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Device for demand-side
power management 6

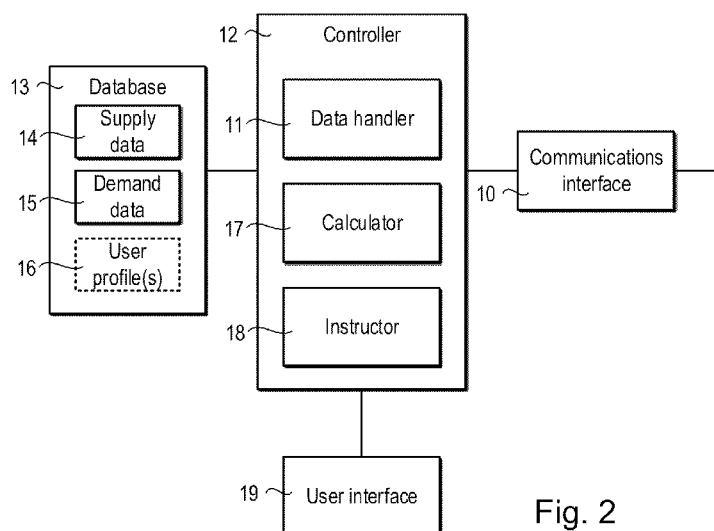


Fig. 2

(57) **Abstract:** A device (6) for demand-side power management is described. The device includes a power management controller (12), at least one communications interface (10) for receiving information about total power supplied to a power network (1) and for communicating with a plurality of demand-side controllers (9), wherein each demand-side controller is for measuring and controlling power supplied to a respective load (8). The power management controller is configured to calculate, based on the total power supplied to the power network and on a plurality of power demand measurements from the demand-side controllers, a power imbalance in the power network. The power management controller is also configured to select, based on the power imbalance, at least one load to manage, and to generate and cause transmission of a control signal to at least one demand-side controller. The control signal is indicative of an amount by which a voltage supplied to the load is to be varied by the demand-side controller.

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Power management

Field

The present invention relates to power management, in particular to a power
5 management device for communicating with a demand-side controller which can vary
power supplied to a load.

Background

In a power network (or “grid”), such as a national power grid, power is generated and
10 supplied to a load. Preferably, power generation and the power required by the load
 (“the load demand”) are balanced. If the balance of load and generation is not
 maintained, the network may become unstable and this may lead to blackout.

Power balance within a power network may be regulated by compensating for the
15 shortfall in power or by absorbing excess power. This issue is becoming more relevant
 in national power grids because an increasing portion of users’ energy requirements is
 being met by intermittent energy sources, such as wind and other renewable energy
 sources.

20 Potential power imbalances within a power network can be ameliorated by storing
 energy for future use. However, most current forms of energy storage, such as
 electrochemical batteries, tend to be costly and can be difficult to dispose of in an
 environmentally friendly way at the end of their life.

Summary

According to a first aspect of the present invention there is provided a device for demand-side power management. The device includes a power management controller, at least one communications interface for receiving information about total power
5 supplied to a power network and for communicating with a plurality of demand-side controllers, wherein each demand-side controller is for measuring and controlling power supplied to a respective load. The power management controller is configured to calculate, based on the total power supplied to the power network and on a plurality of power demand measurements from the demand-side controllers, a power imbalance in
10 the power network. The power management controller is also configured to select, based on the power imbalance, at least one load to manage, and to generate and cause transmission of a control signal to at least one demand-side controller. The control signal is indicative of an amount by which a voltage supplied to the load is to be varied by the demand-side controller.

15 The device for demand-side power management may include a database comprising user profiles. Each user profile may corresponds to a customer of one of the demand-side controllers and each user profile may indicate whether the customer has elected to have the voltage supplied to the respective load varied by the demand-side controller.

20 According to a second aspect of the present invention there is provided a demand-side controller for varying power supplied to a load in a power network. The demand-side controller includes a communications interface for communicating with a device for demand-side power management in the power network, a measurement device
25 arranged to measure power supplied to the load and configured to generate and cause transmission of corresponding power demand measurements to the device for demand-side power management. The demand-side controller also includes a voltage regulator configured to modify, based on a voltage regulator control signal, a voltage supplied to the load, and a voltage regulator controller for communicating with the voltage
30 regulator. The voltage regulator controller is configured to generate, in response to receiving a control signal from the device for demand-side power management, the voltage regulator control signal, and to cause transmission of the voltage regulator control signal to the voltage regulator.

35 Thus, the device can help maintain power balance or to restore power balance in a power network by managing the load demand.

The voltage regulator may be configured to vary the power supplied to the load by between 5% and 10%.

- 5 The voltage regulator may be configured to modify the voltage supplied to the load by no more than 10% of the rated voltage of the load.

The voltage regulator may be a transformer including a plurality of transformer taps and is configured to switch between transformer taps in response to receiving the
10 voltage regulator control signal.

The voltage regulator may include a load tap for connecting the voltage regulator to the load, wherein the voltage regulator is configured to activate the load tap on receiving the voltage regulator control signal.

15 According to a third aspect of the present invention, there is provided a system. The system includes the device for demand side power management according to the first aspect of the present invention. The system also includes at least one demand-side controller according to the second aspect of the present invention. The device for
20 demand-side power management and the at least one demand-side controller are in communication.

According to a fourth aspect of the present invention, there is provided a method of operating the system according to the third aspect of the present invention. The method
25 includes receiving information about the total power supplied to the power network, generating and transmitting power demand measurements to the device for demand-side power management, calculating, based on the total power supplied to the power network and the power demand measurements, the power imbalance in the power network, selecting, based on the power imbalance, at least one load to manage,
30 generating and transmitting a control signal to the at least one demand-side controller, generating, in response to receiving the control signals, a voltage regulator control signal and transmitting the voltage regulator control signal to the voltage regulator, and modifying, based on the voltage regulator control signal, a voltage supplied to the load.

35 The method may include selecting at least one load to manage based on the user profile of the load.

The method may include modifying the voltage supplied to the load such that the power supplied to the load varies by between 5% and 10%.

Brief Description of the Drawings

Certain embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a schematic block diagram of a power network;

5 Figure 2 is a schematic block diagram of a device for demand-side power management;

Figure 3 is a process flow diagram of a method of operating a device for demand-side power management;

Figure 4 is a schematic block diagram of a data processing system;

10 Figure 5 is a schematic block diagram of a demand-side controller and a device for demand-side power management;

Figure 6 is a schematic block diagram of a first simulated power network;

Figure 7 is a plot of change in AC power frequency over time in the first simulated power network shown in Figure 6;

15 Figure 8a is a plot of change in voltage supplied to a second load over time for the first simulated power network shown in Figure 6;

Figure 8b is a plot of change in power supplied to the second load over time for the first simulated power network shown in Figure 6;

Figure 9a is a plot of change in voltage supplied to a first load over time for the first simulated power network shown in Figure 6;

20 Figure 9b is a plot of change in power supplied to the first load over time for the first simulated power network shown in Figure 6;

Figure 10 a schematic bock diagram of a second simulated power network;

Figure 11 is a plot of change in mechanical power supplied to a generator in the second simulated power network shown in Figure 11 over time;

25 Figure 12 is a plot of change in AC power frequency over time for the second simulated power network shown in Figure 11;

Figure 13 is a plot of change in voltage ratio over time for the second simulated power network shown in Figure 11;

30 Figure 14a is a plot of change in voltage supplied to a second load over time for the second simulated power network shown in Figure 11;

Figure 14b is a plot of change in power supplied to the second load over time for the second simulated power network shown in Figure 11;

Figure 15a is a plot of change in voltage supplied to a first load over time for the second simulated power network shown in Figure 11;

35 Figure 15b is a plot of change in power supplied to the first load over time for the second simulated power network shown in Figure 11;

Detailed Description

A power network preferably operates at an alternating current (AC) power frequency within an acceptable range (or “grid frequency requirement”). This grid frequency
5 requirement is pre-set according to the specifications of the power network. For example, a national grid may have a grid frequency requirement of $50\text{Hz} \pm 1\%$.

Disruption/failure in the operation of a power network can occur when the AC power frequency varies beyond the acceptable range.

10 An imbalance between the total power supplied to the power network and the total load demand can cause the AC power frequency to vary, possibly beyond the acceptable range. Specifically, when the total power supplied exceeds the total load demand, the AC power frequency can increase beyond the range. When the total load demand exceeds total power, the AC power frequency can decrease beyond the range.

15 Within the power network, each load is supplied with a voltage. If the voltage drops, the power consumption (or “demand”) of the load is reduced. If the voltage increases, the power consumption of the load increases. Therefore, if the voltage supplied to one or more loads is regulated according to the grid frequency requirement, then this
20 regulation may help to maintain/restore the balance between the total power supplied and the total load demand. Restoring the balance between the total power supplied and the total load demand restores the AC power frequency to within the acceptable range.

The present invention is concerned with a power network which can help to
25 restore/maintain the grid frequency requirement.

Referring to Figure 1, a power network 1 is shown.

The power network 1 includes a plurality of power generators 2 and a plurality of
30 customers 3 (or “end-users”). The power generators 2 provide power to the customers 3. Power generated by the power generators 2 is transmitted via a power transmission network 4 to at least one substation (not shown). The power is then transmitted from the at least one substation (not shown) to the customers 3 via a power distribution network 5.

35

The power network 1 may be a national power network including a plurality of power stations. Each power station may consist of a single power generator 2 or a complex of power generators 2. The power network 1 may be a microgrid. At least one power generator 2 included in the microgrid may consist of a larger power grid, for example a national grid, which may be controllably connected/disconnected from the microgrid.
5 Other power generators 2 in the microgrid may consists of renewable energy resources.

The power network 1 also includes a device for demand-side power management 6 (or “power management device”) which is configured to be in communication with the customers 3 via a communications network 7. The power management device 6 is also
10 configured to be in communication with an operator (not shown) of the power transmission network 4, preferably with the at least one substation (not shown).

Each customer 3 has a corresponding load 8 which is powered by the plurality of power generators 2. Each load 8 is connected to the power distribution network 5. Each
15 customer 3 also has a demand-side controller 9 which is arranged to measure power supplied to the corresponding load 8. The power management device 6 is configured to control at least one of the demand-side controllers 9 to vary the voltage supplied to their corresponding load 8 according to the grid frequency requirement. Thus, the
20 demand-side controller 9 is for measuring and controlling power supplied to a load 8 in the power network 1. This will be explained in more detail hereinafter.

Each load 8 may have a different load demand and each customer 3 may be domestic, industrial, or commercial. Each load 8 may be a single building or a small complex of
25 buildings. Examples of buildings include domestic buildings, office buildings, and industrial buildings. Each load 8 may be a domestic appliance, for example a kitchen appliance, or an electrical vehicle charging station.

The power network 1 may also include an aggregator or Distributed Network Operator (DNO) (not shown). The aggregator/DNO (not shown) monitors the AC power grid frequency of the power network 1. The aggregator/DNO (not shown) generates and transmits a command signal (not shown) to the power management device 6 when the grid frequency requirement is no longer being met. In response to receiving the command signal, the power management device 6 begins controlling at least one
35 demand-side controller 9.

Referring also to Figure 2, the power management device 6 will now be explained in more detail.

5 The power management device 6 includes at least one communications interface 10 for communicating with the communications network 7. The at least one communications interface 10 is also for receiving information about the total power supplied to the power network 1, and also for receiving information about power supplied to the loads 8. The at least one communications interface 10 is configured to transmit the information to a data handler 11. The power management device 6 includes a controller
10 12 (“power management controller”) which includes the data handler 11. The data handler 11 is configured to sort the information received into a database 13, which is also included in the power management device 6.

