Synthetic inertia versus fast frequency response: a definition

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Abstract: This study discusses synthetic inertia from the perspective of a transmission system operator and compares it to fast frequency response based on frequency deviation. A clear distinction of the meanings between these concepts is discussed, the basis of which is a description of their characteristics. A contribution and the purpose is the clarification of these concepts in addition to share the perspectives of a transmission system operator. The frequency response of a power system based on the Nordic system is examined for future scenarios with large amounts of wind power. Conclusions are drawn regarding the benefit of synthetic inertia compared with fast frequency response based on frequency deviation.

1 Introduction

The frequency of a power system is a continuously changing quantity whose derivative indicates the balance between consumed and produced power. A momentary imbalance between these results in a change of system frequency where kinetic energy is stored or released in rotating masses in the system. When a disturbance in the form of disconnection of load or production occurs, the frequency response of the system depends on size of disturbance, inertia and response of controlled frequency responses [1]. Inertia prevents system frequency from experiencing sudden changes which can in turn cause stability issues. Today the bulk of inertia in power systems is made up of rotating masses in synchronous generators. With more non-synchronous generation such as wind and solar power in the power system, inertia is reduced. The inertial response from different generator types has been thoroughly investigated in literature, for example [2], and there are many challenges related to operation of systems with low inertia [3–5]. Examples of systems which operate with relatively small levels of inertia include the power systems in Ireland, New Zealand [5] and Gotland, in Sweden.

Since non-synchronously connected production units, such as modern wind turbine generators, are connected via power converters, their rotational speed is isolated from the system frequency. They do not therefore deliver a natural inertial response and do not contribute to the inertia of the system. We refer to synthetic inertia as the contribution of additional electrical power from a source which does not inherently release energy as its terminal frequency varies, but which mimics the release of kinetic energy from a rotating mass. This provides an electrical torque which is proportional to the rate of change of frequency (RoCoF), which resists changes in frequency. Note that by the term synthetic inertia we mean synthetic inertial response. The first term is the most frequently used in the literature and is therefore used here as well.

To operate a power system securely, the frequency of the system must remain within a narrow band. Momentary imbalances are regulated by primary control responses to provide an immediate balancing action to contain frequency deviations. In the Nordic system, these reserves are called frequency containment reserves. The accepted minimum instantaneous frequency is in the Nordic system 49.0 Hz.

The frequency containment reserves in the Nordic system are currently being re-evaluated. The reason for this is reduced frequency quality and the expected increase of wind power penetration which may, if no actions are taken, cause the system frequency to deviate outside acceptable limits [6, 7]. To mitigate large frequency deviations after disturbances, wind turbines have been proposed as an abundant source of frequency support, and several approaches have been discussed in the literature [1, 3, 8–10]. One such type of frequency support from wind turbines is synthetic inertia.

Supply of synthetic inertia requires energy stored in systems behind power electronic interfaces, such as batteries, rotating masses in wind turbines or even other power systems connected through high voltage dc (HVDC) connections. To supply synthetic inertia, supplementary control of these sources is required, as there is usually no direct relation between power output of these sources and the frequency of the system. Control of wind turbines to supply synthetic inertia has been proposed in literature, and much research has focused on developing controllers which respond to frequency disturbances [9, 11–16]. Much of this research focuses on describing the initial dynamic response of power systems after loss of generation, with indices such as minimum instantaneous frequency, also known as minimum instantaneous frequency, and RoCoF. However, with more HVDC connections, the dimensioning fault may be loss of power export, which could lead to frequency increases.

This paper provides a complete definition of synthetic inertia with a distinction from the general term of fast frequency response. Due to the prevalence of wind power in the power system, focus has been laid on the frequency control responses of wind turbines. These responses are shown and discussed from the perspective of a transmission system operator (TSO). Here the effect of having limited frequency control reserves, such as in the case of solar power and wind power, is also demonstrated.

