POWER SUPPLY SYSTEM WITH PHASE BALANCING

FIELD OF THE INVENTION

[0001] The invention relates to a power supply system. In particular, the invention relates, but is not limited, to a power supply system that provides phase balancing between multiphase, typically three phase, power supply systems.

BACKGROUND TO THE INVENTION

[0002] Reference to background art herein is not to be construed as an admission that such art constitutes common general knowledge.

[0003] Multiphase power, typically three phase power, is often used by electricity networks to transmit high levels of power. It is common for adjacent households along a street to be connected to separate phases of a multiphase power supply. In some cases, however, particularly for large energy users such as industries, all three phases may be delivered to a single user.

[0004] Each of the phases carry a similar AC supply, but out of phase to the other two phases usually by one third of the period of the AC frequency. Three phase power transmission is most efficient when the load is balanced over all three phases. However, in reality, this is often not the case. Unbalanced loads result in power losses and inefficiencies, which can be unavoidable as each phase is often utilised independently of the other phases.

[0005] For example, neighbours on different phases choose how much power to use completely independently of each other, and pay no regard to the power usage of their neighbours on a different phase. Such phase imbalances can be exacerbated even further by some consumers having electricity

generation systems, such as solar panels, which can result in one consumer exporting power on one phase while their neighbour is importing power on another phase.

[0006] Some electricity generation systems, such as solar generation, may be multiphase and an inverter, or the like, may balance the power output over multiple phases when exporting. However, the inverter typically balances the power output so that the export itself is balanced, and does not actually determine which phase(s) would be best to export to in order to assist with balancing an imbalanced grid. For example, a balancing inverter generating approximate 9kw would typically simply export approximately 3kw per phase on a three phase supply.

[0007] These inefficiencies caused by phase imbalance result in increased infrastructure, and associated costs, being required. Furthermore, such imbalances can result in less efficient power transmission and usage.

OBJECT OF THE INVENTION

[0008] It is an aim of this invention to provide a power supply system with phase balancing which overcomes or ameliorates one or more of the disadvantages or problems described above, or which at least provides a useful alternative.

[0009] Other preferred objects of the present invention will become apparent from the following description.

SUMMARY OF INVENTION

[0010] In one form, although it need not be the only or indeed the broadest form, there is provided a method of phase balancing comprising:

measuring electricity characteristics of a plurality of phases of a multiphase electricity network;

communicating the measured electricity characteristics to a static synchronous compensator (statcom) connected to the multiphase electricity network;

using the statcom to import electricity from at least one of the phases and/or export electricity to at least one of the phases according to the measured electricity characteristics.

[0011] The statcom may also be connected to a DC bus. The method preferably further comprises the step of importing energy from at least one phase of the multiphase electricity network to the DC bus. The method preferably further comprises the step of exporting energy from the DC bus to at least one phase of the multiphase electricity network.

[0012] The method may further comprise the step of generating electricity. Preferably the generated electricity is exported to the DC bus. Preferably the step of generating electricity comprises generating renewable electricity using, for example, one or more solar panels and/or a wind generator. The step of generating electricity may also or instead comprise generating electricity using a hydro generator, biomass generator, fuel cell, and/or hydrocarbon generator.

[0013] The method may include charging an energy storage system. The method may include discharging an energy storage system. The step of using the statcom may further comprise charging the energy storage system with at least some of the imported electricity and/or discharging the energy storage

system to export electricity to at least one of the other phases according to the measured electricity characteristics.

[0014] Preferably the energy storage system comprises one or more batteries, typically a battery bank. The energy storage system may be connected to a DC/DC converter which is in turn connected to the DC bus. The DC/DC converter is preferably a bidirectional. Preferably the method comprises bidirectional energy transfer between the energy storage system and the multiphase electricity network.

[0015] The statcom may simultaneously import electricity from at least one of the phases and export electricity to at least one of the other phases according to the measured electricity characteristics. The step of simultaneously importing and exporting may comprise balancing power across the phases, balancing voltage across the phases or balancing current across the phases.

[0016] Preferably the step of measuring electricity characteristics uses a power sensor. Preferably the power sensor measures real and reactive power in each of the plurality of phases. Preferably an electrical load is connected to an AC network between the power sensor and the statcom. Preferably the electrical load has a plurality of phases which correspond to the plurality of phases of the multiphase electricity network.