The database 13 stores supply data 14 corresponding to the information about the total
15 power supplied to the power network 1 and demand data 15 corresponding to the information about power supplied to the loads 8. Optionally, the database 13 also includes user profile(s) 16. Each user profile 16 corresponds to a customer 3 and includes information about that customer 3. The user profile 16 may specify whether the customer 3 has elected to have their load 8 receive a regulated voltage (*i.e.* to
20 receive a power input which is varied according to the grid frequency requirement).

The information about power supplied to the loads 8 consists of the measurements taken by each demand-side controller 9 (also known as “power demand measurements”). Each power demand measurement may consist of a power
25 measurement or a combination of current and voltage measurements. As power demand measurements can be taken for each load 8 within the power network 1, these measurements taken together can be used to determine the total load demand of the power network 1. Specifically, a calculator 17 included in the power management controller 12 is configured to calculate the total load demand.

30 The information about the total power supplied to the power network 1 may be transmitted via the power transmission network 4 to the power management device 6, for example from one of the power generators 2. Typically, the aggregator/DNO (not shown) provides the information about the total power to the power management
35 device 6. The aggregator/DNO may receive a plurality of power measurements via the power transmission network 4, each measurement corresponding to a power generator

2 currently in operation in the power network 1. The power generators 2 in operation may transmit respective power measurements to the aggregator/DNO separately. The aggregator/DNO determines the total power supplied to the power network 1 using the plurality of power measurements.

5

The calculator 17 is configured to calculate a power imbalance within the power network 1 using the total load demand and the total power supplied to the power network 1. The calculator 17 is also configured to determine the increase/decrease in the voltage (or “voltage variance”) supplied to each load 8 which is required to restore the overall power balance. Preferably, the change of the voltage of a given load 8 should be no more 10% of the rated voltage of the load 8. This is to help prevent the voltage variance from producing a noticeable impact on the power quality of the load 8 being regulated. An instructor 18 included in the power management controller 12 is configured to generate a control signal for at least one load 8. The control signal corresponds to or is indicative of the voltage variance calculated for that load 8.

The power management device 6 may also include a user interface 19. The user interface 19 is for receiving input data from a user (not shown). The input data may be indicative of commands from the user to start/end calculations performed by the calculator 17. The input data may indicate pre-selected start and end points of the calculations. The input data may correspond to information about a given user profile 16. Thus, the input data may be used to update a given user profile 16, for example.

Referring also to Figure 3, operation of the device for demand-side power management 6 will now be described.

The calculator 17 calculates a power imbalance within the power system 1 (step S1).

The calculator 17 selects which loads 8 will be used to restore the power balance (step S2). This step will be described in more detail hereinafter.

The calculator 17 calculates, for each selected load 8, the increase/decrease in power supplied to the load 8 required in order to restore the power balance (step S3).

The calculator 17 calculates the voltage variance required to obtain the required increase/decrease in power for each selected load 8 (step S4). Reference is made to GB

2 519 719 A, the contents of which are incorporated herein by reference, which discloses at least one equation for calculating variation in the power supplied to a load as a result of using a voltage regulating device. In particular, reference is made to Figures 7 to 10 of GB 2 519 719 A, and the corresponding description.

5

The instructor 18 then generates a control signal for each selected load 8 (step S5). A given control signal is indicative of the voltage variance required to vary the power supplied to one of the selected loads 8 by the amount corresponding to that load 8 calculated in step S3.

10

Each load 8 may have substantially the same load demand. Some or all loads 8 may have different load demands.

15

Some, all, or a single load 8 within the power network 1 is selected to help restore the power balance. Particular load(s) may be selected to ensure that the power supplied to each selected load 8 is reduced by no more than between 5% and 10%, whilst still restoring power balance.

20

The power management device 6 performs steps S1 to S5 (Figure 3) as part of a frequency service scheme. Each customer 3 can elect to either participate or not participate in the frequency service scheme. The loads 8 corresponding to the customers 3 who have elected to participate in the scheme are available for selection in Step S2. The power management device 6 does not communicate with the loads 8 corresponding to the customers 3 who have elected to not participate in the frequency service scheme.

25

A specific example of how the frequency service scheme may be used to restore power balance will now be described. If one customer or end-user 3 has 50 kW load demand and there is a total of 1,000 such kind of customers 3, the total load demand is 50 MW. Assuming all 1,000 customers 3 elect to participate in the frequency service scheme, varying the voltage supplied to each load 8 such that the power supplied to each load is reduced by 5% gives 2.5 MW surplus power. Thus, in this example a power imbalance of up to 2.5 MW can be corrected using the frequency service scheme.

30

The frequency service scheme may be performed iteratively. Specifically, the power management device 6 may repeat steps S1 to S5 if power balance is not restored to the

power network 1 after step S5 is completed. Steps S1 to S5 may be repeated multiple times up to a pre-set number of iterations. Steps S1 to S5 may be repeated until the power balance is restored, or until the power imbalance is below a pre-determined threshold value.

5

The aggregator/DNO (if present) may monitor the AC power grid frequency of the power network 1 to determine whether the frequency is within the acceptable range after Step S5 is completed. If the grid frequency requirement is still not being met, the aggregator/DNO (not shown) will generate and transmit a new command signal to the power management device 6. Steps S1 to S5 will be repeated in response to the device 6 receiving this new command signal.

The calculator 17 may be configured to recalculate a power imbalance in the power system 1 after step S5 is completed. The calculator 17 is configured to perform the calculation (step S1) in the same way as hereinbefore described. The calculator 17 may be configured to repeat steps S2 to S5 if the power imbalance is calculated to be non-zero, or if the power imbalance is calculated to be above a pre-determined threshold value.

Referring also to Figure 4, the device for demand-side power management 6 may be implemented using a data processing system 24 (or “computer system”).

The data processing system 24 includes at least one processing core 25, memory 26, and input/output interface 27 interconnected by a bus system 28. The data processing system 24 includes non-volatile storage 29 which stores software 30 for implementing the calculator 17 and data 31 such as the data of the database 13. The data processing system 24 also includes a data interface 32 which may include the data handler 11. The processing core 25, memory 26, input/output interface 27, bus system 28, non-volatile storage 29, and data interface 32 may be implemented in a microcontroller 33.

30

The data processing system 24 also includes a user input device 34, such as a keypad, which can be used to input start and end points for calculations performed by the calculator 17, for example. The system 24 also includes a display 35, for example, in the form of a liquid crystal display or light-emitting diode.

35

The data processing system 24 may include a wired network interface 36, such as a USB interface, and a wireless interface 37, such as Bluetooth (RTM) interface, to allow data to be transmitted via a remote device (not shown) such as a personal computer, tablet computer, or mobile phone.

5

Referring also to Figure 5, the demand-side controller 9 will now be described in more detail.

10 The demand-side controller 9 includes a demand-side communications interface 38 for communicating with the power management device 6 via the communications network 7. Specifically, the demand-side communications interface 38 is for receiving the hereinbefore described control signals from the power management device 6 and is also for transmitting the hereinbefore described power demand measurements.

15 The demand-side controller 9 also includes a measurement device 39. As hereinbefore described, a given customer 3 has a load 8 and a corresponding demand-side controller 9. The measurement device 39 of the corresponding demand-side controller 9 is arranged to measure power supplied to the load 8 it corresponds to. The measurement device 39 is configured to generate and transmit the hereinbefore described power
20 demand measurements to the demand-side communications interface 38.

The demand-side controller 9 also includes a voltage regulator 40 and a voltage regulator controller 41. The voltage regulator controller 41 is configured to generate, in response to receiving the hereinbefore described control signals, a voltage regulator
25 control signal. The voltage regulator controller 41 is configured to cause transmission of the voltage regulator control signal to the voltage regulator 40. The voltage regulator 40 is configured to modify or vary the voltage supplied to the load 8 according to the voltage regulator control signal.

30 The voltage regulator 40 may be a transformer including a plurality of taps. The plurality of taps may include a plurality of transformer taps and, optionally, a load tap. The voltage supplied to the load 8 is increased or decreased depending on which transformer taps are activated. The voltage regulator 40 is configured to switch between transformer taps on receiving the voltage regulator control signal. Thus the
35 voltage regulator control signal is for activating or deactivating particular taps.

The voltage regulator 40 is configured to activate the load tap in response to receiving the voltage regulator control signal. The load tap is arranged to connect or disconnect the voltage regulator 40 from the load 8.

5 Simulation studies

Simulating operation of a power network as part of a simulation study can be used to examine how regulating the voltage supplied to load(s) within the power network 1 may affect its AC power frequency.

10 Referring to Figure 6, a first simulated power network 47, 47₁ is shown. The first simulated power network 47₁ is used in a first simulation study in which the total load demand is varied in order to vary the AC power frequency of the first simulated power network 47₁. Power generation and generator excitation are kept constant. Simulink software is used to implement the simulation.

15

The first simulated power network 47₁ is a three-wire three-phase simulated circuit and includes a generator 48. The generator 48 is represented by a Simplified Synchronous Machine block, which is used in Simulink to model mechanical and electrical characteristics of a simple synchronous machine. The generator 48 is supplied with
20 mechanical power P_m of 0.8838 pu, represented by Pm block input 49 in the first simulated power network 47₁. The amplitude of internal voltage of the generator 48 is set to 1.04 pu and is represented by internal voltage block input 50 in the first simulated power network 47₁.

25 The unit “pu” is defined by the ratio according to Equation 1:

$$pu = \frac{\text{rated value}}{\text{real value}} \quad (1)$$

30 The generator 48 includes a ground terminal 51 connected to system ground, and first, second, and third output terminals 52, 52₁, 52₂, 52₃ corresponding to first, second, and third power outputs respectively. There is a phase difference between each power output. The power outputs collectively constitute a three-phase power output which is separately fed into first, second, third, and fourth main loads 53, 53₁, 53₂, 53₃, 53₄ via a three-phase distribution network. This distribution network will be described in more
35 detail hereinafter.

The main loads 53 represent or correspond to the loads 8 included in the power network 1 for which the customer 3 has elected to be a part of the frequency service scheme.

5

Table 1 below indicates the active power and nominal phase-to-phase voltage of each main load 53, 53₁, 53₂, 53₃, 53₄:

Table 1

Load	Active power (W)	Nominal phase-to-phase voltage, V_{rms} (V)
First main load 53 ₁	300×10^6	400
Second main load 53 ₂	248×10^6	400
Third main load 53 ₃	2×10^6	400
Fourth main load 53 ₄	1×10^6	400

10

The first simulated power network 47₁ also includes an additional load 54 and a step-up transformer 55. The additional load 54 and the step-up transformer 55 are jointly electrically connected to the output terminals 52 of the generator 48. The step-up transformer 55 is for receiving the three-phase power output and for increasing the voltage of the power output for transmission.

15

The additional load 54 represents or corresponds to any load 8 included in the power network 1 for which the customer 3 corresponding to that load 8 has not elected to participate in the frequency service scheme.

20

The first simulated power network 47₁ further includes a step-down transformer 56 and a transmission line 57 connected between the step-down transformer 56 and the step-up transformer 55. The step-down transformer 56 is for reducing the voltage of the power output after transmission through the line 57.

25

Third and fourth circuit breakers 58, 58₃, 58₄ are electrically connected between the step-down transformer 56 and the third and fourth main loads 53₃, 53₄ respectively. The first main load 53, 53₁ is jointly electrically connected with the circuit breakers 58 to the step-down transformer 56. A voltage optimizer 59 is electrically connected

between the step-down transformer 56 and the second main load 53, 53₂ and receives the three-phase power output.

Each circuit breaker 58 is for controllably connecting/disconnecting their respective load 53 from the three-phase distribution network. The voltage optimizer 59 is for
5 increasing/decreasing the voltage supplied to the second main load 53, 53₂, as will be described in more detail hereinafter. The input voltages of the first, third, and fourth main loads 53₁, 53₃, 53₄ are not varied as part of the first simulation study.

