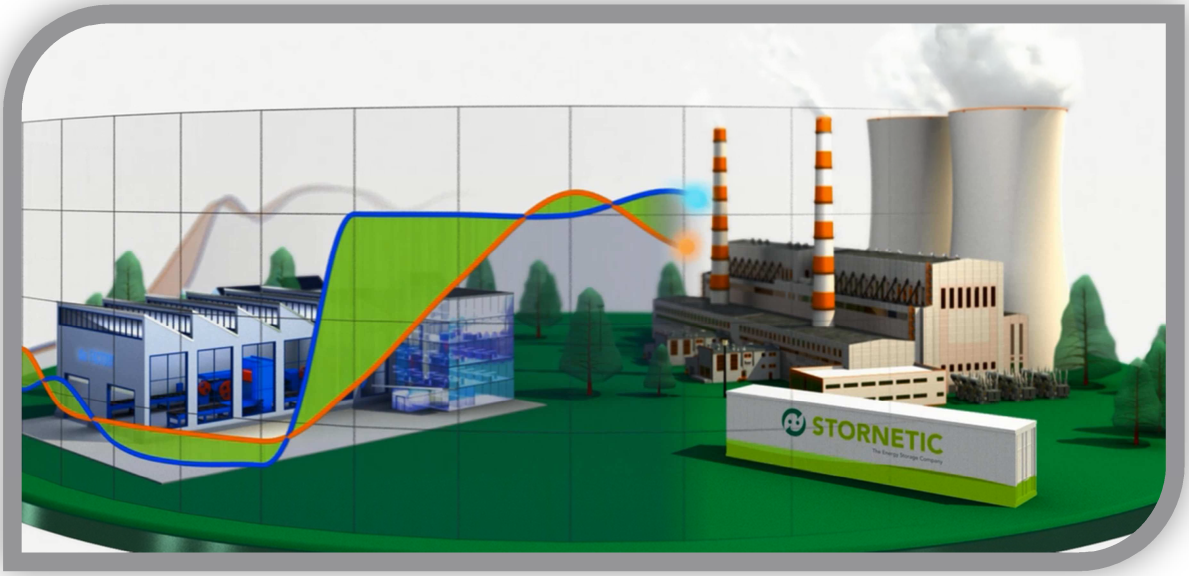
STORNETIC
The Energy Storage Company

White Paper

Safety of Flywheel Storage Systems



Dr. Rainer vor dem Esche
Stornetic GmbH
14th October 2016
info@stornetic.com

Summary

Flywheel Energy Storage Systems (FESS) play an important role in the energy storage business. Its ability to cycle and deliver high power, as well as, high power gradients makes them superior for storage applications such as frequency regulation, voltage support and power firming. Typically, applications with many duty cycles are suitable for FESS, as they have no degradation of capacity over the lifetime. This offers a benefit compared to battery systems used in energy storage today. Recent developments lead to qualifying FESS for use in longer term storage applications.

Today FESS face significant cost pressures to provide cost effective flywheel design solutions, especially as Li-battery prices have dropped significantly in recent years. In addition, the various FESS designs have been challenged to overcome safety concerns given a number of accidents during the past 20 years, which resulted in both fatal and severe injuries (1), (2), (3), (4). Many of these accidents led to major damage to equipment and buildings with material fragments penetrating thick concrete walls or roofs and in some cases being flung over long distances. These events underline the essential need to establish high standards of safety and preventative measures. Efforts must be focused on preventing catastrophic rotor bursts and designing safe housing containments and mountings.

DOE and Sandia recently proposed some guidelines (4) for designers building flywheels with certain minimum safety requirements. This paper provides a view on proven critical mechanical failure mechanisms to support activities aimed at increasing the safety of flywheels. It is partly based on research work performed in Italy (5), the ASME pressure vessel code (6) providing reasonable safety standards for systems containing high energy and aviation turbine standards (7). It also provides observations and experience derived from the results of multiple flywheel safety tests.

Stornetic believes that safety is essential for the further growth of FESS technology. In addition to the Sandia guidelines (4), Stornetic also believes that flywheels up to a certain energy content can be contained and mounted safely even in the event of a severe rotor burst. These designs offer additional safety opportunities to those of the Sandia recommendations. Robust system design, in combination with the use of certified critical materials, relevant quality control measures and documentation, are the basis for the construction of safe flywheel systems. These can be certified by appropriate independent parties as in the manufacture of many other products. In combination with established standards for electrical safety, FESS can be safely installed and operated (as are other storage systems) while providing the additional environmental benefits of non-chemical, non-toxic, fully recyclable materials with scrap values rather than scrap costs.

