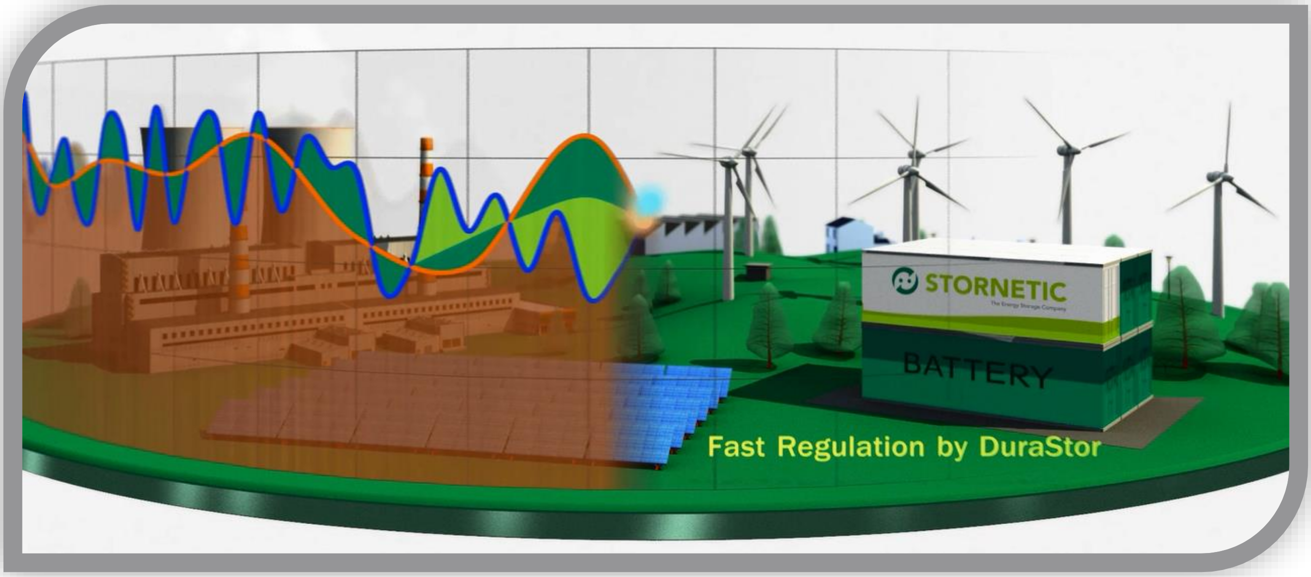
White Paper

Benefits of Flywheels for Grid Stabilization



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Executive Summary

The continued expansion of renewable energy sources like wind power and photovoltaics is gradually reducing short term and long term grid stability, especially as more and more conventional thermal power plants go offline and get decommissioned. Power to Gas, Power to Heat and flexible load management provide a solution to deal with the challenges to long term (5 to 12 hours) grid stability.

Fast response Flywheel Storage provides an efficient and affordable solution to cope with the short term (0 seconds to 5 minutes) challenges to grid stability.

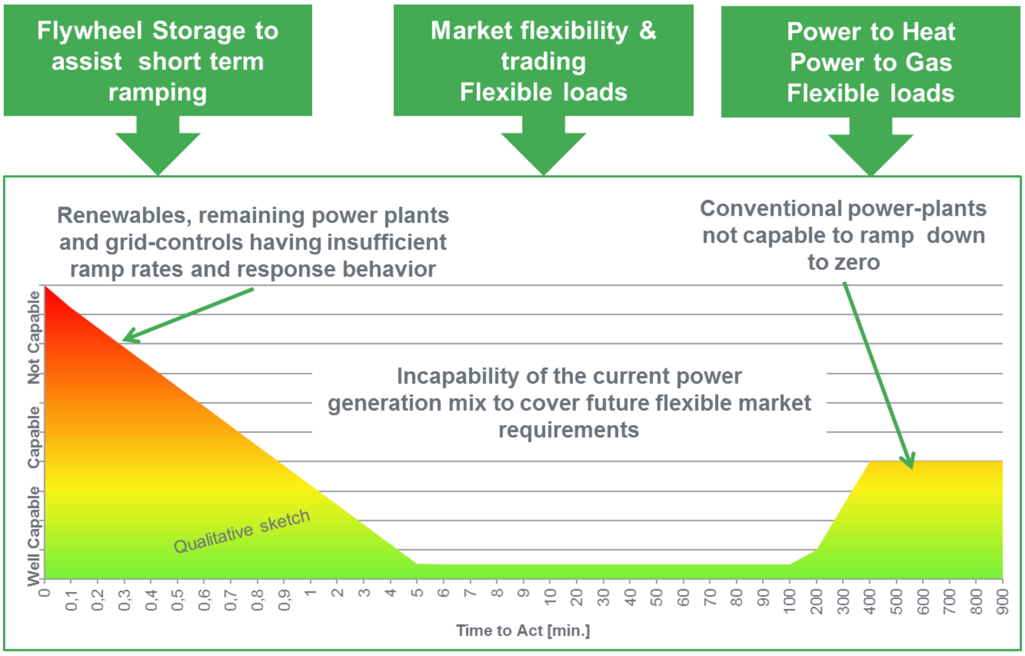


Figure 1: Capability of the current electricity generation mix to follow future grid demands

Figure 1 shows that new technology solutions are needed to deal with challenges to grid stability in the future and that already today with market instruments like day ahead production planning and bidding, intraday, intra-hour and ancillary service trading, many fluctuations longer 5 minutes up to 5 hours can be balanced out quite well and with high flexibility. The remaining fluctuations are currently easy to cover with typical frequency regulation market mechanisms provided by power plants or storage facilities or by managed renewable energy sources like wind turbines or larger controllable solar installations.

Fluctuations longer 5 hours and shorter 24 hours can create a problem with conventional thermal power plants. In case they are needed for intraday peaks and/or grid stabilization services they need to run at a minimum with 30% to 40% of their total capacity. As a consequence they are blocking energy slots which could ideally be filled with renewable energy. This creates limitations in further reducing the CO_2 pollution and increase the renewable share.

On the other hand especially these conventional thermal power plants provide a significant amount of inertia necessary to stabilize the frequency of the power grid today. A good example here is Ireland having an only weakly inter-connected island grid and a renewable penetration growing towards 50%. Currently the renewable growth is limited by grid stability constraints requiring the Irish grid operator to invent new markets and tools to stabilize the grid before the next step to 75% renewable share can be made (1). Another example is Hawaiian Electric Power Supply Improvement Plan (2).

But Figure 1 also shows that the real challenge to grid stability will be the management of very short term fluctuation typically shorter than 5 minutes and especially shorter than 30 seconds. This has multiple reasons. Obviously, power managements systems or operators have only little time to react to fluctuations. Currently the data needed to react appropriately is either not existing or only insufficiently gathered. And even once all the relevant data would be available, a grid managed purely based on data and information technology would be less stable than an almost inherently stable grid, as it exists today.

The main reason for the almost inherent short-term stability of today grids is the fact that grids strongly rely on what is called “grid inertia”. This grid inertia is a physical effect automatically provided by generators producing electricity. Because grid inertia is physical, it is also, within the technical constraints, available immediately or instantaneous. Therefore, it does require an operator interaction. In addition, the generators also “create” with the grid frequency a reference signal allowing other market participants to interact appropriately.

As conventional thermal power plants will more and more disappear from the grid, other methods need to be found to replace their inertia and to guarantee grid stability for the first milliseconds up to at least 60 seconds or more. Figure 2 shows how fast response Flywheel Storage technology can provide reliable and efficient solutions without having the need to operate too much synchronous generators to stabilize the grid frequency. Additionally the Whitepaper shows that the investments needed to provide sufficient synthetic inertia can be financed by the savings from not operating synchronous inertia for the sake of grid stabilization.