10 The generator 48 includes a fourth output terminal 52, 52₄ which is connected to an aggregator 60 via a communication line 61. Measurement signals are transmitted from the fourth output terminal 52₄ to the aggregator 60 via the communication line 61. The measurement signals include a signal indicative of the AC power frequency of the generator 48. The aggregator 60 is for generating and transmitting a command signal
15 to a voltage optimizer 59, as will be described in more detail hereinafter. The aggregator 60 and voltage optimizer 59 are both included in the three-phase distribution network. The voltage optimizer 59 is configured to increase/decrease the voltage of the three-phase power output in response to receiving the command signal from the aggregator 60.

20

As part of the first simulation study, the load demand of the network 47₁ is varied and its AC power frequency response is measured.

The first and second loads 53₁, 53₂ are electrically connected to the three-phase
25 distribution network throughout the first simulation study. The fourth load 53₄ is connected to the network 47₁ by the fourth circuit breaker 58₄ ten seconds after the start of the simulation. The third main load 53₃ is disconnected from the network 47₁ by the third circuit breaker 58₃ fifty seconds after the start of the simulation. Use of circuit
30 breakers 58 to disconnect/connect loads 53 is to simulate sudden changes in load demand and its effect on frequency stability experienced in an unstimulated power network.

Changes in the operation of the first simulated power network 47₁ correspond to a series of states the network 47₁ evolves into throughout the study. States of the
35 simulated power network 47₁ are computed using a continuous solver (not shown) in the power system simulation toolbox of Simulink.

Referring also to Figure 7, a first plot 62, 62₁ of the change in the AC power frequency over time is shown.

5 The first plot 62₁ shows that the AC power frequency drops by 0.12% after approximately ten seconds in response to the fourth load 53₄ being connected to the first simulated power network 47₁. This is because the total load demand exceeds the power generation of the network 47₁. The aggregator 60 generates and transmits the command signal to the voltage optimizer 59 in response to this change in AC power
10 frequency, which triggers the voltage optimizer 59 to reduce the voltage supplied to the second main load 53₂.

This reduces the total load demand. The voltage supplied to the second main load 53₂ is calculated by:

15

$$V_{out} = V_{in} \times K \quad (2)$$

Where V_{out} is the voltage supplied to the second main load 53₂/output voltage of the voltage optimizer 59 in V; V_{in} is the voltage of the three-phase power output in V; K is
20 the voltage ratio of V_{in} and V_{out} .

K is calculated based on the frequency change or the power imbalance of the simulated power network 47₁. As hereinbefore described, in a real world operation (*i.e.* non-simulated) the power network 1 calculates V_{out} using at least one equation disclosed in
25 GB 2 519 719 A.

Referring also to Figures 8a and 8b, second and third plots 62, 62₂, 62₃ are shown. The second plot 62₂ shows how the magnitude of the voltage supplied to the second main load 53₂, V_{out} , varies over time and the third plot 62₃ shows how the power supplied to
30 the second main load 53₂ varies over time.

In the second plot 62₂, a reduction in voltage magnitude is recorded after approximately ten seconds of starting the simulation. V_{out} is reduced by approximately 0.8 V (after V_{out} stabilises at approximately twenty seconds). A corresponding reduction
35 of approximately 0.01×10^8 W in the power supplied is seen in the third plot 62₃.

Because the power supplied to the second main load 53₂ is reduced, the total load demand is also reduced.

Referring also to Figures 9a and 9b, fourth and fifth plots 62, 62₄, 62₅ are shown. The
 5 fourth plot 62₄ shows how the magnitude of the voltage supplied to the first main load 53₁, V_{out} , varies over time and the fifth plot 62₅ shows how the power supplied to the first main load 53₁ varies over time. The first main load 53₁ is directly electrically connected to the step-down transformer 56. Thus, the voltage supplied to the first main load 53₁ is not varied by the voltage optimizer 59.

10

The change in V_{out} observed in the second plot 62₂ and the change in power supplied observed in the third plot 62₃ are due to the actions of the voltage optimizer 59. No such change is observed in the fourth and fifth plots 62₄, 62₅.

15 As hereinbefore described, the third main load 53₃ is disconnected from the first simulated power network 47₁ by the third circuit breaker 57₃ after fifty seconds of beginning the simulation.

The first plot 62₁ shows that the AC power frequency increases by 0.22% after
 20 approximately fifty seconds of beginning the simulation. This is because the power generated by the first simulated power network 47₁ exceeds the total load demand after the third main load 53₃ is disconnected.

The aggregator 60 generates and transmits a command signal to the voltage optimizer
 25 59 in response to this change in AC power frequency. In response to the command signal, the voltage optimizer 59 increases the voltage supplied to the second main load 53₂. As hereinbefore described, the voltage supplied to the second main load 53₂ is calculated using equation (2).

30 The second plot 62₂ shows a corresponding increase of 0.8 V in the magnitude of the voltage supplied to the second main load 53₂ after fifty seconds (after V_{in} stabilises after approximately ten seconds). A corresponding increase of approximately 0.01 W in the power supplied is seen in the third plot 62₃. Because the power supplied to the second main load 53₂ is increased, the total load demand is also increased.

35

The first plot 62₁ shows that the AC power frequency is restored to its original value after approximately sixty seconds of beginning the simulation. This is due to the voltage optimizer 59 increasing the voltage supplied to the second main load 53₂ and thus restoring the balance between the total power generated and the total load demand.

5

Referring to Figure 10, a schematic of a second simulated power network 47, 47₂ is shown. The second simulated power network 47₂ is used in a second simulation study in which power generated is varied in order to vary the AC power frequency of the second simulated power network 47₂. Generation excitation and total load demand is kept constant.

10

The second simulated power network 47₂ is the same as the first simulated power network 47₁. However, the third and fourth main loads 53₃, 53₄, as well as their corresponding circuit breakers 58₃, 58₄, are not present in the second simulated power network 47₂. As with the first simulated power network 47₁, states of the second simulated power network 47₂ are computed using a continuous solver (not shown) in the power system simulation toolbox of Simulink.

15

Table 2 below shows details of the first and second main loads 53₁, 53₂:

20

Table 2

Load	Active power (W)	Nominal phase-to-phase voltage (V _{rms})
First main load 53 ₁	300e6	400
Second main load 53 ₂	250e6	400

As part of the second simulation study, power generation in the second simulated power network 47₂ is reduced after ten seconds of beginning the simulation.

25

Power generation in the second simulated network 47₂ may represent power generation from a combination of different power sources, for example mixed renewable energy sources. Therefore, changes in the power generation can be used to represent power output intermittence in renewable energy sources.

30

Referring to Figure 11, a sixth plot 62, 62₆ of how the mechanical power P_m ("input power" in units pu) supplied to the generator 48 varies with time is shown.

The sixth plot 62₇ shows that the mechanical power $P_m = 0.8838$ pu as hereinbefore discussed at the beginning of the simulation. At ten seconds, P_m is reduced by approximately 1% to 0.8738 pu. This power reduction results in an imbalance between
 5 the power generated by the generator 48 and the total load demand of the second simulated power network 47₂.

Referring to Figure 12, a seventh plot 62, 62₇ of how the AC power frequency varies with time in the second simulated power network 47₂ is shown. The seventh plot 62₇
 10 shows that the AC power frequency of the second simulated power network 47₂ decreases by 0.82% after ten seconds of the beginning of the simulation. This is because the total load demand exceeds the total power generated after ten seconds of the beginning of the simulation.

15 As in the first simulation study, in the second simulation study the aggregator 60 transmits a command signal to the voltage optimizer 59 in response to this change in AC power frequency. This command signal triggers the voltage optimizer 59 to reduce the voltage supplied to the second main load 53₂. As hereinbefore described, the voltage supplied to the second main load 53₂ is calculated using equation (2).

20

Referring to Figure 13, a eighth plot 62, 62₈ shows this reduction in the voltage supplied to the second main load 53₂. The eighth plot 62₈ is a plot of how a voltage ratio of the second main load 53₂ varies over time. The voltage ratio is $V_{out} \cdot V_{in}$ and varies due to the voltage optimizer 59 varying the voltage supplied to the second main load 53₂.

25

Specifically, the eighth plot 62₈ shows that V_{out} is reduced after approximately ten seconds in relation to V_{in} to account for the reduction in mechanical power P_m . Specifically, V_{out} is reduced such that V_{in} is 1.51% greater than V_{out} .

30 The balance between the power generated and the total load demand is restored by reducing the power consumption of the second main load 53₂. Thus the seventh plot 62₇ shows that the AC power frequency is restored to its original value (the value taken at the start of the second simulation study) in response to the voltage optimizer 59 reducing the voltage supplied to the second main load 53₂. After the AC power
 35 frequency is restored to its original value after twenty seconds of beginning the simulation, V_{out} is maintain at a reduced value.

As hereinbefore described in relation to the first simulation study, the voltage optimizer 59 reduces the voltage supplied to the second main load 53₂ based on the command signal from the aggregator 60.

5

Referring also to Figures 14a and 14b, ninth and tenth plots 62₉, 62₁₀ are shown. The ninth plot 62₉ shows how the magnitude of the voltage supplied to the second main load 53₂, V_{out} , varies over time and the tenth plot 62₁₀ shows how the power supplied to the second main load 53₂ varies over time

10

Referring to Figure 14 specifically, the ninth plot 62₉ shows a reduction in voltage magnitude of V_{out} at ten seconds from the start of the second simulation study. This corresponds to the voltage optimizer 59 reducing the voltage supplied to the second main load 53₂. The magnitude of V_{out} is reduced by approximately 0.8 V (after V_{out} stabilises after approximately twenty seconds). Referring specifically to Figure 14b, a corresponding reduction of approximately $0.01 \times 10^8 W$ in the power supplied at ten seconds from the start of the second simulation study is seen in the tenth plot 62₁₀.

15

At fifty seconds from the start of the second simulation study, power generation in the second simulated network 47₂ is increased. The sixth plot 62, 62₆ (Figure 11) shows that the mechanical power P_m increases by 2.5% from 0.8738 pu to 0.8988 pu. This causes an imbalance in the second simulated network 47₂ whereby the power generated exceeds the total load demand. As a result, the AC power frequency of the second simulated network 47₂ increases by 2.16%; this increase in frequency is shown in the seventh plot 62₇ (Figure 13) at fifty seconds after the beginning of the simulation study.

20

25

In response to this increase in frequency, the aggregator 60 transmits a command signal to the voltage optimizer 59. This command signal triggers the voltage optimizer 59 to increase the voltage supplied to the second main load 53₂, thereby increasing the total load demand. As hereinbefore described, the voltage supplied to the second main load 53₂ is calculated using equation (2).

30

The eighth plot 62, 62₈ (Figure 13) shows an increase in the voltage ratio $V_{out}:V_{in}$ of the second main load 53₂ at fifty seconds after the beginning of the simulation study. The increase in the voltage ratio $V_{out}:V_{in}$ corresponds to V_{out} being increased in relation to

35

V_{in} for the second main load 53₂ by the voltage optimizer 59. Specifically, V_{out} is increased such that V_{out} is 2.5% greater than V_{in} .

5 Likewise, the ninth plot 62₉ (Figure 14a) shows an increase in the voltage magnitude, fifty seconds after the beginning of the simulation study, for the second main load 53₂ as a result of the regulation by the voltage optimizer 59. The tenth plot 62₁₀ (Figure 14b) shows the corresponding increase in power of the second main load 53₂ at fifty seconds.

