

VIRTUAL POWER SYSTEM INERTIA APPARATUS AND METHODS OF OPERATION THEREOF

Technical field

5 The invention relates generally to the field of electrical power system control engineering. One aspect of the invention relates to virtual power system inertia apparatus for controlling a voltage of a DC link capacitor. Another aspect of the invention relates to methods of controlling a voltage of a DC link capacitor using virtual power system inertia.

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An aspect of the invention has particular application in compensating frequency deviation in response to system events such as step load changes, tripping of large generators and the like in the electric power grid so as to improve operational stability of the power grid system, or parts thereof. An aspect of the invention has particular application in facilitating restoration of the grid system frequency to normal after reaching frequency nadir.

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Background

In traditional power systems, electricity is generated from, for example, thermal power plants supplied by fossil fuels or hydro power plants that capture the energy of falling water. The rotating masses of synchronous generators and turbines in such power plants provide power system inertia, which is a vital parameter that determines the stability and dynamic response of power system frequency. When a frequency event occurs in the power system, e.g. loss of generation or load units, the rotating masses of synchronous generators and turbines will release kinetic energy to the power grid or absorb it from the grid to counteract the frequency deviation. High power system inertia, i.e. large kinetic energy buffer, is usually desired as it can slow down the dynamics of frequency change and increase the available response time to react to various frequency events or even contingencies. Typically, the grid frequency should be maintained in an acceptable range, e.g. 50 ± 0.2 Hz in Singapore

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(although other ranges may be defined) to ensure the stable and secure operation of power systems. Deviation from this operation range could lead to damaging vibrations in synchronous machines, load shedding, cascading failures, or even large-scale blackouts.

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Nowadays, the control and regulation of power system frequency are challenged by the increasing use of renewable generation such as photovoltaic and wind power devices, because these renewable energy resources are coupled to the electric grid through fast-response power converters (instead of synchronous generators) which do not possess any rotational inertia. Therefore, as the penetration level of renewable generation increases, the equivalent power system inertia will be much reduced and the grid frequency will become very sensitive to the system disturbances caused by the imbalance between generation and load in the power system. This is considered to be one of the major scientific challenges faced by those countries who have committed to raising the share of renewable generation. Moreover, this problem is particularly challenging to countries such as Singapore as the Singapore power grid is basically an islanded power system which has a very limited interconnection capacity with neighbouring countries (around 200 MW), indicating some vulnerability to external disturbances.

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Currently, there are two main ways to manage the reduction of system inertia:

- 1) running multiple synchronous generators at partial load conditions so that collectively they are able to provide high system inertia even with the presence of large-scale renewable generation; and
- 2) installing grid-scale energy storage devices such as batteries, supercapacitors, and flywheels which can provide fast response and compensate system frequency deviations.

Clearly, neither method is ideal as they may significantly increase the system cost, including both capital cost and operation cost. Moreover, energy storage may also bring in other concerns, e.g. low round-trip efficiency, limited lifecycle, safety, and noise, etc.

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To solve this issue, control of operational characteristics of grid-connected power converters that can provide virtual power system inertia are proposed. By implementing such techniques in equipment which converts electricity AC to DC or vice versa, such as power converters in renewable generation systems, the equivalent power system inertia can be increased, leading to smaller changes of grid frequency and more stable operation.

As discussed above, all existing renewable energy resources are coupled to the power grid through power electronic converters which do not possess rotational inertia. This results in reduced system inertia when large-scale renewable generations are integrated into the power system. To tackle this issue, the DC link capacitor in grid-connected power converters can be considered to be a “virtual kinetic energy storage unit”. The energy stored by this capacitor is given by $\frac{1}{2}CV_{dc}^2$, where C is the capacitance and V_{dc} is the voltage. Conventionally, the capacitor voltage is fixed at a predetermined value and the stored energy will be constant regardless of the change of grid frequency. This also explains why there is no inertia in conventional grid-connected power converters.

The capacitor voltage V_{dc} is adaptively controlled according to the grid frequency f_r (or ω_r when the angular frequency is considered, with $\omega_r = 2\pi f_r$). The change of capacitor voltage is preferably limited in a certain range so that it will not affect the normal operation of power converters. In this case, the DC link capacitor essentially becomes a “virtual kinetic energy storage unit” which releases “kinetic energy” to the grid when f_r decreases – by returning power to the grid by the discharging

capacitor – and absorbs “kinetic energy” from the grid when f_r increases – by absorbing extra power from the grid by charging the capacitor. As a consequence, power converters can also counteract the frequency deviation and provide virtual inertia to the grid.

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Moreover, grid-connected power converters are not only used in renewable generation systems but also widely adopted in many energy efficient loads and power conditioning devices, e.g. variable speed drives, power supplies, active power filters, and static VAR compensators, etc. The proposed virtual inertia concept can be implemented in all these devices to increase further the inertia of power system and its robustness, and the market potential of these techniques is vast.

The paper [3] by E. Waffenschmidt, and R. S. Y. Hui, “Virtual inertia with PV inverters using DC-link capacitors,” proposes using DC link capacitors in photovoltaic inverters for virtual inertia for grid control. Such techniques can increase system inertia by modifying the DC link voltage control without significant additional hardware. In summary, one of the ideas behind this paper is to establish a direct connection between power system frequency and the DC voltage of photovoltaic inverters, such that the DC capacitors can provide virtual power system inertia and mitigate frequency deviation. However, the techniques set forth in this paper have their own inherent drawbacks.

Summary

Aspects of the invention are defined in the independent claims. Some optional features of the invention are defined in the dependent claims.

Implementation of the techniques disclosed herein may provide significant technical advantages. Provision of a virtual power system inertia apparatus or the method of operation thereof in which the voltage of the DC link capacitor is varied only in select conditions may provide major benefits. For instance, in implementations where the

DC link capacitor voltage is varied only when the deviation in grid frequency exceeds a minimum threshold mitigates the drawback that DC link capacitors are constantly charged or discharged responsive to the ongoing and continuous small deviations in grid frequency. Because of the proportional relationship between the DC link

5 voltages and grid frequency, the DC link voltages keep changing, indicating that the DC link capacitors will be continuously charged or discharged, which impose disturbances to the control of power converters and also shorten the lifetime of capacitors. Introduction of a frequency dead-band may avoid the unnecessary, and detrimental, continuous charging/discharging of the DC link capacitor. So, when the

10 frequency deviation is small, below a threshold, for example within ± 0.1 Hz of a frequency, such as the grid nominal frequency of 50 Hz, the grid power system is considered to be sufficiently stable to warrant not applying virtual inertia. On the other hand, once frequency deviation exceeds the dead band figure, a “security range”, the proposed virtual inertia is activated to mitigate the prejudicial effects of

15 significant power system frequency change.

