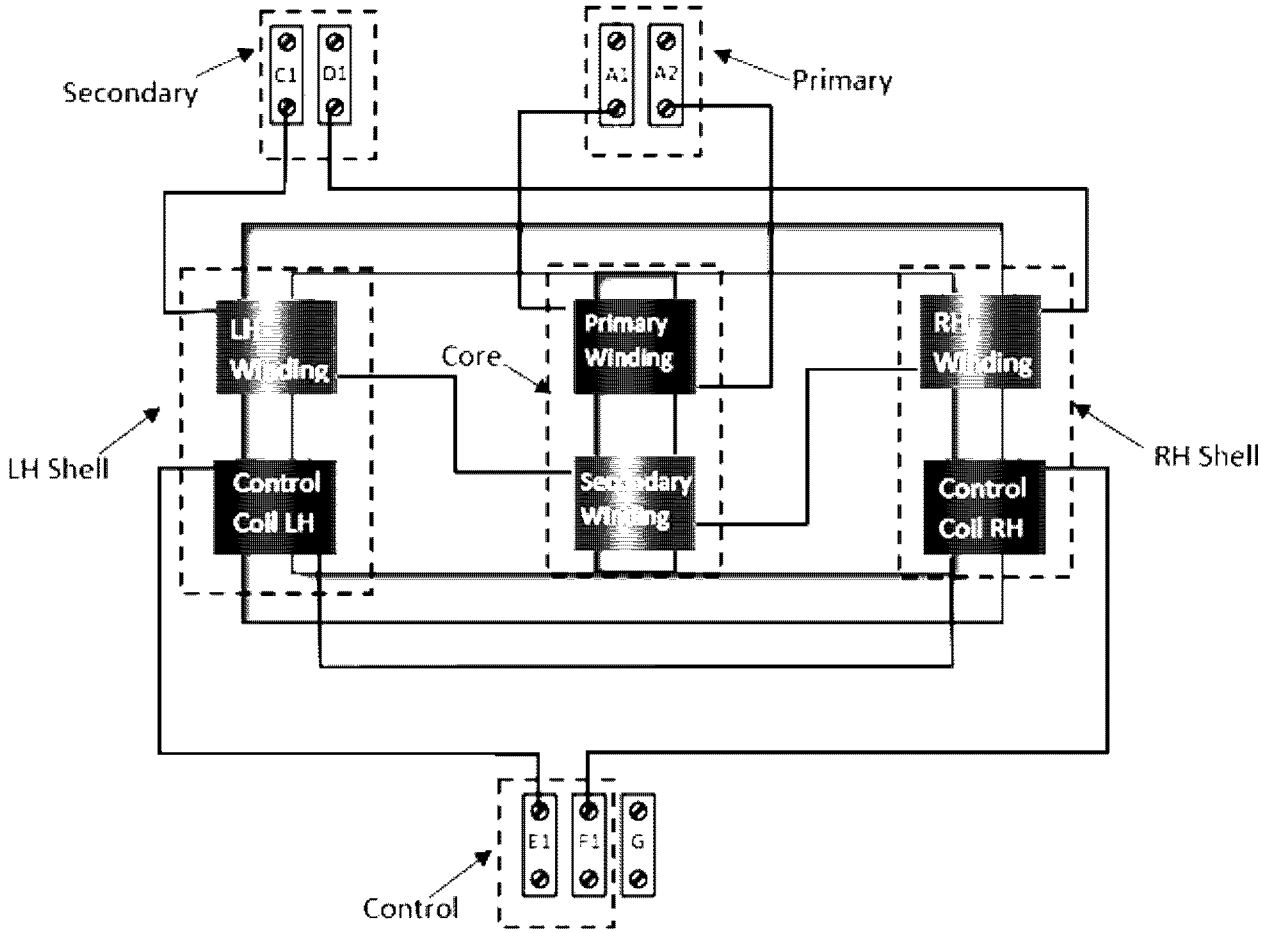

Secondary
C1
D1
A1
A2
Primary
Primary Winding
Core
Control Coil LH
Control Coil RH
LH Shell
RH Shell
E1
F1
G
Control

Figure 4

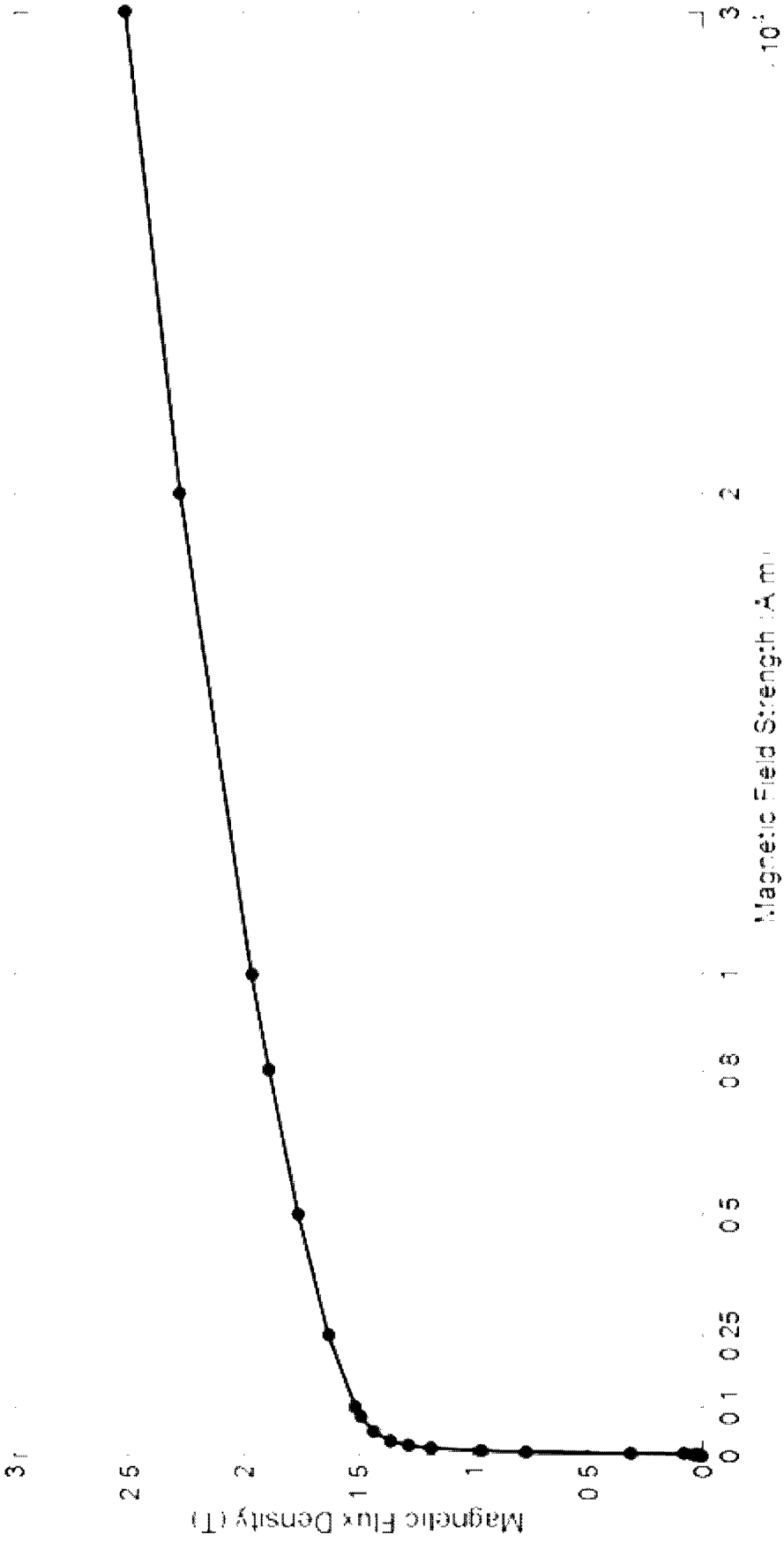


Figure 5

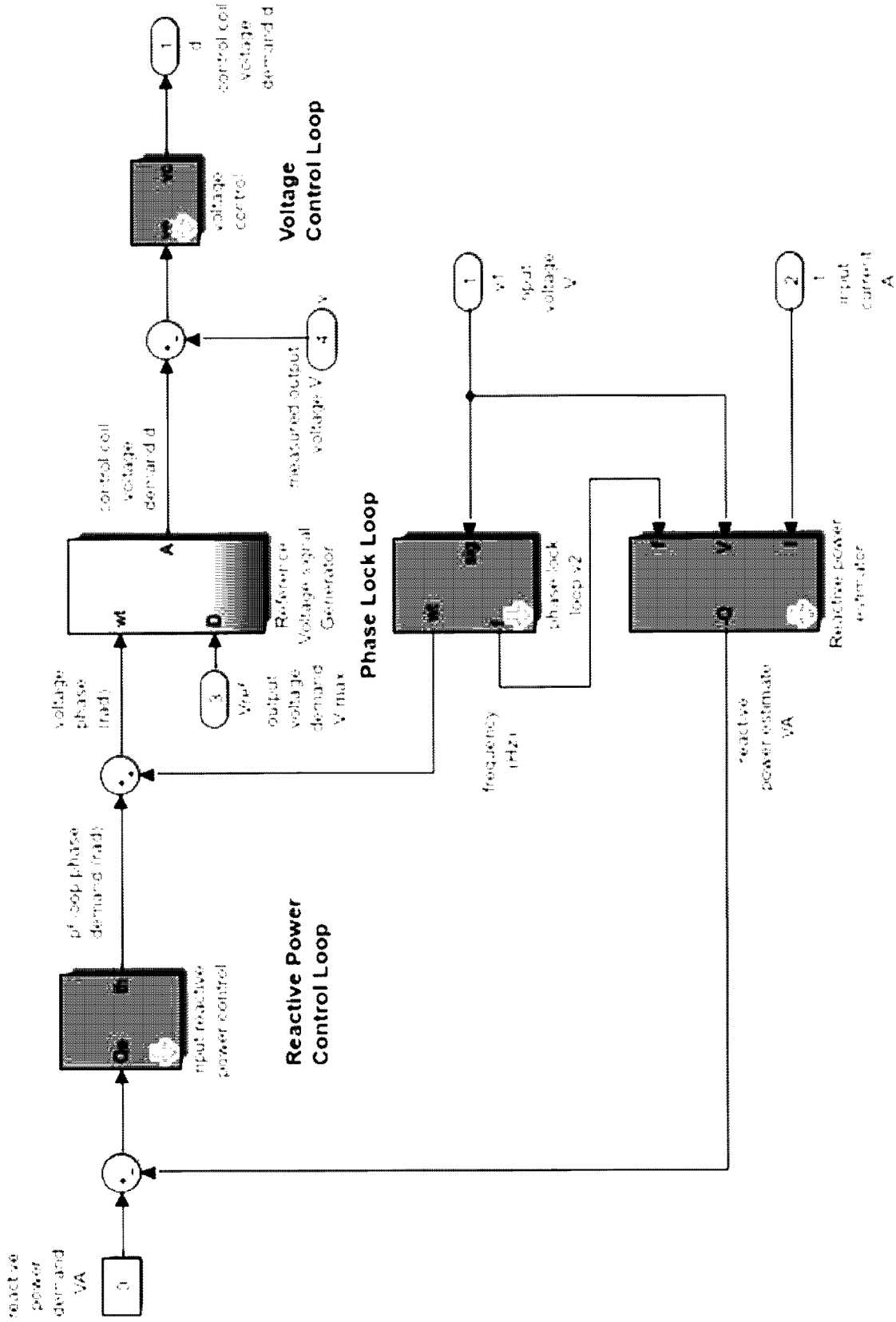

Voltage
Control Loop
Phase Lock Loop
Reactive Power
Control Loop
Reference
Voltage signal
Generator
phase lock
loop v2
Reactive power
estimator
voltage
phase
(rad)
frequency
(Hz)
reactive
power estimate
VA
input reactive
power control
reactive
power
demand
VA
input
voltage
V
input
current
A
measured output
voltage V
control coil
voltage
demand d
voltage
control

