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(54) CONTROL OF SMALL DISTRIBUTED ENERGY RESOURCES

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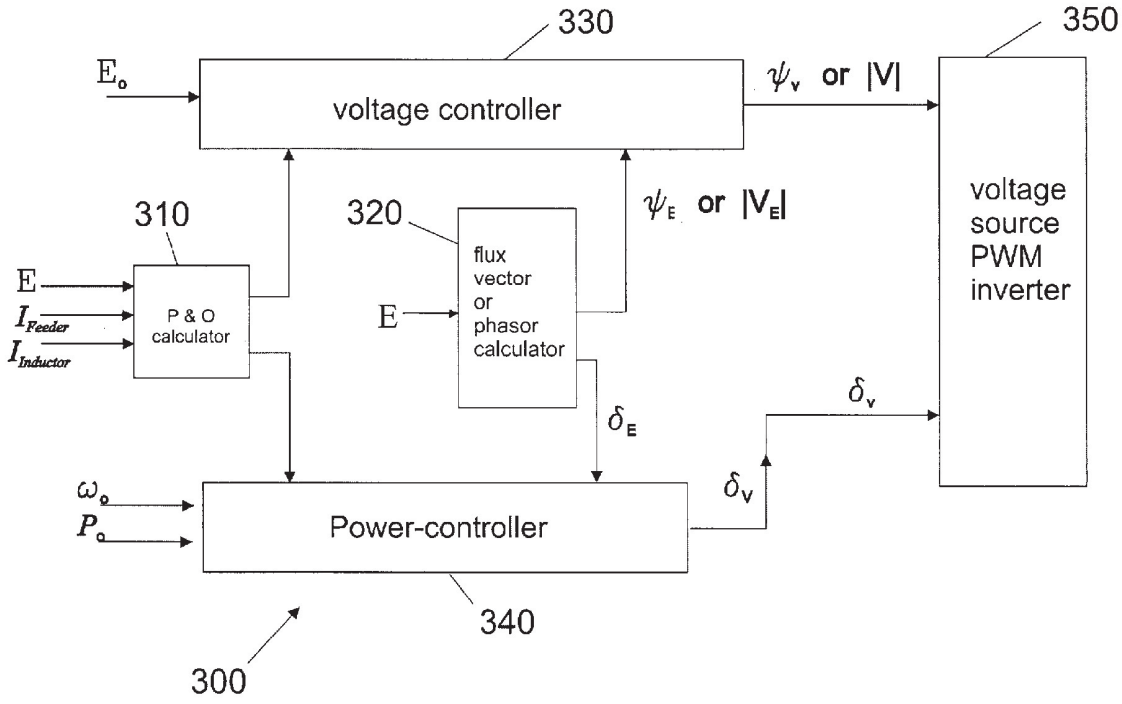
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(57) ABSTRACT

A power electronics interface in a microsource controller allows efficient connection in a power system of small, low cost and reliable distributed generators such as microturbines, fuel cells and photovoltaic. Power electronics provide the control and flexibility to insure stable operation for large numbers of distributed generators. The power electronics controls are designed to insure that new generators can be added to the system without modification of existing equipment. A collection of sources and loads can connect to or isolate from the utility grid in a rapid and seamless fashion, each inverter can respond effectively to load changes without requiring data from other sources, and voltage sag and system imbalances can be corrected.



GENERAC 1020

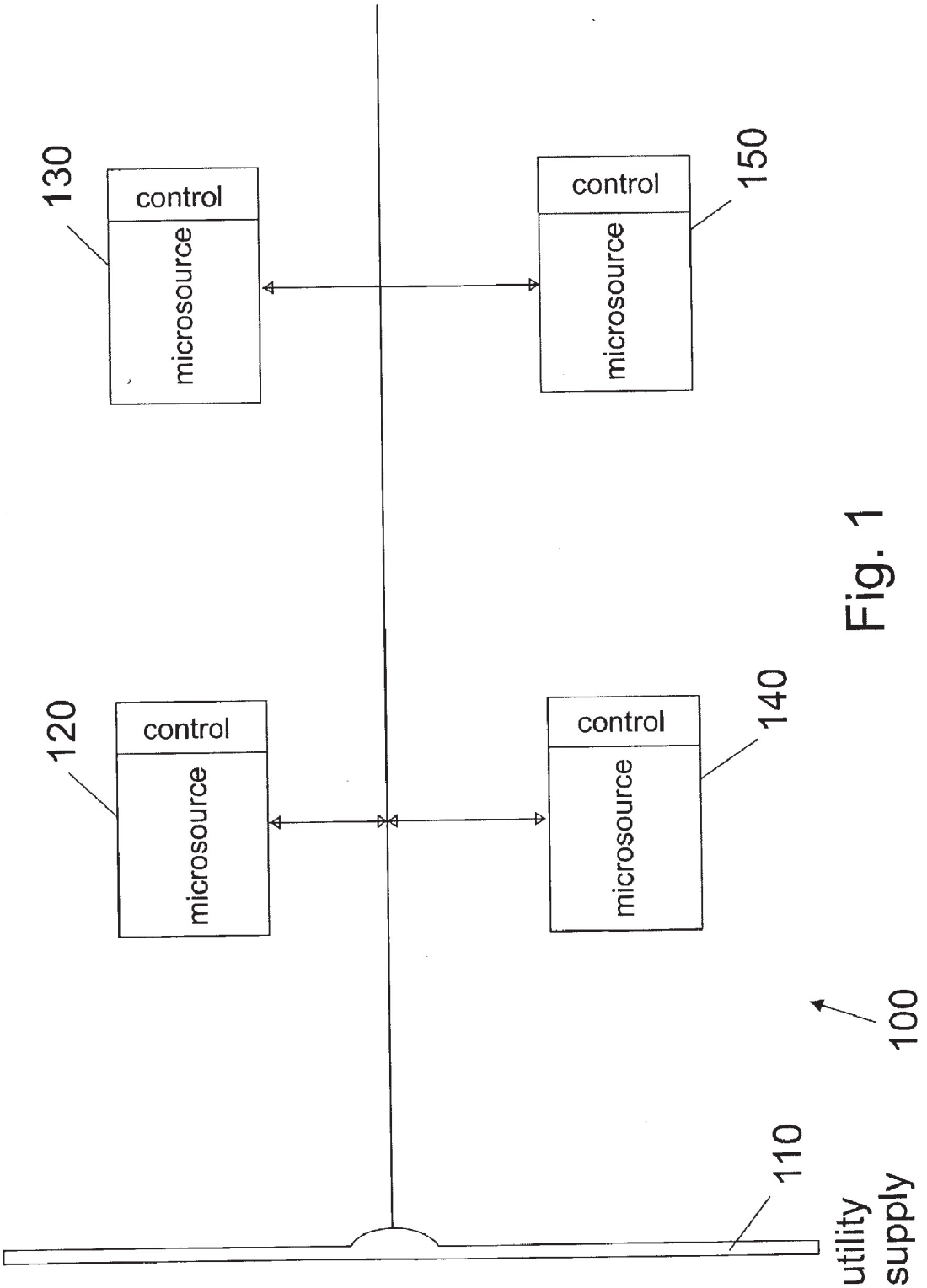

130
control
microsource
150
control
microsource
120
control
microsource
140
control
microsource
100
110
utility
supply

