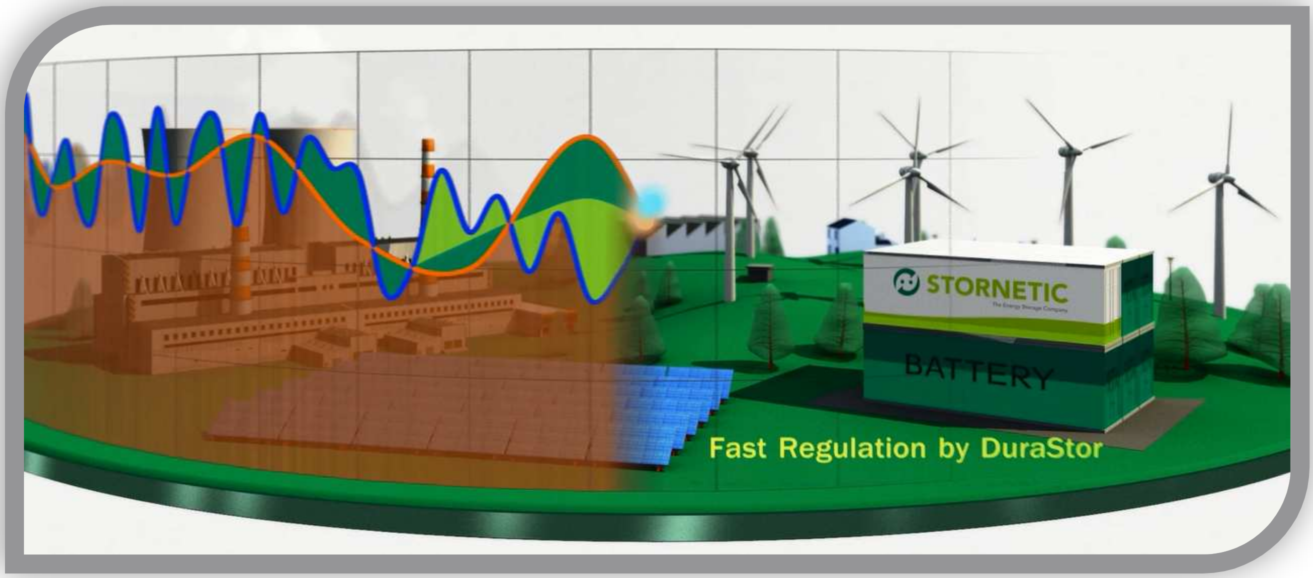
White Paper

Benefits of Fast Reacting Flywheels for Microgrids



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Summary

The continued expansion of renewable energy sources like wind power and photovoltaics is gradually reducing short and long term grid stability, especially as more and more conventional thermal power plants are retired and taken offline. Power to Gas, Power to Heat, Battery Storage and flexible load management provide a solution to deal with the challenges of long term (5 to 12 hours) grid stability, while fast response storage technologies such as Flywheel Storage provides an efficient and affordable solution to manage the short term (0 seconds to 5 minutes) challenges of grid stability.

The EFRE project Quirinus (1) and the EDF concept grid (2) are two demonstration projects being tested in Europe based on a combination of flywheels, gas engines and renewable generation. They explore the ability to stabilize local grids in critical states as well as the potential to reduce cost of transition to future grids with carbon free generation and a very high level of power quality and reliability. The intent of this paper is to introduce and present the findings of these demonstration projects.

Today conventional synchronous generators with their ability to provide inertia and adjust to load changes instantaneously are key for grid stability. When these conventional generators are replaced by renewables, system inertia is reduced, negatively affecting grid stability. A good example is Ireland having a weakly inter-connected <8GW island grid and a renewable penetration growing above 50%. Currently the renewable growth is limited by grid stability constraints requiring the Irish grid operator to invent new market mechanisms and tools to stabilize the grid before the next step to 75% renewable share (3). Similar problems occur in smaller island or microgrids partly operating on renewable generation but still requiring conventional generation for grid stability. The limited size of these grids in combination with load changes makes them sensitive to short term power quality issues. Typically, customers, particularly power intensive industrials, require a high power quality. With the increasing decentralized solar generation in distribution grids, power quality becomes a challenge and these demonstration projects aim to mitigate these challenges.