Figure 6

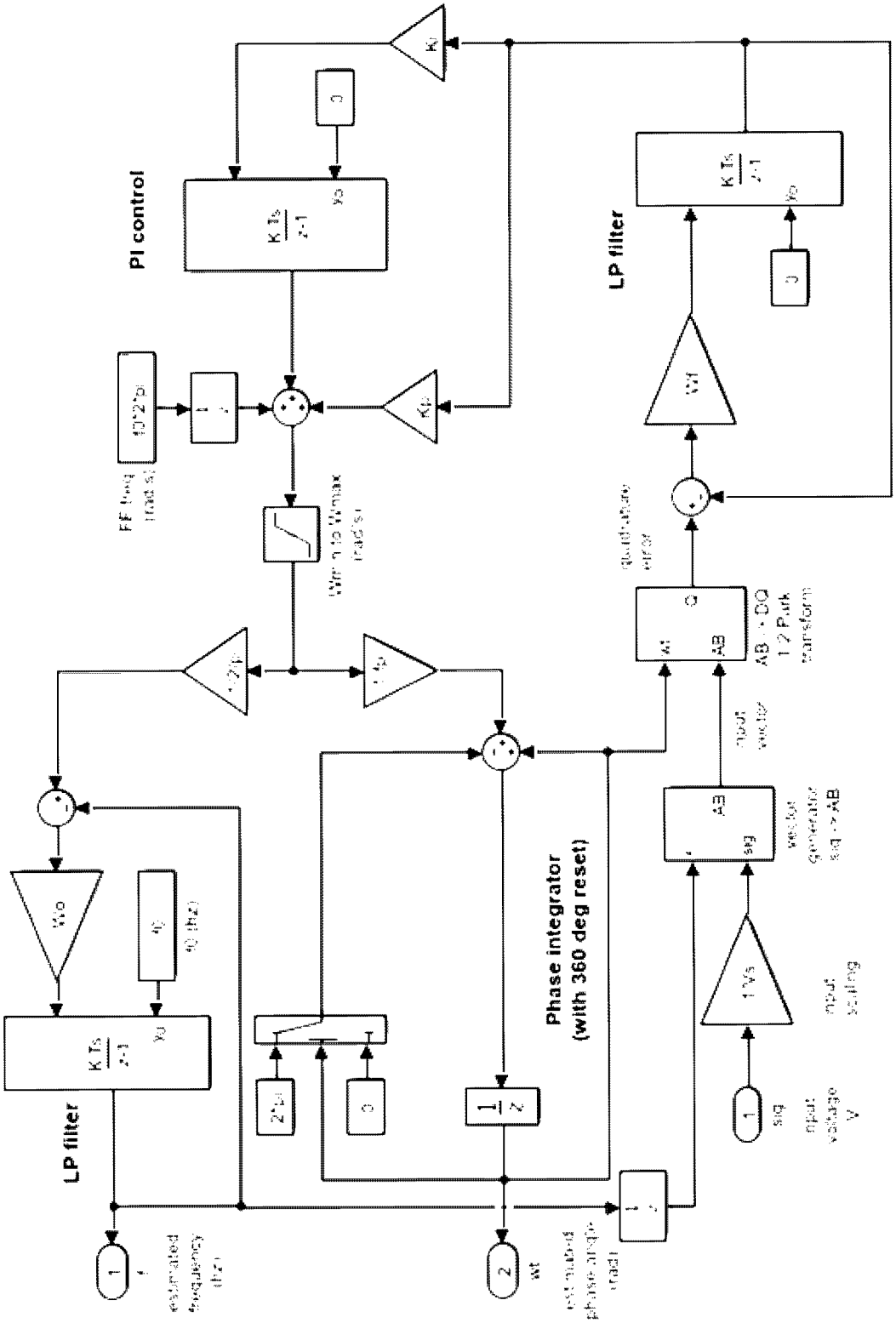


Figure 7 Phase lock loop

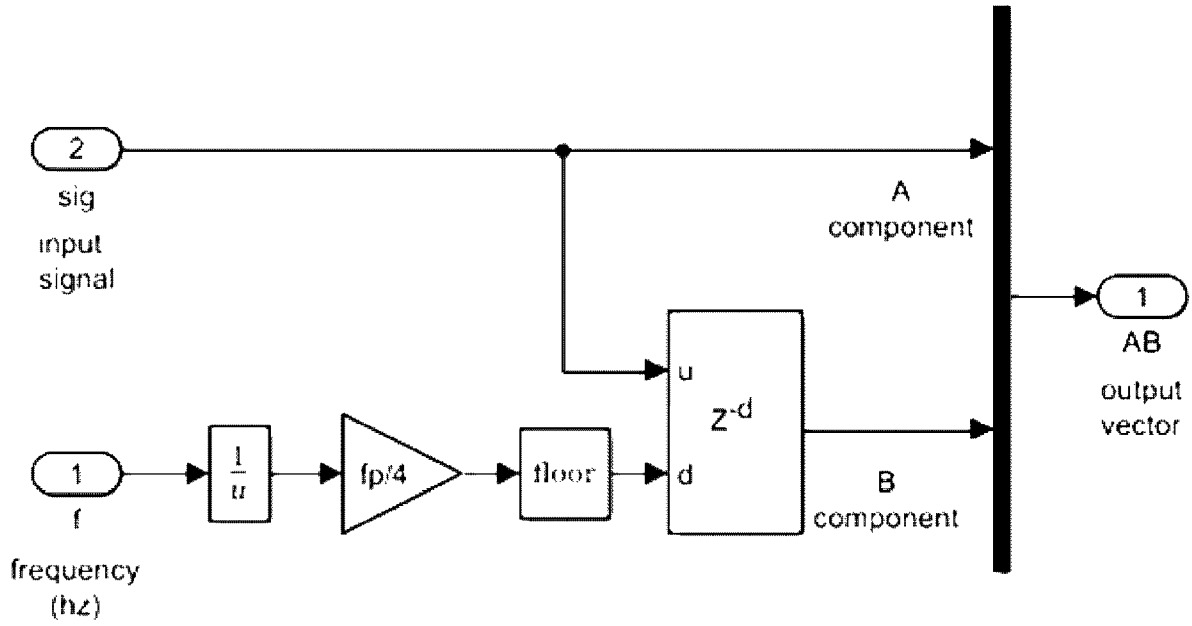


Figure 8 vector signal generator

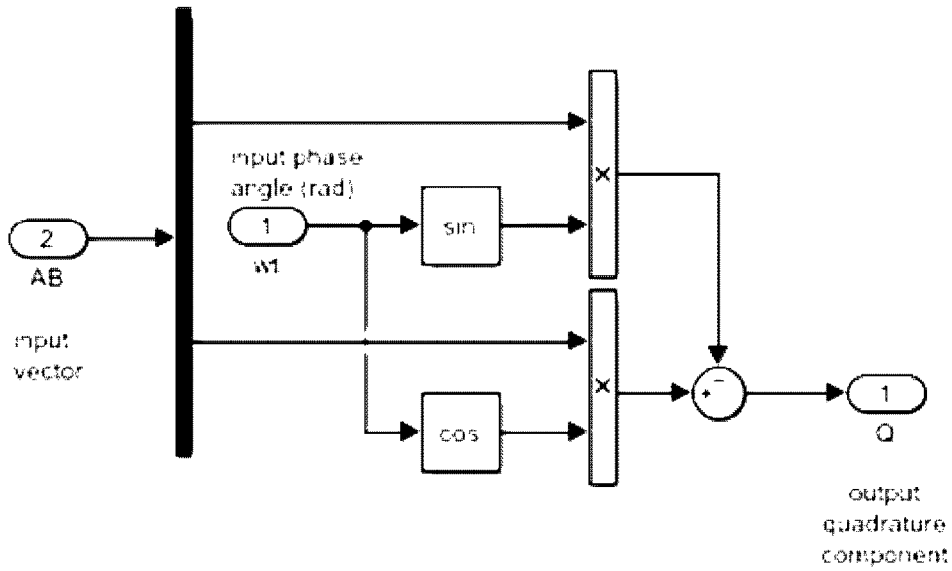


Figure 9 half park transform

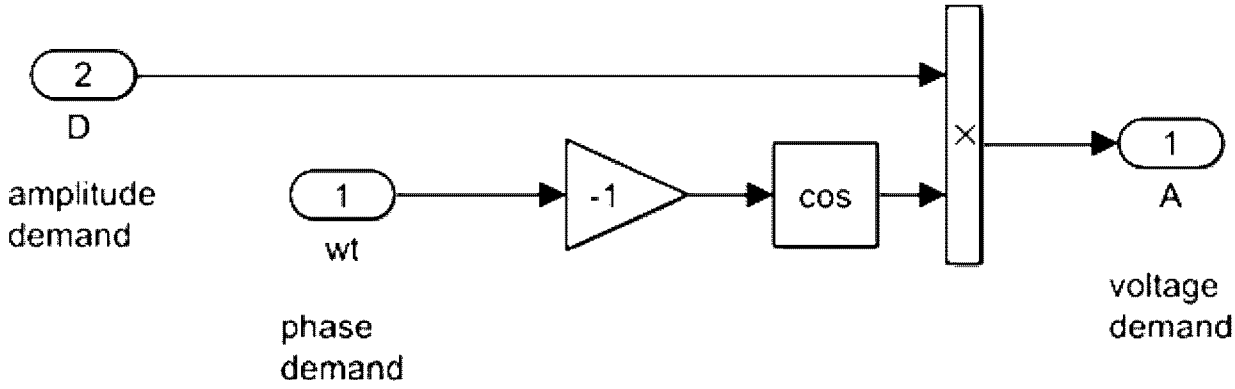


Figure 10 reference voltage generator

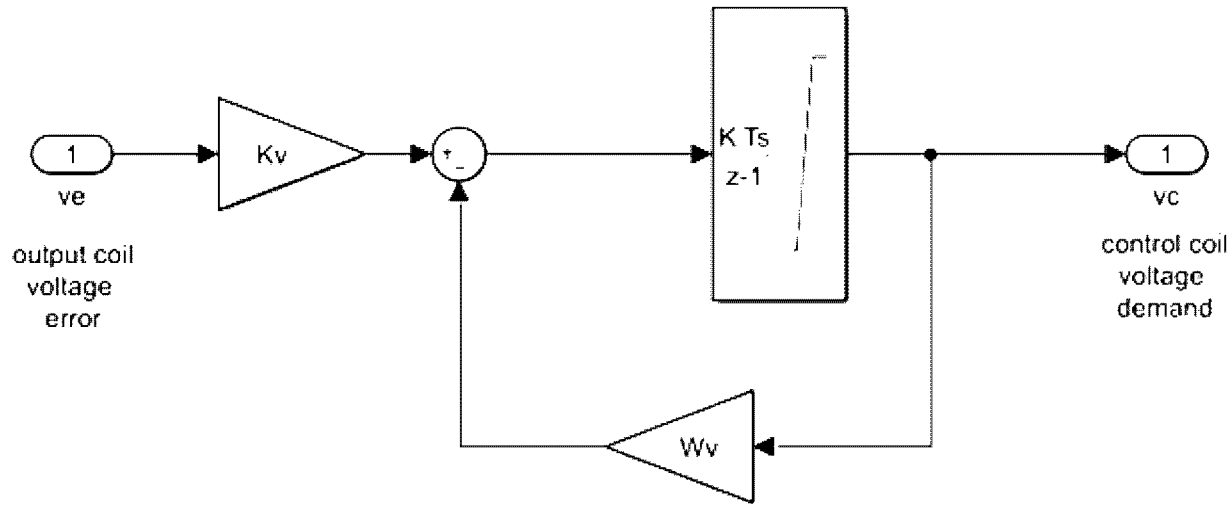


Figure 11 voltage controller

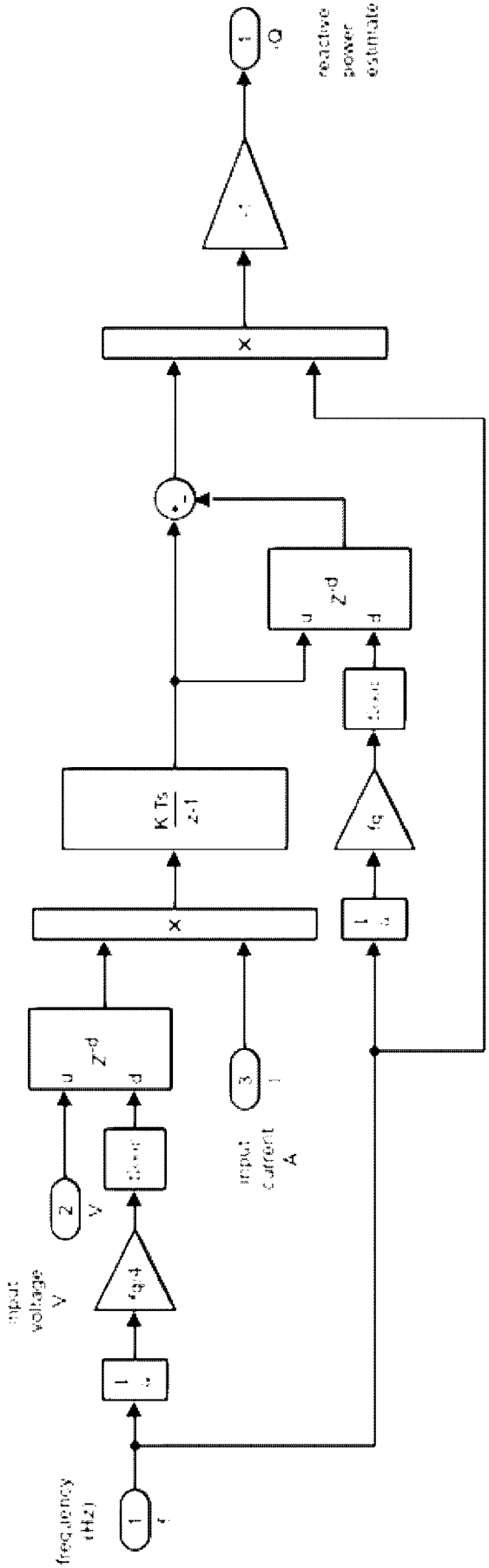


Figure 12 reactive power estimator

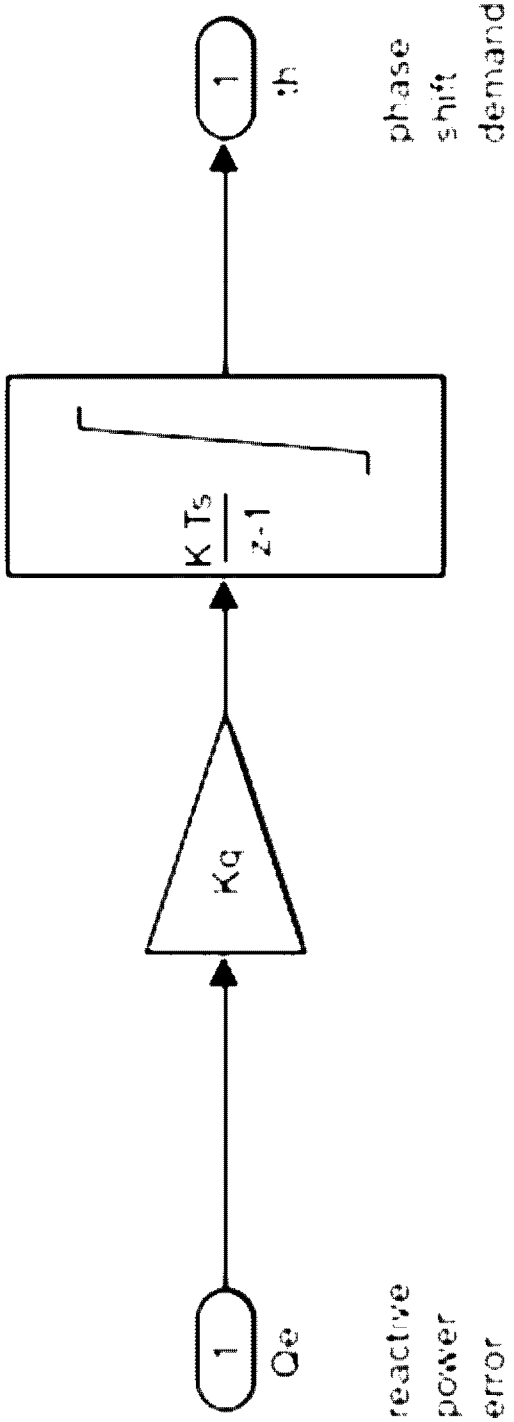


Figure 13 reactive power regulator

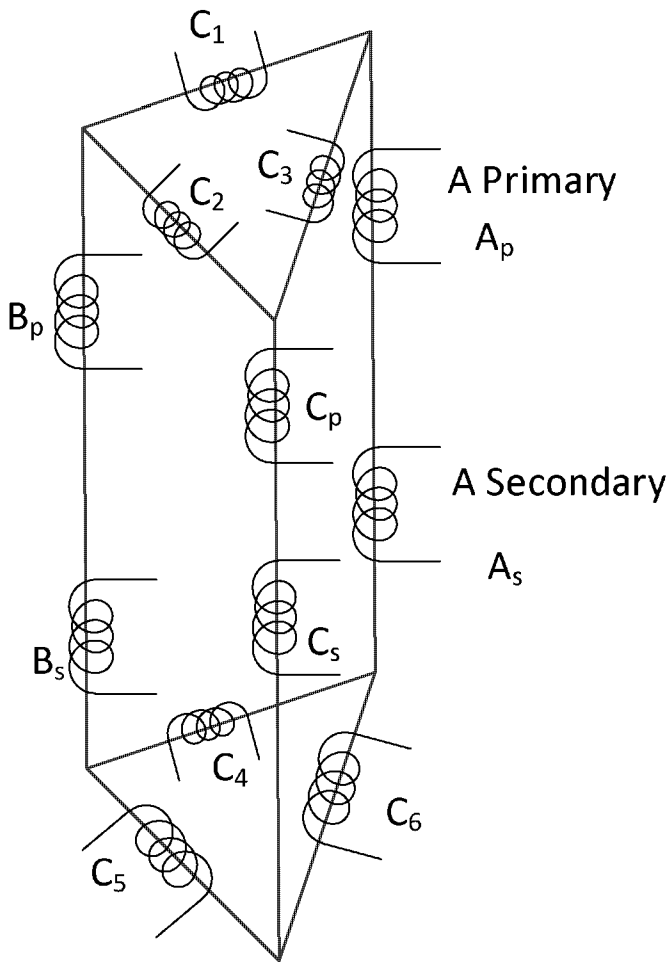


