

Enhancing Power System Frequency Stability with Synthetic Inertia

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Abstract— Nowadays, changes in the generation mix highlighted technical issues which was negligible before. One of the main integration problems could be the stability of the power system with high penetration of non-synchronous generation. The emerging technologies are connecting to the grid via power converters which means that these are practically decoupled from the grid parameter changes. This reduction of the system inertia could lead to higher rate of change of frequency and deviations. One of the possible solutions is providing the inertial response through controlling to enhance the stability. This paper introduces a simulation modeling method of synthetic inertia and a concept to evaluate different applications. With wind generators and energy storage devices provided synthetic inertia to the system during frequency excursions the load shedding could be avoided in the simulation studies. With the evaluation concepts presented, the optimization of synthetic inertia activations can be planned. Simulations showed that wind generators were able to provide a solution in nearly 70% of the load shedding. The remaining cases were solved with properly sized energy storage systems.

Keywords— Frequency control, Renewable energy sources, Power system stability Synthetic inertia

I. BACKGROUND

Policy makers across the world are committed to make changes for a sustainable power system. The goal is clear, renewable energy sources will play a key role in the future. Competitive green energy solutions are knocking on the door even today. However, system integration processes are bringing some complex technical challenges so system planning and operation need to be adapted to this whole new decentralized structure. Transmission and distribution networks should be more flexible, as well as the reserve capacities to provide sufficient balancing. The long-term generation adequacy for a sustainable system is also a key issue and has to be planned carefully. Even if the constraints are met, the operation and control methods have to be adjusted to this whole new decentralized structure with variable generation. At the same time innovation has been fostered with this ever-changing environment, therefore new trends and solutions will emerge to evolve a sustainable power system in the future. Figure 1. demonstrates the exponential pace of change with the installed solar power capacity increase from 1990 to 2015 in the leading countries. [31][1][2]

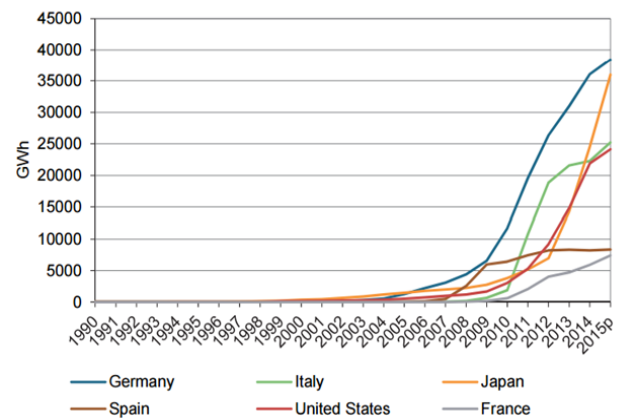


Fig. 1. Installed solar generation capacity in leading countries [31]

The focus of this study is the power system stability issues considering the spreading of non-synchronous generation. Wind and solar are the most commonly used renewable technologies and these are incomparable with the conventional synchronous generators. They are connecting to the grid via power electronic based converters which means that they are practically decoupled from the grid and its parameter changes. For power system operators – whose main task is to maintain the voltage and the frequency values within an acceptable band – this means that they have to face a negative effect on the well-known and widely exploited relationship between the active power and the frequency. The inertial response of the synchronous generators limits the rate of change of frequency (ROCOF) during the initial time of the disturbances until the primary control is being activated. These first seconds are crucial for maintaining the stable operation. The sources of this direct physical response are the conventional synchronous machines which contribute stored kinetical energy by the rotating mass of the rotors. The higher share of non-synchronous generators will decrease the system inertia, therefore controlling and protection schemes needs to be adapted to the new constraints to avoid devastating consequences. This issue is so crucial that the European Network of Transmission System Operators of Electricity (ENTSO-E) listed it as one of the three main topics of the research and development plan from 2015 to 2017. [16][27]

II. CONTROLLING PRINCIPLES

The frequency of a power system is changing proportional to the imbalance between the generation and load. The controlling mechanisms are implemented to react for that. The inherent inertial response limits the ROCOF – thereby defines the gradient - with the kinetic energy changes. Then, the primary response (frequency containment reserve) creates a new working point for the system and stops the deviation. 2. Figure shows the main parameters which could be used for a frequency excursion observation.