10 Referring also to Figures 15a and 15b, eleventh and twelfth plots 62₁₁, 62₁₂ for the first main load 53₁ are shown. The eleventh plot 62₁₁ shows how the magnitude of the voltage supplied to the first main load 53₁ varies over time. The eleventh plot 62₁₁ shows the voltage increasing slightly after ten seconds from the start of the simulation study and shows the voltage decreasing slightly after fifty seconds. The twelfth plot 62₁₂ shows a corresponding increase in the power supplied to the first main load 53₁ after
15 ten seconds and a corresponding decrease in the power supplied after fifty seconds.

Because the generation excitation is kept constant in the second simulation study, the voltage supplied to the first main load 53₁ fluctuates slightly whilst the voltage supplied to the second main load 53₂ is controllably varied. This would not happen in a real (*i.e.*
20 non-simulated) study.

The first and second simulation studies show that regulating the voltage supplied to a load may be used to help correct changes in the AC power frequency of a power network. The frequency changes can be due to either changes in load demand or
25 changes in power generation.

Claims

1. A device for demand-side power management, the device comprising:
a power management controller;
5 at least one communications interface for receiving information about total power supplied to a power network and for communicating with a plurality of demand-side controllers, wherein each demand-side controller is for measuring and controlling power supplied to a respective load;
the power management controller is configured:
10 to calculate, based on the total power supplied to the power network and on a plurality of power demand measurements from the demand-side controllers, a power imbalance in the power network;
to select, based on the power imbalance, at least one load to manage;
to generate and cause transmission of a control signal to at least one
15 demand-side controller, the control signal indicative of an amount by which a voltage supplied to the load is to be varied by the demand-side controller.
2. The device for demand-side power management according to claim 1 further comprising a database comprising user profiles, wherein:
20 each user profile corresponds to a customer of one of the demand-side controllers; and
each user profile indicates whether the customer has elected to have the voltage supplied to the respective load varied by the demand-side controller.
- 25 3. A demand-side controller for measuring and controlling power supplied to a load in a power network, the demand-side controller comprising:
a communications interface for communicating with a device for demand-side power management in the power network;
a measurement device arranged to measure power supplied to the load and
30 configured to generate and cause transmission of corresponding power demand measurements to the device for demand-side power management;
a voltage regulator configured to modify, based on a voltage regulator control signal, a voltage supplied to the load;
a voltage regulator controller for communicating with the voltage regulator, the
35 voltage regulator controller configured:

to generate, in response to receiving a control signal from the device for demand-side power management, the voltage regulator control signal, and to cause transmission of the voltage regulator control signal to the voltage regulator.

5

4. The demand-side controller according to claim 3, wherein the voltage regulator is configured to vary the power supplied to the load by between 5% and 10%.

5. The demand-side controller according to any one of claims 3 or 4, wherein the voltage regulator is configured to modify the voltage supplied to the load by no more than 10% of the rated voltage of the load.

6. The demand-side controller according to any one of claims 3 to 5 wherein: the voltage regulator is a transformer comprising a plurality of transformer taps; and

15

the voltage regulator is configured to switch between transformer taps in response to receiving the voltage regulator control signal.

7. The demand-side controller according to claim 6, wherein the voltage regulator comprises a load tap for connecting the voltage regulator to the load, wherein the voltage regulator is configured to activate the load tap on receiving the voltage regulator control signal.

20

8. A system comprising: the device for demand-side power management according to any one of claims 1 or 2;

25

at least one demand-side controller according to any one of claims 3 to 7; wherein the device for demand-side power management and the at least one demand-side controller are in communication.

30

9. A method of operating the system of claim 8, the method comprising: receiving information about the total power supplied to the power network; generating and transmitting power demand measurements to the device for demand-side power management;

calculating, based on the total power supplied to the power network and the power demand measurements, the power imbalance in the power network;

35

selecting, based on the power imbalance, at least one load to manage;
generating and transmitting a control signal to the at least one demand-side
controller;

5 generating, in response to receiving the control signals, a voltage regulator
control signal and transmitting the voltage regulator control signal to the voltage
regulator;

modifying, based on the voltage regulator control signal, a voltage supplied to
the load.

- 10 10. The method of claim 9, the method further comprising:
selecting at least one load to manage based on the user profile of the load.
11. The method of claims 9 or 10, the method further comprising:
modifying the voltage supplied to the load such that the power supplied to the
15 load varies by between 5% and 10%.

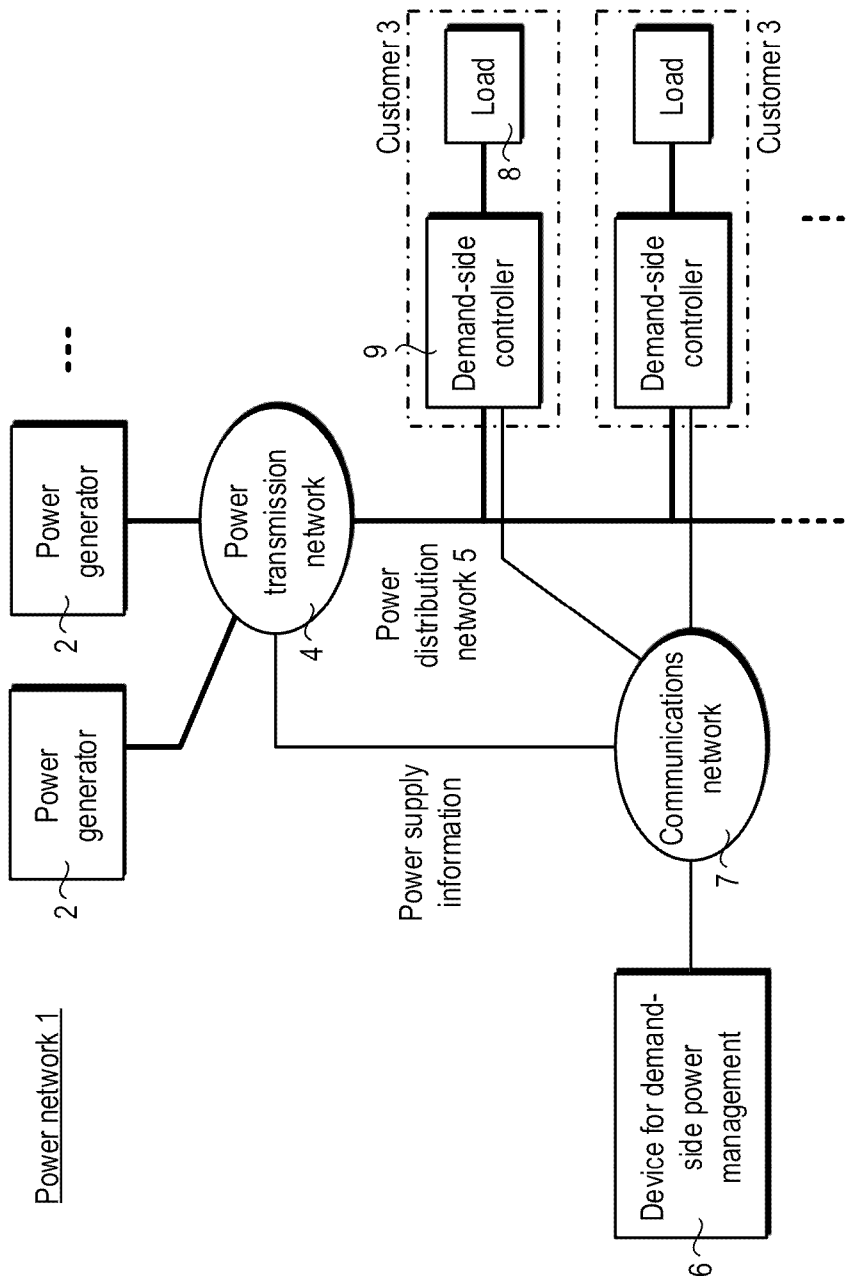


Fig. 1

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Device for demand-side
power management 6

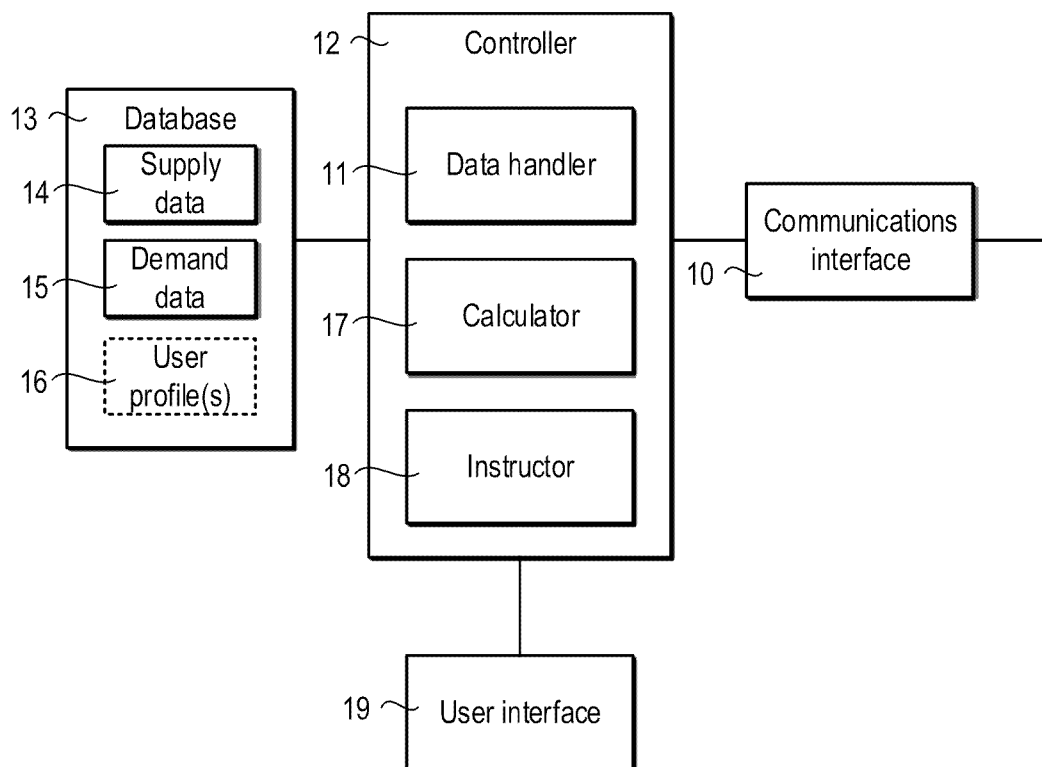


Fig. 2

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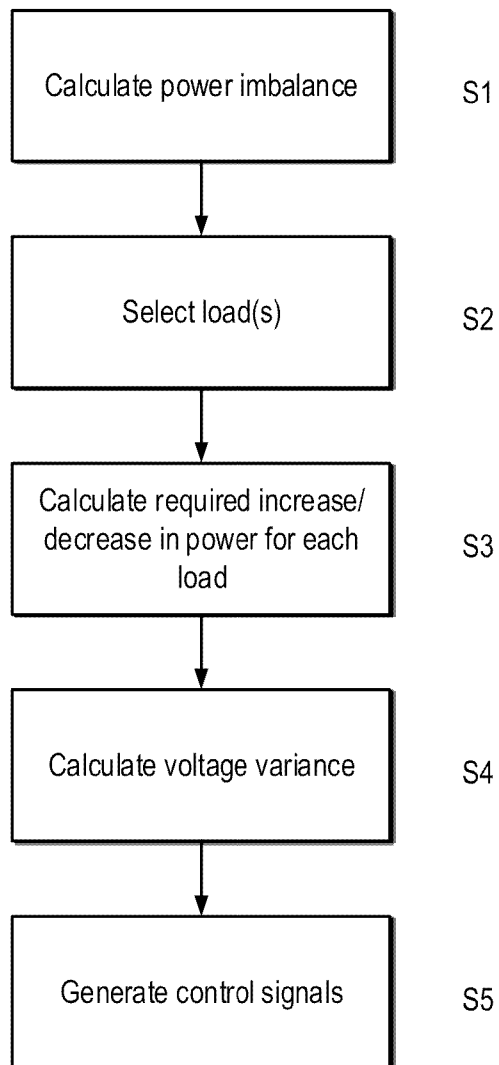