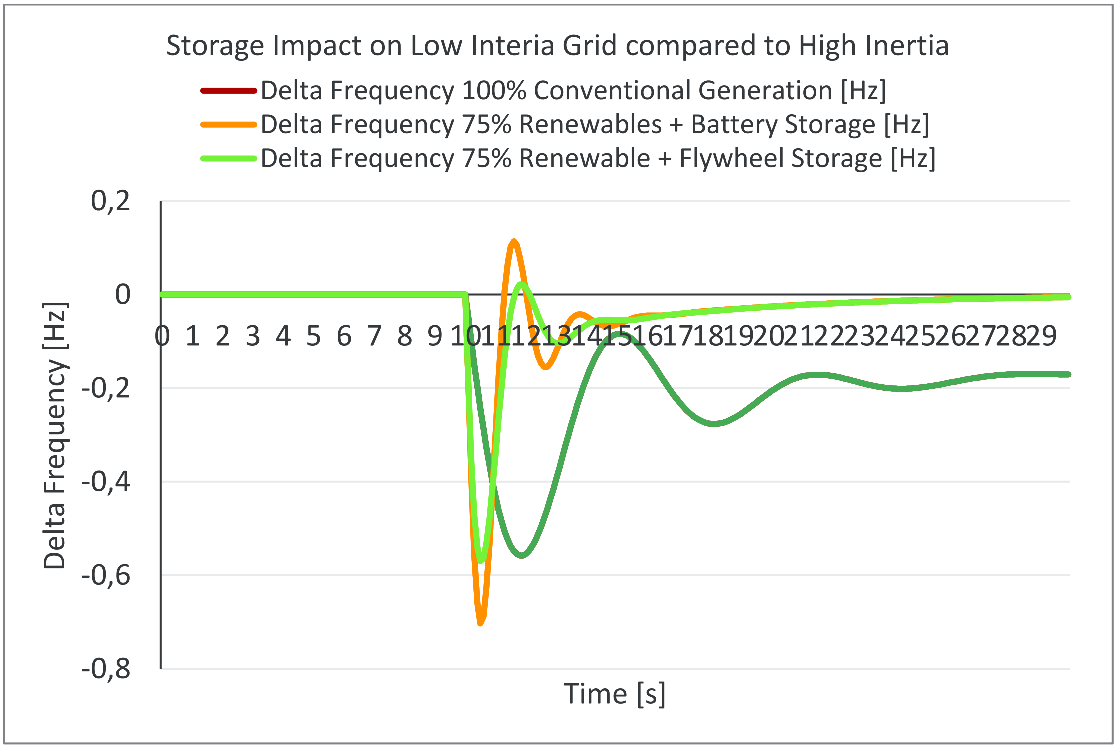


Figure 2: Comparison how Flywheel, Battery or conventional generator support the grid during a fault

Contents

Introduction

Systems with reduced grid inertia are more sensitive against load changes (3), (4), (5), (6). Figure 3 shows the response of the Continental European grid to a critical load change of losing 3000MW (≈5%) of power. The blue curve shows the impact of the European grid with hardly any renewables generation and conventional energy with an average inertia[1] (H) of 6s with primary frequency responses within 30 seconds as it is standard today. The red curve shows the theoretical response to the same fault in the same grid but with 50% renewable energy share. The red curve violates one stability criteria of 500mHz. The diagram also shows that in principle and globally reaction time matters. Even with 50% renewable share the continental European grid could operate after the first seconds even more stable, if the reaction time (T^1) of primary frequency resources can be increased from 30 seconds to 5 seconds, for instance by using fast controllable and fast reacting resources like energy storage systems.

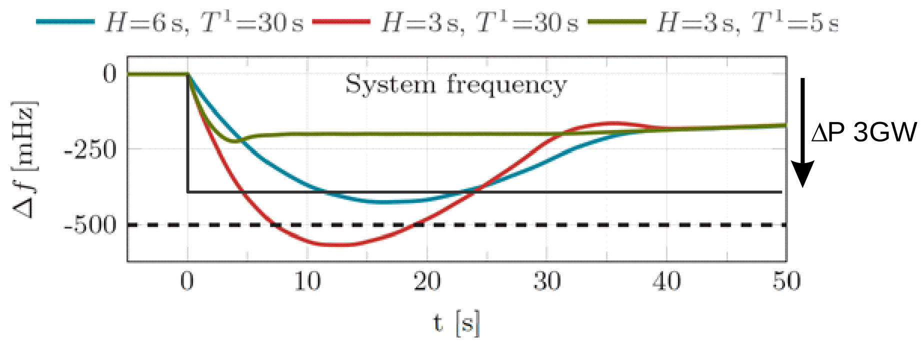


Figure 3: Dynamic Response of the continental European area power system to faults (3), (7)

Looking to Figure 3 one can ask whether we have problem at all. Basically there are following restrictions to considered as well:

- Figure 3 assumes that all regions and powerstations are ideally electrically connected and the current can flow mainly without physical restrictions. This is in principle relatively true for example for the well-interconnected Continental European grid. A regional fault or inbalance will get compensated even by more far distanced power plants as long the power lines can handle the electrical current. For

[1] Inertia Constant H=(Kinetic Energy of a Generator+Turbine)/(rated Electrical Power)

many Island-, or more weakly interconnected regional grids this cannot be assumed, especially then when power-lines are not designed strong enough to handle the required current/power flows.

- The required change of response time to stabilize come along with significant investment, as it requires a change of technology either to fast reacting gas turbines or energy storage solutions. The currently existing market mechanisms are unfortunately not allowing financing such investments, see Figure 4 and Figure 5**Fehler! Verweisquelle konnte nicht gefunden werden.**. Mechanism to monetize reaction speed hardly exist. UK and Ireland are introducing now "Enhanced Frequency Regulation" services paying a bonus for very fast response.

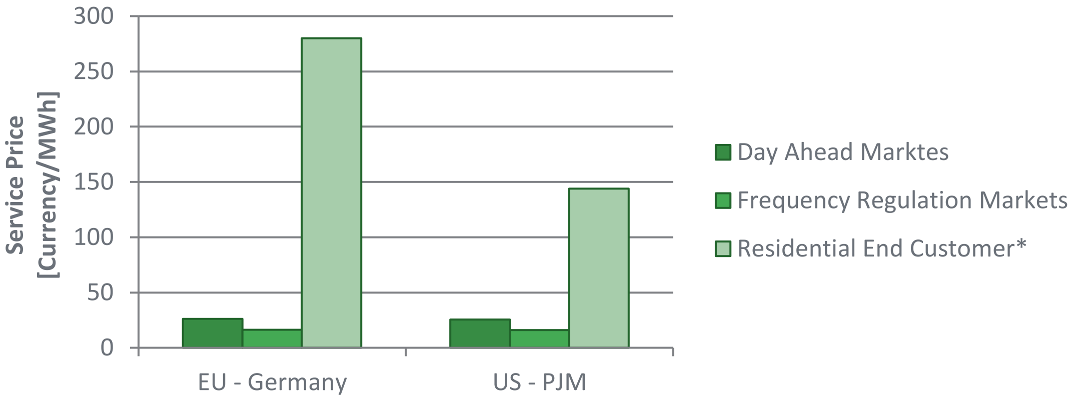
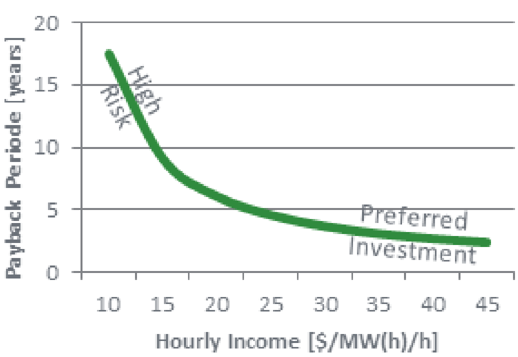


Figure 4: Q1 2016 Energy Prices for Day Ahead Energy Auctions and Primary like Frequency Regulation Service in wholesale markets compare to end customer prices(Data from EEX Spot and PJM Data Portal, , Eurostat, * EIA and Regelleistung.net; May 2016 prices from Pennsylvania)

Figure 4 shows the auction prices for primary frequency regulation in Germany and the US. They are in average below 20$/kW/hour and strongly depend on competition. The market prices for ancillary services have come under pressure in many markets due to overcapacity in conventional generation caused by the renewable growth. This makes business cases less attractive today for energy storage in the wholesale markets. Figure 5 shows risky payback times at hourly rates below 20$/kW/hour. Especially for battery storage projects also increased technical risks exists, because the payback period might be close or longer to the technical lifetime of the battery (8).



Assumptions	Value	Unit
System size	1	MW
Project investment	800	$/kW
Availability	98%	
Annual operating costs	5%	of the invest.
Investment	800000	$
Annual operating costs	40000	$

Figure 5: Exemplary calculation of the impact of the hourly income on the breakeven of an exemplary storage investment

However, storage systems have been successfully used to balance grids and are getting an integral part for system stability for instance in Ireland (1) or the US (9). Studies have shown that the fast response time of flywheel and battery storage systems compared to conventional generators have a positive influence on grid stability and ancillary service costs (10) whilst also reducing the CO_2 pollution by some percent (11).