Content

Introduction

Flywheel energy storage systems are characterized by a rotor typically operating at relatively high circumferential speeds required for the relevant energy content of the application. Even smaller systems such as the Stornetic EnWheels, with an energy content of 4kWh, have significant risks to safety, if they are not designed, produced, installed and operated according to robust safety measures. This becomes easily understandable when it is recognised that 4 kWh of energy is equivalent to a fully loaded, 40 metric ton truck travelling at approximately 100km/h (60mph) on a highway. The damage such a truck can cause makes one aware that safety principles are key to controlling the technology. Unfortunately, flywheel crashes as in 1995 (8), 2014 (2) and 2015 (3) have shown the destructive power of flywheels.

This paper describes safety principles for the safe operation of commercial flywheel systems. Information is taken from analyst reports on various events which have occurred (9) and the experience Stornetic has acquired from performing safety tests and achieving product certification. These experiences support many of the proposals made by DOE, UL and Sandia (4) based on test experience. The paper focusses mainly on mechanical safety, but, of course, all electrical safety codes need to be fulfilled as well. The main safety principles are described in the standards in the chapter Standards.

There are no dedicated international standards for flywheels as such. Therefore, general standards such as the “Safety of Machinery Standard, EN 60204” or in OSHA are applicable and valid. As an example the Cal/OSHA - Title 8 regulations, §3328. Machinery and Equipment states:

- (a) All machinery and equipment:
  - (1) shall be designed or engineered to safely sustain all reasonably anticipated loads in accordance with recognized engineering principles; and
  - (2) shall not be used or operated under conditions of speeds, stresses, loads, or environmental conditions that are contrary to the manufacturer's recommendations or, where such recommendations are not available, the engineered design.
- (b) Machinery and equipment in service shall be inspected and maintained as recommended by the manufacturer where such recommendations are available.
- (c) Machinery and equipment with defective parts which create a hazard shall not be used.
- (d) Machinery and equipment designed for a fixed location shall be restrained so as to prevent walking or moving from its location.
- (e) Machinery and equipment components shall be designed and secured or covered (or both) to minimize hazards caused by breakage, release of mechanical energy (e.g., broken springs), or loosening and/or falling unless the employer can demonstrate that to do so would be inconsistent with the manufacturer's recommendations or would otherwise impair employee safety.
- (f) Any modifications shall be in accordance with (a) and with good engineering practice.
- (g) Machinery and equipment in service shall be maintained in a safe operating condition.
- (h) Only qualified persons shall be permitted to maintain or repair machinery and equipment.

The European “Safety of Machinery Standard, EN 60204” describes comparable requirements. The individual chapter of the relevant directives and standards usually gives a very detailed framework of what needs to be met. Usually HAZOP studies or structured safety assessments, including safety tests, are needed to comply with regulations and to document that a comprehensive engineering risk assessment has been performed. Software and tools exists to guide this process and to demonstrate compliance.

Mechanical Failure Mechanisms

The following paragraphs describe the most critical failure modes of flywheels and design principles to avoid or reduce the impact of these failures. Typically, they are associated with the rotating parts, rotor, motor and bearing. The housing is the first protection barrier and mounting is important to avoid uncontrolled movement of the entire machine, see Figure 1.

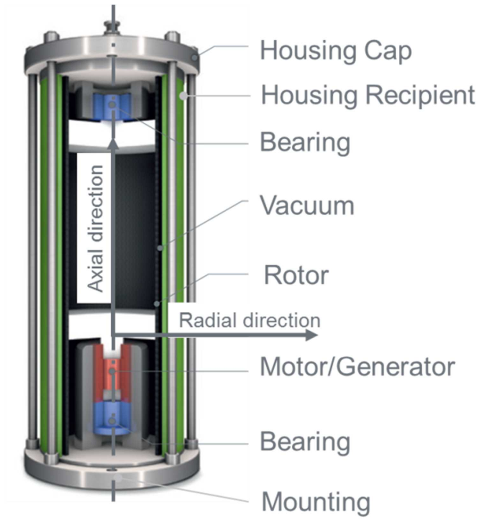


Figure 1: Main Flywheel Components Relevant for Mechanical Safety

Flywheel structural failures can have different root causes and can lead to different hazards. The most important ones are described below. Some failures are general for all rotor material types and some only apply to fiber reinforced rotors.

Logically all flywheel designers strive for the highest possible rotor speed in order to achieve the highest possible energy content and energy density. The maximum specific energy (E/m) is in general limited by the maximum allowable rotor material stress (σ_{max}), the material density (ρ) and a form factor (K), as described by

$\frac{E}{m} = K \times \frac{\sigma_{max}}{\rho}$ (5).