Figure 1 shows how fast response Flywheel Storage technology like Stornetic's DuraStor system can provide reliable and efficient solutions without having the need to operate many synchronous generators to stabilize the grid frequency. This is the basis for the current demonstrations project. This paper also 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.

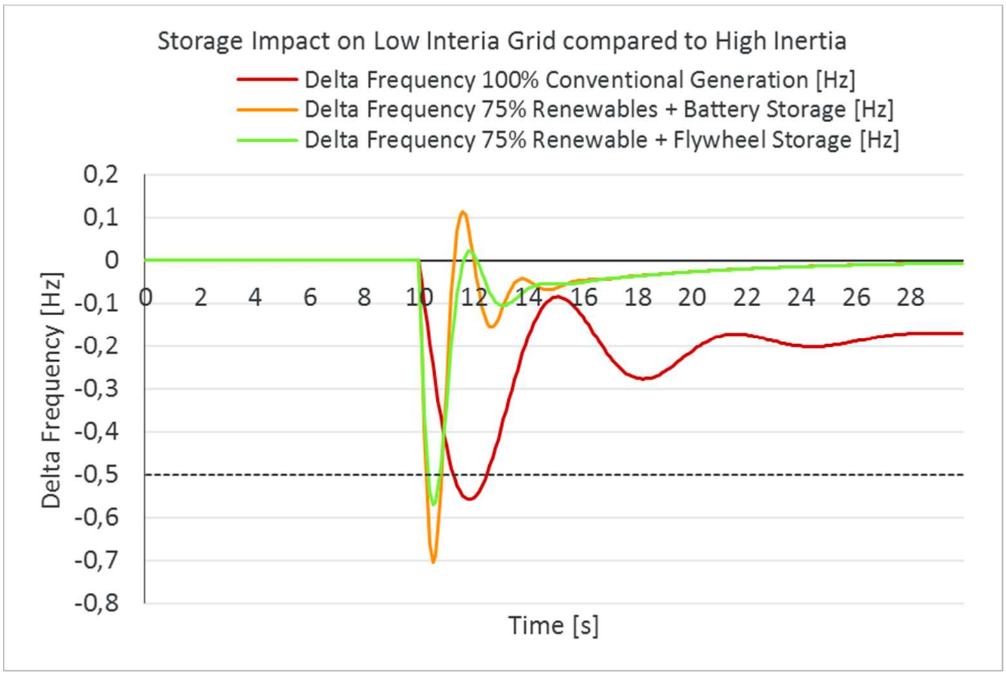

Figure 1: Comparison of flywheels, batteries and conventional generators during grid fault event

Introduction

The government of North Rhine-Westfalia initiated the Quirinus project (1) with funding of the European Regional Development Funds EFRE in an area of traditional lignite mining. 10 GW of lignite electricity generation is paired with a high number of energy–intensive industrial loads. Based on greenhouse emission targets, the plan is to substitute the lignite plants stepwise with renewables. Quirinus will address the challenges to maintain grid stability (power quality, i.e voltage sags and frequency deviation) at the high level of renewable penetration while supporting critical industrial loads.

- Renewables sited in medium and low voltage distribution grids (50/50) instead of large lignite plants feeding top down via the transmission grid.
- Ancillary services provided by distribution grids without overloading lines and devices like transformers.
- Managing intermittent renewable generation and its power fluctuations with storage and CHPs / gas generators.
- Compensate missing inertia of large generators with storage.
- Change to locally managed grid areas with features like automatic islanding, black start and resync capabilities.
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Three scenarios are being prepared for up to four distribution girds starting with a lignite-mining pit as “sand box environment”:

1. Traffic light concept to detect overloading of grid elements combined with mitigation strategies.
2. Ancillary services management provided by distribution grids rather than transmission grids, i.e. to other regional distribution grids.
3. Securing the supply of critical areas with microgrid features like automatic islanding and black start to support a quick regional grid restoration process.