[0017] Preferably the step of using the statcom to simultaneously import electricity from at least one of the phases and export electricity to at least one of the other phases according to the measured electricity characteristics comprises comparing electricity characteristic differences between phases.

Preferably the statcom imports electricity from at least one of the phases and/or exports electricity to at least one of the phases when an electricity characteristic difference between phases is greater than a predetermined amount.

[0018] Preferably the statcom controls how much energy is imported from the electricity network. The step of using the statcom to import electricity from at least one of the phases and export electricity to at least one of the other phases according to the measured electricity characteristics may comprise only exporting electricity up to a predetermined maximum output level.

[0019] Preferably the statcom controls how much energy is exported to the electricity network. Preferably the statcom controls charging and discharging of the energy storage system. The statcom may uses control algorithms that also take into account the date and/or time, electricity network electricity rates, the amount of electricity generation available, the current energy capacity of the energy storage system, and a current electrical load. Preferably the electricity network electricity rates includes both import and export rates.

[0020] The statcom may vary electricity imports and/or exports as a step change. The step change may be based on the maximum difference between phases. The step change could also be based on a difference of some other electricity characteristic(s). The statcom may vary electricity imports and/or exports gradually, preferably over a predetermined time period.

[0021] In another form, there is provided a power supply system comprising:

a statcom connected to a multiphase electricity network and a DC bus;

an electrical load connected to the multiphase electricity network; and

a power sensor in communication with the statcom that measures electricity characteristics of the multiphase electricity network;

wherein the statcom imports electricity from at least one of the phases of the multiphase electricity network and/or exports electricity to at least one of the phases of the multiphase electricity network according to the output of the power sensor.

[0022] Preferably the power sensor measures power, voltage, and/or current of each phase. Preferably the power sensor measures both real and reactive power of each phase.

[0023] Preferably the statcom is configured to at least partially balance the power, voltage, or current of the multiphase electricity network at the electrical load. Preferably the statcom is configured to control the voltage and/or current of the phases of the electricity network using the power sensor as a feedback loop.

[0024] The power supply system may comprise an energy storage system connected to the DC bus. Preferably the energy storage system comprises one or more batteries, typically a battery bank. Preferably the system comprises a DC/DC converter that connects the energy storage system to the DC bus. The system may further comprise an energy generation system. The energy generation system preferably comprises renewable electricity sources such as, for example, solar panels and/or wind turbines. The energy generation system may also or instead comprise a hydro generator, biomass generator, fuel cell,

and/or hydrocarbon generator. The statcom preferably outputs energy from an energy generation system to the phase(s) which are measured to have less voltage and/or current.

[0025] Preferably the DC bus has a voltage of greater than 100V, even more preferably greater than 200V, even more preferably greater than 300V, and even more preferably greater than 400V. The DC bus may have a voltage that varies within the range 200V to 600V, more preferably within the range 300V to 500V, more preferably in the range 400 to 500V, more preferably in the range 420V to 480V, and even more preferably between approximately 430V and 460V. The actual voltage of the DC bus preferably varies depending on whether the energy storage system is inputting or outputting energy.

[0026] Preferably the AC network is a low voltage AC network having a standard voltage for electricity supply to consumers. Preferably the AC network has a voltage of less than 400V, more preferably less than 300V, and typically around 200-250V or 100-150V depending on the country mains voltage electricity supply.

[0027] Further features and advantages of the present invention will become apparent from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] By way of example only, preferred embodiments of the invention will be described more fully hereinafter with reference to the accompanying figures, wherein:

[0029] Figure 1 illustrates an overview of an example power supply system;

[0030] Figure 2 illustrates an overview of another example power supply system with each phase of a three phase AC network illustrated separately;

[0031] Figure 3 illustrates an overview example of power flow using power phase balancing;

[0032] Figure 4 illustrates an overview example of power flow using voltage phase balancing; and

[0033] Figure 5 illustrates an overview example of power flow using current phase balancing.

