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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 June 2018 (21.06.2018)

WIPO | PCT

(10) International Publication Number
WO 2018/108277 A1

(51) International Patent Classification:
H02J 3/38 (2006.01) *G01R 19/25* (2006.01)

(21) International Application Number:
PCT/EP2016/081177

(22) International Filing Date:
15 December 2016 (15.12.2016)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **ABB SCHWEIZ AG** [CH/CH]; Brown Boveri Strasse 6, CH-5400 Baden (CH).

(72) Inventors: **GUERRIERO, Alessandro**; c.da Piano La Barca 33, I-66020 Paglieta (CH) (IT). **LALLI, Filippo**; Via Trento 18/A, I-52024 Loro Ciuffenna (AR) (IT). **SCALETTI, Silvio**; Via Del Poggetto, 23/2, Località Pieve a Maiano, I-52041 Civitella in Val Di Chiana (AR) (IT). **BUCCI, Tiberio**; Via Palmiro Togliatti 8, I-50055 Lastra a Signa (FI) (IT).

(74) Agent: **DE BORTOLI, Eros** et al.; Via Melchiorre Gioia, 64, 20125 Milano (IT).

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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,

WO 2018/108277 A1

(54) Title: METHOD FOR DETECTING ISLANDING CONDITIONS FOR A DC/AC CONVERTER APPARATUS AND A DC/AC CONVERTER APPARATUS THEREOF

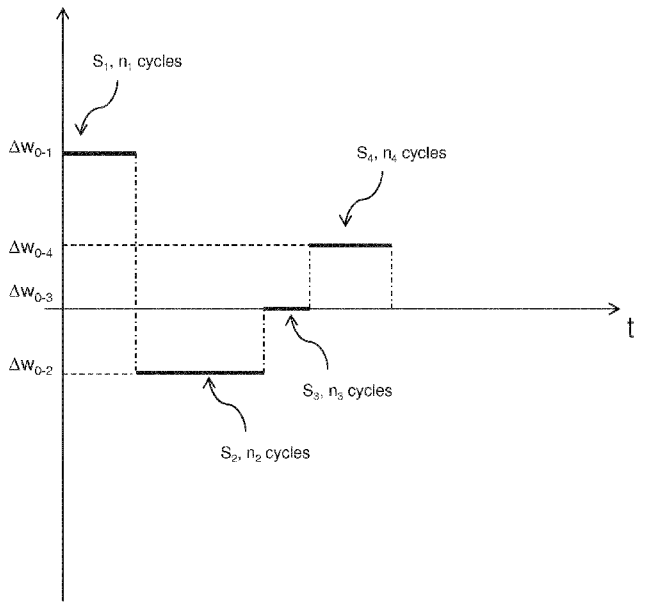

Fig. 4

(57) Abstract: Method for detecting an islanding condition of a grid connected energy conversion system and related DC/AC converter apparatus adapted to optimize performance in terms of preservation of the power quality, provide synchronized frequency perturbation for all the inverters of a plant, provide shut down capability within the time requested by utilities and safety standards and provide immunity to grid frequency fluctuations.

[Continued on next page]

TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

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

METHOD FOR DETECTING ISLANDING CONDITIONS FOR A DC/AC CONVERTER APPARATUS AND A DC/AC CONVERTER APPARATUS THEREOF

DESCRIPTION

The present invention relates to the field of electric power generation systems, especially of electric power generation systems including renewable sources, such as photovoltaic panels or wind turbines.

In particular, the present invention relates to an improved method for detecting islanding conditions for a DC/AC converter apparatus.

Electric power generation systems including renewable sources are typically designed to generate electrical power for direct delivery to a main grid, such as an electric power utility grid.

To this aim, an electric power generation system is generally equipped with one or more DC/AC converter apparatuses, each of which is adapted to convert DC electrical power generated by a respective electric power generation apparatus (e.g. a photovoltaic plant) into AC electric power to be delivered to the main grid.

Normally, the DC/AC converter apparatus of an electric power generation system is always electrically connected to the main grid.

However, in response to system needs or abnormal conditions (e.g. faults or power outages in the main grid), said apparatus may be electrically disconnected from the main grid but still working, operating in a so-called “islanded mode” and no more in “grid connected mode”.

A DC/AC converter apparatus operating in islanded mode can be very dangerous, in particular to utility workers, who may not realize that an electric circuit is still powered as said apparatus is exchanging electric power with a resonant electric circuit electrically connected thereto.

For that reason, a DC/AC converter apparatus of an electric power generation system is typically provided with control means configured to implement a detection method to check whether it is operating in islanding conditions.

Several solutions to detect islanding conditions for a DC/AC converter apparatus have been proposed during the past years.

These solutions can be generally divided in passive and active detection methods.

Passive detection methods typically provide for monitoring given physical parameters (e.g. voltage and frequency, the grid voltage change rate or the grid frequency change rate) at a point of common coupling between the DC/AC converter apparatus and the main grid and preventing said DC/AC converter apparatus from supplying electric power to the main grid, if the detected parameters differ from given nominal or averaged values.

Active detection methods provide for introducing a controlled perturbation in the operation of the DC/AC converter apparatus and monitoring the responsive behavior of the AC voltage at the point of common coupling to determine whether said DC/AC converter apparatus is still connected to the main grid.

Known examples of said active detection methods are the so-called Sandia™-like frequency shift method and Sandia™-like voltage shift methods.

Active detection methods are generally preferred by manufacturers because they are characterized by narrower NDZs (Non Detection Zones) and faster detection times compared to passive detection methods.

EP3079217A1 discloses a method for detecting whether a grid connected DC/AC converter apparatus operates in islanded mode.

According to a disclosed embodiment, an initial frequency disturbance is provided to a reference signal that is normally processed to control the output voltage provided by the DC/AC converter apparatus while the frequency of the AC voltage at the point of common coupling with the main grid is monitored.

Depending on the behavior of the frequency of the AC voltage at the point of common coupling in response to said initial frequency disturbance, the operation of the DC/AC converter apparatus is immediately modified or further stronger frequency disturbances are applied to said reference signal to check whether islanding conditions are present.

According to this method, the mentioned initial frequency disturbance may consist in applying a frequency perturbation having a predefined frequency perturbation value with a positive sign for a first predefined number n of AC cycles and with a negative sign for a second predefined number m of AC cycles.

The above mentioned initial frequency perturbation is applied periodically for subsequent sequences of n+m AC cycles until a responsive frequency drift of the AC voltage at the point of common coupling is detected.

The method disclosed in the above mentioned document shows excellent results in detecting possible islanding conditions for a DC/AC converter apparatus.

However, in the state of the art there is still a need for solutions providing top level islanding detection performances, particularly when multiple DC/AC converter apparatuses are electrically connected at a same common coupling point.

The present invention intends to respond to this need by providing a method for detecting islanding conditions for a DC/AC converter apparatus, according to the following claim 1 and the related dependent claims.

In a further aspect, the present invention relates to a grid connectable DC/AC converter apparatus, according to the following claim 12.

In yet a further aspect, the present invention relates to an electric power generation system, according to the following claim 13.

Features and advantages of the present invention will be apparent in the following description of non-limitative embodiments with reference to the figures in the accompanying drawings, in which:

- figure 1 shows a block diagram of a grid connectable DC/AC converter apparatus provided with a controller module implementing the method, according to the present invention;
- figures 2-7 show block diagrams describing the method for detecting an islanding condition, according to the present invention.

Referring to the cited figures, the present invention relates to a method 1 for detecting islanding conditions for a DC/AC converter apparatus 1.

Figure 1 shows a generic block diagram of a grid connected single-phase or multi-phase DC/AC converter apparatus.

The DC/AC converter apparatus 1 has an input electrically connected to a respective electric power generation apparatus 10, e.g. a photovoltaic generation plant or a wind generation plant.

The output of the DC/AC converter apparatus 1 is electrically connected to a main grid 16 (e.g. a power utility grid) at a point of common coupling Pcc.

Both the DC/AC converter apparatus 1 and the electric power generation apparatus 10 are part of an electric power generation apparatus 100, which may include further DC/AC converter apparatus electrically connected to the main grid 16 at the point of common coupling Pcc.