Fig. 1

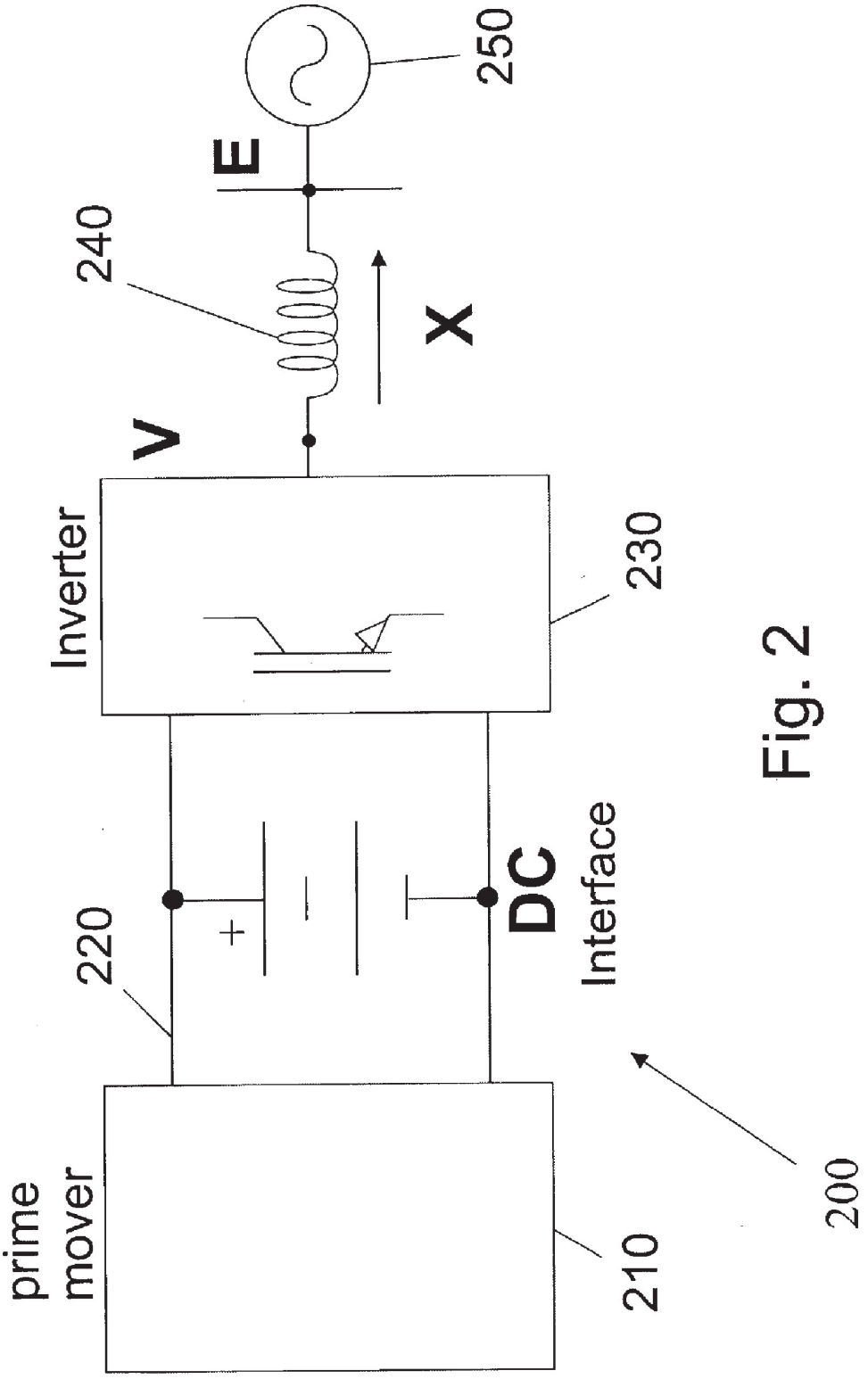

250
E
240
X
V
Inverter
230
220
DC
Interface
prime
mover
210
200

Fig. 2

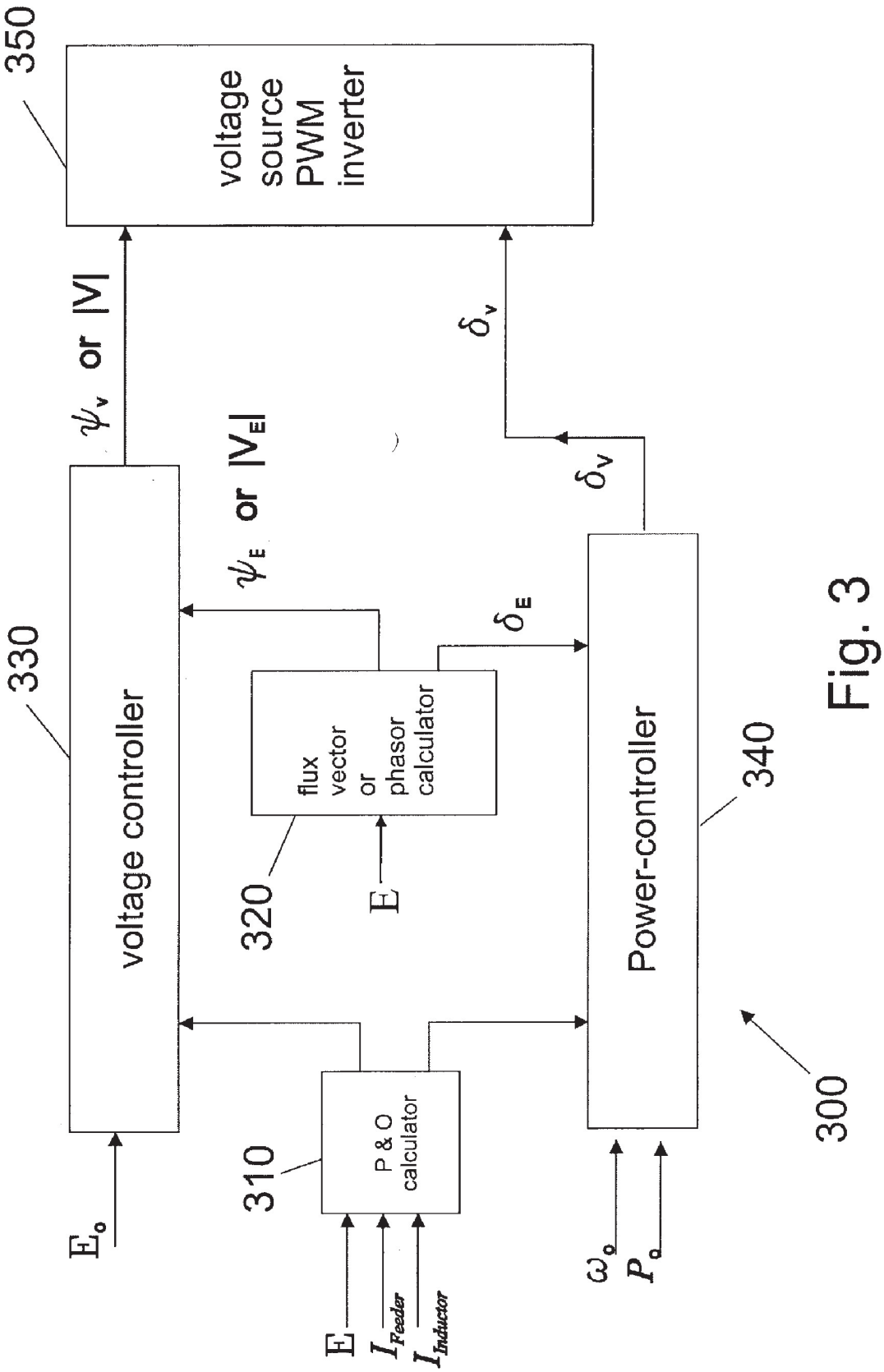

350
voltage source PWM inverter
330
voltage controller
320
flux vector or phasor calculator
310
P & O calculator
340
Power-controller
300
ψ_v or |V|
ψ_E or |V_E|
δ_v
δ_E
E_o
E
I_{Feeder}
$I_{Inductor}$
ω_o
P_o

Fig. 3

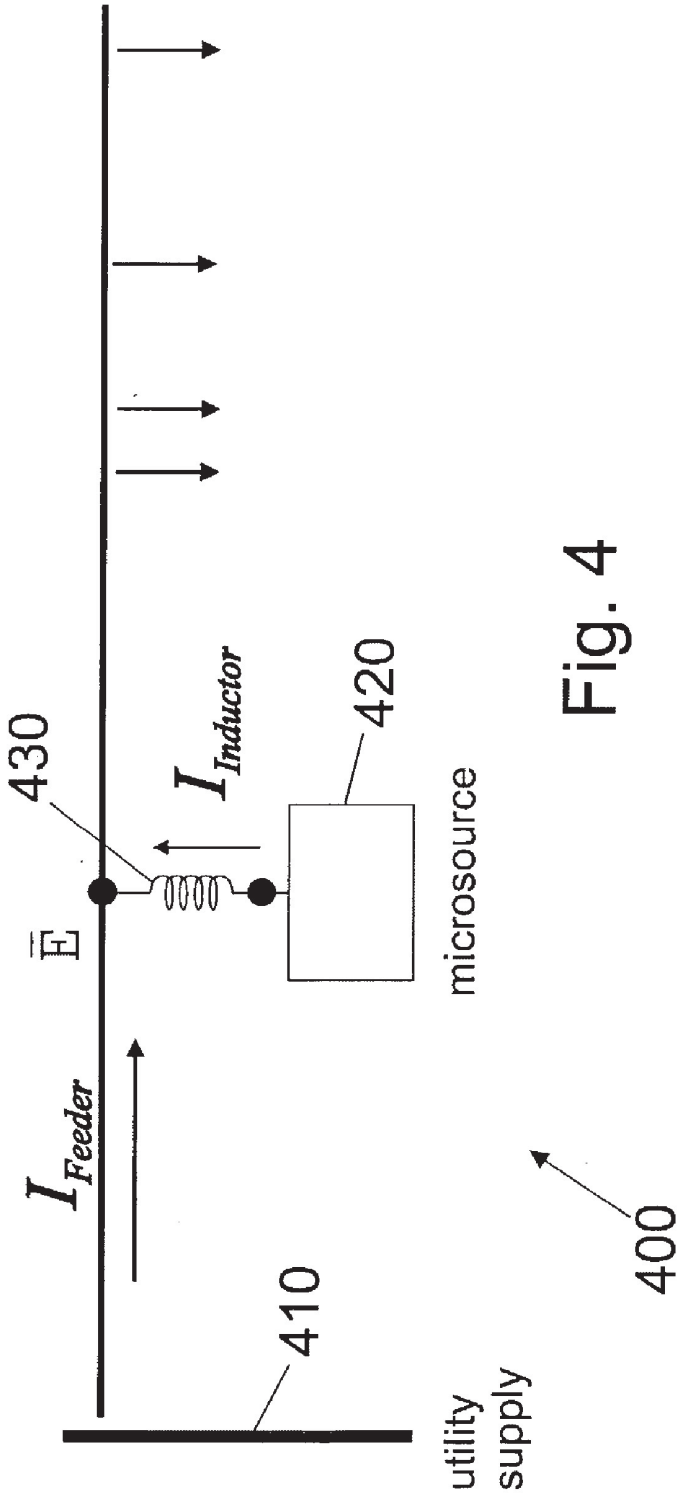

430
$I_{Inductor}$
420
microsource
$\overline{E}$
I_{Feeder}
410
utility
supply
400

Fig. 4

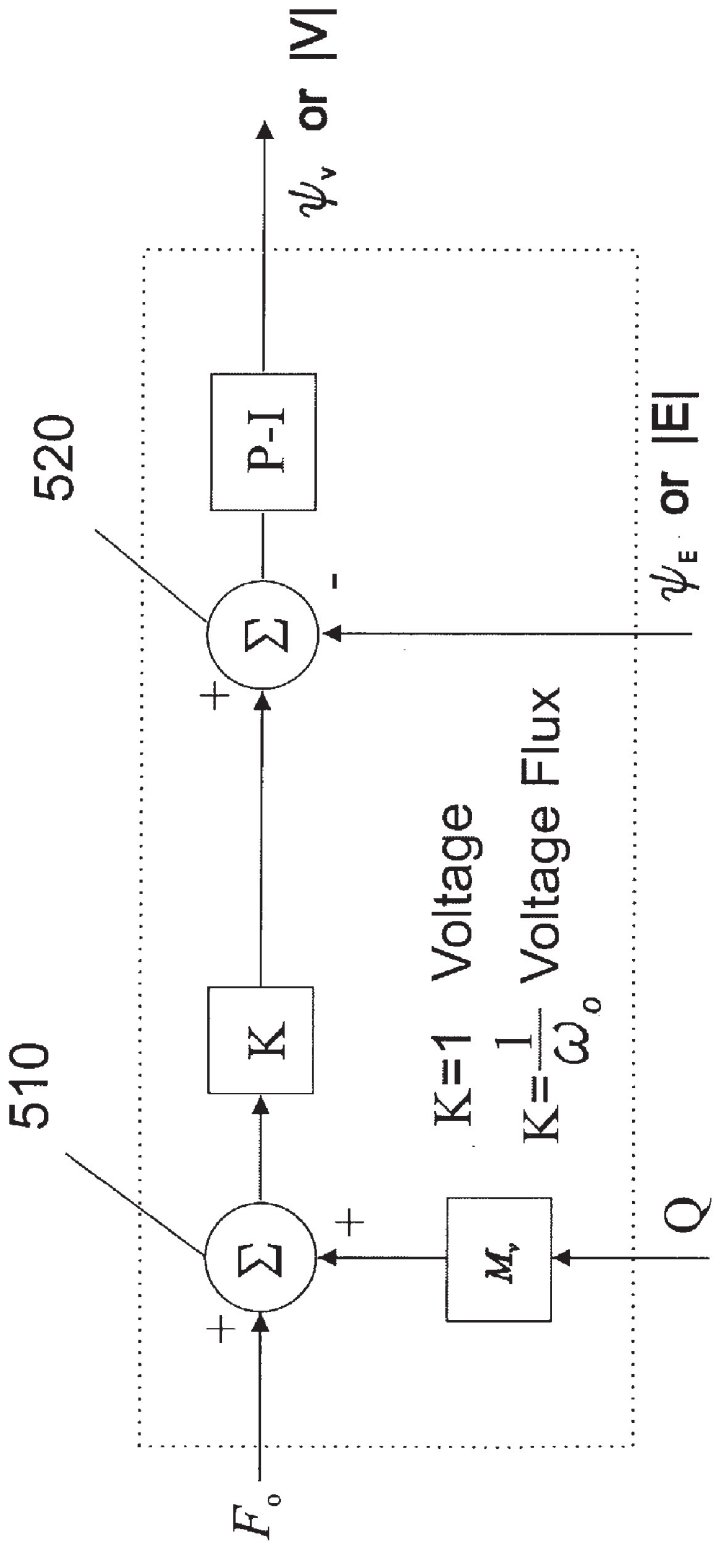

ψ_v or |V|
520
P-I
Σ
-
+
ψ_E or |E|
K
K=1 Voltage
K=$\frac{1}{\omega_o}$ Voltage Flux
510
Σ
+
+
M_v
Q
500
F_o

