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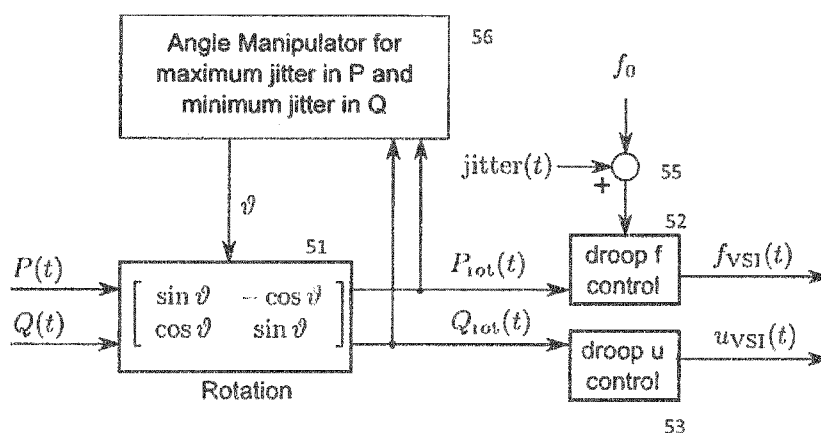


Fig. 5

(57) **Abstract:** The present invention relates to means for adapting a power rotation angle of an electrical inverter to match the unknown grid impedance at the point of connection. The invention further relates to an electrical inverter comprising such means. The present invention also relates to a method of adapting power rotation angle of an electrical inverter to match the unknown grid impedance at the point of connection.

ELECTRICAL INVERTER AND METHOD OF OPERATION

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5 Technical Field

The present invention relates to means for adapting an power rotation angle of an electrical inverter to match the grid impedance angle at the point of interconnection. The invention further relates to an electrical inverter comprising such means. The present
 10 invention also relates to a method of adapting power rotation angle of an electrical inverter to match the grid impedance angle at the point of interconnection.

Background

15 The increasing penetration with distributed renewable energy sources currently characterizes the transformation of the electrical power grid into a sustainable, environmentally friendly and efficient power supply of the future. Renewable energy sources are mostly injecting electrical energy with voltage source inverters (in the following referred to as VSI). When VSIs are operated in droop control mode,
 20 mimicking the behaviour of classical rotating synchronous generators, they are able to sustain and equally share all loads of a – potentially islanded – power grid (Alfred Engler, *Regelung von Batteriestromrichtern in modularen und erweiterbaren Inselnetzen*, PhD thesis, Universität Gesamthochschule Kassel, May 2001, incorporated herein by reference in its entirety).

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The classic droop control concept relates active power load to the grid frequency and the reactive power load to the grid voltage magnitude by a static head line as indicated in Fig 1 which illustrates the known static droop by relating Q with voltage and P with frequency.. The VSI droop control works with a characteristic head line. The VSI adapts
 30 its injection frequency to the momentary rate of injected active power with

$$f_{VSI} = f_0 \left(1 - droop \cdot \frac{P}{P_{rated}} \right)$$

Wherein f_{VSI} is the inverter output frequency, f_0 is the base frequency, P is the momentary active power, P_{rated} is the inverter's rated power, and *droop* is the maximum frequency deviation at P_{rated} expressed in per cent.

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Similarly, it adapts the voltage amplitude according to the actually injected reactive power. When injecting full rated active power, it changes the injection frequency to maximum droop (of e.g. 1% in Fig 1). Usually the base frequency f_0 is a fixed reference

value for the droop controller. The working principle of the droop control of voltage source inverters assures that each inverter adapts its frequency independently, according to its actual power injection. When the injection frequency differs from the current grid frequency, the power angle θ of the VSI voltage drifts with respect to the voltage angle at the end of the connected branch and induces a change in the power flow. This changed power flow provokes frequency changes in the other VSIs in the grid – as these adapt their respective injection frequencies according to the changed power flow – and the whole system finds a new equilibrium point at a new frequency.

This concept allows for decoupled control of frequency and voltage in power grids with inductive line characteristics, i.e. generally the medium and high voltage grids. Distributed renewable energy sources mostly inject their power in the low voltage grid. Due to the resistive nature of the low voltage lines, independent control of frequency and voltage is no longer possible with classic droop control. As a consequence, a change in the grid's active power load not only has an effect on frequency, but also on the grid voltage. Vice versa, a change in reactive power load not only influences the grid voltage, but also the grid frequency. This circumstance is illustrated in Fig 2 showing the known effect of rotated active and reactive power on frequency and voltage.

In an inductive grid, the load $S_1 = P_1 + jQ_1$ would have an effect of f_1 and u_1 on the power grid. But in a low voltage grid, the resistive part R of the line impedance $Z = R + jX$ may be even larger than the reactance X . Thus the impedance relation $R/X \neq 0$ cannot be neglected and the grid impedance angle $\theta = \arctan X/R$ is less than 90° . The active/reactive power coordinates are rotated by the angle $\varphi = \frac{\pi}{2} - \theta$ with respect to the frequency/voltage coordinates, as shown in Fig 2. The very same load situation S_1 has a rotated effect on the low voltage grid and causes a change of f_{rot} and u_{rot} on frequency and voltage.

One solution to this problem is to not apply the droop control directly on the measured values of $S = P + jQ$, but to first rotate the measured power backwards by the angle $\varphi = \frac{\pi}{2} - \theta$ instead and exert the control on the transformed power coordinates $P_{\text{rot}}, Q_{\text{rot}}$:

$$\begin{bmatrix} P_{\text{rot}} \\ Q_{\text{rot}} \end{bmatrix} = \begin{bmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \sin \theta & -\cos \theta \\ \cos \theta & \sin \theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix}.$$

As the grid impedance angle θ is usually not precisely known at the point of connection PoC, the rotation may be performed with an estimated rotation angle ϑ with

- 3 -

$$P_{\text{rot}} = \sin \vartheta \cdot P - \cos \vartheta \cdot Q \quad \text{and}$$

$$Q_{\text{rot}} = \cos \vartheta \cdot P + \sin \vartheta \cdot Q$$

This corrective control concept has been described e.g. by:

- 5 J. Van den Keybus, A. Woyte, J. Driesen, K. De Brabandere, B. Bolsens: "A voltage and frequency droop control method for parallel inverters", in *35th Annual IEEE Power Electronics Specialists Conference*, pages 2501–2507, 2004, incorporated herein by reference in its entirety;

- 10 Frede Blaabjerg, Uffe Borup, Lucian Asiminoaei, Remus Teodorescu: "A digital controlled pv-inverter with grid impedance estimation for ens detection", in *IEEE Transactions on Power Electronics*, 20(6):1480–1490, November 2005, incorporated herein by reference in its entirety; and

- 15 A. Luna, P. Rodríguez, R. Teodorescu, J Vasquez, J. Guerrero: "Adaptive droop control applied to distributed generation inverters connected to the grid", in *IEEE Transactions on Industrial Electronics*, 56(10):4088–4096, October 2009, incorporated herein by reference in its entirety.