Provision of a virtual power system inertia apparatus in which control of the voltage of the DC link capacitor is disabled/deactivated responsive to detection of a frequency nadir, the dropping of the grid frequency to or below a minimum, allows

20 the system frequency to be quickly restored to the nominal value by power system operating reserves. The DC link voltages of the power converters may not be able to restore as long as the frequency deviation exists. As such, power converters may not be capable of contributing virtual inertia under cascaded frequency events where the new frequency event occurs before the frequency restores to or near its nominal

25 value, given the fact the DC link voltage – which varies according to the variation of the grid frequency – has not yet recovered, and the DC link capacitor is not sufficiently charged to provide more virtual inertia to mitigate the effects of a second frequency event following shortly after a first frequency event. Although the introduction of frequency dead-bands can avoid the unnecessary

30 charging/discharging of DC link capacitors, a dead-band features high nonlinearity

and inhibits restoration of the frequency, because the DC link voltage recovers very quickly after the frequency reaches its nadir (i.e. the lowest frequency point). In implementation of these techniques, the DC link capacitor voltage may be held constant – for example at a lower value commensurate with the initial drop of the system grid frequency in the (first) frequency event – and then the DC link capacitor voltage restored to or near nominal voltage after the power system frequency returns to or near the nominal grid frequency value. The benefit(s) to the overall grid performance in such temporary suspension of the control of the DC link voltage may outweigh the benefit(s) of ensuring the DC link voltage is restored to or near nominal quickly. Healthy overall grid system performance is likely to be more critical than immediate or speedy restoration of the voltage in a DC link of a converter.

Brief Description of the Drawings

The invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

- Figure 1 is a simplified schematic diagram of a power system;
- Figure 2 is a series of diagrams illustrating power/angular frequency characteristics for the different components of the power system of Figure 1;
- Figure 3 is a schematic block diagram illustrating a control strategy for a power system operating without virtual inertia;
- Figure 4 is a schematic block diagram illustrating a control strategy for a power system operating with virtual power system inertia;
- Figure 5 is a schematic block diagram illustrating the voltage-loop transfer function of one of the control blocks of Figure 4;
- Figures 5a and 5b are a series of three-dimensional graphs illustrating the variation of the virtual inertia constant with respect to DC link capacitor capacitance and DC link voltage;
- Figures 5c and 5d are a series of graphs illustrating the frequency and voltage responses of the systems of Figures 3 and Figure 4;

- Figure 6 is a schematic block diagram of a grid-connected power converter equipped with virtual power system inertia apparatus as described herein;
- Figure 7 is a graph illustrating the voltage and frequency relationship in the control system of Figure 6 when implementing a dead-band controller in comparison with
5 implementation of a proportional gain controller;
- Figure 8 is a graph illustrating the rate of change of frequency (ROCOF) response over time for a conventional power system not implementing virtual inertia in comparison with the power system implementing the system of Figure 6;
- Figure 9 is a graph illustrating the variation with respect to time in the voltage in the
10 grid frequency deviation signal of the system of Figure 6;
- Figure 10 illustrates experimental results of power converters with and without a high-pass filter in the virtual power system inertia apparatus of the system of Figure 6;
- Figure 11 illustrates experimental results for the DC link voltages under varying
15 system operating conditions with and without a high-pass filter in the virtual power system inertia apparatus of the system of Figure 6;
- Figure 12 is a schematic block diagram illustrating one implementation for a control block in the virtual power system inertia apparatus of Figure 6;
- Figure 13 is a series of graphs illustrating the system frequency and voltage
20 responses for a number of different control strategies;
- Figure 14 is a series of graphs illustrating simulated frequency and voltage responses of systems with and without virtual inertia;
- Figure 15 is a series of graphs illustrating simulated energy and power outputs of systems with and without virtual inertia;
- 25 Figure 16 illustrates an experimental prototype for a virtual power system inertia apparatus;
- Figure 17 is a series of graphs illustrating experimental waveforms of grid voltages and load currents with virtual inertia;
- Figure 18 is a series of graphs illustrating experimental waveforms of frequency and
30 voltage responses under a load change with and without virtual inertia;

Figure 19 is a series of graphs illustrating experimental waveforms of energy and power outputs under a load change with and without virtual inertia.

Detailed Description

5 Referring to Figure 1, this is a simplified schematic diagram of a power system comprising a synchronous generator GS, a power converter, frequency-independent loads such as resistive loads and frequency-dependent loads denoted by M. P_m denotes the power generated by synchronous generators, P_L denotes the power absorbed by frequency-independent resistive-loads, i.e. constant power load, and P_D represents the power absorbed by frequency-dependent loads, e.g. ac motors. P_e is the sum of P_L and P_D . P_{dc} refers to the power absorbed by all the grid-connected power converters, including both DC-AC inverters and AC-DC rectifiers. The variability of renewable generation is considered in detail here, and hence P_{dc} remains to be a constant P_{dc0} under normal operating conditions. The fundamental idea of virtual inertia is to directly link P_{dc} with the system frequency $\omega_r(f_r)$ when frequency events occur. The power generation/absorption versus frequency characteristics of synchronous generators /electric loads are also illustrated in Figure 2, where R designates the droop coefficient, H_p represents the virtual inertia coefficient introduced by grid-connected converters, D denotes the damping factor of frequency-dependent loads, and Δ stands for the deviations of relevant parameters.

First of all, suppose that there is no virtual inertia from the power converter and $P_{dc} = 0$. The system frequency is solely regulated by the speed governors of synchronous generators. The system block diagram is shown in Figure 3, where ω_r is the system angular frequency. R stands for the droop-coefficient and Δ represents the deviations of relevant parameters. The system inertia can be obtained as $2H$ from Figure 3, which is actually the inertia of synchronous generators. Figure 3 describes the frequency dynamics of a conventional power system and more technical details can be found in reference [1] from page 598 to 601

In Figure 3, the essential electromechanical behaviour of synchronous generators, which is described by the well-known swing equation, is modelled by the inertia and load block, and it can be expressed as:

$$2H \frac{d\Delta\omega_r}{dt} + D\Delta\omega_r = P_m - P_L$$

where $H = J\omega_r^2 / (2VA_{\text{rated}})$ represents the inertia coefficient, J stands for the combined moment of inertia of generator and turbine, ω_r is the angular velocity in mechanical, and VA_{rated} is the base power rating of generator. This frequency regulation model and the relevant typical system parameter values can be found in [2], as listed in Table 1, showing exemplary values for turbine-generator power train on the left two columns and for a grid-connected power converter on the right two columns.

