

Composition of inertial response emulation mechanisms for power system frequency stability analysis

Istvan Taczi/MSc. Student (*Author*)

Budapest University of Technology and Economics
Budapest, Hungary
taczi93@gmail.com

Istvan Vokony/Senior Lecturer (*Author*)

Budapest University of Technology and Economics
Budapest, Hungary
vokony.istvan@vet.bme.hu

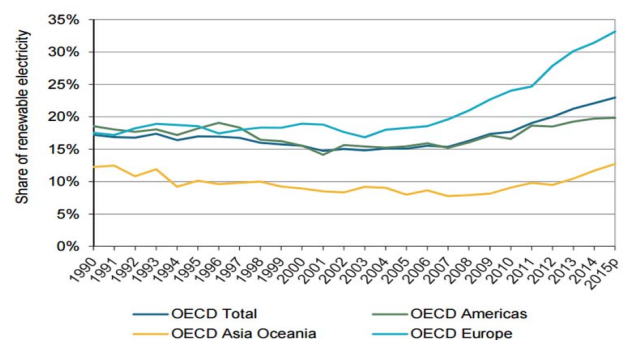
Abstract— Nowadays, the electric power system is rapidly changing around us. Policy makers found a way to incentivise the renewable energy sources to reach the ambitious climate protection goals. Power system operators must adapt to the whole new constraints. The once heavily centralized generation is now dispersed all around the grid and causes problems that were previously unknown. Some of the emerging technologies – such as the most common wind and solar generators – are connecting to the grid via power converters so they are practically decoupled from the grid. This means that the system inertia is decreasing which affects the stability. With less rotating mass behind it, the power grid will face higher rate of change of frequency. One of the possible solutions could be the emulation of inertial response through power converter control methods. This paper introduces some possible implementation of such controlling with different kind of parameters and selectivity. The described algorithms are using the frequency gradient and absolute value, activation and cutting signals for mechanical protection of wind turbines. The purpose is to provide an effective simulation method for the evaluation of the effectiveness of the emulation. The power grid of the future will definitely need some stability support. As one of the most intriguing solution, the effectiveness of the physical inertial response emulation is a crucial question. This paper examines the success of controlling and the impacts of several approaches with different constraints. With the detailed modelling of technical capabilities this approach could be used for evaluating the synthetic inertia as the substitute of the natural inertial response. The controlling methods being tested on different power system models with the DigSilent Power Factory dynamic simulation tools.

Keywords— Power system stability, synthetic inertia, frequency control

I. INTRODUCTION

Recently, the power generation mix is changing rapidly due to the commitment of policy makers to reduce the harm of the environment. Share of fossil fuels such as oil and coal have been decreasing and renewable sources like solar and wind power dominates the new installations. Cost-competitive solutions in those emerging technologies are present due to the innovation incentives. For example, the cost of solar panels has been decreased by 80% from 2009 to 2015 regarding the International Energy Agency. However, system planning must

be adapted to this situation. Balancing reserves have to be increased and fast response generation will be crucial in the future. The long-term adequacy of generation mix is yet to be ensured through capacity markets. The flexibility of the transmission and distribution networks must be improved: more and more configurations and dynamic events could happen in the future and the continuous supply is essential. Figure 1. shows the share of renewable electricity in selected countries measured by the International Energy Agency. From around 2008-2010 a change of pace can be observed in all regions. [1-28]



1. Fig. Share of renewable electricity in the member countries of the Organisation for Economic Co-operation and Development [23]

The consumer behavior also has been changing nowadays. People want to be independent from utilities, and would like to have more and more data and interaction possibilities regarding the energy usage. Rooftop solar panels are spreading with an astonishing pace and these so called ‘prosumers’ has basically different characteristics than the users before. Industrial consumers have been using demand side management to reduce their bills as a part of co-optimization of their technical processes to be as profitable as it is possible. [25]

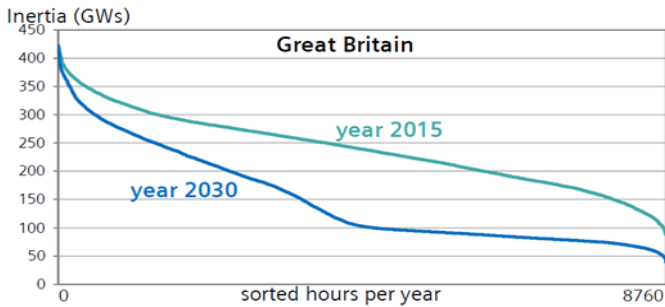
The power grid was designed to operate securely with specific generation and load constraints. The elements of those networks serve the supply for over 30 years and now many countries face the problem that the aging infrastructure must be developed to ensure the security of supply. Questions are raising that the changing constraints should indicate different

approaches in the planning, network development investments, operation and control methods. [1-28]

