(54) Title: METHOD OF REDUCING TORSIONAL OSCILLATIONS IN THE POWER TRAIN OF A WIND TURBINE
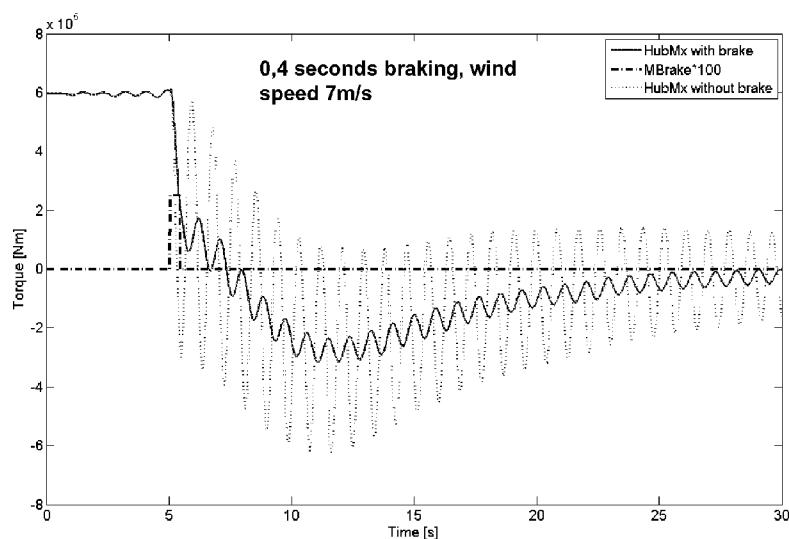

Figure 2

(57) Abstract: The present invention refers to a method of reducing torsional oscillations in the power train of a wind turbine in the event of grid loss. According to the method, after the grid loss, a braking torque is applied to the power train during a period of time and said period of time is determined as a function of the torsional resonance frequency of the power train.

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METHOD OF REDUCING TORSIONAL OSCILLATIONS IN THE
POWER TRAIN OF A WIND TURBINE

The present invention relates to a method of control of a wind turbine. More
5   precisely, it relates to a method of control of a wind turbine in the case of grid
loss.

Modern wind turbines are commonly used to supply electricity into the
electrical grid. Wind turbines of this kind generally comprise a rotor with a
10   plurality of blades. The rotor with the blades is set into rotation under the
influence of the wind on the blades. The rotation of the rotor shaft either
directly drives the generator rotor ("directly driven") or through the use of a
gearbox.

15   During normal operation, the rotational speed of the wind turbine is controlled
by the magnetic torque acting on the generator and the aerodynamic torque
acting on the rotor. Additionally, braking systems are usually foreseen.

Various ways to control the aerodynamic torque acting on the rotor of wind
20   turbines are known. In "pitch-regulated" wind turbines, the rotor blades can be
rotated around their longitudinal axis to control the angle of attack of the wind
on the blades. In "passive-stall" regulated wind turbines, stall automatically
occurs on the blades when the wind speed increases above a predetermined
wind speed. The aerodynamic torque is hereby limited.
25
The braking systems generally act mechanically on the low speed shaft or on
the high speed shaft. Also braking systems that act electrically on the
generator are known. In pitch-regulated wind turbines, pitching of the blades to
their feathering position is used to slow down the wind turbine. The
30   (mechanical) brake is only used to come to a complete stop of the wind
turbine, or to keep the turbine in its park-position.

As mentioned before, during normal operation, the rotational speed of the wind
turbine is controlled by amongst others the magnetic torque acting on the
35   generator. The components of the power train (rotor shaft or slow speed shaft,

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gearbox, high speed shaft, generator) elastically deform under the influence of the aerodynamic torque acting on the rotor and the magnetic torque acting on the generator. Potential energy is stored in this elastic deformation. When a grid loss occurs, the magnetic torque at the generator is very suddenly lost,

5 and the potential energy of the power train is converted into kinetic energy. As a result, the power train suffers from torsional oscillations. These oscillations can be very damaging to especially the gearbox and can significantly reduce its lifetime.

10 In the prior art, various methods of dealing with grid loss and of reducing torsional oscillations are known. WO 2007/082642 describes a method of dealing with grid loss by reducing the pitch angle of the rotor blades, followed by applying a mechanical brake on the high speed shaft. WO 2004/098968 describes a method of braking in the case of a grid failure. The braking device

15 acts on the high speed shaft. The hydraulic pressure of the brake is controlled until the wind turbine comes to a complete stop. The device and its control method are especially adapted to be used in "stall-regulated" wind turbines. WO 03/040556 describes a method of slowing down the wind turbine aimed at avoiding torsional oscillations. In the method, the deceleration torque of the

20 brake is regulated in a predetermined time sequence, based on the natural frequency of the wind energy converter. US 6,254,197 describes an alternative hydraulic braking system and a method of controlling it. A particular method described prescribes to first apply aerodynamic brakes (movable tips of the blades) and after a period of 15 seconds apply the mechanical brake.