Fig. 5

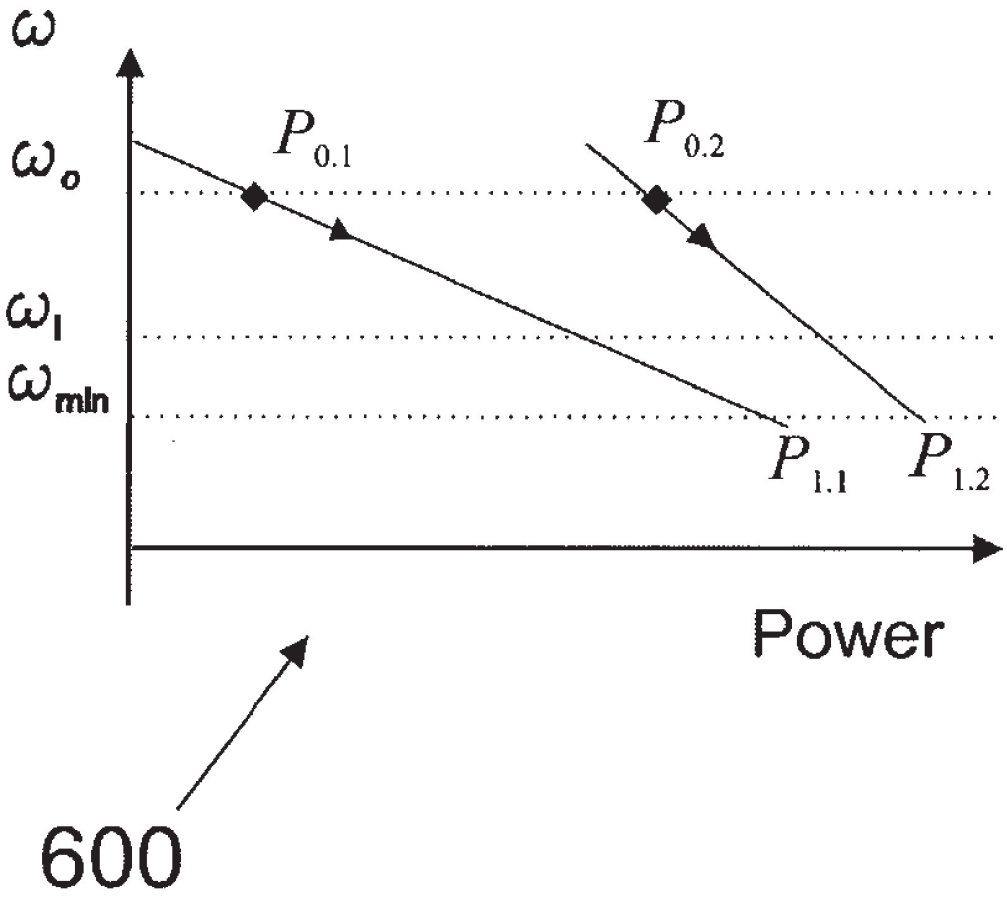


Fig. 6

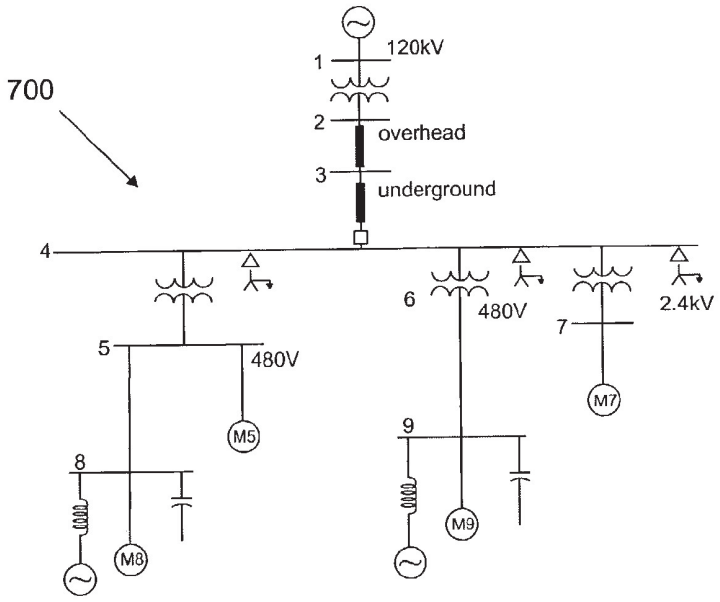

700
1
120kV
2
overhead
3
underground
4
5
480V
M5
6
480V
7
2.4kV
M7
8
M8
9
M9

Fig. 7

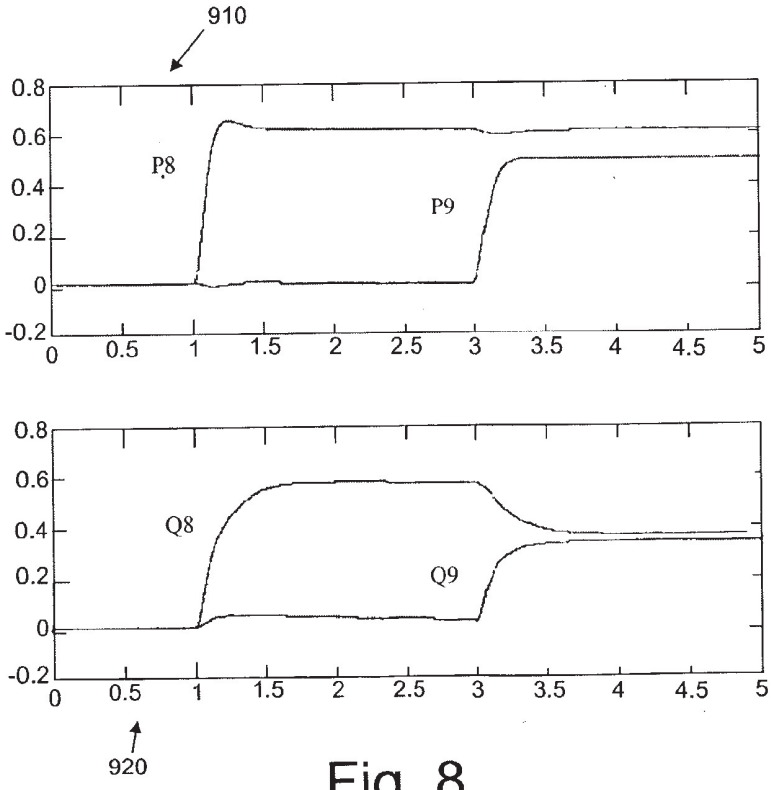

910
P8
P9
Q8
Q9
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
920

Fig. 8

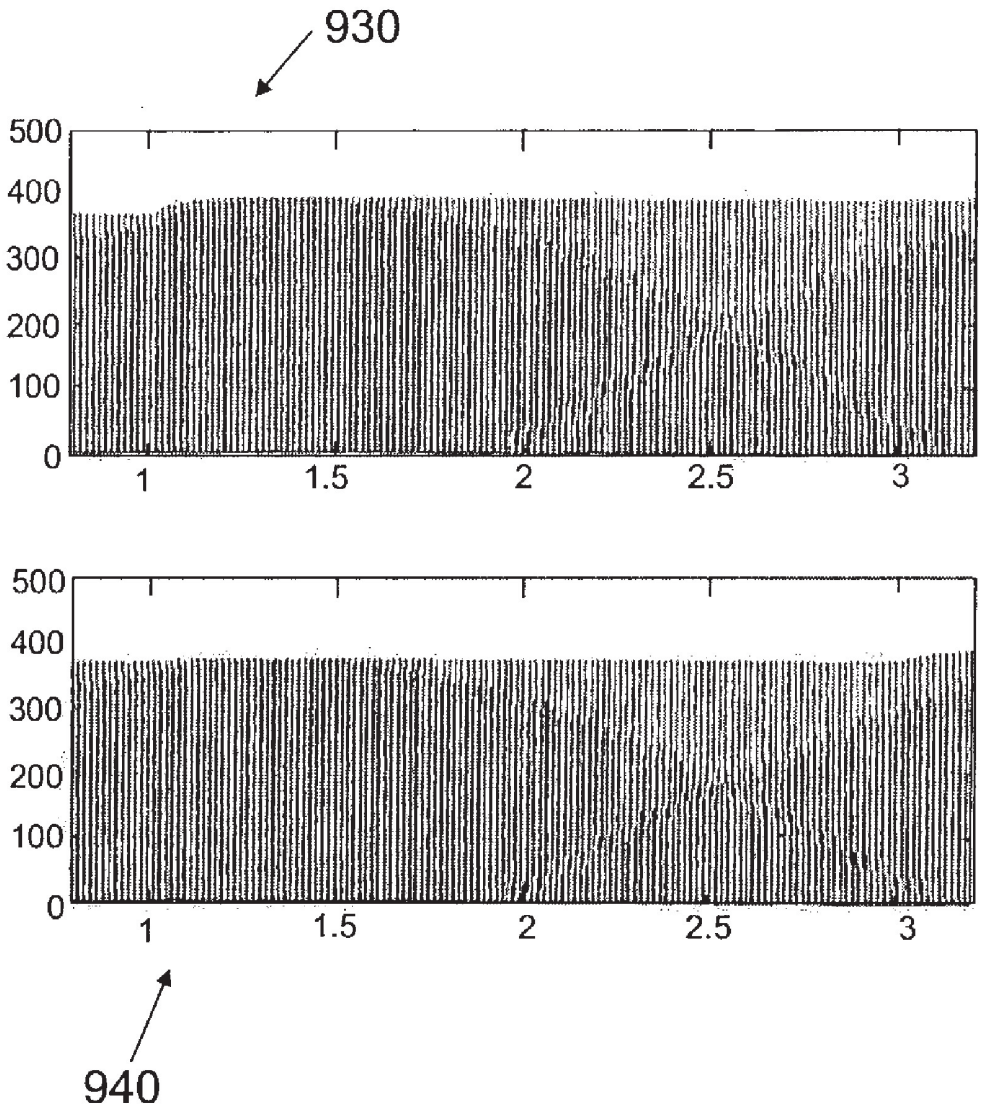

930
500
400
300
200
100
0
1
1.5
2
2.5
3
500
400
300
200
100
0
1
1.5
2
2.5
3
940

Fig. 9

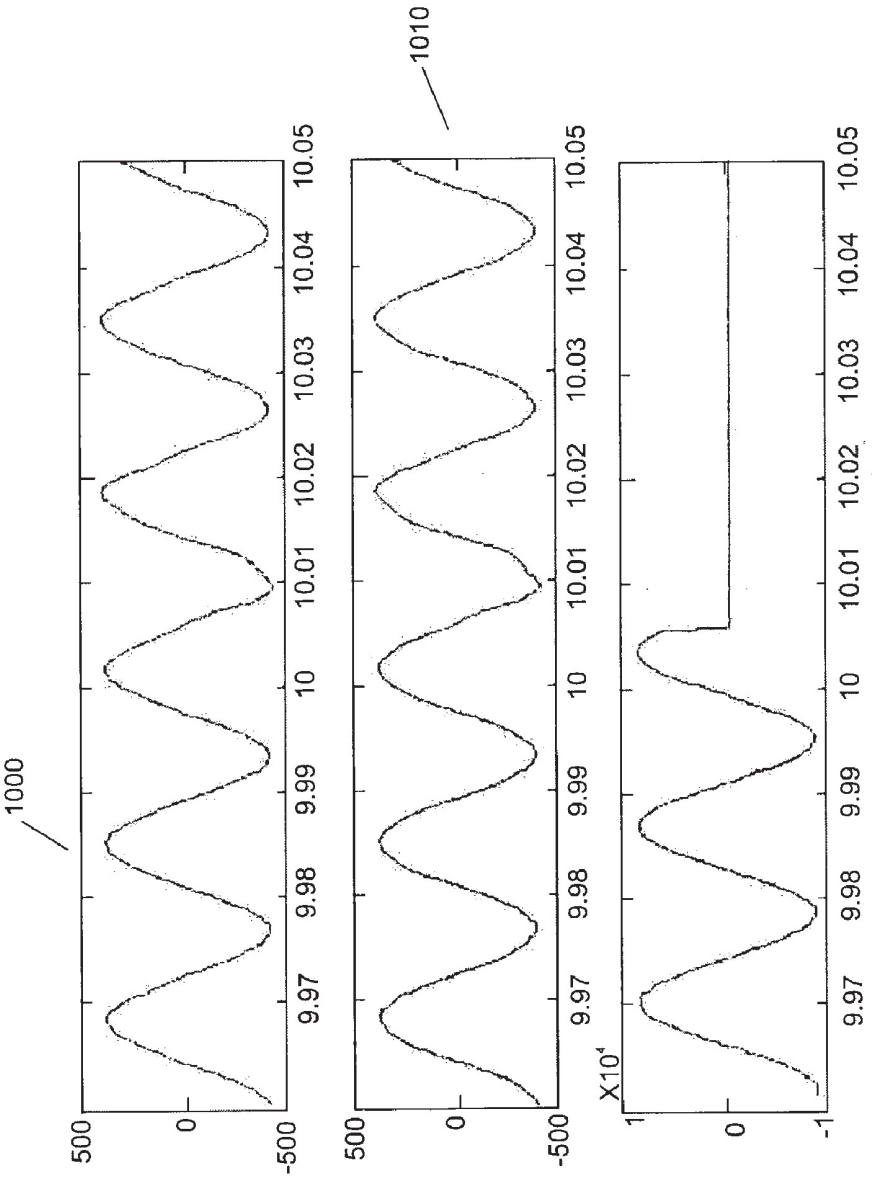

1000
1010
1020
500
0
-500
9.97
9.98
9.99
10
10.01
10.02
10.03
10.04
10.05
X10^4
1
0
-1

Fig. 10

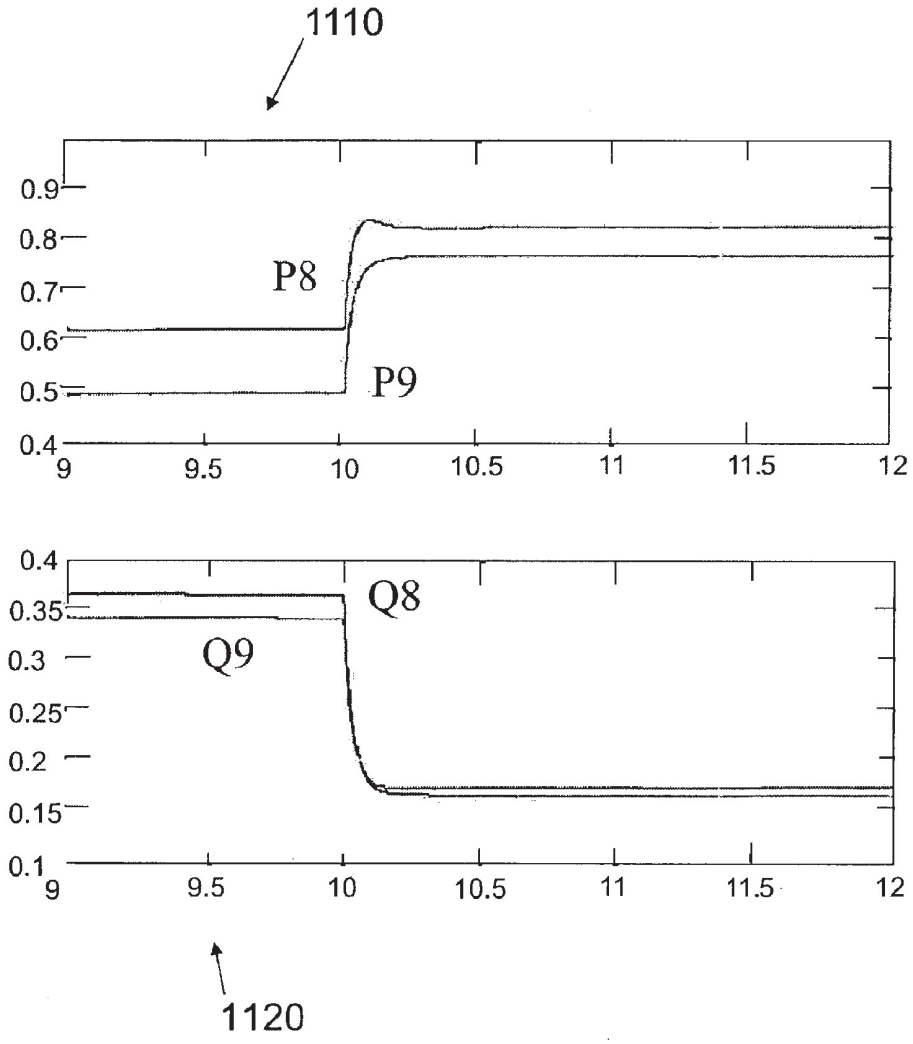

1110
0.9
0.8
0.7
0.6
0.5
0.4
P8
P9
9
9.5
10
10.5