Figure 14 3 phase device configuration

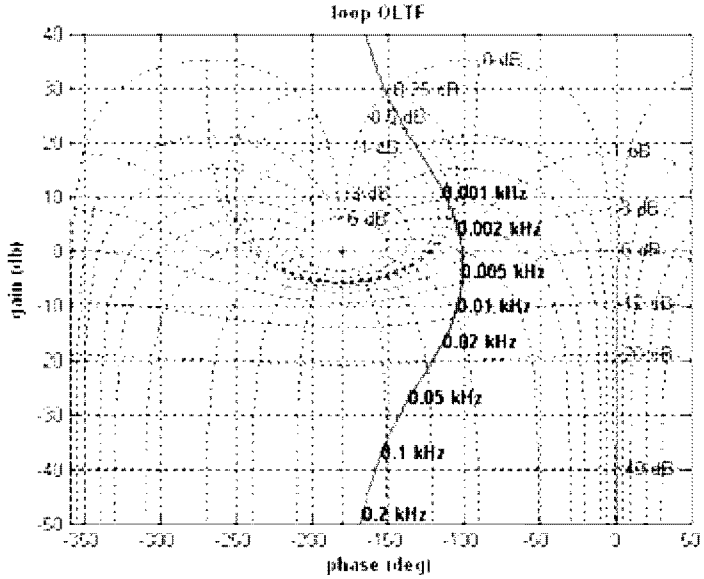


Figure 15 PLL Nichols plot

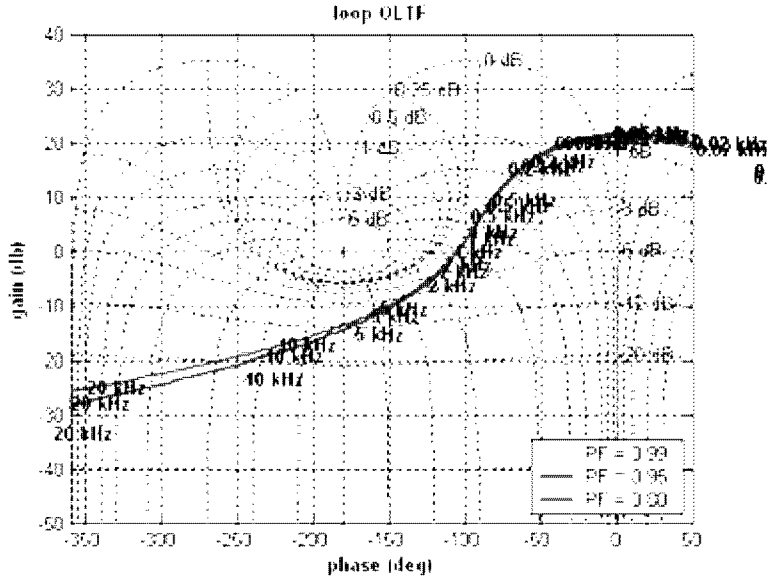


Figure 16 voltage control Nichols plot

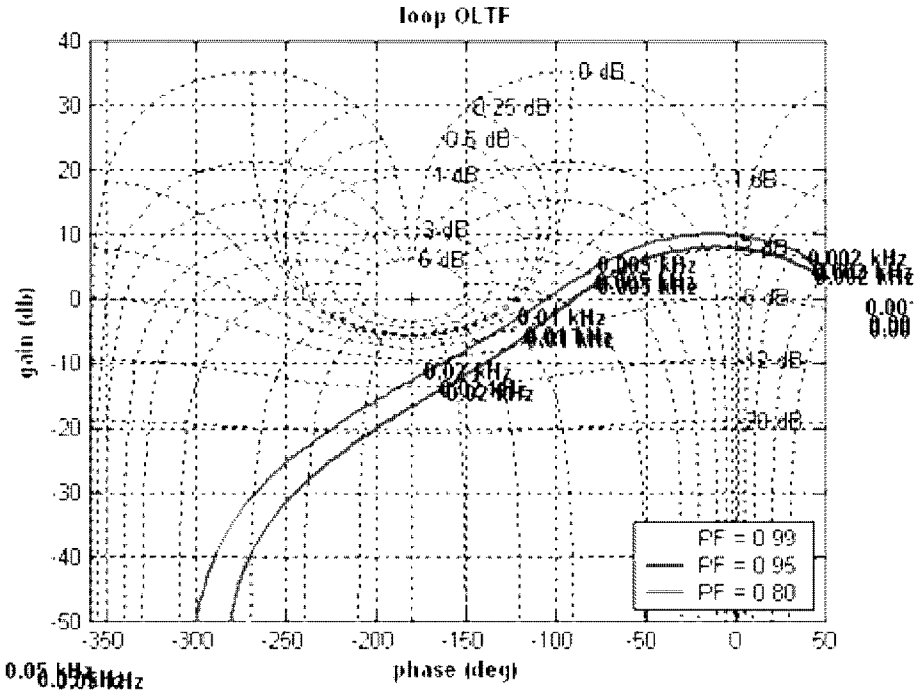


Figure 17 reactive power Nichols plot

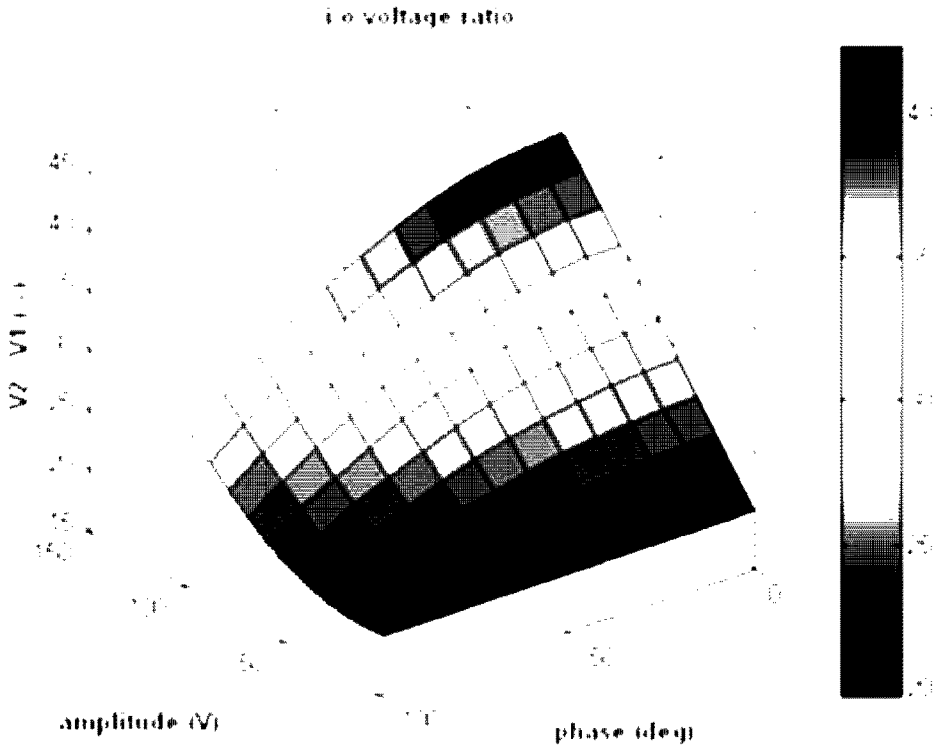


Figure 18 voltage ratio vs control voltage

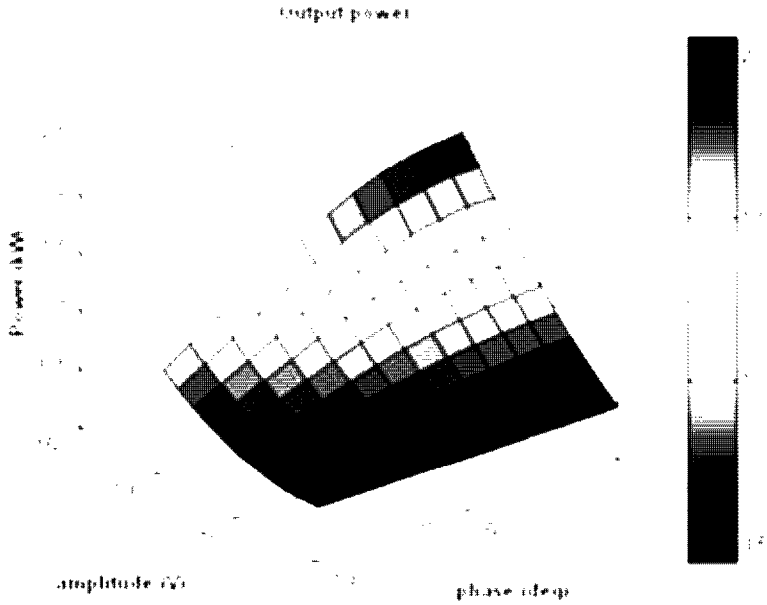


Figure 19 output power vs control voltage

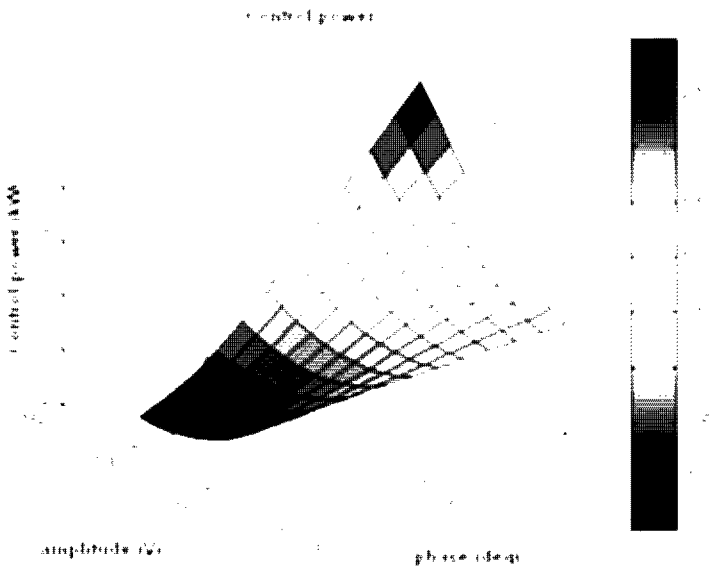


Figure 20 control power vs control voltage

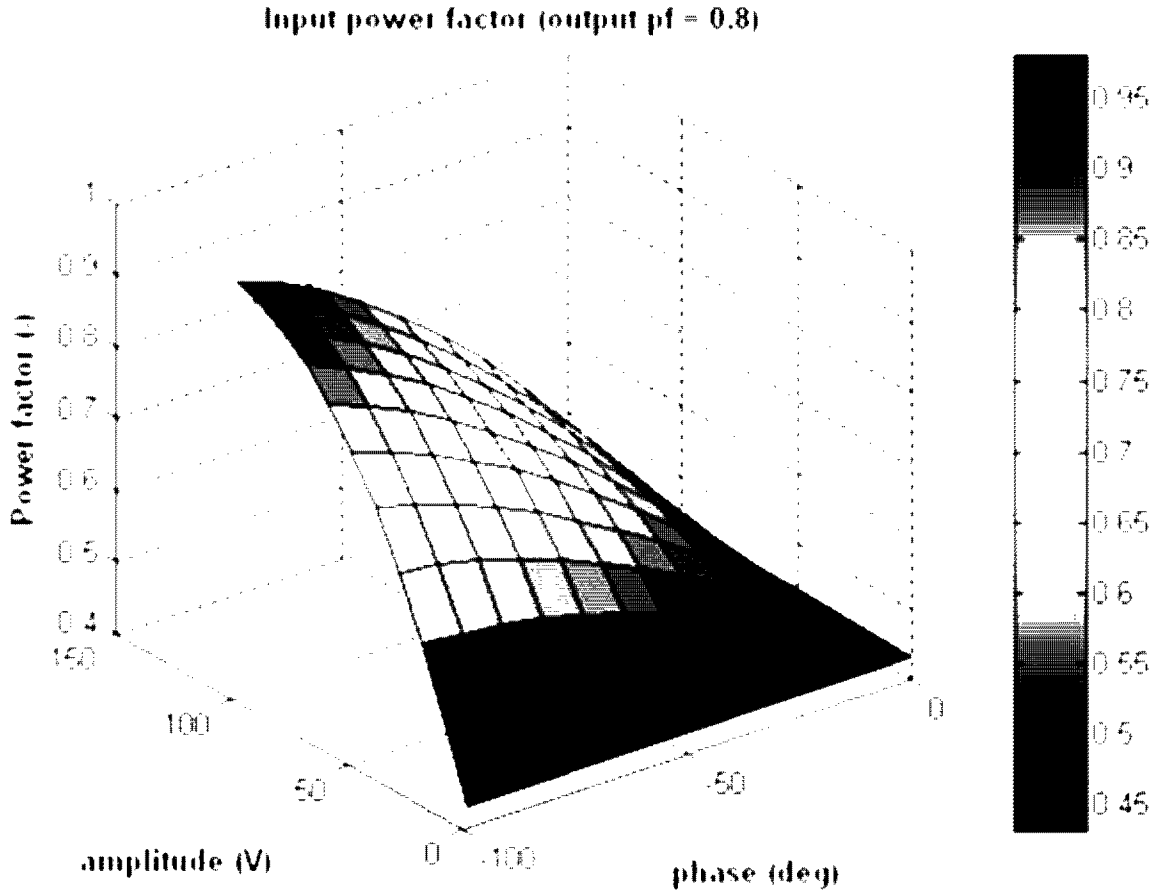
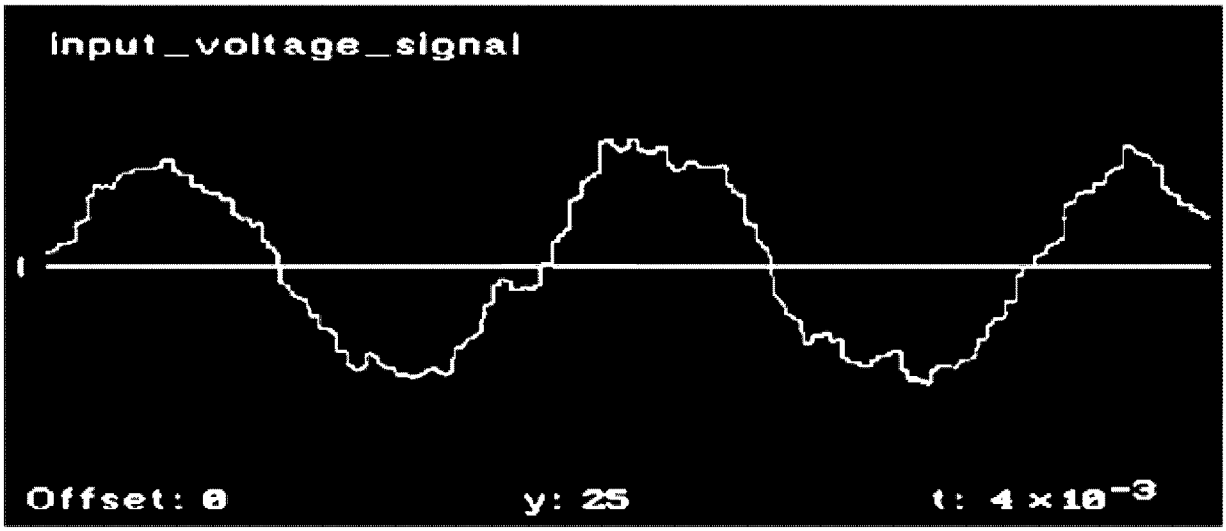