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The prior art methods are complicated and therefore expensive. Besides, they have not always yielded satisfactory results. So, there exists a need for an improved method of control of a wind turbine in the case of grid loss, which is reliable and easily applicable to present-day wind turbines.

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The present invention aims at achieving this goal. The goal is achieved by a method according to claim 1. Further advantageous embodiments are described in the dependent claims.

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In the case of grid loss, a braking torque is applied to the power train during a period of time, said period of time being determined as a function of the torsional resonance frequency of the power train. The power train of the wind turbine has a torsional resonance frequency that is unique for each power train

5 and thus for each type of wind turbine. Upon grid loss, the magnetic torque of the generator disappears and the power train will start to oscillate with a frequency that is its torsional resonance frequency. In determining the period of braking, this frequency should therefore be taken in into account. The way to put the invention into practice is thus to determine the resonance frequency

10 of the power train, to determine (to calculate) the desired braking period as a function of this resonance frequency and after grid loss, apply the brake during the determined braking period.

Preferably, said period of time is also determined as a function of the delay

15 occurring between the moment of grid loss and the moment of applying the braking torque. To obtain optimum results of reducing torsional oscillations, the brake should only be activated in the period immediately following the grid loss in which the torque of the slow speed shaft is decreasing, i.e. the period in which the power train is "unwinding". Applying the brake when the torque in

20 the slow speed shaft is increasing could have the result of increasing the torsional oscillations. Therefore, preferably also the delay occurring between the moment of grid loss and the moment of applying the braking torque is taken into account to determine the period of braking. According to this preferred method, the way to put the invention into practice is thus to

25 determine the resonance frequency of the power train, to determine the delay occurring between the moment of grid loss and the moment of applying the braking torque, then to determine (to calculate) the desired braking period as a function of these two parameters and after grid loss, apply the brake during the determined braking period.

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Preferably, the brake is activated substantially immediately after grid loss is detected.
Any braking system may be used in the method according to the invention and each braking system will has an inherent minimum reaction time. The sooner

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the braking system reacts to the grid loss, the longer the braking torque can be applied while the power train is still unwinding.

Preferably, said period of time is determined to be between 50% and 100% of
5 a maximum allowable period, said maximum allowable period being determined as half the torsional resonance period of the power train minus the delay between the moment of grid loss and the moment of applying the braking torque.

10 More preferably, said period of time is determined to be between 70% and 100%, and most preferably between 80% and 100% of said maximum allowable period.

In other words, said period of time is ideally chosen to be just less than half the
15 torsional resonance period of the power train minus the delay occurring between the moment of grid loss and the moment of applying the braking torque, i.e. the maximum period of braking is determined to be according to the following formula:

$$t_{max\_brake} = 0,5 \cdot t_{resonance\_period\_power\_train} - t_{delay}$$

20
As mentioned before, to obtain optimum results of reducing torsional oscillations, the brake should only be activated in the period immediately following the grid loss in which the torque of the slow speed shaft is decreasing, i.e. the period in which the power train is "unwinding". The power
25 train is unwinding during the first half of the first torsional oscillation period. Ideally, the brake should be activated during this entire time. However, no braking system can react without delay. Therefore, this delay (the time between the moment of grid loss and the moment of applying the braking torque) should be deducted from this half oscillation period to determine the
30 maximum braking period. The formula thus gives the maximum braking period. The brake is ideally applied as long as possible (to have its maximum effect), within this maximum braking period.

Preferably, the period of braking is approximately 0.4 seconds. It has been
35 found that a braking period of approximately 0.4 seconds is sufficiently long for

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significantly reducing the torsional oscillations and at the same time is so short that the torque of the slow speed shaft is still decreasing.

Preferably, the braking torque is applied during a single short period of time.
5 After the brake has been deactivated, it is not necessary to reactivate the brake to further reduce torsional oscillations.

Preferably, the braking torque that is applied by the brake is determined taking the wind speed at the moment of grid loss into account. More preferably, the
10 braking torque is determined taking the aerodynamic torque acting on the rotor into account. Alternatively, the braking torque is determined taking the electrical power generated by the generator at the moment of grid loss into account. The most advantageous results are not necessarily achieved by applying the greatest available braking torque. Rather an optimum braking
15 torque to be used in the method exists.

During operation of a wind turbine, prevailing wind speeds are usually measured. Therefore, a way to determine the optimum braking torque is to take the wind speed at the moment of grid loss into account.
20
A more precise way of determining the optimum braking torque takes the aerodynamic torque at the moment of grid loss into account. The aerodynamic torque at that moment not only depends on the wind speed, but also e.g. on the pitch angle of the blades. More preferably, the optimum braking torque is
25 determined taking the period of braking, the delay occurring between the moment of grid loss and the moment of applying the braking torque, and the aerodynamic torque at the moment of grid into account. This can be expressed using the following formula: $M_{brake.opt} = \kappa \cdot M_{aero}$

30 In this formula, $M_{brake\ opt}$ is the optimum braking torque and M_{aero} is the aerodynamic torque on the rotor at the moment of grid loss. κ is a coefficient that is determined for each wind turbine type according to the period of braking, and the delay occurring between the moment of grid loss and the moment of applying the braking torque. κ will thus have a unique value for
35 each wind turbine type.