Description	Synchronous Generator		Description	Power Converter	
	Symbol	Value		Symbol	Value
Droop coefficient	R	0.05	Rated dc-link voltage	V_{dc}	400 V
Speed governor coefficient	T_G	0.1 s	Maximum dc-link voltage	V_{dc_max}	436 V
Turbine HP coefficient	F_{HP}	0.3 s	Minimum dc-link voltage	V_{dc_min}	364 V
Time constant of reheater	T_{RH}	7.0 s	Maximum voltage deviation	ΔV_{dc_max}	36 V
Time constant of main inlet	T_{CH}	0.2 s	PWM gain	K_{PWM}	1
Inertia coefficient of SG	H	5.0 s	Virtual inertia coefficient	H_p	5.0 s
Rated frequency	f_{ref}	50 Hz	Rated frequency	f_{ref}	50 Hz
Maximum frequency deviation	Δf_{r_max}	0.2 Hz	Maximum frequency	Δf_{r_max}	0.2 Hz
Damping coefficient	D	1.0	Current-loop proportional	K_{ip}	12
-	-	-	Voltage-loop proportional	K_{vp}	0.5
-	-	-	Voltage-loop integral gain	K_{vi}	100
-	-	-	Filter inductance	L_l / L_g	1.0 mH
-	-	-	Damping resistance	R_d	1.0 Ω
-	-	-	Filter capacitance	C_f	5 μ F
-	-	-	Dc-link capacitance	C_{dc}	2.82 mF
-	-	-	Frequency controller	$K_{uv}(s)$	22.5
Power rating	VA_{rated}	1 MVA	Power rating	VA_{rated}	1000 $\times$ 1

Table 1 Exemplary system parameter values

In order to increase system inertia, one control strategy links the system frequency ω_r (f_r) and the dc-link voltage V_{dc} of power converters with a function $K_{\omega v}(s)$ so that the change of frequency $\Delta\omega_r$ will lead to the change of dc-link voltage Δv_{dc} , which further causes the change of power absorbed by the power converters ΔP_{dc} . The

5 block diagram of a system with the proposed control strategy is shown in Figure 4. In Figure 4, Δv_{dc}^* represents the reference value of dc-link voltage. $G_{clv}(s)$ denotes the voltage-loop transfer function, whose response time ranges from 0.01s to 0.1s. A detailed block diagram of $G_{clv}(s)$ can be found in Figure 5, where a typical outer voltage-loop plus inner current-loop controller can be clearly observed. H_c

10 represents the inertia coefficient of capacitors, i.e. the ratio of the rated capacitor energy to the rated power of power converter, which can be expressed as $H_c = CV_{dc}^2 / (2VA_{rated})$, where V_{dc} denotes the rated dc-link voltage and VA_{rated} is the rated power of the power converter. The range of v_{dc} should be confined to (V_{dc_min}, V_{dc_max}) , where the minimum voltage V_{dc_min} is to ensure the linear modulation of

15 power converters. In contrast, the maximum voltage V_{dc_max} is determined by the voltage stress capability of active and passive components. It should be noted that the proposed control strategy is implemented through the modification of dc-link voltage control of power converters, and all other elements in the power system remain unchanged.

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With this additional control loop, the system inertia is changed from $2H$ to $2H + 2H_c K_{\omega v}(s) G_{clv}(s)$, and the second term can be regarded as the virtual inertia, which can be expressed as $2H_c K_{\omega v}(s) G_{clv}(s)$. The simplest form of $K_{\omega v}(s)$ is a proportional

gain, given by $K_{\omega v} = \left(\frac{\Delta V_{dc_max}}{V_{dc}} \right) / \left(\frac{\Delta \omega_{r_max}}{\omega_r} \right)$. Since the dynamic of voltage control $G_{clv}(s)$

25 is much faster than that of the frequency control, $G_{clv}(s)$ can be approximated to be 1. The added virtual inertia is $2H_c K_{\omega v}$, which is a constant. $K_{\omega v}(s)$ could also be a nonlinear function with a frequency dead-band ω_{r_th} introduced to minimize the impact to the power converter. In this case, virtual inertia control will only be activated when the magnitude of system frequency deviation $\Delta\omega_{r_th}$ exceeds ω_{r_th} .

$K_{\omega v}(s)$ could also be other transfer functions to realize compensation of system dynamic response.

This proposed virtual inertia concept has been successfully verified in simulations

5 through the Matlab/Simulink software. For simplicity, $K_{\omega v}(s)$ is chosen to be a

proportional gain, given by
$$K_{\omega v} = \left(\frac{\Delta V_{dc_max}}{V_{dc}} \right) / \left(\frac{\Delta \omega_{r_max}}{\omega_r} \right) = \left(\frac{50}{750} \right) / \left(\frac{0.2 \times 2\pi}{50 \times 2\pi} \right) = 16.67$$
. In this

case, the resulting virtual inertia coefficient is $K_{\omega v} H_c = 16.67 \times 0.28 = 4.67$ s, which is very close to the inertia coefficient of synchronous generator $H = 5$ s. In other words,

replacing synchronous generators with inverter-based renewable generators will not

10 reduce system inertia. Based on the parameter values listed in Table 2 (showing a second set of exemplary values for a turbine-generator power train on the left two columns and for a grid-connected power converter on the right two columns),

system models without ($K_{\omega v} = 0$) and with ($K_{\omega v} = 16.67$) the proposed virtual inertia control have been constructed. The simulation results of their frequency responses

15 when subjected to 5% step-up load change are shown in Figure 5c (With 50 Hz nominal frequency). As can be observed, the maximum frequency deviation of system shown in Figure 5c without the proposed method is around 0.3 Hz. In

contrast, when the proposed control is adopted, the maximum frequency deviation can be limited to be less than 0.25 Hz. Therefore, 17% frequency deviation reduction

20 can be expected with virtual inertia control. Moreover, another critical parameter – the rate of change of frequency (ROCOF) can be reduced from 0.2 Hz/s to 0.05 Hz/s, indicating 75% improvement achieved with this control. A high ROCOF value

exceeding the limit may lead to tripping of generation and load units and result in a large disturbance to the power system. With this inertia control, ROCOF is actually

25 determined by the frequency regulator together with the inertia of power system, and it can be flexibly designed with the virtual inertia $2H_c K_{\omega v}(s) G_{clv}(s)$.

Description	Synchronous		Description	Power Converter	
	Symbol	Value		Symbol	Value
Droop coefficient	R	0.05	Rated dc-link voltage	V_{dc}	750 V
Speed governor coefficient	T_G	0.2	Maximum dc-link	V_{dc_max}	800 V
Turbine HP coefficient	F_{HP}	0.3	Minimum dc-link	V_{dc_min}	700 V
Time constant of reheater	T_{RH}	7.0	Maximum voltage	ΔV_{dc_max}	50 V
Time constant of main	T_{CH}	0.3	PWM gain	K_{PWM}	1
Inertia coefficient of SG	H	5.0	Virtual inertia	H_c	0.28
Rated frequency	f_r	50 Hz	Rated frequency	f_r	50 Hz
Maximum frequency	Δf_{r_max}	0.2 Hz	Maximum frequency	Δf_{r_max}	0.2 Hz
-	-	-	Current-loop	K_{ip}	31.4
-	-	-	Current-loop integral	K_{ii}	6664
-	-	-	Voltage-loop	K_{vp}	0.5
			Voltage-loop integral	K_{vi}	100
-	-	-	Filter inductance	L	3.3 mH
-	-	-	Filter resistance	R_l	0.7 Ω
-	-	-	Dc-link capacitor	C	1 mF
-	-	-	Novel frequency	$K_{\omega v}(s)$	16.67
Power rating	VA_{rated}	1 MW	Power rating	VA_{rated}	1000 $\times$ 1

TABLE 2 Exemplary system parameter values for Figures 4 & 5

The virtual inertia coefficient H_p can be reorganized as:

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$$H_p = \frac{C_{dc} V_{dc}^2}{2VA_{rated}} \cdot \frac{\Delta V_{dc_max} f_{ref}}{V_{dc} \Delta f_{r_max}}$$

As noted from [2], the virtual inertia coefficient of grid-connected power converters under a certain power rating is dependent on the following factors: dc-link capacitance C_{dc} , rated dc-link voltage V_{dc} , maximum voltage variation ratio $\Delta V_{dc_max} / V_{dc}$, and maximum frequency variation ratio $\Delta f_{r_max} / f_{ref}$. For a 1-kVA power converter with its maximum frequency deviation $\Delta f_{r_max} = 0.2$ Hz ($f_{ref} = 50$ Hz), the variation of virtual inertia coefficient H_p versus C_{dc} , V_{dc} , and ΔV_{dc_max} are illustrated in Figures 5a and 5b.

