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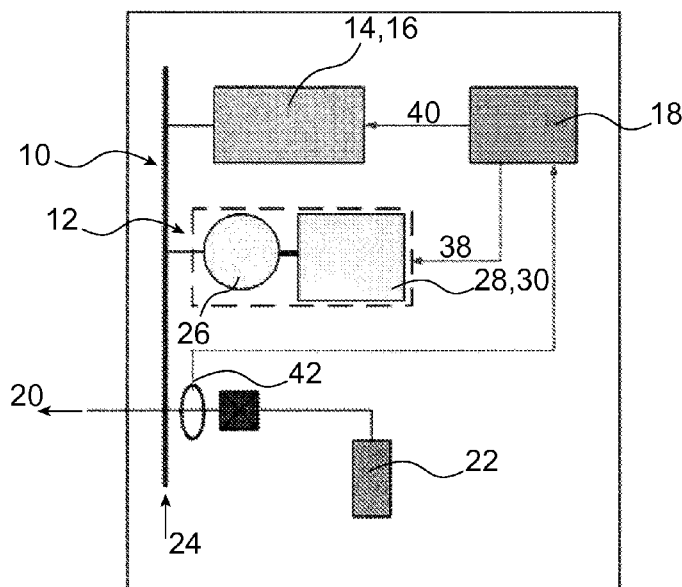


FIG. 1

(57) Abstract: A method is for regulating system frequency in a weak power system (10). The weak power system includes a power generator (12), a static synchronous compensator (14) and an energy storage device (16), where the weak power system (10) is connected to an electrical network (22) and the power generator (12) is operable to generate power for presentation to the electrical network (22). The method comprises the steps of: following a change in load of the electrical network (22), simultaneously modifying a power output of the power generator (12) to match the load of the electrical network (22) and operating the static synchronous compensator (14) to control the energy storage device (16) to either supply real power to the electrical network (22) or absorb real power from the power generator (12).



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POWER SYSTEM

This invention relates to a weak power system and a method for regulating system frequency in the weak power system.

A microgrid is an example of a weak power system. The microgrid produces power at a local level and comprises energy generators, energy storage devices and loads that are locally connected to each other. The energy generators comprise a generator whose shaft is driven by a source of energy - the prime mover. The speed of the prime mover is directly related to the electrical frequency from the generator, and is controlled by a governor. The microgrid may be either connected to a main grid or disconnected from the main grid to enable autonomous operation.

When a step change in load is applied to the microgrid by closing a contactor or a breaker, the sudden change of load will not be immediately be matched by the output of the energy generator of the microgrid if the load is of a comparable rating to the generator. This is because the governor associated with the prime mover is typically slow to respond to the change in load, and the only source of energy to meet the additional load in the moments after the change is the kinetic energy stored in the mass of the prime mover and the generator.

It is therefore necessary for the generator to slow down in order to meet the additional load. However, if the additional load is significant, there is a risk of the generator's output frequency
5 experiencing a change that is sufficiently large to either cause the output frequency to fall outside of a statutory range of operating frequency, or be detected by a rate of change of frequency (ROCOF) relay. Both circumstances can cause tripping of the generator,
10 which potentially leads to further cascade failure and thereby decreases the overall reliability of the microgrid.

According to a first aspect of the
15 invention, there is provided a method for regulating system frequency in a weak power system including a power generator, a static synchronous compensator and an energy storage device, where the weak power system is connected to an electrical network and the power
20 generator is operable to generate power for presentation to the electrical network, the method comprising the steps of: following a change in load of the electrical network, simultaneously modifying a power output of the power generator to match the load
25 of the electrical network and operating the static synchronous compensator to control the energy storage device to either supply real power to the electrical network or absorb real power from the power generator.

30 The simultaneous modification of the power output of the power generator and operation of the

static synchronous compensator as set out above allows the weak power system to temporarily meet the change in load of the connected electrical network until a prime mover of the generator is capable of providing the necessary output power to match the load of the connected electrical network. This allows for a gradual, controlled change of power output of the power generator without running the risk of a change in system frequency that falls outside acceptable values of operating frequencies. This in turn permits the system frequency in the weak power system to be regulated at all times and thereby improves the reliability of the weak power system.

In addition, the inclusion of the static synchronous compensator allows the weak power system to rapidly respond to dynamic and transient power changes, while the inclusion of the energy storage device allows the static synchronous compensator to absorb and inject real power to the weak power system virtually instantaneously. Omission of the energy storage device limits the capabilities of the static synchronous compensator to the absorption and injection of reactive power, and thereby prevents the injection or absorption of real power to compensate for the change in load of the connected electrical network.

In embodiments of the invention, the real power supplied or absorbed by the energy storage device may be initially substantially equal to the change in load of the electrical network.

The ability of the weak power system to rapidly match any change in load of the connected electrical network prevents the occurrence of a rapid fall in system frequency resulting from the step change
5 in load, and thereby reduces the risk of a change in system frequency that falls outside acceptable values of operating frequencies.

In other embodiments, the method may
10 further include the step of operating the static synchronous compensator to control the energy storage device to gradually reduce the supply or absorption of real power over a predetermined period of time.

15 In such embodiments, the method may include the step of operating the static synchronous compensator to control the energy storage device to coordinate the gradual reduction of the supply or absorption of real power with the rate of change of
20 power output of the generator so as to present a substantially constant power to the electrical network.

The presentation of a substantially constant power to the electrical network minimises the
25 variation in system frequency during the time it takes for the power output of the generator to match the load of the connected electrical network. Such coordination of the rates of change of the respective power outputs of the power generator and the energy storage device is
30 possible via the capability of the static synchronous

compensator to finely control the supply or absorption of real power.

In further embodiments, the method may further include the step of calculating the time required to modify the power output of the power generator to match the load of the electrical network following the change in load of the electrical network.

In embodiments of the invention, the method may further include the step of calculating the static synchronous compensator current required to control the energy storage device to either supply real power to the electrical network or absorb real power from the power generator following the change in load of the electrical network.

These calculation steps provide reference values that can be used to coordinate the control of the power generator and the static synchronous compensator when regulating the system frequency in the weak power system.

Preferably the method further includes the step of detecting a change in load of the electrical network connected to the weak power system prior to the step of simultaneously modifying the power output of the power generator and operating the static synchronous compensator to control the energy storage device.

In such embodiments, the step of detecting the change in load of the electrical network connected to the weak power system may include measuring a change in load current of the electrical network.

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In other such embodiments where the components of the weak power system may be interconnected at a point of common coupling, the step of detecting the change in load of the electrical network connected to the weak power system may include measuring a change in voltage at the point of common coupling.

In further such embodiments, the step of detecting the change in load of the electrical network connected to the weak power system may include measuring an instantaneous speed error of the power generator.

In other such embodiments where the components of the weak power system may be interconnected at a point of common coupling, the step of detecting the change in load of the electrical network connected to the weak power system includes monitoring the impedance of the electrical network from the point of common coupling.

The method of detecting the change in load of the connected electrical network can be adjusted for compatibility with the type of weak power system in use. Moreover, it is possible to coordinate the

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detection step with the operation of the power generator and the static synchronous compensator to speed up the response to any change in load of the connected electrical network. This feature is particularly useful for unexpected load changes such as short circuit power system faults.

In embodiments employing the step of detecting the change in load of the electrical network, the method may further include the steps of: generating a first control signal following the detection of the change in load of the electrical network connected to the weak power system; and sending the first control signal to the power generator to effect modification of the power output of the power generator to match the load of the electrical network.

In such embodiments, the first control signal may include the calculated time required to modify the power output of the power generator to match the load of the electrical network.