In some applications like UPS the flywheel mainly operates at a steady full speed while in other applications like frequency regulation the flywheel’s speed cycles up and down. Depending on the use case and application, the designer needs to determine the maximum allowable speed and stress while respecting the usual safety factors. In any case, for those flywheels which do not have penetration preventative housings, the producer has to define the safe lifetime and/or inspection intervals such as is usual in the aviation industry (10) or Process Piping (6) (11).

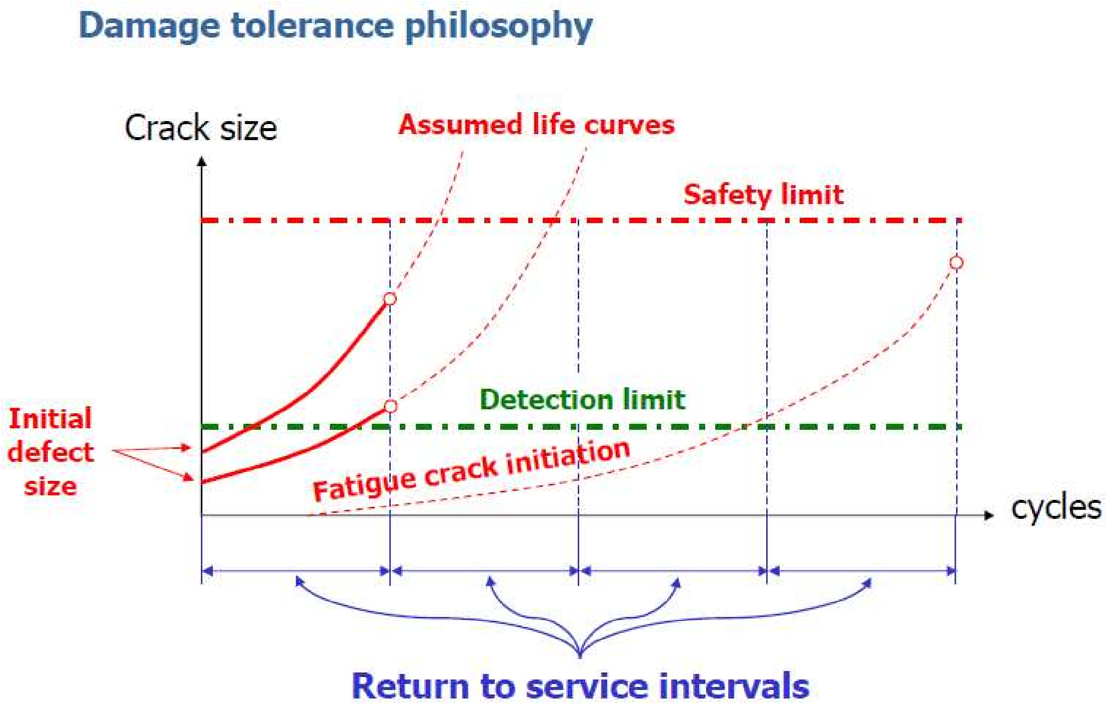


Figure 2: Relation between defects, inspection intervals and cycle life for rotors (12)

In addition to ageing, material defects like voids, cracks or segregations can cause an earlier flywheel failure, see Figure 2. Some defects can be detected by non-destructive testing, although other defects will not be detected or only detected to a limited extent. The thicker the structure gets, the larger the non-detectable defects will be. By using calibration methods, the minimum detectable defect size can be assessed (6). Therefore, those defects which cannot be detected have to be acknowledged during the design and will reduce the maximum flywheel speed (6) (10) (12). Fracture mechanic tools can be used to determine the speed crack growth. SN-Curves in combination with Palmgren & Miner accumulation methods are useful to determine the number of load cycles possible. Because of the range of results these methods, it is recommended to only use 1/3 of the calculated lifetime as a design life (13) and set reasonable inspection intervals, especially if no safe containment exists.

Depending on the complexity of carbon fiber reinforced rotors, the designer needs to decide whether he/or she can, during the design phase, rely on material test parameters or whether load cycle tests are needed to determine composite rotor lifetime. Typically, rotors with 100% hoop fiber orientation are relatively easy to design and much material data like SN Curves is available. For multidirectional laminates, tests with real geometries at real load conditions are needed to conform the theoretical design to real test results to determine load cycle stability and safety factors. As for metal rotors typical defects like voids, cracks or fiber misalignments have to be acknowledged.