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A complication is that wind turbines generally do not comprise a system for measuring the aerodynamic torque directly. To overcome this complication, the electrical power is measured and the aerodynamic torque can then be

5 determined using the following formula:

$$M_{aero\_HSS} = \frac{P_{electr}}{\omega_{HSS}}$$

In this formula, M_{aero_HSS} is the (aerodynamic) torque in the high speed shaft, P_{electr} is the electric power generated by the generator at the moment of grid

10 loss and ω_{HSS} is the rotational velocity of the high speed shaft. The formula gives a very good estimate of the aerodynamic torque. Therefore, using the electric power generated by the generator at the moment of grid loss (which is anyway measured in present day wind turbines) is a good way to determine the optimum braking torque.

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In conclusion, the optimum braking torque can be determined using the aerodynamic torque acting on the rotor at the moment of grid loss into account. An intermediate step in this method can be the estimate of the aerodynamic torque using the above formula. Alternatively, the optimum braking torque is

20 directly determined through the measure of the electric power generated by the generator at the moment of grid loss.

Optionally, the brake is only activated if grid loss occurs at a moment of high wind speeds. The complexity of the system is thereby reduced, leading to

25 further cost reduction. This option is especially preferable if it is determined that the effect of torsional oscillations at low wind speeds does not lead to unacceptable damage.

Another option is to apply the method of braking whenever grid loss occurs,

30 independent of the wind speed. The system will be more complex, since a more complex control algorithm will be needed. However, torsional oscillations can advantageously be reduced in any situation of grid loss.

Preferably, a pitch system is provided in the wind turbine and the pitch system

35 is also activated substantially immediately following grid loss, so that after the

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brake has been released, pitch control of the rotor blades is used to further slow down the wind turbine. The mechanical brake acts more directly on the power train than the pitch system. The mechanical brake is thus more suitable for reducing torsional oscillations immediately. After releasing the brake, only 5 the pitch system is needed to further slow down the wind turbine. In the case of grid loss, both systems are activated. The combination of the mechanical brake and pitching of the blades significantly reduces the torsional oscillations and can guarantee proper shutdown of the wind turbine. The brake is only used again to come to a final complete stop of the wind turbine, or to keep the 10 turbine in its park-position.

Any kind of brake can in principle be used in the method. Advantageously, the brake, that is present for bringing the wind turbine to a complete shut-down, is also used in the method of braking in the case of grid-loss according to the 15 invention. No separate brake needs to be provided.

In principle, any form of actuating mechanism (hydraulic, electrical etc.) can be used for the braking system. However, the system needs to be operational in the case of grid loss. This means that the system should be able to work in the 20 absence of electricity supply from the grid. A battery in the case of an electrical braking system can be foreseen. For a wind turbine comprising a hydraulic brake, a reservoir of hydraulic fluid may be foreseen.

Further possible embodiments of the invention and their advantages will be 25 explained with reference to the figures. The figures show in:

Fig. 1 a wind turbine with a braking system in which the method according to the invention can be applied.

30 Fig. 2 a simulation of torsional oscillations in the rotor shaft after grid loss at a wind speed of 7 m/s.

Fig. 3 a more detailed view of the two seconds after grid loss of figure 2

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Fig. 4 simulation of torsional oscillations in the rotor shaft after grid loss at a wind speed of 12 m/s.

Fig. 5 more detailed view of the two seconds after grid loss of figure 4

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Fig. 6 simulation of torsional oscillations in the rotor shaft after grid loss at a wind speed of 25 m/s.

Fig. 7 simulation of torsional oscillations in the rotor shaft after grid loss at a
10 wind speed of 7 m/s for different braking torques, both applying the method according to the present invention

Fig. 8 simulation of torsional oscillations in the rotor shaft after grid loss at a wind speed of 12 m/s for different braking torques, both applying the method
15 according to the present invention

With reference to figure 1, a schematic drawing of a wind turbine is shown. The rotor 10 comprises a plurality of blades. The blades are mounted on the rotor shaft (also: slow speed shaft) 12. The gearbox 11 transforms the rotary motion
20 of the rotor shaft into rotary motion of the high speed shaft 13. A brake disc 14 is mounted on the high speed shaft. A hydraulic brake is indicated with reference sign 15. In this figure, a possible embodiment of the braking system that can be used in the method according to the present invention is shown. In principle however, any form of brake could be applied in the method according
25 to the invention.

The high speed shaft 13 sets the rotor of the generator 16 into motion. The electricity generated by the generator is supplied into the electrical grid 18, through suitable electrical components, generally indicated with reference sign
30 17. Reference sign 19 indicates a pitch system of the blades, which can rotate the blades along their longitudinal axis. In the method according to the present invention, a pitch system is not necessary. It is however preferable to have one.