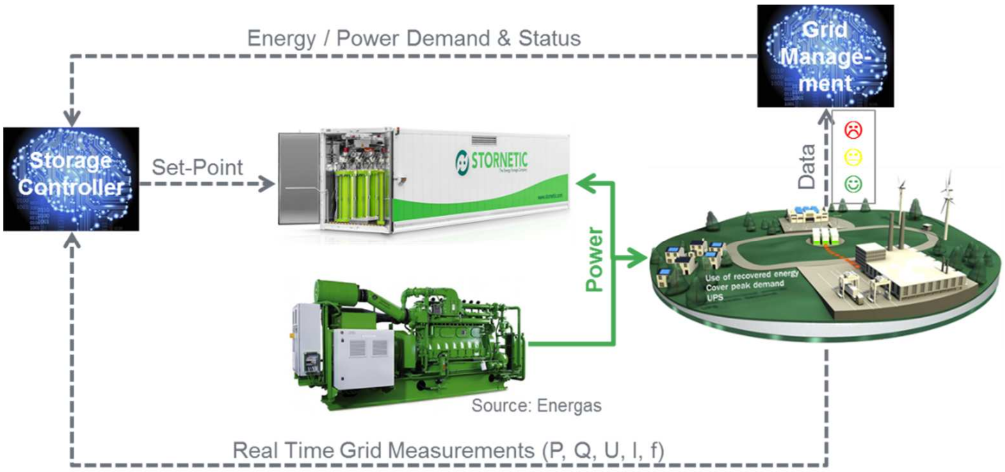

Figure 2: **Typical setup with DuraStor & Gas-motor short term stabilizing the Microgrid**

Advanced grid management systems are required to provide these functions for a further transition to renewable generation, see Figure 2. Its task is to manage the energy balance of the entire system based on the health state of the relevant grid areas. The DuraStor energy storage systems has two key functions:

1. Manage the local grid stability, optional together with gas-motor(s), to maintain frequency and voltage.
2. Support the regional energy balance by charging/discharging electricity on demand
3. Preparing and performing on demand grid recovery together with the gas motor (Black-Start)

Grid Stabilization Challenges

Systems with reduced grid inertia are more sensitive against load changes, (4), (5). Figure 3 shows the response of a typical gas-motor to a significant load change. One can see that the current adjusts automatically resulting in an instantaneous power increase. However, thereafter the frequency, voltage, current and power start to drift away. After about 2seconds the systems stabilizes at a frequency ≈5Hz lower and starts recovering driven by the increasing motor torque. After about 10-15 seconds all parameters are stabilized. Voltage and frequency exceeded critical thresholds.
Typically, a frequency corridor of <±0,5Hz and a voltage corridor <±5% around nominal would be acceptable for industrial grids. International standards for gas-motors permitted today to have dynamic frequency deviations from -15% to 18% and voltage deviations from -25% to 35% as defined in (6).