The Australian Energy Market Operator (AEMO), EirGrid and System Operator for Northern Ireland (SONI) have performed much work on issues related to operation of low inertia systems. In [17], EirGrid and SONI investigate the RoCoF in their system for specific events. They proposed interim Grid Code standards of 1 Hz/s over 500 ms for the Ireland system and 2 Hz/s for the Northern Ireland system. High RoCoF was experienced in the South Australian system during the blackout event on 28 September 2016 [18] and issues related to RoCoF are investigated in the Future Power System Security Program at AEMO. Simulations are performed to demonstrate the behaviour of the system for different fast frequency responses from wind turbines.

A model similar to the Nordic system, with primary control reserves supplied by hydro power units, has been developed in Matlab/Simulink. Wind turbines are modelled by taking into account the reduction in mechanical power from the wind as the...
rotational speed of the wind turbines is reduced. Simulations are then run for large disturbances and for normal operation. Practical aspects regarding implementation are also discussed from the perspective of a TSO. The differences in system response for these frequency control methods are discussed here, but the requirements of the system to handle disturbances are outside the scope of this paper.

2 System dynamics

In order to understand what synthetic inertia is, we present the dynamics of the system which describe system frequency. The dynamic behaviour of a single synchronous machine $i$ can be described by

$$J_i \frac{d\omega_i}{dt} = T_{mi} - T_{ei} \text{ (N m)}$$

(1)

where $J_i$ is moment of inertia, $\omega_{mi}$ is angular velocity, $T_{mi}$ and $T_{ei}$ are the mechanical and electrical torques for generator $i$. Equation (1) can also be expressed in terms of inertia constant $H_i$ and power on a per unit base as

$$2H_i \frac{d\omega}{dt} = P_{mi} - P_{ei} \text{ (p.u.)}$$

(2)

where $\omega$ is the electrical frequency of rotation, $P_{mi}$ and $P_{ei}$ are the mechanical and electrical powers for generator $i$.

The system frequency is the frequency the machines approach when their individual dynamics have died out. As the dominating dynamics for power system frequency comprise the aggregated synchronous generator dynamics and primary frequency control response, the dynamics of the system can be expressed as the dynamics of a lumped machine, which has inertia constant $H_{sys}$, which is the weighted sum of the inertia constants of the individual machines

$$H_{sys} = \frac{\sum_i H_i S_i}{\sum_i S_i} \text{ (s)}$$

(3)

The initial response to a disturbance and frequency change is mainly determined by the total system inertia. The RoCoF is the time derivative of the frequency signal, and relates directly to the inertial response of the system. RoCoF is given by

$$\text{RoCoF} = \frac{df}{dt} = \frac{\Delta f_i}{2H_{sys}} \text{ (Hz/s)}$$

(4)

where $f$ is frequency of the system, $f_i$ is the nominal frequency and is the power imbalance of the system. $P_e$ includes changes to both electrical power production and consumption.

Practical aspects of measuring RoCoF include the choice of a time window over which to calculate the RoCoF, for which different choices will result in different values of RoCoF. RoCoF is an essential measurement that synthetic inertia control depends on. However, RoCoF measurements are challenging, as they are highly susceptible to the disturbances experienced in power systems. Many measurement techniques have been proposed, yet despite the vital nature of this parameter, no appropriate standardisation for RoCoF testing exists. Fig. 1 shows the frequency of a system following a disturbance.

3 Existing views of synthetic inertia

In existing literature there is no unified definition of synthetic inertia, which seems sometimes to have different meanings depending on context. Many interpretations of the concept of synthetic inertia include delivering power quickly when system frequency deviates from its nominal value by a certain amount. The term is also sometimes used to mean the change in control of power being provided during a disturbance. This paper gives a strict description of synthetic inertia, defined in terms of the physical response of a synchronous generator.