All these design assessments are needed to avoid a rotor failure caused by circumferential stresses, which are one of the most common triggers for rotor failure. The main initial triggers for rotor failures are shown in Table 1:

Trigger	Initial Failure Mode
1. Rotor cracks, because of circumferential stresses; e.g. crack growth or overspeed	Rotor fragment(s) break out and fly off in radial and tangential direction
2. Rotor shaft or hub breaks, because of torsional or other stresses; e.g. blocked bearing or radial vibrations	Entire rotor flies-off in a radial direction
3. On composite flywheels overheating can create rotor cracking or softening; e.g. the vacuum is not adequate	Rotor fragment(s) break out and fly off in radial and tangential direction
4. External hazards, such as, earthquake, excitations and penetrations	Excessive rotor forces lead to rotor breakage, rotor fragmentation, air inrush as described in 1., 2. and 3. of this table

Table 1: General failure root causes and their failure mode

These initial failures can create additional hazards once the fragments are touching the housing, see Table 2.

Failure Mode	Description of Consequences
1. Entire rotor is not carried	1. Significant number of large radial bending impulses on the housing and ground attachment 2. Projectiles penetrate the housing and flying out 3. Large torsional loads on the housing and ground attachment 4. Large axial impulses penetrating or lifting the housing cap and stressing the ground attachment 5. Significant noise 6. Hot crash gas 7. In case of organic material, oil or grease presence, risk of fire and/or explosion
2. Rotor fragments fly off	1. Number of significant bending impulses on the housing and attachment 2. Penetration(s) of the housing 3. Significant torsional load(s) on the housing and ground attachment 4. Significant noise 5. Hot crash gas 6. Subsequent imbalance can cause an entire rotor failure with some time delay, see Failure Mode 1

Table 2: Consequences of flywheel rotor failures

Failure mode 1.4. in Table 2 and failure mode 1.2.ii Table 3 describe axial impulses. These failures are, at first glance, not immediately logical, but in fact are, in many cases, one of the main reasons for catastrophic flywheel crash events. Rotor segments are, once in contact with the housing wall, rotating up or down and create very high axial speeds. The force can lift or destroy the housing cap or even break the ground attachment. As a consequence, rotor fragments can be released into the environment with enough energy to destroy concrete ceilings or walls.

In addition to the general and universal failure modes, composite rotors can have the following additional specific failure modes.

Failure Mode	Description of Consequences
1. Rotor Disintegration	1. Rotor disintegrates into multiple small particles creating an abrasive "pyro-plastic flow" and high hydro dynamic pressure (9) 2. Subsequently: i. "Fluid" pressure deforms or cracks the housing ii. "Fluid" flows along the housing and creates large impulses in the axial direction, lifting or cracking the cap or its and stressing the ground
2. Rotor Burst in presence of oxygen	1. Explosion risk caused by high temperature cracking of the composite resin and creating radicals which react exothermically with oxygen

Table 3: Special composite failure modes and their direct consequences

Considering that flywheels operate at high circumferential speeds, sometimes even up to 800m/s, breaching the final safety barrier will be a catastrophic risk. Therefore, basically three design options exist, as follows, in the order of relevance:

1. A safe housing built such that no penetration, breach or gas release/intake can occur as a result of any known type of internal failure.
2. Bunker the system adequately so that neither in the radial direction nor in the axial direction, penetration or bunker destruction can occur including the increased risks of "dust like explosion" once air and oxygen are present.
3. Build the rotor with such a safety margin, that any known type of rotor failure would be very unlikely. The likelihood for machines potentially causing death should be $\leq 10^{-7}$ according to European Directives.

Even for flywheels with safe housings or those in bunkered situations, the rotor should still have a sufficient safety factors, typically $S \approx 2$, to minimize the initial risk of rotor failure. This is, in all cases, good from an investment protection perspective, for fatigue and system lifetime, consequent lowering of financial warranty provisions and subsequently, lowering system operating costs.

Safety Principles and Tests

It is obvious that all these consequences are severe and can cause significant damage and/or injury as unfortunately demonstrated by previous accidents (8), (2) and (3). The impact of such accidents on people, business and reputation is catastrophic and threatens the flywheel industry today. Therefore, it is an obligation on all players in the industry to respect standards and directives of robust and safe engineering and so that safety standards are as high as possible (8).

Today much literature and software is available to describe and analyze rotor failures, the behavior of rotors or fragments during crashes and their consequences. This allows designers to build safe systems and to reduce the amount of testing.

- Rotor dynamic software allows simulations of how rotors toggle in housings during a crash and determine the bending and torsional loads on housings and mounting.

- Crash simulation software allows analysis of fragment penetration and even composite bursts and helps to calculate the loads, moments and pressures generated by these events.
- Standardized tests exist for performing worst case scenario penetration tests of metal fragments with 1/3 rotor segments (7) to ensure that rotor fragments do not escape.