The DC/AC converter apparatus 1 comprises an input DC/DC converter 11 and a cascaded DC/AC inverter 12.

The input DC/DC converter 11 is adapted to boost the DC voltage provided by the energy generation apparatus 10 to a predetermined DC voltage level to charge a capacitor bank 15 at a DC-Link output terminal DL.

The DC/AC inverter 12, which operates as an AC current generator, is adapted to convert the DC voltage at the DC-Link terminal DL into an AC voltage synchronized with the main grid 16.

The DC/AC converter apparatus 1 comprises a control unit 14 adapted to control the operation of said DC/AC converter apparatus.

In order to carry out its functionalities, the control unit 14 comprises data processing resources that may be industrially implemented in an analog and/or digital manner.

If they are implemented in analog manner, said data processing resources comprise one or more electronic circuits suitably arranged to perform the functionalities provided for said data processing resources.

If they are implemented in a digital manner, said data processing resources comprise one or more computerized units (e.g. DSPs or microprocessors) and suitably arranged sets of software instructions stored in a medium and executable by said computerized units to perform the functionalities provided for said data processing resources.

The present invention will be now described in more details with reference to embodiments, in which the data processing resources of the control unit 14 are implemented in a digital manner.

In order to carry out its control functionalities, the control unit 14 comprises data processing modules 17, 18, 19, 20, 21, 22, 23, 24, each of which is preferably formed by suitably arranged sets of software instructions stored in a medium and executable by the computerized units of the control unit 14.

The control unit 14 comprises an inner current control loop adapted to control the current provided in output by the DC/AC inverter 12 (which normally operates as a current generator), in particular to regulate the active current I_D and the reactive current I_Q provided in output by the said DC/AC inverter to the reference values I_{D_ref} and I_{Q_ref}.

Said inner current control loop comprises a current controller 22 and a PWM modulator 24.

The current controller 22 is configured to receive reference signals I_{D_ref} and I_{Q_ref} indicative of the reference amplitude for the active current I_D and the reactive current I_Q to be provided in output, a reference signal F_R indicative of the reference frequency for the active current I_D and the reactive current I_Q to be provided in output and a measurement signal I_M indicative of the actual active current I_D and the reactive current I_Q (measured by a suitably current sensor of known type).

The PWM modulator 24 is adapted to receive control signals from the current controller 22 and provide control signals for the switches of the DC/AC inverter 12.

The control unit 14 preferably comprises also an outer voltage control loop adapted to regulate the power flow balancing within the DC/AC converter apparatus.

Said outer voltage loop preferably comprises a voltage controller 23, which is configured to receive a reference signal $V_{dc_link\ ref}$ indicative of the reference amplitude for the DC voltage at the DC-Link terminal DL and a measurement signal V_{dc_link} indicative of the actual amplitude of the DC voltage at the DC-Link terminal DL (measured by a suitably current sensor of known type).

The voltage controller 23 provides in output the reference signals I_{D_ref} and I_{Q_ref}, which are

received in input by the current controller 22. In this way, the control action carried out by the voltage controller 23 influences the inner current control loop.

In order to perform islanding detection functionalities, the control unit 14 comprises a frequency tracking module 17 adapted to track the grid frequency of the AC voltage provided in output by the DC/AC converter apparatus.

Preferably, the tracking module 17 is a phase locked loop (PLL) 17.

The tracking module 17 receives a reference signal Fv indicative of the AC voltage V_{PCC} at the point of common coupling P_{CC} and provides in output a tracking signal F_R, which forms the frequency reference signal received by the current controller 22.

Conveniently, the control unit 14 comprises an anti-islanding module 18, which, among other functionalities, it is adapted to provide a frequency perturbation to the reference signal Fv received by the tracking module 17.

Thanks to the mentioned modules 17, 18, the control unit 14 can implement methods to detect the presence of islanding conditions, which are based on the introduction of frequency perturbations in the reference signal Fv received by the tracking module 17 to modify the waveform of the tracking signal F_R provided in output by said tracking module.

The enclosed figure 3 shows the waveform of the tracking signal F_R provided in output by the tracking module 17.

When the reference signal Fv, which is received by the tracking module 17, is subject to a frequency perturbation, the tracking signal F_R, which is provided in output by the tracking module 17, is subject to a distortion so that the new signal zero crossing point falls before or after the detected zero crossing point, while the period of the waveform is left unaltered.

As a consequence of the control action carried out by the current controller 22, the waveform of the current provided in output by the DC/AC inverter 12 will be distorted accordingly.

In figure 3, the distorted waveform of the tracking signal F_R of the tracking module 17 (PLL) shows a higher frequency with respect to the actual grid frequency picked up at the point of point of common coupling Pcc.

The distorted waveform ends each half-cycle remaining at zero amplitude for the time t_z before starting the next half-cycle.

Similar considerations would apply in case the chosen frequency perturbation of the tracking signal F_R is such that to force the frequency to be lower than the nominal one.

In this case, the distorted waveform would have a lower frequency than the frequency. detected at the point of common coupling Pcc.

When it is electrically connected with the DC/AC converter apparatus at the point of common

coupling Pcc, the main grid 16 opposes any change in the voltage frequency.

If the DC/AC inverter 12 tries to change the frequency of its output current, the main grid 16 keeps on providing a solid phase and frequency reference to the tracking module 17 thus stabilizing the operating point at the frequency of the grid voltage and no positive feedback involving the tracking module 17 will occur.

Instead, in islanding conditions, the frequency of the AC voltage V_{PCC} at the point of common coupling Pcc will change due to the frequency perturbation injected by the DC/AC inverter 12. The AC voltage V_{PCC} will then follow the injected distorted current waveform and cross the zero amplitude axis in a time ($T_{PCC}/2$ - tz), which is different from nominal half-cycle $T_{PCC}/2$. This applies also to the next half-cycle and the point of zero crossing of the AC voltage V_{PCC} shifts accordingly.

The frequency of the tracking signal F_R will shift as well in order to remain synchronized with the new detected voltage frequency and therefore the frequency perturbation at the next AC cycle is applied on the reference signal Fv with altered frequency, thus producing a positive feedback.

As a result, the AC voltage V_{PCC} is subject to a frequency drift, the detection of which can be used to identify ongoing islanding conditions.

With reference to the enclosed figures 1 and 2, the anti-islanding module 18 preferably comprises a signal injector module 19, which is operatively associated with the tracking module 17.

Preferably, the signal injector module 19 comprises a module 19a for generating a frequency perturbation for the reference signal Fv and a module 19b for providing a frequency perturbation to said reference signal.

Preferably, the anti-islanding module 18 further comprises a frequency extractor module 20, operatively associated with the signal injector module 19.

The frequency extractor module 20 is adapted to periodically (at each AC cycle) measure the frequency of the AC voltage V_{PCC} at the point of common coupling Pcc.

The frequency extractor module 20 is also adapted to detect any change Δf in the frequency of the AC voltage V_{PCC}, where $\Delta f = F_N - F_0$, F_N being the frequency measurement at a time N, F_0 being an average grid frequency that may be calculated as indicated in the following.

The anti-islanding module 18 preferably comprises also an islanding detector module 21, operatively associated to said signal injector module 19.

The islanding detector module 21 is adapted to identify possible islanding conditions, based on the information provided by the frequency extractor module 20, generate an alarm signal if

islanding conditions are identified and change the operation of the DC/AC converter apparatus in case of islanding conditions (e.g. by switching off said apparatus).

The method 1 according to the invention and its practical implementation by the control unit 14 is now described in more details.

The method 1 comprises a step 41 of providing a first weaker frequency perturbation P1 to an input reference signal Fv in order to shift the frequency of the AC voltage V_{PCC} at the point of common coupling P_{CC}.

Conveniently, the first frequency perturbation is generated and applied by the signal injector module 19 and it affects the reference signal Fv in input to the tracking module 17.

According to the invention, the first frequency perturbation has a first frequency perturbation value $\Delta\omega_{0\text{-}1}$ and is repeatable for a series S_1 of AC cycles, which includes a corresponding variable number n_1 of AC cycles (figure 4).