Many studies on synthetic inertia do not focus on distinction between inertia and fast frequency response. From a system perspective, important measures of frequency stability are the minimum instantaneous frequency, and RoCoF. A relaxed view on synthetic inertia might include services which contribute to improving the response of the system, such as lifting the minimum instantaneous frequency, or RoCoF. However, a more strict, unified view of this term would lead to a clearer picture of services being offered to improve system stability.

With the help of power electronics, power units can be controlled in many ways to improve frequency quality after disturbances. The inertial response of a synchronous generator, however, releases torque in direct proportion to the RoCoF it experiences. The term synthetic inertial response must therefore correspond to the controlled response from a generating unit to mimic the exchange of rotational energy from a synchronous machine with the power system. Any other form of fast controlled response can then be termed as fast frequency response. To clarify, synthetic inertial response is a subset of fast frequency response which contains different responses based on frequency and RoCoF.

The term inertia is described by the European Network of Transmission System Operators for Electricity (ENTSO-E) as ‘the facility provided by a power park module or HVDC system to replace the effect of inertia of a synchronous power generating module to a prescribed level of performance’ [20]. While this definition encompasses the definition presented in this paper, many have interpreted this definition to include what we call fast frequency response [21].

Assuming $T_{mi}$ is constant, we can rewrite the change in electrical torque $\Delta T_{ei}$ for a synchronous generator $i$ as a function of an angular velocity change

$$\Delta T_{ei} = -2H_i \frac{d\omega_i}{dt} \text{ (N m)}$$

(6)

which can be converted to power, using the per unit system, as

$$\Delta P_{ei} = -2H_i \frac{d\omega_i}{dt} \text{ (p.u.)}$$

(7)
The main focus is on the fast response. The duration of the delivery will highly depend on the source and other parameters. Required duration must be coordinated with other frequency reserves installed in the system.

5.1 Mechanical and electrical power of wind power plants

The power that can be extracted from the wind is a function of several parameters and is characterised by its performance coefficient $C_p$. The mechanical power is described by

$$P_{\text{Mech}}(\omega_{\text{wind}}) = \frac{1}{2} C_p(\lambda, \theta) \rho r^2 \omega_{\text{wind}}^3 (W)$$  \hspace{1cm} (9)

where $\rho$ is air density, $r$ is the length of the rotor blades and $\omega_{\text{wind}}$ the wind speed. $C_p$ is a function of blade tip speed ratio $\lambda$ and blade pitch angle $\theta$. The tip speed ratio

$$\lambda = \frac{r \omega_{\text{wind}}}{\omega_{\text{e}}}$$  \hspace{1cm} (10)

relates the rotor speed $\omega_{\text{wind}}$ in radians/s to the wind speed $\omega_{\text{e}}$ in m/s. The function $C_p$ depends on several constants, given by [22]

$$C_p(\lambda, \theta) = c_1(\frac{\lambda}{\theta} - c_2 - c_3 \theta^3) - c_4 e^{-c_5(\frac{\lambda}{\theta} - c_2 - c_3 \theta^3) + 10^{-4} \omega_{\text{e}}^2}.$$

When the blades of the wind turbine are not pitched the electrical power output of the turbine follows the maximum mechanical power extracted from the wind, shown in Fig. 2. Maximum power point tracking control ensures the maximal power output by varying the electrical output as a function of rotor speed, according to the maximum power curve. For a constant wind speed, any deviation from the curve results in an imbalance between electrical and mechanical power, which accelerates or decelerates the rotor such that peak power is retained.

6 Model and control function description

In order to examine the differences between synthetic inertial and fast frequency response based on frequency deviation, the model shown in Fig. 3 was built in Matlab/Simulink. It consists of a one-mass model of the power system and wind power plants represented as a lumped variable speed turbine. The plants are controlled to produce the maximum power available at a constant wind speed, implying that the electrical power output $P_i(\omega_{\text{wind}})$ is then a function of the rotor speed of the turbine. Supplementary controllers implementing synthetic inertia and another fast frequency response, which is proportional to frequency deviation, are added. Both of these use a first-order measurement filter with a time constant of 300 ms. By adding the supplementary control function to the maximum power point tracking function, speed recovery is possible. To fully recover the rotor speed the function assumes the RoCoF or frequency returns to the nominal value. If there is a steady-state frequency deviation after a disturbance, the speed recovery function will find a new stable operating point with a lower rotation speed. Note that speed recovery is only relevant in applications where rotating machines are connected to the power system by power electronics, such as wind turbine systems.