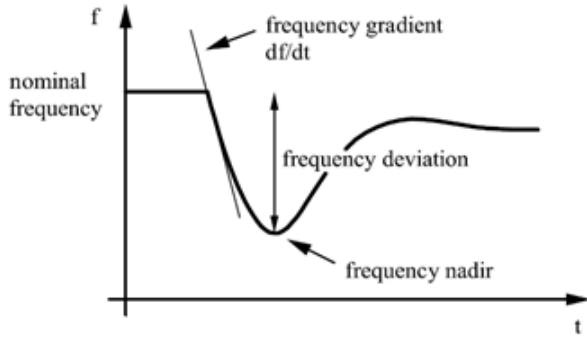


Fig. 2. Frequency response indicators [2]

A. Possibilities to provide synthetic inertia

The main problem in stability issues is the reduced system inertia. There are several ways to provide the additional reserves. Wind generators have moving parts that have stored kinetic energy, therefore they can provide additional torque if needed. Photovoltaic systems do not have any kind of “hidden” energy but could be complemented with energy storage systems to serve as a stability reserve. Another intriguing solution could be the modification of High Voltage Direct Current (HVDC) control systems to have inertial response.

To emulate the inertial response, controllers have to set the power considering an additional signal based on equation 1.

$$\Delta P = 2Hf_{sys} \frac{df_{sys}}{dt} \quad (1)$$

Where ΔP is the additional power required in per unit (p.u.), H is the inertia constant in seconds and f_{sys} is the system frequency in p.u.

B. Technical constraints and selectivity

Power electronic converters have exceptionally fast response time, the output of such devices could be changed in 20-50 ms. This study focuses on wind turbine controls. The methodology concept is the following: in the case that the Automatic Load Shedding (ALS) could not be avoided with wind generation equipped with synthetic inertia I an appropriate storage system will be sized and added to ensure frequency stability in all simulation configurations. The main constraints for the control system are the delay for measurement and processing, the gradient of the change and maximum/minimum limits of the output. With these variables arbitrary technological type of inertial response emulation could be modeled.

TABLE I. TECHNICAL CONSTRAINTS OF INERTIAL RESPONSE CONTROL FOR WIND GENERATORS

Parameter	Value
Minimum rotational speed	0,53 p.u.
Maximum power overload	1,1 p.u..
Maximum torque overload	1,2 p.u.
Minimum power output	0 p.u.
Maximum rate of change of power reference	1 p.u./s
Maximum dynamic rotational speed	1,1 p.u.
Maximum time of providing inertial response	10 s
Recovery time	20 s

Table 1. is a summarization of the technical capabilities for wind turbines. From this input data, the controlling models which emulate the response as in equation 1. was created in the DigSilent Power Factory v15.1. software. The selectivity of the controllers is important because the mechanical stress from the additional torque is spoiling the optimal operation of the device and it should be limited for when it is truly needed.

TABLE II. CONTROLLING PARAMETERS FOR WIND TURBINES

Parameter	Value
Derivative gain	1
ROCOF filter time constant	0,1 s
Inertia constant	10 s
Delay	0,01 s
Maximum output	0,1 p.u.
Minimum output	0
Gradient	1 p.u./s
Gain	1
ROCOF deadband	0,01