In embodiments employing the step of detecting the change in load of the electrical network, the method may further include the steps of: generating a second control signal following the detection of the change in load of the electrical network connected to the weak power system; and sending the second control signal to the static synchronous compensator to effect control of the energy storage device to either supply

real power to the electrical network or absorb real power from the power generator

5 In such embodiments, the second control signal may include the calculated static synchronous compensator current required to control the energy storage device to either supply real power to the electrical network or absorb real power from the power generator.

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The generation of the first and/or second control signals enables the automation of the regulation of the system frequency in the weak power system, and thereby removes the need for an operator to manually operate the prime mover of the power generator and the static synchronous generator. This in turn improves the operational reliability and efficiency of the weak power system.

20 According to a second aspect of the invention, there is provided a weak power system comprising a power generator; a static synchronous compensator, an energy storage device and a control unit, the weak power system being connectable to an electrical network, the power generator being operable to generate power for presentation to the electrical network, and the control unit being operable to control the power generator and the static synchronous compensator, wherein the control unit is operable in accordance with the method of the first aspect of the

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invention to regulate system frequency in the weak power system.

Preferably the energy storage device includes at least one capacitor or at least one other device that is capable of storing or releasing energy. For example, the energy storage device may include one or more short-term energy storage media that can respond within a few milliseconds.

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Energy storage devices with fast charging and discharging characteristics are preferred to provide a fast response of the weak power system to a change in load of the connected electrical network.

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In embodiments of the invention, the control unit is configured to generate a first control signal and send the first control signal to the power generator to effect modification of the power output of the power generator to match the load of the electrical network in response to the detection of the change in load of the electrical network connected to the weak power system.

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In other embodiments, the control unit is configured to generate a second control signal and send the second control signal to the static synchronous compensator to effect control of the energy storage device to either supply real power to the electrical network or absorb real power from the power generator. In such embodiments, the weak power system may further

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include a governor being configured to measure an instantaneous speed error of the power generator and the control unit is configured to generate the second control signal upon measurement of the instantaneous speed error. In such embodiments, the weak power system may further include a high gain, high bandwidth error amplifier configured to amplify the instantaneous speed error measured by the governor for presentation to the control unit.

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The provision of such a governor removes the need to provide a reference value for the time required to modify the power output of the power generator to match the load of the electrical network following the change in load of the electrical network. This is because the measurement of the instantaneous speed error results in a second control signal that is capable of providing a current reference for as long as necessary for the static synchronous compensator to be operated.

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Preferred embodiments of the invention will now be described, by way of non-limiting examples, with reference to the accompanying drawings in which:

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Figure 1 shows, in schematic form, a weak power system according to a first embodiment of the invention;

Figure 2 shows a simplified control diagram illustrating the control of the embedded power generator;

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Figure 3 illustrates a throttle response of a diesel engine;

Figure 4 illustrates a step change in load of the connected electrical network and the variations in the supply of real power from the energy storage device and in the power output of the embedded power generator in response to the step change in load of the connected electrical network;

Figures 5 and 6 respectively show a change in speed of a synchronous generator in response to a change in load of the connected electrical network when real power is supplied and not supplied from the energy storage device;

Figures 7 and 8 respectively show a variation in voltage and voltage angle at a point of common coupling of the weak power system in response to a change in load of the connected electrical network when real power is supplied from the energy storage device;

Figure 9 shows the variation in load current, generator current and static synchronous compensator current in response to a change in load of the connected electrical network when real power is supplied from the energy storage device;

Figures 10 and 11 respectively show the rate of change of system frequency in response to a change in load of the connected electrical network when real power is supplied and not supplied from the energy storage device;

Figure 12 shows, in schematic form, a simulation circuit representing a weak power system according to a second embodiment of the invention; and

Figure 13 shows the changes in speed of the synchronous generator and voltage at the point of common coupling in response to a change in load of the electrical network when real power is supplied and not supplied from the energy storage device.

A weak power system according to a first embodiment of the invention is shown in Figure 1.

For the purposes of this specification, the term "weak power system" refers to a power system connected to a single load that is comparable to the supply rating of the power system.

The weak power system in Figure 1 is a microgrid 10 that comprises an embedded power generator 12, a static synchronous compensator 14, an energy storage device 16 and a control unit 18.

In use, the embedded power generator 12 and the static synchronous compensator 14 are connected to a main grid 20 and a connected electrical network 22 via a point of common coupling 24 of the microgrid 10. It is envisaged that, in other embodiments, the microgrid 10 may be disconnected from the main grid 20.

The embedded power generator 12 includes a synchronous generator 26, a prime mover (not shown), an

automatic voltage regulator 28 and a governor 30. The prime mover is a diesel engine configured to drive the synchronous generator 26. The automatic voltage regulator 28 is configured to regulate the amplitude of the output voltage of the synchronous generator 26 while the governor 30 is configured to control the speed of the prime mover to maintain the frequency of the synchronous generator 26.

Figure 2 shows a simplified control diagram illustrating the control of the embedded power generator 12.

The speed of the synchronous generator 26 is controlled to be set at 50 Hz by measuring the speed and using a proportional plus integral controller to provide a reference value 34 for the control 32 of the prime mover. The output of the prime mover is the torque T_m driving the synchronous generator 26. The load of the connected electrical network 22 is represented by a load torque T_e in the control diagram shown in Figure 2. Both torque values, T_m and T_e , are equal under steady state conditions. However, a change in load of the connected electrical network 22 will result in a change in speed of the synchronous generator 26. For example, when the load torque T_e exceeds the torque driving the synchronous generator 26 T_m , the difference in torque will cause the synchronous generator 26 to decelerate. The resulting speed error will cause the speed control 36 to increase T_m to initially accelerate the speed of the synchronous

generator 26 back to its original value, and to ensure that the load torque T_e matches the torque T_m driving the synchronous generator 26.

5 The static synchronous compensator 14 is configured to control the energy storage device 16 to inject or absorb real power via the point of common coupling 24. The energy storage device 16 may, for example, include one or more short-term energy storage
10 media, such as a capacitor, that can typically respond within a few milliseconds.

 The control unit 18 is configured to generate a first control signal 38, which is
15 subsequently sent to the embedded power generator 12. The control unit 18 is also configured to generate a second control signal 40, which is subsequently sent to the static synchronous compensator 14. Each control signal includes a reference value for the control of
20 the power generator and the static synchronous compensator 14 respectively.

 The control unit 18 is configured to monitor and measure the load current 42 of the
25 connected electrical network 22. This allows the control unit 18 to detect any change in load current of the electrical network, which corresponds to a change in load of the connected electrical network 22. Examples of a change in load of the connected
30 electrical network 22 include, but are not limited to, large step changes in load or short-duration, short

circuit power system faults in the connected electrical network 22 and load shedding in the connected electrical network 22.

5 It is envisaged that, in other embodiments, the control unit 18 for the microgrid 10 may be integrated into a control platform for the static synchronous compensator 14.

10 The detection of the change in load of the connected electrical network 22 may be carried out in different ways.

 For example, the governor 30 may be
15 configured to measure an instantaneous speed error of the synchronous generator 26 and the control unit 18 may be configured to generate the second control signal 40 upon measurement of the instantaneous speed error. Such a weak power system may further include a high
20 gain, high bandwidth error amplifier configured to amplify the instantaneous speed error measured by the governor 30 for presentation to the control unit 18.

 The provision of such a governor 30 removes
25 the need to calculate the time t_{es} required to modify the power output of the power generator to match the load of the electrical network following the change in load of the electrical network. This is because the measurement of the instantaneous speed error results in
30 a second control signal 40 that is capable of providing a current reference for as long as necessary for the

static synchronous compensator 14 to be operated. It was noted that this will result in a more oscillatory response to the change in load of the connected electrical network 22.