DETAILED DESCRIPTION OF THE DRAWINGS

[0034] 1. *System Overview*

[0035] Figure 1 illustrates an example power supply system having user equipment 10 connected to electricity transmission infrastructure 20. Central to the system is a static synchronous compensator (statcom) 140. The statcom 140 is connected between a DC bus 310 and an AC network 320. An electrical load 250, which in the case of a standard household consumer is the electrical load of their household, is connected to the AC network 320. The AC network 320 may be a single phase or multiphase AC network. For the present invention the AC network 320 is preferably a multiphase, typically a three phase, AC network 320 with the statcom 140, electrical load 250, power sensor 150, and electricity network 240 all having multiphase connections.

[0036] The user equipment illustrated in figure 1 includes renewable electricity generation in the form of a solar generator 210 having a photovoltaic (PV) array of solar panels and a wind generator 220. Although the only electricity generators shown are solar and wind, it will be appreciated that other

electricity generation sources could be connected such as, for example, a hydro generator, biomass generator, fuel cell, and/or hydrocarbon generator.

[0037] The solar generator 210 is connected to the DC bus 310 via a PV DC/DC converter 110 which matches the solar generator 210 DC output to the DC bus 310. The wind generator 220 is connected to the DC bus 310 via a wind generator AC/DC converter 120 which converts the wind generated AC electricity output to a DC output that is suitable for connection to the DC bus 310.

[0038] An energy storage system in the form of a battery bank 230 is provided. The battery bank 230 is connected to the DC bus 310 via a battery DC/DC converter 130. The battery DC/DC converter 130 matches the battery bank 230 DC output to the DC bus 310. The battery bank 230 may be any suitable size, but is preferably selected based on at least characteristics of the electrical load 250. The battery DC/DC converter 130 is bidirectional to allow both charging and discharging of the battery bank 230 through the DC bus 310.

[0039] The PV DC/DC converter and wind AC/DC converter output generated electricity to the DC bus 310 which can then be managed by the statcom 140. The battery DC/DC converter can both output electricity to the DC bus 310 and input electricity from the DC bus 310, typically under control of the statcom 140. The statcom 140 uses a number of variables to which determine when and how it inputs and outputs electricity from the DC bus 310 into or from the battery bank 230. These variables include available electricity rates for import, available electricity rates for export, power being generated, energy storage system reserves; and/or current electrical load.

[0040] A power sensor 150 may be provided which can provide a power measurement 330 to the statcom 140. The power sensor 150 measures real and reactive power of the AC network 320. The power sensor 150 measures both magnitude and direction to ascertain whether real power is being exported to the electricity network 240 or imported from the electricity network 240 and whether the reactive power is leading or lagging the real power. The power measurement 330 can be communicated to the statcom 140 using either wired or wireless communication systems.

[0041] 2. *Phase Balancing*

[0042] Figure 2 illustrates an example power supply system which is similar to the one illustrated in figure 1 but showing each phase of a three phase AC network 320 separately. Notably, the statcom 140, electrical load 250, power sensor 150, and electricity network 240 all have three phase connections.

[0043] Additionally, figure 2 does not show electricity generation in the form of the solar generator 210 and the wind generator 220 nor does it show energy storage in the form of a battery bank 230. Although these items have been omitted from figure 2, it will be appreciated that this is merely for the sake of convenience and clarity in description, and that the same or similar electricity generation and energy storage could be connected to the DC bus 310.

[0044] The statcom 140 is configured to receive electricity characteristic measurements of each of the three phases from the power sensor 150. The statcom 140 is also configured to import electricity from at least one of the phases and export electricity to at least one of the other phases according to the measured electricity characteristics. Preferably an energy storage system is

connected to the DC bus 310 which the statcom 140 can control charging and discharging of when importing and exporting electricity across the phases.

[0045] The statcom 140 may be configured to balance power, voltage, or current over the phases as described in the following sections.

[0046] 2.1 *Power Phase Balancing*

[0047] In a preferred form, the statcom 140 is configured to balance power across the phases. Power imbalances across the phases are detected using the power sensor 150 and the statcom consequently prioritises imports from the electricity network 240 to one or more phases with a higher power measurement and prioritises exports to the electricity network 240 to one or more phases with a lower power measurement.