Calculations already provide a good view of what loads can be expected. Nevertheless, real life crash tests at slight overspeed are needed to calibrate and verify the simulations and create a reliable design basis. During these crash tests mounting loads, ground movement and flywheel acceleration and pressure need to be measured to prove the theoretical assumptions. Autopsies of the housings, measurements of penetration depth into the housing and component deformation help to determine safety factor and loads.

Unfortunately, some crash phenomena such as “Axial Impulse” or “Rotor Disintegration” are difficult to trigger. Therefore, a statistically relevant number of full size crash tests are needed to provide a sound basis for the final machine design and safety factor assessments.

Ultimately the producer needs to decide what “Safety Critical Characteristics” need to be defined to ensure that production machines are safe. These are typically:

- Rotor material composition, strength, elongation to break, moduli and other material certificate parameters with allowable defect sizes, such as, voids, cracks or segregation.
- Housing and attachment properties, such as, thickness, geometry diameter, strength and chemical composition.
- Housing material composition, strength, elongation to break and allowable defect size.
- Relevant safety gaps between rotor and housing as well as isolation distances.
- Torque for screws and bolts
- Other relevant features

Additionally, instrumentation requirements (including alarm and shut down criteria) need to be defined. It is relevant for mechanical safety, as well as, for electrical safety, to measure the temperature of the stator or the housing and in some cases the vacuum pressure. Also health state monitoring of bearings is recommended to avoid seizing. Due to the severe consequences of flywheel failures with high energy content, an independent overspeed protection system is required to avoid operation at both untested and unqualified speeds.

Finally, all design information, tests results and safety assessments are to be comprehensively summarized in reports. Documentation of the “Safety Critical Characteristics” is needed during production, testing and sometimes operation. Critical processes like welding or rotor production might need qualification and change management to ensure maintenance of high quality standards. Relevant information for maintenance, inspections or operation has to be given to the user and operator to allow safe operation.

Business Benefits

The effort to design and test the safety of flywheels with high energy content is significant. Several thousand man hours have to be invested to calculate loads, design safe rotors, housings and mountings and to perform comprehensive mechanical and electrical safety assessments.
On top of this, multiple full size component crash tests, as well as, electrical tests are needed to prove safety. In addition, the documentation effort during design, qualification, production, installation and commissioning is considerable.

Of course, these investments have obvious commercial pay back. They create the required trust in the technology and product for customers purchasing flywheels. Safe flywheel installations simplify the licensing process, as they are a prerequisite for public acceptance. As safely contained flywheels do not create environmental hazards, are not toxic or water contaminating, a good proven safety case supports rapid licensing and commissioning with positive cost implications.

Safely mounted and contained, high energy flywheels like Stornetic's EnWheels, offer a high volumetric energy density and faster installation. Tests performed demonstrate that it is also not necessary to bunker the system. Therefore, flywheels can be placed close to each other without a "domino effect" in case of a flywheel accident. This reduces space needs, the civil engineering effort prior to supply, flywheel installation time, siting costs and overall project time. As a result, smaller installations can be commercially viable, because of overall reduced project management and installation costs.

Summary

Flywheel technology is useful for many energy storage applications, such as, enhanced frequency regulation, voltage support, inertia provision or peak shaving. Superior to many competing storage applications, such as batteries or super-capacitors, flywheels offer long service life, load cycle resistance and high availability, as well as having low environmental impacts. They have a high salvage value and are almost 100% recyclable.

Stornetic has decided to design and develop the EnWheel technology as fully compliant with regulations including OSHA and the European Machinery Safety Standard. During the entire development, multiple electrical and mechanical safety tests have been performed to justify the theoretical design. All safety requirements and features, as well as tests, have not only been based on robust, structured risk assessments and valid regulations, but also on experience from accidents which occurred in the past with other parties. During crash tests, all the above failure modes, mechanisms and consequences have been observed and managed.

Stornetic concluded that for its EnWheel technology with an energy content of around 4kWh, a combination of a rotor design with safety factors ≥ 2 and a penetration and burst safe housing were needed to provide the right level of safety and to meet regulations.

As most of the additional safety measures also provide investment protection and increase lifetime, they do not contradict commercial targets, although significant effort and financial investment have been made to design, build and prove the safety of flywheels.

Standards

The list below represents a collection of applicable standards but does not claim to be complete.