Figure 3. shows the block diagram of the controller. The input frequency is being derived and filtered – to avoid swings – and multiplied with H and f as in equation 1. This additional per-unit power signal then gets the dynamics of the inertial response with the delay, gradient and output limiting parameters. The dead band can provide selectivity to avoid unnecessary activations. Figure 4. represents the output signal in a specific disturbance. As it can be seen, the time constant of the activation and deactivation is different: the slope of the synthetic inertial response could be tuned to cooperate with the primary response to avoid further frequency drops. The dead band block is also capable of sensing the sign of the deviation (over or under the nominal value) and the direction of change, therefore if the frequency rises from e.g. 49,7 Hz up it will not try to slow it down with additional power. The time length of active state (10 s) and recovery time (20 s) of the wind turbine (to speed up the rotor for the optimal value again) also could be set. The controller is added to a DigSilent Power Factory Example wind controller to provide all the additional control loops needed. The synthetic inertia provides an augmented power signal for the PQ controller.

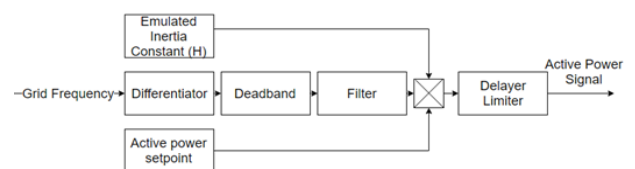


Fig. 3. Controller block diagram

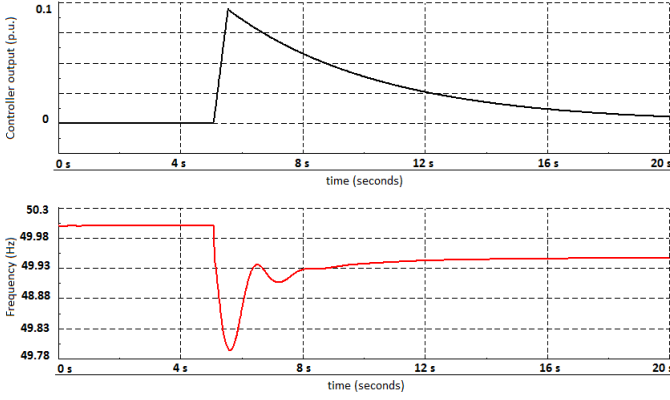


Fig. 4. Synthetic inertial response (black curve) and frequency during the activation

III. MODELLING AND EVALUATION METHODS

A. High penetration of non-synchronous generation

ENTSO-E conducted a research on the frequency stability evaluation criteria for the synchronous zone of continental Europe to identify the most important parameters. The modelling methodology was that non-synchronous generators does not provide inertial response, therefore the acceleration constant of the system is inversely proportional to the increase. [26]

$$T_N = \frac{\Delta P_{\text{imbalance}}}{P_{\text{load}}} * f_0 * \frac{1}{\frac{df}{dt}} \quad (2)$$

$$T_N = \frac{\sum_i T_{\text{syn},i} * S_{N,i}}{P_{\text{load}}} \quad (3)$$

Equation 2-3. are showing the calculation of acceleration time constant T_N and the relation to the other important parameters. $T_{\text{syn},i} * S_{N,i}$ is the kinetic energy of one machine's rotating mass, P_{load} is the system load, f_0 is the nominal frequency and df/dt is the ROCOF. From equation 2 boundary conditions can be set to the minimum inertia from the imbalances (relative to the sum of the load) and ROCOF (or any of those variables with the limiting of the other two).

In this study the external network is being modelled by a synchronous generator equivalent, and the system-wide spreading of renewables decrease the inertia time constant of this machine. The normative incidents are load step changes from 5% to 50%. These two parameters are giving an insight to the actual system state considering the effects of non-synchronous generations. The measured parameter is the minimum frequency during the disturbances. With this concept the inertial control could be seen as a part of the frequency control process. Local system models have different wind penetration and characteristics for further comparison. [26]

B. Evaluation of inertial response

The effects of synthetic inertia could be evaluated through the system operation during the disturbance. This paper is focusing on the disturbances result under frequency, therefore the different margins are only defined for these types of events.