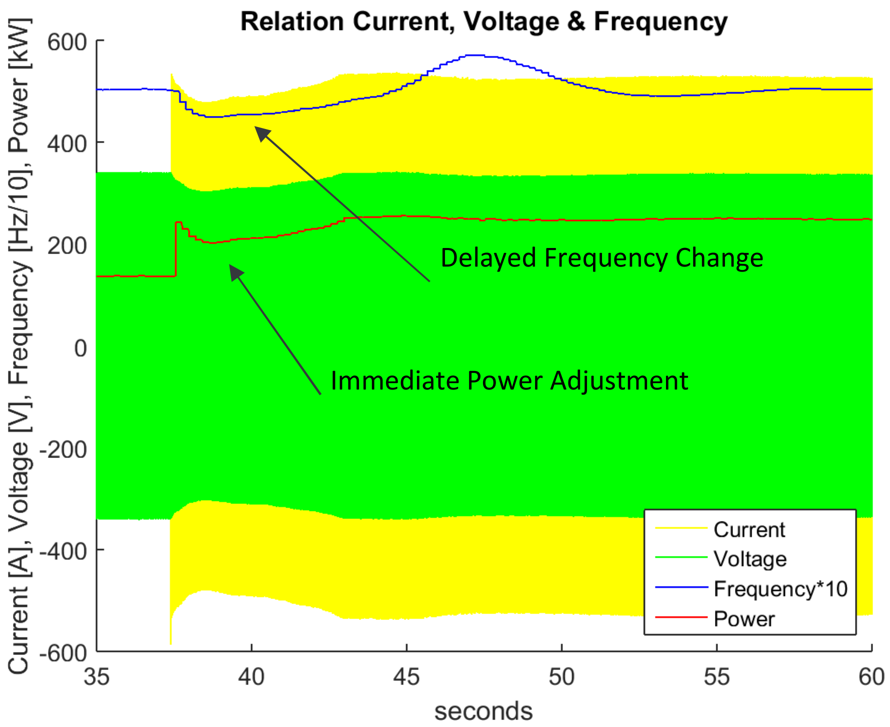

Figure 3: Dynamic Response of a gas-motor to a load step

Additionally, it is predicted that in future even in interconnected grids, some regions have to have the ability to operate in island mode (1), (7). This will be required to avoid larger black-outs when grids become unstable and will also be needed to restore grids after local or regional failures. In the future grids with more decentralized renewable generation and with less system inertia, local grids will need to have more elasticity to support grid restoration. This requires that local or microgrids should support:

- Grid following operation when grid connected supporting regular grid codes and providing regular grid services
- Be able to move swiftly from grid following into island mode when the superordinate grid gets instable and if required by grid management
- Form and operate a microgrid with different grid codes, with operation of critical equipment like gas-motor and energy storage
- Resynchronize and reconnect to the public grid if required by the grid management system

The same demand occurs for “private” microgrids like industrial grids that want to operate in island mode during instabilities. 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 (8) whilst also reducing the CO_2 emission by some percent (9).

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 systems will become more and more decentral and with smaller individual power producers. First steps have been taken to force renewable sources to provide system stability services. Table 1 provides an overview of discussed solutions providing short-term grid stabilization services.

Solution	Pros.	Cons.
Adjust renewable generation at over and under-frequency (Curtailment)	• Low cost solution mainly introduced by software changes • Relatively easy to implement • 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 • It can only provide low frequency support if continuous curtailment is accepted • Increased pay-back times because of opportunity losses • It is not immediate as it needs to balance the interest of energy supply versus system stability (up to 1 second delay)
Use of gas-motors like Biomass or CHP systems	• It's real inertia and thus instantaneous • Biomass is more baseload power and therefore predictable and manageable • Number of installations are increasing • Resynchronisation is possible • Black-Start possible	• Due to the slow response characteristic of gas motors and little mechanical inertia service is limited • If providing primary frequency regulation the owner can have opportunity losses
Battery Storage	• Can be combined with mid and long term storage • Relative responsive (100 to 1,000ms) 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 specialised • Continuing losses
EnWheels (non - synchronous flywheels)	• Provide a lot of power for a few minutes • Very Responsive (toggle from charging to discharging in 10 milliseconds and thus reliable and very fast frequency control • Load cycle resistance and long lifetime • Support resynchronisation and Blackstart	• Non synchronous grid inertia • Limited to a few minutes of grid support

Solution	Pros.	Cons.
Hybrid solutions with EnWheels and Generators or turbines	• Provide real synchronous inertia • Very Responsive (toggle from charging to discharging in 10 milliseconds and thus reliable and very fast frequency control • Load cycle resistance and long lifetime • Resynchronisation and Blackstart possible	• In combination with gas motors only providing synchronous inertia as long the gas motor is in operation • Continuing losses of around 7% to 10%

Table 1: Suitability of various technologies stabilizing the grid

Figure 1 shows the benefit of synchronous reserve but also the benefit of very fast responding systems on grid stability. The combination of both would allow enhancing grid stability at the lowest investment levels. In addition, most of these systems can be installed de-centrally, solving local constraints and being more adaptive.