[0048] With power phase balancing, the power sensor 150 continuously measures real and reactive power in each phase and communicates power measurement characteristics to the statcom 140. The measurement characteristics include magnitude and direction which are used by the statcom 140 to determine if real power is being exported to the electricity network 240, imported from the electricity network 240, and whether the reactive power is leading or lagging.

[0049] The statcom 140 compares the phases and if a power difference is over a predetermined amount then the statcom 140 varies electricity imported from at least one of the phases and varies electricity exported to at least one of the other phases in order to reduce the imbalance. To achieve this the statcom 140 may reduce a maximum output power of at least one of the phases having a higher power measurement. Furthermore, the statcom 140 may increase a

maximum output power of at least one of the phases having a lower power measurement.

[0050] The statcom 140 may alter electricity imports and/or exports as a step change based on a maximum power difference between phases, as a step change based on some other electricity characteristic difference between phases, or as a gradual ramp up or down over time. The statcom 140 modifies the electricity imports and/or exports on each of the phases to minimise differences in power between each phase at the electricity load 250.

[0051] Table 1, below, contains some arbitrary examples showing power phase balancing under various conditions. The examples are based on a 15kVA system with a statcom 140 capable of handling 5kVA per phase, and an electricity generation system, such as a solar array, capable of providing up to 15kW with a negative value representing power being sunk by the statcom 140 or power being imported from the electricity network 240.

Example no.	Electricity Network (kVA) (P_{GR} / P_{GW} / P_{GB})	Electrical Load (kVA) (P_{LR} / P_{LW} / P_{LB})	Statcom (kVA) (P_{SR} / P_{SW} / P_{SB})	DC Bus (kW) (P_{DC})
1	-15 / -12 / -6	15 / 12 / 6	0 / 0 / 0	0
2	-10 / -10 / -10	15 / 12 / 6	5 / 2/ -4	3
3	-7 / -7 / -7	11 / 12 / 9	4 / 5 / 2	11
4	-10 / -8 / -8	15 / 12 / 3	5 / 4 / -5	4
5	-11 / -11 / -11	15 / 12 / 6	4 / 1 / -5	0
6	1 / 1 / 1	3 / 1 / 4	4 / 2 / 5	11
7	-11 / -11 / -8	15 / 12 / 3	4 / 1 / -5	0

TABLE 1

[0052] The relationship between the points of measurement in Table 1 are illustrated in figure 3 where:

a) Electricity Network Power (P_{Gx}) = Statcom Power (P_{Sx}) - Electrical Load Power (P_{Lx}); and

b) Statcom Power ($P_{SR} + P_{SW} + P_{SB}$) = DC Bus Power (P_{DC}).

[0053] With reference to table 1, example no. 1 illustrates the effect of no phase balancing, and examples 5 and 7 illustrate what happens when there is no power generation on the DC Bus (e.g. at night when a solar generation system does not generate any electricity).

[0054] 2.2 *Voltage Phase Balancing*

[0055] In another form, the statcom 140 is configured to balance voltage across the phases. Voltage imbalances are usually the result of load imbalances on the electricity network 240. Improving voltage imbalances is particularly beneficial in reducing issues caused by voltage imbalances in multiphase loads such as, for example, a three phase motor.

[0056] Voltage imbalances across the phases are detected using the power sensor 150 and the statcom consequently prioritises imports from the electricity network 240 to one or more phases with a higher voltage measurement and prioritises exports to the electricity network 240 to one or more phases with a lower voltage measurement.

[0057] With voltage phase balancing, the power sensor 150 continuously measures the voltage of each phase and communicates the voltages to the statcom 140. The statcom 140 compares the phases and if a voltage difference is over a predetermined amount then the statcom 140 varies

electricity imported from at least one of the phases and varies electricity exported to at least one of the other phases in order to reduce the imbalance. To achieve this the statcom 140 may reduce a maximum output power of at least one of the phases having a higher voltage measurement. Furthermore, the statcom 140 may increase a maximum output power of at least one of the phases having a lower voltage measurement.

[0058] The statcom 140 may alter electricity imports and/or exports as a step change based on a maximum voltage difference between phases, as a step change based on some other electricity characteristic difference between phases, or as a gradual ramp up or down over time. The statcom 140 modifies the electricity imports and/or exports on each of the phases to minimise differences in voltage between each phase at the electricity load 250.