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Figure 2 shows the results of a simulation of the torsional oscillation in the power train of a wind turbine. A grid loss occurs at t = 5. The prevailing wind speed at the moment grid loss occurs is 7 m/s. The torsional oscillations in the power train are shown for two different cases. In the first case (dotted line in

5   figure 2), no braking torque is applied, i.e. the brake is not activated. It can be seen that the torsional oscillations are of a high magnitude and the oscillations only die out very gradually. In the second case (continuous line in figure 2), a braking torque is applied for a period of 0.4 seconds, with a delay after grid loss of 0.05 seconds. The brake is preferably applied as soon as possible after

10 the grid loss. The delay of 0.05 seconds was used in the simulation, since it was estimated to be the minimum reaction time of the braking system.

For the method according to the invention, the period of braking does not necessarily have to be 0.4 seconds. Advantageous results can also be

15 achieved with different periods of braking (falling within the scope of the claims).

It can be seen in figure 2 that applying the braking torque for a single short period of time reduces the magnitude of torsional oscillations significantly.

20 Additionally, and as a result of this, the torsional oscillations die out sooner.

Figure 3 shows the results of the same simulation as in figure 2, but shows a more detailed view of the first 2 seconds after grid loss occurs.

25 Figures 4 and 5 show similar simulations, but at a wind speed of 12 m/s. Also here, grid loss occurs at t = 5, a braking period of 0.4 seconds is applied after a delay of 0.05 seconds. Similar results are obtained. Applying the method according to the invention the torsional oscillations are reduced. Comparing the results of figures 4 and 5 with those of figures 2 and 3, it is clear that the

30 magnitude of the torsional oscillations is higher at a wind speed of 12 m/s than at a wind speed of 7 m/s.

Figure 6 shows the torsional oscillations when grid loss occurs at a wind speed of 25 m/s. Once more, the achievable reduction in torsional oscillations

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(continuous line in figure 6) using the method according to the invention is shown.

The resulting torsional oscillations at different wind speeds vary in magnitude.
5 At higher wind speeds, the torsional oscillations are greater and thus the potential damage to the power train components is also greater. If cost reduction is the most important objective, it can therefore be chosen to implement the method of braking only if the grid loss occurs at a moment of high prevailing wind speed. If grid loss occurs at lower wind speeds, the
10 brakes would not be activated and the torsional oscillations would continue for a longer time. This could in certain cases be regarded as acceptable.

If this is not regarded as acceptable however, the braking method could be implemented at any occurrence of grid loss, both at high and at low wind
15 speeds.

Figure 7 shows the results of a simulation of torsional oscillations in the power train after grid loss at a wind speed of 7 m/s for different braking torques, both applying the method according to the present invention. From this figure it can
20 be seen that the most advantageous results are not necessarily achieved applying the greatest braking torque. The torsional oscillations are reduced if a braking torque of 3000 N.m is applied compared to when a braking torque of 4000 N.m is applied.

25 Figure 8 shows the results of a simulation of torsional oscillations in the power train after grid loss at a wind speed of 12 m/s for different braking torques, both applying the method according to the present invention.

Figures 7 and 8 show that in applying the method according to the invention, a
30 certain optimum braking torque exists. Increasing the braking torque beyond this optimum increases the torsional oscillations with respect to the optimum situation. It is preferable in the method according to the invention to determine the braking torque taking the wind speed into account. It is more preferable to take the aerodynamic torque acting on the rotor at the moment of grid loss into
35 account to determine the optimum braking torque.

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Claims

1. A method of reducing torsional oscillations in the power train of a wind turbine in the event of grid loss characterized in that,

5   after the grid loss a braking torque is applied to the power train during a period of time, said period of time being determined as a function of the torsional resonance frequency of the power train.

2. A method of reducing torsional oscillations according to claim 1,

10 characterized in that,
said period of time is also determined as a function of the delay occurring between the moment of grid loss and the moment of applying the braking torque.

15 3. A method of reducing torsional oscillations according to any previous claim, characterized in that,
the braking torque is applied substantially immediately after grid loss occurs.

4. A method of reducing torsional oscillations according to claim 2 or 3,

20 characterized in that,
said period of time is determined to be between 50% and 100% of a maximum allowable period,
said maximum allowable period being determined as half the torsional resonance period of the power train minus the delay occurring between the

25 moment of grid loss and the moment of applying the braking torque.

5. A method of reducing torsional oscillations according to claim 4, characterized in that,
said period of time is determined to be between 70% and 100%, and

30 preferably between 80% and 100% of said maximum allowable period.

6. A method of reducing torsional oscillations according to any previous claim, characterized in that,
said time period is approximately 0.4 seconds.

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7. A method of reducing torsional oscillations according to any previous claim, characterized in that,
the braking torque is applied during a single time period.

5 8. A method of reducing torsional oscillations according to any previous claim, characterized in that,
the braking torque that is applied to the power train is determined taking the wind speed at the moment of grid loss into account.

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9. A method of reducing torsional oscillations according to claim 8, characterized in that,
the braking torque that is applied to the power train is determined taking the aerodynamic torque acting on the rotor at the moment of grid loss into account.

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10. A method of reducing torsional oscillations according to any previous claim, characterized in that,
the braking torque that is applied to the power train is determined taking the electrical power generated by the generator at the moment of grid loss into
20 account.