- Fig 3 illustrates how the droop control is applied to the rotated values of active and reactive power. In the block diagram of Fig 3 the currently injected active power P and reactive power Q are measured and/or calculated. The rotation block 31 rotates P and Q by an angle θ into P_{rot} and Q_{rot} , on which the droop control block 32 for frequency f and the droop control block 33 for voltage u are exerted. Frequency f_{VSI} and voltage u_{VSI} of the AC source are applied to the power grid 34, resulting in active and reactive power.

- 25 Since the grid impedance angle θ at the point of connection is not known, it has to be detected in order to find the optimal power rotation angle ϑ for the VSI, which ideally should match the grid impedance angle θ .

Prior Art

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- There are several known possibilities to obtain the power angle at the point of connection, mostly by determining the exact grid impedance (magnitude and angle) over a wide frequency range at the PoC [E. Gunther R. Bergeron A. Robert, T. Deflandre: "Guide for assessing the network harmonic impedance", in *Proc. Inst. Elect. Eng.*, 2:301–310, 1997, incorporated herein by reference in its entirety]. Possible methods are:

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By estimation

The impedance angle could be estimated by general knowledge of the impedance relation R/X of low voltage grids. This assumed angle will most certainly be wrong, but the non-optimal control and the remaining coupling effect between frequency and voltage are accepted and might be considered “good enough”.

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By calculation

The grid utility company can provide the impedance angle at the point of connection. This value might be the result of calculations based on the grid model of the utility and thus deviate from the real value at the point of connection. The utility might not have a possibility to measure or calculate values for every point of connection. Depending on the number of VSIs installed by different suppliers, inquiring the impedance angle from the utility might take long and be uneconomic.

By specific hardware

The impedance can be measured at the PoC with a particular impedance measuring device. This approach is likely to be inefficient due to the necessary costly equipment and time and effort consumption.

By the VSI

The CPU or DSP of the VSI can be used to implement a measuring method. While numerous publications have proposed different schemes, not all methods can be implemented with the given limited capacities and capabilities of the VSI. It has been proposed by D. Thomas, B. Palethorpe, M. Summer: “System impedance measurement for use with active filter control” in *Power Electronics and Variable Speed Drives*, volume 475, pages 24–28. IEE, September 2000, incorporated herein by reference in its entirety; and Frede Blaabjerg et al., *loc. cit.* that a measurement could be done e.g. by injection of harmonic currents. A. Luna et al., *loc. cit.* have suggested high precision voltage and current frequency measurement. Most commonly the impedance is calculated based on a measurement of voltage and current (transient or steady state) at a specific (inter)harmonic frequency. Some of these methods interpolate the impedance at fundamental frequency, calculating a value deviating from the real situation. Also, harmonic injection leads to waveform distortion during the measurement.

Disadvantages of the prior art

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At least some drawbacks of most methods for determining the impedance angle at the point of connection are

- increased computation efforts;

- for some methods specific and expensive hardware is required;
- often demand change of / interference with the specific current control algorithm;
- both impedance magnitude and angle are determined, although only the angle is needed for decoupled control of frequency and voltage.

5 Without knowledge of the grid power angle at the point of connection, a decoupled control of frequency and voltage cannot be exerted, leading to cross-influence of active power to voltage and reactive power to frequency and thus to undesired effects up to grid instability.

10 Technical problem

It is therefore an object of the present invention to overcome or at least alleviate the disadvantages of the prior art. In particular it is an object of the present invention to propose an electrical inverter and a method which allow determining the exact
15 impedance angle of the power grid at the inverter point of connection (PoC).

Summary of the invention

A first aspect of the present invention relates to means for adapting a power rotation
20 angle ϑ of an electrical inverter to an unknown grid impedance angle θ of the electric grid or busbar at a point of connection of the electrical grid or busbar with the inverter output. The power rotation angle adapting means comprise means for detecting a momentary active power of the inverter; means for detecting a momentary reactive power of the inverter; means for generating a rotated momentary active power and a
25 rotated momentary reactive power by carrying out a rotation operation of the momentary active power and the momentary reactive power by a rotation angle; means for providing a reference frequency, means for controlling a momentary inverter output frequency in response to the rotated momentary active power and the reference frequency; and means for controlling a momentary inverter output voltage. The
30 reference frequency providing means further comprise means for providing a nominal frequency, wherein the nominal frequency corresponds to the nominal grid or busbar frequency, and means for applying a momentary jitter signal to the nominal frequency, so that the reference frequency varies in time. The inverter further comprises means for adapting the power rotation angle in response to the rotated momentary active power
35 and the rotated momentary reactive power.

The means for adapting the power rotation angle in response to the detected rotated momentary active power and the detected rotated momentary reactive power may

further comprise means for detecting fluctuations in time in one or both of the rotated momentary active power and the rotated momentary reactive power.

5 The means for adapting the power rotation angle may further comprise means for adapting the power rotation angle ϑ until it approaches, or optionally matches, the grid impedance angle θ .

10 The means for adapting the power rotation angle may further comprise means for judging the quality of the match.

The means for judging the quality of the match may further comprise means for observing the rotated momentary active and reactive power which are altered through a jittering inverter frequency.

15 The means may further comprise means for controlling a momentary inverter output frequency in response to the rotated momentary active power and the reference frequency.

20 The means for controlling the momentary inverter output frequency may comprise frequency droop control means.

25 The means of any one of the preceding claims may further comprise means for controlling a momentary inverter output voltage in response to the rotated momentary reactive power.

The means for controlling a momentary inverter output voltage may comprise voltage droop control means.

30 The means for manipulating the power angle may comprise a minimum correlation finding means in response to only the rotated momentary reactive power.

The minimum correlation finding means further may comprise means for calculating at least one harmonic coefficient.

35 The means for calculating at least one harmonic coefficient may further comprise means for performing a discrete Fourier transformation.

The minimum correlation finding means may further comprise means for performing an optimal control, optionally e.g. a linear quadratic controller or a H-infinity controller, such as known to the skilled person (http://en.wikipedia.org/wiki/Optimal_control).

- 5 A second aspect of the present invention relates to an electrical inverter comprising means for outputting an alternating current (AC) power to an electric grid or busbar, wherein the grid or busbar represents an unknown impedance to the inverter output, the unknown impedance comprising a resistance and a reactance with $Z = R + jX$, and wherein the unknown grid impedance angle θ is determined by $\arctan R/X$. the inverter
10 also comprises means for adapting an power rotation angle ϑ of the inverter to the unknown grid impedance angle θ of the electric grid or busbar at a point of connection with the inverter output in accordance with one of the configurations of the first aspect.

The inverter may be of the voltage source or the current source type.