[0059] Table 2, below, contains some arbitrary examples showing voltage phase balancing under various conditions. The examples are based on a 15kVA system with a statcom 140 capable of handling 5kVA per phase, and an electricity generation system, such as a solar array, capable of providing up to 15kW. As illustrated in example no. 1, it is assumed that V_{GR0} = 240V, V_{GW0} = 236V, and V_{GB0} = 242V with no electricity load 250 and no statcom 140 power. It is also assumed that there is a linear relationship of 2V/kVA between power flowing through a point to be controlled and the voltage at the point to be controlled (e.g. for every 1kVA imported from the electricity network 240 the voltage drops by 2V).

Example no.	Electricity Network Voltage (V) (P_{GR} / P_{GW} / P_{GB})	Electrical Load (kVA) (P_{LR} / P_{LW} / P_{LB})	Statcom (kVA) (P_{SR} / P_{SW} / P_{SB})	DC Bus (kW) (P_{DC})

1	240 / 236 / 242	0 / 0 / 0	0 / 0 / 0	0
2	246 / 246 / 246	0 / 0 / 0	3 / 5 / 2	10
3	244 / 244 / 244	3 / 1 / 4	5 / 5 / 5	15
4	232 / 232 / 232	3 / 7 / 6	-1 / 5 / 1	5
5	230 / 230 / 230	3 / 7 / 4	-2 / 4 / -2	0
6	226 / 224 / 226	4 / 11 / 6	-3 / 5 / -2	0

TABLE 2

[0060] The relationship between the points of measurement in Table 2 are illustrated in figure 4 where:

a) Electricity Network Voltage (V_{Gx}) = No Load Electricity Network Voltage (V_{Gx0}) – 2 * (Electrical Load Power (P_{Lx}) - Statcom Power (P_{Sx})); and

b) Statcom Power ($P_{SR} + P_{SW} + P_{SB}$) = DC Bus Power (P_{DC}).

[0061] With reference to table 2, example no. 1 example no. 1 shows the effect of no phase balancing and example no. 5 illustrates what happens when there is no power generation on the DC Bus (e.g. at night when a solar generation system does not generate any electricity).

[0062] 2.3 *Current Phase Balancing*

[0063] In another form, the statcom 140 is configured to balance current across the phases. Current imbalances across the phases are detected using the power sensor 150 and the statcom consequently prioritises imports from the electricity network 240 to one or more phases with a higher current measurement and prioritises exports to the electricity network 240 to one or more phases with a lower current measurement.

[0064] With current phase balancing, the power sensor 150 continuously measures the current in each phase and communicates the currents to the

statcom 140. The statcom 140 compares the phases and if a current difference is over a predetermined amount then the statcom 140 varies electricity imported from at least one of the phases and varies electricity exported to at least one of the other phases in order to reduce the imbalance. To achieve this the statcom 140 may reduce a maximum output power of at least one of the phases having a higher current measurement. Furthermore, the statcom 140 may increase a maximum output power of at least one of the phases having a lower current measurement.

[0065] The statcom 140 may alter electricity imports and/or exports as a step change based on a maximum current difference between phases, as a step change based on some other electricity characteristic difference between phases, or as a gradual ramp up or down over time. The statcom 140 modifies the electricity imports and/or exports on each of the phases to minimise differences in current between each phase at the electricity load 250.

[0066] Table 3, below, contains some arbitrary examples showing current phase balancing under various conditions. The examples are based on a 15kVA system with a statcom 140 capable of handling 5kVA per phase, and an electricity generation system, such as a solar array, capable of providing up to 15kW. It is assumed that the voltage of each phase remains constant at 230V.