It is clear from Figures 5a and 5b that the virtual inertia coefficient H_p increases linearly with the increase of C_{dc} and ΔV_{dc_max} . Moreover, when the voltage variation ratio is fixed, e.g. $\Delta V_{dc_max} / V_{dc} = 0.15$, H_p is proportional to the square of dc-link

voltage V_{dc} . Under certain conditions, it is possible for power converters to generate even larger virtual inertia than the inertia produced by synchronous generators (H normally ranges from 2 to 10). However, larger C_{dc} and V_{dc} will inevitably increase the system costs, and a higher ΔV_{dc_max} may bring in new challenges to the design of
 5 voltage controller.

Figure 6 illustrates a schematic diagram of the control system of a grid-connected power converter, incorporating a novel virtual power system inertia apparatus which, in this form, is marked by the dashed line having reference numeral 600. The
 10 PLL 602 denotes the phase-locked-loop, PI 604 represents the proportional integral controller, abc/dq transformation block 606 and dq/abc transformation block 608 correspond to the transformations between the natural abc frame and the synchronous dq0 frame, and PWM 610 refers to the pulse-width modulator. These blocks are required in known grid-connected power converters. Specifically, the PLL
 15 602 aims to detect the grid frequency and phase angle for grid synchronizations, received from the V_{gabc} signal, which is in this example comprises one or more signals representing the grid voltage and/or frequency values in the a, b, c phases. The output of PLL block 602 is a grid frequency signal f_r representative of a grid frequency component, in this case the time-varying grid system frequency. The grid
 20 frequency signal f_r is supplied as an input to a comparator/summer 612, where it is processed with respect to a reference grid frequency value f_{ref} which is, in this example, the grid nominal frequency of 50 Hz. The difference Δf_r between f_r and f_{ref} is output by this comparator/summer block 612, and this difference signal Δf_r comprises a frequency deviation signal representative of a deviation of the grid
 25 frequency component from the reference grid frequency value. As noted above, frequency deviation signal Δf_r may be processed in a number of ways in order to provide virtual inertia control as will be discussed in detail below with respect to Figures 7 to 13.

The frequency deviation signal Δf_r is fed as an input to control block 614, with that control block processing the frequency deviation signal Δf_r in one of the exemplary ways described below to output signal ΔV_{dc_ref} generated as is also described below. This output signal ΔV_{dc_ref} is a DC link capacitor voltage control signal used to vary the voltage of the DC link capacitor. So, in this example, this is a signal representing the amount of change desired in the DC link voltage V_{dc} . ΔV_{dc_ref} is summed at summer 616 with a reference value V_{dc_ref} for the DC link voltage (for example the rated DC link voltage, for instance 400 V DC or 750 V DC), with the actual sensed instantaneous value V_{dc} of the DC link voltage being subtracted to produce a signal V_{dc_ref} representing the value at which the DC link voltage is to be set. This may be fed as the input to the PI controller 604.

The PI controller 604 can also be employed to form the current controller for the currents (i.e. i_{gd} and i_{gq}) tracking.

The abc/dq and dq/abc transformations 606, 608 transform the currents and voltage signals between the abc -frame and the dq -frame for better control. The PWM module 610 generates the pulses 618 for driving semiconductor switches 620 S_1 , ... S_6 according to the modulation references, thereby to vary the DC link voltage V_{dc} in accordance with the change calculated by summer 616 and, thereby, the voltage applied to the DC link capacitor 622 C_{dc} .

It will also be appreciated that Figure 6 illustrates a virtual power system inertia apparatus 600 for controlling a voltage of a DC link capacitor 622, the apparatus 600 being configured: to receive a grid frequency signal f_r representative of a grid frequency component V_{gabc} ; to generate a frequency deviation signal Δf_r representative of a deviation of the grid frequency component f_r from a reference grid frequency value f_{ref} ; wherein the apparatus comprises a control block 614 configured to output a DC link capacitor voltage control signal ΔV_{dc_ref} for varying the

voltage of the DC link capacitor 622 if a component of the frequency deviation signal Δf_r exceeds a threshold.

A corresponding method is also described. Thus, there is a method of controlling a
5 voltage of a DC link capacitor 622 using virtual power system inertia having a control
block 614, the method comprising: receiving a grid frequency signal f_r representative
of a grid frequency component V_{gabc} ; generating a frequency deviation signal Δf_r
representative of a deviation of the grid frequency component from a reference grid
frequency value f_{ref} ; and outputting, from the control block 614, a DC link capacitor
10 voltage control signal ΔV_{dc_ref} for varying the voltage of the DC link capacitor 622 if a
component of the frequency deviation signal Δf_r exceeds a threshold.

The component of the frequency deviation signal mentioned may be the magnitude
of the frequency deviation as described with reference to Figure 7, and the threshold
15 is the upper bound of the frequency dead band, indicated by numerals 702, 704 in
Figure 7. The component of the frequency deviation signal may be the frequency
components which are passed by the high-pass filter, with the threshold being the
cut-off frequency of the high-pass filter, as described in further detail below.

20 It is also worth noting that the virtual power system inertia apparatus 600 can be
provided as part of the power converter equipment, or as a separate, stand-alone
item configured to interface with one or more power converters. As such, the
techniques herein disclosed are also readily deployable in retrofit situations.

25 The novel control block 614 comprises at least part of the proposed virtual inertia
controller, denoted as $K_{\omega v}(s)$. A number of exemplary configurations are presented
herewith for control block 614.

In a first of these configurations, control block 614 implements a dead-band controller, one example of which has principles of operation as illustrated in Figure 7.

- 5 As noted above, the techniques described in the paper [3] by Waffenschmidt and Hui are not without their own drawbacks. For instance, simply controlling the DC link voltage such that there is a direct connection between the power system frequency and the DC link voltage has the significant technical disadvantage in that the DC link capacitor voltages are constantly varying and, as a consequence of this, the
- 10 capacitors are constantly charging or discharging. Introduction of a dead-band controller 614 may mitigate such issues.