Fig. 3

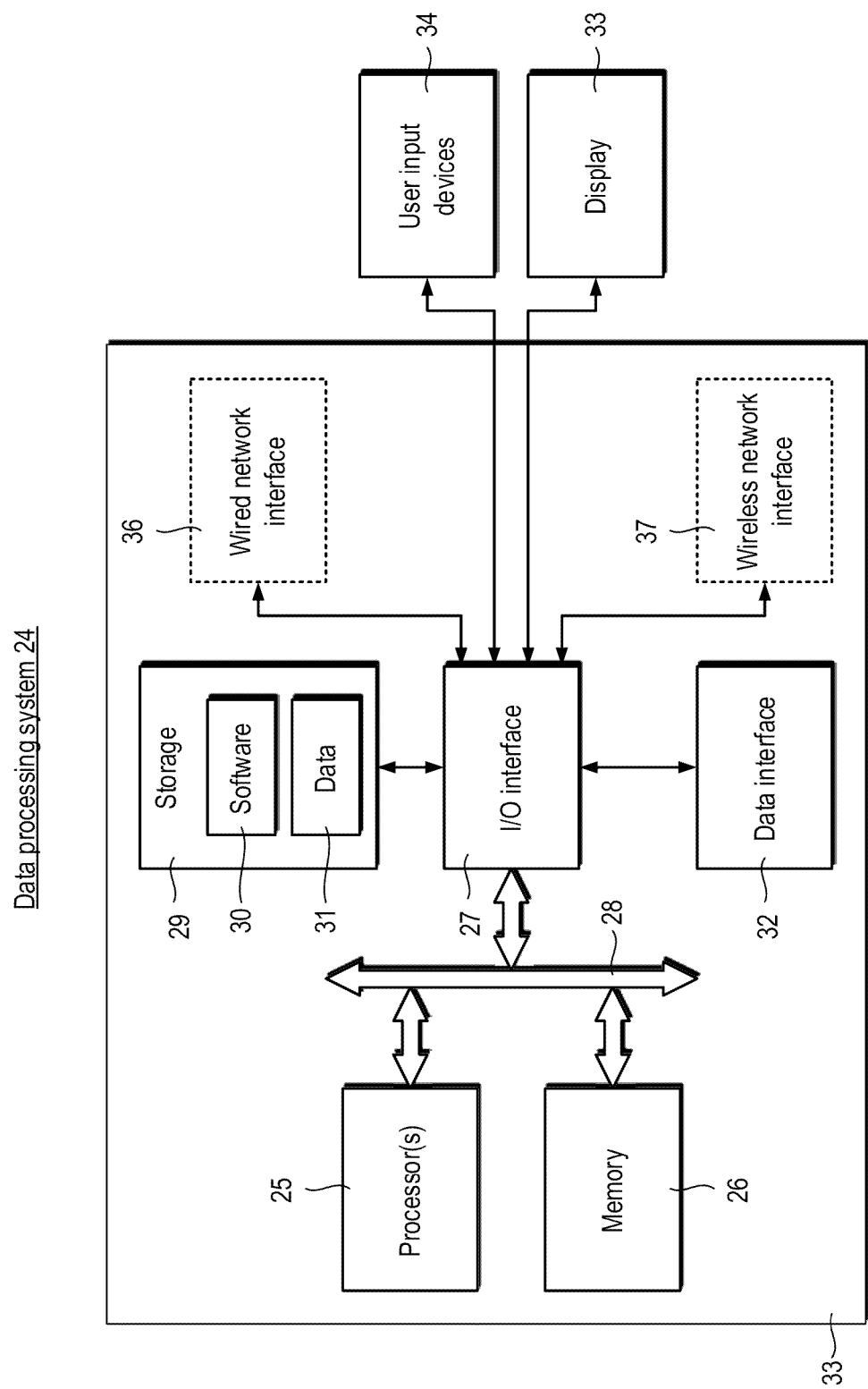


Fig. 4

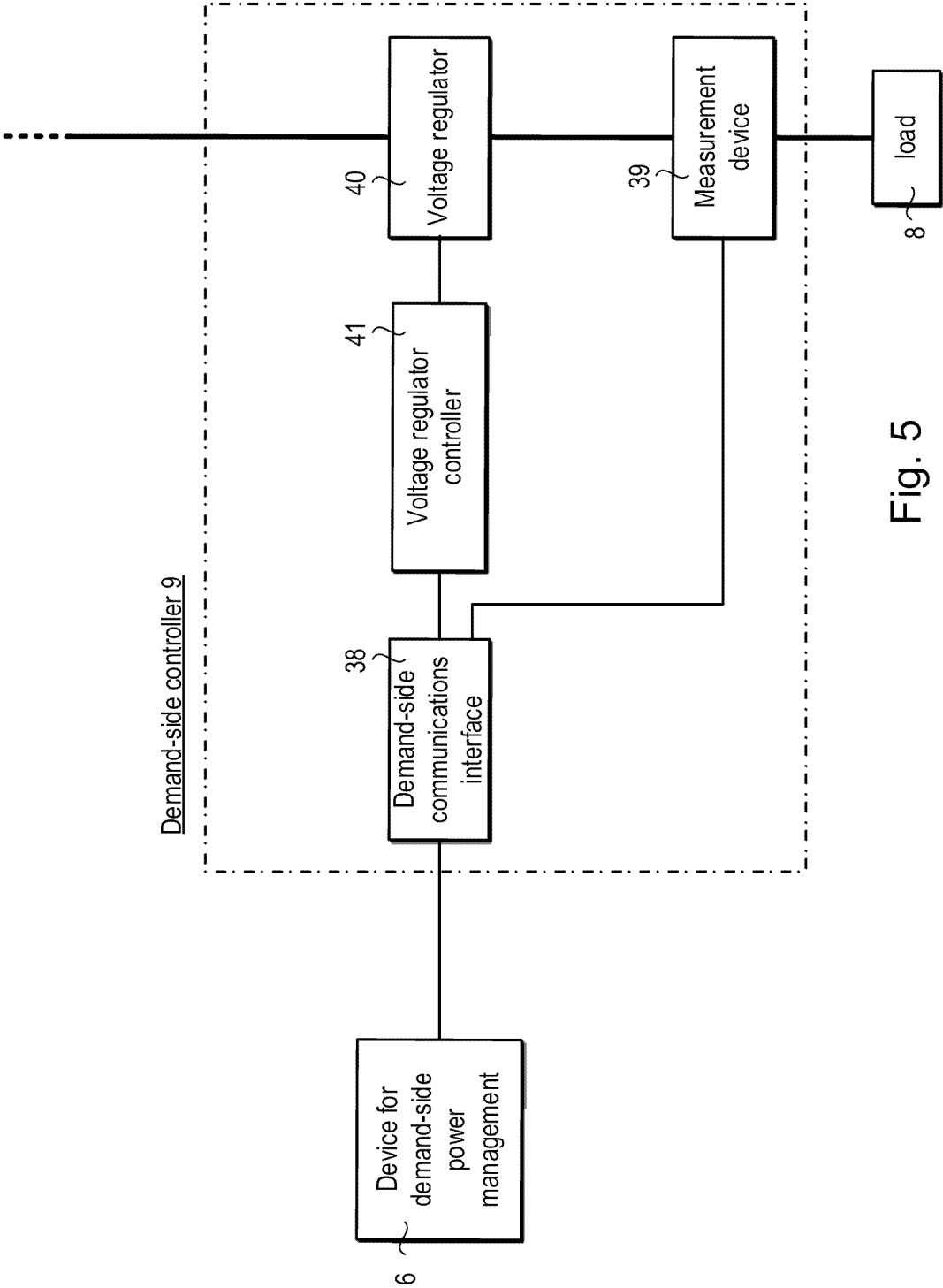


Fig. 5

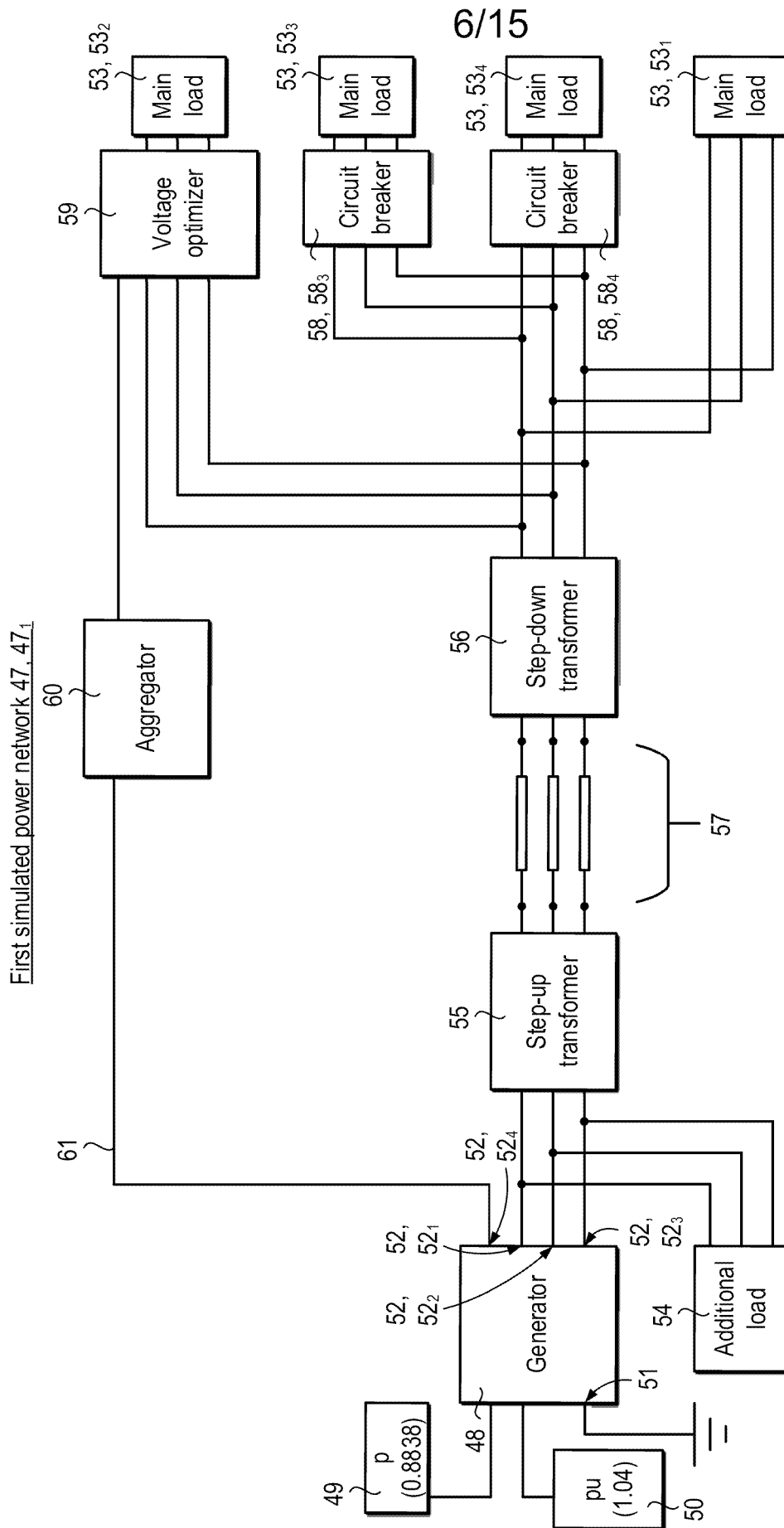


Fig. 6

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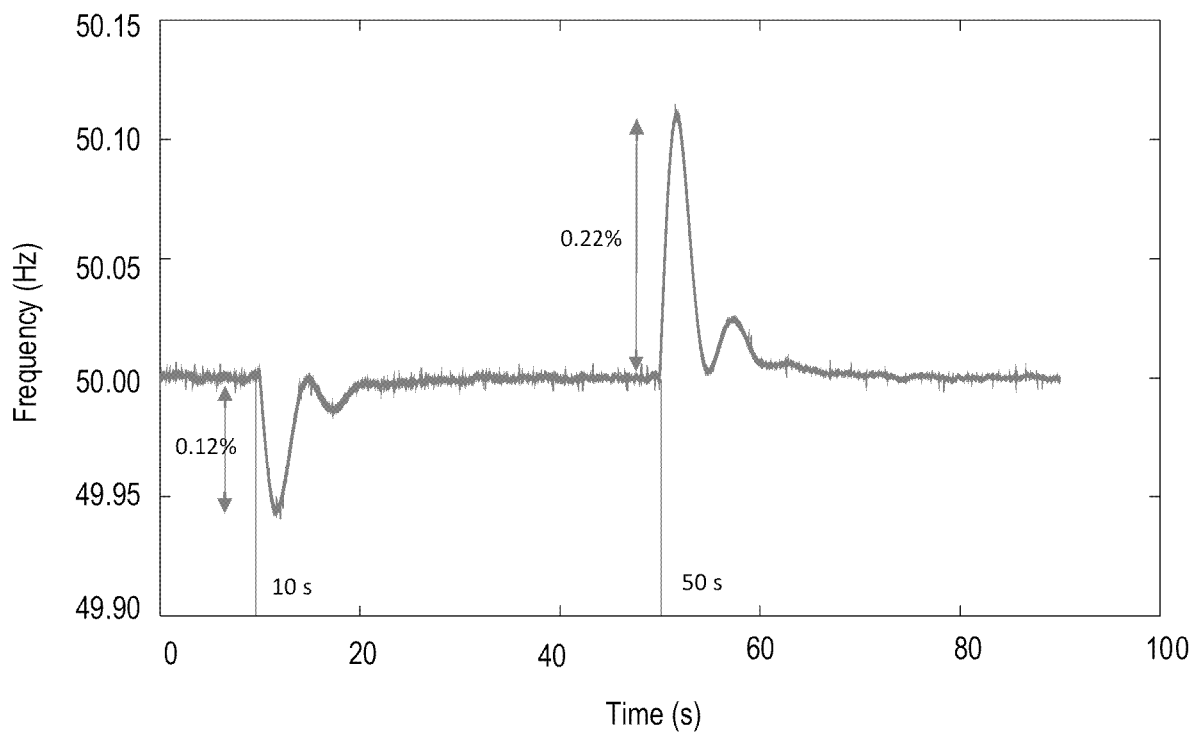
First plot 62, 62₁