- 15 A third aspect of the present invention relates to a method for adapting the power angle of an electrical inverter, the method comprising the steps of: outputting an alternating current (AC) power to an electric grid or busbar, the electric grid or busbar representing at the inverter output an unknown impedance comprising a resistance and a reactance,
20 wherein an unknown grid impedance angle θ is determined by $\arctan R/X$; detecting a momentary active power of the inverter; means for detecting a momentary reactive power of the inverter; generating a rotated momentary active power and a rotated momentary reactive power by carrying out a rotation operation of the momentary active power and the momentary reactive power by a rotation angle ϑ ; providing a reference
25 frequency, wherein the reference frequency corresponds to the nominal inverter output frequency. The step of providing a reference frequency further comprises applying a momentary jitter signal to a nominal frequency, so that the reference frequency applied to the inverter output frequency controlling means varies in time. The method further comprises the step of adapting the power rotation angle ϑ in response to the detected
30 rotated momentary active power and the detected rotated momentary reactive power.

The method may further comprise means for detecting fluctuations in time in one or both of the rotated momentary active power and the rotated momentary reactive power.

- 35 The method may further comprise adapting the power rotation angle ϑ until it approaches, or optionally matches, the grid impedance angle θ .

The method may further comprise judging the quality of the match.

The step of judging the quality of the match may further comprise observing the rotated momentary active and reactive power which are altered through a jittering inverter frequency.

5

The method may further comprise controlling a momentary inverter output frequency in response to the rotated momentary active power and the reference frequency.

10 The step of controlling the momentary inverter output frequency may further comprise applying a frequency droop control.

The method may further comprise controlling a momentary inverter output voltage in response to the rotated momentary reactive power.

15 The step of controlling a momentary inverter output voltage may further comprise applying a voltage droop control.

20 The step of manipulating the power rotation angle may further comprise finding a minimum correlation in response to only the rotated momentary reactive power.

The step of finding a minimum correlation further comprises calculating at least one harmonic coefficient.

25 The the step of calculating at least one harmonic coefficient further comprises performing a discrete Fourier transformation.

The step of finding a minimum correlation further comprises performing an optimal control.

30 The may be applied to an inverter of the voltage source or the current source type.

Further advantageous embodiments are described in the dependent claims and the following description.

35 **Brief description of the drawings**

These aspects and further embodiments of the present invention will be described in the following with reference to the enclosed non-limiting drawings.

Fig 1 is a diagram illustrating the known static droop by relating Q with voltage and P with frequency.

- 5 Fig 2 is a diagram showing the known effect of rotated active and reactive power on frequency and voltage.

Fig 3 is a diagram illustrating the known droop control applied to the rotated values of active and reactive power.

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Fig 4 is a diagram showing the droop head line in accordance with the present invention.

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Fig 5 is a block diagram of a control structure of an electrical inverter in accordance with the present invention.

Fig 5a is a block diagram of a control structure of an electrical inverter and angle quality evaluation and angle manipulation in accordance with the present invention.

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Fig 6 is a flowchart illustrating a method in accordance with the present invention.

Fig 7 is a block diagram of an embodiment with an optimal controller to minimise jitter in Q .

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Fig 8 is a power over time diagram showing the reaction of P , P_{rot} , Q and Q_{rot} .

Detailed technical description of the invention

30 For decoupled control of frequency and voltage, only an adaptation to the grid impedance angle is required, the exact grid impedance magnitude is not measured. This is particularly done by exploiting the following VSI characteristic:

35 Different from classic electric generators with rotating masses, a VSI can adjust its output frequency arbitrarily, which the present invention proposes to exploit for impedance detection.

Based on the working principle explained on page 1, if a VSI slightly alters its injection frequency, it will detect a change in its injected power rates P_{rot}/P and Q_{rot}/Q .

The present invention suggests using this effect in order to detect the grid impedance angle θ for optimal decoupled droop control: When the output frequency f_{VSI} is jittered, the rotation angle ϑ of power rotation is altered until only P jitters and Q remains untouched from changes in frequency f . This means that the rotation angle ϑ then matches the unknown grid impedance angle θ at the inverter's point of connection and the rotation angle ϑ is considered as optimal.

Further, the present invention proposes to combine an adaptive change of rotation angle until optimal adaptation to the impedance angle is reached, and a slowly jittering base frequency for the droop controller as an indicator of the rotation effect.

The exact signal form chosen for the jitter signal may be chosen from any suitable waveform, e.g. sinusoidal, sawtooth, triangle, binary, rectangular, or any other oscillating signal forms.

The present invention proposes to detect the optimal rotation angle ϑ , which is dependent on the grid impedance angle θ , by the VSI applying a slowly oscillating base frequency $f_0 + jitter(t)$ to the subordinate power or current controller. For the further discussion it is assumed that the example of a subordinate droop control has been chosen. As shown in Fig 4, the head line swings vertically with an amplitude A around the base value in the grey band. The jittering of the inverter's injection frequency is independent from the subordinate controller. It can be applied to droop controllers with different types of droops or other types of controllers, like e.g. maximum power point controllers.

If the base frequency is superposed with a jitter function $jitter(t)$, the jitter will also be noticeable at the power measurement. The measured active and reactive power are rotated by the rotation angle ϑ into rotated coordinates of active and reactive power P_{rot} and Q_{rot} . With a non-optimal rotation angle the swing will be visible in both rotated active power P_{rot} and rotated reactive power Q_{rot} . This effect is exploited to adjust the rotation angle in accordance with the present invention: For detection, the power rotation angle ϑ is changed until the jitter in P_{rot} reaches its maximum and/or the jitter in Q_{rot} reaches its minimum.

Fig 5a is a block diagram of a control structure of an electrical inverter and angle quality evaluation and angle manipulation in accordance with the present invention. The evaluation of the maximum jitter in P_{rot} or the minimum jitter in Q_{rot} may be separated

from the adaptation of the rotation angle ϑ . In block 57a, the evaluation of the rotation effect quality can be done automatically, e.g. in block 55a with a detection of the jitter signal in the rotated reactive power $Q_{\text{rot}}(t)$ or e.g. by the calculation of harmonic Fourier coefficients, or it can be done manually by a human user. In block 58a the adaptation of the power rotation angle ϑ can be done e.g. in a linear sweep from 0 to $\pi/2$ (i.e. 90°), or e.g. with an optimal controller freely incrementing or decrementing ϑ between 0 and $\pi/2$ as the quality evaluation indicates, thus approaching the optimal rotation angle ϑ_{opt} in circular trajectories or e.g. with non-linear binary search algorithms or by a human user with a manual control.

10

Preferably the frequency jitters slowly around a base value f_0 with a swing period significantly larger than the grid period, i.e. $T_{\text{osc}} \gg 1/f_0$, e.g. $T_{\text{osc}} \approx 0.5$ seconds, and with an amplitude considerably smaller than the grid frequency $A \ll f_0$, e.g. $A \approx 0.00025 \cdot f_0$.