Figure 21 power factor vs control voltage

(a)



(b)

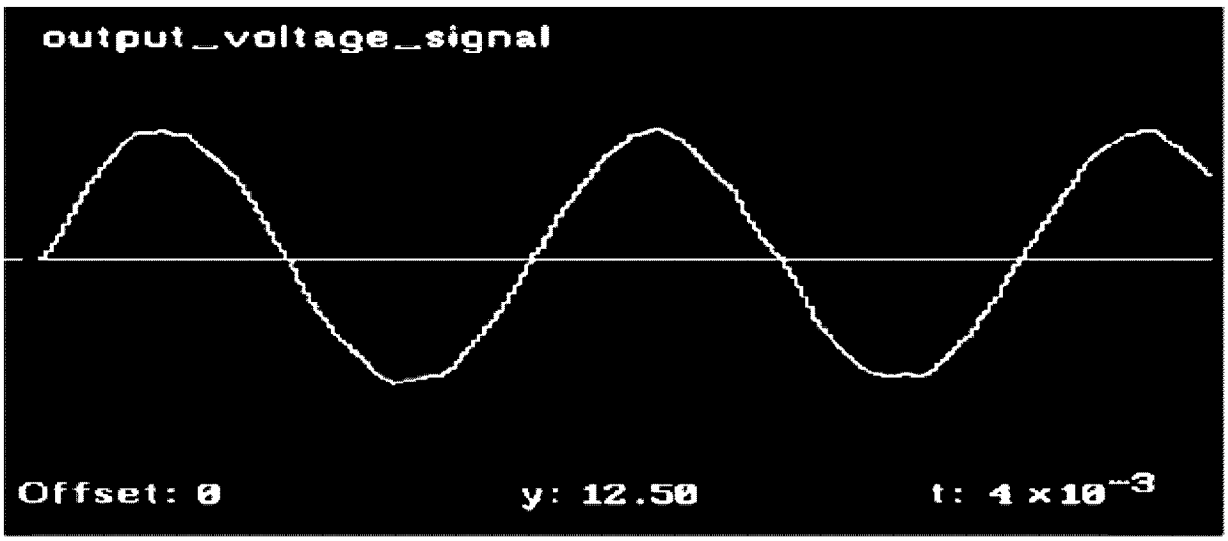
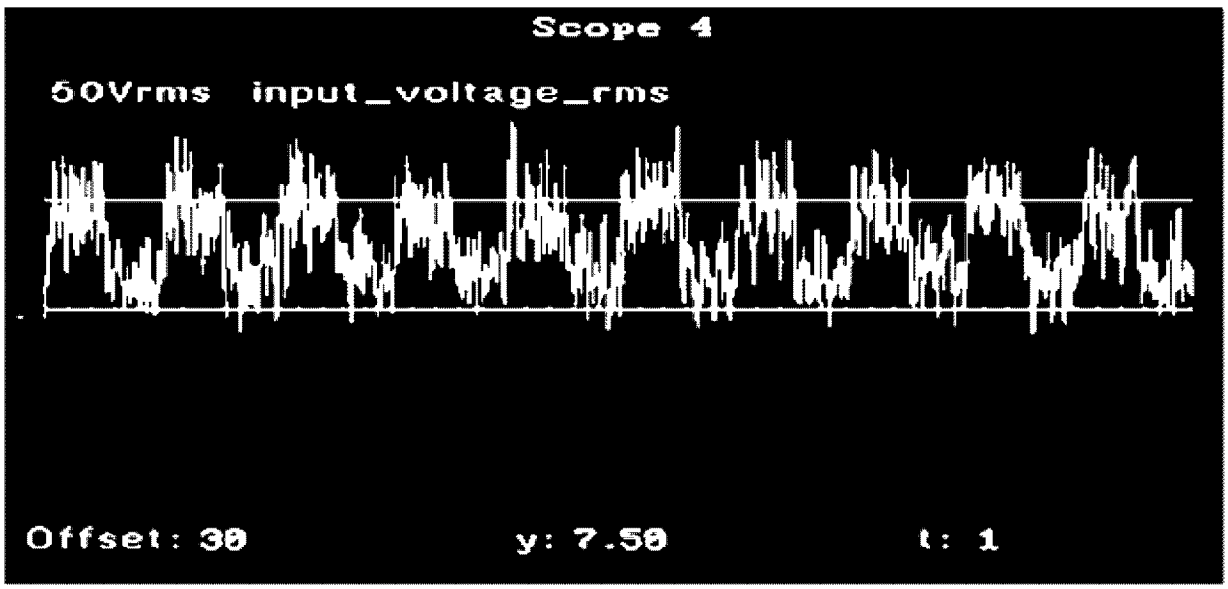


Figure 22 input and output from example device

(c)



(d)

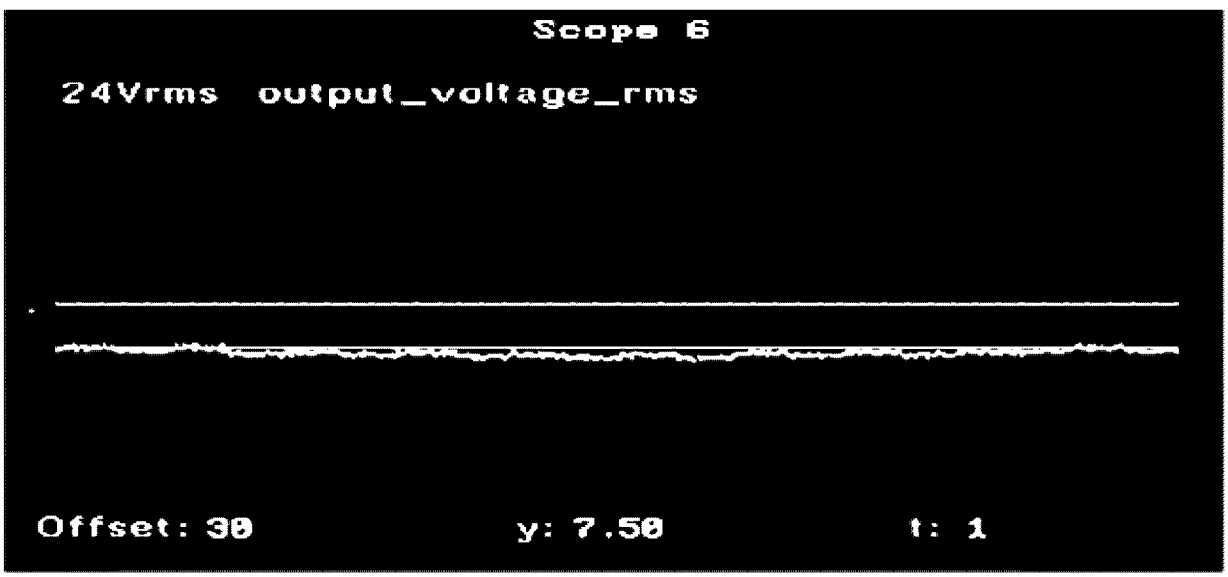
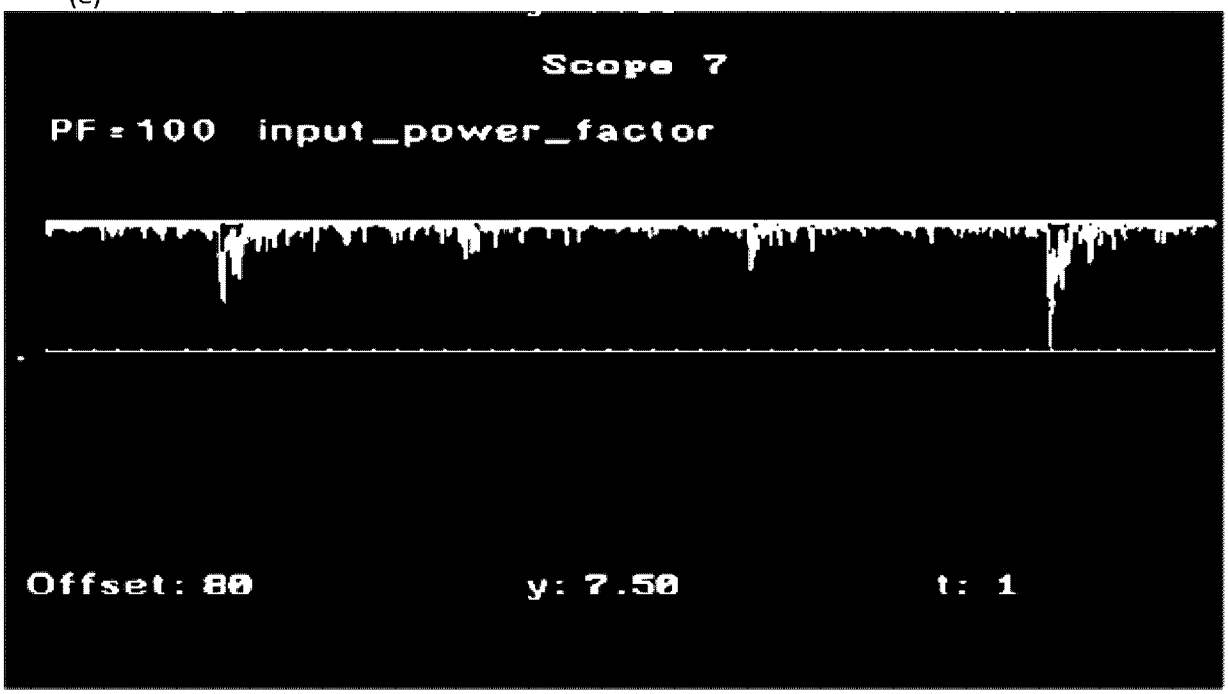


Figure 22 input and output from example device

(e)



(f)

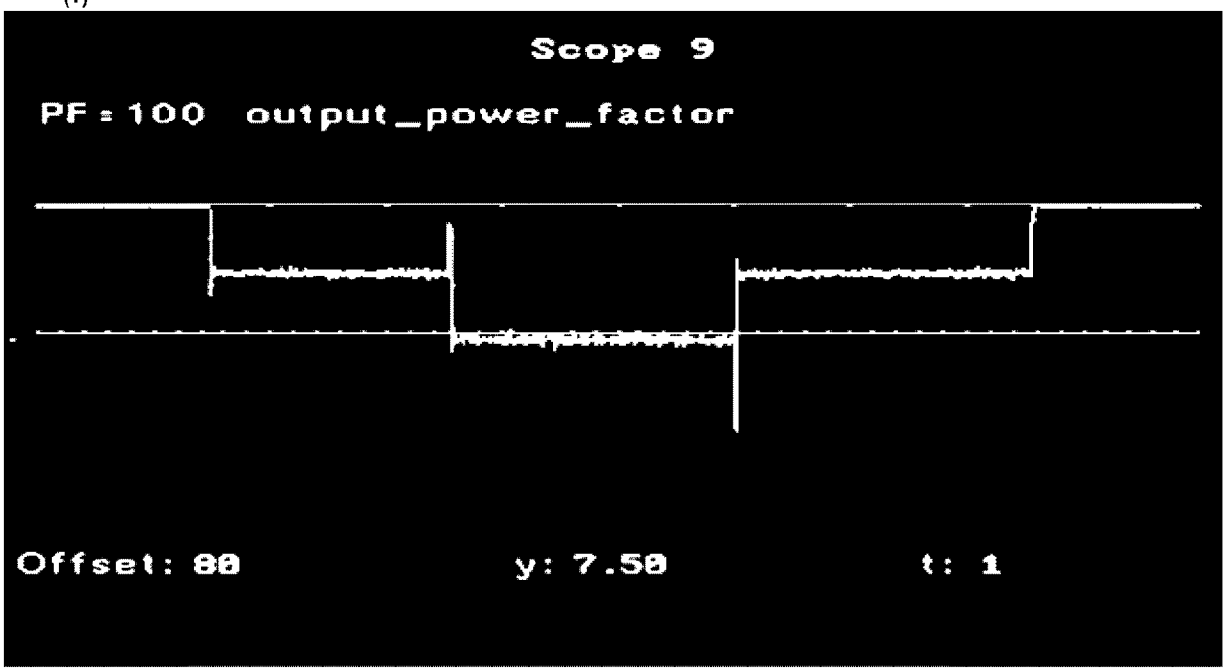


Figure 22 input and output from example device

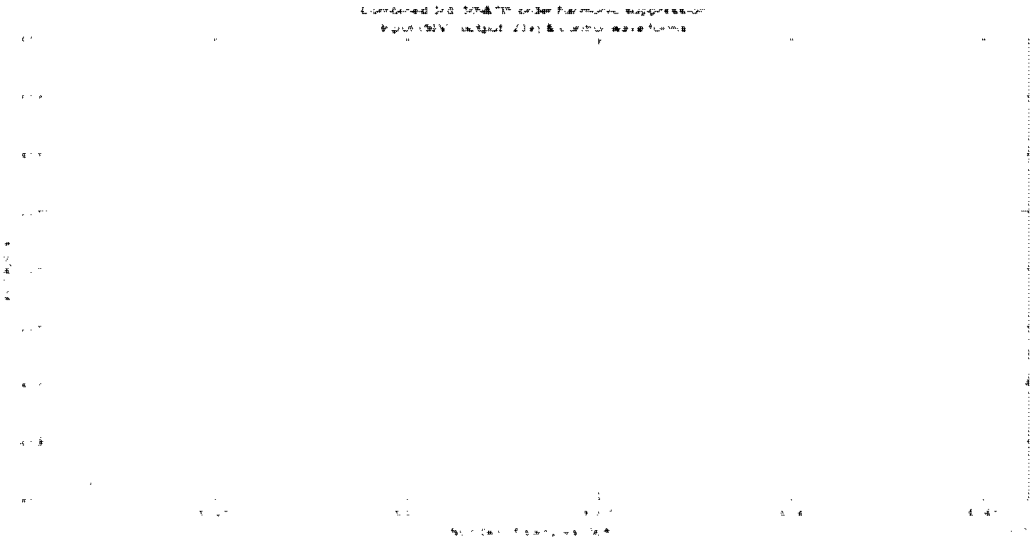


Figure 23 Combined 3rd, 5th & 7th harmionic supression at input of 50V, output of 23V & control wave forms