High Level Solutions

Today multiple solutions are in discussion to cover the upcoming problem of grid stability due to reduced inertia. In general the assumption is that system will get more and more decentral and with this smaller in individual power sizing. First steps have also been taken to make renewable sources providing system stability services. For instance a new regulation "VDE-AR-N 4105 " will require solar systems to smoothly fade out when grid frequency gets close to 50,2Hz. Table 1 provides an overview of discussed solutions providing short-term grid stabilization services.

Solution	Pros.	Cons
Adjust renewable generation at over-frequency (Curtailment)	• Low cost solution mainly introduced by software changes • It provide service proportional to the renewable share • Number of installations is increasing	• It's only available during renewable generation => less predictable and not manageable • Hidden curtailment facing some lobbyist resistance • It is not immediate as it needs to balance the interest of energy supply versus system stability (up to 1 second deadtime)
Adjust renewable generation at under-frequency (Curtailment)	• Relatively easy to implement • It provide service proportional to the renewable share • Number of installations is increasing	• It can only provide low frequency support if continuous curtailment is accepted to have a power reserve needed => • It reduce the overall renewable generation due to power reserve needed • Increased pay-back times because of opportunity losses • It's only available during renewable generation => less predictable and not manageable • It is not immediate as it needs to balance the interest of energy supply versus system stability (up to 1 second deadtime)
Use of gas motors like Biomass or smaller CHP systems	• It's real inertia and thus instantaneous • At least biomass is more baseload power and therefore predictable and manageable • Number of installations is increasing	• Due to the slow response characteristic of gas motors and little mechanical inertia service is limited in impact and the H-Factor is <<1. • If providing primary frequency regulation the owner can have opportunity losses
Use of gas turbines or CHP turbines	• It's real inertia and thus instantaneous	• If providing primary frequency regulation the owner has opportunity losses

Solution	Pros.	Cons
	• It's more baseload power and therefore predictable and manageable • It's very responsive and can well provide shot term primary frequency services	• Technology is getting threatened by battery storage
Pumped hydro in short circuit operation	• It's real inertia and thus instantaneous • It's more baseload power and therefore predictable and manageable • It's very responsive and can well provide shot term primary frequency services	• High operating cost because of continues losses of about 30% • Increased maintenance effort
Battery Storage	• Can be combined with mid and long term storage • Relatively responsive (100 to 1000ms) and thus good fast frequency control	• No real inertia and does not provide support for the first 100 to 500ms • In continuous frequency control load cycles reduce battery lifetime
Synchronous flywheels	• It's real inertia and thus instantaneous • Provide a lot of power for a few seconds	• Can only provide energy for a few seconds (H-Factor <2s) • Relatively expensive and specialized • Continues losses
EnWheels (non - synchronous flywheels)	• Provide a lot of power for a few minutes • Very Responsive (toggle from charging to discharging in a few 10 milliseconds and thus good very fast frequency control • Load cycle resistance and long lifetime	• Non synchronous grid inertia • Limited to few minutes grid support
Hybrid solutions with EnWheels and Generators or turbines	• Provide real synchronous inertia • Very Responsive (toggle from charging to discharging in 10 milliseconds and thus good very fast frequency control • Load cycle resistance and long lifetime	• In combination with gas motors only providing synchronous inertia as long the gas motor is in operation • Continues losses around 7% to 10%

Table 1: Suitability of various technologies stabilizing the grid

Figure 3 shows the benefit of synchronous reserve but also the benefit very fast responding systems on grid stability. The combination of both would allow enhancing grid stability at the most limited investment into power. In addition, most of systems can be installed decentralized solving local constrains and being more adaptive.

System Design

To judge capabilities of the various solutions it is needed to understand constrains existing and where they come from. This finally will also explains the physical gap between synchronous and non-synchronous solutions and the remaining risks of losing more and more synchronous reserve.

Functioning of synchronous generators

A rotor having a magnetic field is typically rotating often with half speed of the grid frequency (f) who is passing stator coils can describe a synchronous generator. The rotor is typically driven by a motor or turbine that creates the required mechanical energy, power and torque, see Figure 6.

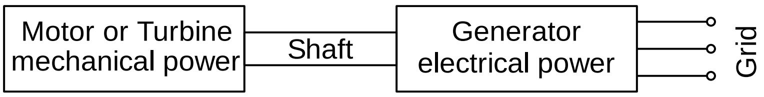


Figure 6: Schematic of the power transfer from Motor/Turbine to Generator and Grid

The magnetic field of the rotor transfers the mechanical energy into the three coils of the stator assembled under an angle of 120° see Figure 7. By doing this, the magnetic field of the rotor (B_{Rotor}) induces electric voltage (u_{ind}) in the coils of the stator and a current (i) and with this electrical energy and power. A generator transforms mechanical power into electro-magnetic power and finally into electrical power delivered to the grid. In a steady state operation the electrical and mechanical energy and power is balanced out and motor and generator are rotating with constant speed. This speed is the equals the grid frequency.

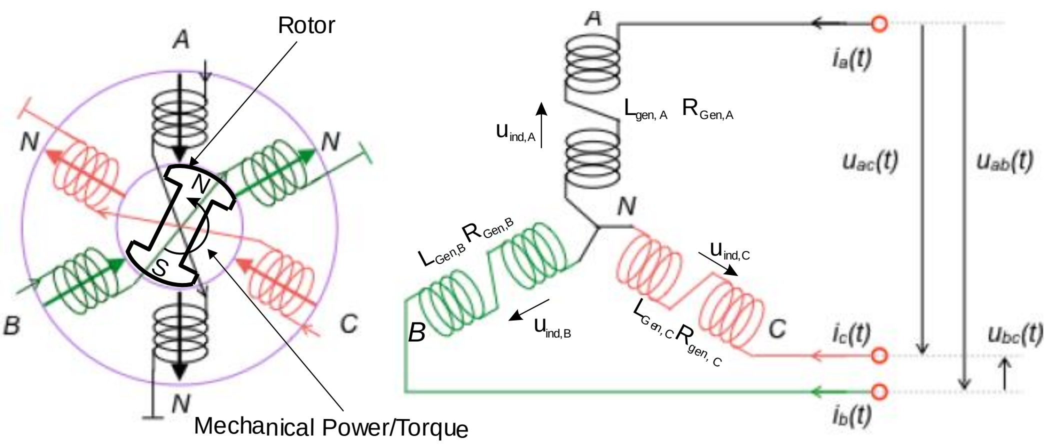


Figure 7: Rotor and Stator Coils and the induced voltages (12)

This voltage is normally controlled and a function of rotor speed, the magnetic field density and the coil design. In generator mode, the generator is typically the point of the highest voltage in the grid ($U_{Ind} > U_{Load}$). Consequently, the electrical current (i) will flow automatically to the direction of the load (R_{Load}) see Figure 8.

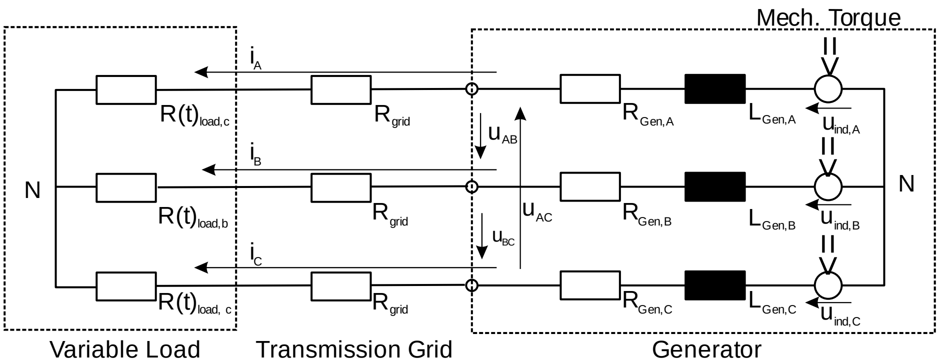


Figure 8: Electrical Layout of a generator in a grid with Voltages and Currents (12)

If now the load changes, because of Ohm's Law, the current (i) will change immediately as well and the coils of generator will automatically deliver the required current (i) in the first milliseconds. Therefore, synchronous generator immediately start to support the grid when the grid load changes.