11
11.5
12
0.4
0.35
0.3
0.25
0.2
0.15
0.1
Q8
Q9
9
9.5
10
10.5
11
11.5
12
1120

Fig. 11

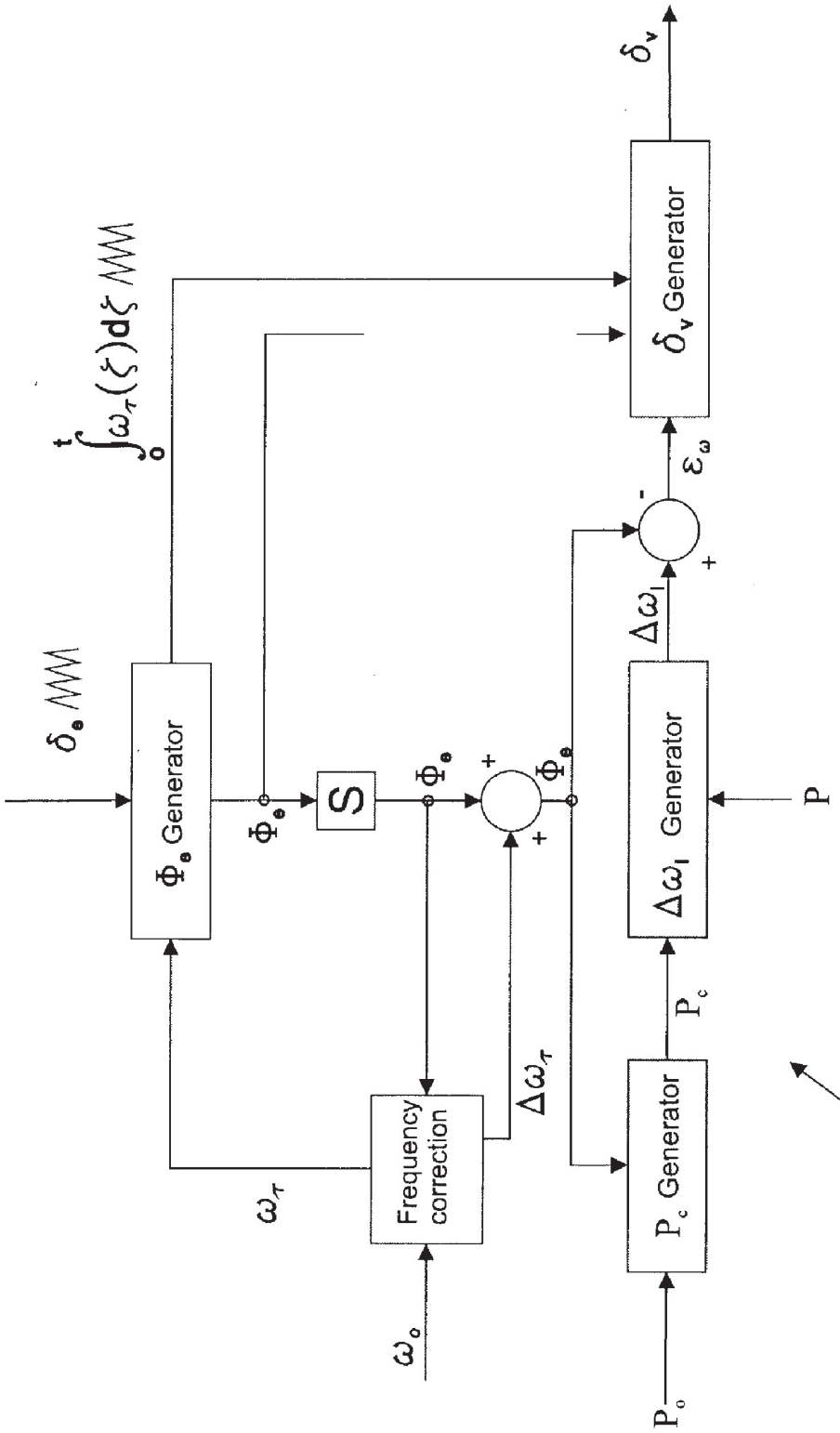

δ_v
δ_v Generator
$\int_0^t \omega_\tau(\zeta)d\zeta$
ε_ω
δ_e
Φ_e Generator
$\Delta\omega_l$
Φ_e
S
Φ_e
Φ_e
$\Delta\omega_l$ Generator
P
$\Delta\omega_\tau$
P_c
ω_τ
Frequency correction
P_c Generator
ω_o
P_o
1200

Fig. 12

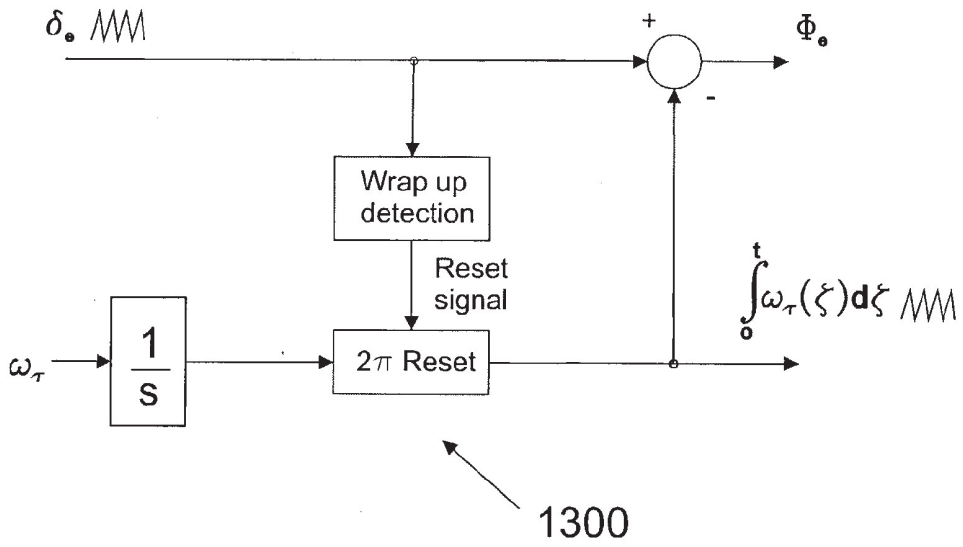

δe
+
Φe
-
Wrap up detection
Reset signal
∫0t ωr(ζ)dζ
ωr
1/s
2π Reset
1300

Fig. 13

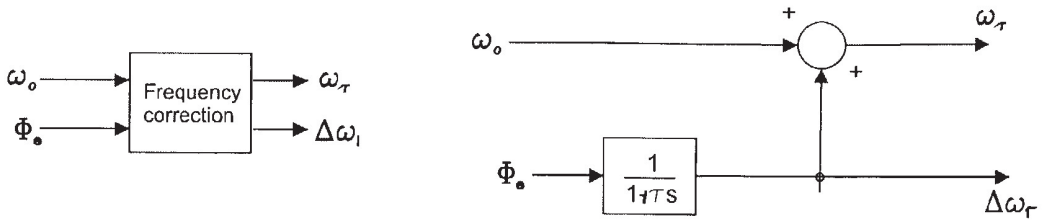

ωo
Φe
Frequency correction
ωr
Δωl
ωo
+
ωr
+
Φe
1/(1+τs)
Δωr

Fig. 14

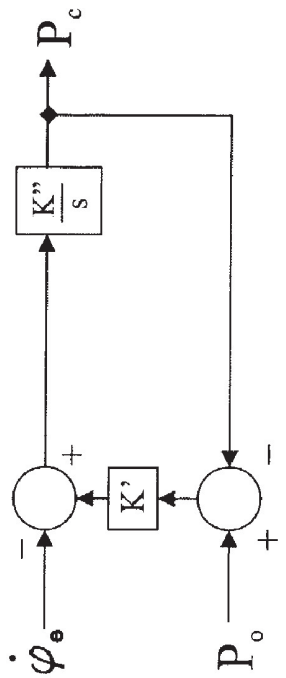
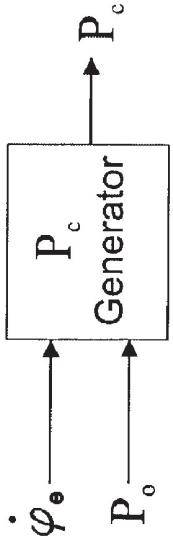