In practice, according to the invention, said first weaker frequency perturbation P1 has a first frequency perturbation value $\Delta\omega_{0\text{-}1}$ and have a duration (the number n_1 of AC cycles) that is variable from time to time (i.e. for each series of AC cycles).

According to some embodiments, the number n_1 of AC cycles is randomly calculated by the signal injector module 19, for example by means of random number generator.

According to other embodiments, the number n_1 of AC cycles is randomly selected by the signal injector module 19 from a set of predefined numbers.

According to an embodiment, the number n_1 of AC cycles is selected by the signal injector module 19 from a set of predefined number according to a given selection order, principle or method.

Preferably, when a first frequency perturbation P1 (having a first frequency perturbation value $\Delta\omega_{0\text{-}1}$) has been repeated for a series S_1 of AC cycles including a given number n_1 of AC cycles, a new first frequency perturbation P1 is generated.

Such a new first frequency perturbation P1 as a new first frequency perturbation value $\Delta\omega_{0\text{-}2}$ and is repeatable for a new series S_2 of AC cycles having a new number n_2 of AC cycles. Such a new number n_2 of AC cycles may be varied with respect to the previous number n_1 of AC cycles corresponding to the series S_1.

As it may be easily understood from the above, the method 1 provides for generating subsequent first frequency perturbations P1 with first frequency perturbation values that may be different in module and sign and, above all, with time durations that are variable from time to time.

The inventors have found that this solution provides surprising effects in terms of detection efficiency as it induces a fast drift of the frequency of the AC voltage V_{PCC} (if islanding

conditions are present), even when a plurality of DC/AC converter apparatus are electrically connected in parallel to a same main grid 16 at a same point of common coupling Pcc.

As is known, multiple DC/AC converter apparatuses sharing a same main grid 16 might have different loads or different points of operation and input power.

As a result, said DC/AC converter apparatuses might react differently to the same frequency perturbation possibly reducing or delaying the frequency drift of the AC voltage V_{PCC} even if islanding conditions are present.

In traditional solutions of the state of the art, these compensation effects among multiple DC/AC converter apparatuses may lead to an incorrect or delayed identification of islanding conditions.

Instead, the described solution is quite efficient in causing a frequency drift of the AC voltage V_{PCC} (if islanding conditions are present) as first frequency perturbations are not periodically repeated as it occurs in a detection method proposed by EP3079217A1 but instead can vary in magnitude and duration at each repetition cycle.

This feature allows efficiently detecting the presence of islanding conditions by remarkably reducing or avoiding the possibility of the undesired compensation effects described above.

As a result, possible NDZs for the DC/AC converter apparatus 1 are drastically narrowed and the time required to detect possible islanding conditions is remarkably reduced (even 2-3 time shorter with respect to traditional solutions), which is a very important factor in plants including multiple DC/AC converter apparatuses electrically connected to a same main grid 16.

This makes the DC/AC converter apparatus 1 adapted to pass the most severe certification tests in terms of anti-islanding safety.

As an additional advantage, it is possible to lower the magnitude of the first weaker frequency perturbation values (which may be of few mHz) with consequent improvement the power quality, e.g. of the THD and cosϕ parameters of the DC/AC converter apparatus 1.

According to some embodiments of the invention, as shown in figure 4, each first perturbation provided to the reference signal Fv has a different first frequency perturbation value $\Delta\omega_{0\text{-}1}$, $\Delta\omega_{0\text{-}2}$ $\Delta\omega_{0\text{-}3}$, $\Delta\omega_{0\text{-}4}$, … .

As shown in figure 4, the first frequency perturbations may even have a first frequency perturbation value that is equal to zero ($\Delta\omega_{0\text{-}3} = 0$).

According to some embodiments of the invention, the first frequency perturbations have first frequency perturbation values $\Delta\omega_{0\text{-}1}$, $\Delta\omega_{0\text{-}2}$ $\Delta\omega_{0\text{-}3}$, $\Delta\omega_{0\text{-}4}$, … that are randomly calculated or randomly selected each time.

According to some embodiments of the invention, the first frequency perturbation values $\Delta\omega_{0\text{-}}$

$_1$, $\Delta\omega_{0\text{-}2}$ $\Delta\omega_{0\text{-}3}$, $\Delta\omega_{0\text{-}4}$, ... are instead predefined and first by uploading them from a reference table stored in a memory for each first frequency perturbation.

According to some embodiments of the invention, as shown in figures 6-7, the sign of the first frequency perturbation value $\Delta\omega_{0\text{-}1}$, $\Delta\omega_{0\text{-}2}$, $\Delta\omega_{0\text{-}3}$, $\Delta\omega_{0\text{-}4}$, ... is maintained constant (positive or negative) at each first frequency perturbation.

According to some embodiments of the invention, as shown in figures 5-7, frequency perturbations having an even generation index (i.e. generated as second, fourth, ... and so on) have a first constant first frequency perturbation value $\Delta\omega_{0\text{-}2} = \Delta\omega_{0\text{-}4}$.

According to some embodiments of the invention, as shown in figures 5-7, frequency perturbations having an odd generation index (i.e. generated as first, third, ... and so on) have a first constant first frequency perturbation value $\Delta\omega_{0\text{-}1} = \Delta\omega_{0\text{-}3}$.

The method 1 comprises a step 42 of frequency tracking the reference signal Fv including a frequency perturbation.

Conveniently, the tracking of the perturbed reference signal Fv is carried out at each AC cycle by the tracking module 17, which provides in output a perturbed tracking signal F_R that, in turn, affects the current control loop of the control unit 14.

The current control loop of the control unit 14 drives the AC/DC inverter 12 to provide in output a current having an output frequency $\omega_0 + \Delta\omega_{0\text{-}1}$, wherein ω_0 is the tracked frequency (expressed in terms of pulsation) and $\Delta\omega_{0\text{-}1}$ is the first frequency perturbation value of the applied frequency perturbation.

As illustrated above, in normal operation with the DC/AC converter apparatus 1 electrically connected to the main grid 16, any frequency drift of the AC voltage V_{PCC} at the point of common coupling Pcc is opposed by the main grid 16.

Thus, even if the AC/DC inverter 12 injects a current having a drifted output frequency $\omega_0 + \Delta\omega_0$, the main grid 16 will maintain constant the frequency of the AC voltage V_{PCC} at the nominal grid frequency. In this way, no positive feedback (induced by the anti-islanding module 18 and tracking module 17) occurs in the current control loop of the control unit 14 .

Instead, if islanding conditions are present, the frequency of the AC voltage V_{PCC} will change due to the current injected by the AC/DC inverter 12. As mentioned above, a positive feedback will occur in the current control loop of the control unit 14.

In view of the considerations above, the method 1 comprises the step 43 of measuring the frequency of the AC voltage V_{PCC} at the point of common coupling Pcc.

Conveniently, said frequency measurement is carried out at each AC cycle by the frequency extractor module 20.

Preferably, said frequency measurement is implemented through an AC voltage zero crossing detection and the following measurement of the time interval between two consecutive wave-fronts having a same slope (positive or negative).

To make the measurement more accurate and evaluate the trend of the frequency of the AC voltage V_{PCC} at the point of common coupling Pcc, the frequency extractor module 20 preferably calculates the short moving average of a small number of frequency samples F_N, for instance a number smaller than 10 samples, and the long moving average of a large number of frequency samples F_N, for instance a number larger than 50 samples, respectively.

The short moving average of a small number of the last frequency samples F_N, is suitable to filter the frequency measurements F_N from noise, EMI and, in general, from inaccuracies in the frequency measurement.

The long moving average of a large number of last samples is suitable to sense the actual trend of the frequency measurement in order to speed up the detection of an islanding condition and the managing of the detected alarm.

Conveniently, the frequency extractor module 20 provides the calculated values to the signal injector module 19.

If no change or, better, no appreciable change Δf in frequency (frequency drift) of the AC voltage V_{PCC} is detected, i.e. if the frequency drift Δf is lower than a start threshold value THS ($\Delta f > THS$, where THS is a tunable value that may be equal to some tens of mHz), the previous steps of method 1 are repeated from the beginning for the next AC cycle.

In this case, a first weaker perturbation P1 is applied also for the next AC cycle.