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Alternatively the detection of the change in load of the connected electrical network 22 may be triggered by measurement of a change in voltage at the point of common coupling 24. or may be triggered by
10 monitoring the impedance to source at the point of common coupling using the static synchronous compensator 14 using the technique described in the publication titled "Sumner M, Palethorpe B and Thomas, D W P T, "Impedance Measurement for Improved Power
15 Quality - Part 1: the Measurement Technique", *IEEE Transactions on Power Delivery*, Volume 19, Issue 3, July 2004 Page(s):1442 - 1448".

The detection of a change in load of the
20 connected electrical network 22 by the control unit 18 triggers the calculation of the time t_{es} required to modify the power output of the embedded power generator 12 to match the load of the connected electrical network 22 following the change in load of the
25 connected electrical network 22. In other words, the value of t_{es} determines the time required to apply a maximum throttle Th_{max} to the input of the diesel engine in order to modify the torque driving the synchronous generator 26 T_m from a value of T_{ebc} to a value of T_{eac} ,
30 where T_{ebs} and T_{eac} are the values of the load torque

required before and after the change in load of the connected electrical network 22 respectively.

The change in load torque before and after the change in load of the connected electrical network 22 is calculated using Equations (1) to (4) based on the assumption that both the system voltage and system frequency of the microgrid 10 are constant during the change in load of the connected electrical network 22.

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$$P_{ebc} = \sqrt{3} \cdot V_{pcc} \cdot I_{pcc} \quad (1)$$

$$T_{ebc} = P_{ebc} / \omega_e \quad (2)$$

$$15 \quad P_{eac} = \sqrt{3} \cdot V_{pcc} \cdot I_{pcc} \quad (3)$$

$$T_{eac} = P_{eac} / \omega_e \quad (4)$$

where V_{pcc} and I_{pcc} are the voltage and current measured at the point of common coupling 24 shown in Figure 1; P_{ebc} and P_{eac} is the output power before and after a change in load of the connected electrical network 22; and ω_e is the system frequency.

25 It is assumed that the response between the throttle demand 44 applied to the input of the diesel generator and the torque T_m driving the synchronous generator 26 is dominated by a first order lag with a time constant T_{gov} and a gain K , as shown in Figure 3.

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The time required to apply the maximum throttle to the input of the diesel engine is calculated using Equations (5) and (6) on the basis of an assumed throttle response of the diesel engine shown in Figure 3.

$$T_{eac} = (K \cdot Th_{max} - T_{ebc}) (1 - e^{-(t_{es}/T_{gov})}) + T_{ebc} \quad (5)$$

Equation (6) is derived by rearranging Equation (5).

$$t_{es} = (-\log((kTh_{max} - T_{eac}) / (kTh_{max} - T_{ebc}))) / T_{gov} \quad (6)$$

The detection of a change in load of the connected electrical network 22 by the control unit 18 also triggers the calculation of the static synchronous compensator current I_{dST} required to control the energy storage device 16 to either supply real power to the connected electrical network 22 or absorb real power from the embedded power generator 12 following the change in load of the connected electrical network 22.

The real power supplied or absorbed by the energy storage device 16 is initially set to be substantially equal to the change in load of the connected electrical network 22. As such, the corresponding initial value of I_{dST} can be calculated using Equation (7)

$$I_{dST} = P_{ebc} - P_{eac} / V_d \quad (7)$$

where V_d is a variable used in the control of the static synchronous compensator 14 to represent the supply voltage of the microgrid 10, and I_{dST} is the in-phase (real) component of the injected static synchronous compensator 14 current.

The calculated values of t_{es} and I_{dST} are respectively included as a reference value in the first and second control signals 38,40, which are simultaneously sent by the control unit 18 to the embedded power generator 12 and the static synchronous generator 26 respectively. This in turn results in the simultaneous modification of the power output of the embedded power generator 12 and operation of the static synchronous compensator 14 to control the energy storage device 16, which is illustrated in Figure 4 in which the change in load of the connected electrical network 22 is represented by a step function 46.

The sending of the first control signal 38 to the embedded power generator 12 effects the application of a maximum throttle Th_{max} to the input of the diesel engine for a period of time equivalent to t_{es} until the torque T_m driving the synchronous generator 26 is equivalent to the value of the load torque T_e required after the change in load of the connected electrical network 22. This result in the modification of the power output of the embedded power generator 12 from P_{ebc} to P_{eac} to match the load of the connected electrical network 22 following the change in load of the connected electrical network 22.

Whilst the output power of the embedded power generator 12 is changing over the interval t_{es} , the sending of the second control signal 40 to the static synchronous compensator 14 effects control of the energy storage device 16 to either supply real power to the electrical network or absorb real power from the embedded power generator 12 depending on whether the load of the connected electrical network 22 increases or decreases.

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Since the real power supplied or absorbed by the energy storage device 16 is initially set to be substantially equal to the change in load of the connected electrical network 22 as set out above, the microgrid 10 is capable of providing real power to temporarily compensate for the change in load of the connected electrical network 22 until the embedded power generator 12 is capable of providing all the necessary power output to match the load of the connected electrical network 22.

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Following the initial injection or absorption real power by the energy storage device 16, the static synchronous compensator 14 is operated to control the energy storage device 16 to linearly decrease the supply or absorption of real power over the interval t_{es} . In Figure 4, the linear decrease of the supply or absorption of real power by the energy storage device 16 over the interval t_{es} is controlled to approximately match the rate of change of embedded generator power output. This allows the microgrid 10

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to present a substantially constant power that matches the load of the connected electrical network 22 over the interval t_{es} and thereby minimises the variation in speed of the synchronous generator 26.

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Figures 5 and 6 respectively show a change 52,54 in speed of a synchronous generator 26 in response to a change in load of the connected electrical network 22 when real power is supplied or
10 not supplied from the energy storage device 16.

The results 52,54 in Figure 5 and 6 are based on a simulation of a microgrid 10 comprising a embedded power generator 12 with approximately 1%
15 source impedance, the microgrid 10 being connected to the electrical network having a load that changes from 0 to 0.8PU at $t = 0.4$ s. The prime mover, i.e. the diesel engine, is represented by a time constant (T_{gov}) which is equal to 100 ms and represents a delay in
20 actuation. Any delay in combustion is ignored. The control of the prime mover of the embedded power generator 12 is a proportional plus integral controller designed to give a closed loop bandwidth of 5Hz, and the system inertia is 0.2 kgm^2 .

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The result 50 in Figure 5 includes the operation of the static synchronous compensator 14 to control the energy storage device 16 to supply real power to the connected electrical network 22 following
30 the change in load of the electrical network. The static synchronous compensator 14 has a current control

bandwidth of 150Hz, and operates at a switching frequency of 5kHz. The DC link of the static synchronous compensator 14 is fed from a bank of supercapacitors with a power capability of 1 PU for 5 100ms.

In Figure 5, the speed of the synchronous generator 26 changes by less than 0.1% during the change in load of the connected electrical network 22. 10 This simulation result 50 includes a delay of 0.5 ms to represent the communication delay between the static synchronous compensator 14 and the control of the embedded power generator 12. The communication delay is shown in Figure 5 to have minimal influence on the 15 behaviour of the microgrid 10.

The result 52 in Figure 6 omits the operation of the static synchronous compensator 14 to control the energy storage device 16 to supply real 20 power to the connected electrical network 22 following the change in load of the electrical network.

In Figure 6, the speed of the power generator changes by over 2.5% and the initial rate of change of frequency is 75 Hz/s. As set out earlier, 25 this change 52 in speed of the power generator may be sufficiently large to either cause the output frequency go outside of a statutory range of operating frequency, or be detected by a rate of change of frequency (ROCOF) 30 relay, which could cause tripping of the embedded power generator 12 and potential system failure.

