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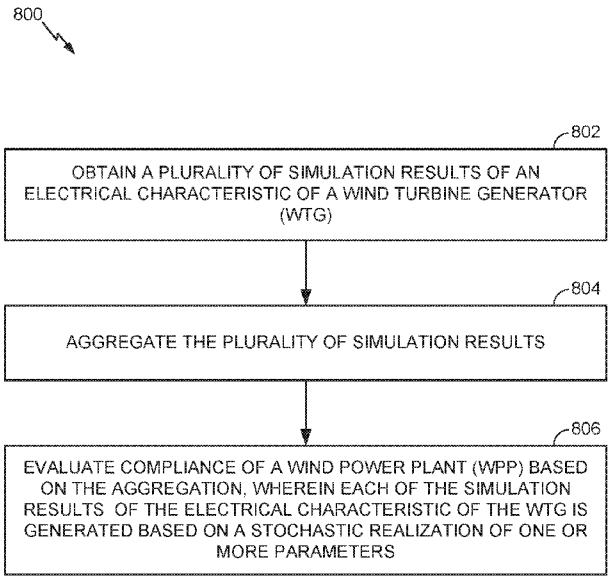

FIG. 8

(57) Abstract: Aspects of the present disclosure provide techniques for evaluating the effects of power oscillations at a point of common coupling (PCC) for a wind power plant (WPP) using Monte Carlo simulations. The techniques may involve simulating an electrical characteristic of a wind turbine generator (WTG) based on one or more parameters, the realization of which may be derived stochastically based on a random seed. The electrical characteristic of the WTG is simulated for a pre- determined time period and for a plurality of values for the random seed. The evaluation of power oscillations at the PCC may be performed by extracting simulation results corresponding to a random time segment and a random seed, for each of the WTGs, and aggregating the simulation results to generate a quality metric. The quality metric may be used to evaluate compliance of the WPP with, for example, a grid code.

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ESTIMATION OF POWER QUALITY AT POINT OF COMMON COUPLING

BACKGROUND

Field of the Invention

Aspects presented in this disclosure generally relate to techniques for evaluating electrical characteristics of a wind power plant (WPP) at a point of common coupling (PCC).

Description of the Related Art

Modern power generation and distribution networks increasingly rely on renewable energy sources, such as wind turbine generators (WTG). In some cases, the WTGs may be substituted for conventional, fossil fuel-based generators. A wind power plant (WPP), which may also be referred to as a wind turbine park, typically includes multiple WTGs that feed into a common grid at a point of common coupling (PCC).

SUMMARY

Certain aspects of the present disclosure are directed to a method of evaluating electrical characteristics at a point of common coupling (PCC) of a wind power plant (WPP). The method generally comprises obtaining a plurality of simulation results of an electrical characteristic of a wind turbine generator (WTG), aggregating the plurality of simulation results, and evaluating compliance of the WPP (e.g. evaluating the compliance of the WPP with a grid code) based on the aggregation, wherein each of the simulation results of the electrical characteristic of the WTG is generated based on a stochastic realization of one or more parameters.

Certain aspects of the present disclosure are directed to an apparatus for evaluating electrical characteristics at a point of common coupling (PCC) of a WPP. The apparatus may generally include a processing system configured to obtain a plurality of simulation results of an electrical characteristics of a WTG, aggregate the plurality of simulation results, and evaluate compliance of the WPP based on the

aggregation, wherein each of the simulation results of the electrical characteristic of the WTG is generated based on a stochastic realization of one or more parameters.

Certain aspects of the present disclosure are directed to a computer program product for wireless communications comprising a computer readable medium having instructions stored thereon, the instructions executable by one or more processors for obtaining a plurality of simulation results of an electrical characteristic of a WTG, aggregating the plurality of simulation results, and evaluating compliance of a WPP based on the aggregation, wherein each of the simulation results of the electrical characteristic of the WTG is generated based on a stochastic realization of one or more parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to aspects, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only aspects of this disclosure and are therefore not to be considered limiting of its scope, for the disclosure may admit to other equally effective aspects.

FIG. 1 illustrates an example wind power plant (WPP).

FIG. 2 illustrates maximum discrete Fourier transform (DFT) peak of a vibration controller power offset at a wind turbine generator (WTG) tower's natural frequency for different wave directions.

FIG. 3 illustrates the maximum DFT peak of a grid active power at a WTG tower's natural frequency for different wave directions.

FIG. 4 illustrates the maximum DFT grid power around a WTG tower's natural frequency with vibration control as compared to a reference WTG operated without vibration control.

FIG. 5A illustrates example power oscillations of a WTG when the effects of misalignment between wind and wave direction is at ninety degrees.

FIG. 5B illustrates example power oscillations of a WTG having the same configurations as the WTG used to generate the power oscillations of FIG. 5A, but with wind and wave directions aligned.

FIG. 6 illustrates randomly chosen realizations of active power produced by WTGs in a WPP in the frequency and time domain with waves hitting a respective tower of the WTGs at ninety degrees.

FIG. 7 illustrates randomly chosen realizations of the active power produced by WTGs in a WPP in the frequency and time domain with waves hitting a respective tower of the WTGs at thirty degrees.

FIG. 8 illustrates example operations for evaluating power oscillations at a point of common coupling (PCC) of a WPP, in accordance with aspects of the present disclosure.

FIG. 9A is an example heat map illustrating simulations used to evaluate compliance of a WPP, in accordance with certain aspects of the present disclosure.

FIG. 9B illustrates aggregation of simulation results corresponding to a plurality of wind turbine of a WPP, in accordance with certain aspects of the present disclosure.

FIG. 10 illustrates convergence of a quality metric, in accordance with certain aspects of the present disclosure.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements disclosed in one aspect may be beneficially utilized on other aspects without specific recitation.

DETAILED DESCRIPTION

Aspects of the present disclosure provide techniques for evaluating the effects of power or voltage oscillations at a point of common coupling for a wind power plant (WPP) of any size using Monte Carlo simulations. Monte Carlo methods are a class of computational algorithms that rely on repeated random sampling to obtain numerical results in order to obtain the distribution of an unknown probabilistic entity.

For example, the techniques may involve simulating electrical characteristics of a wind turbine generator (WTG) based on one or more parameters (e.g., climate conditions such as wind), the behavior of which may be derived stochastically based on a random seed of an aero elastic simulation tool. The electrical characteristics may correspond to output power and/or voltage of the WTG. For example, a power spectral density (PSD) may be used to simulate the electrical characteristics of the WTG, as described in more detail herein. The electrical characteristics of the WTG may be simulated for a pre-determined time period and for a plurality of values for the random seed. These simulations may be used to evaluate the effects of power oscillations at a point of common coupling (PCC) of a number of WTGs of a WPP.

For example, the evaluation may be performed by selecting a random seed and a random time segment within the seeds and time period simulated, for each of the WTGs of a WPP under evaluation. The results of the simulation corresponding to the selected time segment and seeds, for each of the WTGs, may be aggregated to generate a quality metric. For example, the quality metric may be based on power or voltage oscillations within a certain frequency band. This process may be repeated until the quality metric converges to a value which may be used to evaluate compliance of the WPP.

The techniques provided herein allow for the determination of the likely power quality at a PCC of a WPP of arbitrary size from a single turbine aero elastic output. The benefit of such a tool may lie in the improved capability to assess the expected power quality when evaluating new technologies or WTG installations, which may be especially useful in markets characterized in strict grid codes. Thus, the benefit of

aspects of the present disclosure is in an increased awareness of the expected level of compliancy, especially in relation to low frequency oscillations.

Having at hand a tool able to predict the amount of compliancy to be expected in relation to specific grid codes could allow site engineers to correctly de-tune technologies for specific countries and markets while still harvesting the benefits stemming from the specific control technologies influencing the power variations. Furthermore, aspects of the present disclosure include techniques for determining the power quality in a robust way by means of evaluation of the power spectral density in a band of frequencies of interest.

The techniques may assume that active power oscillations from each turbine is varying in amplitude and are not synchronized. By modeling the harmonics in a range of frequencies of interest in the active produced power, certain aspects of the present disclosure, via a Monte Carlo simulation, may extrapolate the average (and other second moment statistics) of a set of quality metrics at the point of common coupling. This may allow for evaluation of the impact of existing or new technologies to a grid delivered power during the siting process of a WPP. The Monte Carlo simulations of present disclosure may take into account several factors that impact power oscillations at the PCC that are explained in more detail with respect to FIGs. 1-7.

FIG. 1 illustrates an example WPP 100 with multiple WTGs that generate power signals that are aggregated at a PCC 102. Each WTG may include a plurality of blades coupled to an electrical generator (e.g., a permanent magnet generator (PMG)) and a power conversion system. One or more vibration controllers may be designed to reduce tower lateral fatigue damage for each of the WTGs of the WPP 100. For example, the vibration controller may include an active control feature which varies the active power of a WTG in order to dampen certain vibrations or movements within the WTG. That is, a vibration controller for each of a plurality of WTGs may be used to vary the active power of a respective WTG based on a measured acceleration or loading that is local to the respective WTG. For example,

one or more vibration controllers may vary the active power of each of the WTGs proportionally to the measured lateral tower acceleration. A dynamic range compression algorithm ensures that control signals are within a range (ΔPmax) chosen during design. The lateral direction (also called crosswind) refers to a direction that is perpendicular to the wind direction. Therefore, considering a WPP, each WTG may vary its active power in order to damp the tower oscillations. Each individual power signal is then aggregated at the PCC 102 and then delivered into the grid, as illustrated in FIG. 1.