The assumption is that a wind turbine can deliver about 10% additional power during 10 s. The synthetic inertia is adjusted such that $H_{\text{syn}} = 7 s$, and the gain of the fast frequency response controller is tuned such that the output power peaks for both synthetic inertia and proportional control without speed recovery are approximately the same. See peaks of functions 1 and 3 in Fig. 4.

The dynamics for primary control in the system are based on the dynamics of a hydro power plant. Parameters for primary control, inertia and frequency dependency $D$ of the load have been estimated using a measured frequency disturbance that has occurred in the Nordic system. The primary control is modelled without dead band and power headroom limitation.
Two scenarios are defined, one with 20% wind power production and one with 80% wind power production, which has low inertia. These are described in Table 1. The wind power plants are assumed to operate with a blade pitch angle of zero and a constant wind speed. No pitch control is used in order to not have interference between the control functions and the pitch control.

Five different types of supplementary wind power control are modelled, wind turbines which do not contribute to frequency support, wind turbines which contribute with synthetic inertia and those which contribute with fast frequency response proportional to frequency deviation. Both synthetic inertia and fast frequency response are active all the time and will provide a response according to the measured RoCoF and frequency deviation. If the speed of the rotor decreases by 10%, support from synthetic inertia or other fast frequency response is withdrawn, and maximum power point tracking is resumed. For the control schemes which contribute to frequency stability, the schemes are modelled both with and without speed recovery functions. The five types have the following functions:

- **Base case**: In this case wind power provides a constant power, but does not contribute to frequency support.
- **Function 1**: Synthetic inertia without speed recovery.
- **Function 2**: Synthetic inertia with speed recovery.
- **Function 3**: Fast frequency response proportional to frequency deviation, without speed recovery.
- **Function 4**: Fast frequency response proportional to frequency deviation, with speed recovery.

Functions 1 and 3 are studied without any speed recovery during the frequency disturbance to avoid interference between the speed recovery and the frequency control. Speed recovery for energy storage is not needed for non-rotating units such as batteries. Functions 1 and 3 can be used without any consideration of rotor speed for such energy sources. Practically the type 4 wind power turbines have speed control. In functions 1 and 3 the speed control is disabled in order to show the concept of the two frequency controls.

In functions 2 and 4 the speed recovery function is active all the time. The function is one example of a speed recovery and is not optimised in any way. The speed recovery function uses the current rotor speed of the turbine to calculate a new active power set point based on the maximum power point tracking curve. When the rotor speed decreases, the power set point also decreases, resulting in a stabilising effect. When the supplementary control signal is reduced to zero the rotation speed will return to the initial value.

There are also other possible solutions to implement frequency control from wind turbines. For example, measured signals can be further processed in order to reduce the interaction between speed and frequency control. Research on how to practically implement frequency control on wind turbines is ongoing.

### Table 1 Scenario parameters

| Scenario 1 |  | Scenario 2 |
|------------|---|------------|
| system load | 30 GW | 24 GW |
| primary regulation strength | 2972 MW/Hz | 300 MW/Hz |
| frequency-dependent load | 300 MW/Hz | |
| number of wind power plants | 4000 | |
| wing length | 50 m | |
| wind power production | 6 GW | |
| wind speed | 8.6 m/s | 13.7 m/s |
| initial rotational speed | 1.22 rad/s | 1.93 rad/s |
| system inertia | 177 GWs | 44 GWs |
Large disturbance: generator trip

This section provides the results of a simulated generator trip. The model and control functions are described in Section 6.