System Design

To judge the capabilities of the various solutions it is necessary to understand where constraints originate. This finally will also explain 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 with a magnetic field is passing stator coils connected to an AC supply producing a rotating field. At synchronous speed (the grid frequency (f)) the rotor poles lock to the rotating magnetic field. The rotor is typically driven by a motor or turbine that creates the required mechanical energy, power and torque, see Figure 4.

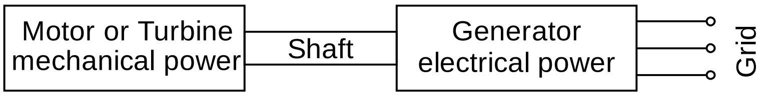

Figure 4: Schematic of the power transfer from Motor/Turbine to Generator and Grid

If load changes, the changed current also flows through the stator coils of the generator, which 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 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. As a consequence, the speed/frequency of the generator changes. This change will only stop when the mechanical torque (T_{mech}) is adjusted to the electrical torque and a new equilibrium is achieved. The mechanical part of this process is described by the “swing equation” (10). 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 ($\dot{\omega}$). In a microgrid this influences the grid frequency immediately because J can be small compared to the torque change.
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 behaviour stabilising the grid

All systems producing energy without using a synchronous generator need inverters to deliver electrical power into the grid. Examples are solar and battery systems as well as most wind power systems or battery storage systems.

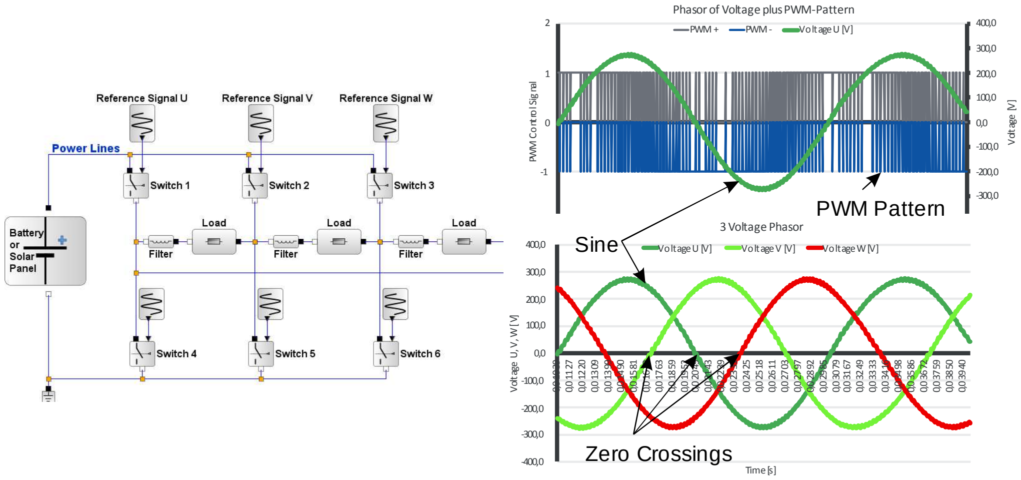

Figure 5: H-Bridge creating 3 Phase Voltage (11)

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 “Pulse Width Modulation” (PWM). A typical design is shown in Figure 6. Based on a reference signal for every phase a dedicated PWM pattern is generated that switches the semiconductors. Typically, grid connected inverters measure and predict constantly the three grid phasors and create out of this the reference signal controlling the semiconductors.
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 characterised properly in amplitude, angle and speed. These measurements take time. 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 conscious 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

Table 2 highlights the differences between synthetic inertia and synchronous inertia at different points in time after an event occurs. Compared to the case with high grid inertia, inverter based systems have disadvantages within the first second. These disadvantages are strongly related to the response time of the system. Systems with short response times and short dead times compensate fast. Systems with response times longer 1,000ms do not contribute to short term grid stability. Dependent on the storage / generation technology as part of the inverter-based system the grid is allowed to recover faster compared to pure synchronous reserves.