Knowing that the vibration controller offset may be bound to a tunable maximum peak level, a straightforward approach to evaluate the expected power oscillations at the PCC would be to multiply the maximum power offset with a number of turbines of a WPP 100, per the following equation:

$$GridDisturbance = \Delta Pmax * NWTGs$$

where NWTGs is the number of wind turbine generators. However, for this equation to hold true, the individual vibration controllers of each WTG may have to be saturated and in phase, which is an unlikely scenario. In reality, the probability of high wind/wave direction misalignment (i.e. >60°) in the WPP lifetime may be approximately fifteen percent and dependent on the local climate and sea currents. There may be coherency between wave periods and wave heights hitting turbines within a wind farm. However, coherency is not expected between the phases of wave-induced tower excitations between different turbines due to the very large spacing between the turbines when the wave frequencies are close to the tower natural frequency. Moreover, variations in wake effects and turbulence within the WPP induce differences in the average rotor wind speed felt by each turbine of the WPP, making both the operating point and the oscillation levels different. Even assuming perfect towers and foundations production (i.e. zero tolerance), differences in soil, water depth and seabed movements will induce variations to the tower oscillation frequency. Since the manufacturing tolerances are not zero, there is a

significant probability that each turbine in a WPP is oscillating at its own natural frequency which is not exactly equal to any other.

The cancellation effect at the PCC 102 may be dependent on the tuning of the control feature of the vibration controller and the number of turbines installed. The feedback loop gain maps proportionally, with saturation, the measured lateral acceleration into the allowed power variation range.

Given the complexity and the variety of factors impacting power generated by WTGs as described, aspects of the present disclosure use a Monte Carlo simulation to obtain an estimate of the power quality at the PCC. The Monte Carlo simulation may be performed using a variety of parameters. For example, vibration controllers may be tuned for a peak power oscillation amplitude (e.g., of 200kW), which may be the right trade-off for lateral tower damping. For the sake of conservativeness, vibration controller activation strategy may be tuned with high gain to favor the use of power in the worst turbine operating points. Moreover, PCC power quality metrics may depend on a climate in which the WPP is to operate as illustrated in FIGs. 2-4, which may be taken into account by the Monte Carlo simulation.

FIG. 2 is a graph 200 of the maximum discrete Fourier transform (DFT) peak of the vibration controller power offset in a neighborhood of a WTG tower's natural frequency. The graph 200 provides a one minute average control action for different wave directions (e.g., wind/wave misalignment) as a function of average rotor wind for an example WTG. FIG. 3 is a graph 300 of the maximum DFT peak of a grid active power at a WTG tower's natural frequency. As illustrated by graphs 200 and 300, wave directions with respect to wind direction influence the lateral acceleration levels and thereby the vibration controller control action. The tower frequency of the example WTG evaluated in FIGs. 2 and 3 is about 0.26Hz, meaning that over one minute, the vibration controller action is averaged over approximately fifteen oscillation periods. The actual grid power delivered by a turbine is based on the sum of the individual contribution of the vibration controllers to other internal control

features devoted to speed control, as may be realized by comparing FIG. 2 and FIG. 3, the latter being representative of the final power delivered by a single WTG.

FIG. 4 is a graph 400 of the maximum DFT grid power around tower frequency as compared to a reference WTG operated without vibration controllers. As compared to the reference data points, the vibration controller feature doubles the average DFT peak in the worst misaligned case. The reference turbine data points (not operated with a vibration controller) exhibit power oscillations at the tower frequency when operating in sea waves misaligned from the wind direction.

Although a WTG is not expected to run at high wind/wave misalignments for a significant portion of its lifetime, the worst misalignment (90° misalignment) may be combined with the worst average wind speed to represent the worst case for evaluating the power quality performance.

Following the expected coherency between wave period and wave heights, independent time traces, generated from the same wind and wave parameters but from different random seeds may be considered to be representative of single WTG active power trajectories. Thus, summing these independent time traces may be a reasonable and conservative approach to calculate the harmonic effects on a WPP level. Summing an arbitrary set of time series leads to a realization of the underlying stochastic process to determine the power at the PCC 102. This is considered to be conservative from an aero elastic point of view, as the time series aggregated do not include any wake effect nor any difference in foundation stiffness due to soil conditions.

In certain aspects, an aero elastic simulator may be used to generate a number of different seeds (e.g., 805 seeds) for wind and wave time series. For example, forty different simulations may be ran for positive and negative relative wind direction of six degrees and for wave/wind misalignment of zero, thirty and ninety degrees.

FIG. 5A is a graph 500 of power oscillations of a WTG in a worst case scenario where the effects of misalignment between wind and wave direction (e.g., ninety degree misalignment) may lead to the worst lateral oscillations. FIG. 5B is a graph 502 of power oscillations of the WTG having the same configurations as the WTG used to generate the power oscillations of FIG. 5A, but with wind and wave directions aligned. As illustrated, the peak power of a WTG with aligned wind and wave directions is greatly reduced. However, the likelihood that every WTG of a WPP experiencing the worst case scenario depicted in FIG. 5A is low.

FIG. 6 illustrates randomly chosen realizations of the active power produced by WTGs in a WPP in the frequency and time domain with waves hitting a respective tower of the WTGs at ninety degrees. The graphs are generated based on ten meters per second (m/s) average winds over a ten minute time period. To illustrate power oscillations at the PCC, the active power produced by five turbines is simulated for a one minute time period. That is, five random seeds are chosen, at the same average wind speed and from the same aero elastic run. Moreover, a simulation of each WTG may be ran for a ten minute time interval, from which an arbitrary (e.g., random) one minute window may be extracted for each of the five turbines. Each of the extractions for each WTG is illustrated in graph 602 in the time domain, and graph 604 in the frequency domain.

After aligning the time series of each extraction for each of the WTGs, the aggregate power of the WTGs at the PCC may be simulated. Graphs 606 and 608 depict the active grid power at the PCC delivered by the five turbines during the one minute interval in the time and frequency domain, respectively. Being that the power at the PCC is the sum in time of the power produced individually, the expected PCC power is the summation of the chosen power trajectories, in accordance with the following equation:

$$PCC(k) = \sum_{i=1}^{nTurbines} Power_i(k)$$

FIG. 7 illustrates randomly chosen realizations of the active power produced by WTGs in a WPP in the frequency and time domain with waves hitting a respective tower of the WTGs at thirty degrees. FIG. 7 includes graphs 702 and 704 of one minute window extractions (e.g., from a ten minute simulation of the output power of a WTG) for each WTG in the time and frequency domain, respectively. Graphs 706 and 708 depict the active grid power at the PCC delivered by the five turbines during the one minute interval in the time and frequency domain, respectively. Comparing FIG. 6 with FIG. 7, it can be seen how the instantaneous behavior of the power at the PCC may be dependent on the current power levels of the turbines and their operating points.

An example power quality metric generated based on a Monte Carlo simulation in accordance with aspects of the present disclosure may analyze a peak power at the PCC within a frequency band 610 of interest. Frequency band 610 may be determined based on a grid code. For example, it may not be allowed for the power at the point of connection with the grid to oscillate with harmonics within a certain frequency range (e.g. 0.1Hz – 0.2Hz). This may be to avoid resonating other machines connected to grid. Thereby, it may be important to devise quality metrics able to capture this concern and extrapolate the plant level cancellation. Quality metrics can be evaluated as absolute terms or related to the registered or available capacity. Registered capacity may be the maximum power production capability a WPP may be allowed to output, which may be fixed. Available capacity is the currently maximum achievable power production given the current wind speed, which varies with time. Power oscillations may reduce quadratically as a function of WPP size.

In the time domain, certain power quality metrics may be generated to evaluate power at the PCC. For example, standard deviation of a power signal at the PCC within a time window may be calculated using the following equation:

$$PPCstd = std(X(t)),\ t=0\ldots t_{max}$$

Using standard deviation is simple to implement, however, may not be selective in frequency and may depend on the length of the observation window. Other quality metrics may include peak-to-peak amplitude after bandpass filtering the power in a time window. This is also simple to implement, however, may be dependent on band pass filter implementation, length of the observation window, and may not link directly to the resonance problem (e.g., power limits within a band width corresponding to the resonant frequency of a WTG). Using a standard deviation after band pass filtering the power in a time window may be selective in frequency, but may have the same issues as using the peak-to-peak amplitude quality metric.

Certain quality metrics may be implemented in the frequency domain. These may include an amplitude spectrum obtained via a DFT to extract the maximum peak amplitude within a frequency band, in accordance with the following equation:

$$DFTpeak_{[f_{min},\ f_{max}]} = \max_{f \in [f_{min},\ f_{max}]} (|X(f)|)$$

where $X(f)=\mathcal{F}\{x(t)\}$ represents the DFT. This approach is simple to implement, selective in frequency, and captures the averaging effect due to the oscillation of turbines at slightly different frequencies. However, this approach may be dependent on the frequency resolution, dependent on averaging methods and observation windows, dependent on any windowing used, and may not be a unique measure from the same data. That is, performing the calculations for this quality metric with different DFT points or different calculation tools (e.g., Matlab) might lead to different results.

Moreover, while an amplitude DFT may be used, an amplitude DFT depends on the frequency resolution. Running a DFT on the same dataset but with different frequency resolutions might lead to a wrong estimation of the amplitude of a harmonic.

Another option may be to use a power spectrum density (PSD) (e.g., via Periodogram) to compute the average power within a frequency band of interest, using, for example, the following equation:

$$PSDrange_{[f_{min},\ f_{max}]} = \frac{1}{C}\sum_{f=f_{min}}^{f_{max}} |X(f)|^2$$

where $(f)=\mathcal{F}\{x(t)\}$ represents the discrete Fourier transform and C is a normalization factor function. This metric would be rather conservative as it gives a representation of the entire range of interest.