The two defined scenarios are simulated with a 1450 MW generator trip. To represent the worst case the frequency before the disturbance is set to 49.9 Hz, which is the lowest allowed system frequency in normal operation.

7.1 Results – scenario 1: 20% wind power production

The system frequency for scenario 1 is shown in Fig. 5. Compared with the base case, the minimum instantaneous frequency is improved by all of the supplementary frequency support functions, except for function 3. For function 3, the nadir is even lower than in the base case. This is because the rotational speed is reduced so much that normal operation has to be interrupted and speed recovery activated. For this function wind power is reduced by 1700 MW, as shown in Fig. 4. A similar event could also be seen for function 1 beyond the simulation time, and is indicated by the slow reduction of rotor speed in Fig. 6. Function 2 reduces the RoCoF of the system but the minimum instantaneous frequency is similar to the nadir of the base case. The fast frequency response functions based on frequency deviation do not improve the system RoCoF significantly.

Electrical power output is activated more quickly for the synthetic inertia functions but support is also reduced more quickly compared with the fast frequency response functions based on frequency deviation, as shown in Fig. 4. Function 2 has a more oscillatory behaviour compared with function 1 because it uses speed recovery. Without the recovery function however, it becomes impossible to maintain rotor speed. When rotor speed decreases, the mechanical power to the wind turbine also decreases, and the rotor speed continues to decrease even faster. This is shown in Fig. 6. For both of the functions without speed recovery, rotor speed continues to decrease until the lower limit for the rotor speed is reached. Rotor speed for a wind turbine with function 4 will reach another steady-state operation because the frequency of the system deviates. The rotor speed is lower compared with its level before the disturbance, but it is a stable operating point. When the frequency is restored to the nominal frequency the rotor speed will return to its initial value. For practical implementation a more sophisticated rotor speed recovery function may be required.

Activation of the primary control reserves is shown in Fig. 7. The lowest output power peak of the primary control output is achieved with function 4 but the steady-state value is somewhat higher because of the new operating point of the wind power.

7.2 Results – scenario 2: 80% wind power production

The frequency of the system for the low inertia scenario is shown in Fig. 8. As there is less inertia in the system in scenario 2, the damping of the oscillatory behaviour for function 2 is reduced. In this scenario, the minimum instantaneous frequency is significantly improved with both functions 1 and 4. Since there is 60% more wind power in this scenario, the contributions from both synthetic inertia and fast frequency response based on frequency deviation are greater than they are in scenario 1, and there is a larger difference between the base case and the other controllers. The speed of the wind turbine is shown in Fig. 9. Apart from the increased oscillations in the case with function 2, the results
show similar behaviour of the wind turbines compared with scenario 1.

7.3 Discussion

Simulations show that both the synthetic inertial response and the fast frequency response, which are proportional to frequency deviation, improve the minimum instantaneous frequency, however, only synthetic inertia improves the RoCoF. For the synthetic inertia with a speed recovery function based on maximum power point tracking, the minimum instantaneous frequency is not improved compared with the base case. From the results it is obvious the design of the speed recovery is of great importance to avoid interactions between the synthetic inertia control and the standard inertia. Further work may include analysing how the speed recovery function can be better designed. Synthetic inertia without speed recovery improves both frequency deviation and RoCoF significantly and if a slow acting speed recovery is implemented this response would be possible from a wind power turbine. It is important that the contribution of energy to the power system is positive before the minimum instantaneous frequency is reached, and improvements to system performance could be gained by not starting any speed recovery process until after the minimum instantaneous frequency has been reached. If the recovery starts too quickly, there is a risk of two minimum instantaneous frequencies, as for the fast frequency response function, shown in Fig. 5.