Different system states:

- If the frequency is staying above 49.8 Hz, the state remains **ordinary**.
- Within the range of 49.8 Hz and 49 Hz the system is in **alert** state
- When the integrity of the system is endangered, ALS activation occurs (if applicable) which is chosen at a 49 Hz point for this modelling. Then the system is in an **emergency state**. If the frequency is falling below 47.5 Hz a system blackout can hardly be avoided. [26]

So the result parameter will be the frequency nadir during the disturbance. The non-synchronous generation varies from 0% to 90% (with a step of 10%) and the load increase varies from 5% to 50% (with a step of 5%). Firstly, there is no synthetic inertia implemented: this is the base case. After that the base case alert and emergency states could be identified and the selectivity could be set to only activate when the frequency falls below 49.8 Hz. The parameters of Table 2. was used in all the simulations to provide synthetic inertia with wind turbines. If this additional power is not enough to avoid ALS activation, then an energy storage system will be added and sized to provide enough emulated inertia in all system cases. Thus all the emergency states are being removed by the controlling of wind turbines and energy storage systems (only if necessary, and it has properly sized power output from iterative simulations).

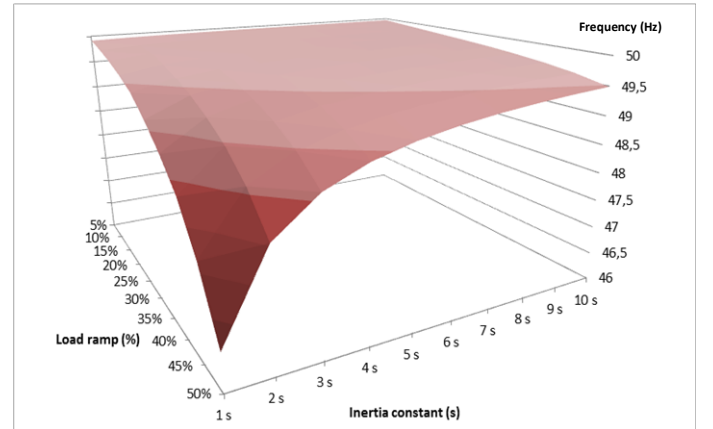


Fig. 5. Frequency nadir during disturbances without synthetic inertia, Mosonmagyaróvár (Hungarian network model)

Figure 5. shows the base case for the first test system, which a system model of Mosonmagyaróvár, a town in the north-west of Hungary. The simulations show that over 60% of non-synchronous generation and high imbalances ALS activations occur (in 10% of the 100 cases). The two parameter sets provide 100 different states which could be examined to evaluate the effects of the controlling methods.

IV. SIMULATION STUDIES

The following simulations were prepared with the DigSilent Power Factory 15.1 balanced RMS analysis which is capable of analyzing the electromechanical transients and frequency stability. There is no active ALS system implemented on the system which means that even under 49 Hz only the primary response (and the synthetic inertia control) could stabilize the system. The self-regulating effect of the loads (which is around 2% according to [26]) is negligible due to the worst case approach.

A. Hungarian network example

Figure 6. shows the network model of Mosonmagyaróvár. [31] There are some inactive elements on the topology because the system is capable of islanding operation with an additional slack generator and further work will include the island system frequency stability with high penetration of renewables. There are two wind farms connected (Mosonmagyaróvár and Mosonszolnok: the actual capacity of the wind farms is less than 50 MW right now but the order of magnitude is correct), and that will provide 44 MW and 6 MW during the simulations. The summarized load is 100 MW (13 Mvar). There is also a 15 MW gas turbine which has primary control assignments. The model includes the 10 kV cable system of the nearby town and the 20 kV transmission line system of the local villages. The external point is the 400 kV substation of Győr, where an international transmission line connects to the Hungarian system.