In Figure 7, line 700 depicts proportional gain virtual inertia control such as that disclosed by Waffenschmidt and Hui [3]. For an input frequency deviation signal Δf ,

15 the change in DC link capacitor voltage ΔV_{dc_ref} varies proportionally so that, for example, for a frequency deviation Δf of +0.2 Hz (that is, grid frequency departs from the nominal grid frequency by +0.2 Hz), the desired change in the DC link capacitor voltage ΔV is changed by +50 V. By the same token, for a frequency deviation Δf of -0.2 Hz (that is, grid frequency departs from the nominal grid frequency by -0.2 Hz,

20 the desired change in the DC link capacitor voltage ΔV is changed by -50 V.

To avoid unnecessary charging/discharging of the DC link capacitors for small deviations in grid frequency, the frequency dead-band controller 614 having the characteristics of the line 702 is introduced. With this characteristic, a frequency

25 dead-band 704 of characteristic 702 is defined in which, for frequency deviations within the dead-band, no change in the DC link capacitor voltage is defined. It is only when the frequency deviation exceeds the dead-band magnitude that changes in the DC link capacitor voltage are effected. So, in this example, for frequency deviations less than or equal to ± 0.1 Hz, no change in DC link capacitor voltage is effected. That

30 is, if the magnitude of the frequency deviation is below a threshold, in this example

0.1 Hz (the range of the frequency dead band from -0.1 Hz to +0.1 Hz), virtual inertia is not applied. Various techniques may be employed for the non-application of the virtual inertia such as, for example, not outputting any ΔV_{dc_ref} signal as illustrated in Figure 6, or setting the ΔV_{dc_ref} signal to 0 V.

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It will be noted that the $\Delta V/\Delta f$ slope characteristic 706 of line 702 is programmable to define a particular DC link capacitor voltage control signal ΔV_{dc_ref} for a particular frequency deviation. By way of exemplary comparison with the techniques of Waffenschmidt and Hui [3], for the same values of maximum Δf of ± 0.2 Hz and maximum ΔV of ± 50 V, with the introduction of the dead band 704, the controller is programmed so that the gradient of the $\Delta V/\Delta f$ slope 706 of characteristic 702 is twice that of the gradient of the proportional gain slope 700 meaning that, for smaller frequency deviations outside of the dead band, smaller voltage changes are required. For instance, and reading from slope 700, for a frequency deviation of

10 +0.15 Hz, a change of DC link voltage of approximately +37.5 V is defined. In contrast and reading from slope 706 in respect of the dead-band controller 614 characteristic, for the same frequency deviation of +0.15 Hz, a voltage change of approximately +25 V is required. Therefore, and remembering that the energy stored by a DC link

capacitor can be given by $\frac{1}{2}CV_{dc}^2$, it will be realised that an ancillary benefit of the provision of the dead-band controller 614 is that the converters can be fitted with DC link capacitors of lower rating/capacity and still provide the same virtual inertia as provided by the techniques of Waffenschmidt and Hui [3]. The use of dead-band control reduces the energy required for inertia emulation.

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25 It will be appreciated that the gradient of the slope 706 can be varied to cater for different system requirements, such as different dead bands and different values in the maximum Δf and ΔV . The gradient of the slope 706 can be defined as the change in DC link capacitor voltage control signal for a change in frequency deviation signal.

It will also be appreciated that a virtual power system inertia apparatus 600 has been described in which the control block 614 comprises a dead-band controller and the threshold comprises a frequency deviation threshold 702, 704, wherein the apparatus is configured to generate the DC link capacitor voltage control signal

5 ΔV_{dc_ref} if a magnitude of the frequency deviation signal Δf_r exceeds the frequency deviation threshold 702, 704.

Further, a parameter of the DC link capacitor voltage control signal ΔV_{dc_ref} representative of a magnitude of the variation of the voltage V_{dc} of the DC link

10 capacitor 622, and for the parameter of the DC link capacitor voltage control signal ΔV_{dc_ref} to vary with the magnitude of the frequency deviation signal Δf_r above the frequency deviation threshold 702, 704. The DC link capacitor voltage control signal ΔV_{dc_ref} varies the voltage V_{dc} of the DC link capacitor 622 such that the magnitude of the variation of the voltage of the DC link capacitor increases over a range of

15 frequency deviations at a rate which is greater than the rate of increase of frequency deviation in the range of frequency deviations.

Figure 8 illustrates the simulated ROCOF curves of the power converters with and without the virtual inertia techniques disclosed herein, such as the use of the dead

20 band controller when compared with conventional systems not implementing virtual inertia control. The curves are plotted for a frequency event of a 5% step up load change. As can be seen, the control system proposed by Figure 6 manages to improve the ROCOF from -0.2 Hz/s to -0.05 Hz/s. However, it is worth noting that the degree of the ROCOF improvement depends on the capacity of the virtual inertia

25 which can be flexibly designed according to system demands.

As an alternative to the dead-band controller, or in addition to this as described below with reference to Figure 12, control block 614 may implement $K_{\omega v}(s)$ as a high-pass filter, i.e. $K_{\omega v}(s) = K_{\omega v} s / (s + 2\pi f_{cut})$, where f_{cut} denotes the cut-off frequency of the high-

30 pass filter. Referring to Figure 9, this is a graph illustrating one example of how the Δf_r

may be time-varying in accordance with variations in system grid frequency.

Referring again to Figure 6, it will be remembered that the signal f_r is representative of the grid frequency. The signal is constantly varying to follow the instantaneous variations in grid frequency. So, as an example, consider f_{r1} represents the grid frequency at time t_1 of 49.8 Hz, f_{r2} represents the grid frequency at time t_2 of 49.85Hz, f_{r3} represents the grid frequency at time t_3 of 49.9Hz. f_{ref} is signal which is representative of the reference grid frequency, say grid nominal frequency of 50Hz.

Δf_r is the difference between the signal representative of the grid frequency and the reference grid frequency, so for each of the grid frequencies f_{r1} , f_{r2} , f_{r3} , at times t_1 , t_2 , t_3 respectively, we have $\Delta f_{r1} = -0.2\text{Hz}$, $\Delta f_{r2} = -0.15\text{Hz}$, $\Delta f_{r3} = -0.1\text{Hz}$. Each of these frequency deviation signals are represented in the electrical circuit by a DC voltage of, for example, +0.5 V for Δf_{r1} at time t_1 , +1.25 V for Δf_{r2} at time t_2 and +2.5 V for Δf_{r3} at time t_3 . However, and as mentioned above, given the fact the grid frequency is subject to ongoing minor deviations as illustrated by curve 902, it will be appreciated that the resultant electrical signal is a time-varying DC voltage signal comprising a DC component and multiple high-frequency harmonic components. As such it will also be appreciated that high-frequency components are generated in the signal when the grid voltage is subject to high rate of change of frequency, ROCOF. The higher the ROCOF of the grid frequency, the higher the magnitude of the high-frequency components. Conversely, when the grid frequency is stable or relatively stable, the electrical signal represented by curve 902 will be, likewise, relatively stable resulting in minimal or no high-frequency components; for instance, for a steady-state, non-changing grid frequency, the Δf_r signal will be a continuous DC voltage having no frequency components.