15

Description of an embodiment

The frequency set point is overlaid with a sinusoidal jitter signal, e.g.

$$\text{jitter}(t) = A \cdot \sin\left(\frac{2\pi}{T_{\text{osc}}} t\right)$$

20

The optimization can e.g. be done by detecting the exciter signal $\text{jitter}(t)$ in the measured reactive power signal $Q(t)$. Since the oscillation period T_{osc} is known, only one complex Fourier coefficient needs to be calculated with very low computing resources from the measured (discrete) reactive power measurements $Q[k]$. With the sample time T_{sample} the number of samples per oscillation is

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$$N = \frac{T_{\text{osc}}}{T_{\text{sample}}}$$

and for a sampling buffer of s oscillations the Fourier coefficient of the s^{th} fundamental is calculated as

$$X_s = \sum_{k=0}^n Q[k] \left(\cos\left(2\pi \frac{s}{N} k\right) - j \sin\left(2\pi \frac{s}{N} k\right) \right).$$

30

Usually we can set $s = 1$. In order to find the minimum correlation, the absolute value of the correlation signal

$$|X_s| = \sqrt{\Re(X_s)^2 + \Im(X_s)^2}$$

can be fed to an optimal controller.. The controller output is the rotation angle ϑ which is fed into the rotation matrix. While the droop control is continuously enacted on the active and reactive power, the influence of the slow frequency oscillations on the reactive power will be influenced by the actual rotation angle ϑ .

35

Fig 5 is a block diagram depicting a control structure of an electrical inverter in

accordance with the present invention. The adaptation of the rotation angle ϑ through a minimum correlation finder 56, is based on the measurement of the reactive power Q . The currently injected active power P and reactive power Q are measured and/or calculated. The rotation block 51 rotates P and Q by an angle θ into P_{rot} and Q_{rot} . In
 5 block 55, a jitter signal $jitter(t)$ is added to the reference frequency f_0 .

The droop control block 52 therefore applies a modulated headline corresponding to $f_0 + jitter(t)$ for droop control of frequency f_{VSI} . By contrast, the droop control block 53 applies a non-modulated headline for droop control of voltage u_{VSI} .

10

Frequency f_{VSI} and voltage u_{VSI} of the AC source are applied to the power grid 54, resulting in active and reactive power. The jitter signal $jitter(t)$ which has been applied to the reference frequency f_0 becomes detectable in the measured values of $P(t)$ and $Q(t)$, and in the rotated values $P_{\text{rot}}(t)$ and $Q_{\text{rot}}(t)$.

15

Via a minimum correlation finder 56 the rotation angle θ is changed, until correlation coefficient reaches its minimum in Q_{rot} . Thus the frequency variation reaches a minimum influence on Q , and simultaneously reaches a maximum influence on active power P when the rotation angle θ matches the grid impedance angle at the point of
 20 connection.

At the point of minimal correlation between f and Q , the optimum power rotation angle ϑ_{opt} is determined as the grid impedance angle θ . With this optimum power rotation angle ϑ_{opt} the droop control can be applied to the rotated values of P and Q for
 25 independent control of frequency and voltage.

The general method is illustrated as a flowchart in Fig 6. When, e.g. in normal operation of the inverter, an adaptation of the power rotation angle ϑ is requested, see step 61, step 62 foresees that a jitter signal $jitter(t)$ is applied to the reference frequency f_0 . In step 63
 30 the power rotation angle ϑ is changed, and reactive power is monitored for a decrease in Q_{rot} , and/or active power is monitored for an increase in P_{rot} . If this is the case, step 64 foresees a further change of the power rotation angle ϑ , and step 63 is executed again. If no further change in reactive power Q_{rot} and/or active power P_{rot} is observed, step 65 provides that the output power rotation angle ϑ is stored. Finally, in step 66 the jitter
 35 signal is stopped and normal operation is resumed.

The initial output power rotation angle ϑ depends on the application environment and the search algorithm. In a medium voltage grid the initial output power rotation angle ϑ

may e.g. be chosen at 0, and then increase; in a low voltage grid it may be preferable to start at 45° and then let the minimum finder control operate. It may be advantageous if the minimum search finder can also apply negative increments, i.e. decrease the output power rotation angle ϑ . In the embodiment described here, the rotation angle search
 5 began at an angle of $\vartheta = 0$.

The search of the optimal rotation angle can be done arbitrarily in the range of ϑ from 0 to $\pi/2$. The search can done e.g. linearly in a single sweep or e.g. in a circular search or e.g. in a non-linear binary search.

10

The increment of the power rotation angle ϑ depends on the sample rate, i.e. on the clock rate of execution of the program, respectively how fast the power can be measured and calculated, as well as on setting of the minimum finder control. The person skilled in the art is aware of the classical control problem to tune a controller so
 15 that it quickly reaches its set point, perhaps including an overshoot, but without becoming instable. The increment thus depends strongly on the implementation chosen. In the implemented embodiment the step size was variable due to the type of controllers used: the bigger the DFT coefficient, the bigger the step size.

20 Fig 7 shows a block diagram of an implementation with an optimal controller to minimise jitter in Q_{rot} . Fig. 7 shows the adaptation of the rotation angle through a minimum correlation finder, based on the measurement of the reactive power Q_{rot} . The currently injected active power P and reactive power Q are measured and/or calculated. The rotation block 71 rotates P and Q by an angle ϑ into P_{rot} and Q_{rot} . In block 75, a
 25 jitter signal $jitter(t)$ is added to the reference frequency f_0 .

The droop control block 72 therefore applies a modulated headline corresponding to $f_0 + jitter(t)$ for droop control of frequency f_{VSI} . By contrast, the droop control block 73 applies a non-modulated headline for droop control of voltage u_{VSI} .

30

Frequency f_{VSI} and voltage u_{VSI} of the AC source are applied to the power grid 74, resulting in active and reactive power. The jitter signal $jitter(t)$ which has been applied to the reference frequency f_0 becomes detectable in the measured values of $P(t)$ and $Q(t)$, and in the rotated values $P_{\text{rot}}(t)$ and $Q_{\text{rot}}(t)$.

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Although the jitter signal $jitter(t)$ may be chosen sinusoidal, sawtooth, triangle, binary or any other oscillating signal forms, in the present embodiment it is preferred that the jitter signal $jitter(t)$ be a sine wave, hence the minimum correlation finder 76 comprises

a Digital Fourier Transformation (DFT) 77 and an optimal controller 78. The DFT 77 calculates preferably the coefficient of first sine fundamental of the jitter signal $jitter(t)$ from the value of $Q_{rot}(t)$. Of course, one or more alternative fundamentals might also be used. Via a controller 78 the power rotation angle ϑ is changed, until the DFT
 5 coefficient reaches its minimum in Q_{rot} . Thus the frequency variation reaches a minimum influence on Q , and simultaneously reaches a maximum influence on active power P when the power rotation angle ϑ matches the grid impedance angle θ at the point of connection.