The behaviour of the microgrid 10 in Figure 1 is further illustrated in Figures 7 to 10.

Figures 7 and 8 respectively shows a variation in voltage and voltage angle at a point of common coupling 24 of the microgrid 10 in response to a change in load of the connected electrical network 22 when real power is supplied from the energy storage device 16.

It was found that the supply impedance causes a significant voltage disturbance 54 at $t = 0.4s$, i.e. the point of change of load of the connected electrical network 22 prior to the detection of the change in load by the control unit 18 of the microgrid 10. This voltage disturbance 54 however is quickly minimised by the fast and correct control of the static synchronous compensator 14 and energy storage device 16 upon detection of the change in load of the connected electrical network 22, as seen in Figure 7. The use of a phased locked loop to derive the measured angle 56 of the supply voltage used by the static synchronous compensator 14 controller was found to be sufficient with this voltage disturbance, as shown in Figure 8.

Figure 9 shows the variations 58,60,62 in load current, generator current and static synchronous compensator current in response to a change in load of the connected electrical network 22 when real power is supplied from the energy storage device 16. The load current 58 is represented as a step function, whereas

the generator current 60 includes an initial fast transient followed by a comparatively slow, controlled change as the load torque of the embedded power generator 12 is built up with minimal variation in synchronous generator speed. The initial fast transient of the generator current is required to briefly match the load of the connected electrical network 22 in the time it takes for the static synchronous compensator 14 to respond to the change in load of the connected electrical network 22. The static synchronous compensator current is seen to be increasing quickly once the change in load is detected. The current profiles in Figure 9 are comparable to the ideal profiles shown in Figure 3, but includes a rise time of approximately 3-4ms.

The rate of change of system frequency 64 in the microgrid 10 according to the invention is shown in Figure 10. The rate of change of frequency 64 is calculated as the derivative of the synchronous generator speed, and is passed through a first order filter with a time constant of six fundamental cycles, as described in the publication titled "Performance of ROCOF relays for embedded generation applications", Affonso, C.M.; Freitas, W.; Xu, W.; da Silva, L.C.P.; *IEE Proceedings Generation, Transmission & Distribution*, Vol 152, Jan. 2005, pp 109 - 114". When the static synchronous compensator 14 is operated to control the energy storage device 16 to supply real power to the connected electrical network 22 in response to the change in load of the connected

electrical network 22, the rate of change of system frequency 64 was found to be less than 0.4 Hz/s, which is within typical threshold ranges of 0.1Hz/s and 1.0Hz/s for ROCOF relays.

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In comparison, when real power is not supplied to the connected electrical network 22 in response to the change in load of the connected electrical network 22, the rate of change of system frequency 66 is found to exceed 50 Hz/s, which exceeds the typical threshold ranges for ROCOF relays set out above.

Figure 12 shows, in schematic form, a simulation circuit representing a weak power system according to a second embodiment of the invention.

The weak power system in Figure 12 is an isolated microgrid 110 that is connected via a point of common coupling 124 to a 10kW load 122a and an electrical network 122b that is capable of producing a 3MW step change of load, as illustrated in Figure 12. The isolated microgrid 110 is also connected via the point of common coupling 124 to a 3.5 MVA diesel generator 112 via a transformer and a static synchronous compensator 114 connected an energy storage device 16.

The variation in generator rotor speed 68 and voltage 70 during the 3MW step change of load is shown in Figure 13. It can be seen that there is a

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speed drop 72 of over 5% for over 4 seconds when real power is not supplied to the connected electrical network 22 in response to the change in load of the connected electrical network 22. When the static synchronous compensator 114 is operated to control the energy storage device 116 to supply real power to the connected electrical network 122b in response to the change in load of the connected electrical network 122b, the corresponding speed drop 74 is reduced to less than 1%, as shown in Figure 14.

The simultaneous modification of the power output of the power generator and operation of the static synchronous compensator during a change in load of the connected electrical network therefore minimises the change in speed of the synchronous power generator and thereby enables regulation of the system frequency in the microgrid. This improves the overall reliability of the microgrid.

In addition, the inclusion of the static synchronous compensator not only allows the weak power system to rapidly respond to dynamic and transient power changes, but also allows the virtually instantaneous absorption and injection of real power to the microgrid. Moreover, the coordination of the rates of change of the respective power outputs of the power generator and the energy storage device is possible via the capability of the static synchronous compensator to finely control the supply or absorption of real power.

CLAIMS

1. A method of regulating system frequency in a weak power system (10) including a power generator (12); a static synchronous compensator (14) and an energy storage device (16), where the weak power system (10) is connected to an electrical network (22) and the power generator (12) is operable to generate power for presentation to the electrical network (22), the method comprising the steps of: following a change in load of the electrical network (22), simultaneously modifying a power output of the power generator (12) to match the load of the electrical network (22) and operating the static synchronous compensator (14) to control the energy storage device (16) to either supply real power to the electrical network (22) or absorb real power from the power generator (12).

2. A method according to Claim 1 wherein the real power supplied or absorbed by the energy storage device (16) is initially substantially equal to the change in load of the electrical network (22).

3. A method according to Claim 1 or Claim 2 further including the step of operating the static synchronous compensator (14) to control the energy storage device (16) to gradually reduce the supply or absorption of real power over a predetermined period of time.

4. A method according to Claim 3 including the step of operating the static synchronous compensator (14) to control the energy storage device (16) to coordinate the gradual reduction of the supply or absorption of real power with the rate of change of power output of the generator so as to present a substantially constant power to the electrical network (22).

5. A method according to any preceding claim further including the step of calculating the time required to modify the power output of the power generator (12) to match the load of the electrical network (22) following the change in load of the electrical network (22).

6. A method according to any preceding claim further including the step of calculating the static synchronous compensator (14) current required to control the energy storage device (16) to either supply real power to the electrical network (22) or absorb real power from the power generator (12) following the change in load of the electrical network (22).

7. A method according to any preceding claim further including the step of detecting a change in load of the electrical network (22) connected to the weak power system (10) prior to the step of simultaneously modifying the power output of the power generator (12) and operating the static synchronous

compensator (14) to control the energy storage device (16).

8. A method according to Claim 7 wherein
5 the step of detecting the change in load of the electrical network (22) connected to the weak power system (10) includes measuring a change in load current (58) of the electrical network (22).

10 9. A method according to Claim 7, where the components of the weak power system (10) are interconnected at a point of common coupling (24), the step of detecting the change in load of the electrical network (22) connected to the weak power system (10)
15 includes measuring a change in voltage at the point of common coupling (24).

10. A method according to Claim 7 wherein the step of detecting the change in load of the
20 electrical network (22) connected to the weak power system (10) includes measuring an instantaneous speed error of the power generator (12).

11. A method according to Claim 7,
25 where the components of the weak power system (10) are interconnected at a point of common coupling (24), wherein the step of detecting the change in load of the electrical network (22) connected to the weak power system (10) includes monitoring the impedance to source
30 at the point of common coupling (24).

12. A method according to any of Claims 7 to 11 further including the steps of: generating a first control signal (38) following the detection of the change in load of the electrical network (22) connected to the weak power system (10); and sending the first control signal (38) to the power generator (12) to effect modification of the power output of the power generator (12) to match the load of the electrical network (22).

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13. A method according to Claim 12 when dependent from Claim 5 wherein the first control signal (38) includes the calculated time required to modify the power output of the power generator (12) to match the load of the electrical network (22).