One drawback in using virtual inertia control is that the DC link voltages of the power converters cannot restore as long as the frequency deviation exists. The power converters are incapable of contributing inertia under cascaded frequency events where, when a frequency event occurs before the grid frequency is restored at or

near nominal value following the occurrence of an earlier frequency event. This is because, given the fact the DC link voltage is tied to the grid frequency, when the grid frequency falls, the DC link capacitor voltage also falls, thereby discharging energy from the DC link capacitor. The grid frequency must recover for the DC link voltage to recover thereby allowing recharging of the DC link capacitor. This cannot happen in cascaded frequency events.

As such, the high-frequency components in the Δf_r signal can be useful in that only these high-frequency signal components above the cut-off frequency of the high-pass filter 614 are passed, and these signals are used to control the variation in the DC link capacitor voltage. For example, the DC link capacitor voltage can be controlled using the techniques described above with respect to Figure 7. In its simplest form, for the resultant waveform of the high-frequency signal components passed by high-pass filter 614, a proportional gain can be applied thereby to determine the magnitude of the ΔV_{dc_ref} signal.

In contrast, during a period of relative stability where the ΔV_{dc_ref} is a pure DC signal (or has minimal varying frequency components), the DC component (or any frequency component below the cut-off frequency) are blocked by the high-pass filter 614 meaning that no change is applied to the DC link voltage.

As such, it may be considered that the control block 614 comprises a high-pass filter and the threshold comprises a frequency threshold defined by a cut-off frequency of the high-pass filter, wherein the apparatus 600 is configured to generate the DC link capacitor voltage control signal ΔV_{dc_ref} based on the component of the frequency deviation signal passed by the high-pass filter

Implementation of the high-pass filter 614 can be used to facilitate recovery of the DC link voltages after individual frequency events as well as reduce the voltage deviations during regular system operations.

In summary, when control block 614 is implemented as a dead band controller, DC link capacitor voltage changes are blocked for small variations in the magnitude of the frequency deviations. The dead band controller stops constant charging and discharging of the DC link capacitor for small variations in grid system frequency

- 5 When control block 614 is implemented as a high-pass filter, DC link capacitor voltage changes are blocked for small variations in the rate of change of grid frequency. The high-pass filter blocks changes to the DC link capacitor voltage during periods of operation when the grid frequency is relatively stable.

- 10 Simulations and experiments are carried out based on the system parameters listed in Table 3, where the definitions of parameters are as given above.

Symbol	Description	Value	Symbol	Description	Value
T_G	Speed governor coefficient	0.1 s	$K_{\omega v}$	Virtual inertia control gain	22.5
T_{CH}	Time constant of main inlet volumes	0.2 s	V_{dc}	Rated DC-link voltage	400 V
T_{RH}	Time constant of reheater	7.0 s	ΔV_{dc_max}	Maximum DC-link voltage deviation	36 V
F_{HP}	Turbine HP coefficient	0.3 s	C_{dc}	DC-link capacitance	2.82 mF
R	Droop coefficient	0.05	Δf_{max}	Maximum frequency deviation	0.2 Hz
D	Damping coefficient	1.0	VA_{rated}	Power rating	1 kVA
H	Inertia coefficient of SG	5.0 s	f_{cut}	Cut-off frequency of high-pass filter	0.01 Hz

Table 3 System parameters.

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Figure 10 illustrates the experimental results of the power converters with and without the proposed high-pass filter-based method when subjected to the frequency events of cascaded 4% step-up load changes. In the face of the first

frequency event, the frequency nadirs of the two cases are almost the same. However, the case without the high-pass filter cannot restore its dc-link voltage after the first frequency event and thus being unable to provide enough frequency support during the second frequency event, resulting in a frequency nadir of 49.66 Hz. With the proposed method, the DC-link voltage can quickly restore after the first frequency event. When the first frequency event happens, the ROCOF changes very fast. Therefore, both cases provide inertia support before the frequency reaches its nadir. After the frequency settles down at around $t_0 + 10$ s, the frequency remains almost unchanged until $t_0 + 15$ s. During this period, in the case without the high-pass filter, this has an almost fixed DC-link voltage deviation, because the voltage deviation is in proportional to the frequency deviation. In contrast, for the case with the high-pass filter, the DC-link voltage recovers, as the almost fixed frequency deviation (DC component) will be blocked by the high-pass filter so that the DC-link voltage goes back its nominal value. With the DC-link voltage recovered, the case with the high-pass filter can provide inertia support during the second frequency event. Because of this, it is possible to provide inertia support during the second frequency event, and the associated frequency nadir is improved from 49.66 Hz to 49.70 Hz. In the figure, the upper traces represent the variations in the DC link voltage and the lower traces represent the variations in the grid frequency. It will also be noted that the DC link voltage recovers much more quickly with the implementation of the high-pass filter.

Figure 11 presents the experimental waveforms of the DC link voltages under regular system operating conditions, where the 6-minute grid frequency data is taken from real power system operator data. In this case, it is clear that the proposed control method greatly reduces the voltage deviation from 11 V to 3 V, thereby indicating the effectiveness of the proposed high-pass filter-based virtual inertia control.

As noted above, control block 614 may implement both the dead-band controller and the high-pass filter, in which case an exemplary arrangement for such an

implementation is illustrated in Figure 12. With such an arrangement, the frequency deviation signal Δf_r is input to the dead band controller 614a, and the output signal 1202 – which may take the form of, say, the characteristic 702 illustrated in Figure 7 – is input to high-pass filter 614b, which filters any DC or low-frequency components below the high-pass filter cut-off frequency. As such, control block 614 will “block” all frequency deviation signal components within the dead-band regardless of the frequency of the components and pass only those frequency deviation signal components where the magnitude of the frequency deviation is above the dead band threshold (greater than ± 0.1 Hz keeping with the example of Figure 7) and having a frequency above the cut-off frequency of the high-pass filter 614b.

In this respect, there is a virtual power system inertia apparatus in which the control block 614 comprises a dead-band controller 614a and a high-pass filter 614b and the threshold comprises a frequency threshold defined by a cut-off frequency of the high-pass filter, wherein the dead-band controller is configured to generate a dead-band controller output signal 1202 if the magnitude of the frequency deviation exceeds the frequency deviation threshold 702, 704, the high-pass filter 614b arranged to receive the dead-band controller output signal 1202 and wherein the apparatus 600 is configured to generate the DC link capacitor voltage control signal ΔV_{dc_ref} based on the component of the dead-band controller output signal passed by the high-pass filter.

In another arrangement it is also possible to implement a type of “adaptive” virtual inertia control to accelerate the process of power system frequency restoration. When the power system frequency drops to a minimum value, often referred to as “frequency nadir”, virtual inertia control is deactivated such that the system frequency can be quickly restored to the nominal value by the power system operating reserves. During this process, the DC link voltage of the capacitors is held constant, and voltage restoration of the capacitors is performed after the power system frequency returns to the nominal value – say, at or around 50 Hz – as the DC

link voltages of individual power converters are less critical as compared to overall power system frequency.