System-level controlling was designed to ensure the equilibrium between generation and load (including loss). The main task of the system operator is to keep the voltage and frequency within acceptable levels with generation and controllable network element controls. Energy storage was neglected because there was not a clear technical need for high amount of flexibility and storage solutions were not been able to compete with the controlled generation alternatives. [1][2][28]

II. Inertial response

One of the urging issues regarding to the spreading of renewables is the stability of the system. Most of the newly installed generation is connected to the grid via power electronic converters. These devices are incomparable with the synchronous generators from the stability viewpoint since being practically decoupled from the grid. Conventional synchronous generators have an inherent physical response to electric power imbalances, which is called inertial response. The stored kinetic energy in the rotating mass of those machines limits the rate of change of frequency (ROCOF) and contributes as a fast-acting stability reserve. With the spreading of the non-synchronous generation, this inherent physical response will decrease. The primary frequency control (frequency containment control) is the first level of the automated actors, but it takes time while it is being activated. Therefore, the decreasing inertia could lead to devastating stability issues if nothing is implemented to support the system during disturbances. Figure 2. shows the kinetical energy stored in synchronous generators in the power system of Great Britain in the percentage of hours. This means that the necessary time until actors could react, which was created by the “hidden stability reserve” will decrease significantly in the upcoming years. [1-28]



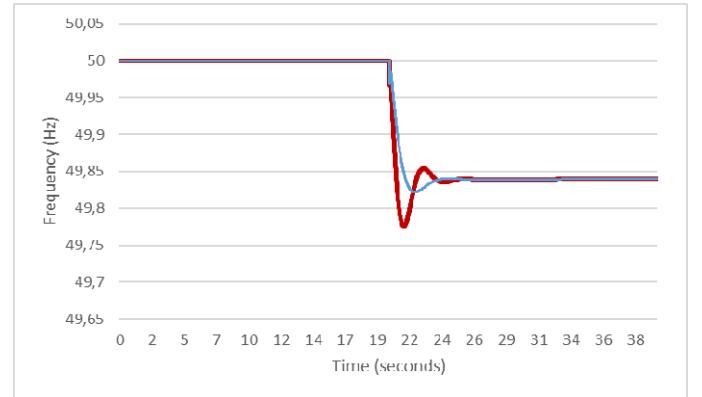
2. Fig. Percentage of hours in a full year where estimated inertia (hidden kinetic energy) is above a given value in Great-Britain for the year 2015 and 2030. [IEEE PES Webinar]

The frequency of a power system changes proportionally to the imbalance between the generation and the load. [4]

$$\Delta P = 2H \frac{df}{dt} \quad (1)$$

Equation 1. describes the relation between the active power imbalance of the system and the frequency. ΔP is the imbalance in the active power components; H is the system inertia constant. All variables are in per unit. With the decrease

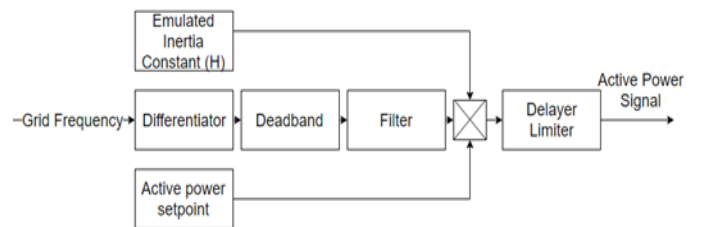
of the inertia constant, the same imbalance causes higher frequency deviation. Figure 3. represents this issue on a test system, which was composed to analyze inertial response. The simulation was prepared on a test system with two gas turbines (blue line) first, and after that wind power replaced one of the turbines (red line) therefore the system inertia was halved and deeper excursion occurred. [4][9][28]