Obviously, the changed current also flows through the stator coils of the generator, this changes the electro-magnetic counter-field (B_{Stator}), and with this, the electro-magnetic torque of the stator (T_{el}), see next formula with k being a generator constant.

$$T_{el} = \frac{k}{2 * \pi * f} * B_{Stator} * B_{Rotor} * \sin \delta(t)$$

To achieve again a new electro-magnetic energetic equilibrium the angle (sin $\delta(\tau)$) changes automatically until the magnetically transferred energy equals the electrical energy. This will change the electrical torque (T_{el}). Now the equilibrium between the electrical Torque (Tel) and the mechanical torque (T_{mech}) of the motor/turbine gets disturbed.

$$T_{mech} \neq T_{el}$$

As a consequence the speed of the generator changes and with this the grid frequency. This change will only stop if the mechanical torque (T_{mech}) is adjusted to the electrical torque and a new equilibrium is again achieved. The mechanical part of this process is described by the so called swing equation (13), (14). J is the mechanical inertia of the turbine-generator set.

$$J * \dot{\omega}(t) = T_{mech} - T_{el}$$

The formula describes that mechanical energy is taken out of the rotating mechanical inertia (J) until by other means/adjustments the mechanical and electrical torque equilibrium is achieved again. Consequently, the shaft accelerates or decelerates ($\dot{\omega}$).

Figure 9 shows, that grid synchronous generators

- Immediately deliver the electrical current into the grid by physical means
- React to a load change by changing its speed. If the load increases the generators slows down if the load decreases the generator accelerates.
- Support the grid all the time but also changes the grid frequency as a consequence
- Need a change of mechanical power or torque to compensate the frequency change
- Always providing a sinus wave voltage signal being synchronous to the grid frequency

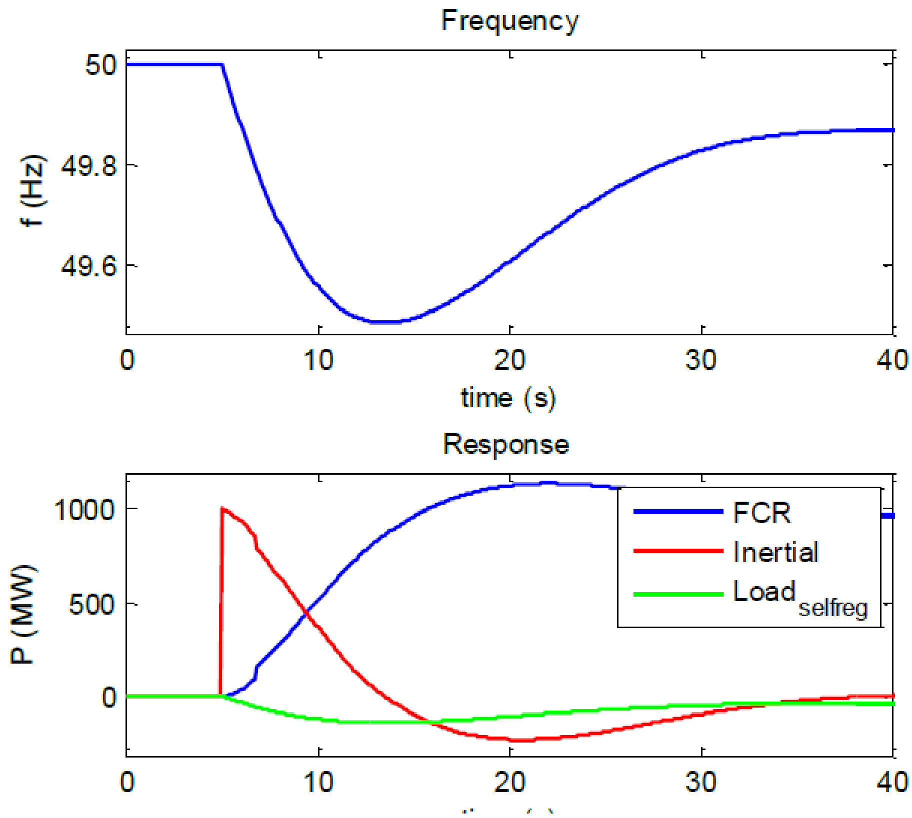


Figure 9: Frequency, Inertial Response and Frequency recovery of a network of synchronous generators (14)

This service is called "Synchronous Grid Inertia" and is a very important factor for grid stability. The swing equation also shows that the change of grid frequency (ω) is by definitions a consequence of load change always being delayed compared to the load step as also shown in Figure 3.

Inverter based systems and their behavior stabilizing the grid

All systems producing energy without using a synchronous generator need inverters to deliver inject electrical power into the grid. For example, are solar and battery systems inverter based and most wind turbines as well.

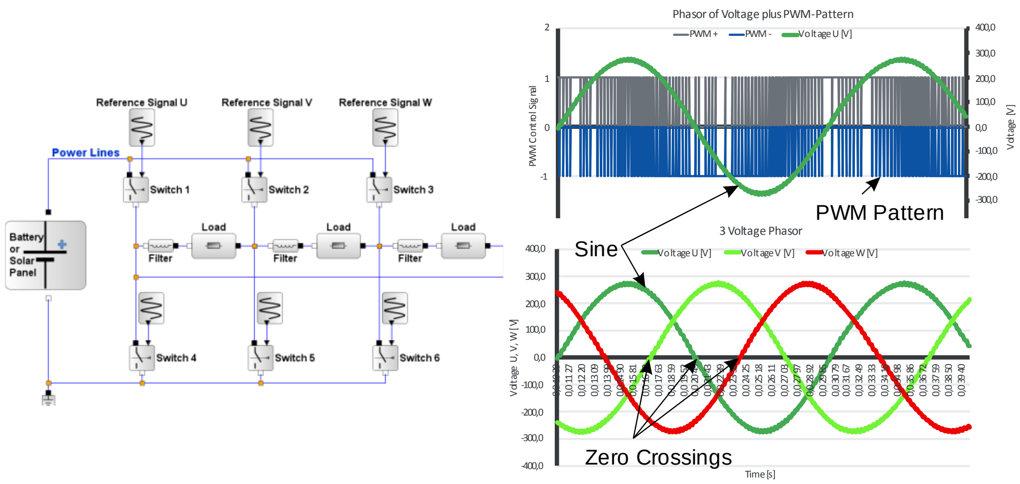


Figure 10: H-Bridge creating 3 Phase Voltage (12)

The inverter uses DC current and voltage and creates a sinus like AC voltage and current using power electronic switches chopping the DC-current into rectangular pulses with a moduled length. This method is called “Puls Width Modulation” (PWM). With the help on LC-Filters an almost sinus like current is injected to the grid. A typical design is shown in Figure 10. Based on a reference signal for every phase a dedicated PWM pattern is generated that switches the semiconductors. With every switch current is released into the grid formed to sinus by using an LC filter.

Figure 10 shows that a reference signal is needed to create the AC power. Typically, grid connected inverters measure and predict constantly the three grid phasors and create out of this the reference signal controlling the semiconductors. The inverter insures that electrical current is injected in phase with the rest of the grid to avoid severe problems. Only very small misalignments are acceptable. The phasor measurement is especially problematic. Due to the sinus character, signals are constantly changing and need to be measured and computed with a high sampling rate.

As long conditions are not changing significantly, the phasors can be predicted well. If conditions change, some interpolations are needed before the phasor change is characterized properly in amplitude, angle and speed. These measurements take time, especially if it concerns grid frequency typically 2 phasor zerocrossing, see Figure 10, are needed before the new frequency is measured properly. This already creates a delay of 8ms (15) to 35ms (9). In addition, out the new measurement, a new reference signals needs to be computed causing an additional delay up to a few milliseconds, before an inverter-based system can react to grid changes. In addition to this, some technologies like batteries have often a slope on the response ramp to avoid operating in conditions not specified. Lithium batteries typically have slope between 100ms to 1000ms.

Therefore, inverter driven systems have the following fundamental difference compared with synchronous generators:

- Inverter based systems always respond with a delay and do not support the grid immediately
- All interactions and changes are based on computations, are consciously and not coming from physical effects
- Depending on the DC source additional reaction delays can exist
- The sine is not perfect and can have harmonics

Grid voltage or frequency support provided by inverter-based systems is therefore often called “Synthetic Inertia”. Although the name implies the existence of inertia it is not based on inertia at all. Systems, if programmed to provide this service, only try to deliver current/power to the grid in a way that it supports the grid. Table 2 highlights the differences between synthetic inertia and synchronous inertia at different points in time after an event occurs and