14. A method according to any of Claims 7 to 13 further including the steps of: generating a second control signal (40) following the detection of the change in load of the electrical network (22) connected to the weak power system (10); and sending the second control signal (40) to the static synchronous compensator (14) to effect control of the energy storage device (16) to either supply real power to the electrical network or (22) absorb real power from the power generator.

15. A method according to Claim 14 when dependent from Claim 6 wherein the second control signal (40) includes the calculated static synchronous compensator current (62) required to control the energy

30

storage device (16) to either supply real power to the electrical network (22) or absorb real power from the power generator (12).

5 16. A weak power system (10) comprising
a power generator (12), a static synchronous
compensator (14), an energy storage device (16) and a
control unit (18), the weak power system (10) being
connectable to an electrical network (22), the power
10 generator (12) being operable to generate power for
presentation to the electrical network (22), and the
control unit (18) being operable to control the power
generator (12) and the static synchronous compensator
(14) , wherein the control unit (18) is operable in
15 accordance with the method of Claims 1 to 15 to
regulate system frequency in the weak power system
(10).

 17. A weak power system (10) according
20 to Claim 16 wherein the energy storage device (16)
includes at least one capacitor.

 18. A weak power system (10) according
to Claim 16 or Claim 17 wherein the control unit (18)
25 is configured to generate a first control signal (38)
and send the first control signal (38) to the power
generator (12) to effect modification of the power
output of the power generator (12) to match the load of
the electrical network (22) in response to the
30 detection of the change in load of the electrical
network (22) connected to the weak power system (10).

19. A weak power system (10) according to any of Claims 16 to 18 wherein the control unit (18) is configured to generate a second control signal (40) and send the second control signal (40) to the static synchronous compensator (14) to effect control of the energy storage device (16) to either supply real power to the electrical network (22) or absorb real power from the power generator (12).

10

20. A weak power system (10) according to Claim 19 further including a governor (30), the governor (30) being configured to measure an instantaneous speed error of the power generator (12) and the control unit (18) being configured to generate the second control signal (40) upon measurement of the instantaneous speed error.

21. A weak power system (10) according to Claim 20 further including a high gain, high bandwidth error amplifier configured to amplify the instantaneous speed error measured by the governor (30) for presentation to the control unit (18).