3. Fig. Frequency excursion with $H=10s$ (blue) and $H=5s$ (red) through simulations [28]

III. Controlling methodology

The scope of the research was to compose inertial response control to non-synchronous generation for power system stability analysis. DigSilent Power Factory v15.1 was chosen because of various available built-in models and wide range of dynamic analysis toolset. The software tutorial has a 2 MW dynamic wind turbine model with detailed implementation of controlling. This model was used to represent the wind power synthetic inertia with the addition of the self-composed controlling function. Depending on the parameters these models are fully compatible with any device models such as energy storage systems. The controlling mechanisms could be implemented through common and composite models. Common models incorporate the different function blocks with the equations inside, while the composite models could be used to connect the variables between the common models – both the control elements and network elements such as generators. The synthetic inertia controller is a composite model, and the schematic of relations between the different common models could be seen in Figure 4. This figure shows the most detailed level where every alternative method can be drawn similar. The exact functions are implemented to offer different operational advantages. The technical examination of each type could be discussed easily through the evolution of the controller alternatives. [21]



4. Fig. Block diagram of the synthetic inertia controller composite model

A. Continuous synthetic inertia controller

The first step of the composition was to create a functioning controller which implements equation 1., namely to create an active power response which decreases the imbalance of the system and proportional to the frequency gradient. All controllers have the same input– the system frequency in per unit – and output parameter which is an additional active power signal which could be connected to P-Q controllers of power electronic devices. There is an additional internal signal which is active power setpoint (Figure 1. at the bottom). This could be used in devices where the synthetic inertia composite model is the only power controller to provide a signal for steady-state operation. The emulated inertia constant can be set through the initial parameter intake. The frequency is being measured with a phase-locked loop (PLL), but it could be changed to any method if it is needed. The input frequency is being differentiated in the first step to gather the gradient component as in Equation 1 (Figure 4., blocks in the middle). The derivative of power system frequency is usually a noisy signal so a first-order filter was chosen to ensure proper activation. The continuous operation does not need any deadband calculation but this element was designed to provide selectivity for the controller. It is also responsible for sensing the gradient sign: the controller must not activate when the system is actually restoring. After the desired active power signal was created with the multiplication of the inertia constant and the frequency gradient the limiting parameters take place to provide the realistic simulation of different devices. There is a possibility for a simple delay (time of the measurement, calculation etc.), gradient and absolute value limiting. This block is also able to provide an automatic permitting and a forbidding signal. For example a wind turbine could not be overstressed mechanically for long periods:

- the gradient limit is 1 p.u./second
- the absolute value limit is 0.1 p.u.
- the maximum activation time is 10 s, after that a 20 s recovery period should be used for recovering the lost torque (this is also implemented in these models) [5]

The problem with the continuous operation is that it reacts to every gradient which is not filtered. Selectivity is a key component in synthetic inertia because it is only needed when system stability is endangered. [4][5][9][17][21]

B. Frequency gradient selectivity

The difference between the continuous and gradient selective controllers can be found inside the deadband block. This block evaluates its input: if the gradient is over or under the preset values (which mean a high ROCOF) the synthetic inertia control is activated, else it overlaps the fluctuations and let the controlled element operate in undisturbed condition. This could be used for tuning in systems: the preset ROCOF values – it is also possible to set an asymmetrical deadband – provide opportunity to activate inertial response when instability is possible.

C. Selectivity considering the frequency absolute value

The third type of synthetic inertia controller is able to evaluate the input system frequency in the deadband block. It is essential for the effective operation to ensure that the controller does not provide extra power against restoration processes: for example if the frequency is 49,75 Hz, but the gradient is positive, then the system is heading to optimal operation conditions (a secondary control reserve was being activated, load shedding occurs etc.). In this case, there is no synthetic inertia needed. Table I. summarizes the cases.

I. TABLE: GRADIENT SIGN SENSITIVITY

	$df/dt > 0$	$df/dt < 0$
$f_{input} > f_{nomi}$ nal	synthetic inertia	no activation
$f_{input} < f_{nomi}$ nal	no activation	synthetic inertia