Again, various techniques may be employed for the deactivation of the virtual inertia such as, for example, not outputting any ΔV_{dc_ref} signal as illustrated in Figure 6, or setting the ΔV_{dc_ref} signal to 0 V. Other options may also be possible including, for example, controlling the opening and closing of a switch (not shown in the figures) to block or pass the DC link voltage control signal ΔV_{dc_ref} in dependence of a determination that the grid frequency has reached the frequency nadir

Thus, a virtual power system inertia apparatus 600 for controlling a voltage of a DC link capacitor 622 is configured to detect a grid frequency component f_r is below a minimum grid frequency and to disable control of the voltage of the DC link capacitor 622 in dependence thereof.

It is to be noted that the adaptive virtual inertia control as described above can be implemented on its own or in combination with the other techniques described above, where a dead-band controller and/or high-pass filter are implemented in control block 614.

Figure 13 shows the simulation results of power system frequency under a 5% load step change for a number of the circuit arrangements discussed above:

Case I: no virtual inertia;

Case II: virtual inertia proposed by Waffenschmidt and Hui [3];

Case III: virtual inertia with frequency dead-band (one of the novel techniques as herein proposed);

Case IV: virtual inertia with frequency dead-band and adaptive control (one of the novel techniques as herein proposed).

- As can be seen, the maximum frequency deviation of the system without virtual inertia (Case I) is 0.293 Hz. In contrast, with the virtual inertia proposed by Waffenschmidt and Hui [3]; (Case II), the maximum frequency deviation can be reduced to 0.244 Hz. The techniques herein proposed (Case III and Case IV) can
- 5 further reduce frequency deviation to 0.221 Hz, indicating a 9.4% improvement as compared with the virtual inertia proposed by Waffenschmidt and Hui [3]. This is due at least in part to the careful selection of the gradient of the V/f slope or large equivalent virtual inertia as shown in Figure 7. When adaptive virtual inertia control is incorporated, the DC link voltage becomes constant during frequency restoration,
- 10 and power system frequency can reach the steady state value, i.e. 49.881 Hz within 15s, which is the same as that without virtual inertia control. However, for the method proposed by Waffenschmidt and Hui [3], it takes 20s for the power system frequency to reach the steady state.
- 15 The performances of these four cases are summarized and compared in Table 4, and it is clear that Case IV gives the best frequency regulation performance.

Power system frequency with a 5% step load change	Frequency Nadir (Hz)	Restoration Time (s)
Case I (no virtual inertia)	49.707	15
Case II (virtual inertia in D1)	49.756	20
Case III (virtual inertia with dead-band)	49.779	23
Case IV (virtual inertia with dead-band and adaptive control)	49.779	15

Table 4. Performance comparison of different virtual inertia control.

In other words, the techniques disclosed herein can be considered to relate to a grid connected power converter which provides virtual inertia to compensate frequency deviation of the grid so as to ensure stable operation of the whole power system.

- 5 The proposed power converter comprises a DC link capacitor, which releases or absorbs the energy in response to the grid frequency deviation. The voltage of the capacitor is dynamically coupled (or varied according) to the grid frequency.

- 10 In a first arrangement, there is provided a method of dynamically controlling the voltage of a DC link capacitor. The control method comprises:
- a) providing a range of frequency deviation (dead-band);
 - b) activating the charging and discharging operation of the DC link capacitor only when the grid frequency exceeds the limit of the range.

- 15 In a second arrangement, the control method comprises:
- a) decoupling the DC link capacitor from the grid frequency when the grid frequency reaches the minimum value;
 - b) holding the DC voltage as constant until the grid frequency is restored.

20 Commercial applications of the invention

- The proposed invention can be applied to all grid-connected power conversion applications where a DC/AC or AC/DC power converter is present. These commercial applications include grid-tied photovoltaic or wind power inverters, front-end power factor correction (PFC) circuits, active power filters (APFs), static VAR compensators
- 25 (STATCOMs), and uninterruptible power supplies (UPSs) in both single-phase and three-phase systems.

Further simulation and experimental results

A. Simulation Results

The proposed distributed virtual inertia concept has been successfully verified in simulations through the Matlab/Simulink software. As listed in Table 1 above, $\Delta V_{dc_max} = 36$ V, $C_{dc} = 2.82$ mF, and $K_{\omega v}(s) = 22.5$ can be obtained. Under this condition, the resulting virtual inertia coefficient is $H_p = 5.0$ s, which is the same as the inertia coefficient of synchronous generator $H = 5$ s. In other words, replacing synchronous generators with the inverter-based renewable generators will not reduce system inertia. The system models without and with distributed virtual inertia have been constructed. The simulation results of their frequency and voltage responses when subjected to a 3% step-up load change are shown in Figure 14 (with 50 Hz nominal frequency).

As it can be observed from Figure 14(a), the maximum frequency deviation without the proposed method is around 0.16 Hz. In contrast, when the proposed frequency controller shown in Figure 5 is activated, the maximum frequency deviation can be limited to be 0.14 Hz. Therefore, 12.5% frequency deviation reduction can be expected with the proposed virtual inertia method. Moreover, another critical parameter – ROCOF – can be reduced from 0.150 Hz/s to 0.075 Hz/s, indicating 50% improvement achieved with the proposed method. A high ROCOF value exceeding the limit, e.g. 1 Hz/s, may lead to tripping of protection relays and result in a large disturbance to the power system. With the proposed virtual inertia, ROCOF is actually determined by the frequency regulator together with the inertia of power system, and it can be flexibly designed with the virtual inertia coefficient H_p . As seen from Figure 14(b), the steady state voltage deviation is around 13 V, which is in proportion to the steady-state frequency deviation.

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Figure 15 demonstrates the energy and power outputs of power converters during frequency dynamics. As it can be observed from Figure 15(a), power converters output energy during the frequency event to provide frequency support. Moreover, it is clear from Figure 15(b) that the proposed method would not pose any threats on

the normal operation of power converters, since their output power is maintained as zero in the steady-state.

B. Experimental Results

- 5 In order to illustrate the effectiveness of the proposed concept, experiments were carried out based on the system parameter values listed in Table 1, except for the power rating, which was scaled down to 1-kVA. It should be mentioned that although only one power converter and one VSG were incorporated, they were designed with the same per-unit values as the real single-area power system, where
- 10 the system frequency signals seen by individual converters and generators are the same. Therefore, the experimental system can be regarded as an aggregated model and it is dynamically equivalent to the simulated system presented above in Section A Simulation Results.
- 15 A photo of the experimental prototype is illustrated in Figure 16. As seen, a dSPACE control platform (dSPACE: Microlabbox) was used to implement the control algorithms of both VSG and grid-connected converter (GCC). In Figure 17, the frequency control was implemented by the VSG. Additionally, the grid-connected converter equipped with distributed virtual inertia was connected in parallel with the
- 20 VSG. Its detailed control structure can be found in Figure 6. The DC link voltage of VSG was maintained as a constant by a dc power supply (Itehc: IT6500C). This voltage was then converted into ac voltages v_{ga} - v_{gc} to emulate grid voltages as well as supplying a three-phase load with a resistance of R_l . Litz wires with low equivalent-series-resistances (ESR) were used as inductor windings. An oscilloscope
- 25 (TELEDYNE LECROY: HDO8038) was involved to capture the experimental waveforms and export them into Matlab/Simulink for further analysis.