Fig. 7

Second plot 62, 62₂

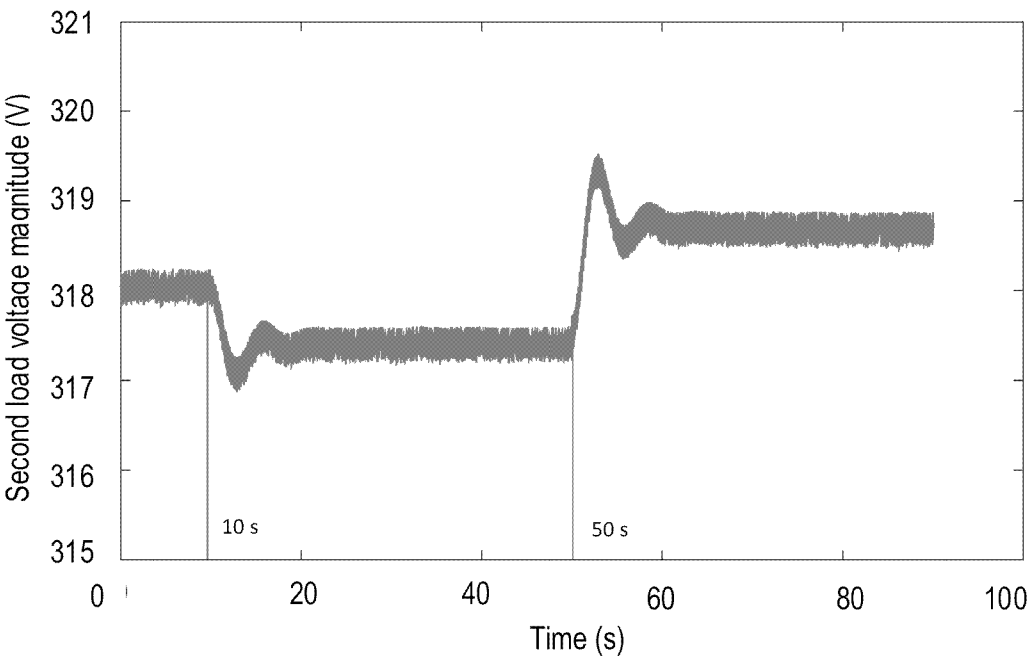


Fig. 8a

Third plot 62, 62₃

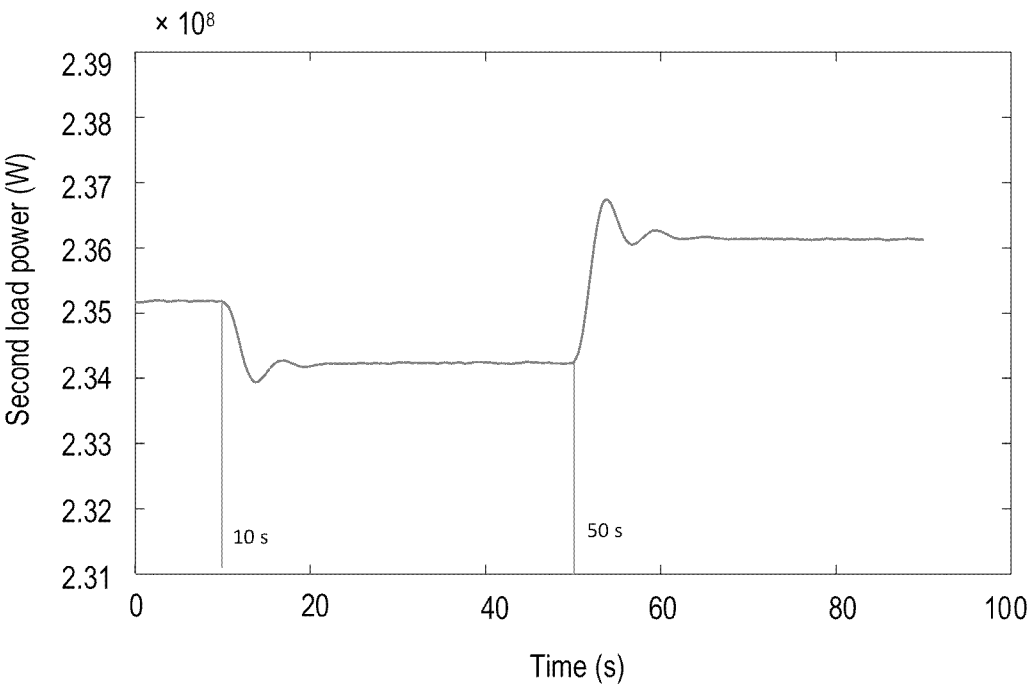


Fig. 8b

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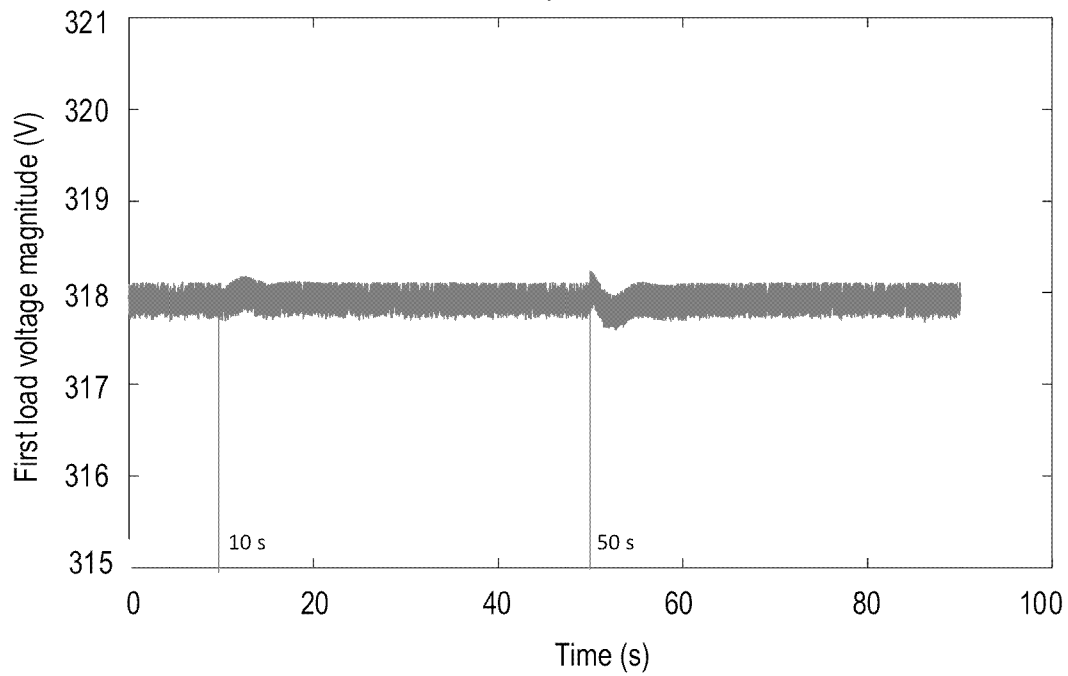
Fourth plot 62, 62₄