The metric could be further reworked to find the average power close to the maximum in the frequency band of interest, in accordance with the following equation:

$$PSDpeak_{[f_{min},\ f_{max}]} = \sum_{f=f_1}^{f_2} |X(f)|^2$$

where f_1 and f_2 are a narrow band around $\max_{f\in[fmin,fmax,]}|X(f)|^2$. This approach may result in a more robust and conservative quality metric when compared to its corresponding DFT counterpart. The two metrics defined could be further combined into a measure of power concentration in accordance with the following equation:

$$PSDrangePeakConcentration_{[f_{min},\ f_{max}]} = \frac{PSDpeak_{[f_{min},\ f_{max}]}}{PSDrange_{[f_{min},\ f_{max}]}} \begin{cases} \to 1, the\ power\ is\ concentrated\ all\ around\ the\ peak \\ \to 0, the\ power\ is\ uniformly\ spread\ in\ the\ range \end{cases}$$

As the result of the ratio is contained between [0, 1], any intermediate result may be interpreted accordingly. The same quality metric could be implemented in the time domain using a band pass filter, however, with the drawback of depending on the filter design. This approach is selective in frequency, independent of frequency resolution (e.g., for sufficiently large frequency band), provides a unique solution (e.g., per the Perseval's theorem), may be linked to the resonance as it describes how much power is injected at a specific frequency, and is independent of the oscillation frequency distribution (e.g., the index on the aggregated power may not be influenced based on whether turbines oscillate at slightly different frequencies).

However, the normalization factors may be dependent on how the DFT is implemented (e.g., based on a fast Fourier Transform (FFT) algorithm).

As an example, system operator for North Ireland (SONI) grid code provides that the WTGs and the Wind Farm Controller shall not cause active power oscillations at the Wind Farm Connection Point in the frequency range 0.25Hz to 1.75Hz which exceed in peak-to-peak magnitude equivalent to 1% of the Registered Capacity. Using the techniques provided in the present disclosure, a WPP may be evaluated to determine compliance with this grid code. For example, the grid code can be verified by showing that the peak to peak variation $P(t)_{peak}-P(t)_{valley}$ in the range of frequencies of interest is below 1% of the registered capacity (P_0), in accordance with the following equation:

$$P(t)_{peak} - P(t)_{valley} \leq P_0 * 0.01 \xrightarrow{yields} 2P_1 \leq \frac{P_0}{100}$$

Thus, the grid code specification may be satisfied if the largest harmonic amplitude (P_1) in the band of interest satisfies the following equation:

$$P_1 \leq \frac{P_0}{200} \xrightarrow{yields} \frac{P_1}{P_0} \leq \frac{1}{200}$$

Consider now a signal composed of a pure harmonic of amplitude P_1 at frequency f_1. The power of the signal may be determined in accordance with the following equation:

$$P(t) = P_1 \cos(2\pi f_1 + \varphi_1)$$

Then the average "power" of P(t) may be defined as:

$$Power(P(t)) = RMS(P(t))^2 = f_1 \int_0^{1/f_1} P_1 \cos(2\pi f_1 + \varphi_1) = \frac{(P_1)^2}{2}$$

Replacing P_1 with the maximum amplitude for which the grid code specification is fulfilled, it can be determined whether the SONI grid code specification is fulfilled based on the following equation:

$$Power(P(t)) \leq \frac{\left(\frac{P_0}{200}\right)^2}{2} \xrightarrow{yields} \frac{Power(P(t))}{(P_0)^2} \leq \frac{1}{80000}$$

Numerical examples may be used to further explain and verify this concept. Assume a simple signal:

$$P(t) = P_1 \cos(2\pi f_1 + \varphi_1)$$

Considering a grid code similar to the SONI grid code which provides that P(t) shall not contain any peak-to-peak oscillation magnitude equivalent to 1% of a P_0 value in a range of frequencies $f_1 \pm 10\%$. Where for convenience $P_0=1$ and the frequency and phase f_1, φ_1 are chosen arbitrarily.

Then the following cases can be explored to determine whether, for each case, the grid code specification are met. For example, where $P_1=0.01$, the grid code specification is not fulfilled as determined based on the following equation in the DFT domain:

$$\frac{P_1}{P_0} = \frac{0.1}{1} = 0.1 > \frac{1}{200}$$

and based on the following equation in the PSD domain:

$$\frac{Power(P(t))}{(P_0)^2} = \frac{\frac{0.1^2}{2}}{1} = 0.005 > \frac{1}{80000}$$

However, where $P_1=0.005$, the grid code specification is fulfilled per the following equation in the DFT domain:

$$\frac{P_1}{P_0} = \frac{0.005}{1} = 0.005 = \frac{1}{200}$$

and in the PSD domain per the following equation:

$$\frac{Power(P(t))}{(P_0)^2} = \frac{\frac{0.005^2}{2}}{1} = 1.2500e^{-5} = \frac{1}{80000}$$

As another example, where P_1=0.0025, the grid code specification is fulfilled per the following equation in the DFT domain:

$$\frac{P_1}{P_0} = \frac{0.0025}{1} = 0.0025 < \frac{1}{200}$$

and per the following equation in the PSD domain:

$$\frac{Power(P(t))}{(P_0)^2} = \frac{\frac{0.0025^2}{2}}{1} = 3.1250e^{-6} = \frac{1}{80000}$$

The parameters and techniques for generating a quality metric to determine compliance of a WTG (e.g., with respect to a grid code) may be applied to a Monte Carlo type simulation, as described with respect to the following flow diagram.

FIG. 8 illustrates example operations 800 for evaluating electrical characteristics at a point of common coupling (PCC) of a plurality of wind turbine generators (WTG) of a wind power plant (WPP), in accordance with aspects of the present disclosure. The operations 800 may be performed, for example, by a processor.

The operations 800 begin, at 802, by obtaining a plurality of simulation results of an electrical characteristic of a WTG. At 804, the operations continue by aggregating the plurality of simulation results, and at 806, evaluating compliance of the WPP based on the aggregation, e.g. evaluating the compliance of a WPP with a

grid code. In some cases, the WTG for which the plurality of simulation results are obtained may correspond to a WTG of the WPP associated with the evaluation. In certain aspects, each of the simulation results correspond to a realization of a stochastic model of the electrical characteristic. For example, each of the simulation results may correspond to a random seed (e.g., which may be selected based on random integer value) used to generate the simulation results. In some cases, each of the simulation results correspond to a random time segment within a time period used to generate the simulation results. The operations 800 may be visualized using a heat map as illustrated in FIG. 9.

FIG. 9A is an example heat map 900 illustrating simulations used to evaluate compliance of a WPP, in accordance with certain aspects of the present disclosure. As illustrated, the simulations represented in the heat map of FIG. 9 are run for a time period of 600 seconds and across a range 80 random seeds. The shade of each pixel is a function of the grid power at a time sample for a random seed (e.g., an aero elastic simulator seed) used to generate the simulation results.

The Monte Carlo method of the present disclosure extracts a number of simulation results from the simulation results represented in the heat map of FIG. 9. For example, an extractions of the simulation results may be made at a random value of the random seed (e.g., an aero elastic simulator seed) and at a random time segment within the 600 second time period of the simulations results (e.g., a random integer may be used as a starting point for extraction of the simulation results). Each of the values of the random seed (e.g., selected at random) may provide a different realization of the grid power. For example, using an aero elastic simulation tool, a simulation of wind or sea waves may be generated by adding coherency to a random signal generated from the random seed. Therefore, different random seeds may provide different realizations of a signal (e.g., representing wind or sea waves), which may be used to generate the simulation results. In certain aspects, a random integer may be used to determine whether or not to reverse a time series of the extraction for extra randomness. In some cases, the sign of the power oscillations may be reversed for extra randomness.

The extractions may be repeated (e.g., at a random seed and time segment) for each WTG of a WPP under evaluation (e.g., seven WTGs in the example of FIG. 9, represented by the blocks labeled 1 through 7). As illustrated in FIG. 9B, the extractions of the simulation results for each of the WTGs may be aggregated. That is, the time series extracted for each of the WTGs may be aligned and summed in time.

The aggregate of the time series may be used to calculate a quality metric to evaluate the compliance of the WPP. In certain aspects, this method may be repeated to generate a plurality of quality metrics, until the mean of the quality metrics converges. That is, the quality metrics may be derived until a ratio of change of the mean of the quality metrics across two consecutive Monte Carlo iterations is below a tolerance threshold, in accordance with the following equation:

$$\frac{MEAN\,(QualityMet\ ric(1:Iter-1)-MEAN\,(QualityMet\ ric(1:Iter))}{MEAN\,(QualityMet\ ric(1:Iter))} \leq Tolerance$$

FIG. 10 is a graph 1000 of an example quality metric (e.g., average peak power at PPC) corresponding to WPPs of different sizes, in accordance with certain aspects of the present disclosure. As illustrated, while the mean of the quality metric may have wide variations at first (e.g., before the first 100 iterations), the mean of the quality metric eventually diverges to a value, which may be used to determine the compliance of a respective WPP. For example, once a quality metric has converged, the quality metric may be used to determine the compliance of a WPP with a grid code. The Monte Carlo method of the present disclosure may be used for calculations of different scenarios or probability distributions as desired. The method could be extended to include bootstrapping algorithms if estimates of standard errors and confidence intervals of complex parameters of the resulting Monte Carlo distribution, such as percentile points, proportions, odds ratio, and correlation coefficients are desirable.