Such a further first frequency perturbation is identical to the previous frequency perturbation applied at the previous AC cycle, if the repetition series of said previous frequency perturbation is not over.

Otherwise, such a further first frequency perturbation is different from the previous frequency perturbation applied at the previous AC cycle, if the repetition series of said previous frequency perturbation is over and the further first frequency perturbation is generated *ex-novo*.

If an appreciable change Δf in frequency of the AC voltage V_{PCC} is instead detected, i.e. if the frequency drift Δf is higher than the start threshold value THS ($\Delta f > THS$, the method 1 comprises the step 44 of comparing the measured frequency of the AC voltage V_{PCC} with a first threshold value T_{ISL} (e.g. of few Hz over a nominal grid frequency).

Such a comparison is conveniently carried out by the islanding detector module 21.

If the frequency of the AC voltage V_{PCC} is higher than a first predetermined threshold value

T_{ISL} for a given number of AC cycles, islanding conditions are identified.

In this case, conveniently, the islanding detector module 21 generates an alarm signal and, for instance, intervenes to switch off the DC/AC converter apparatus 1 in order to interrupt the output flow of electric power from this latter and ensure safety for possible maintenance interventions.

If the frequency change of the AC voltage V_{PCC} is lower than the first threshold value T_{ISL}, this means islanding conditions are likely to be present but are not clearly identified yet.

In practice, the method has identified a certain frequency drift Δf, which cannot be attributed with certainty to the presence of islanding conditions yet.

In this case, the method 1 provides for a series of steps (reference 45) aimed at providing second stronger frequency perturbations to the reference signal Fv in order to induce a possible frequency drift of the AC voltage V_{PCC}.

In particular, the method 1 comprises the step of selecting a constant frequency perturbation value $\Delta\omega_0$.

According to some embodiments, the constant frequency perturbation value $\Delta\omega_0$ is selected (e.g. by the signal injector module 19) equal to the last first frequency perturbation value $\Delta\omega_{0\text{-}1}$, $\Delta\omega_{0\text{-}2}$, $\Delta\omega_{0\text{-}3}$, $\Delta\omega_{0\text{-}4}$, … used in the last series of AC cycles to provide a first perturbation to the reference signal Fv before the frequency drift Δf was found higher than the start threshold value THS.

According to other embodiments, the constant frequency perturbation value $\Delta\omega_0$ (and its sign) may be selected or calculated (e.g. by the signal injector module 19) in an adaptive way, e.g. depending on the behavior of a measured average frequency.

The method 1 then comprises the step of calculating an additional frequency perturbation value $\Delta\omega$.

The additional frequency perturbation value $\Delta\omega$ is calculated (e.g. by the signal injector module 19) based on the trend of the frequency measurements performed by said frequency extractor module 20.

Preferably, the additional frequency perturbation value $\Delta\omega$ is calculated as follows:

$\Delta\omega = k\ \Delta F_L$ wherein

k can be a constant value or an adaptive value, $k = f(\Delta F_L)$, and

$\Delta F_L = F_N - F_{AVGL}$,

F_N being the frequency measurement at the time N and F_{AVGL} being the moving average of the last large number of frequency measurements F_N, said large number being, for instance, larger than 50.

Preferably, the parameter k described above is chosen in a group comprising: a first value k1 to be initially applied, and a second value k2, higher than the first value k1, to be subsequently applied in order to make the detection of the islanding condition faster.

In higher details, the parameter k is preferably selected as follows:

- if ΔF_L is lower than a second threshold value T_{K1} ($\Delta F_L < T_{K1}$ or $\Delta F_L > -T_{K1}$), then k = k0 (e.g. k= 0);
- if ΔF_L is higher than said second threshold value T_{K1} ($\Delta F_L > T_{K1}$ or $\Delta F_L < -T_{K1}$), then k = k1 with k1 > k0;
- if $\Delta F_L > T_{K1}$ (or $\Delta F_L < -T_{K1}$) constantly within a predetermined time interval and ΔF_L is higher than the third threshold value T_{K2} ($\Delta F_L > T_{K2}$ or $\Delta F_L < -T_{K2}$), then k = k2 with k2 > k1.

It is observed that the second and third threshold values T_{K1}, T_{K2} are conceptually quite different from the above mentioned first threshold value T_{ISL}.

The second and third threshold values T_{K1}, T_{K2} refer to given frequency ranges to take as references to select the parameter k whereas the first threshold value T_{ISL} refers to an absolute frequency value taken as a reference to determine whether islanding conditions are present.

Also from a numerical point of view, the second and third threshold values T_{K1}, T_{K2} are quite lower (e.g. some tenth of Hz) with respect to the first threshold value T_{ISL} mentioned above.

Preferably, the additional frequency perturbation value $\Delta\omega$ is not applied if $F_{AVGS} < F_{MAX}$ or $F_{AVGS} > F_{MIN}$ wherein F_{AVGS} is the moving average of the last small number of frequency measurements F_N (said small number being, for instance, equal to 8), F_{MAX}, F_{MIN} are the maximum and minimum acceptable values for the frequency of the AC voltage V_{PCC}, respectively. In this case, the parameter k can be lowered, e.g. it can be set as null (k = 0).

The method 1 comprises the step of calculating a second frequency perturbation value $\Delta\omega_0 + \Delta\omega$ by adding the additional frequency perturbation value $\Delta\omega$ to the selected constant frequency perturbation value $\Delta\omega_0$.

Then, the method 1 comprises the step of providing a second stronger frequency perturbation P2 to said input reference signal Fv, said second frequency perturbation having the second frequency perturbation value $\Delta\omega_0 + \Delta\omega$ previously calculated.

The steps 42-44 of the method 1 are then repeated.

The reference signal Fv including the second stronger frequency perturbation P2 is tracked by the tracking module 17, which provides in output a perturbed tracking signal F_R that, in turn, affects the current control loop of the control unit 14.

The current control loop of the control unit 14 drives the AC/DC inverter 12 to provide in output

a current having an output frequency $\omega_0 + \Delta\omega_0 + \Delta\omega$, herein ω_0 is the tracked frequency, $\Delta\omega_0$ is the constant frequency perturbation value, $\Delta\omega$ is the additional frequency perturbation value.

The frequency extractor module 20 measures the frequency of the AC voltage V_{PCC} at the point of common coupling Pcc.

If no change Δf in the frequency of the AC voltage V_{PCC} is detected, the steps 41-45 of method 1 are repeated from the beginning.

In this case, a first weaker perturbation P1 (generated as described above) is again applied for the next AC cycle and the following steps 42-45 are then executed.

If a frequency drift of the AC voltage V_{PCC} is detected, the islanding detector module 21 compares the frequency of the AC voltage V_{PCC} with the threshold value T_{ISL}.

If it identifies islanding conditions, the islanding detector module 21 generates an alarm signal and, for instance, intervenes to switch off the DC/AC converter apparatus 1.

If islanding conditions are not identified by the islanding detector module 21, the previous series of steps 45 may be conveniently repeated.

In this case, a new additional frequency perturbation value $\Delta\omega'$ may be conveniently calculated by using a term k selected basing on the conditions described above.

For example, a term $k = k2 > k1$ may be selected or a term $k = k1$ may be maintained constant or, in particular conditions (as mentioned above) a term $k = 0$ may be selected.

A new second stronger frequency perturbation is provided in input to the reference signal Fv, where said further frequency perturbation has said new second frequency perturbation value $\Delta\omega_0 + \Delta\omega'$.

The reference signal Fv including the new second frequency perturbation is tracked by the tracking module 17, which provides in output a perturbed tracking signal F_R that, in turn, affects the current control loop of the control unit 14.

The current control loop of the control unit 14 drives the AC/DC inverter 12 to provide in output a current having a output frequency $\omega_0 + \Delta\omega_0 + \Delta\omega'$, herein ω_0 is the tracked frequency, $\Delta\omega_0$ is the constant frequency perturbation value, $\Delta\omega'$ is the additional frequency perturbation value.

The frequency extractor module 20 then measures the frequency of the AC voltage V_{PCC} at the point of common coupling Pcc.

If no change Δf in the frequency of the AC voltage V_{PCC} is detected, the previous steps 41-45 of method 1 are repeated from the beginning for the next AC cycle.