Fig. 9a

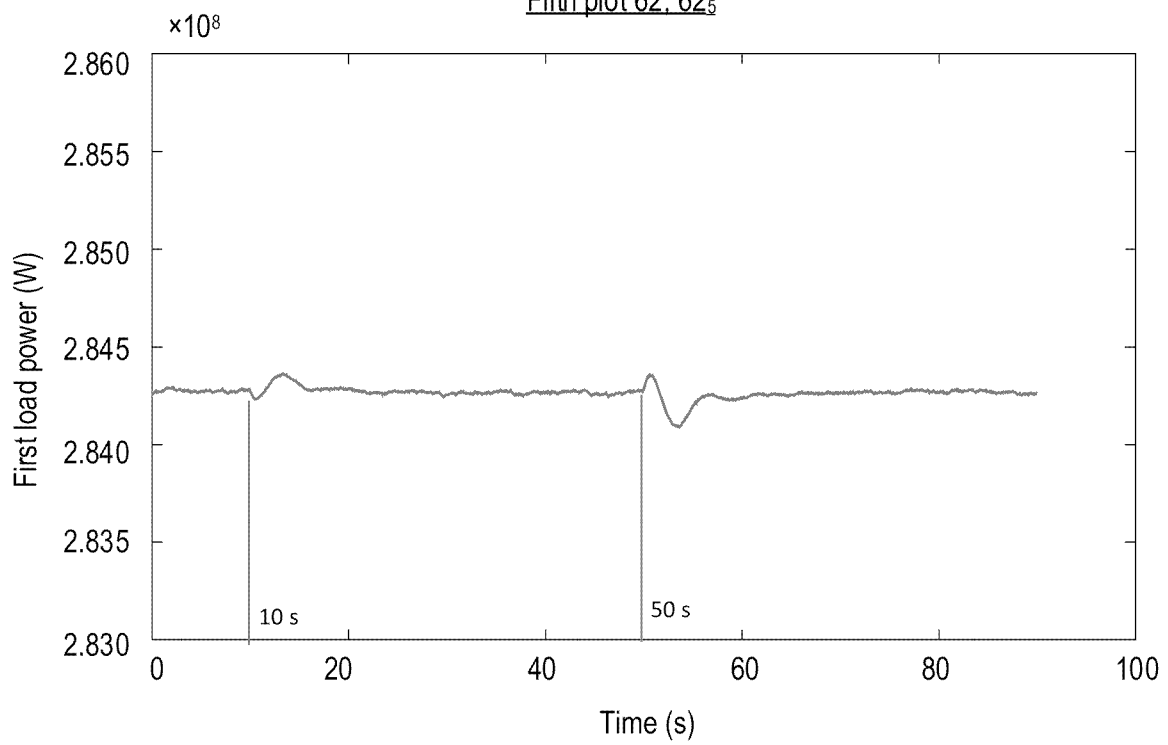
Fifth plot 62, 62₅

Fig. 9b

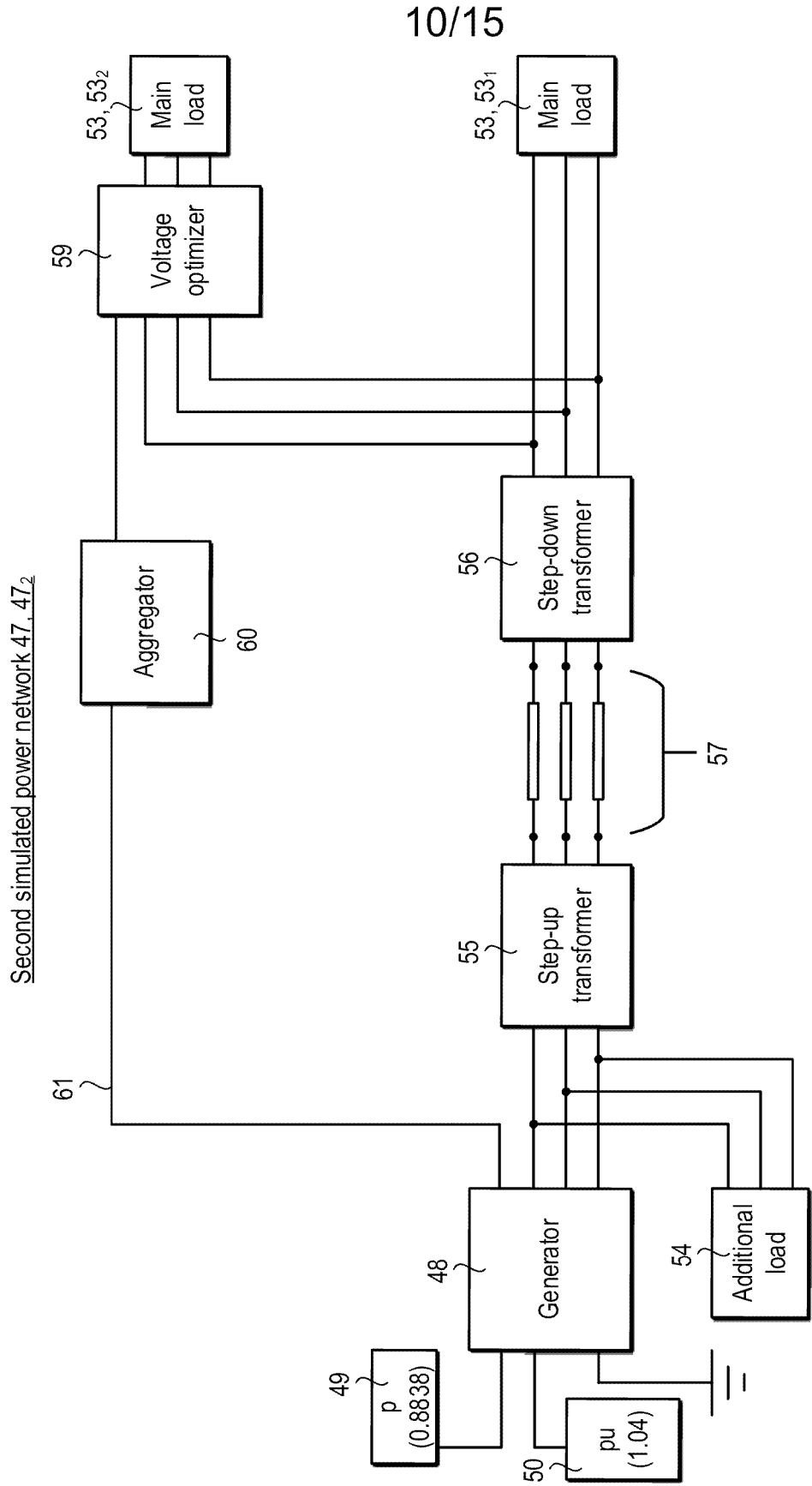


Fig. 10

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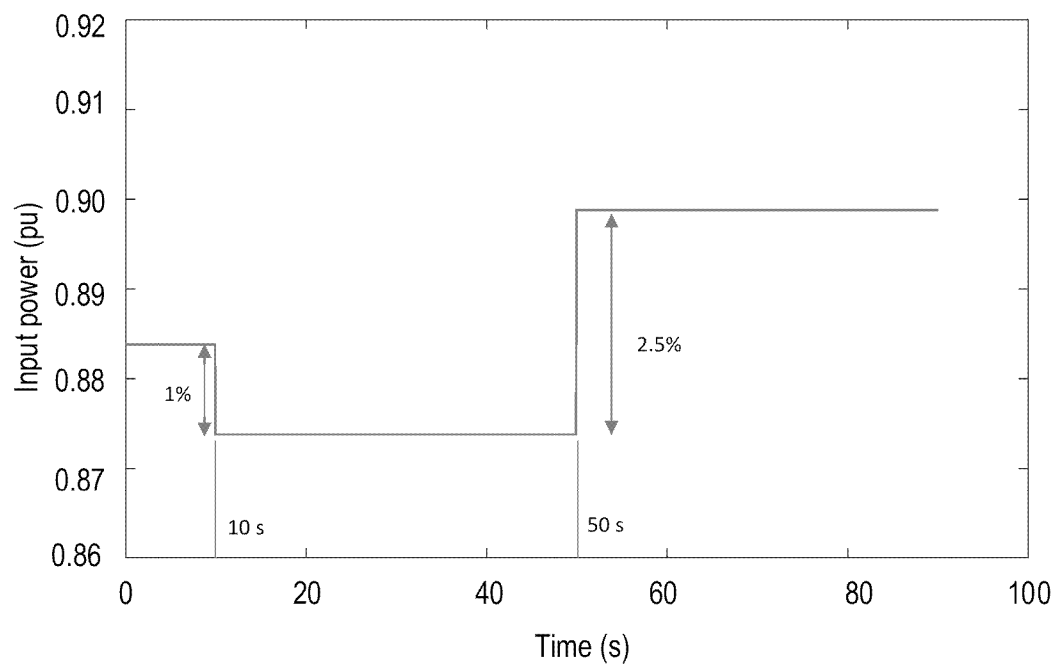
Sixth plot 62, 62₆

Fig. 11

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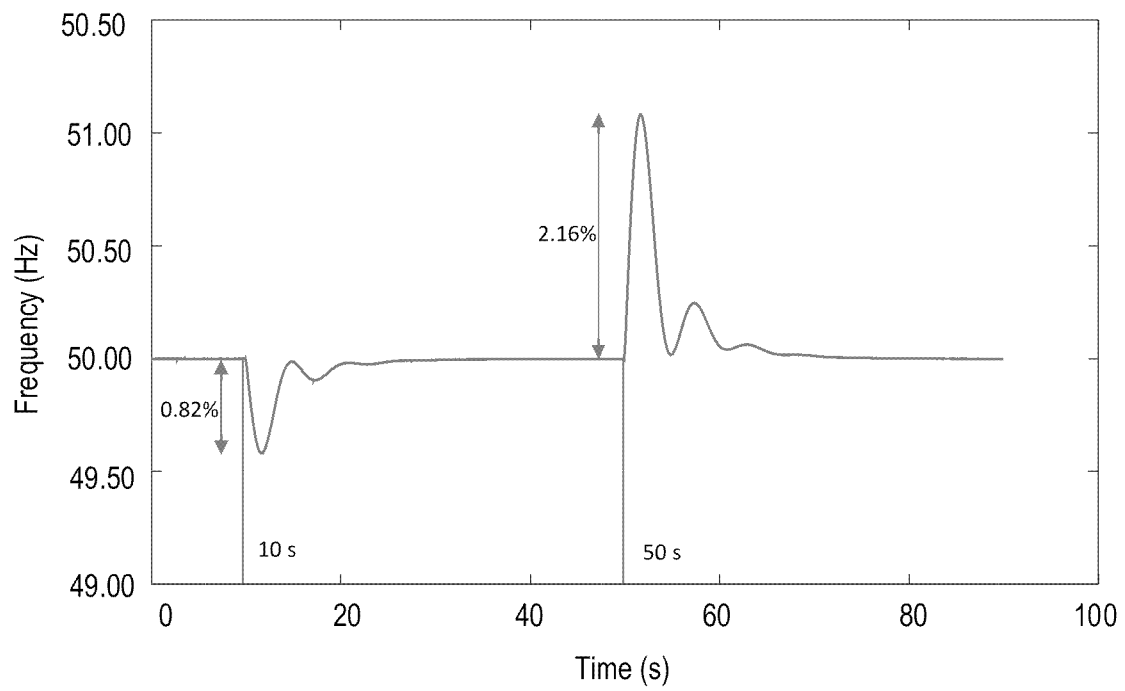
Seventh plot 62, 62₇

Fig. 12

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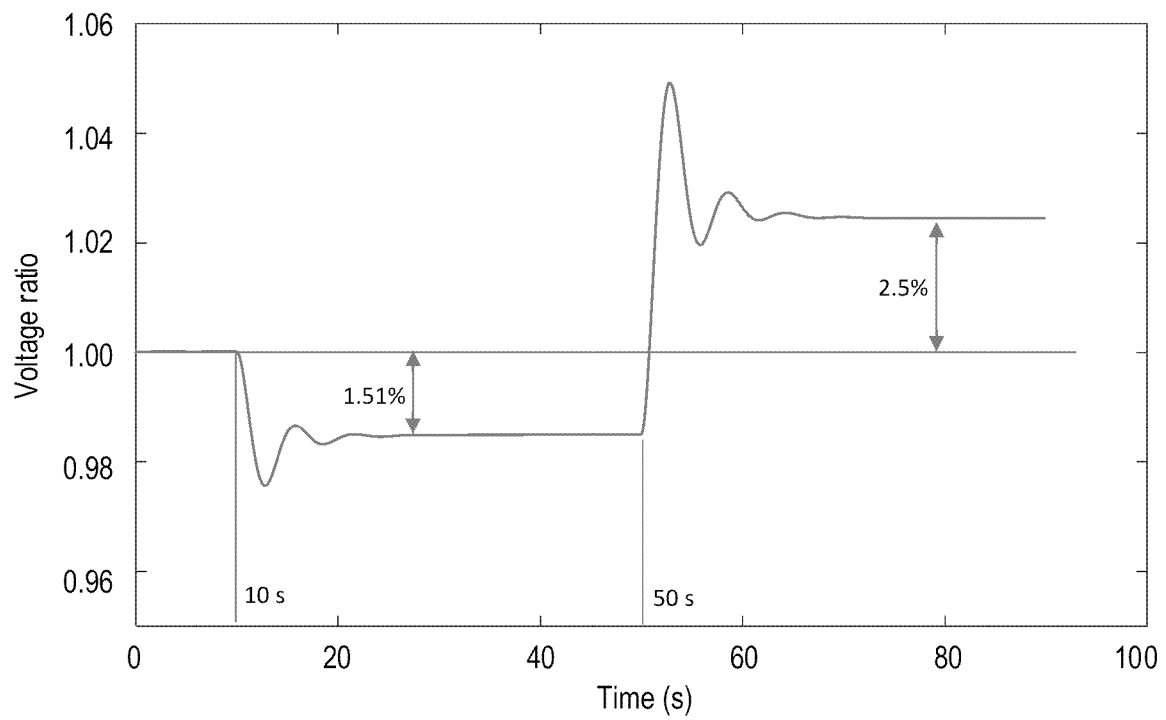
Eighth plot 62, 62_s