Figure 24 voltage dip response

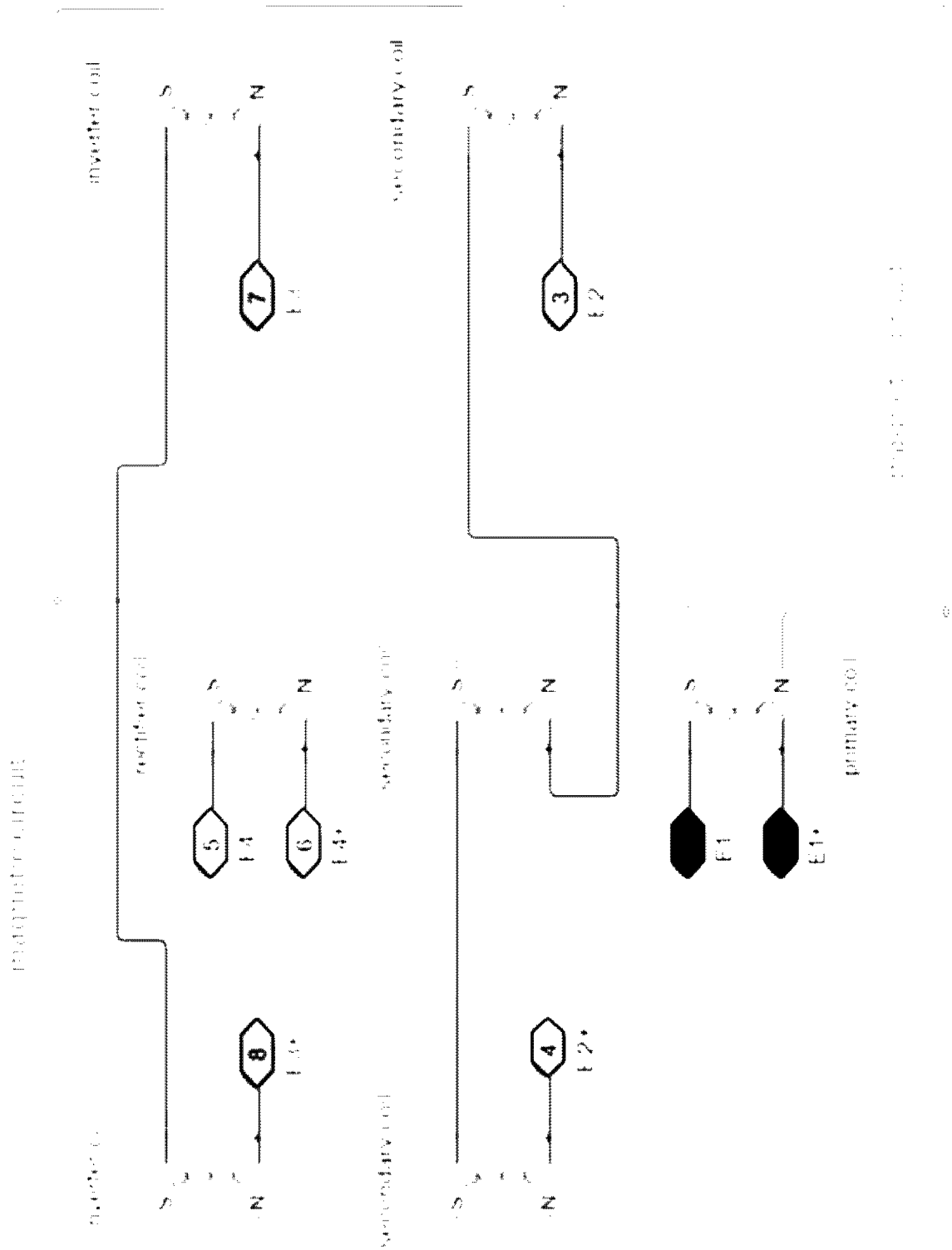


Figure 25 Magnetic circuit

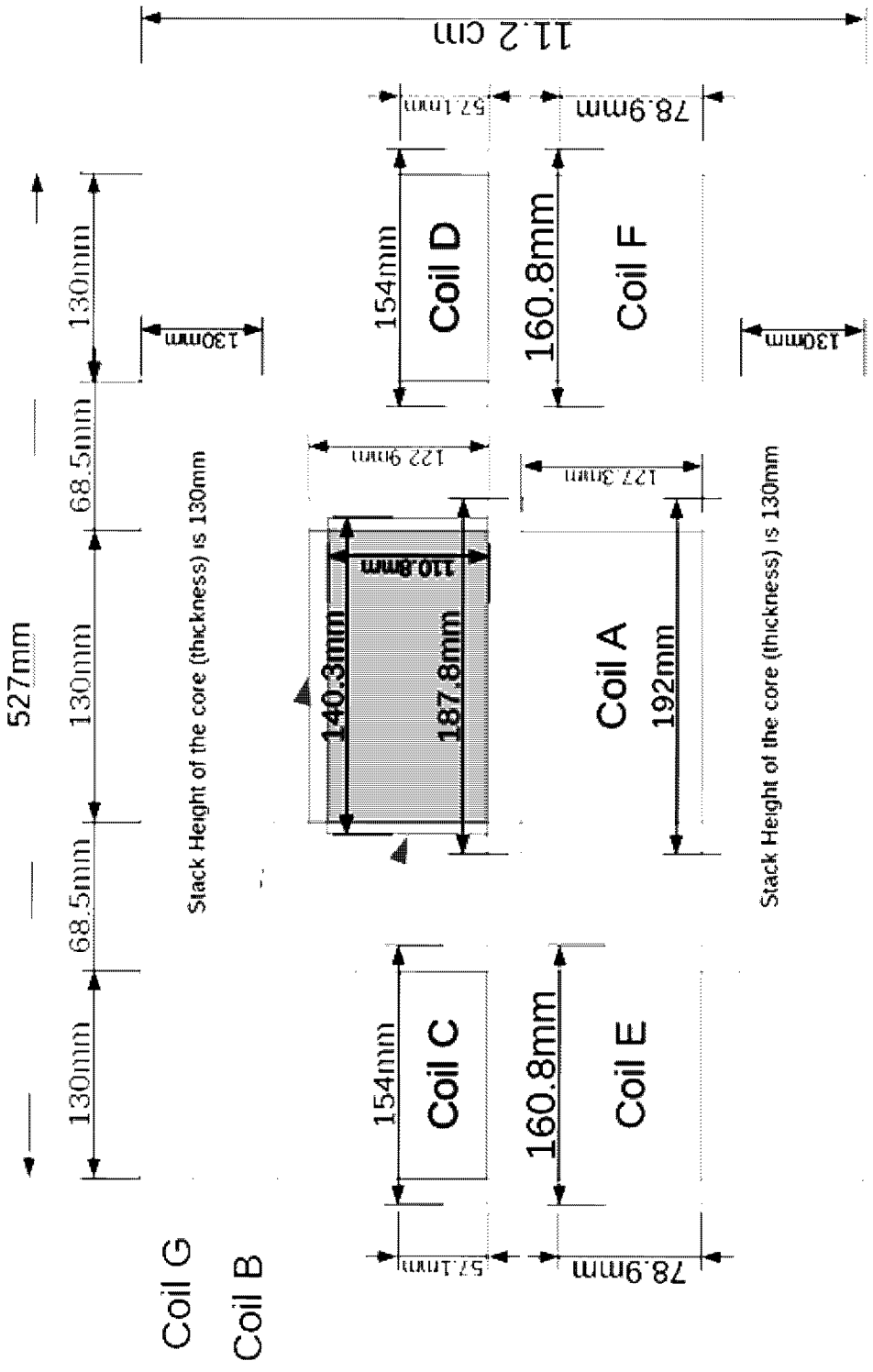

11.2 cm
57.1mm
78.9mm
154mm
Coil D
160.8mm
Coil F
130mm
130mm
68.5mm
130mm
527mm
68.5mm
130mm
Stack Height of the core (thickness) is 130mm
122.9mm
127.3mm
110.8mm
140.3mm
187.8mm
Coil A
192mm
Stack Height of the core (thickness) is 130mm
154mm
Coil C
160.8mm
Coil E
57.1mm
78.9mm
Coil G
Coil B