North American Standards

In general, the following codes, standards and guidelines are to be followed:

- National Electric Safety Code (NESC)
- Occupational Safety and Health Act (OSHA)
- American National Standards Institute (ANSI)
- American Society for Testing and Materials (ASTM)
- American Welding Society (AWS)
- National Fire Protection Association (NFPA)

UL 50E	Enclosures for Electrical Equipment, Environmental Considerations
UL 94 5VA	Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances
UL 508A	Standard for Industrial Control Panels
UL 508C	Standard for Power Conversion Equipment
UL1741	Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources
UL 9540	Outline of Investigation for Energy Storage Systems and Equipment

CSA-C22.2 NO. 0-10	General requirements - Canadian electrical code, Part II
CSA-C22.2 NO. 94.1-07	Enclosures for Electrical Equipment, Non-Environmental Considerations
CSA-C22.2 NO. 94.2-07	Enclosures for Electrical Equipment, Environmental Considerations

IEEE 142	Recommended Practice for Grounding of Industrial and Commercial Power Systems
IEEE C62.72-2007	IEEE Guide for the Application of Surge Protective Devices for Low Voltage (1000 Volts or Less) AC Power Circuits

European Standards

Storage systems need to fulfil the

- EC machinery directive (2006/42/EC),
- Electromagnetic compatibility directive (2004/108/EC)
- Low voltage directive (2006/95/EC)

and need CE Declaration.

EN 349+A1	Safety of machinery - Minimum gaps to avoid crushing of parts of the human body
EN 547-2+A1	Safety of machinery - Human body measurements - Part 2: Principles for determining the dimensions required for access

	openings
EN 547-1+A1	Safety of machinery - Human body measurements - Part 1: Principles for determining the dimensions required for openings for whole body access into machinery
EN 547-3+A1	Safety of machinery - Human body measurements - Part 3: Anthropometric data
EN 614-1+A1	Safety of machinery - Ergonomic design principles - Part 1: Terminology and general principles
EN 614-2+A1	Safety of machinery - Ergonomic design principles - Part 2: Interactions between the design of machinery and work tasks
EN 626-1+A1	Safety of machinery - Reduction of risks to health from hazardous substances emitted by machinery - Part 1: Principles and specifications for machinery manufacturers
EN 626-2+A1	Safety of machinery - Reduction of risk to health from hazardous substances emitted by machinery - Part 2: Methodology leading to verification procedures
EN 953+A1	Safety of machinery - Guards - General requirements for the design and construction of fixed and movable guards
EN 981+A1	Safety of machinery - System of auditory and visual danger and information signals
EN 1037+A1	Safety of machinery - Prevention of unexpected start-up
EN 1088+A2	Safety of machinery - Interlocking devices associated with guards - Principles for design and selection
EN ISO 12100-03	Safety of machinery - General principles for design - Risk assessment and risk reduction (ISO 12100)
EN 13478+A1	Safety of machinery - Fire prevention and protection
EN ISO 13849-1	Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design (ISO 13849-1)
EN ISO 13849-2	Safety of machinery - Safety-related parts of control systems - Part 2: Validation (ISO 13849-2)
EN 60204-1	Safety of machinery - Electrical equipment of machines - Part 1: General requirements

References

1. **ORNL, J. G. R. Hansen, D. U. O'Kain.** *An Assessment of Flywheel High Power Energy Storage Technology for Hybrid Vehicles.* Oak Ridge, TE, 37831-6285 : OAK RIDGE NATIONAL LABORATORY, 2011. ORNL/TM-2010/280.
2. **Göttinger Tageblatt, eb.** *Schwerer Unfall bei Piller in Osterode.* Göttingen : Göttinger Tageblatt, Nov. 2011.
3. *Blast injures 8 at Poway business.* **UT San Diego, P. Repard, H. Jones.** San Diego : The San Diego Union-Tribune, 2015.
4. **SANDIA, D. Bender.** *Recommended Practices for the Safe Design and Operation of Flywheels.* Sandia National Laboratories : Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550, 2015. SAND2015-10759.
5. **Genta, G.** *Kinetic Energy Storage.* s.l. : Butterworth & Co. Ltd., 1985. ISBN 0-4801396-6.
6. **ASME.** *ASME Boiler & Pressure Vessel Code, 2013 edition, VIII Rules for Construction.* New York : American Society of Mechanical Engineers , 2013.