1 / 7

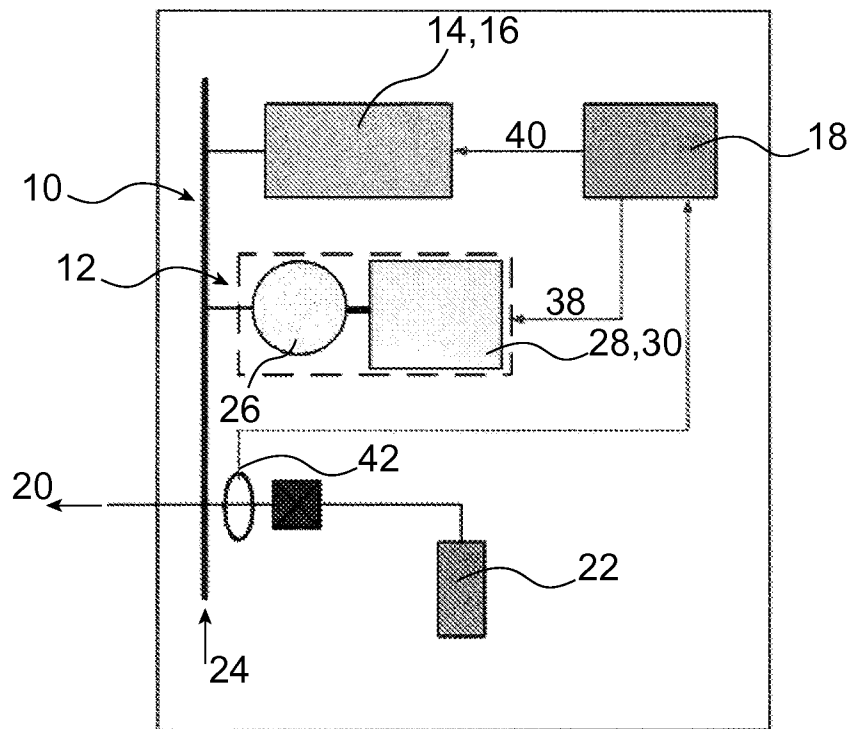


FIG. 1

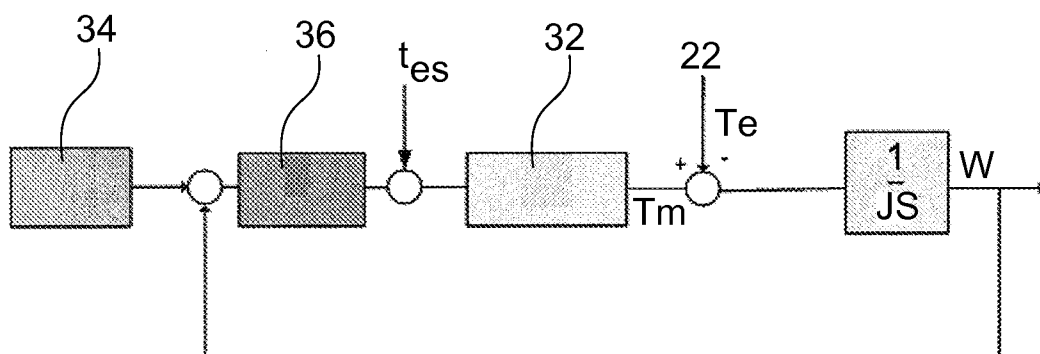


FIG. 2

2 / 7

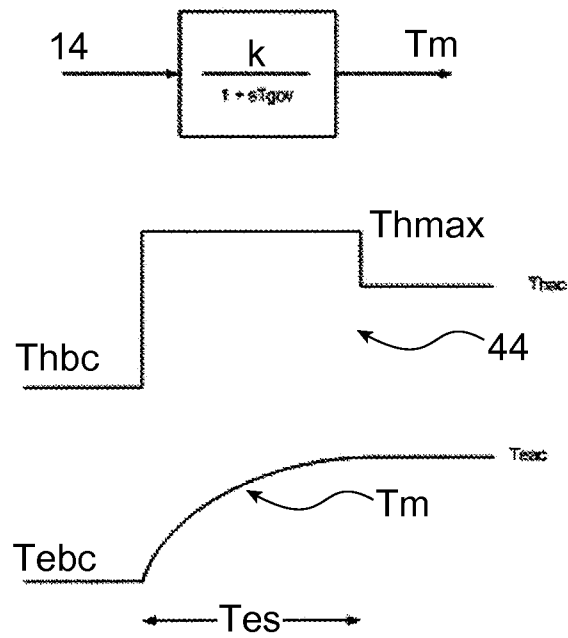


FIG. 3

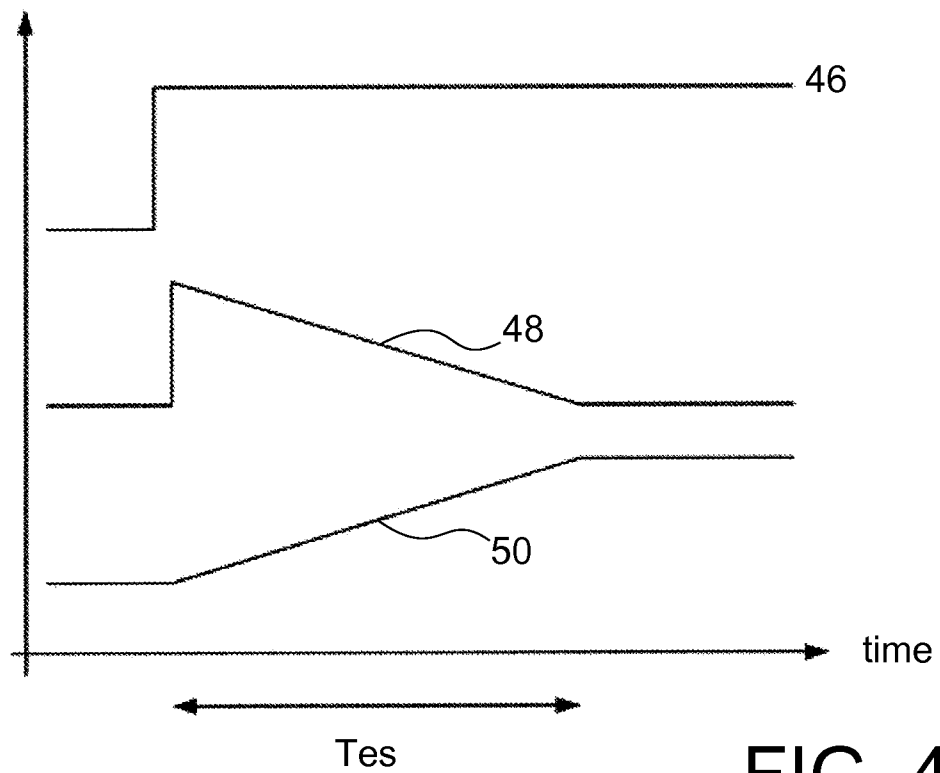


FIG. 4

3 / 7

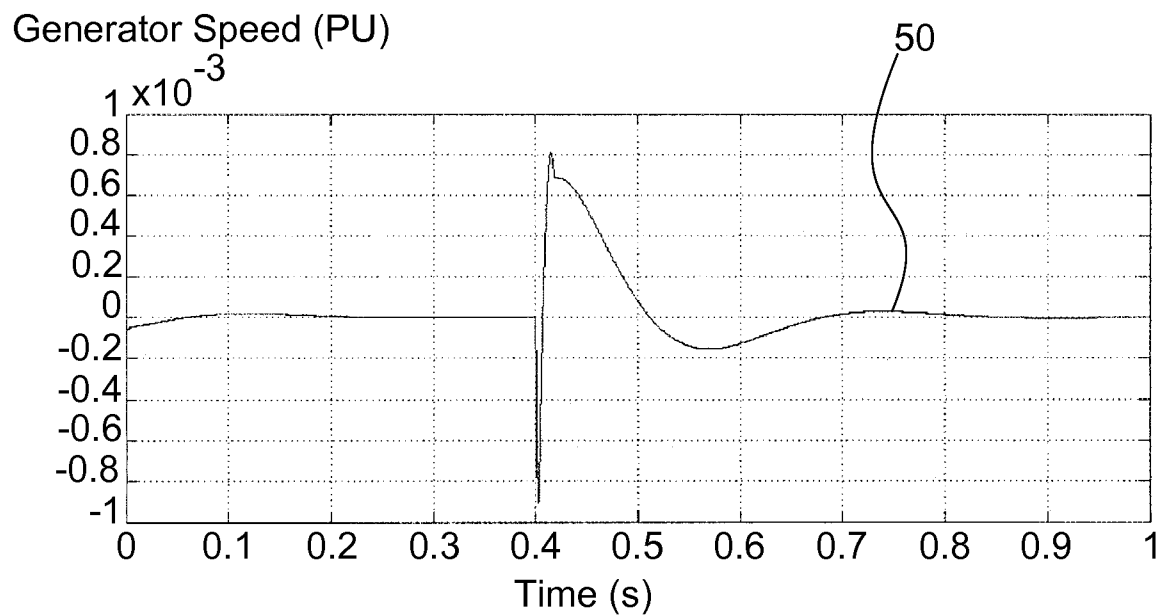


FIG. 5

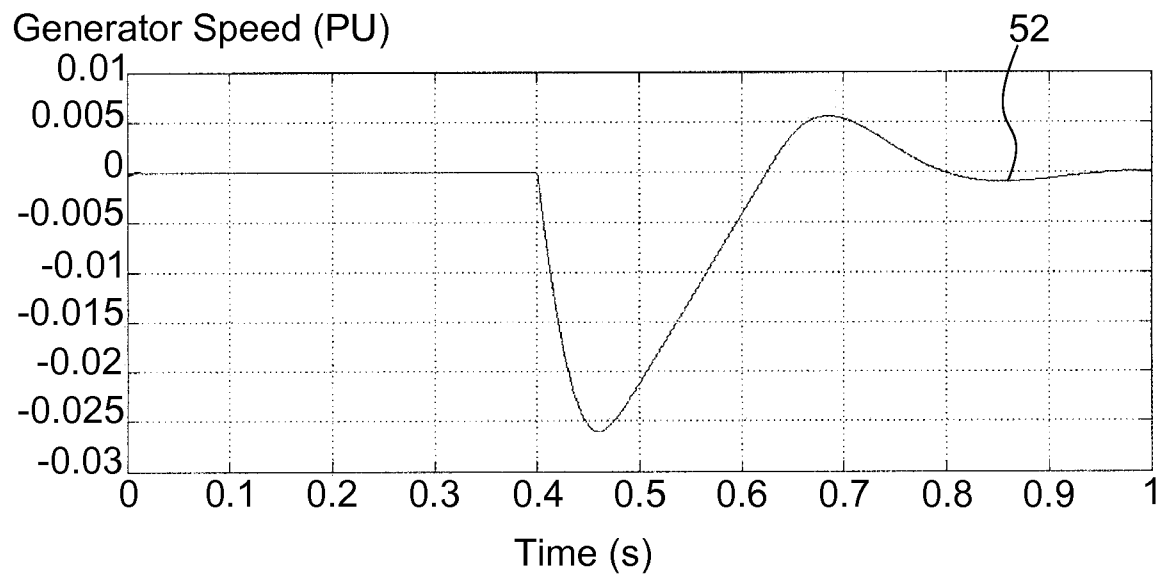


FIG. 6

4 / 7

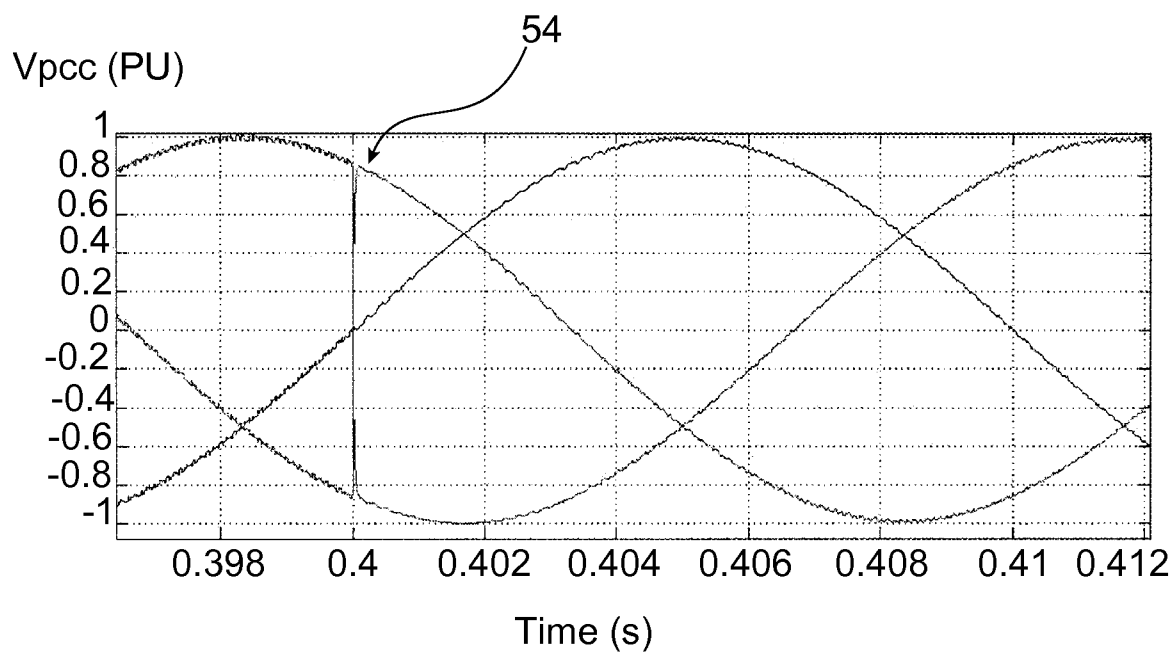


FIG. 7

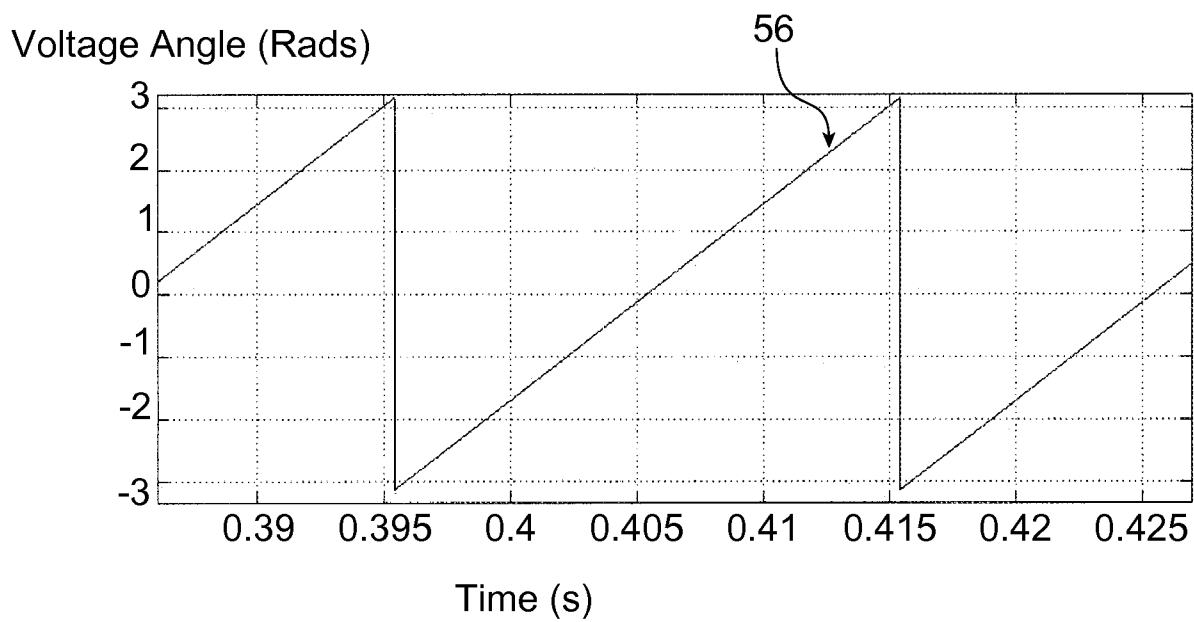


FIG. 8

5 / 7

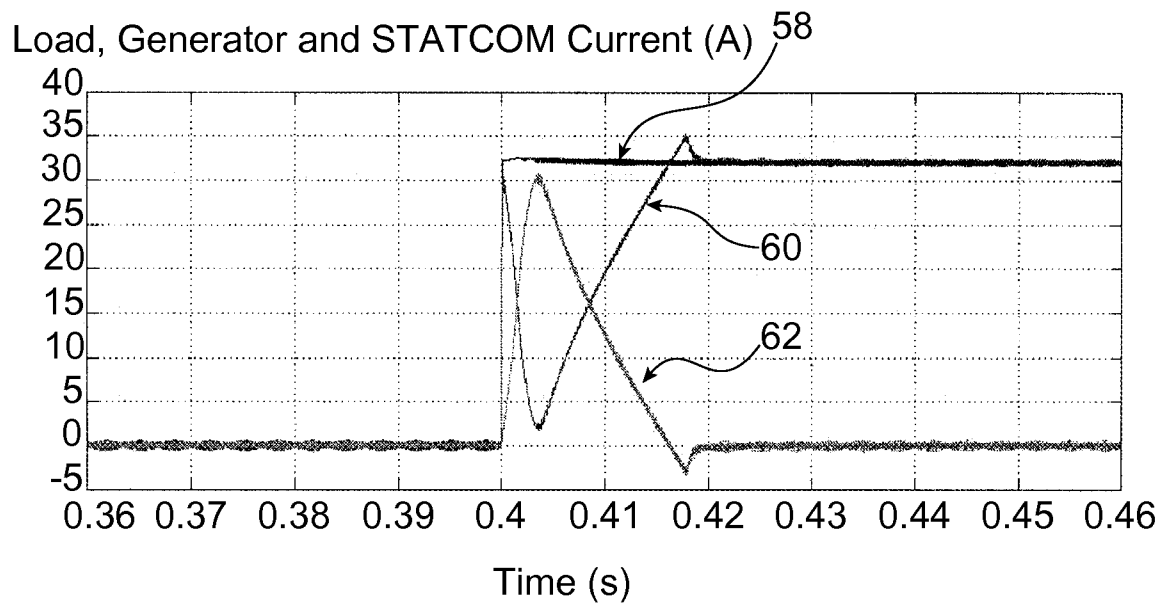


FIG. 9

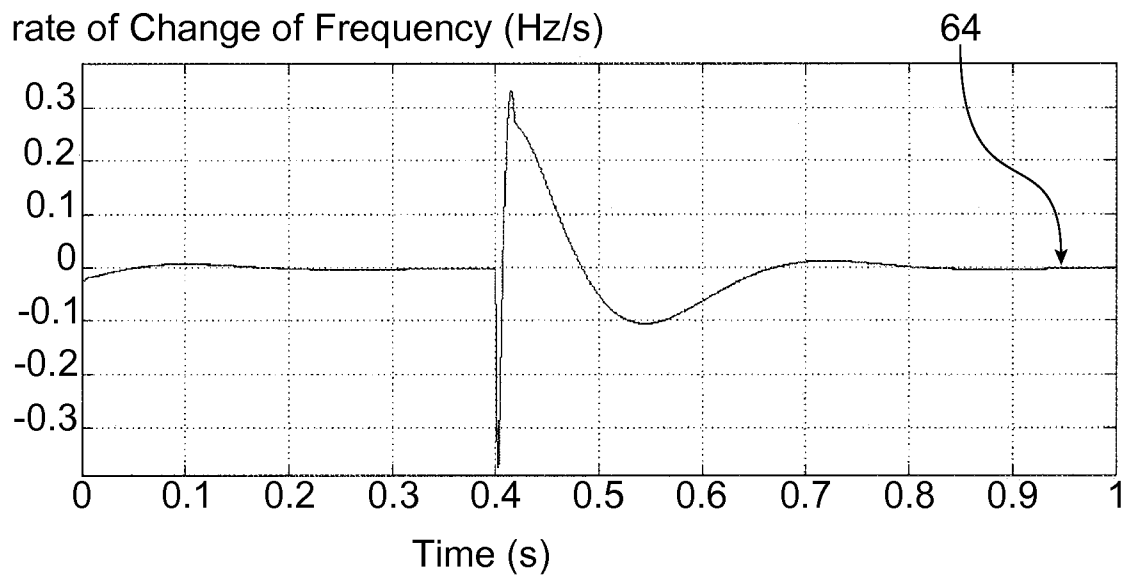


FIG. 10

6 / 7

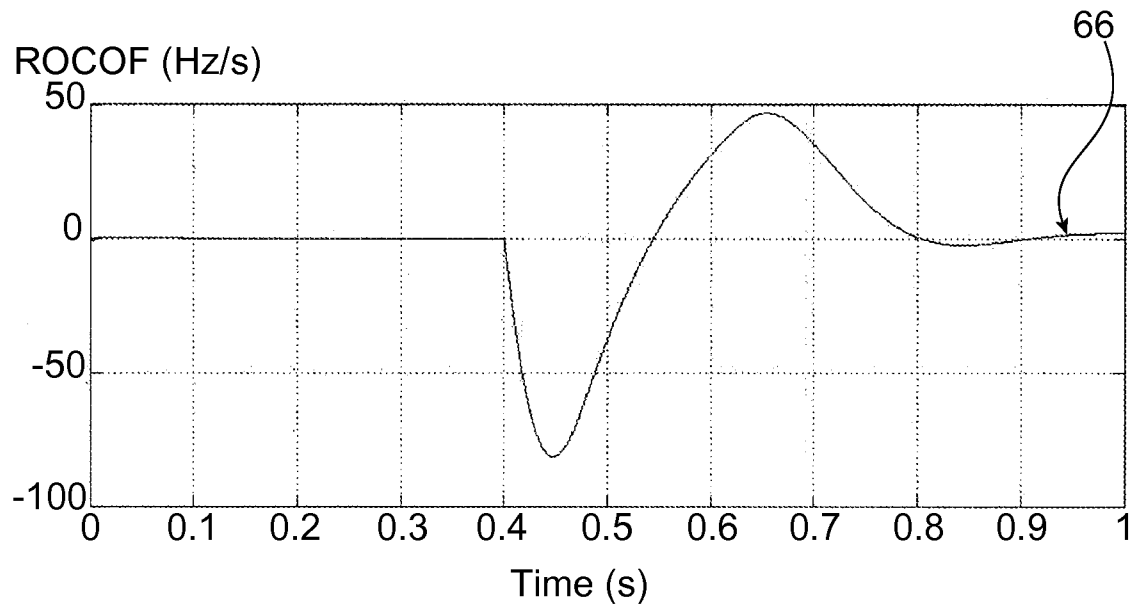


FIG. 11