Studies indicate that synthetic inertia has some benefits over other types of fast frequency responses that have previously been proposed. One benefit is that synthetic inertia emulates synchronous generators whose response does not need to be adjusted for different operating points and the natural development of the power system over longer periods of time. It can also improve the RoCoF after a disturbance. Fast frequency response based on frequency deviation can also, however, improve the minimum instantaneous frequency after disturbances. The chosen method for doing this should be chosen in such a way to reduce societal costs, and should take into account the dynamics of the primary frequency control.

With a measurement filter the initial RoCoF directly after the disturbance is not affected as there is latency in the supply of electrical torque. It is important to know how fast and accurate both frequency and RoCoF can be measured when using these as control signals as a longer measurement time and dead band will impact the result with a slower response. In this paper, the calculation of the RoCoF assumes symmetrical operation. In practice, the measurement must also be able to account for unbalanced faults.

After a disturbance has occurred, supplying the system with energy during the first few seconds can help to mitigate the resulting frequency deviation. The imbalance between production and consumption results in a certain RoCoF, and the integral of this imbalance over time results in the instantaneous frequency of the system. It is therefore important to lower this imbalance over time, to reduce the minimum instantaneous frequency. The ability of supporting units to provide energy then becomes important for preventing large frequency dips.

To conclude, both the simulated synthetic inertia and the fast frequency response improve the minimum instantaneous frequency. The RoCoF is only improved by the synthetic inertia. The implemented speed recovery reduces the effectiveness of the controls because of the interactions with frequency control.

8 Normal operation: stochastic net power variations

To study how the synthetic inertial response and fast frequency response based on frequency deviation contribute in normal operation analysis is performed using the same model as in the large disturbance study, with a 24 h imbalance power series injected to the system, where here an imbalance refers to the momentary difference in power between production and consumption. The power series represents the imbalance in the Nordic power system for a typical day in May. The imbalance shown in Fig. 10 was estimated in a Nordic project where the frequency was used to derive the system power imbalance [23]. In order to analyse how the supplementary frequency control of wind power affects the frequency quality, the index \( \text{time outside normal frequency band (TONFB)} \) is used. This index is used today in the Nordic system, and is the number of minutes that the system frequency is outside the normal operating band of \( \pm 0.1 \text{ Hz} \).

Due to the small size of the data series, the relative change of TONFB compared with the base case will be analysed.

As functions 1 and 3 are implemented without the speed recovery, these control methods will result in a rotor speed which exceeds the limits and the control is shifted to the maximum power point tracking in the same was as seen in Fig. 6. Due to this fact functions 1 and 3 are excluded from the normal operation study. The study is performed for scenario 2 with 80% wind production. The models use the same parameters as in the Large disturbance study except for the measurement filter time constant which is increased from 300 ms to 2 s. This is done to make the controller less aggressive compared with the controller in the Large disturbance study.

8.1 Results – scenario 2: 80% wind power production

The resulting system frequencies for functions 2 and 4 are shown in Fig. 11 for the power imbalance shown in Fig. 10. The relative change of the TONFB from the base case was:

- Function 2: 6.4%.
- Function 4: -10.7%.

In order to better compare the system frequencies for the different alternatives, a frequency distribution graph is shown in Fig. 12.

Function 2 increases TONFB compared with the base case, whereas function 4 decreases the TONFB, which can be clearly seen in the lower frequency distribution.

Another way of looking at the frequency is by looking at the frequency distribution of the RoCoF in Fig. 13. Function 2 makes the peak of the distribution around 0 Hz/s higher than the base case and function 4, which also makes the peak higher than the base case. Both of these functions improve upon the RoCoF characteristics of the base case.

The electrical output power and rotor speed of the wind turbine are shown in Figs. 14 and 15. The electrical output power can, at first glance, look small compared with the system imbalance. The reason the activation is small is that the stored kinetic energy is limited. When the controller activates, the speed starts to decrease and the set point is changed in order to recover the rotor speed. This allows the controller to only respond to short term changes in power imbalance. The simulated power imbalance contains mainly slower dynamics, making the response from the wind turbine small.