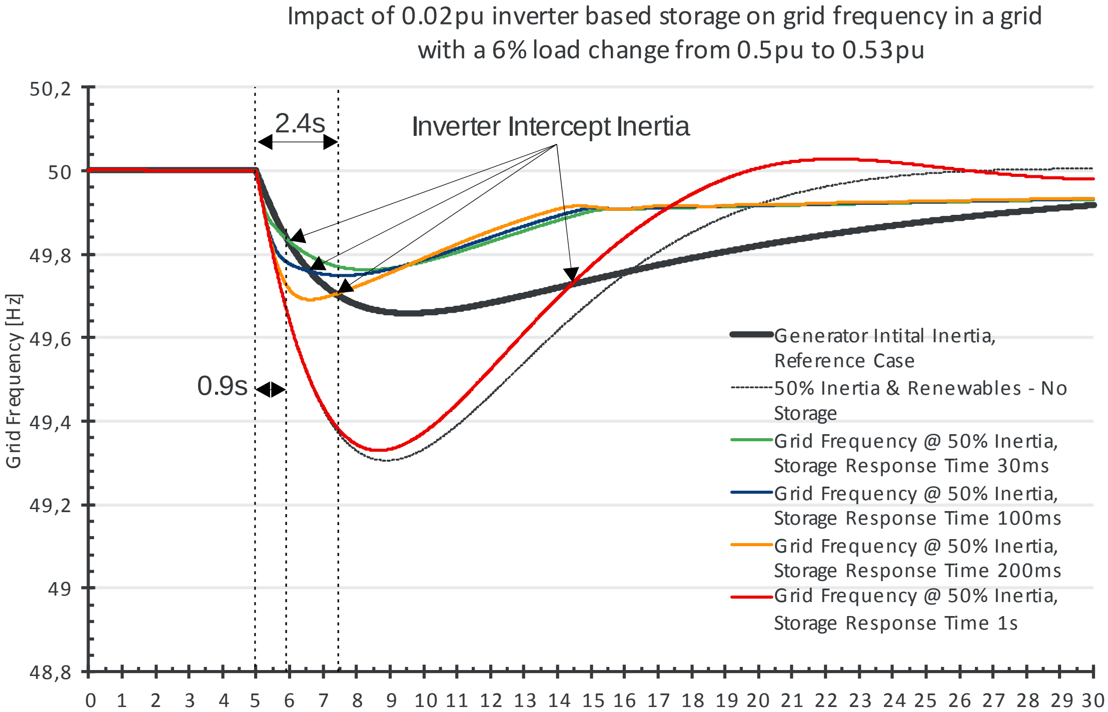


Figure 11 visualizes the differences.

Compared to case with high grid inertia inverter based systems have disadvantage within the first seconds. The disadvantage is strongly related to the response time of the system. Systems with short response times and little deadtimes compensate fast. Systems with response times longer 1000ms almost do not contribute to short term grid stability.
Most inverter-based systems allow the grid recovering faster compared to pure synchronous reserves assuming identical setting for the generators remaining in the grid.

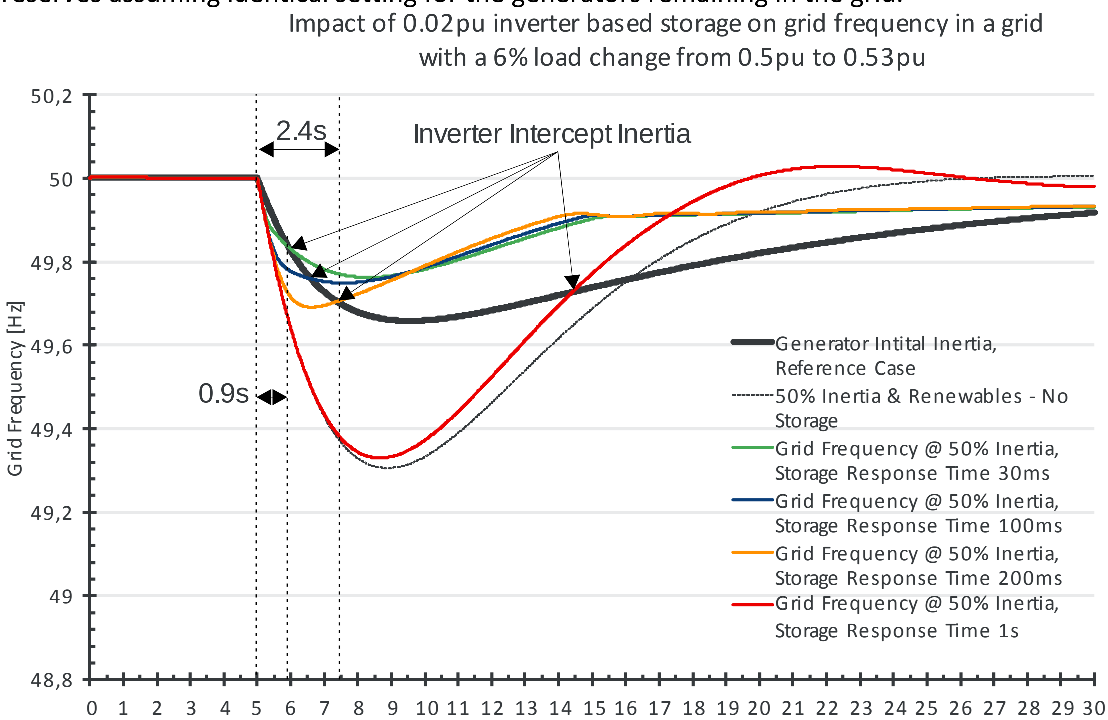


Figure 11: Impact of inverter based storage on grid frequency compared to inertial responses

Timeframe[2]	Synchronous Inertia[3]	Inverter Based (synthetic) Inertia[4]
0ms up to ≈30ms	• Provides required power based on Ohm's law • Grid frequency change hardly visible	• No support
≈30ms up to ≤1s	• Provides required power • Frequency starts changing visibly	• Provides power ramping up based on technology and control algorithm within ≈50ms up to ≤1 second
≤1s up to ≈5s	• Provides required power • Depending on load step strong change of frequency visible • Mechanical torque starts to adjust	• Delivers required power • Stops frequency drift • Based on control algorithm frequency drift starts to recovers
≈5s up to ≈30s	• Provides required power • Torque adjustment stops frequency drift	• Delivers required power • Grid frequency is recovering
≈30s up to ≈5min	• Provides required power • Torque adjustment helps to recover frequency	• Delivers required power • Grid frequency is recovered

Table 2: Grid support of synchronous and inverter based generation at various timeframes

For grid services it is key to further reduce the reaction time of the inverter based system, allowing to further close the gap to synchronous generation within the first second and allow stable grid operation with less synchronous generation.

Improved responsiveness of inverter based storage systems

[2] Timeframe can vary based on technology and vendor. Figures are indicative representing typical solutions existing today or requirements from typical grid codes (7), (18),
[3] Statements is assuming sufficient power installed
[4] Statements is assuming sufficient power installed. Figures are indicative representing typical solutions existing today.