10 At the point of minimal correlation between f and Q , the impedance angle is determined as ϑ_{opt} . With this optimal angle ϑ_{opt} the droop control can be applied to the rotated values of P and Q for independent control of frequency and voltage. As can be seen in Fig 8, in the chosen implementation the swing in Q minimises only two seconds after the algorithm was started.

15 Other implementations are, of course, possible. Instead of using an optimum controller on the Fourier coefficient in $Q(t)$, a simple angle sweep from 0 to $\pi/2$ could be performed manually. In fact, it is obvious to the person skilled in the art there are several ways to implement the present invention in order to find the optimal power
 20 angle. The present invention is based on the concept to exploit a frequency oscillation and read back power (or current) to find the power rotation angle ϑ matching grid impedance angle θ .

A subordinate droop control is not mandatory for the present invention to work. The
 25 power angle detection can be performed in inverters with different control concepts.

Advantages of the invention

- There are several favourable properties of this solution compared to the state of the art:
- 30
- An adaptation is performed only on the impedance angle. No need to calculate the exact impedance value.
 - No particular measurement equipment is necessary.
 - No interference with (and thus no dependency on) the underlying control mechanism (be it droop controller or other).
- 35
- No low-level interference with current controller (be it PI control on d/q coordinates, THD optimal controllers, etc.), as no additional current is injected.
 - No voltage or current waveform distortion.
 - Very low computational effort for VSI DSP or CPU as only one DFT coefficient is

- calculated (for chosen implementation).
- Rather low sample rate possible for measurement of power.
 - Low power disturbance in grid, as oscillation amplitude can be chosen according to actual power injection.
- 5 • Works for single phase systems as well as for 3 phase systems.
- The present invention works also for other droop modes like $Q(P)$ or $\phi(\Delta f)$ on a stiff grid, such as those mentioned in J. Van den Keybus, *loc. cit.*
 - Can be run superposed on normal operation and repeated as deemed necessary.
 - Simultaneous adaptation of several VSI possible by choice of arbitrary oscillation
- 10 periods T_{osc} (longer duration for adaptation).
- VSI equipped with the present invention are able to control voltage and frequency in an independent manner at any point of connection.

CLAIMS

1. Means for adapting a power rotation angle (ϑ) of an electrical inverter to an unknown grid impedance angle (θ) of the electric grid or busbar at a point of connection of the electrical grid or busbar with the inverter output, the output power angle adapting means comprising,
 - means for detecting a momentary active power ($P(t)$) of the inverter;
 - means for detecting a momentary reactive power ($Q(t)$) of the inverter;
 - means for generating a rotated momentary active power ($P_{\text{rot}}(t)$) and a rotated momentary reactive power ($Q_{\text{rot}}(t)$) by carrying out a rotation operation of the momentary active power ($P(t)$) and the momentary reactive power ($Q(t)$) by a power rotation angle (ϑ); and
 - means for providing a reference frequency ($f(t)$),
wherein the reference frequency providing means further comprise
 - means for providing a nominal frequency (f_0), wherein the nominal frequency corresponds to the nominal grid or busbar frequency, and
 - means for applying a momentary jitter signal ($jitter(t)$) to the nominal frequency (f_0) for generating a reference frequency ($f(t)$), so that the reference frequency ($f(t)$) varies in time; and
 - the inverter further comprises means for adapting the power rotation angle (ϑ) in response to the rotated momentary active power ($P_{\text{rot}}(t)$) and the rotated momentary reactive power ($Q_{\text{rot}}(t)$).
2. The means of claim 1, further comprising means for detecting fluctuations in time in one or both of the rotated momentary active power and the rotated momentary reactive power.
3. The means of claim 1 or 6, further comprising means for adapting the power rotation angle (ϑ) until it approaches, or optionally matches, the grid impedance angle (θ).
4. The means of claim 3, further comprising means for judging the quality of the match between the power rotation angle (ϑ) and the grid impedance angle (θ).
5. The means of claim 4, wherein the means for judging the quality of the match further comprise means for observing the rotated momentary active and reactive power which are altered through a jittering inverter frequency.

6. The means of any one of the preceding claims, further comprising means for controlling a momentary inverter output frequency ($f_{\text{vSI}}(t)$) in response to the rotated momentary active power ($P_{\text{rot}}(t)$) and the reference frequency ($f(t)$).
- 5 7. The means of claim 6, wherein the means for controlling the momentary inverter output frequency ($f_{\text{vSI}}(t)$) comprise frequency droop control means.
8. The means of any one of the preceding claims, further comprising means for
10 controlling a momentary inverter output voltage ($u_{\text{vSI}}(t)$) in response to the rotated momentary reactive power ($Q_{\text{rot}}(t)$);
9. The means of claim 8, wherein the means for controlling a momentary inverter output voltage ($u_{\text{vSI}}(t)$) comprise voltage droop control means.
- 15 10. The means of any preceding claim, wherein the means for adapting the power rotation angle (ϑ) comprise a minimum correlation finding means in response to only the rotated momentary reactive power ($Q_{\text{rot}}(t)$).
- 20 11. The means of claim 10, wherein the minimum correlation finding means further comprise means for calculating at least one harmonic coefficient.
12. The means of claim 11, wherein the means for calculating at least one harmonic coefficient further comprise means for performing a discrete Fourier
25 transformation.
13. The means of any one of claims 10 to 12, wherein the minimum correlation finding means further comprises means for performing an optimal control.
- 30 14. An electrical inverter comprising
means for outputting an alternating current (AC) power to an electric grid or busbar, wherein the grid or busbar represents an unknown impedance (Z) to the inverter output, the unknown impedance (Z) comprising a resistance (R) and a reactance (X) with $Z = R + jX$, and wherein the unknown grid impedance
35 angle is determined by $\arctan R/X$; and
means for adapting an output power angle of the inverter to the unknown grid impedance angle of the electric grid or busbar at a point of connection with the inverter output in accordance with one of the preceding claims.