In this case, a first weaker perturbation P1 (generated as described above) is again applied for the next AC cycle and the following steps 42-45 are then executed.

If a frequency drift of the AC voltage V_{PCC} is detected, the islanding detector module 21

compares the frequency of the AC voltage V_{PCC} with the threshold value T_{ISL}.

If it identifies islanding conditions, the islanding detector module 21 generates an alarm signal and, for example, intervenes to switch off the DC/AC converter apparatus 1.

If islanding conditions are not identified by the islanding detector module 21, the previous series of steps 45 may be conveniently repeated.

However, if it is observed that the quantity $\Delta F_L = F_N - F_{AVGL}$ is converging to zero the previous steps 41-45 of the method 1 is conveniently repeated from the beginning.

In this case, a first weaker perturbation P1 (generated as described above) is again applied for the next AC cycle and the following steps 42-45 are then executed.

The method 1 for detecting islanding conditions according to the present invention provides several advantages with respect to the state of the art.

As illustrated above, the method 1 provides top level performances in terms of reliability and efficiency in the identification of possible islanding conditions and in terms of power quality, particularly when multiple DC/AC converter share a same main grid at the point of common coupling Pcc.

The method 1 further provides a high immunity to grid frequency variations as in these cases the intervention of the anti-islanding module 18 and of the tracking module 17 would not automatically cause a positive feedback phenomena in the current control loop.

The method 1 is of relatively easy implementation at industrial level. As an example, the step of the method according to the invention can be easily carry out by processing devices on board the DC/AC converter apparatus 1, such as μcontroller or a DSP included in the control unit 14 to control the operation of the DC/AC converter apparatus 1.

CLAIMS

1. Method (4) for detecting islanding conditions for a DC/AC converter apparatus (1) electrically connected with a main grid (16) at a point of common coupling (P_{CC}), characterized in that it comprises:
   - providing (41) a first frequency perturbation (P1) to a reference signal (Fv) in order to try shifting the frequency of an AC voltage (V_{PCC}) at said point of common coupling (P_{CC}), said first frequency perturbation having a first frequency perturbation value ($\Delta\omega_{0\text{-}1}$, $\Delta\omega_{0\text{-}2}$ $\Delta\omega_{0\text{-}3}$, $\Delta\omega_{0\text{-}4}$) and being repeatable for a corresponding series (S_1, S_2, S_3, S_4) of AC cycles, each series of AC cycles having a corresponding variable number (n_1, n_2, n_3, n_4) of AC cycles;
   - frequency tracking (42) said reference signal (Fv) including a frequency perturbation;
   - measuring (43) the frequency of said AC voltage (V_{PCC}) at said point of common coupling (P_{CC});
   - If a change (Δf) in frequency of said AC voltage (V_{PCC}) lower than a start threshold value (THS) is detected repeating the previous steps;
   - if a change (Δf) in frequency of said AC voltage (V_{PCC}) higher than said start threshold value (THS) is detected, comparing (44) the frequency of said AC voltage at said point of common coupling (P_{CC}) with a first threshold value (T_{ISL});
   - if the frequency of said AC voltage at said point of common coupling (P_{CC}) is higher than said first threshold value, islanding conditions are identified;
   - if the frequency of said AC voltage at said point of common coupling (P_{CC}) is lower than said first threshold value, executing (45) the following steps:
     - selecting a constant frequency perturbation value ($\Delta\omega_0$);
     - calculating an additional frequency perturbation value ($\Delta\omega$);
     - calculating a second frequency perturbation value ($\Delta\omega_0 + \Delta\omega$) by adding said additional frequency perturbation value ($\Delta\omega$) to the constant frequency perturbation value ($\Delta\omega_0$);
     - providing a second frequency perturbation (P2) to said input reference signal (Fv), said second frequency perturbation having said further frequency perturbation value ($\Delta\omega_0 + \Delta\omega$).
2. Method, according to claim 1, characterized in that each series of AC cycles (S_1, S_2, S_3, S_4) has a corresponding variable number (n_1, n_2, n_3, n_4) of AC cycles that is randomly calculated or randomly selected from a set of predefined numbers or selected from a set of predefined

numbers according to a given selection order or principle or method.

3. Method, according to one or more of the previous claims, characterized in that when a first frequency perturbation has been repeated for a given series (S_1, S_2, S_3,S_4) of AC cycles, a new first frequency perturbation is generated, said new first frequency perturbation having a new first frequency perturbation value ($\Delta\omega_{0-1}$, $\Delta\omega_{0-2}$, $\Delta\omega_{0-3}$, $\Delta\omega_{0-4}$, ...) and being repeatable for a new series (S_1, S_2, S_3, S_4) of AC cycles having a new varied number of AC cycles.
4. Method, according to one or more of the previous claims, characterized in that said first frequency perturbation value ($\Delta\omega_{0-1}$, $\Delta\omega_{0-2}$ $\Delta\omega_{0-3}$, $\Delta\omega_{0-4}$) is predefined or randomly calculated or randomly selected for each first perturbation.
5. Method, according to one or more of the previous claims, characterized in that first frequency perturbations with an even generation index have a same constant first frequency perturbation value ($\Delta\omega_{0-2}$, $\Delta\omega_{0-4}$).
6. Method, according to one or more of the previous claims, characterized in that first frequency perturbations with an odd generation index have a same constant first frequency perturbation value ($\Delta\omega_{0-1}$, $\Delta\omega_{0-3}$).
7. Method, according to one or more of the previous claims, characterized in that the sign of said first frequency perturbation value ($\Delta\omega_{0-1}$, $\Delta\omega_{0-2}$, $\Delta\omega_{0-4}$, $\Delta\omega_{0-4}$, ...) is maintained constant for each first frequency perturbation.
8. Method, according to one or more of the previous claims, characterized in that each first frequency perturbations has a different first frequency perturbation value ($\Delta\omega_{0-1}$, $\Delta\omega_{0-2}$ $\Delta\omega_{0-3}$, $\Delta\omega_{0-4}$).
9. Method, according to one or more of the previous claims, characterized in that said additional frequency perturbation value ($\Delta\omega$) is such that $\Delta\omega = k\Delta F_L$ wherein: $\Delta F_L = F_N - F_{AVGL}$, F_N is a frequency measurement sampled at a time N, F_{AVGL} is a long moving average of said frequency samples F_N, k is a constant value or an adaptive value $k = f(\Delta F_L)$.
10. Method according to claim 9, characterized in that said parameter k is chosen in a group comprising at least a first value (k1) and a second value (k2), higher than said first value (k1).
11. Method, according to one or more of the previous claims, characterized in that said constant frequency perturbation value ($\Delta\omega_0$) is equal to the last used first frequency perturbation value ($\Delta\omega_{0-1}$, $\Delta\omega_{0-2}$ $\Delta\omega_{0-3}$, $\Delta\omega_{0-4}$) or is a selected adaptive value.
12. A DC/AC converter apparatus (1) electrically connectable with a main grid (16) at a point

of common coupling (P_{CC}), said DC/AC converter apparatus comprising a control module (14) to control the operation of said converter apparatus characterized in that said control module (14) comprises data processing resources (17, 19, 20, 21, 22, 23, 24) configured to carry out a method (4), according to one or more of the previous claims.

13. An electric power generation system (100) electrically connectable with a main grid (16) at a point of common coupling (P_{CC}), said electric power generation system comprising an electric power generation apparatus (10) for producing DC electric power and being characterized in that it comprises a DC/AC converter apparatus (1), according to claim 11, electrically connected between said electric power generation apparatus (10) and said point of common coupling (Pcc).