7. **FAA Advisor Circular.** *Dsign Considerations for Minimising the Hazards Caused by Uncontained Turbine Engines and Auxilliary Power Unit Rotor Failure.* s.l. : US Department of Transportation - Federal Aviation Administration, 1997. AC 20-128S.
8. **Ashley, S.** *Design Safer Flywheels.* s.l. : Mechanical Engineering Magazine, ASME International, Vol. 118, No11, pp. 88-91 , 1996.
9. **G. Fischer, R. Grothaus, W. Hufenbach.** Experimental Failure Effect Analysis of Composite High-Speed Flywheel Rotors. *Composite Materials: Testing and Design, Fourteens Volume.* West Conshohockem, PA, USA : ASTM STP 1436, ASTM International, 2003.
10. **RWTH Aachen, D. Böhn, F. Strößenreuther.** *Machbarkeitsstudie und Konzept einer stationären Schwungradanlage zur dezentralen verbraucherorientierten Energiespeicherung.* Aachen : s.n., May 1996.
11. **ASME.** *Process Piping - ASME Code for Pressure Piping, B31.* New York : American Society of Mechanical Engineers, 2006.
12. **University of Liege, J.-C. GOLINVAL.** *Mechanical Design of Turbojet Engines - An Introduction.* http://www.ltas-cm3.ulg.ac.be/AERO0023-1/ConceptionMecaTurbomachine.pdf : University of Liege. AERO0015-1 - MECHANICAL DESIGN OF TURBOMACHINERY.
13. **K.H. Grote, J Feldhusen.** *Dubbel - Taschenbuch für den Maschinenbau, 13. Auflage.* s.l. : Springer, 2011. ISBN 978-3-642-17305-.
14. **TERNA, Anna Carolina Tortora.** *Energy Storage Value Proposition - A TSO's Perspective.* Charlotte, ESA Conference April 2016 : s.n., 2016.
15. **PNNL , Sandia, DR Conover, SR Ferreira, AJ Crawford, DA Schoenwald, J Fuller DM Rosewater, SN Gourisetti, V Viswanathan.** *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems.* s.l. : PNNL, Sandia, 2016. SAND2016-3078 R, PNNL-22010 Rev.
16. **RECHARGE aisbl, JP. Wiaux, C. Chanson.** *The Lithium-Ion Battery Service Life Parameters.* Geneva, EVE IWG Session : s.n., 2013.
17. **Argonne, P.A. Nelson, K.G. Gallagher, I. Bloom, D.W. Dees.** *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles.* Chicago : Argonne National Laboratory, 2011. ANL-11/32.
18. **KEMA, Manuel Atanacio, Richard Fioravanti, Dr. Warren Katzenstein, Dr. Khoi Vu.** *Emission II Study of Advanced Storage used for Frequency Regulation.* s.l. : Department of Energy – Sandia National Labs, 2012. Project Number: Sandia Negotiation 96362.
19. **KEMA.** *Benefits of Fast-Response Storage Devices for System Regulation in ISO Markets.* Fairfax, VA, USA : AES Cooperation , 2008.
20. **IHS Technology, Marianne Boust.** grid-connected-energy-storage-projects-in-pipeline-to-hit-2gw-led-by-us-china-and-south-korea. *altenergymag.com.* [Online] IHS Technology, 11. 07 2016. [Zitat vom: 04. 08 2016.] http://www.altenergymag.com/news/2016/07/11/grid-connected-energy-storage-projects-in-pipeline-to-hit-2gw-led-by-us-china-and-south-korea/24109/.
21. **Energy Storage News, Tom Kenning.** www.energy-storage.news. [Online] Energy Storge News, 17. 12 2015. [Zitat vom: 04. 08 2016.] http://www.energy-storage.news/news/lg-chem-signs-its-largest-supply-contract-for-stationary-storage-with-aes-e.
22. **CEMAC, Donald Chung, Emma Elgquist, Shriram Santhanagopalan.** *Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations.* s.l. : NREL, April 2016. NREL/TP-6A20-66086.
23. **Pacific Northwest National Laboratory, DR Conover, VV Viswanathan, AJ Crawford.** *PNNL-23390 Determination of Duty Cycle for Energy Storage Systems Integrated with Microgrids.* s.l. : Prepared for the U.S. Department of Energy, 2014.