Example no.	Electricity Network Current (A) (I_{GR} / I_{GW} / I_{GB})	Electrical Load (kVA) (P_{LR} / P_{LW} / P_{LB})	Statcom (kVA) (P_{SR} / P_{SW} / P_{SB})	DC Bus (kW) (P_{DC})
1	-65.2 / -52.2 / -26.1	15 / 12 / 6	0 / 0 / 0	0
2	-43.5 / -43.5 / -43.5	15 / 12 / 6	5 / 2/ -4	3
3	-30.4 / -30.4 / -30.4	11 / 12 / 9	4 / 5 / 2	11

4	-43.5 / -34.8 / -34.8	15 / 12 / 3	5 / 4 / -5	4
5	-47.8 / -47.8 / -47.8	15 / 12 / 6	4 / 1 / -5	0
6	4.3 / 4.3 / 4.3	3 / 1 / 4	4 / 2 / 5	11
7	-47.8 / -47.8 / -34.8	15 / 12 / 3	4 / 1 / -5	0

TABLE 3

[0067] The relationship between the points of measurement in Table 3 are illustrated in figure 5 where:

a) Electricity Network Current (P_{Gx}) = (Statcom Power (P_{Sx}) - Electrical Load Power (P_{Lx})) / 230; and

b) Statcom Power ($P_{SR} + P_{SW} + P_{SB}$) = DC Bus Power (P_{DC}).

[0068] With reference to table 3, example no. 1 illustrates the effect of no phase balancing, and examples 5 and 7 illustrate what happens when there is no power generation on the DC Bus (e.g. at night when a solar generation system does not generate any electricity).

[0069] 3. *Advantages*

[0070] Advantageously, the system and method of phase balancing improves phase imbalances on the electricity network 240 and reduces the associated problems and inefficiencies that arise from having an imbalanced network. An overall improvement of quality in the electricity network 240 is mutually beneficial to both network operators and connected users.

[0071] Some multiphase appliances connected to the electrical load 250 can have operational and efficiency issues when connected to a heavily imbalanced network, so the improved phase balancing also not only assists with improving the operation and efficiency of electricity transmission

infrastructure 20 for the network operators, but also the user equipment 10, in particular the electrical load 250, for the connected consumer.

[0072] The system and method of phase balancing is particularly useful for systems that include electricity generation, such as a solar generator 210 and/or wind generator 220, as it ensures electricity exports to the electricity network 240 are distributed to the phases optimally to reduce phase imbalances. It is also particularly useful for ensuring that the electrical load 250 is drawn from the electricity network 240 in an optimal manner. Additionally, however, the system and method of phase balancing can also be used to source power from one phase and sink it to another phase, resulting in improved electricity network 240 phase balancing independent of the electrical load 250 and any power generation or energy storage connected to the DC bus 310.

[0073] In this specification, adjectives such as first and second, left and right, top and bottom, and the like may be used solely to distinguish one element or action from another element or action without necessarily requiring or implying any actual such relationship or order. Where the context permits, reference to an integer or a component or step (or the like) is not to be interpreted as being limited to only one of that integer, component, or step, but rather could be one or more of that integer, component, or step etc.

[0074] The above description of various embodiments of the present invention is provided for purposes of description to one of ordinary skill in the related art. It is not intended to be exhaustive or to limit the invention to a single disclosed embodiment. As mentioned above, numerous alternatives and

variations to the present invention will be apparent to those skilled in the art of the above teaching. Accordingly, while some alternative embodiments have been discussed specifically, other embodiments will be apparent or relatively easily developed by those of ordinary skill in the art. The invention is intended to embrace all alternatives, modifications, and variations of the present invention that have been discussed herein, and other embodiments that fall within the spirit and scope of the above described invention.

[0075] In this specification, the terms ‘comprises’, ‘comprising’, ‘includes’, ‘including’, or similar terms are intended to mean a non-exclusive inclusion, such that a method, system or apparatus that comprises a list of elements does not include those elements solely, but may well include other elements not listed.

PROVISIONAL CLAIMS:

1. A method of phase balancing comprising:

measuring electricity characteristics of a plurality of phases of a multiphase electricity network;

communicating the measured electricity characteristics to a static synchronous compensator (statcom) connected to the multiphase electricity network;

using the statcom to import electricity from at least one of the phases and/or export electricity to at least one of the phases according to the measured electricity characteristics.

2. A power supply system comprising:

a statcom connected to a multiphase electricity network and a DC bus;

an electrical load connected to the multiphase electricity network; and

a power sensor in communication with the statcom that measures electricity characteristics of the multiphase electricity network;

wherein the statcom imports electricity from at least one of the phases of the multiphase electricity network and/or exports electricity to at least one of the phases of the multiphase electricity network according to the output of the power sensor.