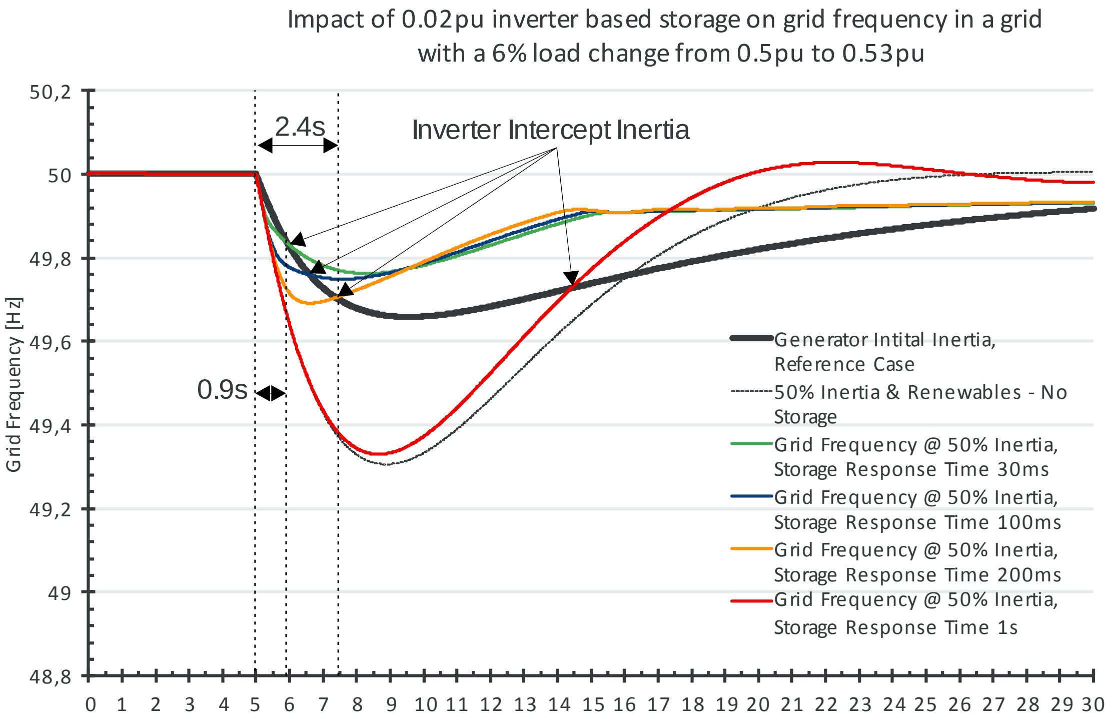
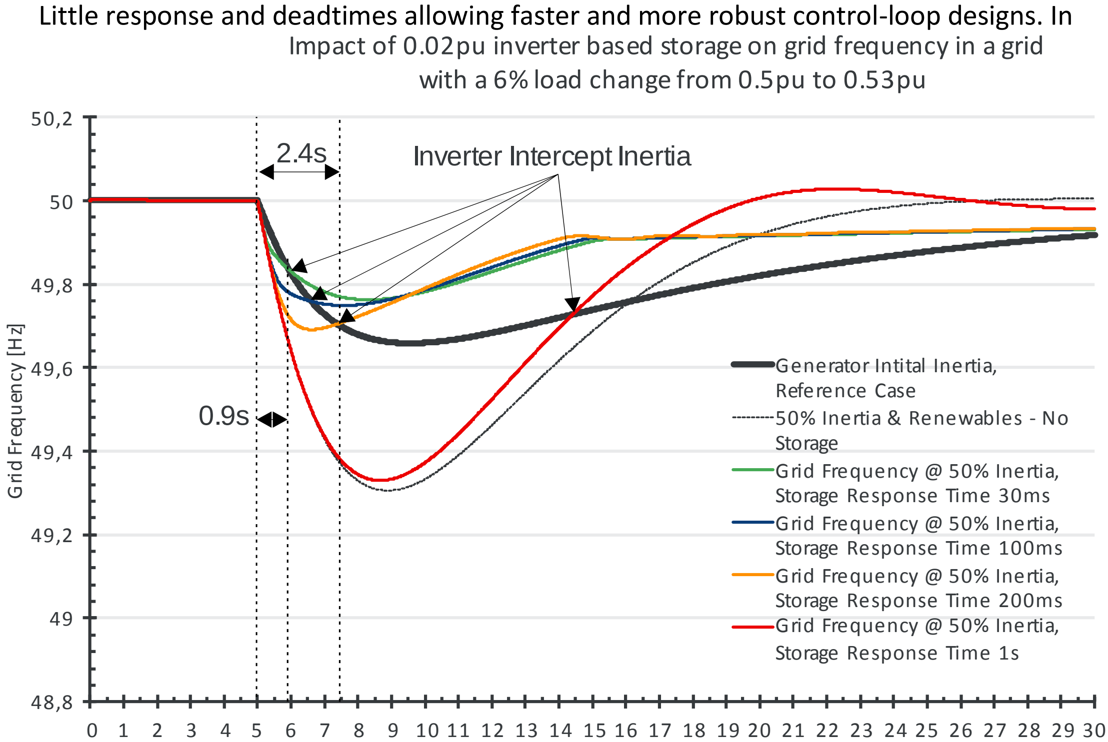


Figure 11 and Table 2 show the benefit of fast responding inverter based resources for grid stability. Storage systems in particular allow compensating bidirectional load changes whilst today renewable generation curtailment is mainly used in high frequency scenarios. Fast response with little deadtimes helps grid recovering because of mainly two effects:

- Fast adjustment of power obviously leads into faster achieving a new equilibrium giving stability

Little response and deadtimes allowing faster and more robust control-loop designs. In



- Figure 11 the orange and red curves are already at the edge of start swinging while the other curves are showing a more robust process setup. This effect directly relates with the response time of the process supplying the power. The longer the response time gets the softer the controller has to act to avoid instabilities. This leads to additional system response delays.

To understand system response and its impact on grid frequency it is helpful analyze the system including measurements, computation, system component responses and control loop designs.

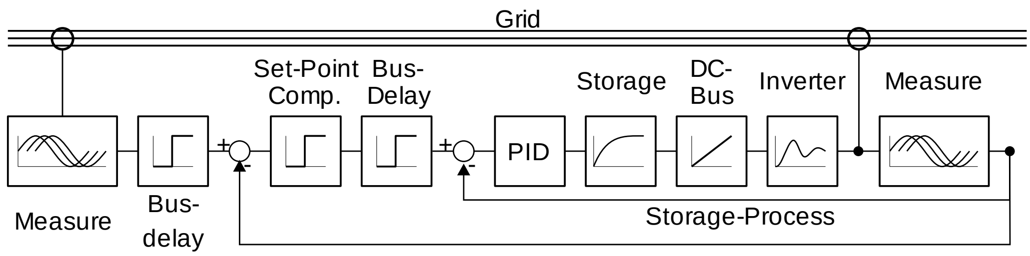


Figure 12: Typical process of an inverter based storage system

Critical processes are the grid measurements, the computation times and the storage response. Depending on the measurements methods chosen measurement times can vary from 10ms up to > 0.5s. Especially true RMS measurements require more time. Bus- and computation delays can additionally add up to 10ms or more. The response of the storage itself depends on technologies and has often artificially limited ramp rates or slopes. All in all control loops can get long limiting the use of energy storage systems for frequency regulation, but fast control designs are possible too.

To achieve shorter to very short reaction times system operator have to make a choice. Today frequency regulation services are typically designed having a corridor of no action (deadband) followed by a proportional correction action (P-Controller). A long slope time (I-Controller with long integration time) is usual before a service is fully triggered. Typical examples for such services are primary and secondary frequency response. By definition, these PI systems are slow but they avoid radical interactions. To replace inertia with synthetic inertia a different control behavior is needed acting proportionally with reasonable short integration time but in addition maybe even differentially acting on the rate of change (PI(D)-Controller) see Figure 14.

Figure 13 shows the response of a simulated grid to a ROCOF event of 13% of the nominal grid capacity at various level of inertia and with storage support. Within the first second a small difference exists between a high inertial grid and a grid supported with fast storage. Nevertheless, if the amount of power installed is sufficient, the total frequency drop is about the same as of a high inertia grid. The storage supported grid recovers after one second much faster than a grid with high inertia. To achieve this the system requires fast responding control loops with 50ms response times and ramp rates 20MW/s/(Installed MW) resulting in a demanding load profile.

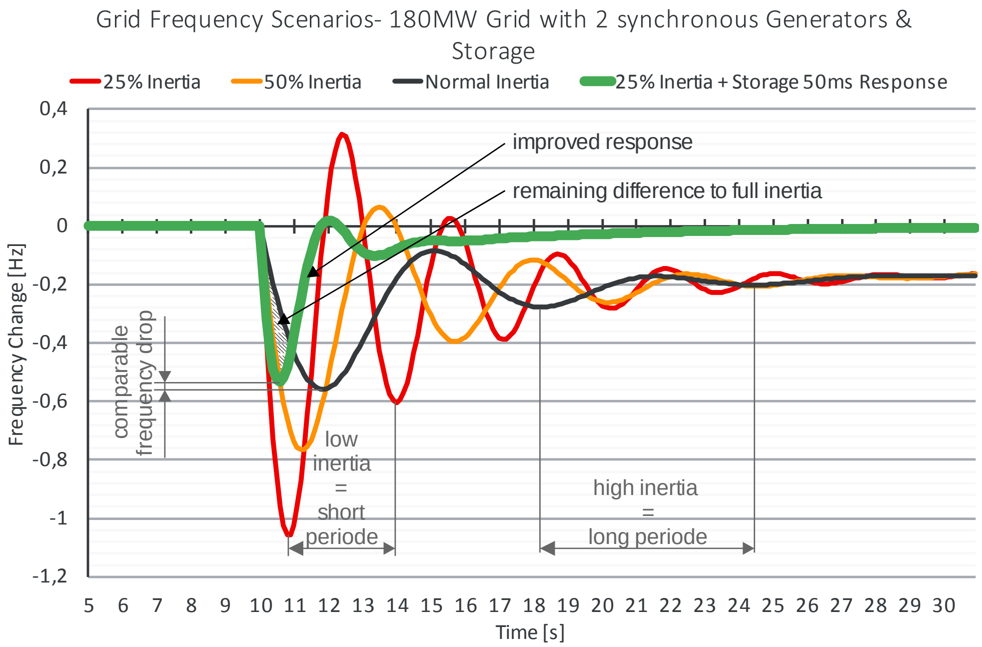


Figure 13: Frequency change of grid with 180MW to a 10% load step based on different rate of inertia and storage support

Figure 14 shows the power supply of the storage system to the ROCOF event. The power gradient and the volatility of the process becomes visible.