15. The electrical inverter of claim 14, wherein inverter is of the voltage source or the current source type.
- 5 16. A method for adapting the power rotation angle (ϑ) of an electrical inverter, the method comprising the steps of
- outputting an alternating current (AC) power to an electric grid or busbar, the electric grid or busbar representing at the inverter output an unknown impedance (Z) comprising a resistance (R) and a reactance (X), wherein an
- 10 unknown grid impedance angle θ is determined by $\arctan R/X$;
- detecting a momentary active power ($P(t)$) of the inverter;
- means for detecting a momentary reactive power ($Q(t)$) of the inverter;
- generating a rotated momentary active power ($P_{\text{rot}}(t)$) and a rotated momentary reactive power ($Q_{\text{rot}}(t)$) by carrying out a rotation operation of the
- 15 momentary active power ($P(t)$) and the momentary reactive power ($Q(t)$) by a power angle (θ); and
- providing a reference frequency ($f(t)$);
- wherein the step of providing a reference frequency (f_{ref}) further comprises applying a momentary jitter signal ($jitter(t)$) to a nominal frequency f_0
- 20 for generating the reference frequency, so that the reference frequency $f(t)$ applied to the inverter output frequency controlling means varies in time; and
- the method further comprises the step of adapting the power rotation angle (ϑ) in response to the rotated momentary active power ($P_{\text{rot}}(t)$) and the rotated momentary reactive power ($Q_{\text{rot}}(t)$).
- 25
17. The method of claim 12, further comprising means for detecting fluctuations in time in one or both of the rotated momentary active power and the rotated momentary reactive power.
- 30 18. The means of claim 16 or 17, further comprising means for adapting the power rotation angle (ϑ) until it approaches, or optionally matches, the grid impedance angle (θ).
19. The means of claim 18, further comprising means for judging the quality of the
- 35 match between the power rotation angle (ϑ) and the grid impedance angle (θ).
20. The means of claim 19, wherein the means for judging the quality of the match further comprise means for observing the rotated momentary active and reactive

power which are altered through a jittering inverter frequency.

21. The method of any one of claims 16 to 20, further comprising controlling a momentary inverter output frequency ($f_{\text{VSI}}(t)$) in response to the rotated momentary active power ($P_{\text{rot}}(t)$) and the reference frequency ($f(t)$);
22. The method of claim 17, wherein the step of controlling the momentary inverter output frequency ($f_{\text{VSI}}(t)$) further comprises applying a frequency droop control.
23. The method of any one of claims 16 to 22, further comprising controlling a momentary inverter output voltage ($u_{\text{VSI}}(t)$) in response to the rotated momentary reactive power ($Q_{\text{rot}}(t)$);
24. The method of claim 23, wherein the step of controlling a momentary inverter output voltage ($u_{\text{VSI}}(t)$) further comprises applying a voltage droop control.
25. The method of any one of claims 16 to 24, wherein the step of adapting the power rotation angle (θ) comprises finding a minimum correlation in response to only the rotated momentary reactive power ($Q_{\text{rot}}(t)$).
26. The method of any one of claims 16 to 25, wherein the step of finding a minimum correlation further comprises calculating at least one harmonic coefficient.
27. The method of any one of claims 16 to 26, wherein the step of calculating at least one harmonic coefficient further comprises performing a discrete Fourier transformation.
28. The method of any one of claims 16 to 27, wherein the step of finding a minimum correlation further comprises performing an optimal control.
29. The method of any one of claims 16 to 28, wherein the inverter is of the voltage source or the current source type.

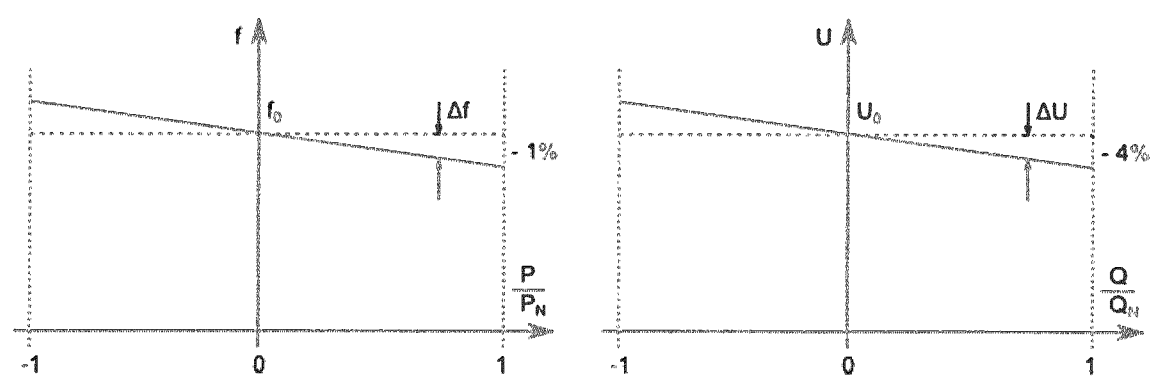
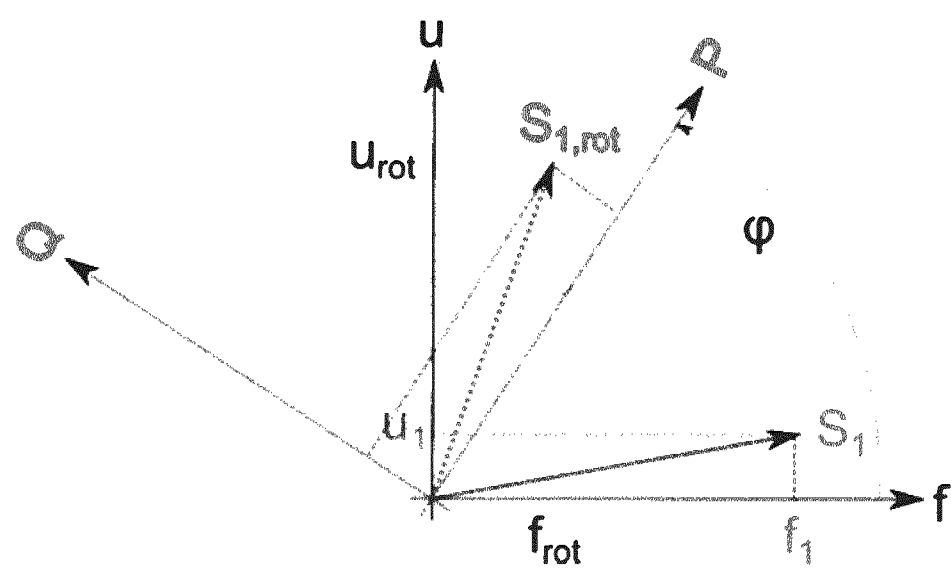