In the preceding, reference is made to aspects presented in this disclosure. However, the scope of the present disclosure is not limited to specific described

aspects. Instead, any combination of the preceding features and elements, whether related to different aspects or not, is contemplated to implement and practice contemplated aspects. Furthermore, although aspects disclosed herein may achieve advantages over other possible solutions or over the prior art, whether or not a particular advantage is achieved by a given aspect is not limiting of the scope of the present disclosure. Thus, the preceding aspects, features, and advantages are merely illustrative and are not considered elements or limitations of the appended claims except where explicitly recited in a claim(s). Likewise, reference to "the invention" shall not be construed as a generalization of any inventive subject matter disclosed herein and shall not be considered to be an element or limitation of the appended claims except where explicitly recited in a claim(s).

As will be appreciated by one skilled in the art, the aspects disclosed herein may be embodied as a system, method, or computer program product. Accordingly, aspects may take the form of an entirely hardware aspect, an entirely software aspect (including firmware, resident software, micro-code, etc.) or an aspect combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module," or "system." Furthermore, aspects may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied thereon. Program code embodied on a computer readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

Aspects of the present disclosure are described above with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to aspects presented in this disclosure. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other devices to

function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

The flowchart and block diagrams in the figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various aspects. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

In view of the foregoing, the scope of the present disclosure is determined by the claims that follow.

CLAIMS

1. A method of evaluating electrical characteristics at a point of common coupling, PCC, of a plurality of wind turbine generators, WTG, of a wind power plant, WPP, the method comprising:

obtaining a plurality of simulation results of an electrical characteristic of a WTG;

aggregating the plurality of simulation results; and

evaluating compliance of the WPP based on the aggregation, wherein each of the simulation results of the electrical characteristic of the WTG is generated based on a stochastic realization of one or more parameters.

2. The method of claim 1, wherein each of the simulation results correspond to a random time segment within a time period used to generate the simulation results.

3. The method of claim 1 or 2, further comprising generating a quality metric based on the aggregated simulation results, wherein the evaluation is based on the quality metric.

4. The method of claim 3, wherein simulation results are obtained and aggregated to generate quality metrics until a mean of the quality metrics converge.

5. The method of claim 3 or 4, wherein the quality metric corresponds to voltage or power oscillations at the PCC within a frequency band.

6. The method of claim 5, wherein the frequency band is determined based on a grid code.

7. The method of any of claims 3 to 6, further comprising reversing a time series of at least one of the simulation results prior to generating the quality metric.

8. The method of any of claims 1 to 7, wherein a number of simulation results obtained corresponds to a number of WTGs of the WPP under evaluations.

9. The method of any of claims 1 to 8, wherein the stochastic realization of the one or more parameters are based on a random seed.

10. The method of claim 9, wherein an average value of a parameter of the one or more parameters is the same across the plurality of simulation results.

11. The method of claim 9 or 10, further comprising generating a random integer number, wherein the random seed is selected based on the random integer number.

12. An apparatus for evaluating electrical characteristics at a point of common coupling, PCC, of a plurality of wind turbine generators, WTG, of a wind power plant, WPP, the apparatus comprising:

a processing system configured to:

obtain a plurality of simulation results of an electrical characteristic of a WTG;

aggregate the plurality of simulation results; and

evaluate compliance of the WPP based on the aggregation, wherein each of the simulation results of the electrical characteristic of the WTG is generated based on a stochastic realization of one or more parameters.

13. The apparatus of claim 12, wherein each of the simulation results correspond to a random time segment within a time period used to generate the simulation results.

14. The apparatus of claim 12 or 13, wherein the processing system is further configured to generate a quality metric based on the aggregated simulation results, wherein the evaluation is based on the quality metric, and wherein the quality metric corresponds to voltage or power oscillations at the PCC within a frequency band.

15. The apparatus of any of claims 12 to 14, wherein the stochastic realization of the one or more parameters are based on a random seed.

16. A computer program product for wireless communications comprising a computer readable medium having instructions stored thereon, the instructions executable by one or more processors for carrying out a method according to any of claims 1 to 11.