P_c
K''/s
K'
+
−
−
+
φ̇_e
P_o

Fig. 15


P_c
P_c Generator
φ̇_e
P_o

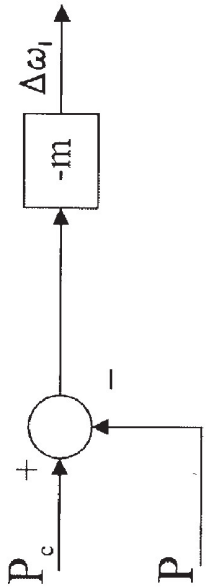
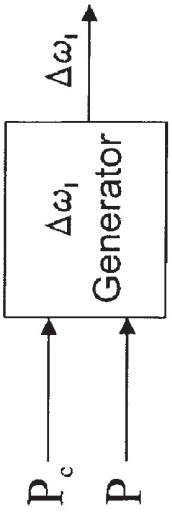

Δω_I
-m
−
+
P_c
P

Fig. 16


Δω_I
Δω_I Generator
P_c
P

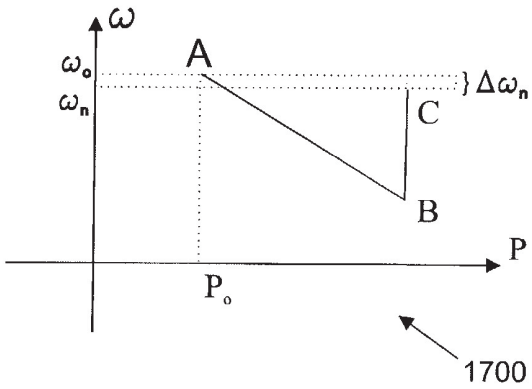


Fig. 17

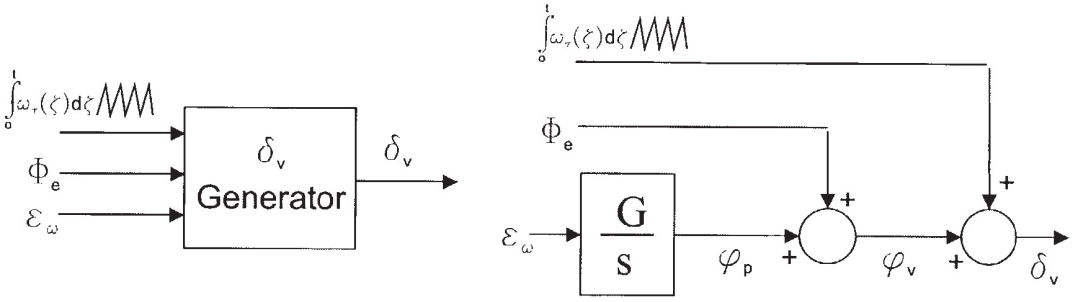


Fig. 18

CONTROL OF SMALL DISTRIBUTED ENERGY RESOURCES

STATEMENT REGARDING GOVERNMENT RIGHTS

[0001] This invention was made with United States government support awarded by the following agencies:

[0002] DOE DE-AC36-99-G010337

[0003] NSF EEC-0119230

[0004] The United States government has certain rights in this invention.

FIELD OF THE INVENTION

[0005] The present invention relates generally to power systems, including distributed energy resources (DER) systems and methods. More particularly, the present invention relates to control of small distributed energy resources.

BACKGROUND OF THE INVENTION

[0006] Construction of new large power generating plants has not kept pace with growing electricity demand. For example, in the western and northeastern regions of the United States, electricity demand has outpaced supply from power generating plants. At the same time, customer demand for even more highly reliable power is growing across the nation. Even if a sufficient number of new generating plants were built, the country's aging transmission and distribution systems are unlikely to reliably deliver the increased power supply that is needed. Moreover, the cost of the upgrades required to enable today's power system to deliver the level of reliability being demanded is far in excess of what society has so far been willing to bear.

[0007] In this context, distributed energy resources (DER), small power generators typically located at customers sites where the energy they generate is used, have emerged as a promising option to meet customers current and future demands for increasingly more reliable electric power. DER can include electricity generators, energy storage, load control, and, for certain classes of systems, advanced power electronic interfaces between the generators and the distribution grid.

[0008] DER systems range in size and capacity from a few kilowatts up to 50 MW. They comprise a variety of technologies, both supply-side and demand-side, that can be located at or near the location where the energy is used.

[0009] DER devices can provide opportunities for greater local control of electricity delivery and consumption. They also enable more efficient utilization of waste heat in combined heat and power (CHP) applications boosting efficiency and lowering emissions. CHP systems can provide electricity, hot water, heat for industrial processes, space heating and cooling, refrigeration, and humidity control to improve indoor air quality and comfort.

[0010] Current trends in DER are toward small technologies. One DER technology is small gas-fired microturbines in the 25-100 kW range, which many expect can be mass produced at low cost. These devices—which are high-speed (50,000-100,000 rpm) turbines with air foil bearings—are designed to combine the reliability of on-board commercial aircraft generators with the low cost of automotive turbochargers. Microturbines rely on power electronics to interface with loads. Example products include: Allison Engine Company's 50-kW generator, Capstone's 30-kW and 60-kW systems, and Honeywell's 75-kW Turbogenerator.

[0011] Fuel cells are also well suited for distributed generation applications. They offer high efficiency and low emissions but are currently expensive. Phosphoric acid cells are commercially available in the 200 kW range, and solid-oxide and molten-carbonate cells have been demonstrated. A major development effort by automotive companies has focused on the possibility of using gasoline as a fuel for polymer electrolyte membrane (PEM) fuel cells. In 1997, Ballard Generation Systems formed a strategic alliance with Daimler-Benz and Ford to develop new vehicle engines using Ballard's PEM fuel cell. Fuel cell costs for these engines are expected to be $200 per kW. Fuel cell engine designs are attractive because they promise high efficiency without the significant polluting emissions associated with internal combustion engines. Many other major international companies are investing in fuel cells, including General Motors, Chrysler, Honda, Nissan, Volkswagen, Volvo, and Matsushita Electric.

[0012] Microturbines and fuel cells are a major improvement over conventional combustion engines in their emissions of ozone, particulate matter less 10 μm in diameter (PM-10), nitrogen oxide (NOx), and carbon monoxide (CO). The primary fuel for microsources is natural gas, which has few particulates and less carbon than most traditional fuels for combustion engines.

[0013] Microsources that effectively use waste heat can have CO emissions as low as those of combined-cycle generators. NOx emissions are mainly a consequence of combustion. Some traditional combustion fuels, notably coal, contain nitrogen that is oxidized during the combustion process. However, even fuels that contain no nitrogen emit NOx, which forms at high combustion temperatures from the nitrogen and oxygen in the air. Gas turbines, reciprocating engines, and reformers all involve high temperatures that result in NOx production. Microturbines and fuel cells have much lower NOx emissions because of their lower combustion temperatures.

[0014] Distributed resources include more than microturbines and fuel cells. Storage technologies such as batteries, ultracapacitors, and flywheels are important. Combining storage with microsources provides peak power and ride-through capabilities during system disturbances. Storage systems have become far more efficient than they were five years ago. Flywheel systems can deliver 700 kW for five seconds, and 28-cell ultracapacitors can provide up to 12.5 kW for a few seconds.

[0015] There is a significant potential for smaller DER (e.g., <100 kW/unit) with advanced power electronic interfaces which can be manufactured at a low cost, have low emissions, and be placed near the customers load to make effective use of waste heat, sometimes called microsources.

[0016] In general, there are two basic classes of microsources: DC sources, such as fuel cells, photovoltaic cells, and battery storage; and high-frequency AC sources, such as microturbines and wind turbines, which need to be rectified. In both of these classes of microsources, the DC

voltage that is produced is converted to AC voltage or current at the required frequency, magnitude, and phase angle. In most cases, the conversion is performed by a voltage inverter that can rapidly control the magnitude and phase of its output voltage. Fundamental frequency in an inverter is created using an internal clock that does not change as the system is loaded. This arrangement is very different from that of synchronous generators for which the inertia from spinning mass determines and maintains system frequency. Inverter-based microsources, by contrast, are effectively inertia-less. As a result, basic system problems include controlling the power feeder from the grid, the microsource's response speed, the sharing and tracking of loads among the distributed resources, the reactive power flow, the power factor, and the system's steady-state and transient stability cannot be achieved using methods developed over time for synchronous generators.

[0017] Heretofore, adding a microsource to a distributed energy resource (DER) system has required modifying existing equipment in the system. Further, conventional control of microsources in such a system has been dependent on control of units already in the system. As such, power from a microsource in a DER system has not been independently controlled.

[0018] Thus, there is a need for microsource controls to insure that new microsources can be added to the system without modification of existing equipment, sources can connect to or isolate from the utility grid in a rapid and seamless fashion, reactive and active power can be independently controlled, and voltage sag and system imbalances can be corrected. Further, there is a need for control of inverters used to supply power based on information available locally at each inverter. Yet further, there is a need for a local controller at the microsource to enable "plug and play" operation of the microsource. In other words, there is a need to add microsources to a distributed energy resource system without changes to the control and protection of units that are already part of the system.

SUMMARY OF THE INVENTION

[0019] In accordance with the invention, a microsource system provides power in any one of an isolation mode and a grid mode and is configured to couple to a power system without modification of existing equipment in the power system. The microsource system can include a microsource power source configured to provide electrical power and a controller coupled to the microsource power source to control the microsource power source based only on information available locally at the microsource power source.

[0020] The invention may be embodied in a microsource system configured for use in a microgrid which is capable of separation from a power grid while continuing to operate independently when power grid problems occur and reconnecting to the power grid once the problems are solved. The system can include a microsource including a prime mover, a DC interface, and a voltage source inverter; means for controlling real and reactive power coupled to the microsource; and means for regulating voltage through droop control to the microsource.

[0021] A power system in accordance with the invention can include a microsource and a controller. The microsource includes a voltage source inverter and is configured to connect to a utility grid. The utility grid couples a plurality of power sources. The controller is coupled to the voltage source inverter and is configured to control reactive and active power independently from the plurality of power sources coupled to the utility grid.

[0022] A microsource can be controlled in a microgrid system such that the microgrid can operate independently from a power grid or in cooperation with the power grid. The method of operation can include receiving inputs from voltage at a connection point, current injected by the microsource, and current in a feeder from a utility supply. The method reduces a local voltage set point as current injected by the microsource becomes more capacitive and increases the local voltage set point as current generated by the microsource becomes more capacitive.

[0023] Other objects, features and advantages of the invention will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] In the drawings:

[0025] **FIG. 1** is a diagrammatic representation of a distributed energy resource system in accordance with an exemplary embodiment;

[0026] **FIG. 2** is a diagrammatic representation of an exemplary microsource included in the distributed energy resource system of **FIG. 1**;

[0027] **FIG. 3** is a diagrammatic representation of an inverter control system included in the distributed energy resource system of **FIG. 1**;

[0028] **FIG. 4** is a diagrammatic representation of local system input states for a microsource in the distributed energy resource system of **FIG. 1**;

[0029] **FIG. 5** is a diagrammatic representation of a voltage controller in an exemplary microsource system;

[0030] **FIG. 6** is a graph of an exemplary voltage droop regulation characteristic when two machines are present;

[0031] **FIG. 7** is a diagrammatic representation of an industrial plant including microsource systems in accordance with an exemplary embodiment;

[0032] **FIG. 8** is a diagrammatic representation of graphs of exemplary simulations of grid-connected operation of microsource systems in accordance with an exemplary embodiment;

[0033] **FIG. 9** is a diagrammatic representation of graphs of exemplary simulations of grid-connected operation of microsource systems in accordance with an exemplary embodiment;

[0034] **FIG. 10** is a diagrammatic representation of graphs of regulated voltages during an exemplary transfer to island operation in accordance with an exemplary embodiment;

[0035] **FIG. 11** is a diagrammatic representation of graphs of active and reactive power changes during an exemplary transition;

[0036] **FIG. 12** is a diagrammatic representation of an exemplary control system having power-frequency droop control;

[0037] **FIG. 13** is a diagrammatic representation of an Φ_e generator system in the control system of **FIG. 12**;

[0038] **FIG. 14** is a diagrammatic representation of an exemplary frequency correction system in the control system of **FIG. 12**;

[0039] **FIG. 15** is a diagrammatic representation of an exemplary P_c generator system in the control system of **FIG. 12**;

[0040] **FIG. 16** is a diagrammatic representation of an exemplary $\Delta\omega_i$ generator system in the control system of **FIG. 12**;

[0041] **FIG. 17** is a graph of an exemplary power-frequency droop; and

[0042] **FIG. 18** is a diagrammatic representation of an exemplary δ_v generator system in the control system of **FIG. 12**.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0043] In the following description, for purposes of explanation, numerous specific details are set forth to provide a thorough understanding of exemplary embodiments of the invention. It will be evident, however, to one skilled in the art that the invention may be practiced without these specific details. In other instances, structures and devices are shown in block diagram form to facilitate description of the exemplary embodiments.