8.2 Discussion

Simulations show that function 2 increases the TONFB compared with the base case but moves the RoCoFs toward 0 Hz/s. Function 4 reduces the variance of the frequency deviation seen in both the TONFB and the frequency distribution of the system frequency, however it does not improve the RoCoF as much as function 2. The reason for the higher TONFB using function 2 is that RoCoF is reduced by using synthetic inertia resulting in longer frequency restoration times. Additionally, due to the low inertia in scenario 2, damping of the slow frequency oscillatory behaviour for function 2 is reduced. When the damping is lower the impact of interactions between measurement filter, implemented speed recovery and the system frequency is more prominent. It is important that speed recovery is implemented in order to not decrease the stability margin of the system. One goal of minimising RoCoF levels in the system is to reduce wear and tear in the turbine governor actuator. Wear and tear of the turbine governor actuator is related to two indices. One is the accumulated travelled distance by the actuator and the other is the number of directional changes of
the actuator [24]. Lower RoCoFs make the governor actuator experience smoother and fewer directional changes. Synthetic inertia may be used to achieve this.

These results are not surprising since the TONFB in many cases is a result of the frequency slowly diverging from 50 Hz. In such cases, function 4 will provide stronger support as the frequency is further away from 50 Hz. Function 2 will not be able to offer as much support unless frequency changes are fast. The results are in line with the results from the large disturbance study.

Differences in electrical power magnitude for functions 2 and 4 for the normal operation disturbances are explained by the use of the same gains as in the large disturbance study. Function 2 uses more power on average compared to Function 4 but for shorter durations, resulting in low usage of the wind turbine kinetic energy.
This is also reflected in the angular frequency where function 2 results in an angular frequency which stays closer to the nominal compared with function 4. Since function 2 does not exchange as much energy with the power system as function 4, the effect on the frequency quality is low. The gains for the functions could be chosen differently and for normal operation, but that has not been done here.

9 Additional stability aspects

This paper addresses issues related to the frequency of the system. The synthetic inertia response and proportional fast frequency response contribute to synchronising and damping torques in the system. The change in electrical torque of a synchronous machine \( i \) followed a perturbation can be divided into two components as

\[
\Delta T_i = \Delta T_{id} + j \Delta T_{id} = K_{i_d} \Delta \delta_i + j K_{i_q} \Delta \omega_i
\]

where \( \Delta T_i \) is change in electrical torque of synchronous machine \( i \), \( \Delta T_{id} \) and \( \Delta T_{id} \) are synchronising and damping torque aligned with the change in electrical rotor angle \( \Delta \delta_i \) and speed \( \Delta \omega_i \), respectively. \( K_{i_d} \) and \( K_{i_q} \) are the coefficients of the synchronising and damping torque, respectively. Thus, controlled response contributes to electrical torque where synthetic inertia response is aligned with RoCoF, and therefore contributes with synchronising torque. Similarly proportional fast frequency response contributes with damping torque to the system. The contributions can be derived from a linearisation of the power system equations and are not examined further here. These may, however, be important to consider as all stability aspects have to be considered in the design and operation.

10 Conclusions

This paper presents a complete definition of synthetic inertia which separates it from other fast frequency response. Synthetic inertia is related to the supply of electrical torque in proportion to RoCoF. To improve the RoCoF of a system, electrical power needs to be controlled in response to the RoCoF. A simulation study shows that both synthetic inertia and fast frequency response based on frequency deviation can improve the minimum instantaneous frequency after a disturbance compared with a system without any frequency support from wind power. It has been shown that both synthetic inertia and fast frequency response based on frequency deviation can improve the minimum instantaneous frequency after a disturbance compared to a system without any support from wind power. It has also been shown that fast frequency response based on frequency deviation improves normal operation frequency quality and reduces absolute RoCoF, and that synthetic inertia does not improve the frequency quality but reduces the absolute RoCoF.

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