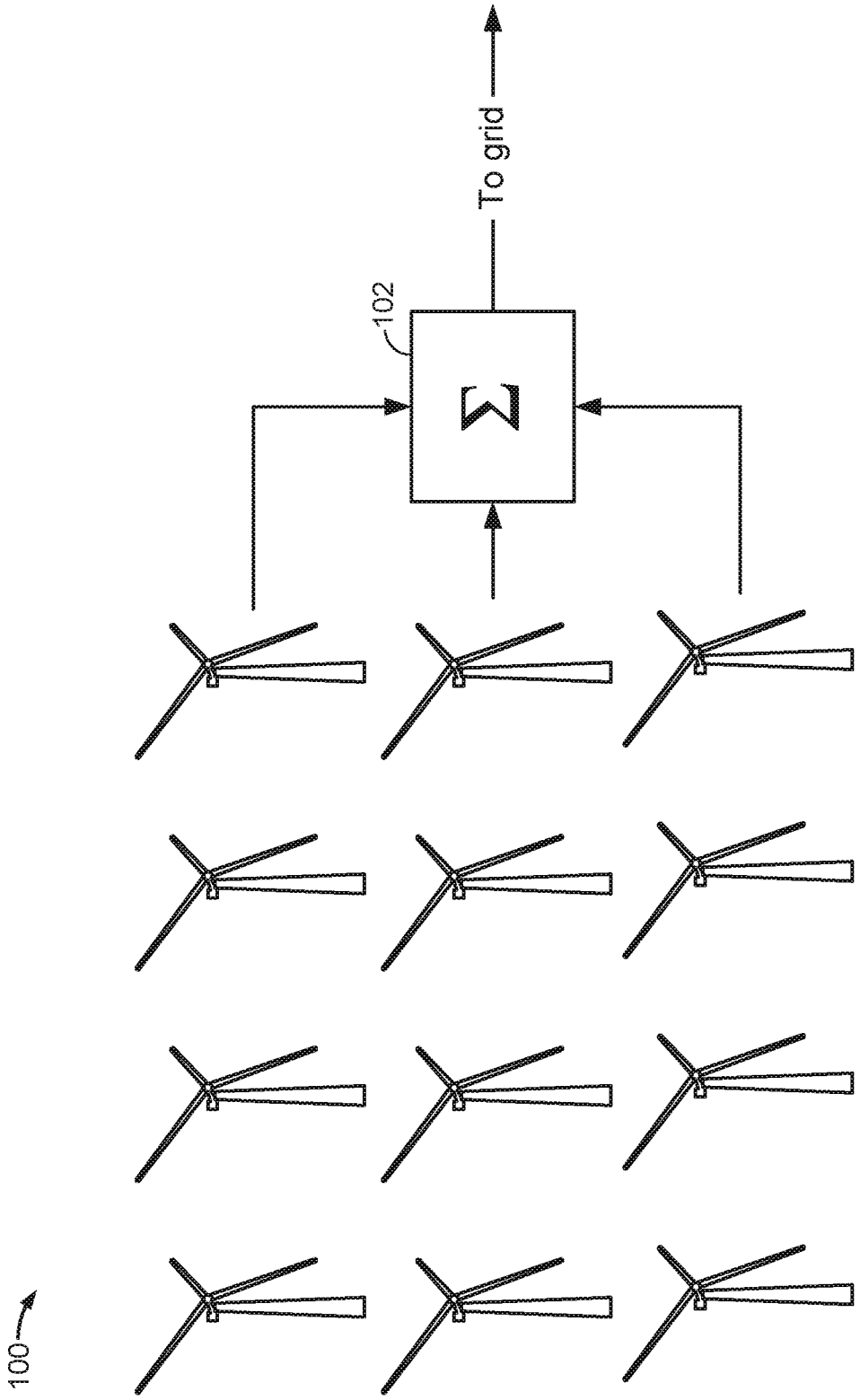


FIG. 1

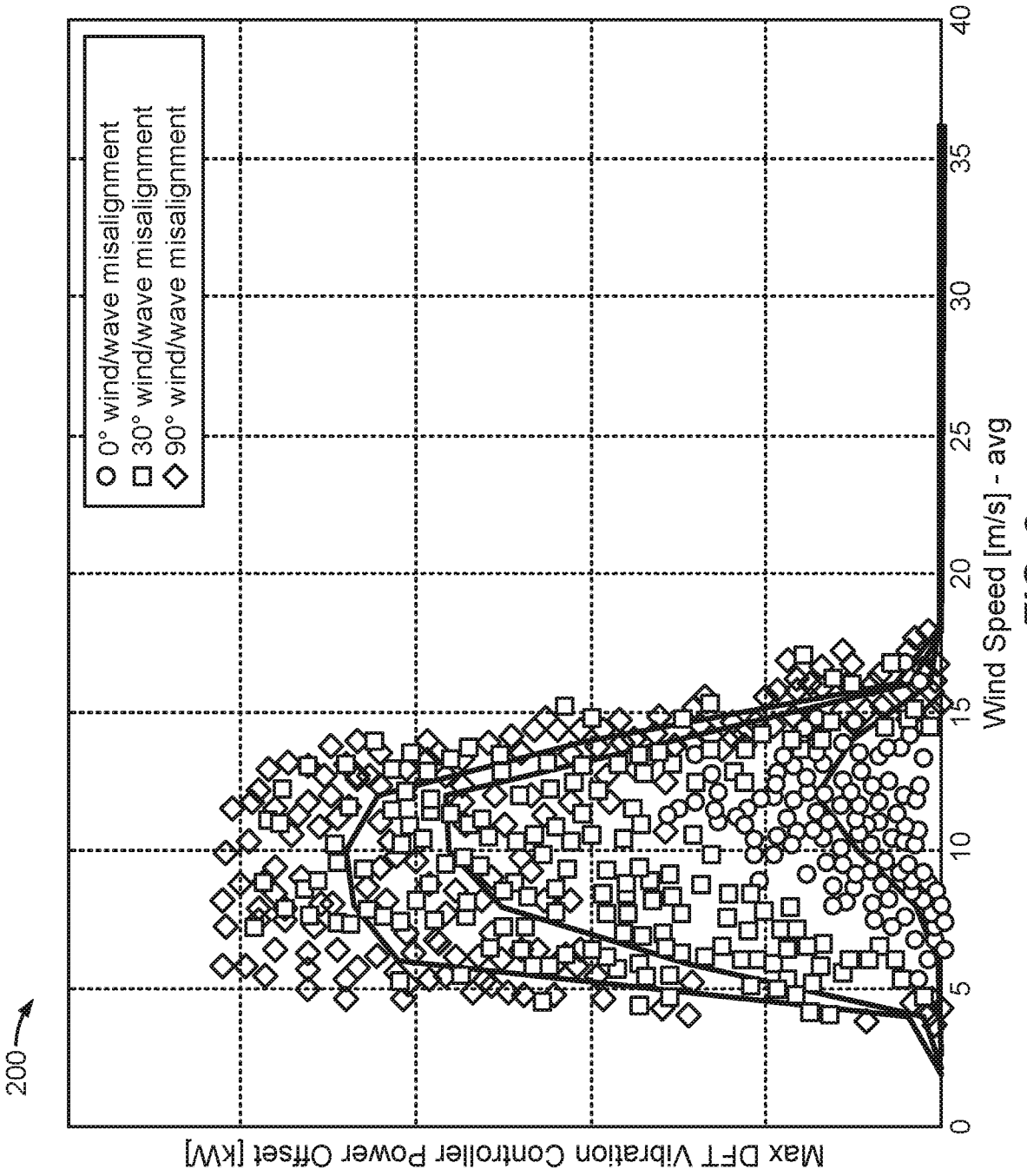

200
0° wind/wave misalignment
30° wind/wave misalignment
90° wind/wave misalignment
Max DFT Vibration Controller Power Offset [kW]
Wind Speed [m/s] - avg
0
5
10
15
20
25
30
35
40

FIG. 2

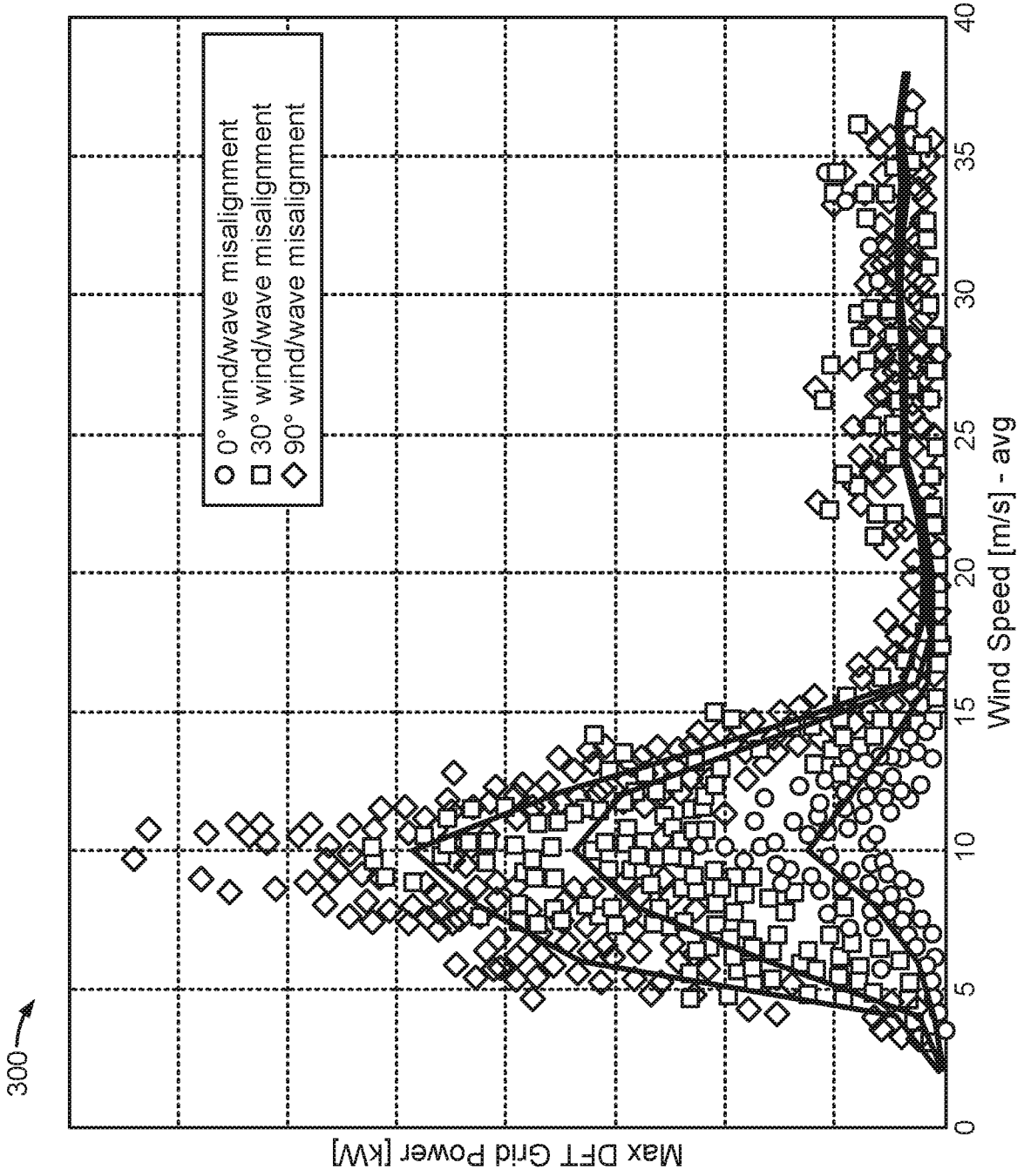

300
0° wind/wave misalignment
30° wind/wave misalignment
90° wind/wave misalignment
Max DFT Grid Power [kW]
Wind Speed [m/s] - avg
0
5
10
15
20
25
30
35
40

FIG. 3

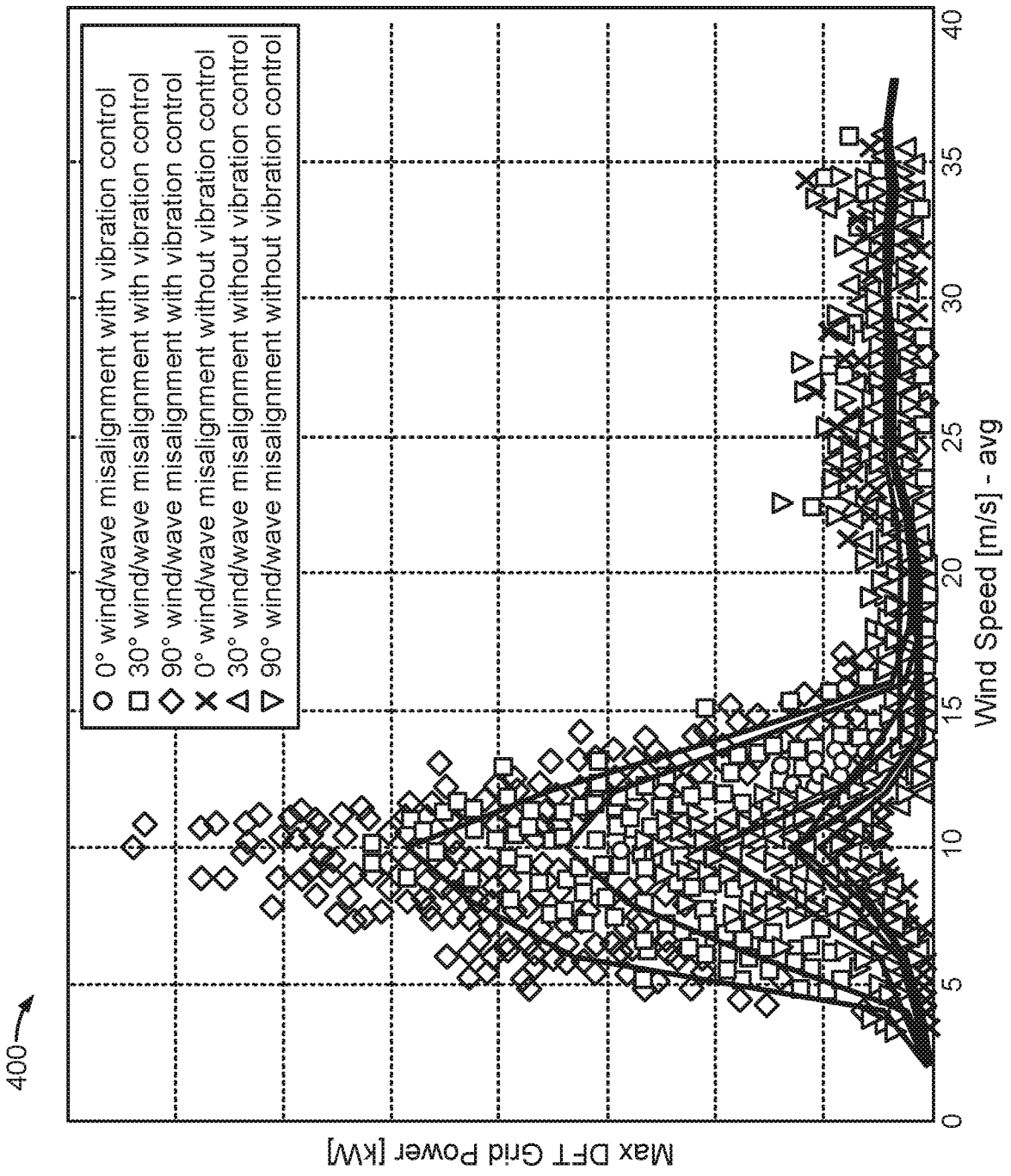

400
0° wind/wave misalignment with vibration control
30° wind/wave misalignment with vibration control
90° wind/wave misalignment with vibration control
0° wind/wave misalignment without vibration control
30° wind/wave misalignment without vibration control
90° wind/wave misalignment without vibration control
Max DFT Grid Power [kW]
Wind Speed [m/s] - avg
0
5
10
15
20
25
30
35
40