Figure 17 illustrates the steady-state waveforms of grid voltages v_a - v_c and load currents i_a - i_c when the proposed virtual inertia method is activated. It is clear that

30 these waveforms are perfect sinusoidal with low distortions thanks to the help of

VSG. Another observation is that the proposed virtual inertia method would not pose any threats on the normal operation of power system.

Figure 18 shows the experimental waveforms of frequency and voltage responses when subjected to a 3% step-up load change. As it can be seen from Figure 19, when the proposed method is disabled, the dc-link voltage v_{dc} remains unchanged while the maximum frequency deviation $|f_{ref} - f_{r_peak}|$ is around 0.17 Hz. This value can be reduced to 0.14 Hz after enabling the proposed frequency controller. Under this condition, the dc-link voltage v_{dc} varies in proportional to the frequency f_r .

In addition, as verified by Figure 19, the GCC outputs power and energy during frequency dynamics to support frequency regulation, and then its output power returns back to 0 W in steady-state. The errors between the simulation results and experimental results may be caused by the inaccuracy of measurement.

Conclusion

The techniques disclosed herein propose concepts for grid-connected power converters to generate distributed virtual inertia through selectively regulating their DC link voltages, resulting in the increase of power system inertia and reduction of system frequency deviation as well as its changing rate under frequency events. The proposed methods feature a simple structure and an easy implementation, which brings no extra burden on the system hardware. The decisive factors of virtual inertia, e.g. DC link capacitance, DC link voltage, and DC link voltage deviation have been identified. The feasibility of the proposed distributed virtual inertia method is verified through simulation and experimental results, which indicate that more than 10% frequency deviation reduction and 50% improvement of rate of change of frequency (ROCOF) can be expected with distributed virtual inertia.

It will be appreciated that the invention has been described by way of example only.

Various modifications may be made to the techniques described herein without

departing from the spirit and scope of the appended claims. The disclosed techniques comprise techniques which may be provided in a stand-alone manner, or in combination with one another. Therefore, features described with respect to one technique may also be presented in combination with another technique.

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Claims

1. Virtual power system inertia apparatus for controlling a voltage of a DC link capacitor, the apparatus being configured:
 - 5 to receive a grid frequency signal representative of a grid frequency component;
 - to generate a frequency deviation signal representative of a deviation of the grid frequency component from a reference grid frequency value; wherein
 - the apparatus comprises a control block configured to output a DC link
 - 10 capacitor voltage control signal for varying the voltage of the DC link capacitor if a component of the frequency deviation signal exceeds a threshold; the control block comprising a dead-band controller, the threshold comprising a frequency deviation threshold, and wherein the apparatus is configured to generate the DC link capacitor voltage control signal if a magnitude of the frequency deviation signal exceeds the
 - 15 frequency deviation threshold.
2. The virtual power system inertia apparatus of claim 1, wherein the control block comprises an input for receiving the frequency deviation signal.
- 20 3. The virtual power system inertia apparatus of claim 1 or claim 2, configured for a parameter of the DC link capacitor voltage control signal to be representative of a magnitude of the variation of the voltage of the DC link capacitor, and for the parameter of the DC link capacitor voltage control signal to vary with the magnitude of the frequency deviation signal above the frequency deviation threshold.
- 25 4. The virtual power system inertia apparatus of claim 3, configured for the DC link capacitor voltage control signal to vary the voltage of the DC link capacitor such that the magnitude of the variation of the voltage of the DC link capacitor increases over a range of frequency deviations at a rate which is greater than the rate of
- 30 increase of frequency deviation in the range of frequency deviations.

5. The virtual power system inertia apparatus of claim 1, wherein the control block comprises a high-pass filter and the threshold comprises a frequency threshold defined by a cut-off frequency of the high-pass filter, wherein the apparatus is configured to generate the DC link capacitor voltage control signal based on the component of the frequency deviation signal passed by the high-pass filter.
6. The virtual power system inertia apparatus of claim 1 or claim 2, wherein the control block comprises a high-pass filter and the control block is configured for a frequency threshold to be defined by a cut-off frequency of the high-pass filter, wherein the dead-band controller is configured to generate a dead-band controller output signal if the magnitude of the frequency deviation exceeds the frequency deviation threshold, the high-pass filter being arranged to receive the dead-band controller output signal and wherein the apparatus is configured to generate the DC link capacitor voltage control signal based on the component of the dead-band controller output signal passed by the high-pass filter.
7. The virtual power system inertia apparatus of any preceding claim, configured to detect a grid frequency component is below a minimum grid frequency and to disable generation of the DC link capacitor voltage signal in dependence thereof.
8. A method of controlling a voltage of a DC link capacitor using virtual power system inertia having a control block, the method comprising:
receiving a grid frequency signal representative of a grid frequency component;
generating a frequency deviation signal representative of a deviation of the grid frequency component from a reference grid frequency value; and
outputting, from the control block, a DC link capacitor voltage control signal for varying the voltage of the DC link capacitor if a component of the frequency deviation signal exceeds a threshold; wherein the control block comprises a dead-

band controller and the threshold comprises a frequency deviation threshold, the method comprising generating the DC link capacitor voltage control signal if a magnitude of the frequency deviation signal exceeds the frequency deviation threshold.

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9. The method of claim 8, wherein the frequency deviation signal is received at an input of the control block.

10 10. The method of claim 8, wherein a parameter of the DC link capacitor voltage control signal is representative of a magnitude of the variation of the voltage of the DC link capacitor, and for the parameter of the DC link capacitor voltage control signal to be varied with the magnitude of the frequency deviation signal above the frequency deviation threshold.

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11. The method of claim 10, wherein the DC link capacitor voltage control signal varies the voltage of the DC link capacitor such that the magnitude of the variation of the voltage of the DC link capacitor increases over a range of frequency deviations at a rate which is greater than the rate of increase of frequency deviation in the range of frequency deviations.

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12. The method of claim 8, wherein the control block comprises a high-pass filter and the threshold comprises a frequency threshold defined by a cut-off frequency of the high-pass filter, the method comprising generating the DC link capacitor voltage control signal based on the component of the frequency deviation signal passed by the high-pass filter.

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13. The method of claim 8 or claim 9, wherein the control block comprises a dead-band controller and a high-pass filter and the threshold comprises a frequency threshold defined by a cut-off frequency of the high-pass filter, the method

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comprising generating a dead-band controller output signal if the magnitude of the frequency deviation exceeds the frequency deviation threshold, receiving the dead-band controller output signal at the high-pass filter and generating the DC link capacitor voltage control signal based on the component of the dead-band controller output signal passed by the high-pass filter.

14. The method of any of claims 8 to 13, comprising detecting a grid frequency component is below a minimum grid frequency and disabling generation of the DC link capacitor voltage control signal in dependence thereof.

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