D. Fixed output controller

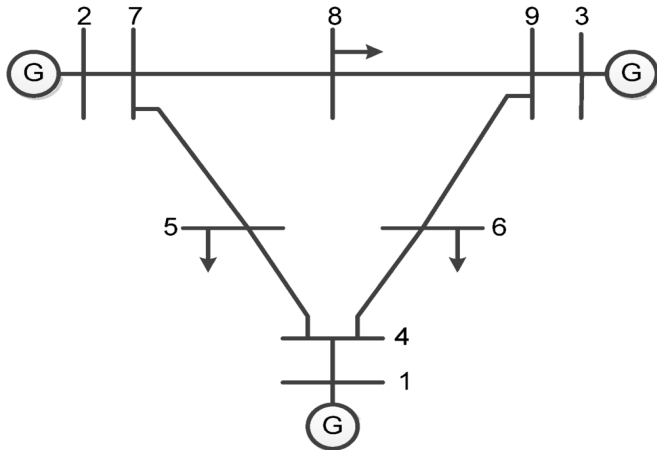
Until now, all three types were adaptive to the frequency gradient. A simpler solution is to fix the output in every case to a preset level. Then the inertial responses of the controlled elements are always the same amount of active power change if the activating constraints occur. This method was implemented to test the permitting and forbidding signals, which were designed for wind turbines (but also useful for fast response and low capacity storage devices). The coordination between the synthetic inertia and primary response is also feasible. Finally, Table II. summarizes the parameters of each proposed models.

II. TABLE: MODEL PARAMETERS

Parameter	Meaning
dfmin	frequency gradient selectivity low edge (p.u.)
dfmax	frequency gradient selectivity high edge (p.u.)
fmin	frequency absolute value selectivity high edge (p.u.)
fmax	frequency absolute value low edge (p.u.)
cut_time	maximum continuous active output length (seconds)
rec_time	recovery period length (seconds)
delay	delay of controller (seconds)
gradmax_up	maximum rise gradient (p.u.)
gradmax_down	maximum fall gradient (p.u.)
H	inertia constant (seconds)
T	filter constant (seconds)
Pact	actual power setpoint (p.u.)

IV. SIMULATION ANALYSIS OF THE COMPOSED MODELS

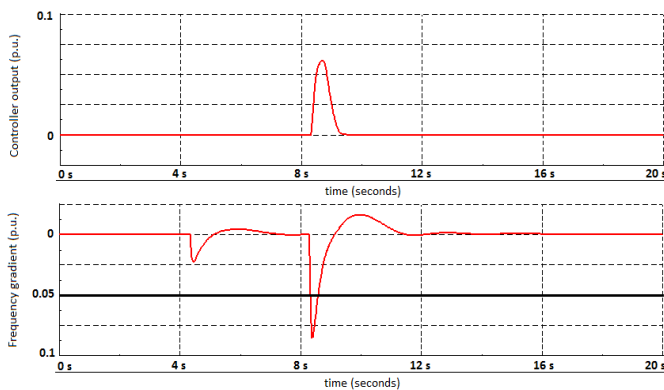
All simulations were conducted in RMS type simulation, which has three-phase steady state models for network elements. This tool is essential for examining electromechanical transients and it considers all the important electromechanical, control and thermal properties of the elements. The purpose of the analysis was to test the different operation modes and selectivity described above to validate the models. The controlled element was a built-in wind turbine model in the IEEE 9 Bus System. The disturbances which caused the activation of synthetic inertia control were load increases. Figure 5. shows the topology, the wind generators which are equipped with synthetic inertia control were connected to the busbar 2. The nominal value of frequency was 50 Hz in all analysis proposed.



5. Fig. System topology of the IEEE 9 Bus System: there are 3 generators (examined wind generation was connected to busbar 2) and 3 loads

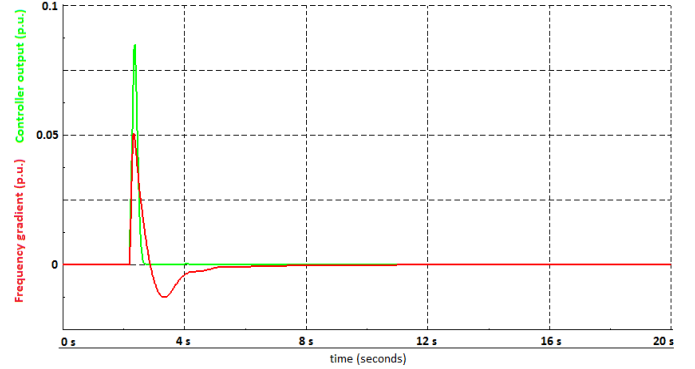
A. Selectivity

The first function under testing was the gradient selectivity of the synthetic inertia controller. Figure 6. shows the outcome of the simulation. The preset trigger constant was 0.05 p.u. for the activation. There were two disturbances (load increase), the first one at 5 seconds was negligible considering the tuning, but in the second case the gradient was higher than the preset value so the controller reacted to the event, as it can be seen on the upper diagram.