FIG. 4

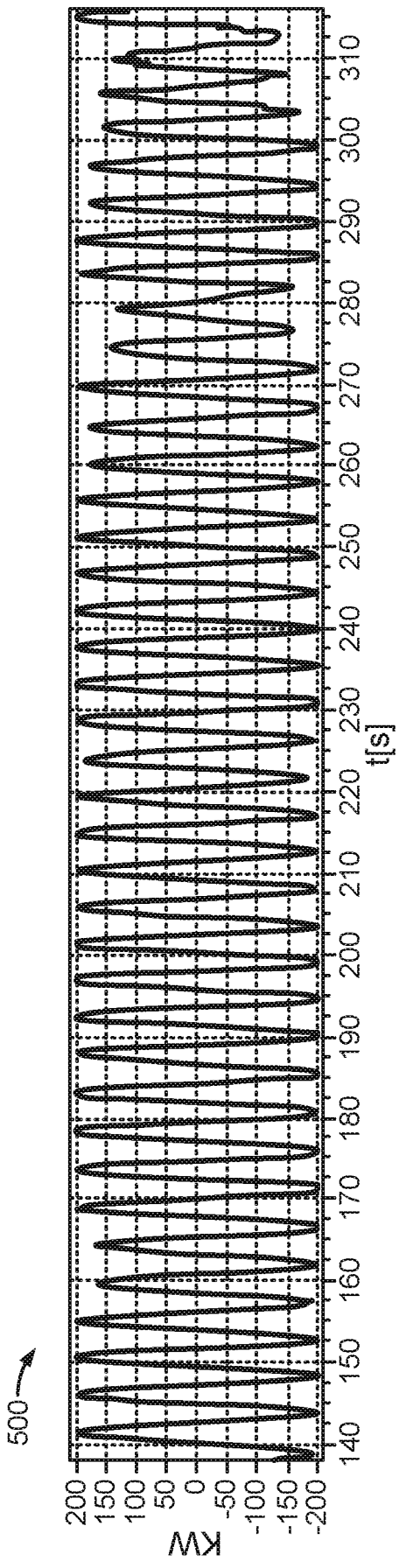

500
KW
200
150
100
50
0
-50
-100
-150
-200
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
t[s]

FIG. 5A

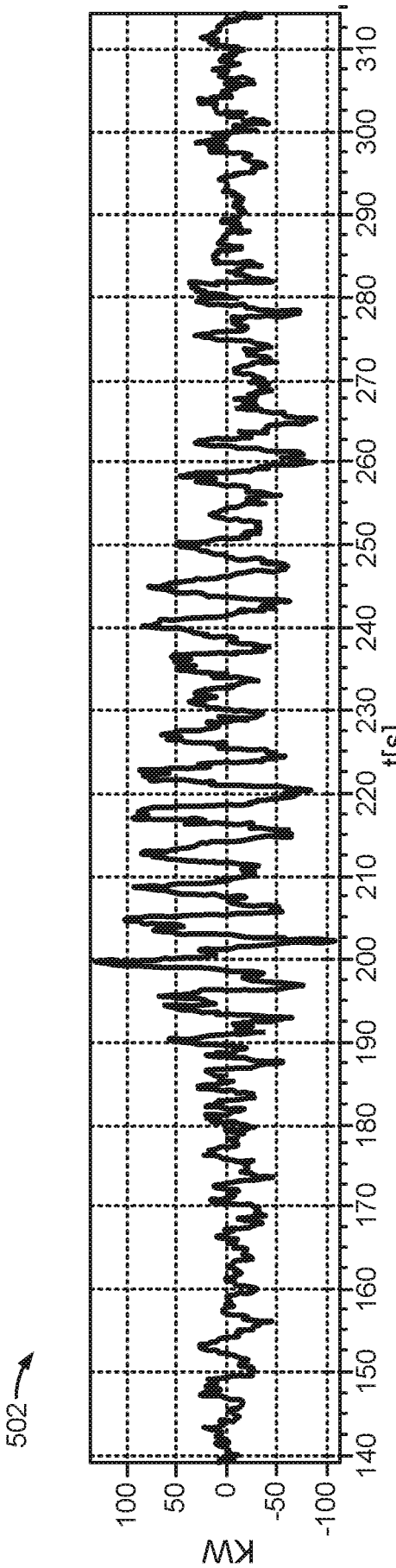

502
KW
100
50
0
-50
-100
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
t[s]

FIG. 5B

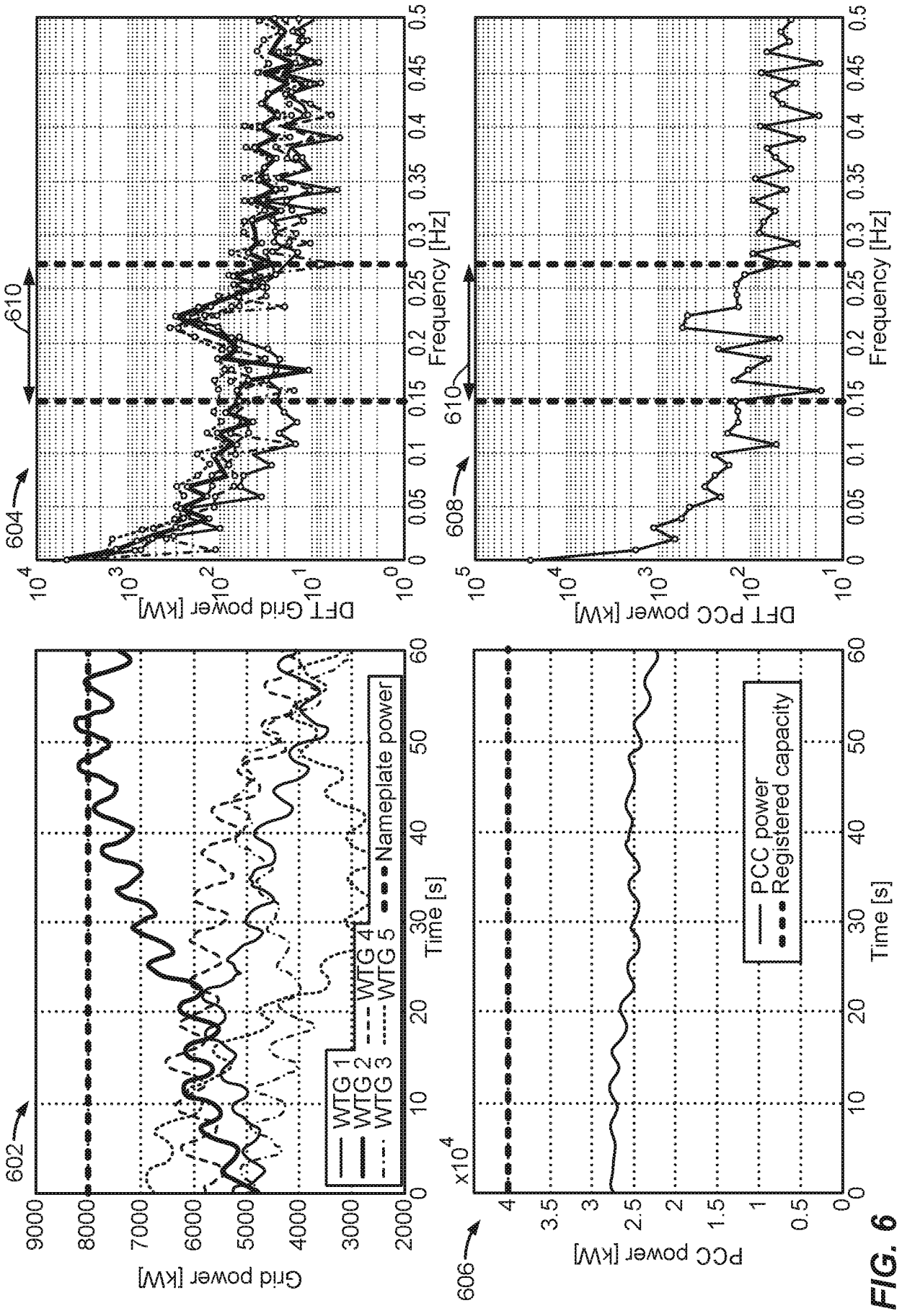

602
Grid power [kW]
Time [s]
WTG 1
WTG 2
WTG 3
WTG 4
WTG 5
Nameplate power
604
DFT Grid power [kW]
Frequency [Hz]
606
PCC power [kW]
Time [s]
PCC power
Registered capacity
608
DFT PCC power [kW]
Frequency [Hz]
610