Timeframe[1]	Synchronous Inertia[2]	Inverter Based (synthetic) Inertia[3]
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 systems, 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

Table 2 show the benefits of fast responding inverter based resources for grid stability. Storage systems in particular, allow compensating bi-directional load changes whilst currently renewable generation curtailment is mainly used to stabilize high frequency scenarios. Fast response with little dead time helps grids recovering because of mainly two effects:

- Fast adjustment of power obviously leads to faster achieving a new equilibrium giving grid stability
- Little response and dead times allow for faster and more robust control-loop designs

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[1] Timeframe can vary based on technology and vendor. Figures are indicative representing typical solutions existing today or requirements from typical grid codes,

[2] Statements is assuming sufficient power installed

[3] Statements is assuming sufficient power installed. Figures are indicative representing typical solutions existing today.

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

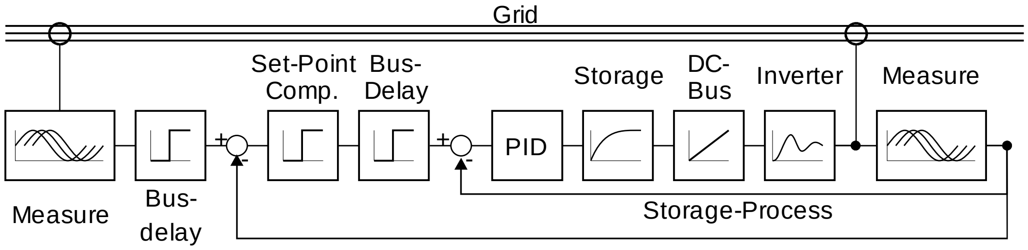

Figure 6: Typical control loop of an inverter based storage system

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. The response of the storage itself depends on technologies and has often limited ramp rates or slopes. Overall, control loops can get very long limiting the use of energy storage systems for frequency regulation, but it is possible to design fast control systems. To achieve shorter to very short reaction times system operators have to make a choice. Currently non-synchronous frequency regulation services are typically designed with a corridor of no action (dead band) 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. To replace inertia with synthetic inertia a different control behaviour is needed, acting proportionally with reasonably short integration time but in addition maybe even acting differentially on the rate of change (PI(D)-Controller).
Figure 7 shows the response of a simulated grid to a RoCoF event of 13% of the nominal grid capacity at various levels 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 storage power installed is sufficient and acting fast, the total frequency drop is about the same as the one with a high inertia grid. The storage supported grid recovers after one second much faster than a usual grid with high inertia. To achieve this the system requires fast responding control loops with 50ms response times and ramp rates of 20MW/s per installed MW. This results in demanding load profile for the storage with constant current flows in and out.

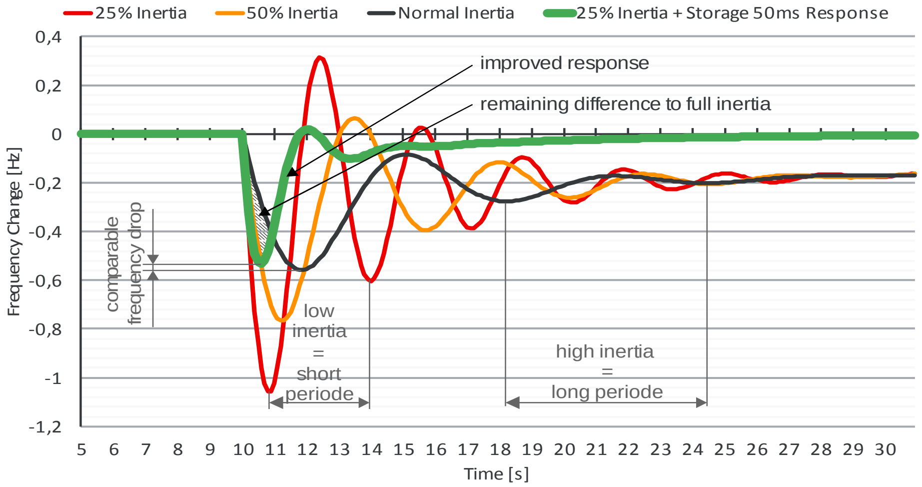

Figure 7: Frequency change of grid two generators to a 10% load step based on different rate of inertia and storage support

The graphs in Figure 8 show the response a gas-motor storage in a grid with statistical load variations in the range of ≤5% of the nominal grid load. The system consists of a 1MW gas motor and a 240kW DuraStor® flywheel system. The results are compared to the grid without storage.