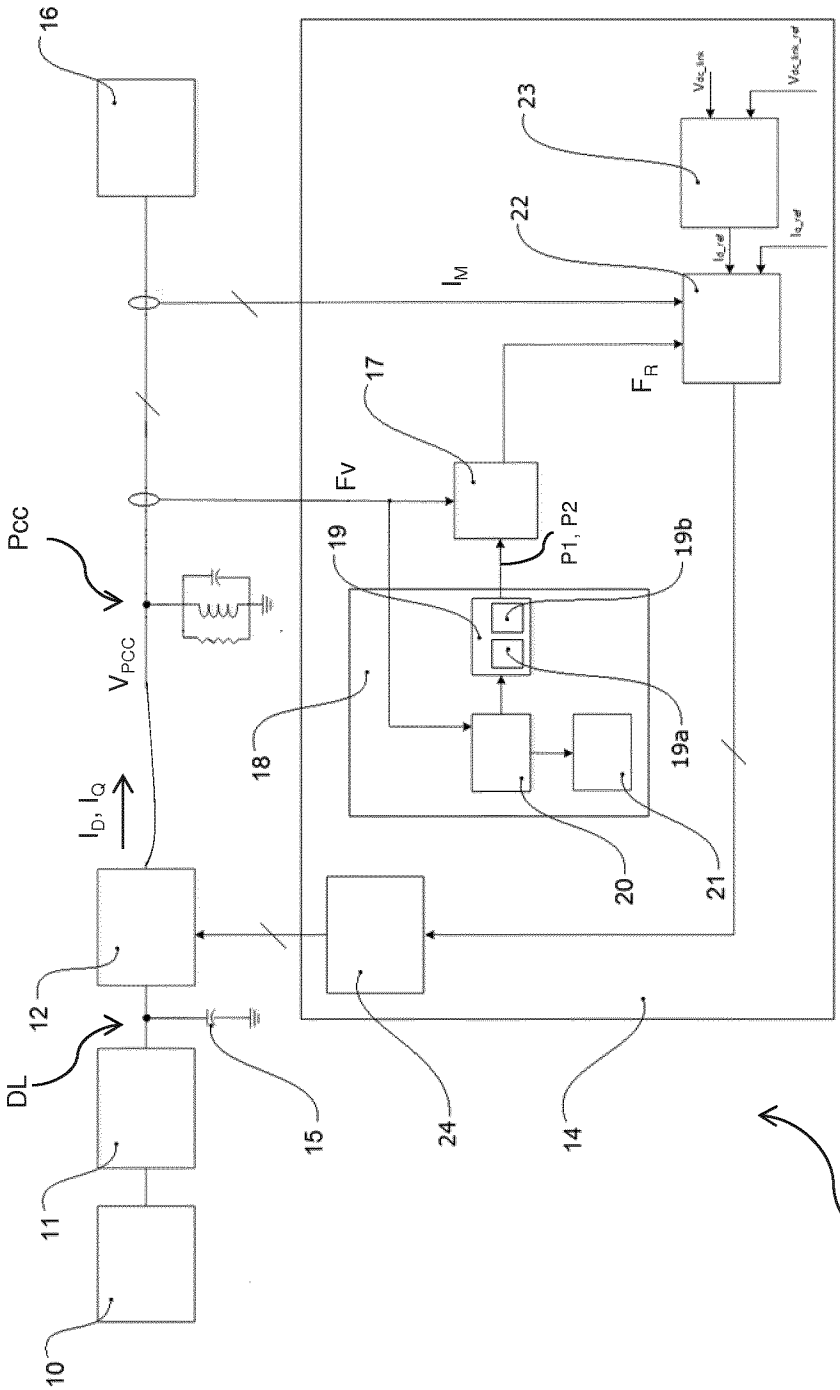
16
23
22
17
19
19b
18
19a
20
21
12
11
10
15
24
14
1
100
DL
Pcc
V_{PCC}
I_D, I_Q
I_M
F_R
Fv
P1, P2

Fig. 1

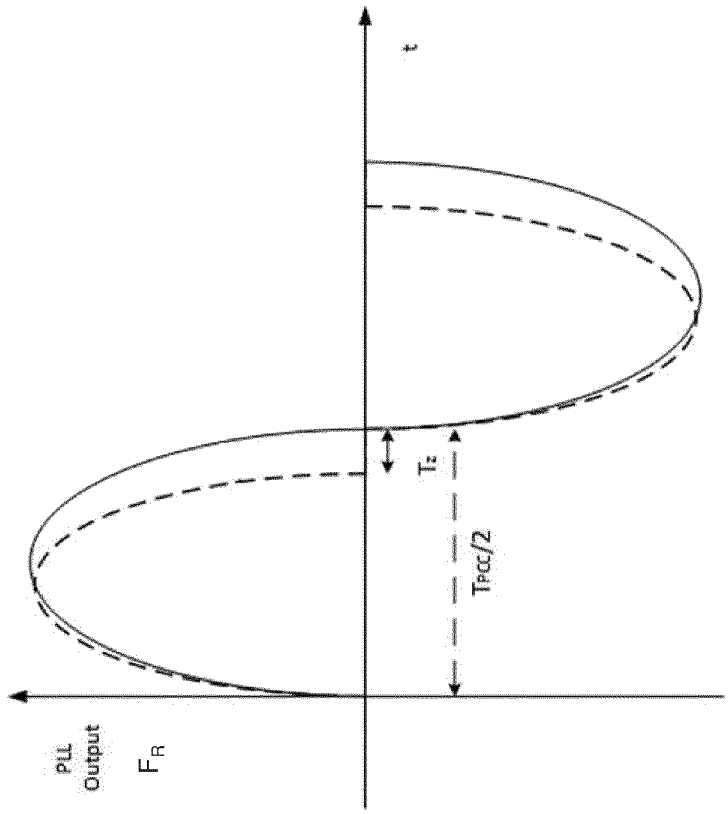

Fig. 2

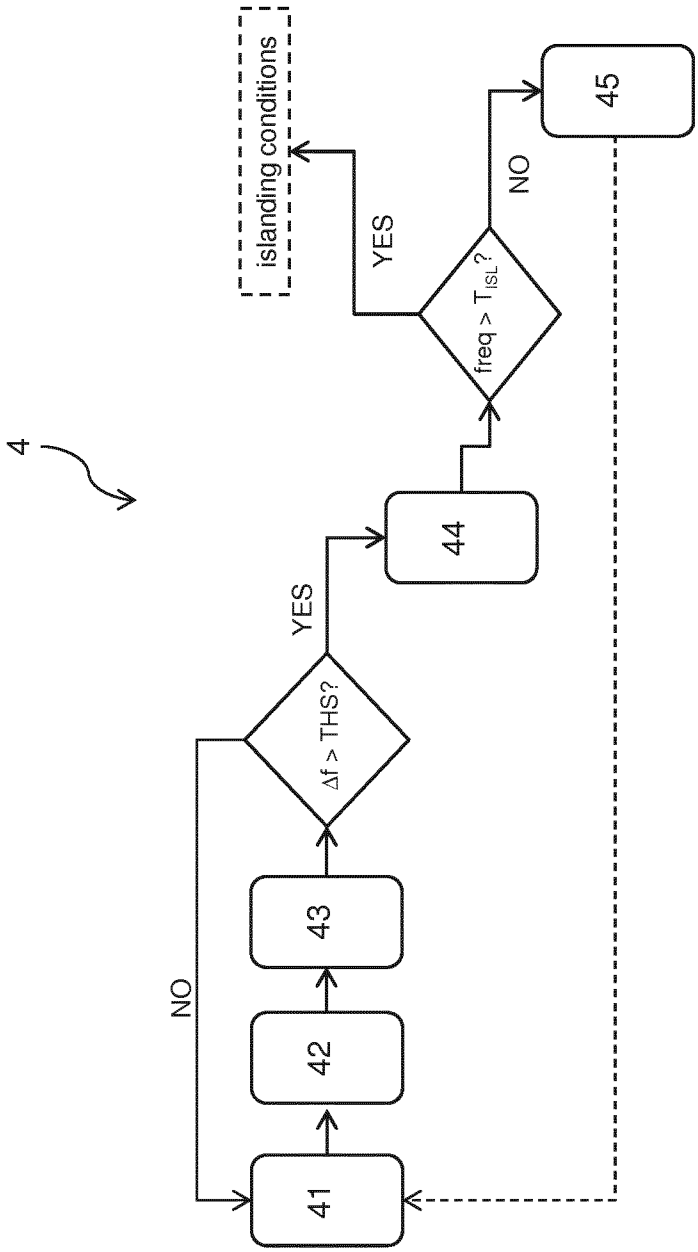
4
41
42
43
Δf > THS?
NO
YES
44
freq > T_{ISL}?
YES
NO
islanding conditions
45