Fig. 1



Fia. 2

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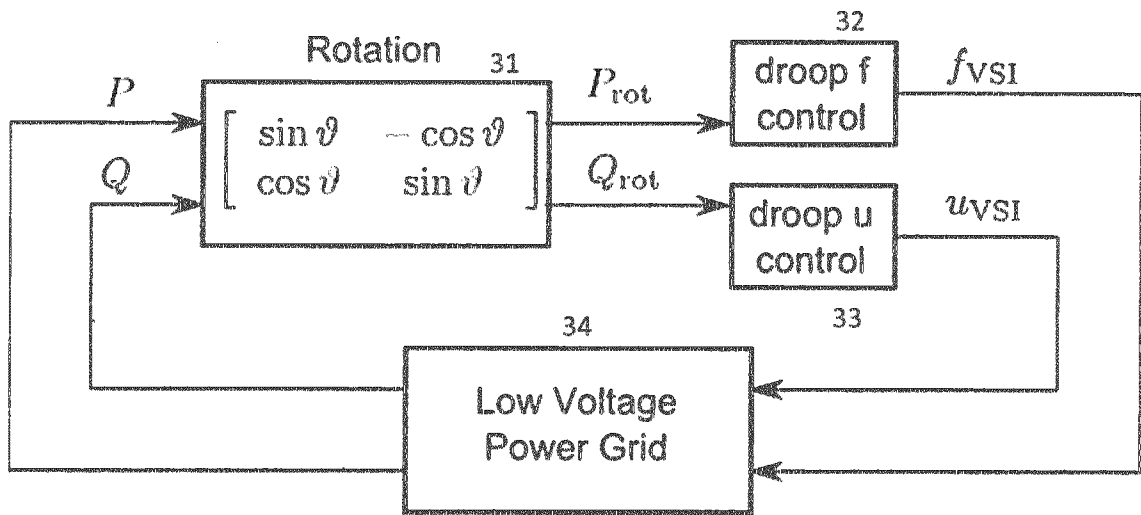


Fig. 3

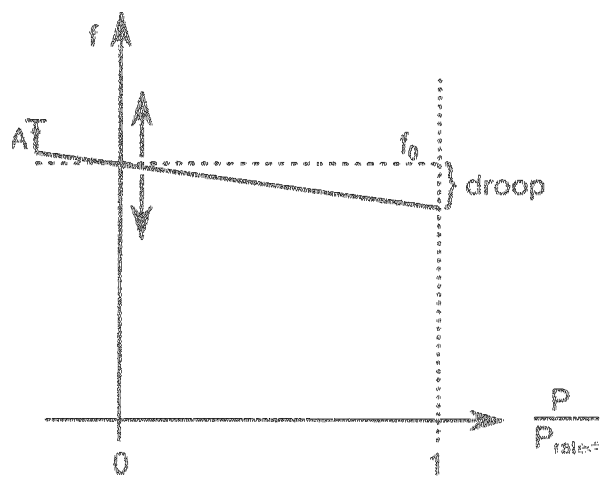


Fig. 4

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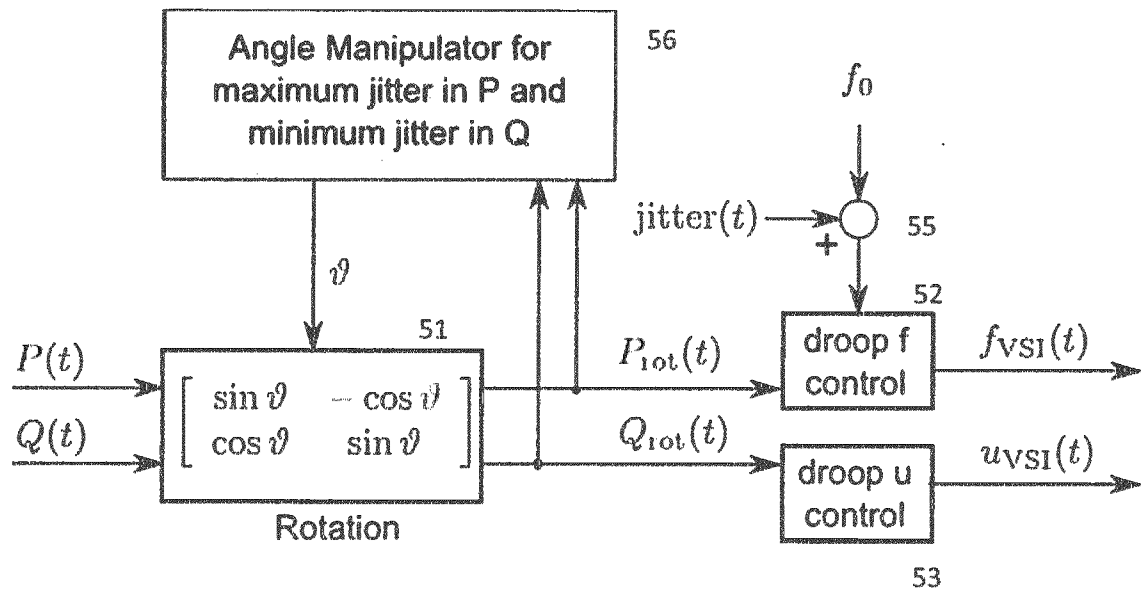


Fig. 5

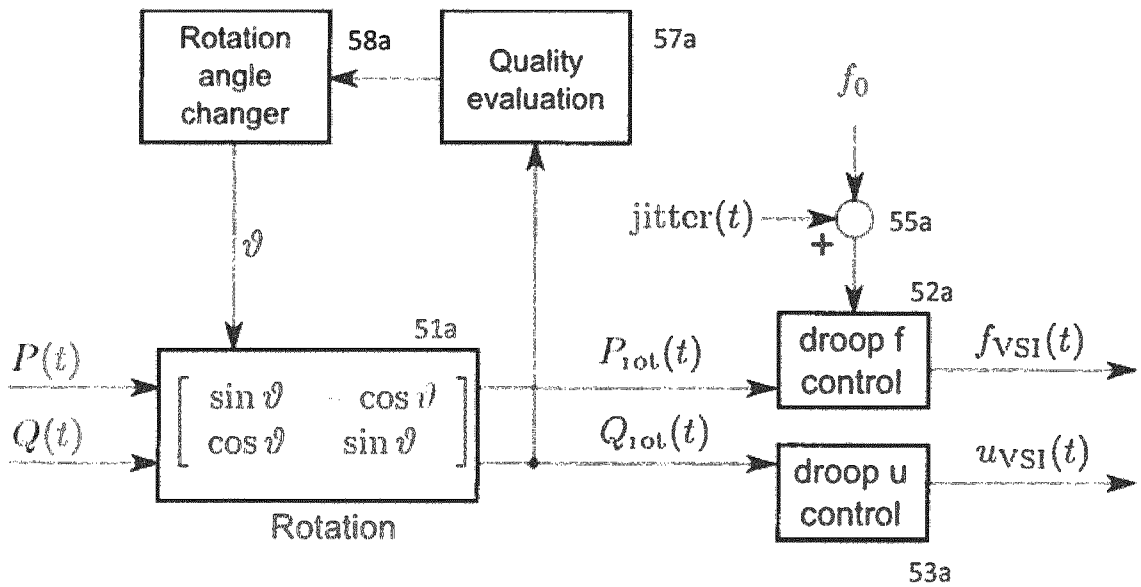
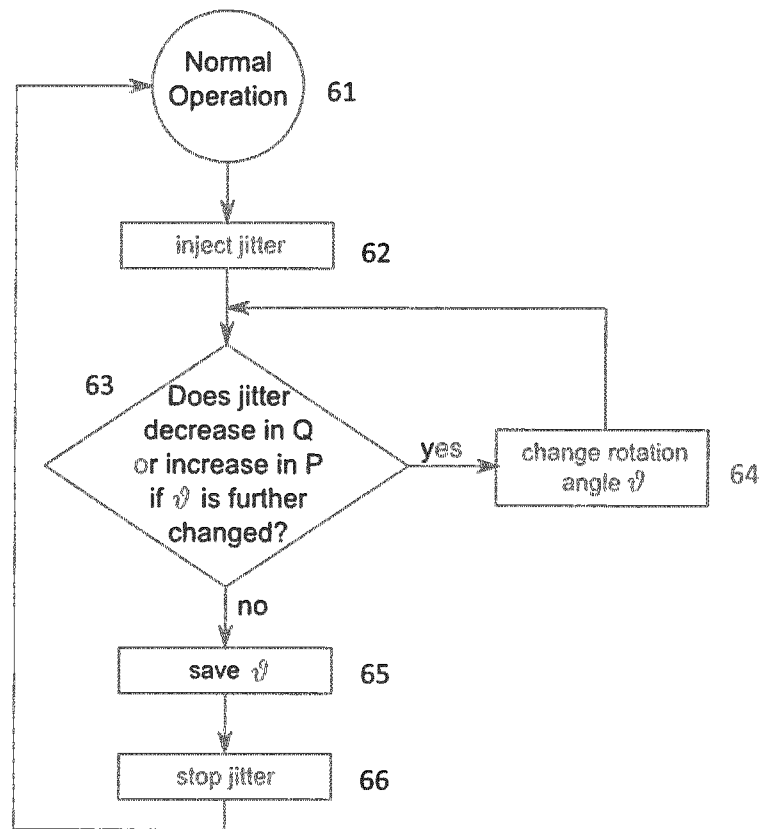