Figure 26

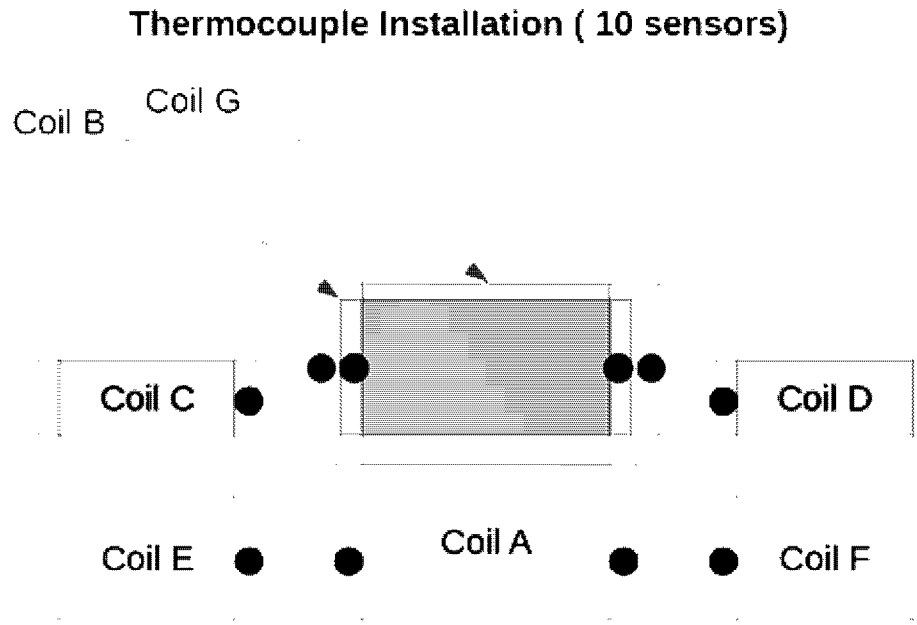


Figure 27

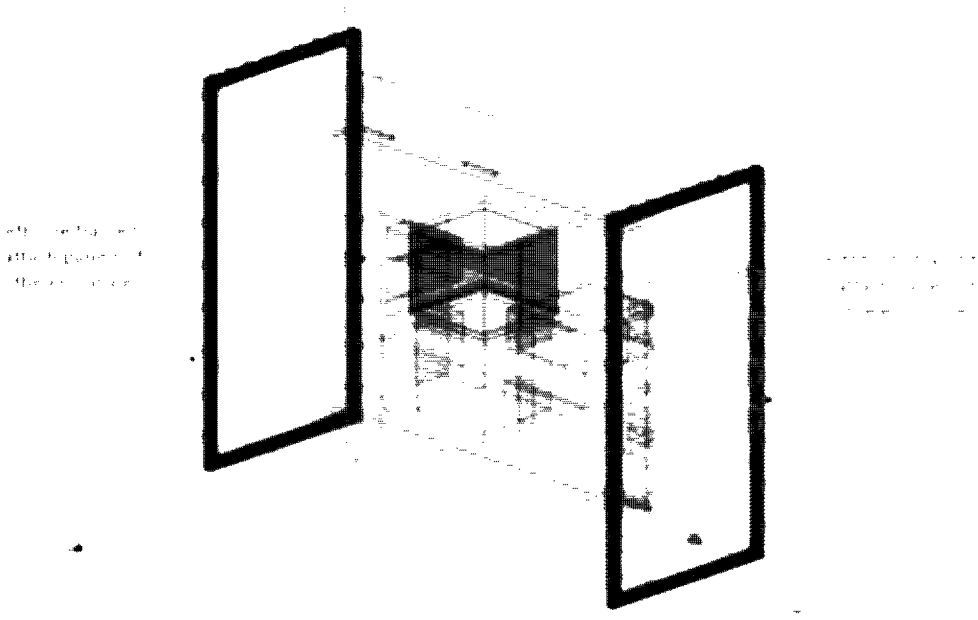


Figure 28

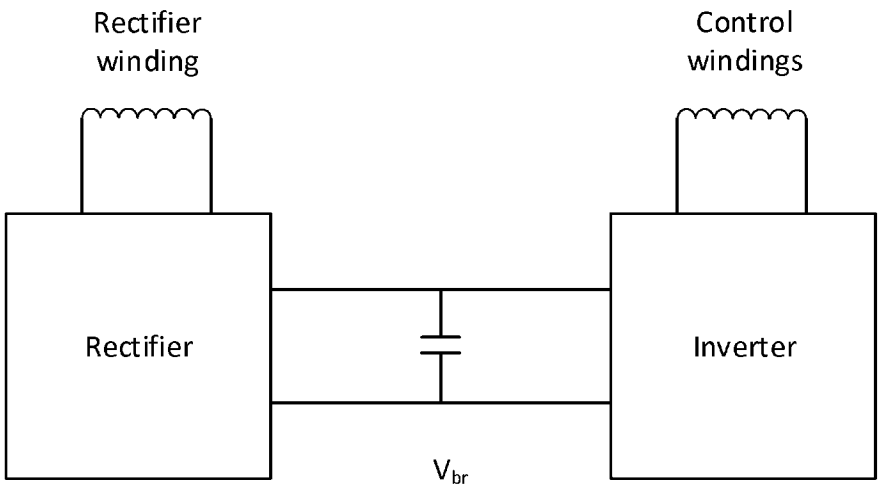

Rectifier winding
Control windings
Rectifier
Inverter
V_{br}

Figure 29

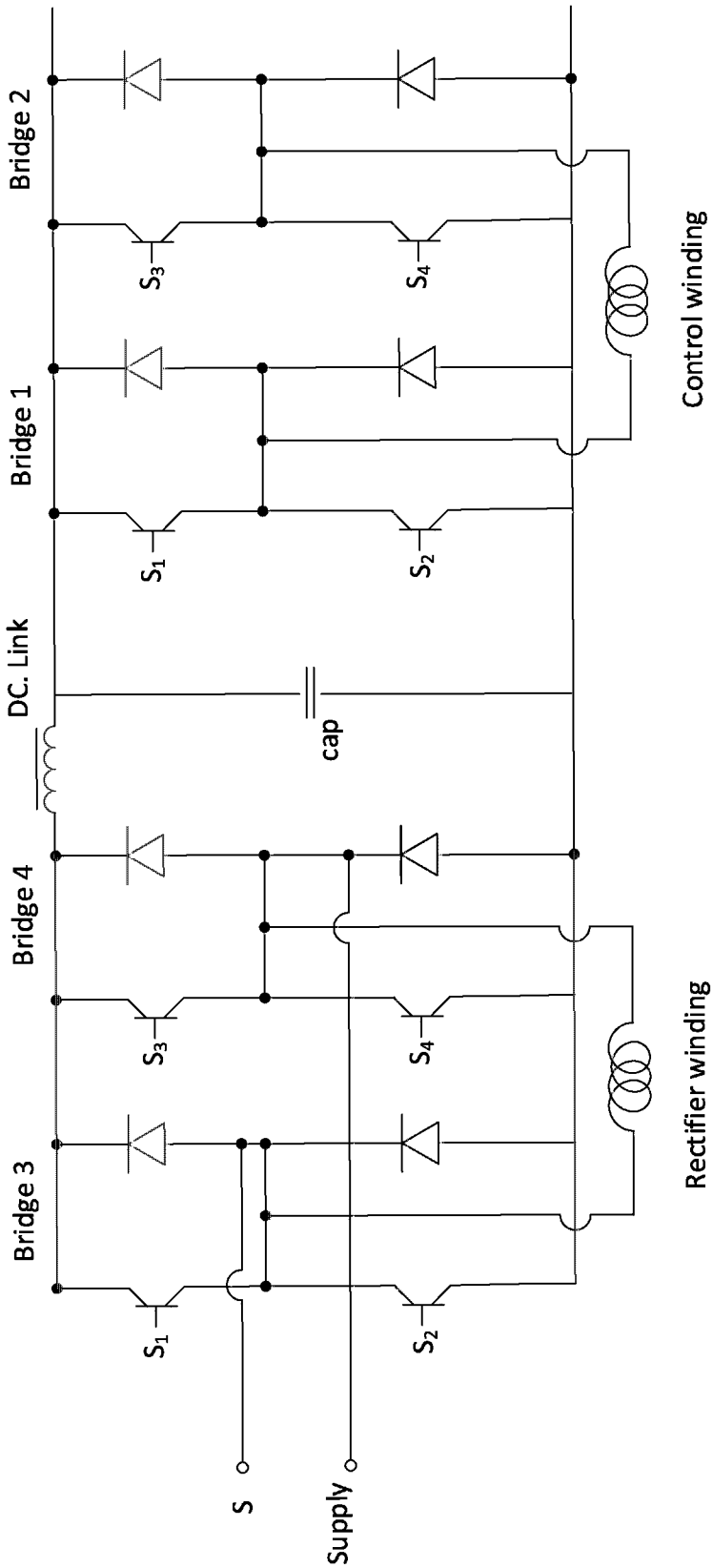

Bridge 2
Bridge 1
DC. Link
Bridge 4
Bridge 3
S_3
S_4
S_1
S_2
cap
Control winding
Rectifier winding
S
Supply

Figure 30

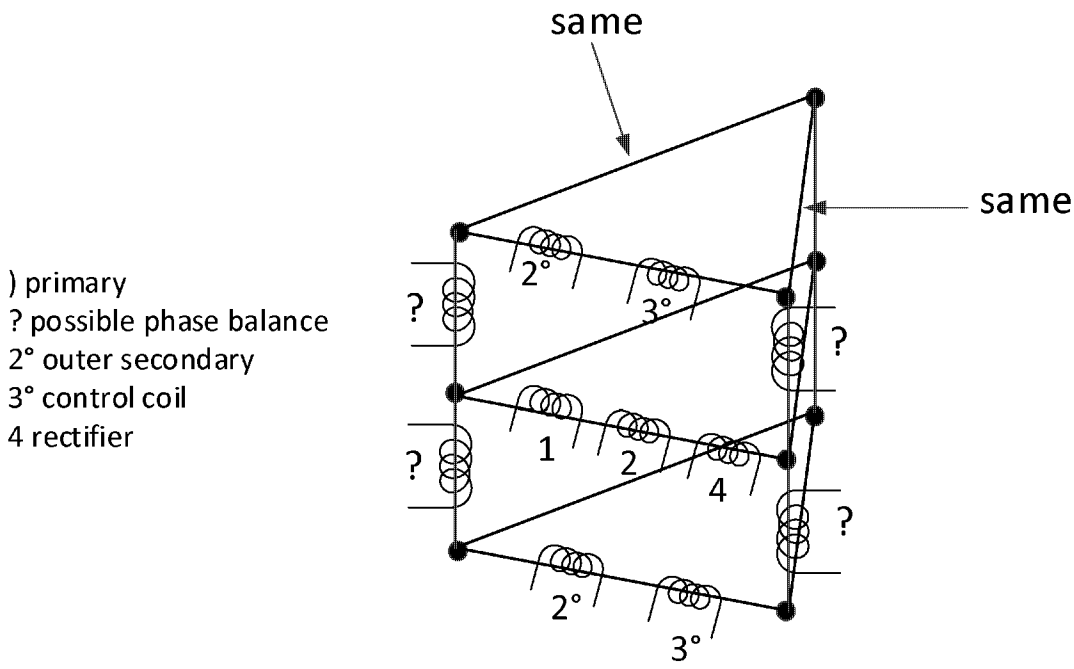


Figure 31

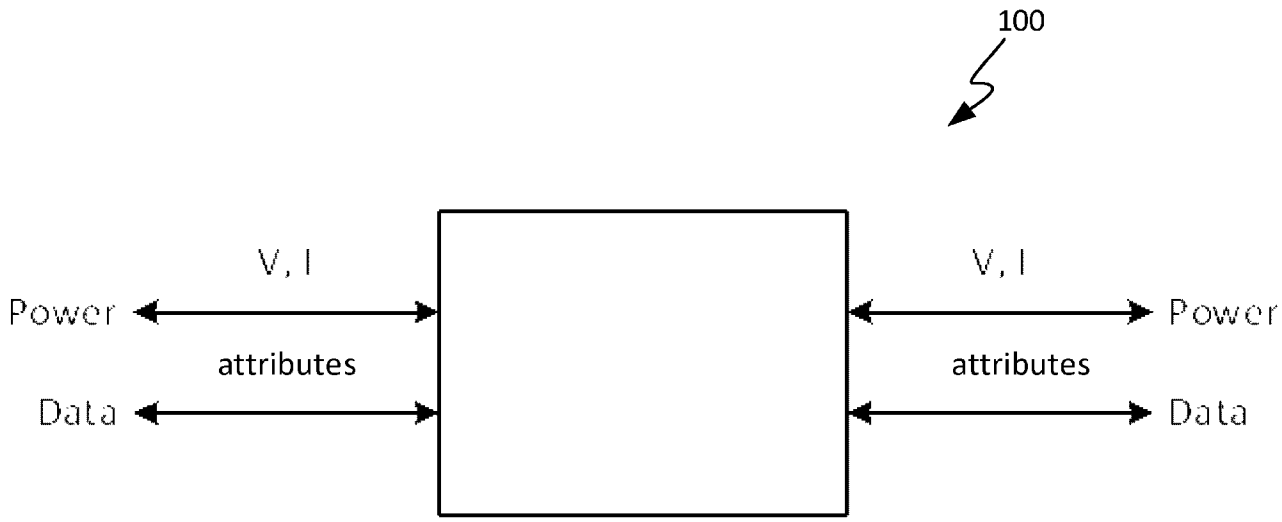


Figure 32

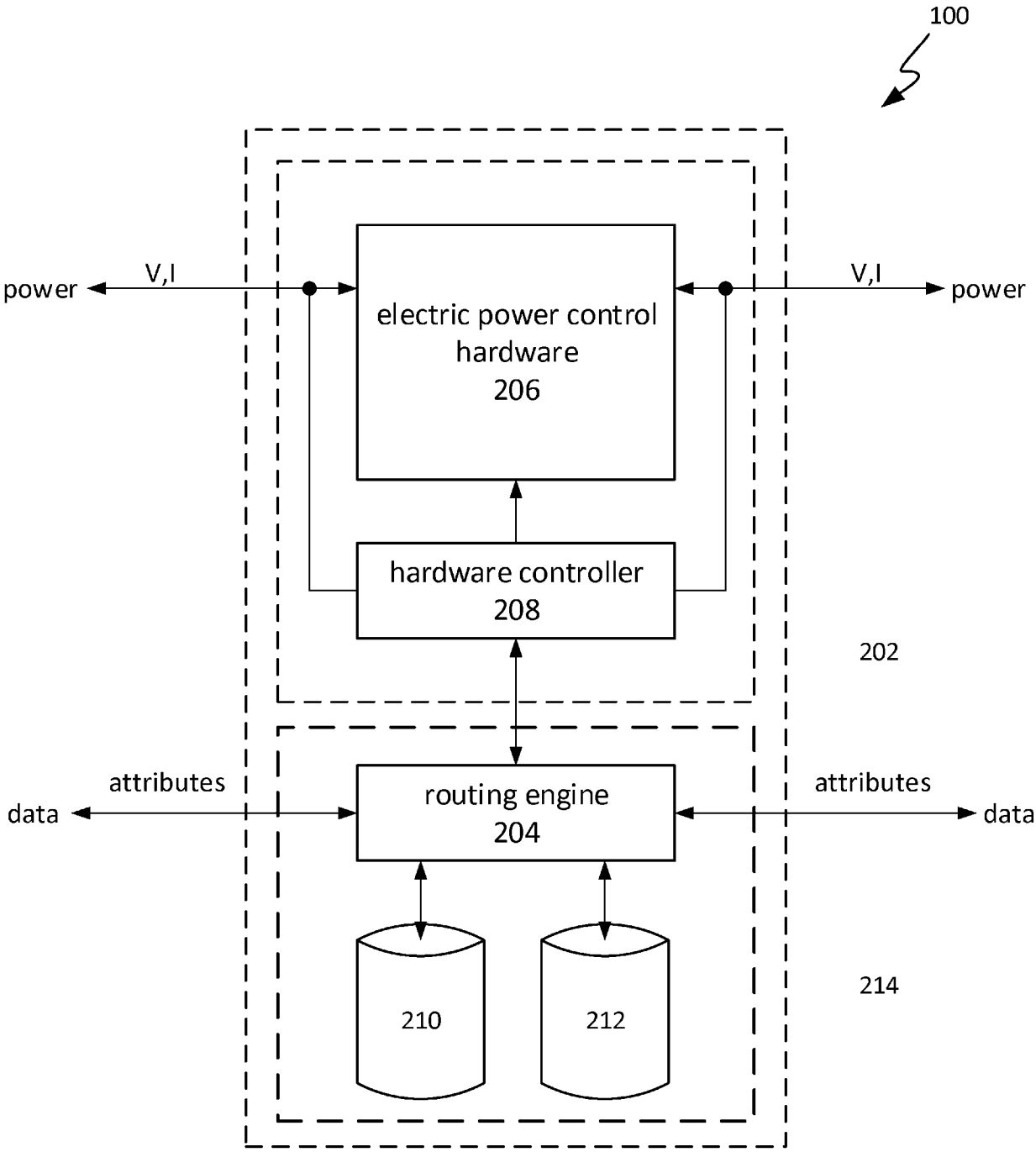

100
power
V,I
electric power control hardware 206
V,I
power
hardware controller 208
202
attributes
data
routing engine 204
attributes
data
210
212
214

Figure 33

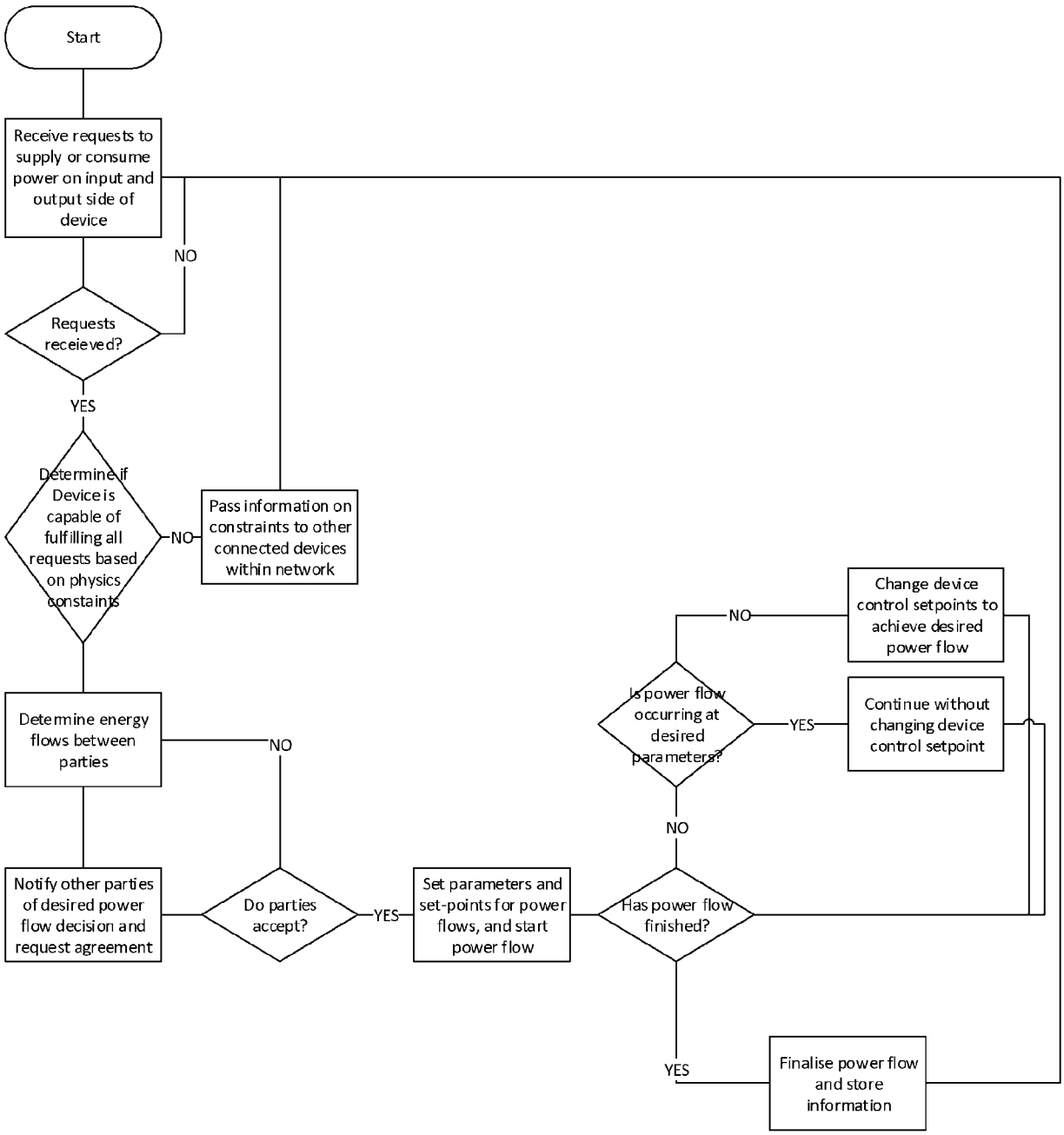

Start
Receive requests to supply or consume power on input and output side of device
NO
Requests receieved?
YES
Determine if Device is capable of fulfilling all requests based on physics constaints
NO
Pass information on constraints to other connected devices within network
Determine energy flows between parties
NO
Notify other parties of desired power flow decision and request agreement
Do parties accept?
YES
Set parameters and set-points for power flows, and start power flow
Has power flow finished?
NO
Is power flow occurring at desired parameters?
NO
Change device control setpoints to achieve desired power flow
YES
Continue without changing device control setpoint
YES
Finalise power flow and store information