FIG. 6

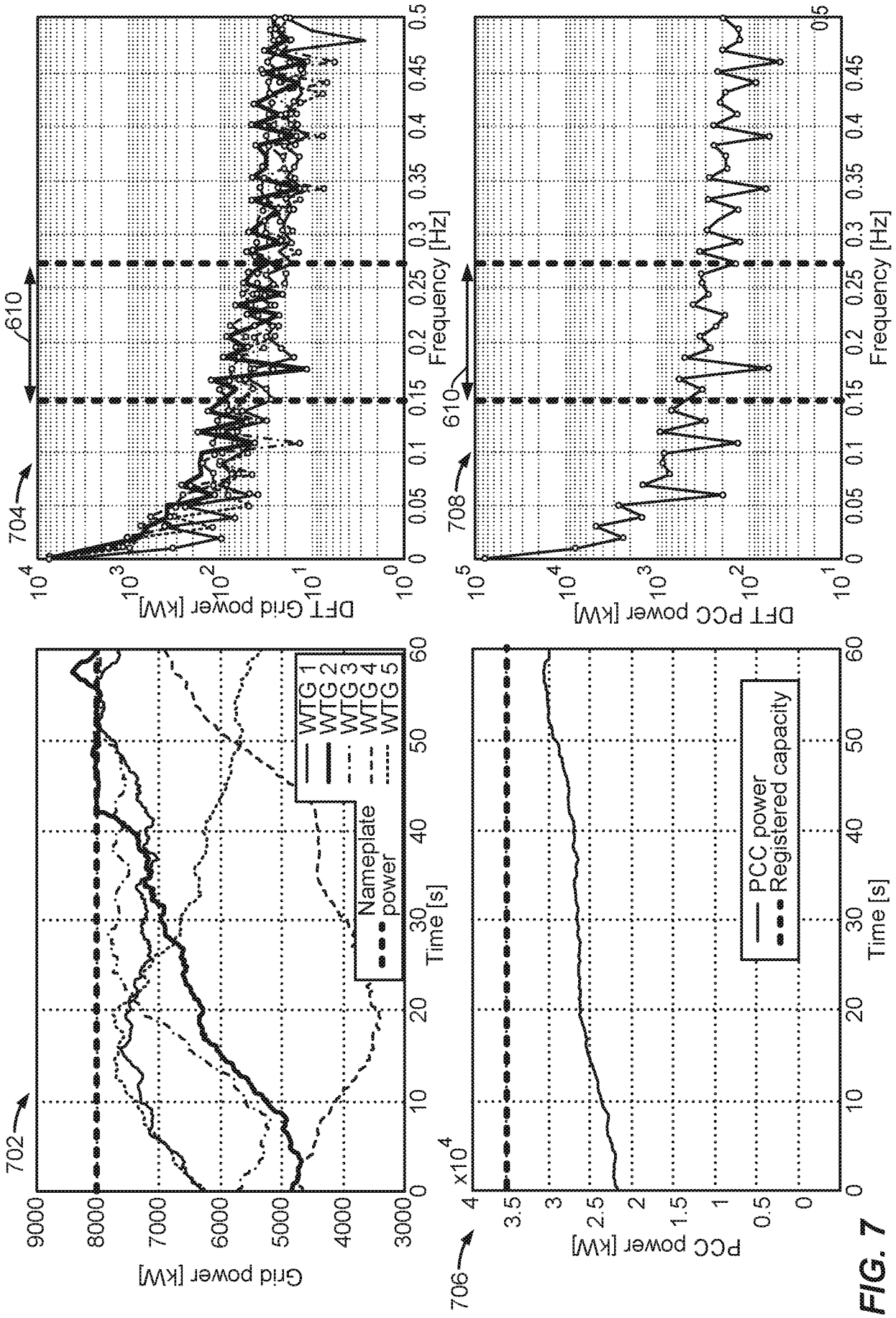

702
Grid power [kW]
Time [s]
WTG 1
WTG 2
WTG 3
WTG 4
WTG 5
Nameplate power
706
PCC power [kW]
x10^4
PCC power
Registered capacity
704
DFT Grid power [kW]
Frequency [Hz]
610
708
DFT PCC power [kW]
Frequency [Hz]
610

FIG. 7

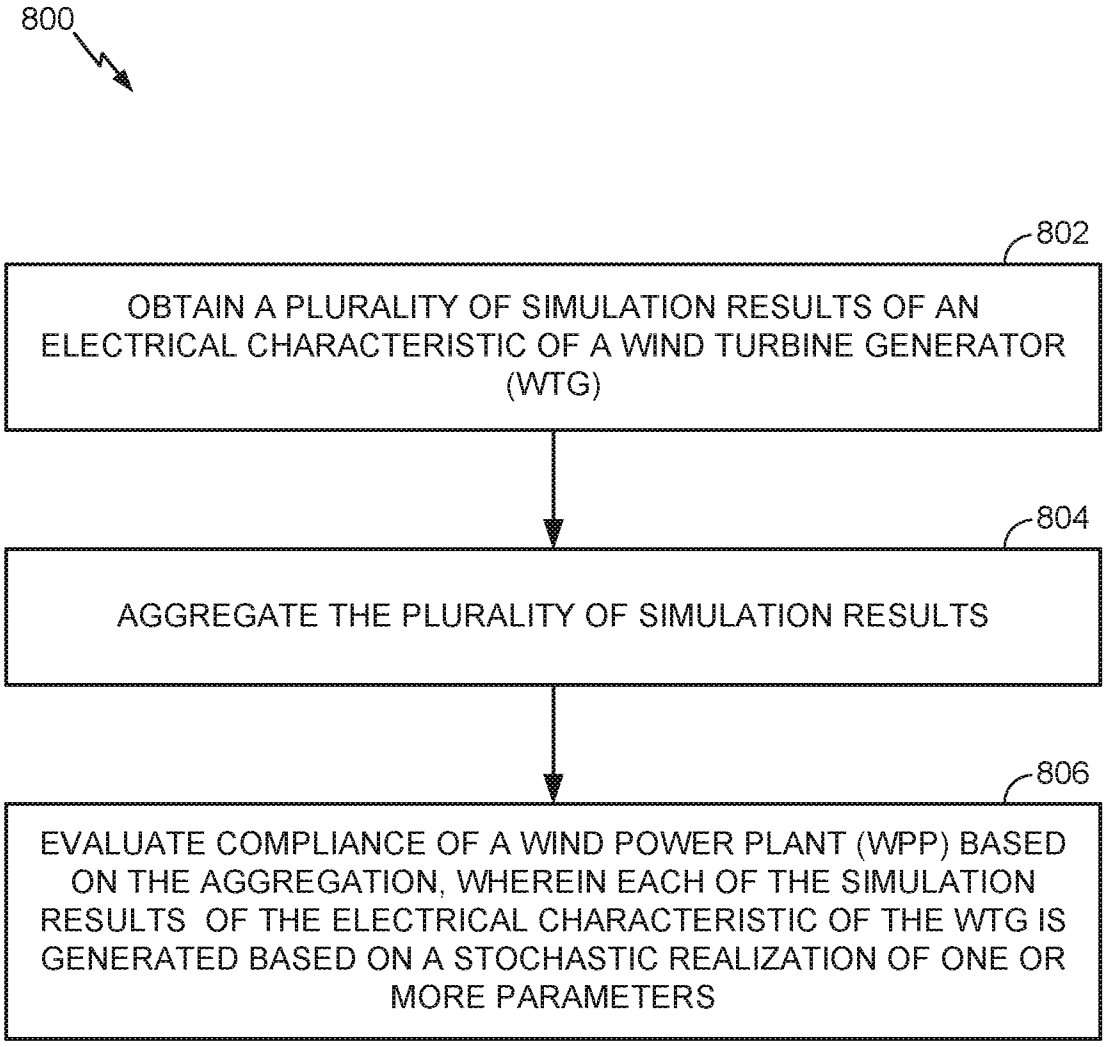

800
802
OBTAIN A PLURALITY OF SIMULATION RESULTS OF AN ELECTRICAL CHARACTERISTIC OF A WIND TURBINE GENERATOR (WTG)
804
AGGREGATE THE PLURALITY OF SIMULATION RESULTS
806
EVALUATE COMPLIANCE OF A WIND POWER PLANT (WPP) BASED ON THE AGGREGATION, WHEREIN EACH OF THE SIMULATION RESULTS OF THE ELECTRICAL CHARACTERISTIC OF THE WTG IS GENERATED BASED ON A STOCHASTIC REALIZATION OF ONE OR MORE PARAMETERS