Fig. 3

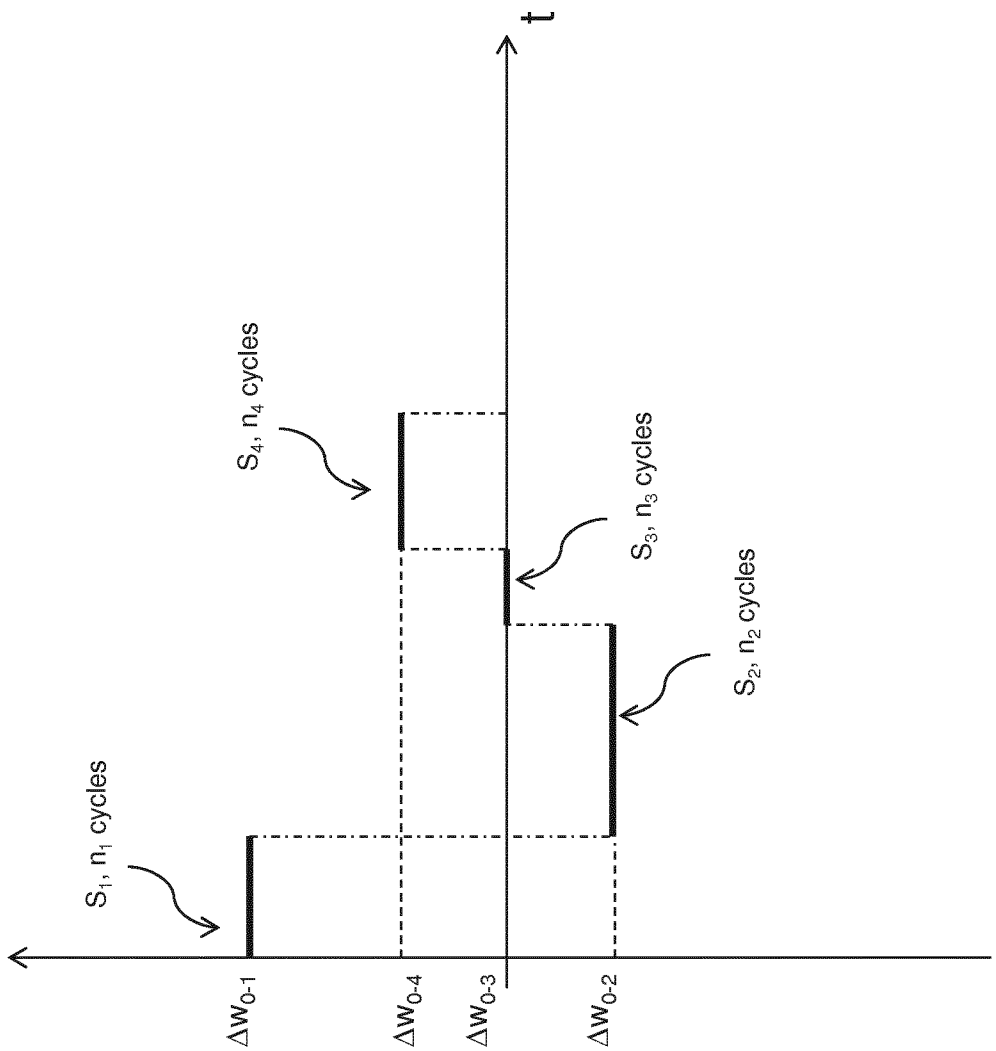
t
S_1, n_1 cycles
S_4, n_4 cycles
S_3, n_3 cycles
S_2, n_2 cycles
Δw_{0-1}
Δw_{0-4}
Δw_{0-3}
Δw_{0-2}

Fig. 4

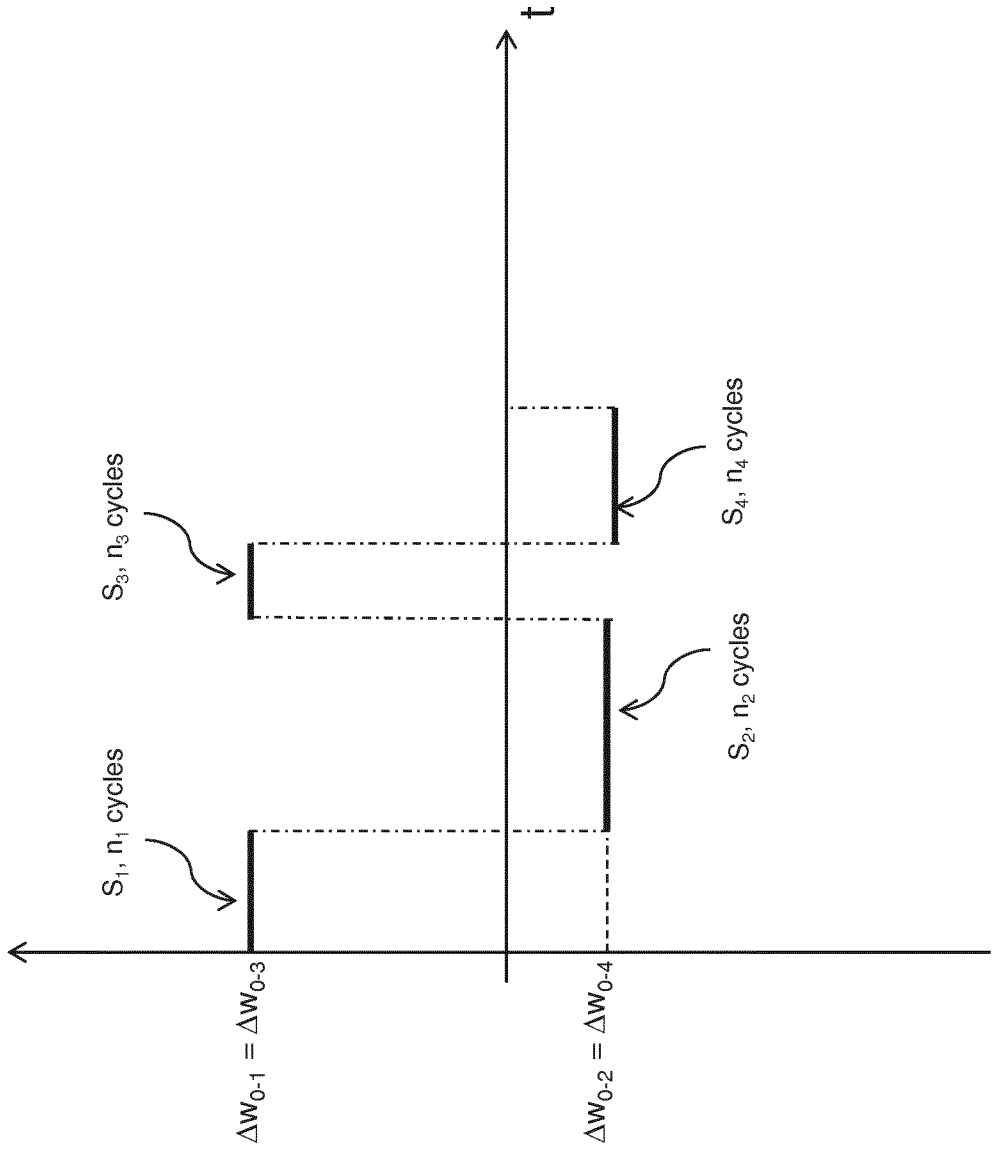
t
S_1, n_1 cycles
S_3, n_3 cycles
S_2, n_2 cycles
S_4, n_4 cycles
$\Delta w_{0-1} = \Delta w_{0-3}$
$\Delta w_{0-2} = \Delta w_{0-4}$