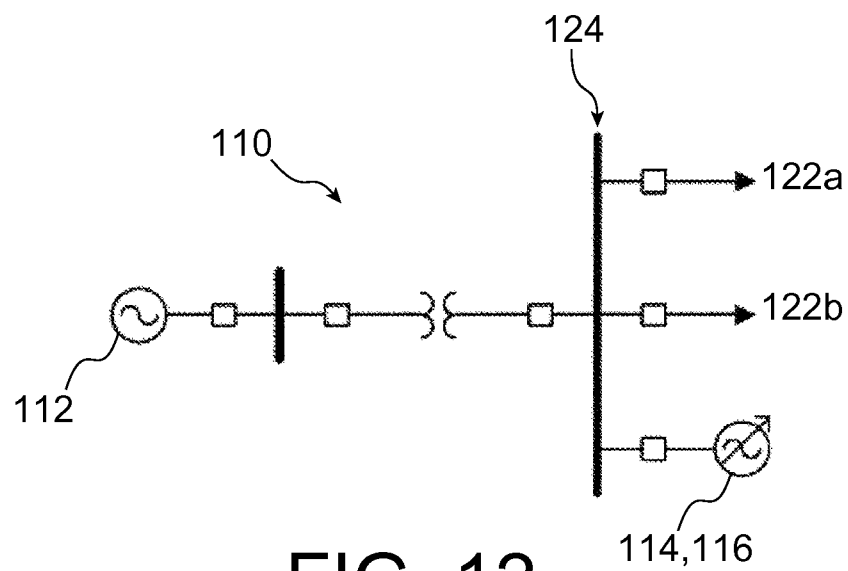


FIG. 12

7 / 7

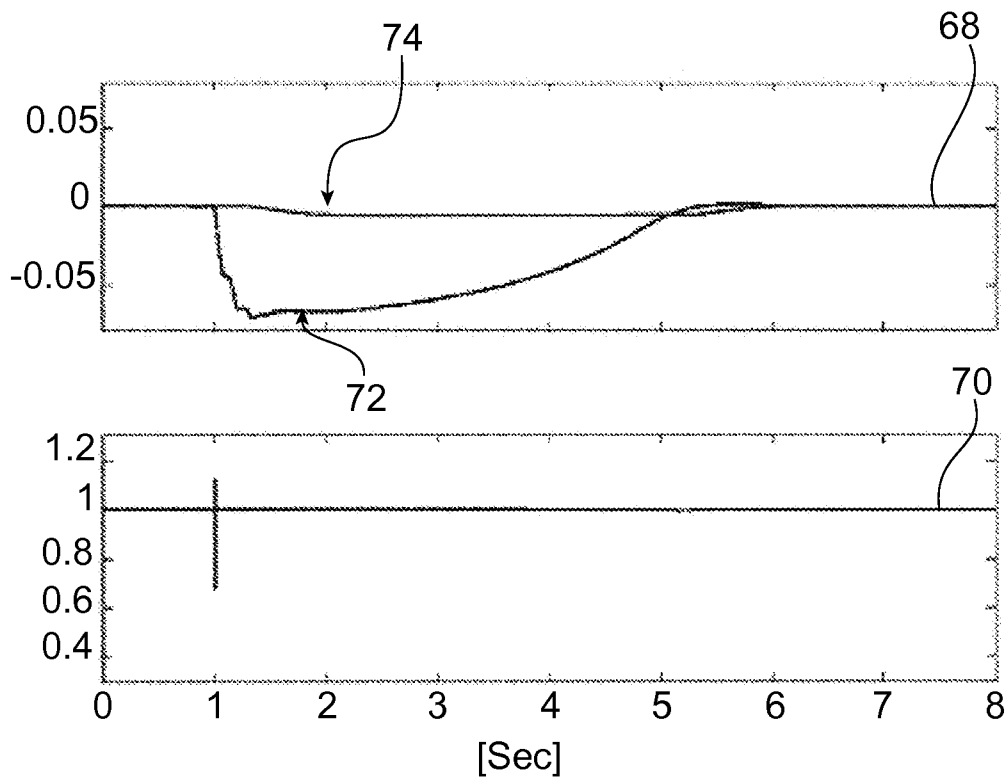


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/058691

A. CLASSIFICATION OF SUBJECT MATTER

INV. H02J3/16 H02J3/32 H02J3/48 H02J3/50
ADD.

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)
H02J

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 1 122 856 A2 (SUMITOMO ELECTRIC INDUSTRIES [JP]; KANSAI ELECTRIC POWER CO [JP]) 8 August 2001 (2001-08-08) abstract paragraph [0009] - paragraph [0015] paragraph [0025] - paragraph [0030] paragraph [0032] - paragraph [0034] paragraph [0038] - paragraph [0053] figures 1-3 -----	1-4,6-9, 12,14-19
Y	EP 1 887 674 A1 (ENDESA GENERACION S A [ES]) 13 February 2008 (2008-02-13) abstract paragraph [0002] - paragraph [0007] paragraphs [0010], [0012] - [0023] paragraph [0032] figures ----- -/-	1-4,6-9, 12,14-19



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

25 April 2012

Date of mailing of the international search report

08/05/2012

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/058691

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

International application No

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