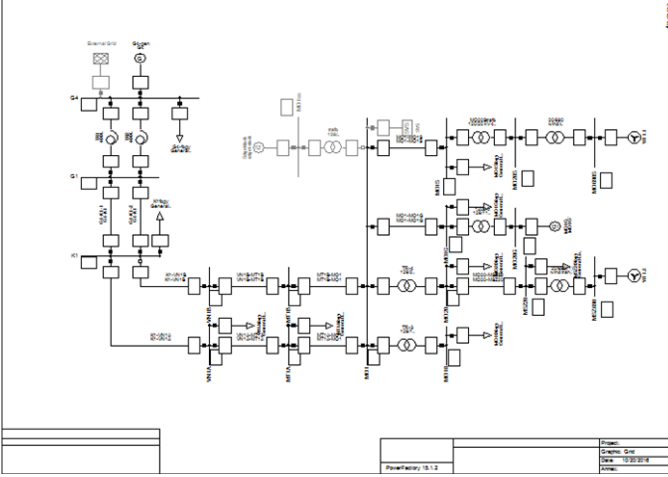


Fig. 6. Mosonmagyaróvár (Hungary) test system topology

Figure 7. represents the normalized ROCOF values in the base case. The reduction of inertia results in higher ROCOF as well as the higher imbalance. With the increase of intermittent generation, these two parameters will raise hand in hand, so proactive planning in frequency control is necessary.

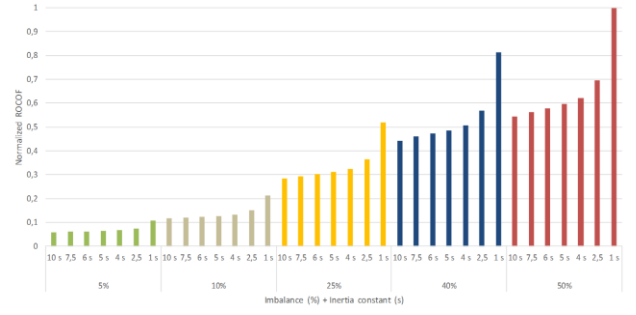


Fig. 7. Normalized ROCOF values without synthetic inertia, Mosonmagyaróvár test system

Table 3 summarizes the frequency nadir in the base case of Mosonmagyaróvár. If the frequency nadir stays above 49.8 Hz during the excursion the table cell has green background. The alert state has yellow coloring while the emergency has red. There are 10 ALS activations with low system inertia and high imbalance ratio. The 90% level of non-synchronous generation results exceptionally low frequency nadirs.

TABLE III. FREQUENCY NADIR DURING DISTURBANCES WITHOUT SYNTHETIC INERTIA, MOSONMAGYARÓVÁR

H(s)\dP(%)	5	10	15	20	25	30	35	40	45	50
1	49,912	49,823	49,716	49,581	49,410	49,120	48,768	48,334	47,644	46,648
2	49,931	49,862	49,790	49,698	49,581	49,428	49,228	48,967	48,586	48,037
3	49,941	49,882	49,823	49,755	49,669	49,560	49,422	49,237	48,978	48,600
4	49,948	49,895	49,843	49,788	49,720	49,636	49,529	49,386	49,189	48,903
5	49,952	49,905	49,857	49,809	49,754	49,684	49,597	49,481	49,322	49,093
6	49,956	49,912	49,868	49,825	49,777	49,718	49,643	49,546	49,414	49,222
7	49,959	49,918	49,878	49,837	49,794	49,743	49,677	49,593	49,480	49,315
8	49,961	49,923	49,885	49,846	49,808	49,762	49,703	49,629	49,531	49,387
9	49,963	49,927	49,890	49,854	49,817	49,776	49,723	49,658	49,570	49,442
10	49,965	49,930	49,895	49,860	49,825	49,787	49,740	49,681	49,602	49,487

Table 4. summarizes the simulation results with synthetic inertia control. The activation was tuned to the ROCOF measured in the first alert case of the base simulations, so in the ordinary states there are no changes. As it can be seen, 60% of the ALS activations could be avoided with the wind turbines on the system but there are still four activations. Therefore, an energy storage device has to be implemented to ensure the frequency stability of the system.