Fig. 5A

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**Fig. 6**

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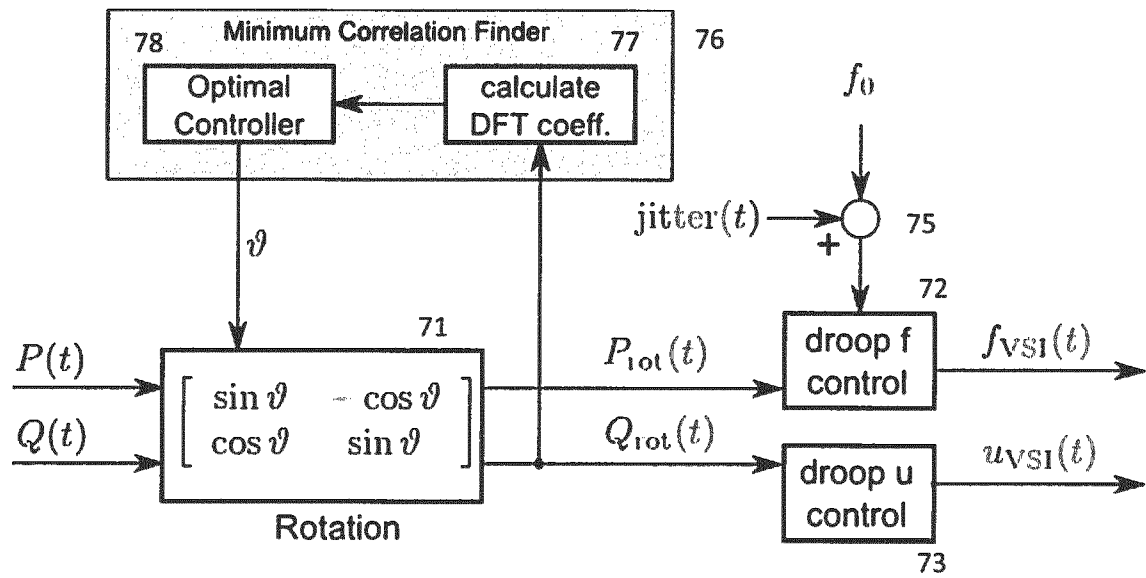


Fig. 7

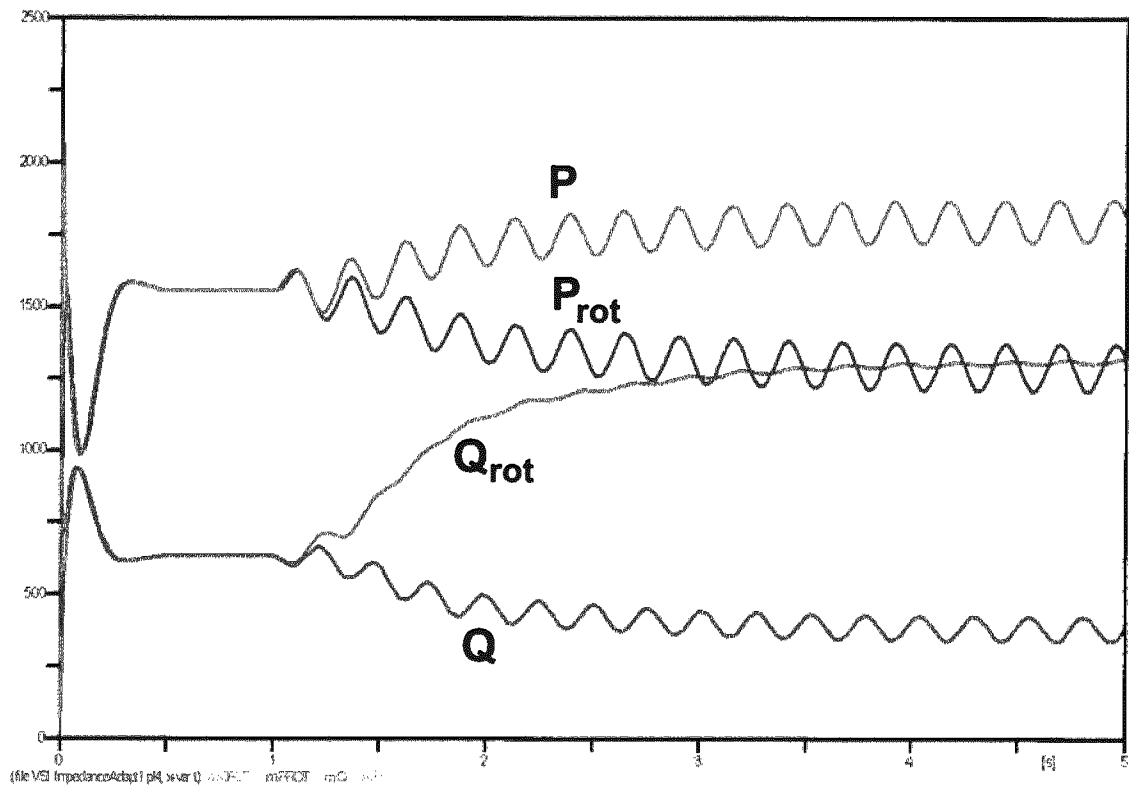


Fig. 8