Fig. 5

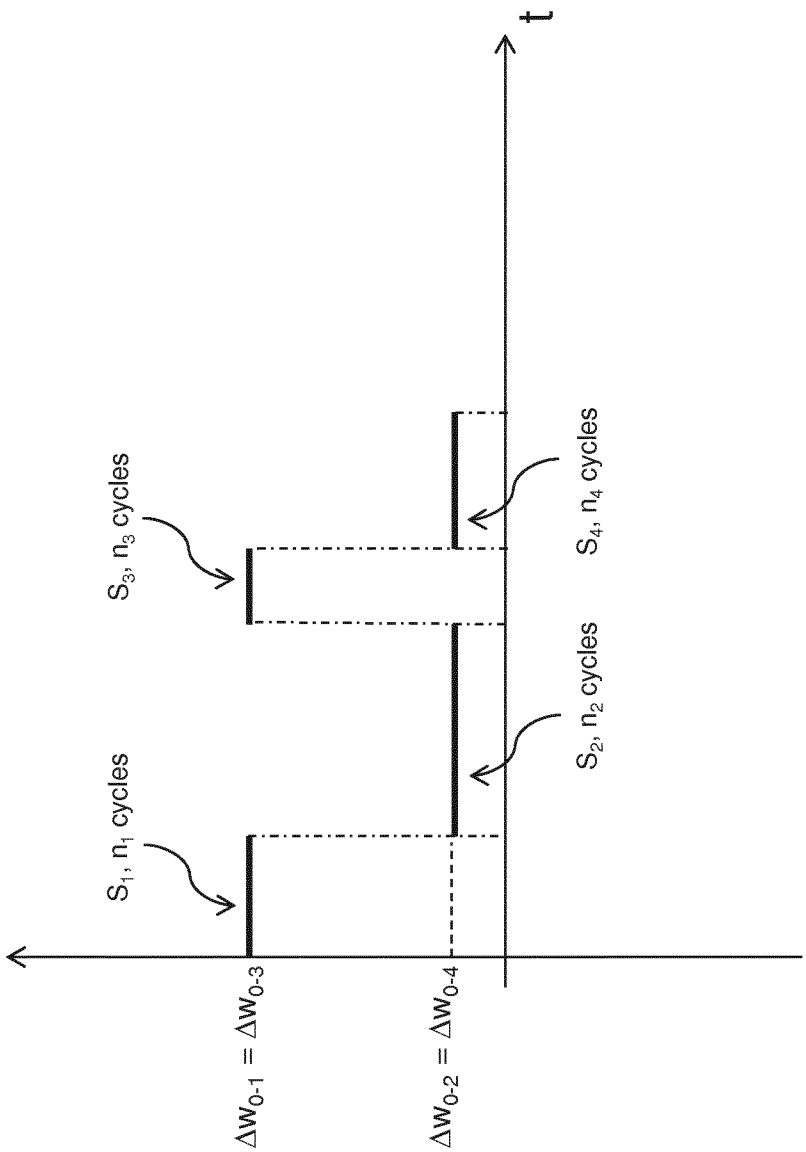
t
S_1, n_1 cycles
S_3, n_3 cycles
S_2, n_2 cycles
S_4, n_4 cycles
$\Delta w_{0-1} = \Delta w_{0-3}$
$\Delta w_{0-2} = \Delta w_{0-4}$

Fig. 6

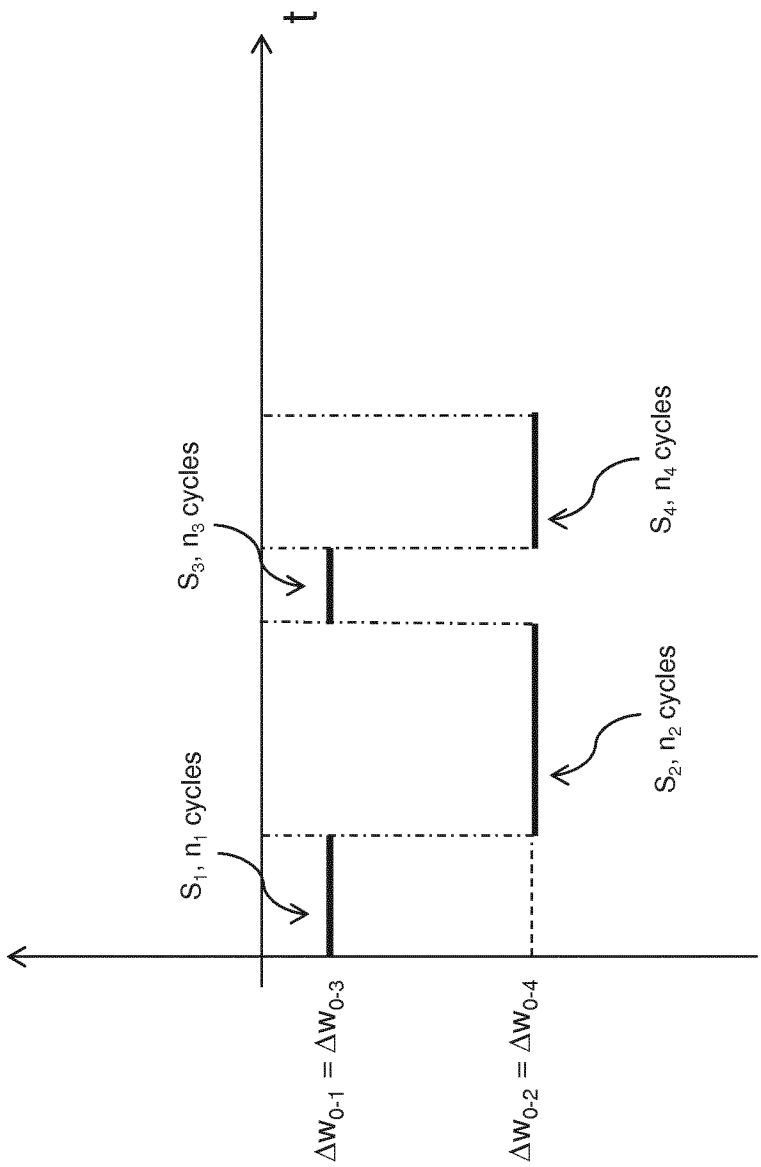
t
S_3, n_3 cycles
S_4, n_4 cycles
S_1, n_1 cycles
S_2, n_2 cycles
$\Delta w_{0-1} = \Delta w_{0-3}$
$\Delta w_{0-2} = \Delta w_{0-4}$

Fig. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/081177

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02J3/38 G01R19/25
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 G01R

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 3 079 217 A1 (ABB TECHNOLOGY AG [CH]) 12 October 2016 (2016-10-12) cited in the application	1,2,4-13
Y	figures 1,4 columns 22,57-70	3,8

Y	EP 1 808 947 A2 (OMRON TATEISI ELECTRONICS CO [JP]) 18 July 2007 (2007-07-18) figures 1,2,13-23 paragraphs [0012] - [0014], [0043] - [0065]	3,8

Y	EP 0 810 713 A2 (SHARP KK [JP]) 3 December 1997 (1997-12-03) figures 1,11 column 1, lines 5-12 column 15, line 10 - column 16, line 25	3,8

	-/--	

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

[X] See patent family annex.

* Special categories of cited documents :

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

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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

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

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 August 2017	28/08/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Berger, Josef

2

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/081177

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2011 055678 A (OMRON TATEISI ELECTRONICS CO) 17 March 2011 (2011-03-17) paragraphs [0001], [0007], [0083] - [0096]; figures 1,11-13	3,8

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2016/081177

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 3079217 A1	12-10-2016	CN 106058911 A	26-10-2016
		EP 3079217 A1	12-10-2016
		US 2016301328 A1	13-10-2016
EP 1808947 A2	18-07-2007	CN 101017981 A	15-08-2007
		EP 1808947 A2	18-07-2007
		JP 3948487 B1	25-07-2007
		JP 2007215392 A	23-08-2007
		KR 20070076407 A	24-07-2007
		KR 20090031702 A	27-03-2009
		US 2007179724 A1	02-08-2007
EP 0810713 A2	03-12-1997	DE 69724037 D1	18-09-2003
		DE 69724037 T2	03-06-2004
		EP 0810713 A2	03-12-1997
		JP 3227480 B2	12-11-2001
		JP H09322554 A	12-12-1997
		US 6172889 B1	09-01-2001
JP 2011055678 A	17-03-2011	JP 5418079 B2	19-02-2014
		JP 2011055678 A	17-03-2011