TABLE IV. FREQUENCY NADIR DURING DISTURBANCES WITH SYNTHETIC INERTIA FROM WIND GENERATORS, MOSONMAGYARÓVÁR

H(s)\dP(%)	5	10	15	20	25	30	35	40	45	50
1	49,912	49,823	49,810	49,708	49,591	49,445	49,196	48,864	48,482	47,871
2	49,931	49,862	49,807	49,799	49,714	49,611	49,470	49,286	49,056	48,720
3	49,941	49,882	49,823	49,829	49,773	49,694	49,592	49,465	49,302	49,070
4	49,948	49,895	49,843	49,808	49,801	49,742	49,663	49,564	49,436	49,261
5	49,952	49,905	49,857	49,809	49,811	49,771	49,701	49,627	49,522	49,380
6	49,956	49,912	49,868	49,825	49,817	49,785	49,739	49,670	49,581	49,462
7	49,959	49,918	49,878	49,837	49,810	49,796	49,753	49,701	49,623	49,522
8	49,961	49,923	49,885	49,846	49,808	49,801	49,768	49,723	49,655	49,567
9	49,963	49,927	49,890	49,854	49,817	49,806	49,778	49,733	49,680	49,602
10	49,965	49,930	49,895	49,860	49,825	49,815	49,786	49,747	49,693	49,630

With further iterative simulations, a 20 MW battery energy storage (which has the same dynamics of the wind turbine controller above) was chosen to avoid every ALS activation, and in that case the remaining frequency nadirs are all above the 49 Hz value

- $H=2\text{ s}, \Delta p=50\% \rightarrow f_n=49.6\text{ Hz}$
- $H=1\text{ s}, \Delta p=40\% \rightarrow f_n=49.524\text{ Hz}$
- $H=1\text{ s}, \Delta p=45\% \rightarrow f_n=49.327\text{ Hz}$
- $H=1\text{ s}, \Delta p=50\% \rightarrow f_n=49.001\text{ Hz}$

Figure 8. shows the frequency nadir surplus achieved with wind turbine synthetic inertia controlling (storage device effects not included). As it can be seen, in the emergency states there is a possibility to provide even 0,5-1,2 Hz rise which is astonishing.

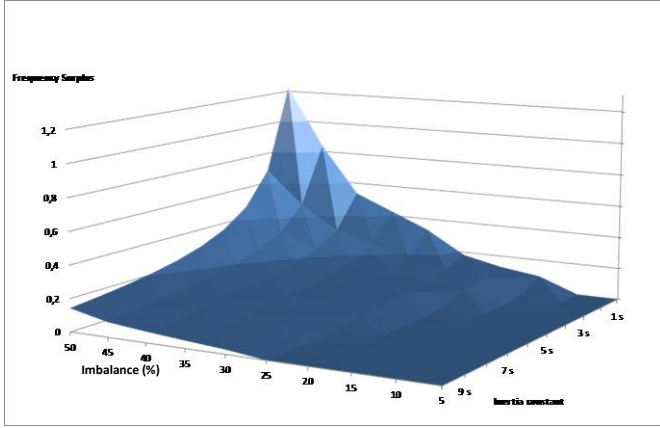


Fig. 8. Rising of the frequency nadir during disturbances: synthetic inertia control case surplus from the base case

B. IEEE modified 9-bus system

The second analyzed model is the IEEE 9-bus system [32]. The system load is 315 MW (115 Mvar). 2 synchronous generators replaced by wind farms. There are 12 buses, 6 transmission lines, 6 transformers and 3 constant impedance loads. A 100 MW wind farm is operating with synthetic inertia control while the other 50 MW has the built-in wind turbine control of a DigSilent Power Factory Example. This system is well-known and widely used for stability purpose studies, therefore it could be used as a validation of the methodology.