[0044] In some embodiments, hardwired circuitry may be used in place of, or in combination with, software instructions to implement the functions described. Thus, the embodiments described herein are not limited to any specific combination of hardware circuitry and software, nor to any particular source for the instructions executed by a computerized control system.

[0045] Exemplary embodiments of a system for and method of control of small distributed energy resources are described below. These exemplary embodiments can include distributed generators controlled by power electronics. The power electronics controls can be designed to insure that: (1) new generators can be added to the system without modification of existing equipment; (2) a collection of sources and loads can connect to or isolate from the utility grid in a rapid and seamless fashion; (3) each inverter can respond effectively to load changes without requiring data from other sources; and (4) voltage sag and system imbalances can be corrected.

[0046] The system and method for control of small distributed energy resources can be implemented in a wide variety of different ways. Various embodiments may include, for example, DC sources or AC sources. The invention is not limited to a particular embodiment, but extends to various modifications, combinations, and permutations within the scope of the appended claims.

[0047] **FIG. 1** illustrates a power distribution system **100** including a utility supply **110** and microsource systems **120**, **130**, **140**, and **150**. The utility supply **110** can include a power network or power grid coupling multiple machines or units that utilize power from the utility supply **110**. The utility supply **100** can be included in a distributed energy resource (DER) system in which the utility supply **110** connects units distributed throughout the DER system.

[0048] The microsource systems **120**, **130**, **140**, and **150** include exemplary microsource power sources and controllers. By way of example, the microsource system **120** can include a power source, such as a fuel cell, battery, or microturbine. Controllers in the microsource systems **120**, **130**, **140**, and **150** can provide control to power sources. In more than one exemplary embodiment, microsource controllers can provide control to inverter interfaces found in microsource power sources.

[0049] Advantageously, the system **100** includes clusters of microsources and storage designed to operate both in isolation and connected to the power grid or utility supply **110**. When the microsources operate in isolation, load-tracking problems can arise because microturbines and fuel cells respond slowly (with time constants ranging from 10 to 200 seconds) and are inertia-less. Conventional utility power systems have storage in the form of generators inertia. When a new load comes on-line, the initial energy balance is satisfied by the system's inertia, which results in a slight reduction in system frequency. A microsource does not rely on generators inertia, providing power storage to insure initial energy balance.

[0050] System storage for island operation can come in several forms: batteries or super-capacitors on the DC bus for each microsource; direct connection of AC storage devices (batteries, flywheels etc.); or use of traditional generation with inertia along with microsource generators. In an exemplary embodiment, if the system **100** is not required to operate in island mode, the energy imbalance can be met by the AC system, and storage is not necessary.

[0051] In at least one of the exemplary embodiments, microsource controller techniques described below rely on inverter interfaces found in fuel cells, photovoltaic panels, microturbines, windturbines, and storage technologies. Advantageously, communication among microsources is unnecessary for basic system control. Each inverter responds effectively to load changes without requiring data from other sources or locations.

[0052] **FIG. 2** illustrates a microsource **200** in accordance with an exemplary embodiment. The microsource **200** can include a prime mover **210**, a DC interface **220**, and a voltage source inverter **230**. The prime mover **210** can be a fuel cell, microturbine, PV, or windturbine. The time constants of changes in power output for the prime mover **210** can range from 10 to 200 seconds. This response speed requires that either the AC system or DC bus has adequate storage to insure fast load tracking.

[0053] The microsource **200** couples to a power system **250** using an inductor **240**. The voltage source inverter **230** controls both the magnitude and phase of its output voltage, V. The vector relationship between the inverter voltage, V, and the system voltage, E, along with the reactance, X, of the inductor **240** determines the flow of real and reactive power (P &Q) from the microsource **200** to the system **250**.

[0054] P & Q magnitudes are determined as shown in the equations (1), (2), and (3) below. For small changes, P is

predominantly dependent on the power angle, δ_p, and Q is dependent on the magnitude of the voltage, V, of the inverter **230**. These relationships constitute a basic feedback loop for the control of output power and bus voltage, E, through regulation of reactive power flow.

$$P = \frac{3}{2}\frac{VE}{X}\sin\delta_p \quad \text{Eq. (1)}$$

$$Q = \frac{3}{2}\frac{V}{X}(V - E\cos\delta_p) \quad \text{Eq. (2)}$$

$$\delta_p = \delta_v - \delta_E \quad \text{Eq. (b 3)}$$

[**0055**] Advantageously, the inverter **230** supplies power to an AC system in a distributed environment and has controls that are only based on information available locally at the inverter **230**. In a system with many microsources such as the system **100** described with reference to **FIG. 1**, communication of information between machines or units is impractical. As such, control of the inverter **230** is based on terminal quantities. Control of the frequency of the inverter **230** dynamically controls the power angle and the flow of the real power. To prevent overloading the inverter **230** and the microsources, load changes are taken up by the inverter **230** in a predetermined manner, without communication.

[**0056**] **FIG. 3** illustrates an inverter control system **300** in which each microsource provides a real and reactive power (P&Q) calculator **310**, a flux vector or phasor calculator **320**, a voltage controller **330**, a power controller **340**, and an inverter **350**. Exemplary input and outputs to the controller can include three set points and three measured states. Set points can include E_o: the desired voltage value; P_o: the desired power flow from the microsource or distribution feeder; and ω_o: the fundamental frequency. Measured states can include $\bar{E}$: time varying voltage at a connection point; $I_{inductive}$: time varying current injected by the microsource; and I_{feeder}: time varying current in feeder. Two variables that are directly output to the inverter **350** are the magnitude and phase of the voltage flux, Ψ_v, or the requested voltage V.

[**0057**] The P & Q calculator **310** can have three inputs: $\bar{E}$, $I_{inductive}$, and I_{feeder} which are used to calculate the real power, P, and the reactive power, Q. Real power can be either the power being injected by the microsource using the inductor current, $I_{inductive}$, or the power in the utility feeder using the feeder current, I_{feeder}. The reactive power is the Q being injected by the microsource.

[**0058**] The flux vector or phase calculator **320** calculates the instantaneous magnitude and phase of the system voltage, E, at the point where the microsource is connection. This calculation can be achieved through standard d-q methods or by using voltage flux techniques. Normally, it can be more stable to control the flux of the voltage, rather than the actual voltage. This continuous quantity is the time-integral of the inverter output voltage, often called the flux vector Ψ_E:

$$\psi_E(t) = \psi_E(t_O) + \int_o^\tau E\,d\tau \quad \text{Eq. (4)}$$

[**0059**] Three phase input phase voltages, E, can be transformed to the stationary d-q reference frame. The resulting d-q components are time integrated, resulting in the flux vector, $\Psi_{\bar{e}}$, for the AC system voltage.

[**0060**] Two variables that are directly input to the inverter **350** are the magnitude and phase of the flux Ψ_v, or the magnitude and phase of the voltage $\bar{V}$. The vector Ψ_V is controlled so as to have a specific magnitude and a specified position relative to the AC system flux vector $\Psi_{\bar{e}}$, or voltage vector $\bar{E}$ as described with reference to **FIG. 2**. This control forms the innermost control loop, and can be fast. For example, the speed of the control can be a few milliseconds. The AC system voltage vector, E, is obtained from instantaneous voltage measurements and is available locally. Voltage source inverter **350** can be a pulse width modulation (PWM) inverter.

[**0061**] Conventially, integration of large numbers of microsources into a system is not possible with basic P-Q controls; voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources can experience voltage and or reactive power oscillations. Voltage control must insure that there are no large circulating reactive currents between sources. The issues are identical to those involved in control of large synchronous generators. In the power grid, the impedance between generators is usually large enough to greatly reduce the possibility of circulating currents.

[**0062**] However, in a distribution system, which is typically radial, the problem of large circulating reactive currents is immense. With small errors in voltage set points, the circulating current can exceed the ratings of the microsources. Therefore, this situation requires a voltage vs. reactive current droop controller so that, as the reactive current generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as the current becomes more inductive, the voltage set point is increased.

[**0063**] **FIG. 4** illustrates a system **400** having local system input states. The system **400** includes a utility supply **410** providing a feeder current and a microsource **420** providing an inductor current through an inductor **430**. In most cases, control of feeder power is the more stable mode of control. These input states are used by P & Q calculator **310** described with reference to **FIG. 3** to calculate real and reactive power.

[**0064**] **FIG. 5** illustrates a voltage controller **500**. The voltage controller **500** can be the voltage controller **330** described with reference to **FIG. 3**. In an exemplary embodiment, there are three inputs to the voltage controller **500**. One input is the voltage set point E_o. Another input is the reactive power being injected by the microsource, Q. A third input is the magnitude of the system voltage or voltage flux, Ψ_E, or |E|. The slope of the voltage droop is defined by Mv and the gain K depends on whether the inverter input assumes a voltage magnitude or voltage flux inputs. In an exemplary embodiment, K=1 for a voltage phasor and

$$K = \frac{1}{\omega_o}$$

[0065] for a voltage flux.

[0066] In an exemplary embodiment, the voltage set point, E_o, is added to the product of the voltage droop slope, Mv, and the reactive power, Q, using a summer **510**. The total of this sum is multiplied by a gain, K. The resulting product is added to the magnitude of the system voltage or voltage flux, |E| or Ψ_E, using a summer **520**. This voltage error is input to a PI (proportional plus integral) controller. The controller's output is a voltage magnitude or voltage flux, |V| or Ψ_v. The voltage magnitude or voltage flux is provided to the inverter **350** described with reference to **FIG. 3**.

[0067] **FIG. 6** illustrates a graph **600** depicting an exemplary characteristic of droop regulation when only two machines are present. Machine **2** operates at higher output, than machine **1**. As the system-enters island mode, the frequency is reduced. With the full load of the system, the new frequency is ω_{min}, while if the system is at a lighter load, the new frequency is somewhere in between $_{\omega o}$ and $_{\omega min}$. The slower loop increases the frequency, ω upwards, until $\omega_1 \approx \omega_0$.

[0068] **FIG. 7** illustrates an industrial plant **700** with high motor loads to illustrate the dynamics of the microsource controls described with reference to FIGS. **1-6**. The example industrial plant **800** can have nearly 1.6 MW of motor load with motors ranging from 50 to 150 hp each. A 120 kV line provides power through a long 13.8 kV feeder consisting of overhead lines and underground cables. The plant has three main feeders: two at 480V and one at 2.4 kV. The loads on the 480-V feeders are critical and must continue to be served if utility power is lost. The induction machine clusters (M**8** and M**9**) are connected to buses **8** and **9** with capacitive voltage support. Two clusters of microsources are also connected to buses **8** and **9** to provide power and voltage support. In the absence of locally generated power, the voltages of buses **8** and **9** are 0.933 and 0.941 per unit (pu, on 480-V base), respectively. Total losses are 70 kW. Each cluster of microsources is rated at 600 KVA and provides both power injection and local voltage support. The microsource power injection is approximately one half the total power. With these sources operating, the voltages on buses **8** and **9** are regulated at 1 pu, and the total losses drop to 6 kW, a reduction of 64 kW.