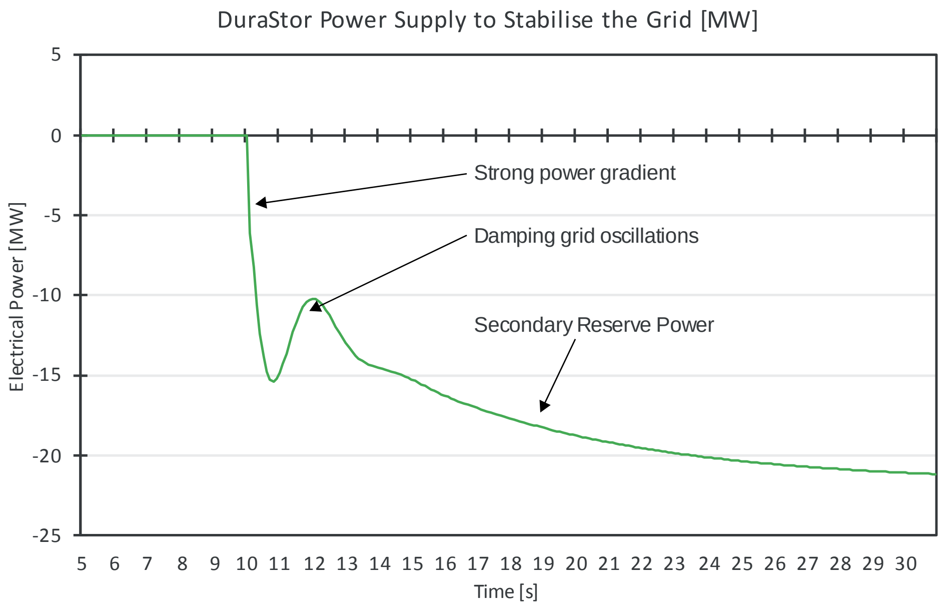
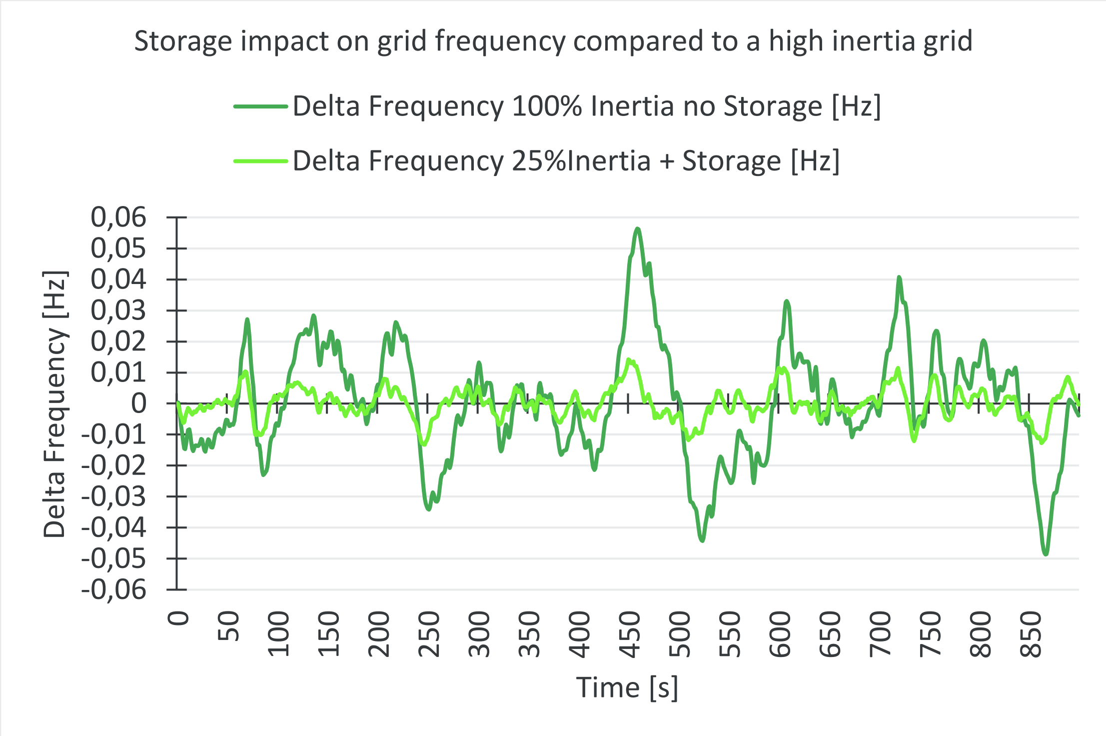


Figure 14: Power injected by the fast storage solution to stabilize the grid

The graphs in Figure 15 shows the response of such a system in a regular grid environment with statistically load variations in the range of lower than 1 to 2% of the nominal grid load. The system modelled consists of two conventional power plants with in total 200MW. The smaller generator provides secondary frequency response and both provide primary response. For simulation purpose, the total inertia has been reduced to 25% assuming that the power plant with the higher inertia gets off grid. The results are compared to a grid with full inertia.


Storage impact on grid frequency compared to a high inertia grid
Delta Frequency 100% Inertia no Storage [Hz]
Delta Frequency 25%Inertia + Storage [Hz]
Delta Frequency [Hz]
0,06
0,05
0,04
0,03
0,02
0,01
0
-0,01
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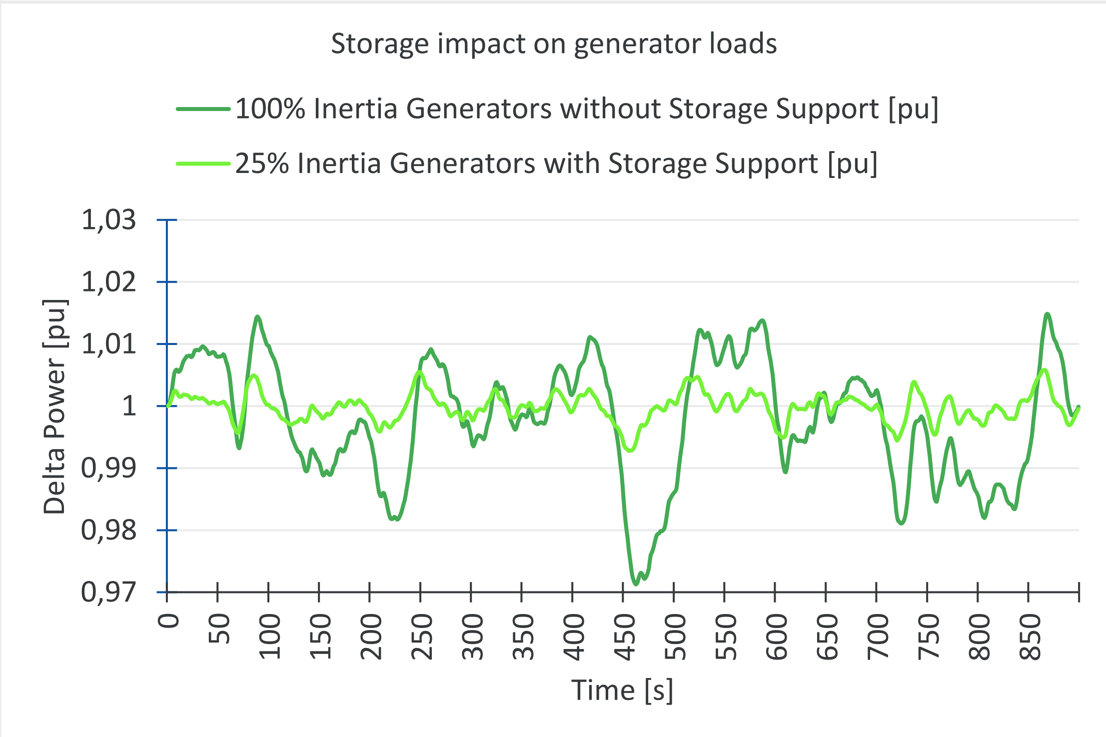
Storage impact on generator loads
100% Inertia Generators without Storage Support [pu]
25% Inertia Generators with Storage Support [pu]
Delta Power [pu]
1,03
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1,01
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0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850
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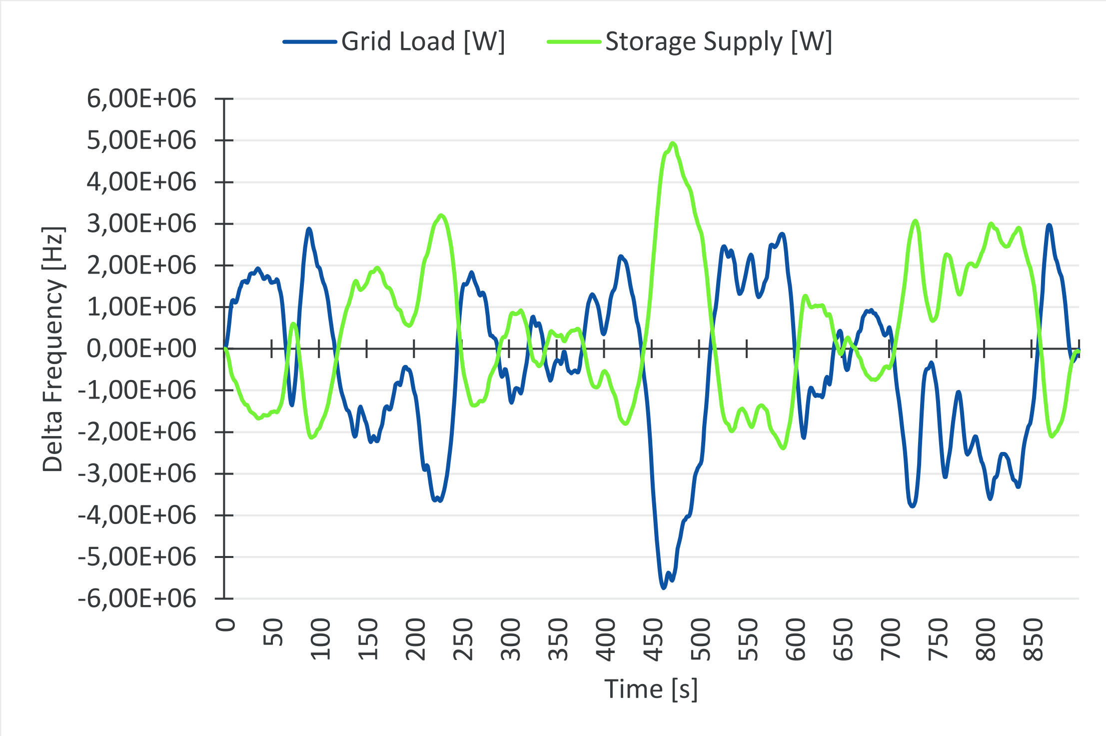