11. A method of reducing torsional oscillations according to claim 8, 9 or 10, characterized in that,
the braking torque that is applied to the power train is determined also taking
25 the delay occurring between the moment of grid loss and the moment of applying the braking torque, and the period of braking into account.

12. A method of reducing torsional oscillations according to any previous claim, characterized in that,
30 the braking torque is only applied if the grid loss occurs at a wind speed above a predetermined minimum wind speed.

13. A method of reducing torsional oscillations according to any previous claim, characterized in that,

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the braking torque is applied regardless of the prevailing wind speed at grid
loss.

14. A method of reducing torsional oscillations according to any previous
5   claim, characterized in that,
    a pitch control system of the wind turbine blades is also activated substantially
    immediately following grid loss, so that after the brake has been released,
    pitch control of the rotor blades is used to further slow down the wind turbine.

10 15. A method of reducing torsional oscillations according to any previous
    claim, characterized in that,
    the braking torque acts on the high speed shaft of the power train.
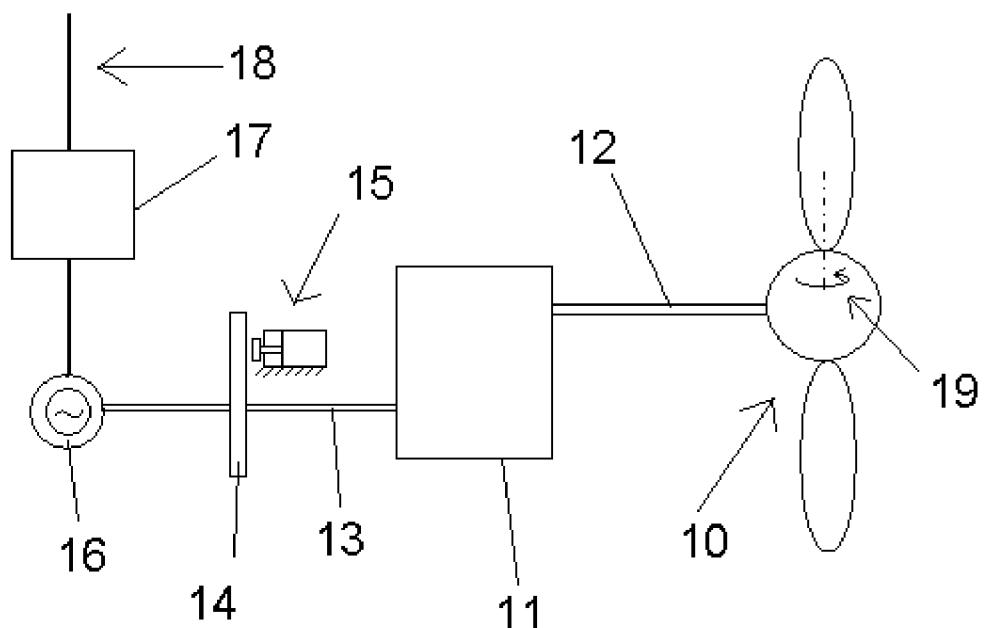
Figure 1
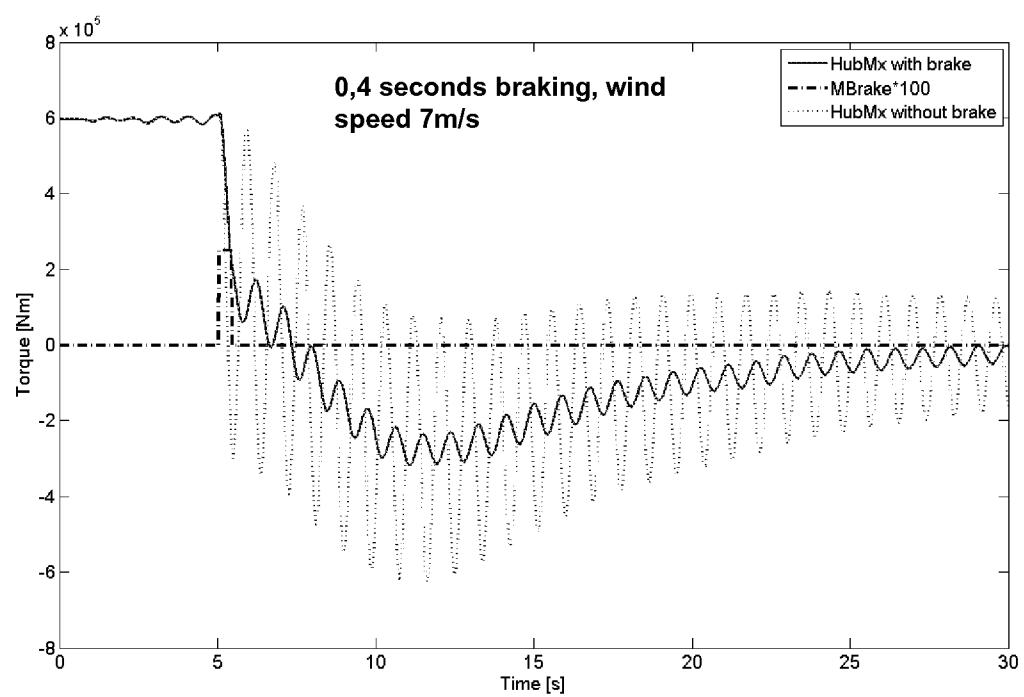