Figure 34

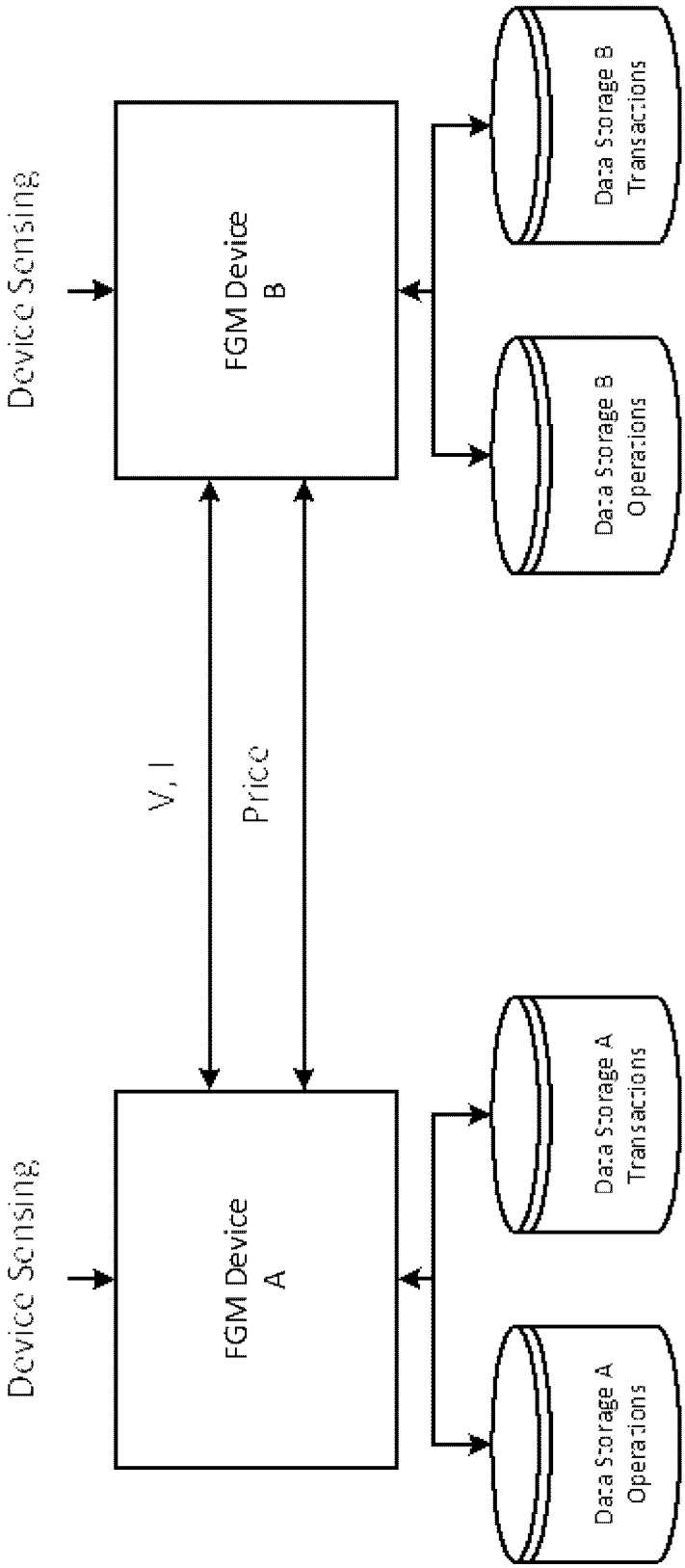

Device Sensing
FGM Device B
Data Storage B Transactions
Data Storage B Operations
V, I
Price
Device Sensing
FGM Device A
Data Storage A Transactions
Data Storage A Operations

Figure 35

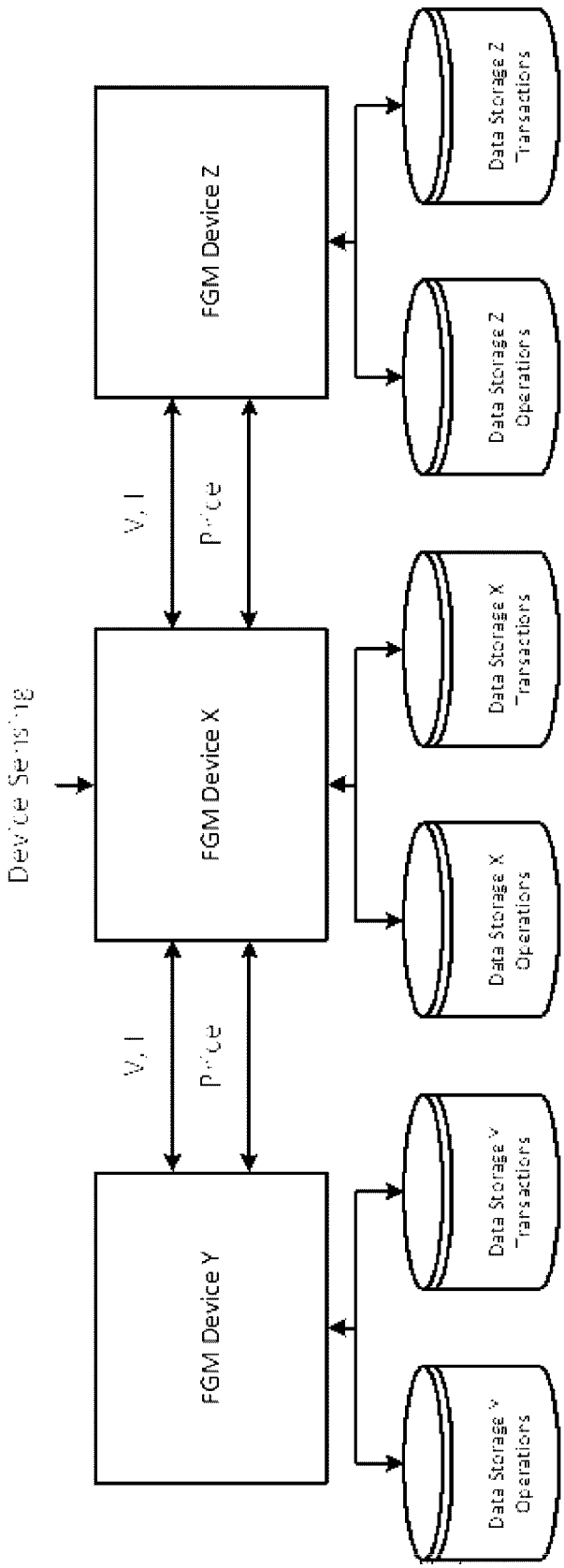

FGM Device Z
FGM Device X
FGM Device Y
Data Storage Z Transactions
Data Storage Z Operations
Data Storage X Transactions
Data Storage X Operations
Data Storage Y Transactions
Data Storage Y Operations

Figure 36

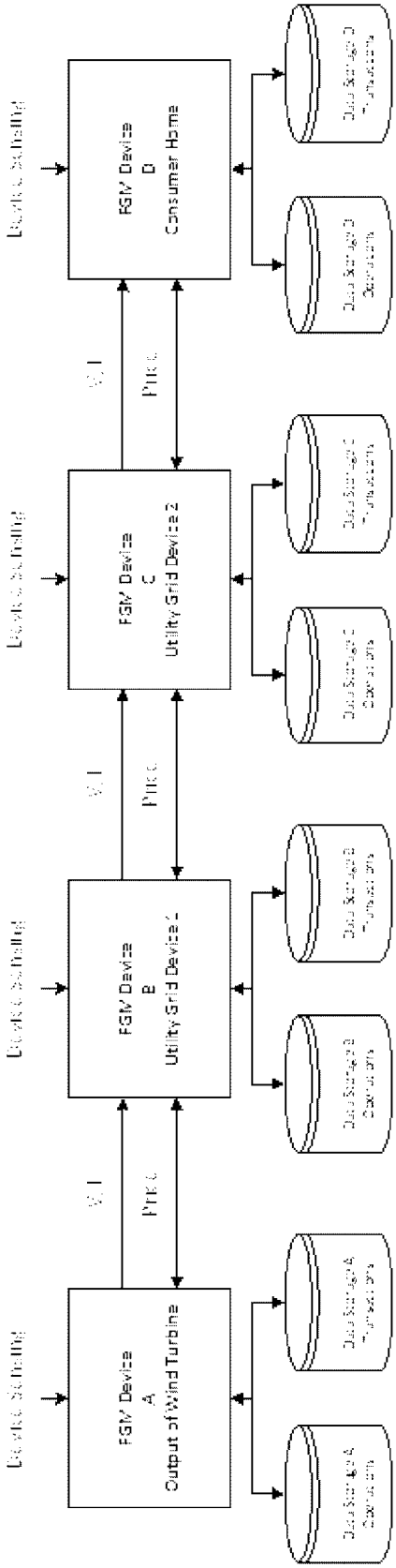

FGM Device
A
Output of Wind Turbine
FGM Device
B
Utility Grid Device 1
FGM Device
C
Utility Grid Device 2
FGM Device
D
Consumer Home

Figure 37

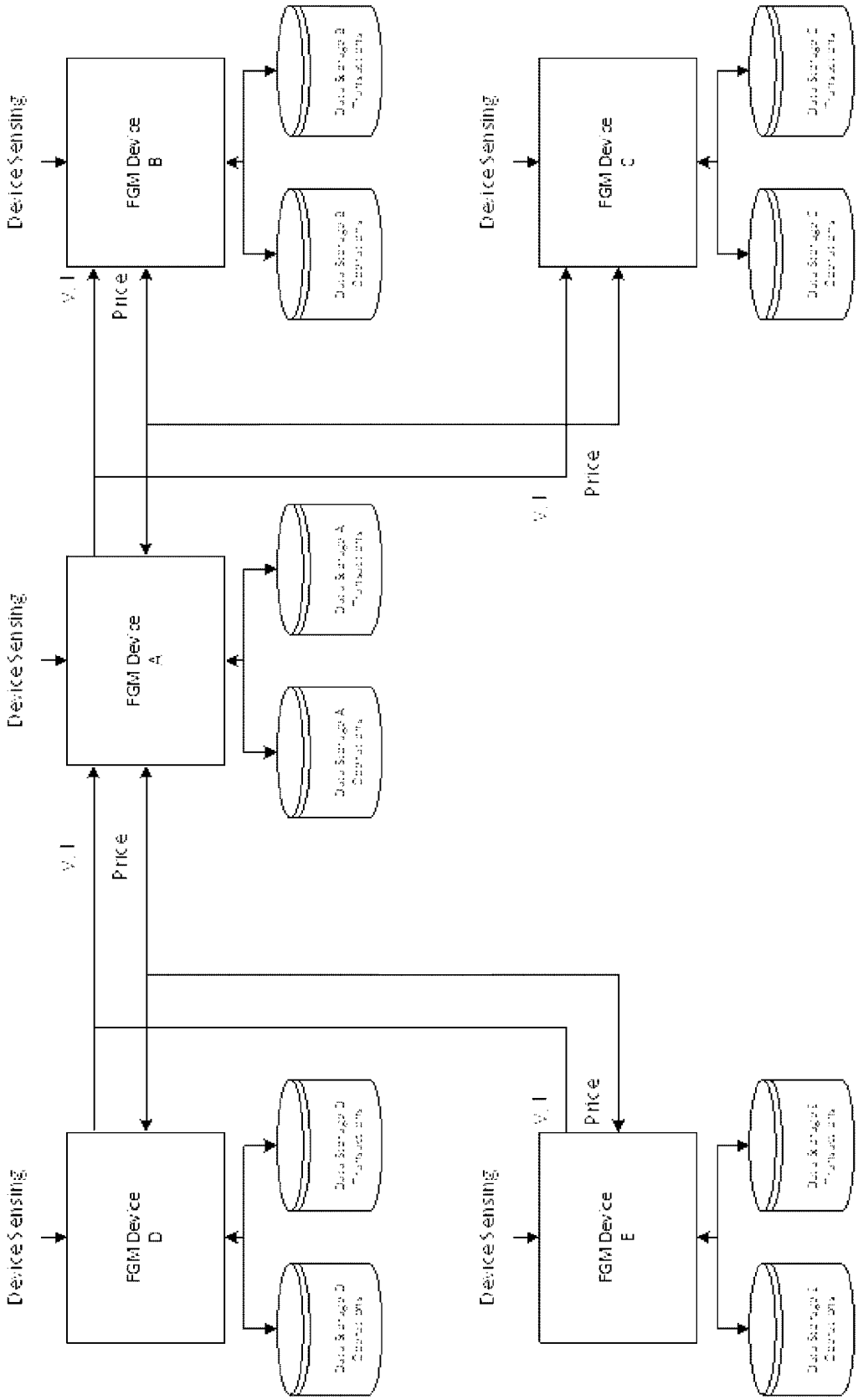

Device Sensing
FGM Device A
FGM Device B
FGM Device C
FGM Device D
FGM Device E
Price
V, I