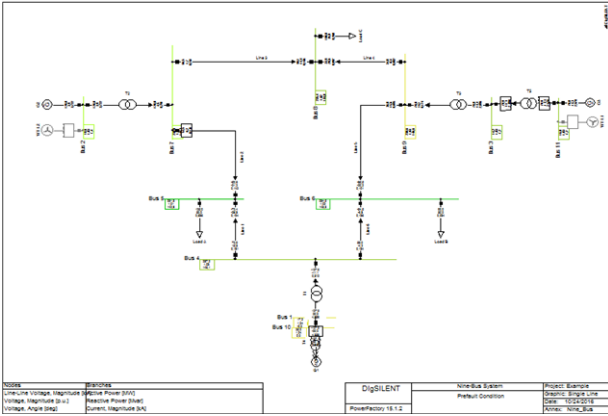


Fig. 9. 9-bus system topology in the DigSilent Power Factory software

Table 5. summarizes the base case frequency nadirs. As it can be seen, there are more alert states (marked with yellow) but only nine ALS activations (marked with red) happened here. The concept was the same again: during the first simulation scenario the effects of the wind turbine synthetic inertia control was observed. If there is still an ALS activation (nadir below 49 Hz) on the system, then an energy storage device assists to ensure the stability of the system. The power sizing of the device could be done with iterative simulations of different scenarios. The necessary capacity could be calculated from long-term frequency measurements (and it depends on the restrictions for charging: it can be scheduled easily with a

conventional generator). The possibility of an aggregated operation of such storage system (stability service is mostly a power requirement, therefore in ordinary states it can serve as e.g. a balancing provider).

TABLE V. FREQUENCY NADIR DURING DISTURBANCES WITHOUT SYNTHETIC INERTIA, 9-BUS SYSTEM

H(s)\dP(%)	5	10	15	20	25	30	35	40	45	50
1	49,860	49,715	49,565	49,388	49,192	48,986	48,770	48,549	48,325	48,100
2	49,892	49,784	49,679	49,569	49,439	49,293	49,136	48,970	48,795	48,614
3	49,912	49,817	49,728	49,640	49,546	49,437	49,316	49,182	49,034	48,887
4	49,921	49,838	49,758	49,680	49,604	49,518	49,420	49,310	49,189	49,058
5	49,927	49,852	49,779	49,709	49,640	49,569	49,486	49,393	49,289	49,175
6	49,932	49,863	49,796	49,730	49,666	49,603	49,532	49,452	49,361	49,259
7	49,936	49,871	49,808	49,747	49,686	49,627	49,566	49,495	49,414	49,322
8	49,939	49,878	49,818	49,760	49,702	49,647	49,591	49,528	49,455	49,371
9	49,942	49,883	49,826	49,771	49,716	49,663	49,611	49,554	49,488	49,411
10	49,943	49,888	49,833	49,780	49,727	49,676	49,626	49,575	49,514	49,443

Table 6. represents the effects of the synthetic inertia control of the 100 MW wind farm. The positive effects are clear; the system even remains in the ordinary state in every case under 10% load increase and load shedding is only occurring in the case of the highest non-synchronous generation.

TABLE VI. FREQUENCY NADIR DURING DISTURBANCES WITH SYNTHETIC INERTIA FROM WIND POWER, 9-BUS SYSTEM

H(s)\dP(%)	5	10	15	20	25	30	35	40	45	50
1	49,860	49,838	49,776	49,683	49,553	49,411	49,270	49,150	48,960	48,800
2	49,892	49,853	49,784	49,738	49,674	49,575	49,493	49,375	49,250	49,145
3	49,912	49,817	49,806	49,751	49,683	49,622	49,560	49,500	49,422	49,318
4	49,921	49,838	49,834	49,783	49,722	49,646	49,585	49,525	49,470	49,414
5	49,927	49,852	49,850	49,798	49,729	49,670	49,613	49,556	49,487	49,434
6	49,932	49,863	49,834	49,796	49,747	49,692	49,640	49,586	49,527	49,455
7	49,936	49,871	49,808	49,807	49,761	49,710	49,656	49,607	49,555	49,496
8	49,939	49,878	49,818	49,816	49,772	49,720	49,673	49,627	49,580	49,523
9	49,942	49,883	49,826	49,824	49,781	49,731	49,686	49,642	49,596	49,548
10	49,943	49,888	49,833	49,830	49,794	49,740	49,697	49,655	49,611	49,568