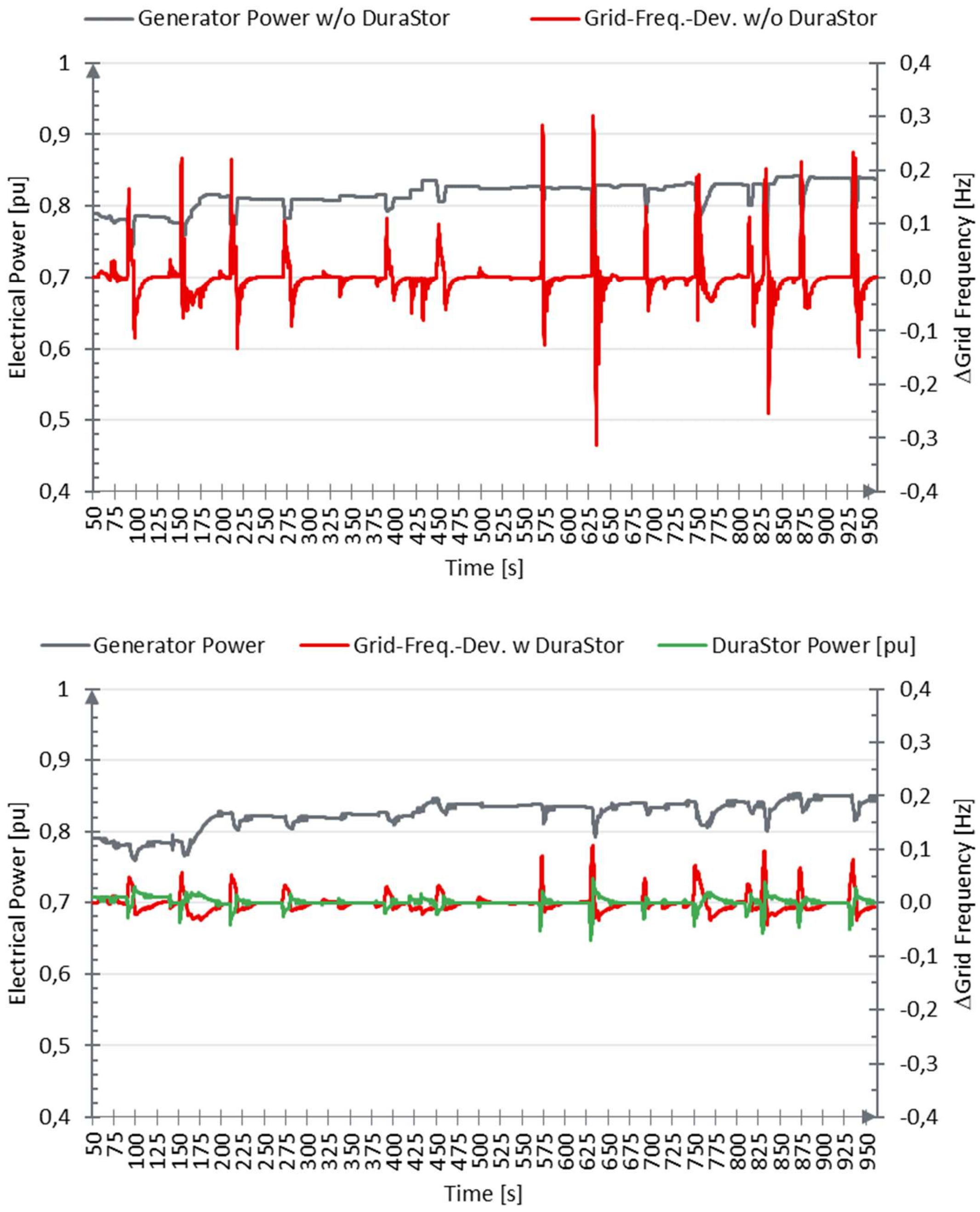

Figure 8: **Frequency variation in a microgrid with and without responsive storage**

The grid frequency is in general more stable by a factor 3. Additionally, the generators have to provide less primary and secondary frequency regulation service and therefore run more smoothly.