[0069] **FIGS. 8 and 9** illustrate graphs **910**, **920**, **930**, and **940** depicting exemplary simulations of grid-connected operation. In the initial state, local sources are not generating power, so **FIG. 9** shows zero real and reactive power injection and reduced voltages on buses **8** and **9**. At t=one second, the generators at bus **8** are brought on line with a power setting of 446 kW and local voltage control. Note the voltage correction in graph **930** of **FIG. 9**.

[0070] At t=three seconds, the units at bus **9** are brought on line with a power set point of 360 kW and local voltage control. **FIG. 9** shows the active and reactive power injections at the buses where units are located. As the second microsource is brought on line, the Q injection at bus **8** to maintain local voltage magnitude drops. **FIG. 9** shows half of the voltage envelope at the regulated buses during the start-up sequence. Voltage on bus **9** is controlled to 1 pu within a few cycles.

[0071] This example can also be used to simulate island operation with power sharing through droop. It is assumed that the ratings of the microsources are not adequate to supply the total load. The two 480-V feeders supply critical loads, and the M**7** load on bus **7** can be dropped using breaker S_2 (see **FIG. 7**).

[0072] **FIG. 10** illustrates graphs **1000**, **1010**, and **1020** depicting regulated voltages during an exemplary transfer to island operation for bus **8** (graph **1000**), for bus **9** (graph **1010**), and for a 13.8 kV feeder (graph **1020**). At t=10 seconds, the system moves from grid-connected to island operation by the tripping of switch S_1 (**FIG. 7**) in response to supply problems (graph **1020**). At the same time, the non-critical feeder is dropped using S_2. Waveforms for bus **8** and **9** voltages during the switch to island mode are shown in graphs **1000** and **1010**. As shown in the graph, there is only a slight change from the sinusoidal steady state after t=10 seconds and the change lasts less than a cycle.

[0073] **FIG. 11** illustrates graphs **1110** and **1120** depicting changes in active and reactive power during an exemplary transition. Active power has to take up the critical load in the absence of grid power. Both machine clusters increase their power injection as expected from the design of the droop characteristics. The machine with lighter load at bus **9** picks up the largest part of the new load demands, as seen in the graph **1110**. Reactive power injection reduces but holds the voltages at 1 pu. Power regulation takes place very rapidly, and steady-state power is restored in less than one second. In this case, system frequency droops a little more than 0.5 Hz. Meanwhile, the frequency restoration loop has started and restores the frequency to 60 Hz.

[0074] As described with reference to FIGS. **1-11**, a local controller at each microsource can insure stable operation in an electrical distribution system. This controller can respond in milliseconds and use local information to control the microsource during all system or grid events. Advantageously, communication among microsources is not necessary for basic system operation; each inverter is able to respond to load changes in a predetermined manner without data from other sources or locations. This arrangement enables microsources to "plug and play." That is, microsources can be added without changes to the control and protection of units that are already part of the system.

[0075] The power controller **340** in **FIG. 3** is described with reference to FIGS. **12-18** as a specific approach for implementation. Other approaches can also be used with the systems and methods described.

[0076] As previously described, a microsource interfaces a network through an inverter that is connected to the local feeder by an impedance X. A controller can regulate feeder voltage and active power to desired values. The control is designed so that it also allows operation during island mode. When the local microgrid is no longer connected to the main grid because of a failure, the microsources redispatch their output power to new values, consistent with the fact that all the loads in the microgrid have to be supplied with electrical energy, knowing that the power grid injection is zero.

[0077] To better understand an implementation of the power controller, a detailed implementation of the flux

vector calculator **320** in **FIG. 3** is described. The voltages, E, in the time domain are projected in a stationary frame by means of the following equations:

$$e_{ds}(t) = \frac{e_c(t) - e_b(t)}{\sqrt{3}} \qquad \text{Eq. (14)}$$

$$e_{qs}(t) = \left(\frac{2}{3}\right)\left(e_a(t) - \frac{1}{2}e_b(t) - \frac{1}{2}e_c(t)\right)$$

[0078] These voltages are integrated to yield the components of the quantity called voltage vector flux. It is possible to transform these rectangular coordinates to polar quantities by means of the following equations:

$$\Psi_{ed} = \int_{-\infty}^{t} e_{ds}(\tau)\,d\tau \qquad \Psi_{eq} = \int_{-\infty}^{t} e_{qs}(\tau)\,d\tau \qquad \text{Eq. (15)}$$

$$=> \quad |\Psi_e| = \sqrt{\Psi_{ed}^2 + \Psi_{eq}^2} \qquad \delta_e = -\tan^{-1}\left(\frac{\Psi_{ed}}{\Psi_{eq}}\right)$$

[0079] The measure of the angle is given by the inverse tangent of the ratio of the components, with a reversed sign, to keep into account the choice of the direction of the axis d and q. By itself, the arctangent yields values that are between $-\pi/2$ and $\pi/2$, as the ratio of the rectangular components change. To be precise, it is worth noticing that $\tan(x)=\tan(x+\pi)=y$. When the arctangent of 'y' is taken, it is not known which one angle (x or $x+\pi$) is the current solution. To solve this problem, the sign of the cosine component of the voltage flux can be monitored. A negative component means that the arctangent output has to be added to π. To make this issue more transparent, this operation can be embedded in the sawtooth, adding a π whenever it is needed. The result of this manipulation yields a sawtooth that is not bound between $-\pi/2$ and $\pi/2$, but rather from $-\pi/2$ and $3\pi/2$. Notice that this is the angle of the flux of the voltage vector. This vector, being the integral of the stationary frame voltage vector, is $\pi/2$ delayed with respect of the voltage vector itself. To obtain the value of the voltage angle, $\pi/2$ is added to the angle of the flux vector. The bounds of the sawtooth wave of the arctangent are no longer $-\pi/2$ and $3\pi/2$, but rather O and 2π, in accordance with the fact that $\pi/2$ is added to obtain the sawtooth relative to the angle of the voltage.

[0080] Since the angle of the voltage flux increases in time with rate ω_o, the arctangent assumes a sawtooth trend. As such, if the angle, δ_e, of the voltage flux is found by wrapping up the sawtooth wave to yield a function growing with rate ω_o, then sooner or later the number representing this function requires more bits than may be available inside a programmable logic DSP.

[0081] **FIG. 12** illustrates a power controller system **1200** having power-frequency droop control. Power-frequency droop control maintains the active power injection to a constant value, P_o, during normal operation while redispatching output power during islanding to maintain supply at the loads, providing the extra quota of power that was once injected by the grid. Inputs to the system **1200** can include the power request P_o, the current measure of the active power, and the nominal network frequency, ω_o. The output is the inverter voltage angle, or the desired angle that the inverter has to synthesize at its own terminals.

[0082] In **FIG. 12**, there is a sawtooth icon near δ_e and near the integral of the quantity $\omega\tau$; meaning that those variables are not growing constantly in time, but rather are wrapped between limited values.

[0083] The derivative of Φ_e is calculated in real time and filtered to ensure that a bounded quantity is manipulated. During transients ensuing from changes in commands or from transfer to island, it is possible that the derivative of the signal Φ_e may have a high frequency content, associated with possible large instantaneous values. The control is filtered to avoid using such a quantity in the control. The filter has a time constant of one tenth of a second, making it fast enough to track changes and yet, effective in obtaining well behaved outputs even in the face of transients.

[0084] **FIG. 13** illustrates operations of the Φ_e generator block of the control system **1200** described with reference to **FIG. 12**. This generator is responsible for generating a voltage angle that is always constant in steady state. The inputs of the Φ_e are the sawtooth wave for the regulated bus voltage, ranging from 0 to 2π and the corrected frequency ω_τ. The outputs are the steady state constant quantity Φ_e and the sawtooth of the integral in time of ω_τ. To appreciate the meaning of the operations of the ω_e generator, it is important to define some quantities. The sawtooth quantity representing the voltage angle coming from the measurement is:

$$\delta_e = \omega_o t + \phi_e(t) \qquad \text{Eq. (16)}$$

[0085] When connected to the grid and in steady state, $(\phi_e(t)$ is a constant. In island mode, however, this angle is worth:

$$\varphi_e(t) = \int_0^t \Delta\omega_n(\varsigma)\,d\varsigma + \Phi_e \qquad \text{Eq. (17)}$$

[0086] A difference is experienced because the frequency instantly drops during regulation and is restored to a value slightly smaller than ω_o. The value $\Delta\omega_n(t)$ is the measure of the difference between the actual frequency and the nominal value. Therefore:

$$\Delta\omega_n = \omega_n - \omega_o < 0 \qquad \text{Eq. (18)}$$

[0087] The derivative of ϕ_e is:

$$\frac{d\varphi_e}{dt} = \Delta\omega_n \qquad \text{Eq. (19)}$$

[0088] In steady state, the quantity $\Delta\omega_n$ is a constant, but during transients it is a function of time. As such, to obtain the angle change, an integration is performed (as in Eq. 17).

[0089] To obtain Φ_e from Eq.16, an appropriate quantity is subtracted from the sawtooth wave. From Eq. 17, Eq. 16, and Eq. 5:

$$\delta_e = \omega_o t + \int_0^t \Delta\omega_n(\varsigma)\,d\varsigma + \Phi_e = \qquad \text{Eq. (20)}$$

-continued

$$\int_0^t (\omega_o + \Delta\omega_n(\varsigma))\,d\varsigma + \Phi_e = \int_0^t \omega_n(\varsigma)\,d\varsigma + \Phi_e$$

[0090] This yields:

$$\Phi_e = \delta_e - \int_o^t \omega_n(\varsigma)d\varsigma \quad \text{Eq. (21)}$$

[0091] Φ_e can change during the transient subsequent to the transition to island, but in steady state, a value for Φ_e is measured that is constant. As such, the integral of ω_n is not subtracted but the integral of $\omega_\tau$is. This quantity is created by adding ω_o not with $\Delta\omega_n$ (that would yield ω_n), but rather $\Delta\omega_\tau$which is a delayed signal of $\Delta\omega_n$:

$$\Delta\omega_\tau = \frac{1}{1+\tau s}\Delta\omega_n \quad \text{Eq. (22)}$$

[0092] In this case, τ is a time constant that determines how quickly the delayed deviation of speed reaches the new steady state value of $\Delta\omega_n$. The larger the time constant, the longer it takes. Preferably, the speed should not be too fast to ensure that only the DC changes in $\Delta\omega_n$ are tracked, while completely filtering out any small transient deviation from nominal. This time constant is preferably in the range of 10 seconds or more.

[0093] Whatever sustained non-zero difference of frequency from the nominal is present, then this equation generates a signal that in time is equal to that amount. Thus,

$$\omega_\tau=\omega_o+\Delta\omega_\tau, \text{ with } \Delta\omega_\tau<0 \quad \text{Eq. (23)}$$

[0094] and Eq. 21 reduces to the following relation:

$$\Phi_e - \delta_e - \int_o^t \omega_\tau(\varsigma)d\varsigma \quad \text{Eq. (24)}$$

[0095] In this case any instant discrepancy in frequency is not removed (operation performed in Eq. 21), but the sustained, steady state value of the difference in frequency (Eq. 24) is removed as encountered in island mode operation.

[0096] Details of the Φ_e generator are illustrated in **FIG. 13**. As illustrated in **FIG. 13, a** sawtooth wave can be generated from the integral of ω_τ. This wave can be generated by resetting the integral back of 2π each time the waveform δ_e is reset of 2π. The value of Φ_e is obtained by subtracting the generated sawtooth from the sawtooth coming from the measure of δ_e (Eq. 24). The wave δ_e grows with rate ω_n while the generated sawtooth grows with rate ω_τ. This means that the two rates coincide in steady state (Eq. 22), yielding Φ_e constant, but during transients the derivative of Φ_e is different from zero.

[0097] **FIG. 14** illustrates operations of the frequency correction block of the control system **1200** described with reference to **FIG. 12**. The frequency correction block is responsible to create a delayed signal $\Delta\omega_\tau$that tracks in steady state the value of $\Delta\omega_n$. From Eq. 20 it is possible to see that a transient change is manifest in a non-zero derivative of Φ_e but in steady state (when $\Delta\omega_\tau=\Delta\omega_n$), then the derivative of Φ_e is zero.