Figure 10. shows the raise of the frequency nadir caused by the synthetic inertia control (storage device effects not included). In emergency states it is also over 0,5 Hz ascent just like in IV/A.

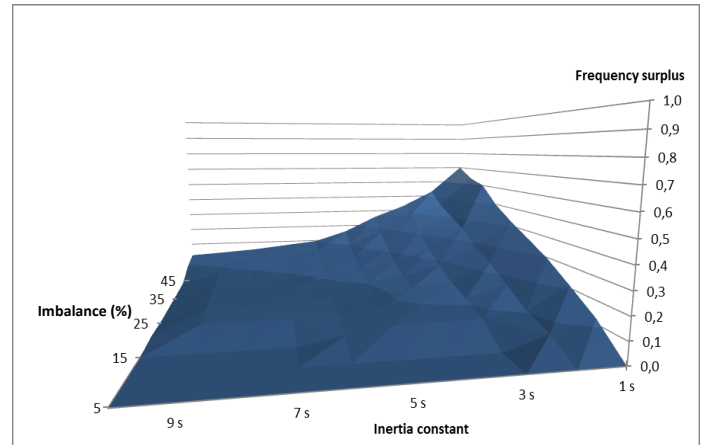


Fig. 10. Raise of the frequency nadir during disturbances: difference between synthetic inertia aided case and base case

Only two ALS activation remained so a rather smaller storage system is enough to solve the problem. Based on iterative simulations, a 6 MW battery system (with the same dynamics as above) was enough to keep the system away from emergency states the surplus is over 0.5 Hz. It is also important that just wind generation could bring up the worst state to the first level of ALS if a 0.2 Hz step size is considered. Simulations shows that wind turbines are capable of providing

a 0.5-1 Hz nadir ascent and only fail to avoid ALS activations in the highest imbalance-low system inertia cases.

V. CONCLUSIONS

The purpose of this work was to take a look at the possible role of synthetic inertia and the effects it could have on certain power system. The spreading of renewable energy sources – especially the non-synchronous type of generation – reduces inertia and it threatens the frequency stability of the power system.

An adequate answer for the problem could be the augmented control of those devices to provide inertial response. The technological options offer wide-range of solutions such as additional torque from wind turbines, energy storage systems and modification of direct current networks. The controlling methods needs proper dynamic and limiting parameters such as rate of change of power output, emulated inertia constant and maximum deviation from nominal output and has to be coherent with the technology. Selectivity of the process is also important to avoid unnecessary operation.

The ENTSO-E conducted a research about the possible criteria for system inertia, and based on that methodology an evaluation process was composed to measure the effects. The aim was to avoid the automatic load shedding which is determined to activate at 49 Hz. During the simulations, a detailed synthetic inertia controller was examined. The wide range of parameter settings allows the usage of technology measurement data, therefore the tuning of inertial response control is feasible with the composed models. Nearly 70% of the examined system states were alert and emergency ones. More than half of the ALS activations was avoided with only wind generators in both models which means that implementing synthetic inertia control for non-synchronous generations enhance stability. To evade all, a properly sized energy storage system was added to the grid models to enhance stability, which had 20 MW power in Mosonmagyaróvár and 6 MW in the 9-bus system for the 6 worst scenarios. With the evaluation concepts presented, the optimization of synthetic inertia activations can be planned effectively. In the further work frequency stability of islanding systems should be examined properly to understand the processes after a worst-case system-split.

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