Fig. 13

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Ninth plot 62, 62₉

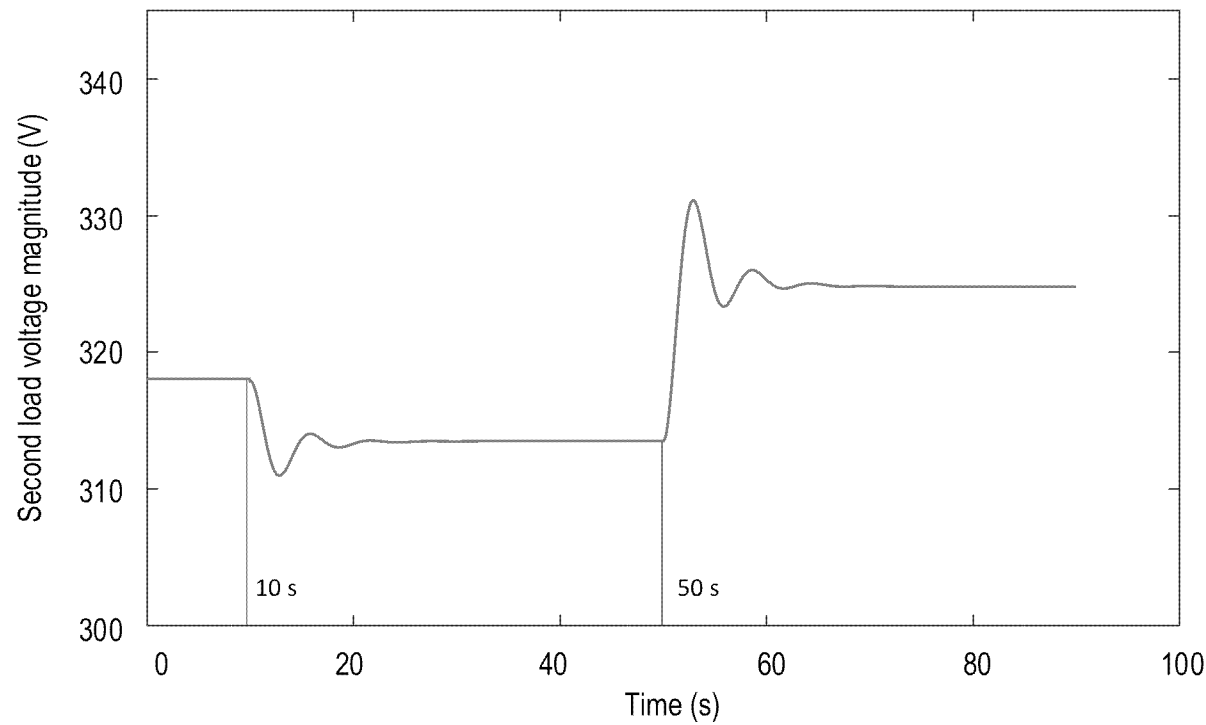


Fig. 14a

Tenth data plot 62, 62₁₀

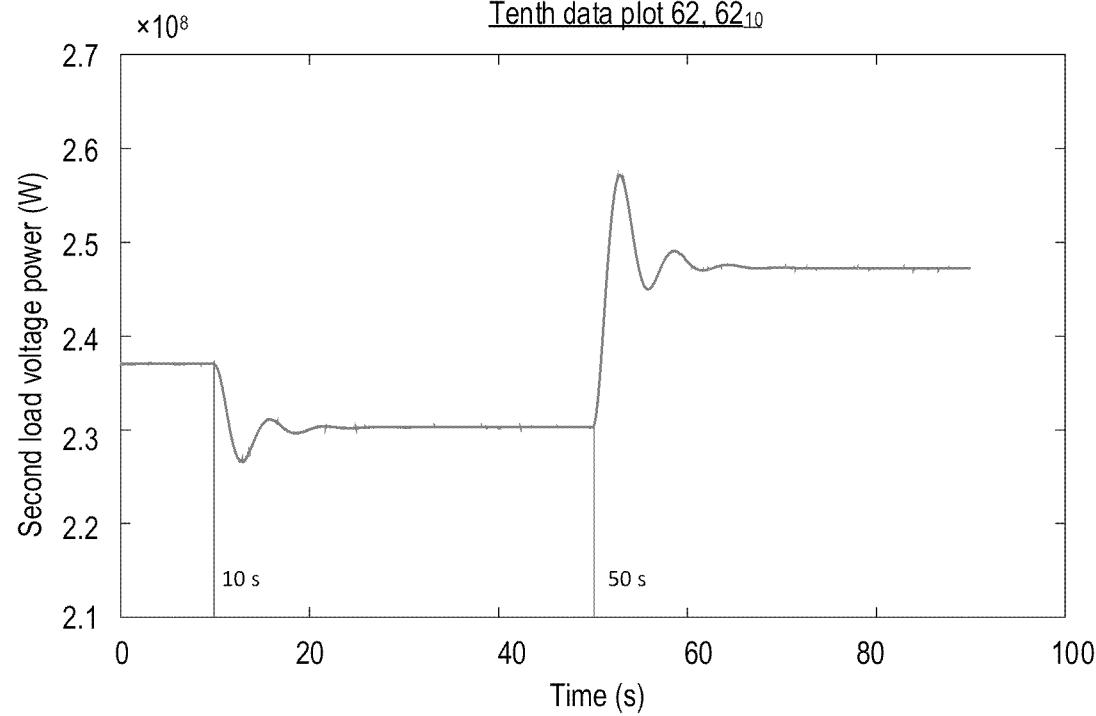


Fig. 14b

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Eleventh plot 62, 62₁₁

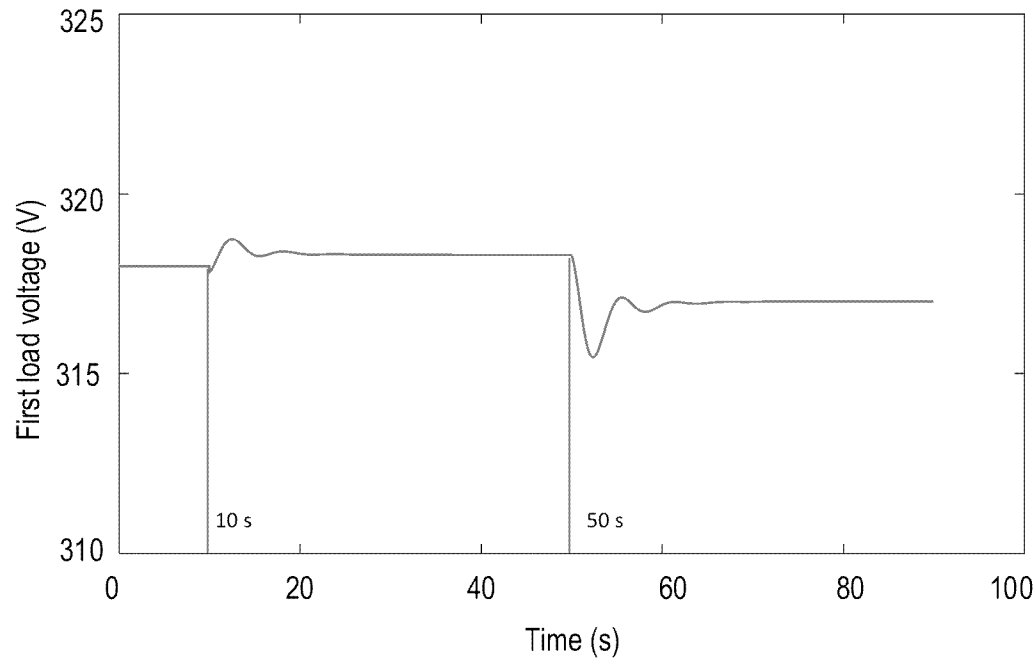


Fig. 15a

Twelfth plot 62, 62₁₂

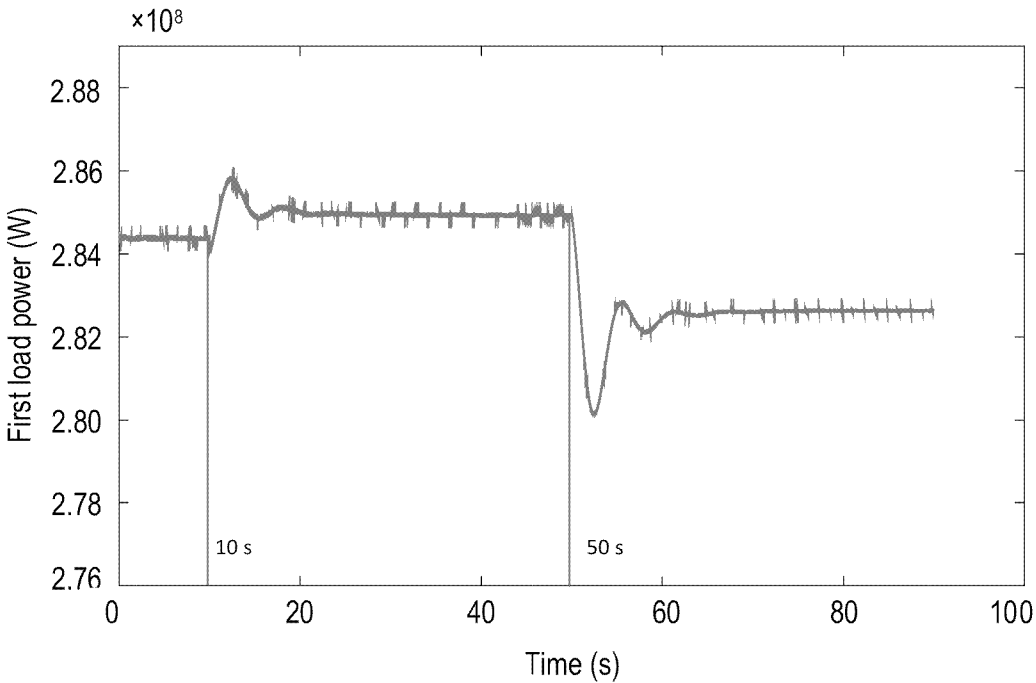


Fig. 15b

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2022/000006

A. CLASSIFICATION OF SUBJECT MATTER

INV. H02J3/14 H02J3/48 H02J13/00
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.
X	EP 3 660 999 A1 (ELECTRICITY NORTH WEST PROPERTY LTD [GB]) 3 June 2020 (2020-06-03) paragraphs [0077] - [0107]; figures 1-3 -----	1-11
X	US 2019/356163 A1 (WIEHINK LUUK JOHANNES MARIA [NL] ET AL) 21 November 2019 (2019-11-21) paragraphs [0026] - [0051], [0247] - [0251]; figures 1-4 -----	1-3, 8-10



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

7 April 2022

Date of mailing of the international search report

19/04/2022

Name and mailing address of the ISA/

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Authorized officer

Telega, Pawel

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2022/000006

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
EP 3660999	A1	03-06-2020	NONE	

US 2019356163	A1	21-11-2019	EP 3560065 A1	30-10-2019
			US 2019356163 A1	21-11-2019
			WO 2018117848 A1	28-06-2018