Figure 2
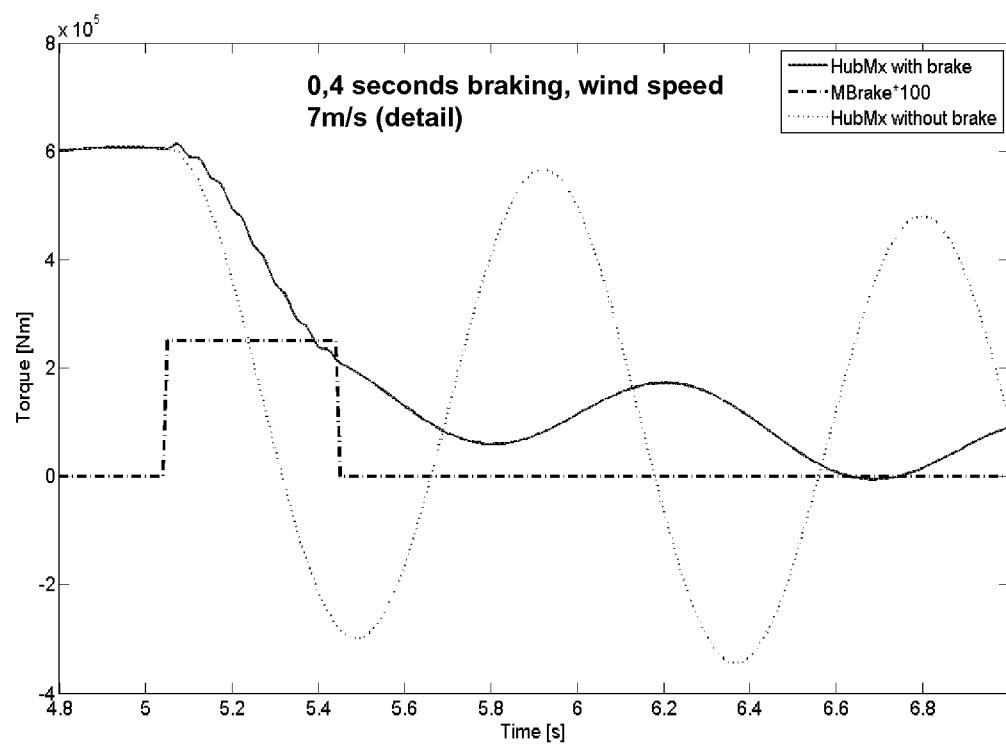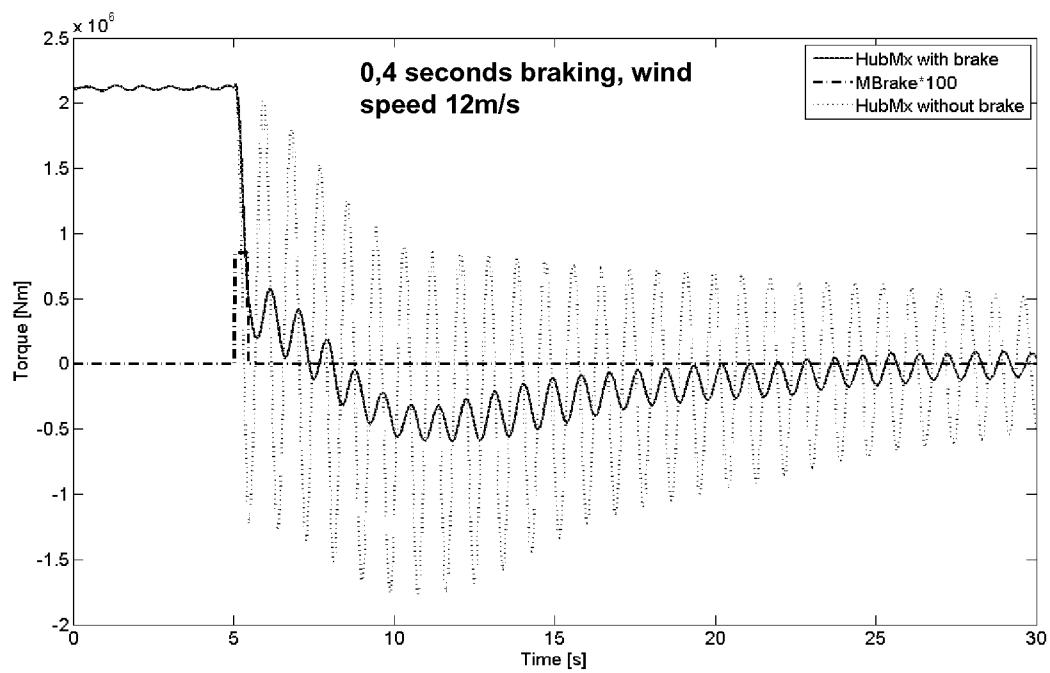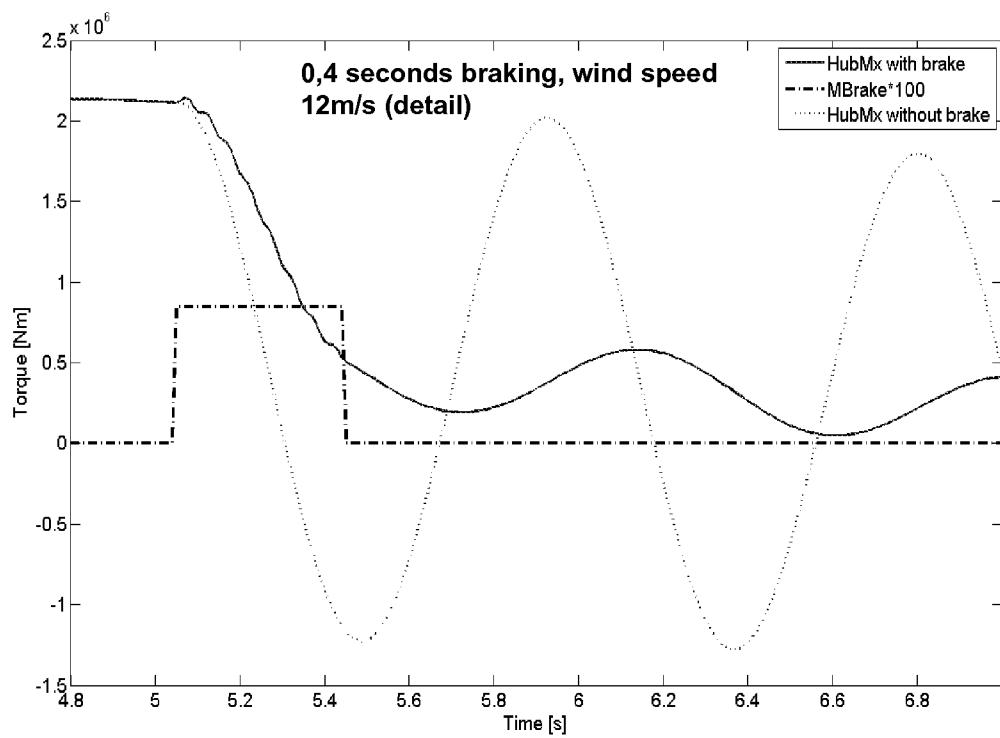
Figure 3
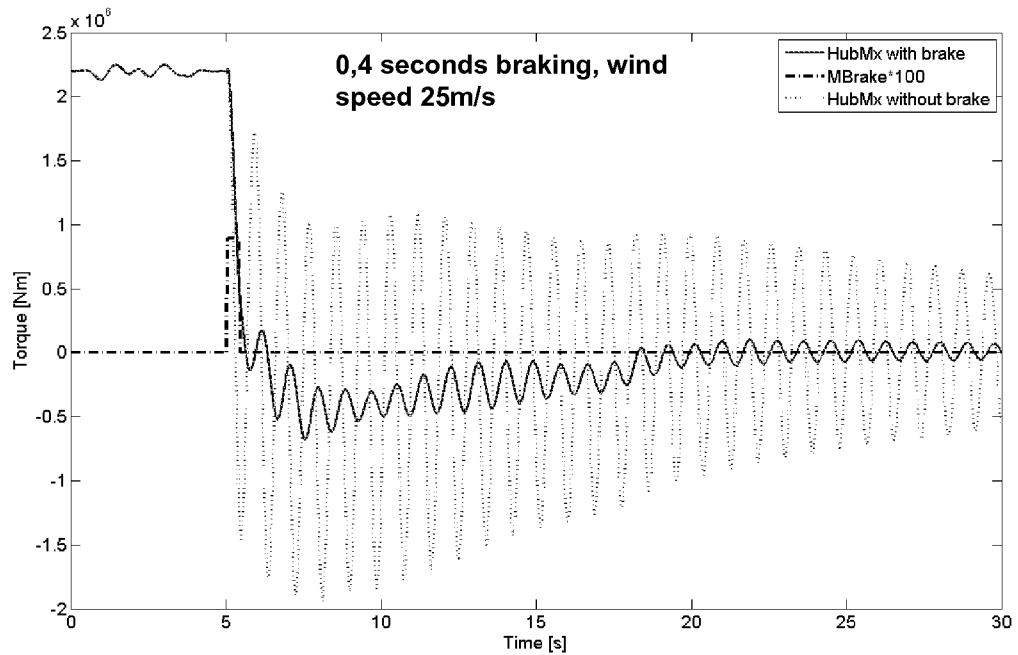
Figure 4
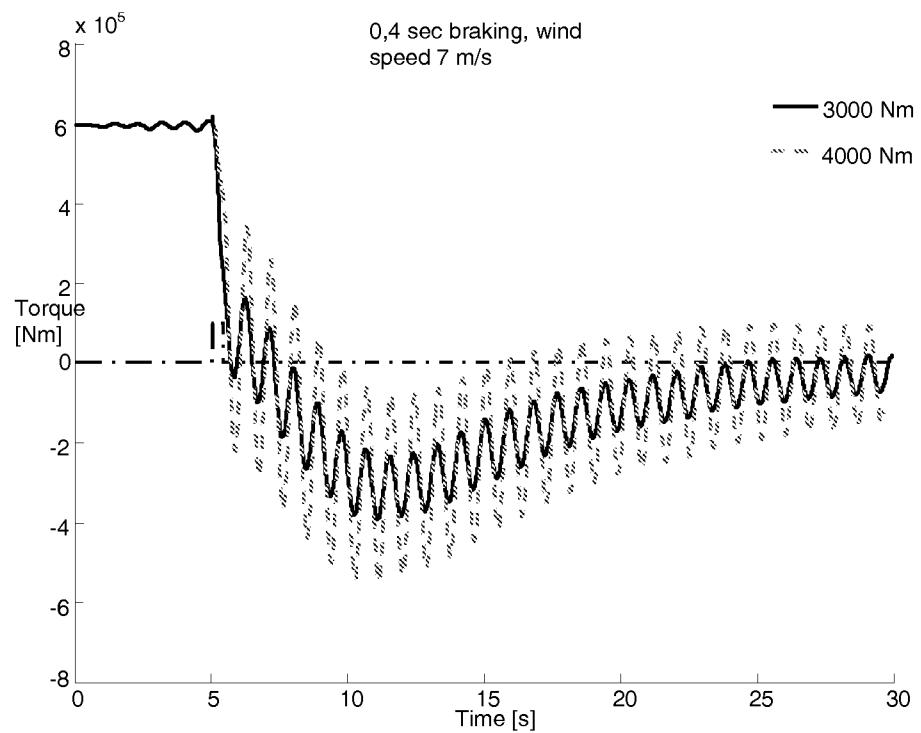
Figure 5
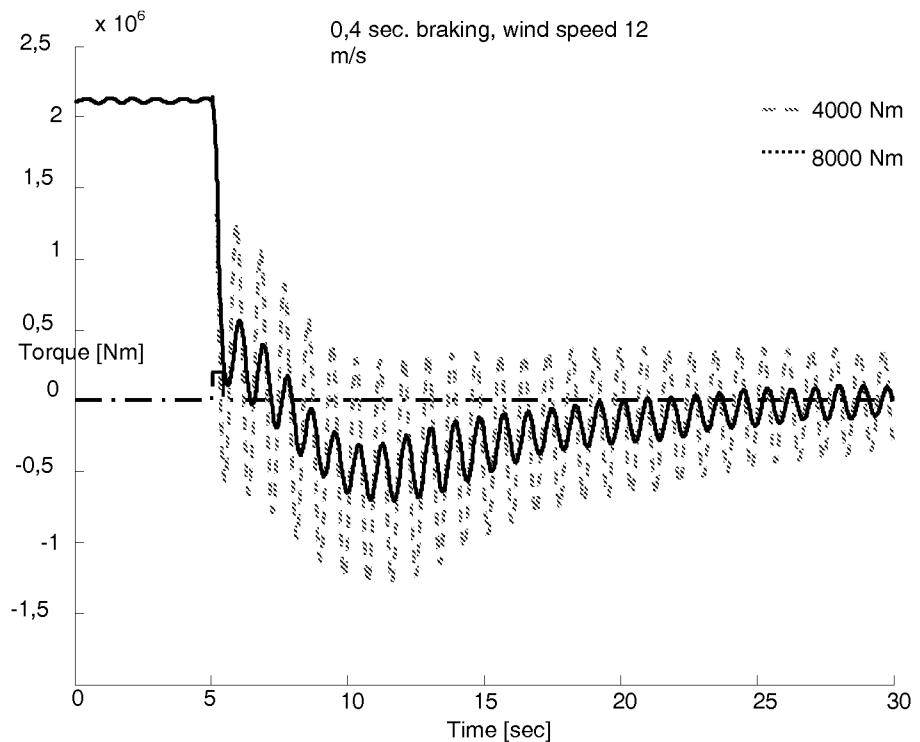
Figure 6

Figure 7

Figure 8

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D11/02
ADD. F03D7/02

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

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A	DE 10 2006 001613 A1 (REPOWER SYSTEMS AG [DE]) 12 July 2007 (2007-07-12) cited in the application paragraphs [0079] - [0081], [0087], [0088]	1-15
A	DE 197 05 948 A1 (ITT MFG ENTERPRISES INC [US]) 20 August 1998 (1998-08-20) column 1, lines 29-40; claim 1	1-15

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| X | Further documents are listed in the continuation of Box C. | | X | See patent family annex. |

Date of the actual completion of the international search	Date of mailing of the international search report
28 August 2009	09/09/2009

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1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2007/140787 A (VESTAS WIND SYS AS [DK]; SLOTH ERIK BILLESKOV [DK]) 13 December 2007 (2007-12-13) page 7, lines 16-27; claim 16	1-15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

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