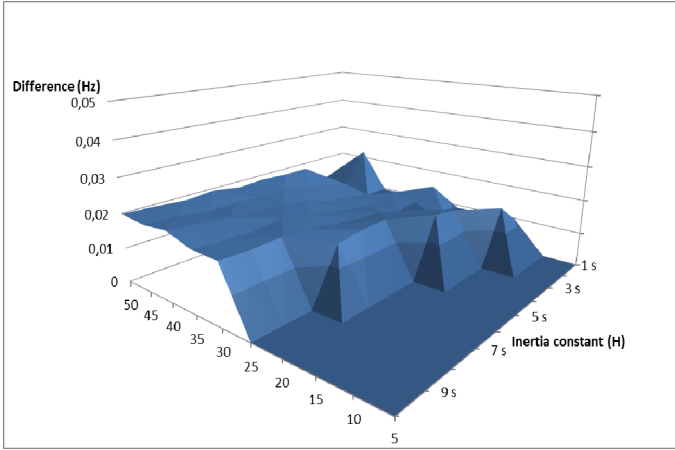
6. Fig. Gradient value selectivity: the controller only provides synthetic inertia if the gradient is higher than a preset constant (thick black line)

The next simulation test was the selectivity of the gradient sign which requires the actual input frequency value. In this case the frequency gradient was exported from inside the controller, where it was inverted to ensure that the inertial response acts against the disturbance, which caused the activation. Immediately after the load increase the controller reacted rapidly. When the frequency was started to increase the controller output was set to zero. So if the controller is equipped with that capability, it does not harm the restoration process with unnecessary activation. Figure 7. represents the operation process with the controller output and inverted frequency gradient.



7. Fig. Gradient sign sensitivity: the controller is able to evaluate the input and avoid the harm of the restoration process

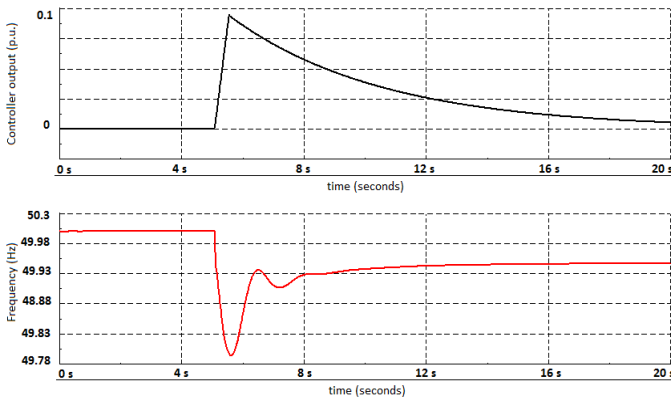
Selectivity is a crucial part of the tuning of the synthetic inertia controller. With proper handling of the different states the stability of the system could be enhanced, while the optimal operation of generators is also being ensured. Energy storage devices have huge potential with the wide-range of applicability and providing synthetic inertia – acting as a stability reserve – is an operation, which could be aggregated effectively not only with other levels of frequency control, but with any application. Figure 8. shows an interesting fact about the frequency absolute value selectivity operations. The measured value was the minimum frequency of the system during the disturbance. Different system states were shaped to analyze the various operation scenarios. The inertia constant shows the actual non-synchronous generation penetration, while the variable load increase (in percentage of the total load of the system) represents the size of the disturbance. f_{min} from 100 different states creates a plain, which consists data from minimum frequencies. This method was chosen because avoiding automatic load shedding (ALS) with synthetic inertia has the upside that the purpose of the system remains intact: serve the customers energy needs continuously. The ALS is triggered by the frequency absolute value so keeping f_{min} over this trigger is a perfect measure of the effectiveness of synthetic inertia. The increase of minimum frequency was in the range of 0-0.7 Hz. Figure 8. shows the difference of the result plain between the one with only gradient selectivity and the result plain of the controller with absolute value selectivity type. The setpoint – which was 49.8 Hz during a rapid load increase - does not cause significant drops, the maximum difference was around 0.03 Hz, which is less than 5% of loss. This means that different kind of selectivity could be taken into account in various systems to ensure the maximum utilization of synthetic inertia.