[0098] The expression that allows the tracking of the quantity $\Delta\omega_n$ is shown in Eq. 22 and in the block diagram of **FIG. 14**. It is now possible to see how the correction takes place. From Eq. 19 and **FIG. 12**:

$$\frac{d\varphi_e}{dt} = \Delta\omega_n = \frac{d\Phi_e}{dt} + \Delta\omega_\tau \quad \text{Eq. (25)}$$

[0099] Note that the outside world is only aware of the term

$$\frac{d\varphi_e}{dt},$$

[0100] therefore there is no way to notice that the correction takes place. Indeed, the correction can be thought as a way to book-keep the derivative. From Eq. 25 it appears that at the beginning $\Delta\omega_n$ shows up entirely in the term

$$\frac{d\Phi_e}{dt},$$

[0101] but in steady state it is all in the term $\Delta\omega_\tau$ (forcing

$$\text{(forcing } \frac{d\Phi_e}{dt} = 0).$$

[0102] The sum of the two is always the same, which is why an observer outside this block cannot notice that the signal has been split in these two quantities.

[0103] **FIG. 15** illustrates the P_c generator block from **FIG. 12**. The PC generator block is responsible to correct the frequency back to a value near ω_o after the islanding and the transient ensuing might have taken the frequency to a value that is too far away from ω_o to be sustained for more than a small amount of time.

[0104] In grid connection, $\Delta\omega_n=\Delta\omega_\tau=0$ in steady state, since the frequency is commanded to be ω_o. This means (from Eq. 25) that the term

$$\frac{d\Phi_e}{dt} = 0,$$

[0105] since in steady state the input of the integral must be zero. Thus, $P_c=P_o$, which is the desired power. During islanding, the input of the integral must be zero, but now $P_c\neq P_o$. This means that:

$$\Delta\omega_n=K'(P_o-P_c) \quad \text{Eq. (26)}$$

[0106] With a given term P_o-P_c, K' is smaller and is responsible for deviation in frequency at steady state from the nominal value. The constant K" is responsible for the change of P_C after the transfer to island. The larger K" is, the quicker the frequency is restored to a value near to ω_o. These constants are related to the droop characteristic slope 'm' by the following relations:

$$K' = -a\,m$$

$$K'' = -\frac{b}{m}$$

[0107] Different microsources have different values for 'm', but they share the same real positive scalar coefficients 'a' and 'b'. This constraint is derived from the fact that during frequency restoration, the frequency must rise at the same rate everywhere in the isolated microgrid to maintain the same active power dispatching level. In other words, if the frequency does not rise with the same rate, then different points in the microgrid end up at different frequencies and therefore the active power dispatch changes as a consequence of this. It is desirable to maintain the same level of dispatched power during frequency recovery, hence the same scalars are needed in all the units of the microgrid.

[0108] **FIG. 16** illustrates a $\Delta\omega_i$ generator block (see **FIG. 12**). The quantity $\Delta\omega_i$ is the desired discrepancy in frequency from the nominal value commanded by the inverter. Whenever connected to the grid, $\Delta\omega_i$ is zero in steady state, but during transients it is non-zero to allow for a change in the voltage angle. During island operation, $\Delta\omega_i$ is non-zero in steady state, assuming:

$$\Delta\omega_i = \Delta\omega_n = \frac{d\varphi_e}{dt} = \Delta\omega_\tau. \qquad \text{Eq. (27)}$$

[0109] The signal $\Delta\omega_i$ is generated according to the power-frequency droop characteristic. **FIG. 17** illustrates a graph **1700** of the power-frequency droop. It is possible to see that whenever the frequency is locked to ω_o by the grid, then the output power matches the desired setpoint, P_o. During island mode, the frequency is no longer locked and it is used by the different microsources to reach a new steady state point, with higher output power (to compensate for the missing power from the grid) and at a lower frequency. As such, all the units in the isolated microgrid will operate at the same new, reduced frequency.

[0110] Referring again to **FIG. 16**, when connected to the grid, P_c=P_o and $\Delta\omega_i$=0 in steady state. As soon as the transfer to island occurs, the frequency drops, but then the signal P_c is increased by the integrator K"/s to a new value such that Eq. 26 is satisfied. As P_c is increases, $\Delta\omega_i$ is reduced and this desired discrepancy in frequency is reflected in Eq. 26 by the measured term $\Delta\omega_n$ as the inverter generates a $\Delta\omega_1$ at its own terminals. Here, $\Delta\omega_i$ equals:

$$\Delta\omega_i = -m(P_c - P) \qquad \text{Eq. (28)}$$

[0111] The coefficient 'm' is a negative scalar given by the following relation:

$$m = \frac{\omega_o - \omega_{\min}}{P_o - P_{\max}}$$

[0112] where ω_o is the nominal angular frequency of the grid, ω_{min} is the minimum value allowed for the angular frequency to sag to, P_o is the value that the active power has at the nominal frequency (that is, when there is a connection with the grid) and P_{max} is the maximum rated power of the machine, which is reached when the frequency is at the minimum level. Different machines can have different values of 'm', depending upon their rating (P_{max}) and on their current operating point (P_o). Looking at **FIG. 17**, it is possible to understand what these values mean: ω_o and P_o represent the operating point with the grid (point A), while ω_{min} and P_{max} is the other point that defines a slope for the characteristic. This second point is an extreme of the range of operation, the point B usually has $\omega_{min}<\omega_B<\omega_o$ and $P_{max}>P_B>P_O$.

[0113] As a side note, notice that if the block that generates P_c were missing, then P_c would be replaced by P_o all the time, and the frequency would stay in steady state at the low value reached during redispatching (point B), without possibility of restoration. In other words, with the signal P_c, an islanding event can be traced on the P-ω plane (**FIG. 17**) as a trajectory that moves from A (steady state with grid) to B when islanding occurs (and the restoration process is activated), to C, when the new steady state in island mode is reached. Notice that the part from A to B is described by a linear equation with rate of growth 'm', which is a negative number.

[0114] **FIG. 18** illustrates a δ_v generator which is the part of the control responsible for generating the voltage angle that is synthetized at the inverter terminals. Once the signal $\Delta\omega_i$ has been generated, it is subtracted from the measured

$$\Delta\omega_n = \frac{d\varphi_e}{dt}$$

[0115] to yield the error in frequency. This error commands the angle to increase or decrease in order to catch up with the desired instantaneous desired frequency.

[0116] This error is integrated through a gain to yield the difference in angle between the voltage at the inverter and the voltage at the regulated bus. This angle, ϕ_p, is constant during steady state regardless whether connected to grid or not. Regardless of the frequency that the voltages are rotating, in steady state the difference of their phases is constant. This means that the error ϵ_ω is zero in steady state, consistent with the fact that desired deviation in speed ($\Delta\omega_i$) and actual deviation ($\Delta\omega_n$) are the same in steady state regardless if we are in grid mode ($\Delta\omega_i$=0) or in island ($\Delta\omega_i \neq 0$).

[0117] The angle (Φ_p is added to the angle Φ_e to yield the quantity ϕ_v, by adding the integral of ω_τ then we obtain δ_v:

$$\delta_v = \int_o^t \omega_\tau(\varsigma)\, d\varsigma + \Phi_e + \varphi_p \qquad \text{Eq. (29)}$$

[0118] By substituting Eq. 25 into Eq. 16 we get:

$$\delta_e = \omega_o t + \int_o^t \frac{d\varphi_e(\varsigma)}{d\varsigma} d\varsigma = \omega_o t + \int_o^t \left[\Delta\omega_\tau(\varsigma) + \frac{d\varphi_e(\varsigma)}{d\varsigma}\right] d\varsigma = \qquad \text{Eq. (30)}$$

$$= \omega_o t + \int_o^t \Delta\omega_\tau(\varsigma) d\varsigma + \Phi_e = \int_o^t \omega_\tau(\varsigma) d\varsigma + \Phi_e$$

[0119] Comparison between Eq. 29 and 30 shows that these two angles are exactly (ϕ_p apart from each other. A PWM inverter is interested in knowing the angle ϕ_v, sum of Φ_e and ϕ_p. An inverter implementing space vector technique uses the signal δ_v.

[0120] While the exemplary embodiments illustrated in the figures and described above are presently preferred, it should be understood that these embodiments are offered by way of example only. Other embodiments may include, for example, different techniques for power calculation, voltage control, power control, or droop control. The invention is not limited to a particular embodiment, but extends to various modifications, combinations, and permutations that nevertheless fall within the scope and spirit of the appended claims.

What is claimed is:

1. A microsource system providing power in any one of an isolation mode and a grid mode and being configured to couple to a power system without modification of existing equipment in the power system, the microsource system comprising:

a microsource power source configured to provide electrical power; and

a controller coupled to the microsource power source to control the microsource power source based only on information available locally at the microsource power source.

2. The microsource system of claim 1 wherein the controller includes a voltage controller and a power controller.

3. The microsource system of claim 2 wherein the voltage controller and the power control receive inputs from a real power and reactive power calculator and a flux vector or phasor calculator.

4. The microsource system of claim 3 wherein the real power and reactive power calculator receive inputs from voltage at a connection point, current injected by the microsource power source, and current in a feeder from a utility supply.

5. The microsource system of claim 2 wherein the power controller includes a frequency droop governor where if frequency (ω_1) decreases below ω_o power increases linearly by a coefficient m.

6. The microsource system of claim 1 wherein the microsource power source is a fuel cell.

7. The microsource system of claim 1 wherein the microsource power source is a microturbine.

8. The microsource system of claim 1 wherein the controller reduces a local voltage set point as reactive current generated by the microsource power source become more capacitive.

9. The microsource system of claim 1 wherein the controller increases a local voltage set point as current generated by the microsource power source becomes more inductive.

10. The microsource system of claim 1 wherein the microsource power source includes a prime mover, a DC interface, and a voltage source inverter.

11. A microsource system configured for use in a microgrid which is capable of separation from a power grid while continuing to operate independently when problems occur and reconnecting to the power grid once the problems are solved, the system comprising:

a microsource including a prime mover, a DC interface, and a voltage source inverter;

means for controlling real and reactive power coupled to the microsource; and means for regulating voltage through droop control to the microsource.

12. The system of claim 11 further comprising means for fast load tracking and storage coupled to the microsource.

13. The system of claim 11 further comprising means for frequency droop control for power sharing coupled to the microsource.

14. The system of claim 11 wherein the means for regulating voltage through droop reduces a local voltage set point as reactive current generated by the microsource becomes more capacitive.

15. The system of claim 11 wherein the means for regulating voltage through droop increases a local voltage set point as current generated by the microsource becomes more inductive.

16. A power system comprising:

a microsource including a voltage source inverter, the microsource being configured to connect to a utility grid, the utility grid coupling a plurality of power sources; and

a controller coupled to the voltage source inverter and configured to control reactive and active power independently from the plurality of power sources coupled to the utility grid.

17. The power system of claim 16 wherein the microsource includes a high frequency AC source that is rectified.

18. The power system of claim 16 wherein the microsource includes a DC battery storage source.

19. The power system of claim 16 wherein the controller includes a droop controller.

20. The power system of claim 19 wherein the droop controller comprises means for reducing a local voltage set point as reactive current generated by a microsource becomes more capacitive; and

means for increasing the local voltage set point as current generated by the microsource becomes more inductive.

21. A method of controlling a microsource in a microgrid system where the microgrid can operate independently from a power grid or in cooperation with the grid, the method comprising:

receiving inputs from voltage at a connection point, current injected by the microsource, and current in a feeder from a utility supply;

reducing a local voltage set point as current injected by the microsource becomes more capacitive; and

increasing the local voltage set point as current generated by the microsource becomes more capacitive.

22. The method of claim 21 further comprising controlling voltage and power of the microsource using the inputs.

23. The method of claim 22 wherein controlling the power of the microsource includes using a frequency governor.

24. The method of claim 22 wherein constant power is provided during microgrid connected mode.

25. The method of claim 22 wherein dynamic load tracking is provided during island mode.

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