Figure 15: Power-Plants and Storage System response to a statistically loaded grid

Because storage systems provide better primary and secondary response compared to conventional generators, see Figure 13, the grid frequency is in general more stable. Additionally the generators have to provide less primary and secondary frequency regulation service and therefore run more steadily.

In general grids could become more stable if sufficient fast reacting storage is provided. Only is the very first second the Rate of Change of Frequency (RoCoF) is higher during strong load changes. Because the overall grid frequency is not changing more compared to high inertia grids, the effect of the first second can be managed.

To achieve this stabilization performance with storage systems, fast reacting control loops are keeping the storage constantly in duty reacting against every load change. This will stress the storage system much more than usual with today's systems in operation.

Business Case

The difficulty with storage business cases for frequency regulation is the fact that they need to replace existing technologies typically operating since many years and often depreciated. In many countries, coal power plants are providing today this service and in some countries like Germany, Ireland and UK some coal units are already declared as must-run-systems for grid stability. As this study shows, they can be technically replaced by storage systems.

Economically the storage investment needs to be valued against the must-run cost of fossil power-plants kept on-line for grid stability purpose only. Coal units today have boundary operating costs in the area of 40€/MW/hour when running partial load (16). Most systems cannot produce less than 30% of the nominal power. Assuming a 100MW power plant could be closed because it's must-run capacity is not needed anymore for grid stability purpose it would save around 10 M€ operating costs. (365days*24hours*30MW*40€/MW). Because the energy is still needed is has to be produced by renewables at stock market conditions typically below 30€/MW/hour costing 7.5M€. Savings around 2.5M€/anno can be achieved used to finance storage projects.

To replace the power plant in the example above around 20MW of Storage are needed. At costs less than 1000€/MW break even can be achieved in less than 8 years allowing a transitions into energy production with much less CO2 emissions.

Today experience exists with battery and flywheel storage providing frequency stabilization service mainly in the US in the PJM grid. This PJM grid has a relatively demanding load characteristic (9) but still less demanding than needed to replace the majority of real inertia. Most systems in PJM are designed for 8 to 10 years lifetime and one flywheel installation has been now for almost 8 years in operation in NYISO (17).

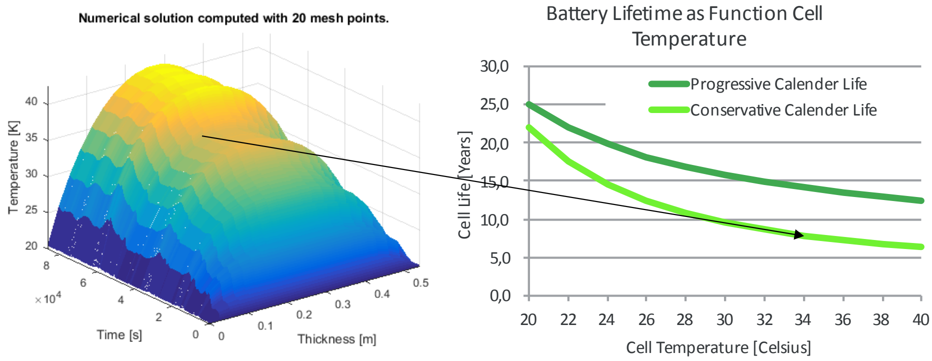

Figure 16: Temperature inside a battery cell pack loaded by a continuous frequency stabilization load cycle profile

Because of the cycle profile, see Figure 15, aging of storage is mainly driven by temperature coming from constant load flows and inner resistance rather than from energy exchange. As described in (8) the increase battery temperature is the predominant aging mechanism in PJM like frequency regulation markets for batteries whereas the number of full load cycles, typically used for batteries lifetime assessment, is less critical, see Figure 16. Nevertheless, batteries lifetime is close the payback period giving an advantage for flywheels systems lasting significantly longer. To achieve longer liftetime lower C-Rates[5] are required to reduce the volumetric thermal load within the battery.

Another advantage is the increased specific power ramp rate of flywheels. Flywheels can provide full power in less than 50ms whereas batteries typically ramp within 200 to 500 ms. The specific ramp rate per installed MW is therefore for Stornetic flywheels 1MW/0,05s=20MW/s compared to 1MW/0,2= max 5MW/s for batteries.

DENA has calculated for Germany the existence of 372MW inertial power with a kinetic energy content of 0.95MWh this represents a C-Rate of close to 400. Today batteries provide C-Rates of 0.25 to maximum 2, whereas flywheels are often higher 15. Most battery systems today giving longer term guarantuess operate a c-rates of 0,25 to max 0.5. According DENA in 2030 Germany needs 245MW with 0.68MWh provided by other means to handle the renewable growth roadmap (18).

[5] C-Rate is defined as Maximum Power/Energy Content [W/Wh or kW/kWh]

Taking the DENA example investments can be calculated comparing flywheel and battery technology.

Technology	Demand	Specific costs	Total Costs
Lithium Battery 0,5C-Rate	245MW=490MWh	600k€/MWh	294 M€
Stornetic Flywheel	245MW	800€/MW	196 M€

Table 3: Total Investment in Inertia Replacement for Germany by 2030 based on today's cost of technology

Further reductions are possible with the development of more powerful Flywheels systems offering system cost below 600k€/MW in near future. Because of the extended lifetime flywheel technology additional offers higher Return on Investments as for example shown in (8).

Summary

As traditional base load coal generation plants get retired and replaced with renewable generation, system operators will look to replace the missing system inertia thru distributed resources that solve multiple grid imbalance issues and insure grid stability.

This Whitepaper shows that short-term grid stability can be technically and economically achieved with very fast responding storage technologies. The missing grid inertia, a consequence of especially retiring steam power plants, can be almost replaced by flywheel storage systems, if reaction time and response characteristic is tuned to be fast responding at minimized delays.

To achieve this special control loops and measurement technologies are needed in combination with storage providing steep ramp-rates $\geq 20 \frac{MW}{s*Installed\ MW}$. The system operate continuously and without hardly any restingtime, creating a technically very demanding load case for the storage technology well suited for flywheels especially designed to continuously operate with steep ramp-rates and frequent load changes.

The paper also works out that the savings achieved by retiring the must-run generators create a sufficient pay-back to invest into storage technologies with reasonable low risks and sufficient benefit. This supports the effort to operate safe and reliable grids with renewable shares higher 50%.

Stornetic GMBH, a Germany based containerized flywheel energy storage systems is introducing hybrid energy storage to service multiple grid services.

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