Figure 38

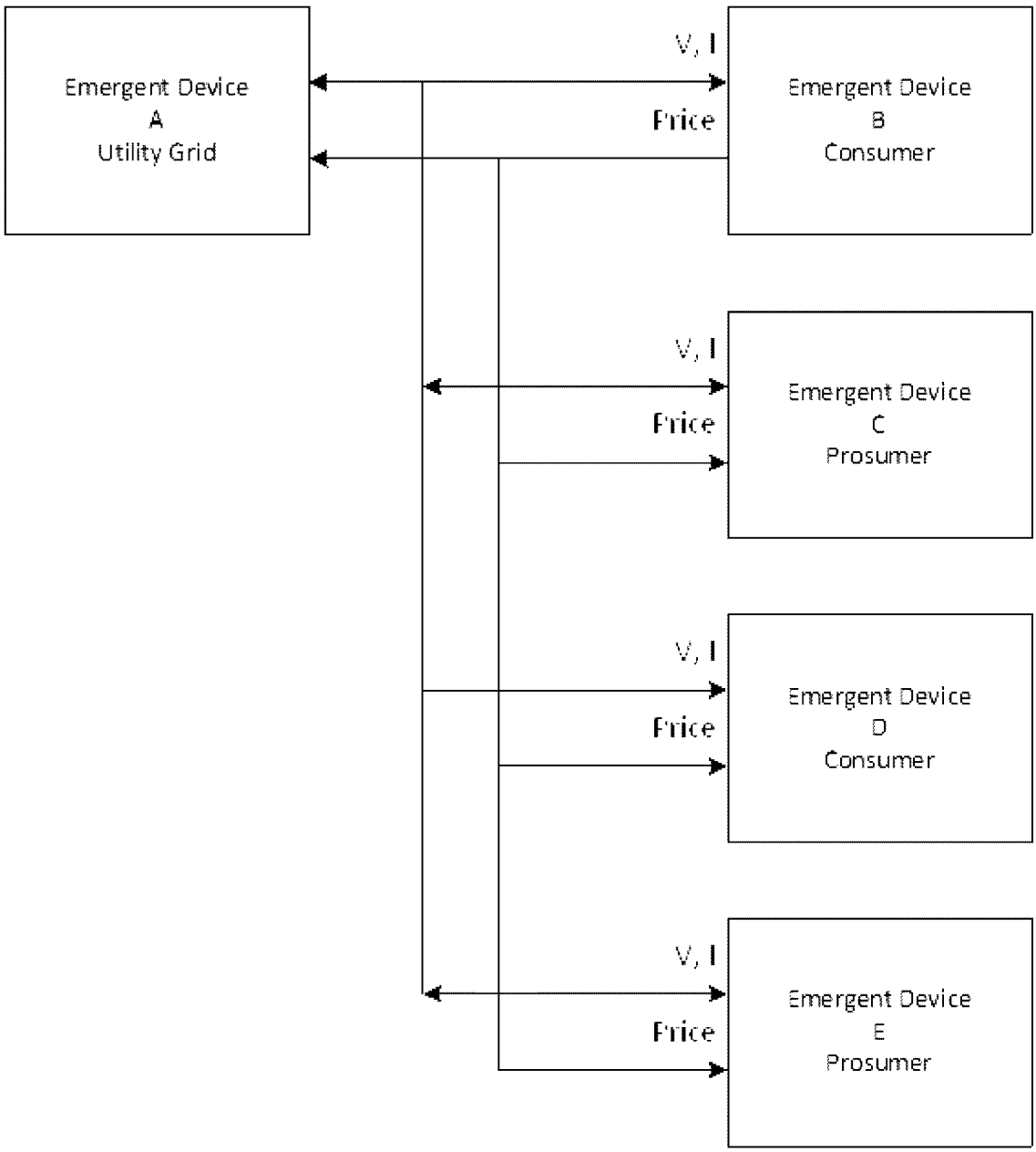

Emergent Device
A
Utility Grid
V, I
Price
Emergent Device
B
Consumer
V, I
Price
Emergent Device
C
Prosumer
V, I
Price
Emergent Device
D
Consumer
V, I
Price
Emergent Device
E
Prosumer

Figure 39

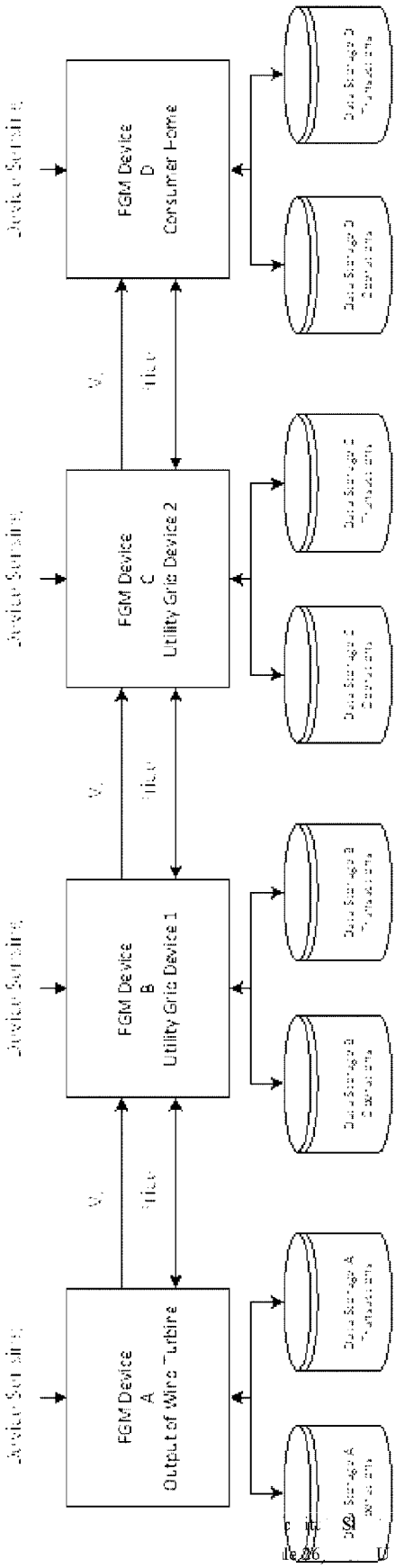

FGM Device
A
Output of Wind Turbine
FGM Device
B
Utility Grid Device 1
FGM Device
C
Utility Grid Device 2
FGM Device
D
Consumer Home

Figure 40

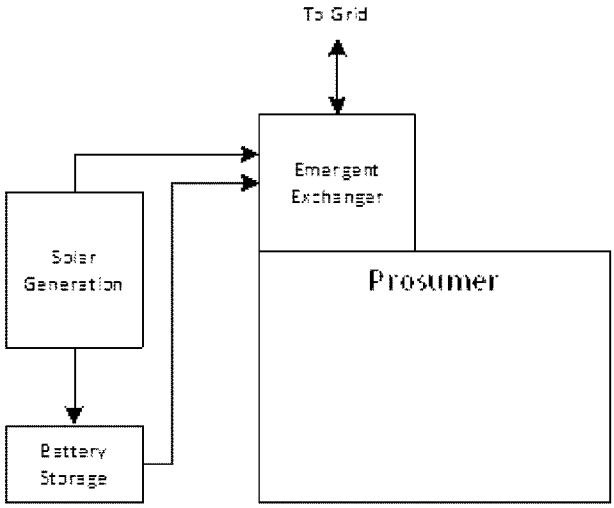


Figure 41

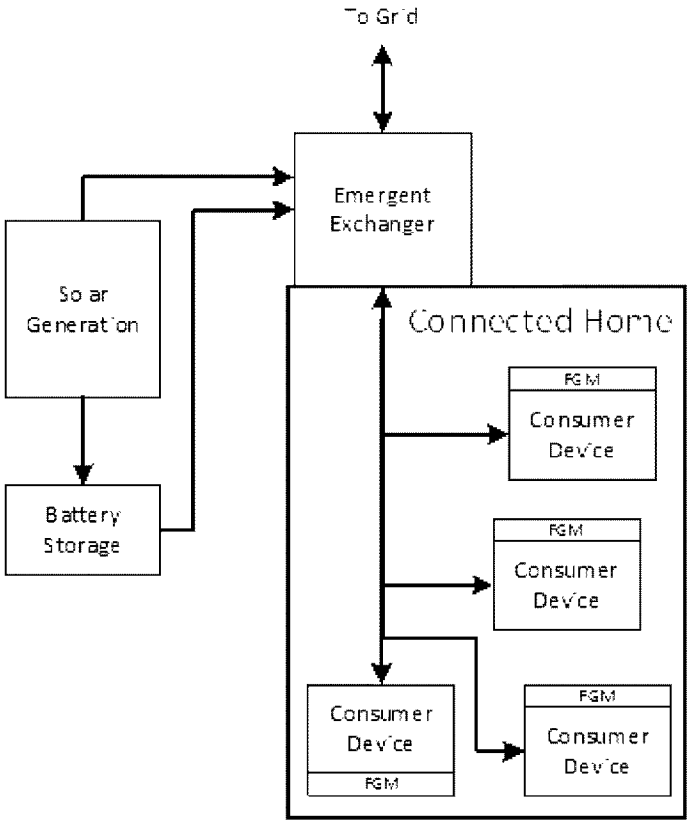


Figure 42

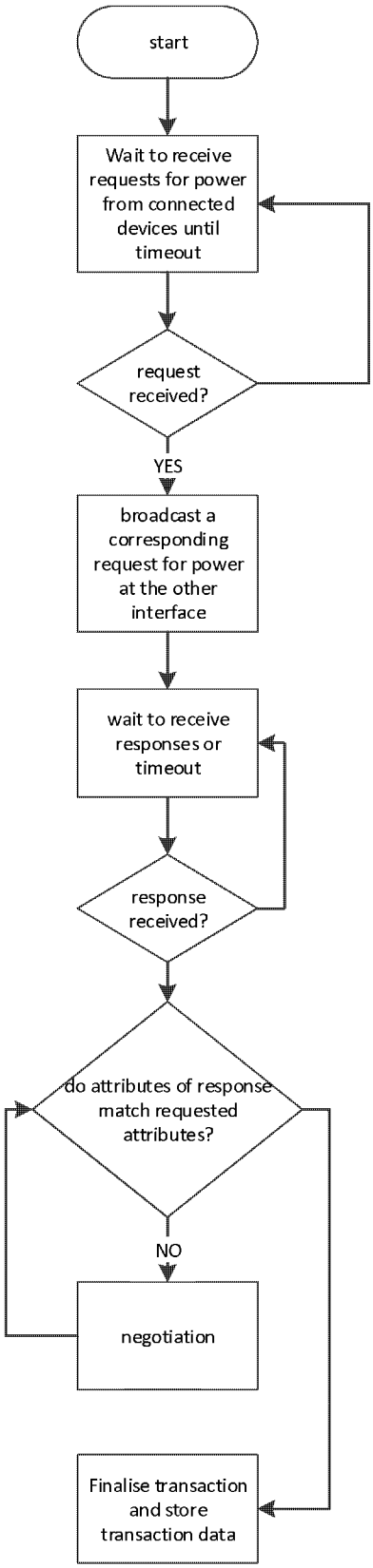

start
Wait to receive requests for power from connected devices until timeout
request received?
YES
broadcast a corresponding request for power at the other interface
wait to receive responses or timeout
response received?
do attributes of response match requested attributes?
NO
negotiation
Finalise transaction and store transaction data

Figure 43

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2019/051019

A. CLASSIFICATION OF SUBJECT MATTER

H02J 3/06 (2006.01) H02J 3/14 (2006.01) G05F 1/32 (2006.01) G05F 5/00 (2006.01) H02M 5/00 (2006.01) H02M 7/00 (2006.01)

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)

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)

PATENW (WPIAP, EPODOC, TXTE) IPC/CPC: H02J3/06, G05F1/32, H02M1/4208, G05F5/00, H02M7/527, H02M5/04, H02J3/16, G05F1/66, H02J3/28, H02M3/008, H02M1/42, H02M3/381, G05B15/02 & keywords: ELECTRIC POWER, DISTRIBUTION, CONTROLLER, CONVERTER, POWER FACTOR, MAGNETIC CORE, THREE LIMBS, PRIMARY, PRICE, UPSTREAM and similar terms and phrases.

GOOGLE keywords: ELECTRIC POWER, DISTRIBUTION, CONTROLLER, CONVERTER, INVERTER, VOLTAGE, POWER FACTOR, FREQUENCY, MAGNETIC CORE, THREE LIMBS, MAGNETIC AMPLIFIER, SATURABLE REACTOR, POWER FLOW, ACTIVE POWER TRANSFORMER, ATTRIBUTE, PRICE, RESIDENTIAL, HOUSEHOLD, DEMAND, SCHEDULING, RESPONSE, ROUTING ENGINE, UPSTREAM, DOWNSTREAM and similar terms and phrases.

Applicant(s)/Inventor(s) names searched in Esp@cenet, Auspat and internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"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	Date of mailing of the international search report
3 December 2019	03 December 2019

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INTERNATIONAL SEARCH REPORT C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		International application No. **PCT/AU2019/051019**
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2017/0149244 A1 (THE POWERWISE GROUP, INC.) 25 May 2017 Whole document, especially abstract, paragraphs [0034]-[0062], Figs. 1-13, claim 1 Whole document, especially abstract, paragraphs [0034]-[0062], Figs. 1-13, claim 1	1-7, 9-18 8
Y	US 2013/0021126 A1 (GAJEWSKI ET AL.) 24 January 2013 Whole document, especially abstract, paragraphs [0020]-[0030], Fig.2	8
Y	Marcus Aaron Young II: "Saturable Reactor for Power Flow Control in Electric Transmission Systems: Modeling and System Impact Study", PhD dissertation, University of Tennessee, 2015, p.i-183. Available on: https://trace.tennessee.edu/cgi/viewcontent.cgi?article=4566&context=utk_graddiss Downloaded on 29.11.2019. Whole document, especially abstract, chapters I, II, Figs. 10, 15, 39, 54	8
X	HUSSAIN SHAREEF et al: "Review on Home Energy Management System Considering Demand Responses, Smart Technologies, and Intelligent Controllers", IEEE Access, SPECIAL SECTION ON ENERGY MANAGEMENT IN BUILDINGS, 30 April 2018, p. 24498-24509. Whole document, especially abstract, sections I-IV, Figs.1, 2	1-7, 9-18
X	US 2012/0063334 A1 (DRAKE) 15 March 2012 Whole document, especially abstract, paragraphs [0013]-[0031], Fig.1.	1-7, 9-18
X	US 2003/0233201 A1 (HORST ET AL.) 18 December 2003 Whole document ,especially abstract.	1-7, 9-18
X	US 8670875 B2 (LO ET AL.) 11 March 2014 Whole document, especially abstract.	1-7, 9-18
X	US 2016/0079752 A1 (STEFAN MATAN ET AL.) 17 March 2016 Whole document, especially abstract	1-7, 9-18
Y	US 9261890 B2 (DIMITROVSKI) 16 February 2016 Whole document, especially abstract, Figs. 1, 2, 7,	8

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2019/051019**

This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document/s Cited in Search Report		**Patent Family Member/s**	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
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		US 10326272 B2	18 Jun 2019
		AU 2016359188 A1	14 Jun 2018
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		NO 20110868 A1	17 Dec 2012
		NO 332845 B1	21 Jan 2013
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Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2019/051019**

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		US 2019074694 A1	07 Mar 2019
		US 2019267804 A1	29 Aug 2019

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INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2019/051019**

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Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	**Publication Date**	**Publication Number**	**Publication Date**
		WO 2016004432 A1	07 Jan 2016
		WO 2016004433 A1	07 Jan 2016
US 9261890 B2	16 February 2016	US 2013320940 A1	05 Dec 2013
		US 9261890 B2	16 Feb 2016
		WO 2012128882 A2	27 Sep 2012

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.