8. Fig. Loss of minimum frequency rise with the absolute value selectivity

B. Limitation considerations

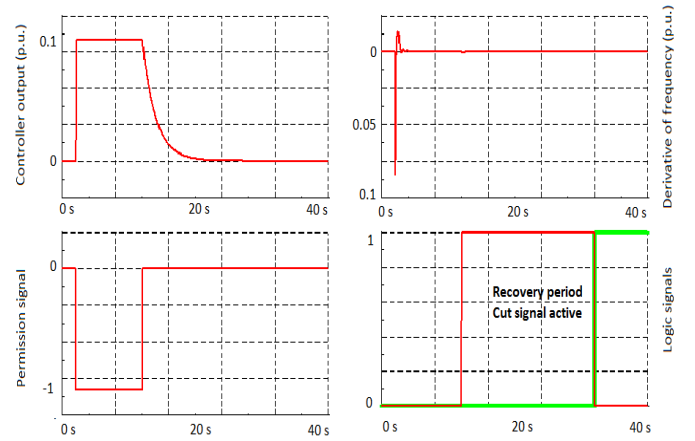
The limiter block provides the dynamic behavior settings in the modeling. The minimum/ maximum absolute and gradient values could be tuned and also the delay (response time) of the synthetic inertia controller. It is clearly a fascinating simulation tool for system operators, who would like to plan system stability preservation scenarios. The rise and fall of the output could be set separately, therefore the fast response of power electronic converters could be utilized with the advantage of slow decline to make a handover between the inertial control and the primary (frequency containment) control. It is important to mention that integrating energy storage system could bring opportunities for aggregated operation, which means that a fast-response storage device is able to provide synthetic inertia, containment and restoration as well. The integration of such service is potentially beneficial. Figure 9. shows the controller output during a given disturbance. As it can be seen, the rapid increase stopped the frequency decrease and the synthetic inertia does not disappear until some seconds. This time span provides an opportunity for slower actors – e.g. governors – to take over.



9. Fig. Separated tuning of response and deactivation: controller output (black) and input frequency (red)

Synthetic inertia from wind power should be treated with extra caution. The loss of torque (or extra torque) in the rotating blades of the turbine due to the additional control signal must be compensated as soon – and as smooth – as

possible. Unintended mechanical damage must be avoided with the adherent use of limiting constraints. Logical control signals were being used to avoid such cases. Figure 10. summarizes all the important signals during the operation. On the upper-right graph the frequency gradient could be observed. The disturbance which caused the activation was a load step increase. The right graph in the bottom shows 2 important logic signals: the red is the cut signal, which is zero if the synthetic inertia control is available and rise to one if the additional power must be perished due to the wind turbine capabilities. The green is the recovery state signal, which is zero if the turbine cannot provide synthetic inertia and becomes one if the controlling possibility is available. The first activation does not require the recovery state signal, therefore the initial value is zero. The signal on the left graph in the bottom functions as an enabler for synthetic inertia: it is composed from the triggering, cut and recovery signal. The edges of this signal provide the rise and fall of the additional power signal, but the output is further equipped with the absolute and gradient value limiting as well as the delays. The actual controller output (in per unit) could be seen on the left at the top. These figures summarize the concept of the limitation constraints due to the wind turbine characteristics, but this methodology is also capable of handling the capacity restraint of a storage device.



10. Fig. Controller output constraints with permitting and forbidding signals to provide recovery period

V. CONCLUSIONS

The spreading of non-synchronous generation reduces the system inertia, therefore threatens the frequency stability of power systems. Several studies show that in certain situations this issue could lead to devastating consequences so proactive and cautious planning is necessary. [1-28]

The controlling structures composed in DigSilent Power Factory 15.1 software were operating effectively through different set of simulations. Wide range of selectivity could be achieved through this modelling methodology: the controllers could take the frequency absolute and gradient value into account during the operation. The dynamic response parameters of each controller could be tuned based on measurement data. The delay and power output gradient could both be set. The rise and fall gradient of the inertial controller output could be set separately so handover to the primary response is achievable. The controllers were designed to be

compatible with wind turbine and energy storage models and the implementation on built-in models was successful. Any control variable could be changed and tuned for optimal solutions.

Proper system inertial response planning and decision making on technological solutions are also feasible with this methodology. The software offers wide-range of simulation studies to ensure the satisfying operation and scripts could be used for iterative sizing of controllers. Further research should include different system states and simulation on long time span. The integration of inertial control to the power system operation is essential from both technical and economic viewpoints. These models could be used for network development and operational planning studies to integrate synthetic inertia in the coordinated frequency control of power systems.

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