FIG. 8

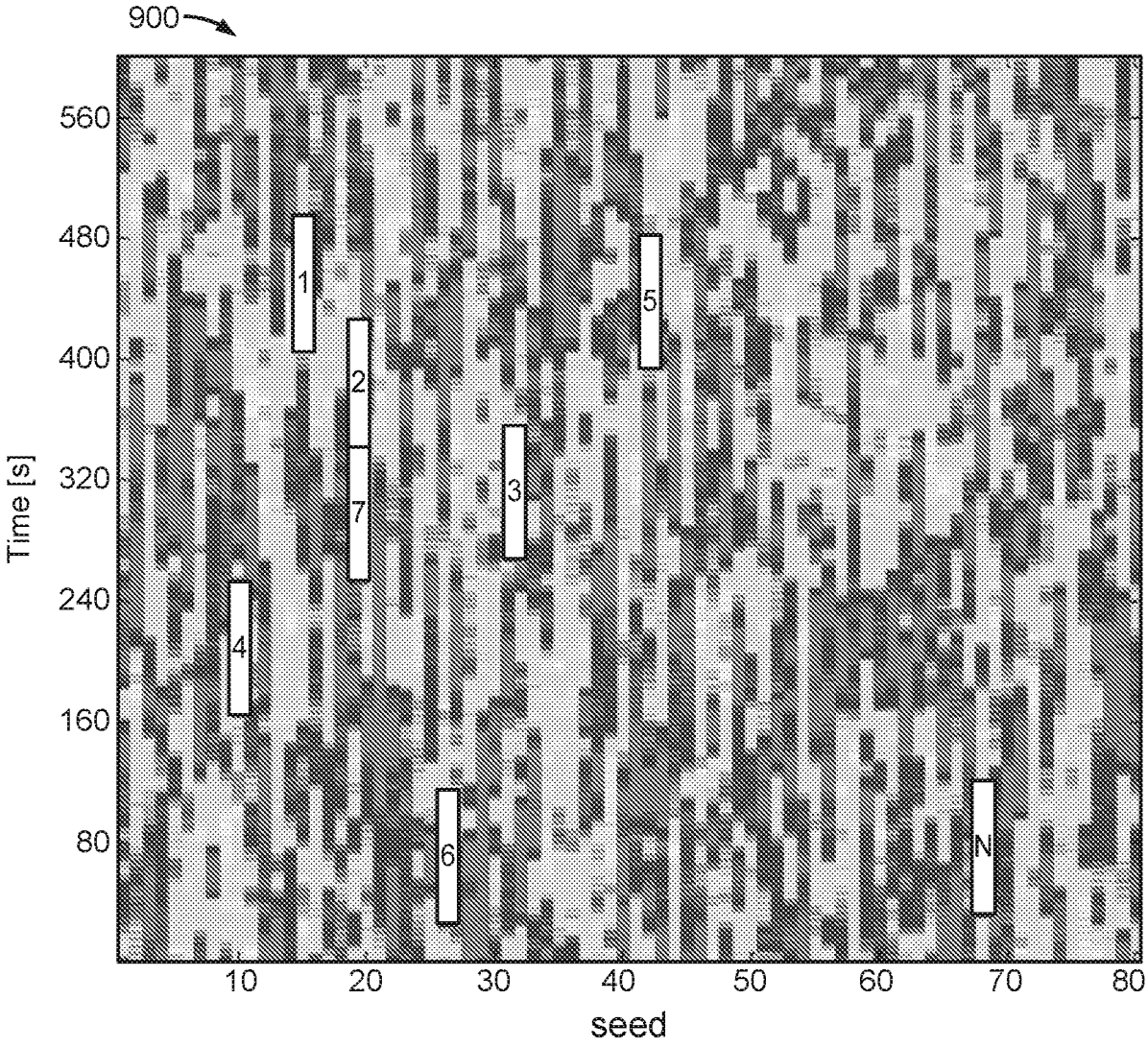
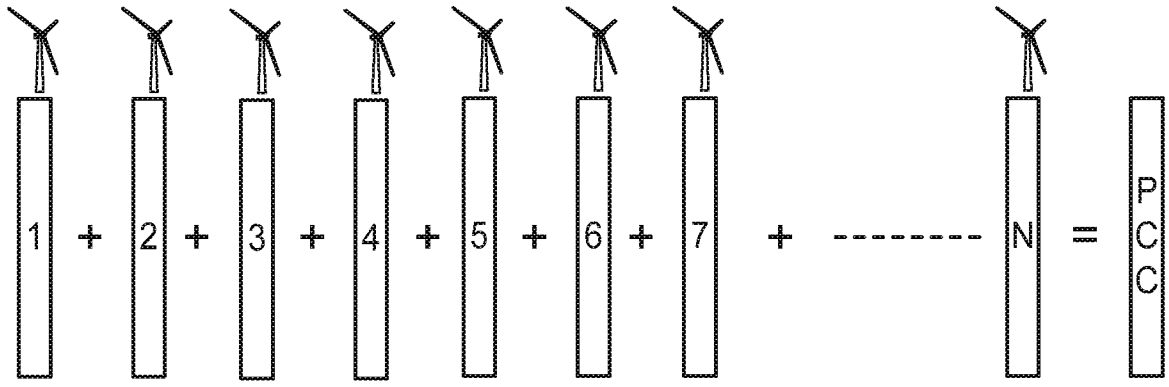

900
560
480
400
320
240
160
80
Time [s]
10
20
30
40
50
60
70
80
seed
1
2
3
4
5
6
7
N

FIG. 9A


1
+
2
+
3
+
4
+
5
+
6
+
7
+

N
=
PCC

FIG. 9B

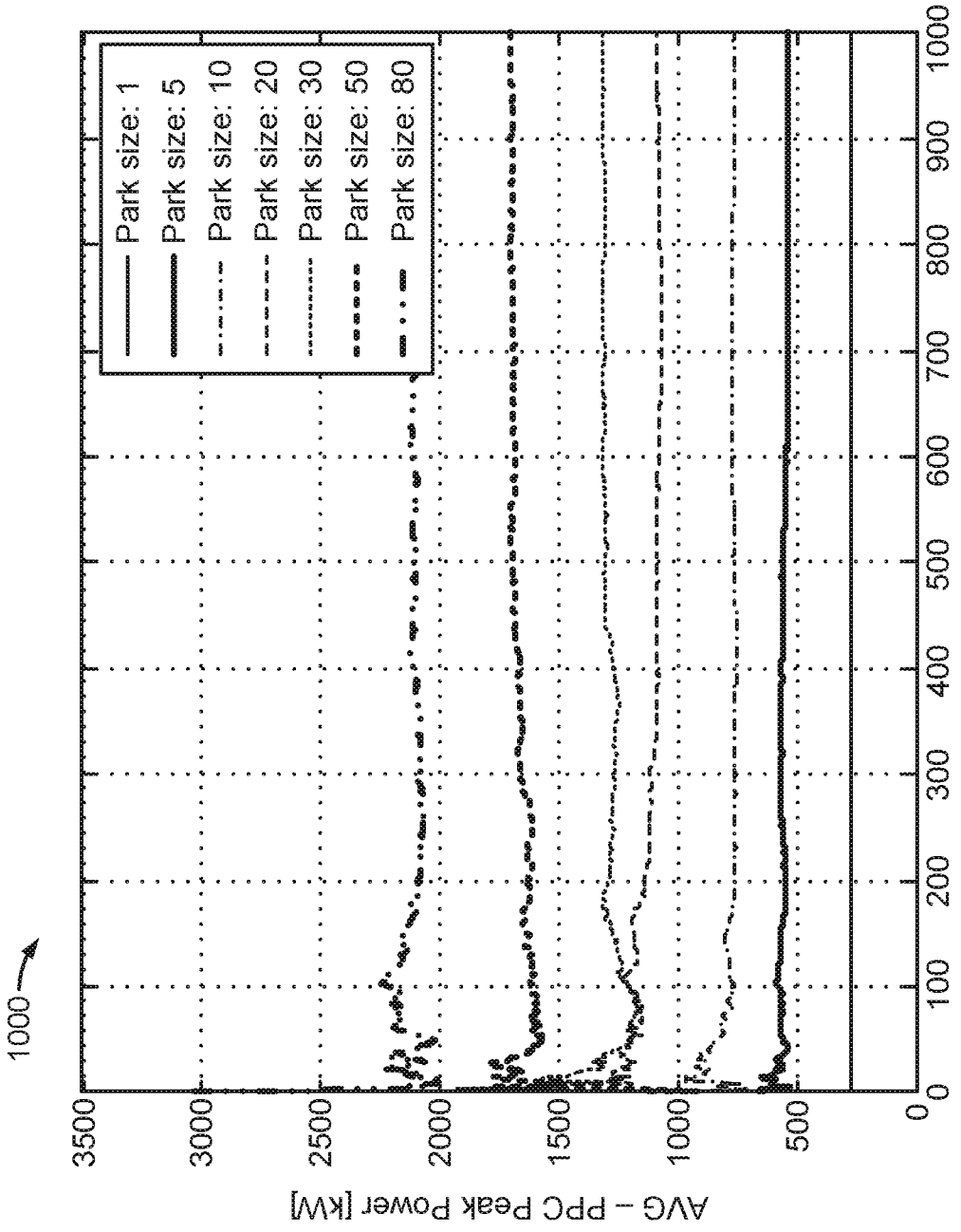

1000
Park size: 1
Park size: 5
Park size: 10
Park size: 20
Park size: 30
Park size: 50
Park size: 80
AVG – PPC Peak Power [kW]
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800
900
1000
Iteration n.

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2016/050422

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D17/00 F03D9/25
ADD. H02J3/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03D H02J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JIANG XIN ET AL: "Assessing the effect of wind power peaking characteristics on the maximum penetration level of wind power", IET GENERATION, TRANSMISSION&DISTRIBUTION, IET, UK, vol. 9, no. 16, 3 December 2015 (2015-12-03), pages 2466-2473, XP006054516, ISSN: 1751-8687, DOI: 10.1049/IET-GTD.2015.0483 the whole document ----- -/--	1-16

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

[X] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 March 2017	17/03/2017

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

1

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

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2016/050422

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MALEKIAN KAVEH ET AL: "A probabilistic approach to analyze and model the simultaneity of power produced by wind turbines in a wind farm", 2014 6TH INTERNATIONAL CONFERENCE ON INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING (ICITEE), IEEE, 7 October 2014 (2014-10-07), pages 1-7, XP032720194, DOI: 10.1109/ICITEED.2014.7007931 ISBN: 978-1-4799-5302-8 [retrieved on 2015-01-12] the whole document -----	1-16
X	US 2012/143537 A1 (NIELSEN PETER [DK]) 7 June 2012 (2012-06-07) paragraphs [0004] - [0028], [0048] - [0050], [0081] - [0089], [0057] -----	1,2,8, 12,13,16
A	ZHANG S ET AL: "Statistical voltage quality assessment method for grids with wind power generation", IET RENEWABLE POWER GENERATION,, vol. 4, no. 1, 13 January 2010 (2010-01-13), pages 43-54, XP006034551, ISSN: 1752-1424, DOI: 10.1049/IET-RPG:20080067 the whole document -----	1-16

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/DK2016/050422

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012143537 A1	07-06-2012	US 2012143537 A1	07-06-2012
		WO 2011000825 A2	06-01-2011