To achieve this stabilization performance with storage systems, fast reacting control loops are keeping the storage systems 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 challenge with energy storage business cases for frequency regulation is the fact that they need to replace existing generation technologies typically operating for many years and often fully depreciated. In many countries, steam power plants are providing this service today and in some countries like Ireland, some steam units are already declared as must-run-systems for grid stability.
Economically the fast reacting storage investment needs to be valued against the must-run cost of generators kept on-line for grid stability purposes. Steam power-plants today have boundary costs in the area of 40€/MWh when running partial load (12) while diesel generators have operating costs of >100€/MWh (13) and gas-motors are around 60€/MWh. Most systems cannot produce less than 30% of the nominal power. Assuming in a microgrid a 300kW gas-motor could be shut down, because it's must-run capacity is not needed anymore for grid stability purpose, it would save around 160k€ operating costs per year (365days*24h*0.3MW*60€/MW).
To replace the must run in this example, around 250kW of storage capacity is needed. At capital costs less than 1,000€/MW, break even can be achieved in less than 2 years with high power quality allowing a transition into energy production with much less CO2 emissions. Experience exists with battery and flywheel storage systems providing frequency stabilization service mainly in the US and Ireland (3). The PJM grid has a relatively demanding load characteristic (14), but still less demanding than needed to replace the real inertia as described in this document.

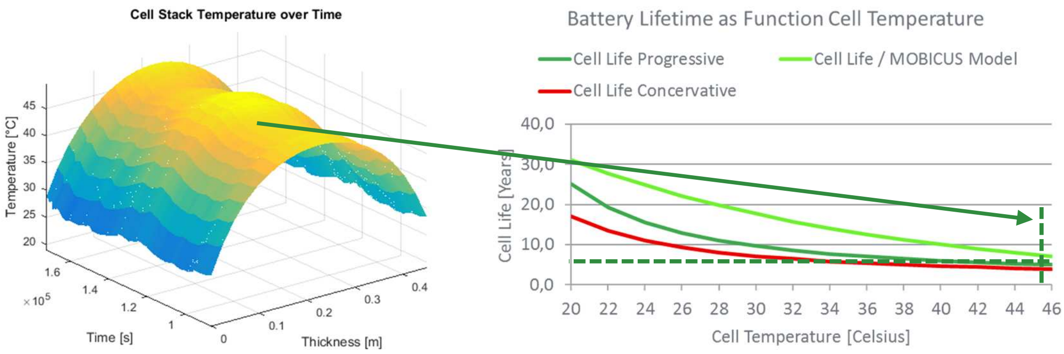

Figure 9: **Temperature inside a battery cell pack operating in continuous grid stabilization mode (15), (16), (17)**

Because of the extreme cyclic profile needed for short-term grid stabilization, aging of storage technology is the main challenge. The lifetime of batteries is mainly driven by temperature coming from constant load flows and inner resistance rather than from energy exchange. Figure 9 shows that already after a few hours in operation battery temperature becomes quite high peaking >40°C (>105F) and resulting in replacement patterns <5 years. Nevertheless, batteries lifetime is close to the payback period giving an advantage for flywheels systems lasting significantly longer.
Another advantage of flywheels versus batteries 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 500ms. The specific ramp rate per installed MW for Stornetic flywheels is 1MW/0,05s=20MW/s compared to 1MW/0,2= max 5MW/s for batteries.
Further reductions are possible with the development of more powerful flywheels systems offering system cost below 600k€/MW in the near future. Because of the extended lifetime, flywheel technology additionally offers higher return on investments as for example shown in (17).

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