24. **ie³, Prof. Dr.-Ing. C. Rehtanz, M. Greve, T. Noll, J. Schwippe.** *Bedarf und Erbringung von Momentanreserve im Jahr 2030.* s.l. : DENA, Nov 2015.
25. *The Integration of Renewable Energy Sources Into the Distribtion Grid.* **German Renewable Energy Federation, H. Loew.** Berlin, Türk-Alman Enerji Inovasyon Forumu 2013 : Bunderverband Eneuerbare Energie e.V., 2013.
26. **SWECO.** *Study on the effective integration of Distributed Energy Resources for providing flexibility to the electricity system.* s.l. : The European Commission, 2015. Proj no: 54697590000.
27. **RMI, Kaitlyn Bunker, Stephen Doig, Kate Hawley, Jesse Morris.** *RENEWABLE MICROGRIDS: PROFILES FROM ISLANDS AND REMOTE COMMUNITIES ACROSS THE GLOBE.* s.l. : ROCKY MOUNTAIN INSTITUTE, 2015.
28. **RMI, Garrett Fitzgerald, James Mandel, Jesse Morris, Hervé Touati.** *The Economics of Battery Energy Storage.* Boulder, CO, USA : Rocky Mountain Institute, October 2015.
29. **ABB, William Galton.** *Stabilizing and maximizing renewables using a flywheel-inverter system.* RPI CFES Workshop on Microgrid Technology and Applications : ABB, Oct. 2013.
30. **EIA.** *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015.* s.l. : US Energy Information Administration, June 2015.
31. **Wikipedia.** Cost of electricity by source. [Online] Wikipedia, 03. 08 2016. [Zitat vom: 05. 08 2016.] https://en.wikipedia.org/wiki/Cost_of_electricity_by_source.
32. *Redox Flow Batteries for the Stable Supply of Renewable Energy.* **Power System R&D Lab, T. SHIBATA, T. KUMAMOTO, Y. NAGAOKA, K. KAWASE, K. YANO.** NUMBER 76 , SEI TECHNICAL REVIEW : s.n., APRIL 2013 .
33. **ETH Zuerich, Bolun Xu, G oran Andersson.** *Degradation-limiting Optimization of Battery Energy Storage Systems Operation.* Zurich : ETH Zurich, 2013. PSL1316.
34. **NREL, Smith Kandler.** *Predictive Models of Li-ion Battery Lifetime.* Golden, Colorado : IEEE Conference on Reliability Science for Advanced Materials and Devices, September 2014. NREL/PR-5400-62813.
35. **Nature, Feng Leng, Cher Ming Tan, Michael Pecht.** *Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature .* s.l. : Nature, 2015. 12967(2015).
36. **S. Jensen, K. Engebrecht.** *Measurements of Electric Performance and Impedance of a 75 Ah NMC Lithium Battery Module.* s.l. : Electrochemical Society. Journal, 159(6), A791-A797., 2012. DOI: 10.1149/2.088206jes.
37. **Matthias Fleckenstein, Oliver Bohlen, Bernard Bäker.** *Aging Effect of Temperature Gradients in Li-ion Cells Experimental and Simulative Investigations and the Consequences on Thermal Battery Management.* EVS 26, Los Angeles, California : World Electric Vehicle Journal Vol. 5, May 6 - 9, 2012. ISSN 2032-6653 - © 2012 WEVA.
38. **Department of Automotive Engineering, Xuebing Han, Minggao Ouyang*, Languang Lu, Jianqiu Li, Yuejiu Zheng, Zhe Li.** *A comparative study of commercial lithium ion battery cycle life in electrical vehicle: Aging mechanism identification.* Department of Automotive Engineering, State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China : Journal of Power Sources 251 (2014) 38e54, 2014.
39. **AIT Austrian Institute of Technology, D. Dvorak, T. Bäuml, D. Simic, H. Popp, H. Kapeller.** *Arrhenius-Equation Based Approach for Modelling Lithium-Ion Battery Aging Effects.* A-1210 Vienna : AIT, 2014, Aug. 15. DOI: 10.13140/2.1.3382.2405.
40. **PR Newswire (November 17, 2015 - 8:00 AM EST).** First Kinetic Energy Storage Unit by STORNETIC Put Into Commercial Operation. *Oil & Gas 360.* [Online] Oil and Gas 360, 17. November 2015. [Zitat vom: 16. 08 2016.] http://www.oilandgas360.com/first-kinetic-energy-storage-unit-by-stornetic-put-into-commercial-operation/#.

Disclaimer

The information within this White Paper is believed to be reliable and has been obtained from sources believed to be reliable, but Stornetic GmbH makes no representation or warranty, express or implied, with respect to the fairness, correctness, accuracy, reasonableness or completeness of such information. In addition, we have no obligation to update, modify, or amend the content or to otherwise notify a recipient in the event that any matter stated within it, or any opinion, projection, forecast or estimate set out in it, changes or subsequently becomes inaccurate.

We are not acting and do not purport to act in any way as an advisor or in a fiduciary capacity. We therefore strongly suggest that recipients seek their own independent advice in relation to any investment, financial, legal, or regulatory issues referred to. Analyses and opinions contained in the White Paper may be based on assumptions that, if altered, can change the analyses or opinions expressed.

This communication is provided for information purposes only, it is not an offer to sell, or a solicitation of an offer to buy, nor to enter into any agreement or contract with Stornetic GmbH or any affiliates. Any offering or potential transaction that may be related to the subject matter of this White Paper will be made pursuant to separate and distinct documentation and in such case the information contained herein will be superseded in its entirety by such documentation in final form.

Because this White Paper is a summary only it may not contain all material terms, and therefore this communication in and of itself should not form the basis for any investment decision.

The White Paper and the information contained within it is for the recipient only and may not be further disseminated, reproduced or distributed in whole or in part without Stornetic's prior written consent.