Ultra-Fast Charging Boosters with Flywheel Energy Storage

By: Ilan Ben-David

At many fast-charging sites, it's often discovered that the power available to the charging station is significantly lower than the required power. A charging booster can bridge this gap: this article presents the technology and operation of a charging booster based on kinetic energy storage using flywheel technology.

The issue of fatigue is critically important to the safety of the flywheel, as the energy stored in a single rotor, which weighs about 400 kg and spins at maximum speed, is equivalent to the kinetic energy of a 40-ton truck traveling at 105 km/h.

The shift from gasoline and diesel vehicles is part of the broader effort to reduce greenhouse gas emissions and combat global warming. To enable the widespread adoption of electric vehicles (EVs), an extensive deployment of charging infrastructure is essential. Ultra-fast charging allows EVs to be charged in less than 30 minutes, which is critical for vehicles covering long distances or those without access to slow charging stations. Ultra-fast chargers are typically rated above 100 kW, with most installations ranging from 150 to 180 kW, and there are also chargers capable of delivering up to 350 kW.

In many locations where fast chargers are intended to be installed, it turns out that the available power supply is insufficient to meet the demand. The typical solution to this problem is upgrading the electrical connection to the site. However, due to the rapid growth in electric vehicle adoption and the increased demand for ultra-fast charging stations, a gap has emerged between the needed infrastructure upgrades and the capacity of power companies to implement them. Charging boosters are designed to bridge this gap by providing local energy storage that supplements the grid when the required power exceeds the available supply. These systems are well-suited for charging stations with two to eight fast chargers, as they can handle the short bursts of high-power demand that occur throughout the day.

This article explains the technology behind charging boosters based on kinetic energy storage using flywheels. This technology is particularly well-adapted to handling the frequent power surges at charging stations. Flywheels are not limited in their number of charge cycles, making them highly reliable with a lifespan that matches that of a charging station. Moreover, flywheels are the most environmentally friendly energy storage option.

The article is divided into three parts: The first part introduces flywheel technology and the main challenges in developing such a storage system. The second part explains how the charging booster integrates into a charging station, and the third part presents data demonstrating the operation of the charging booster at an actual site.

Flywheel Technology

A flywheel is a mechanical energy storage device, and its main advantage is its unlimited charge cycles, unlike batteries. Energy is stored as the kinetic energy of a rotating mass. The amount of stored energy is proportional to the moment of inertia of the mass and the square of its rotational speed:

$E_{kinetic} = 1/2 \cdot I \cdot \omega^2$

- I - the moment of inertia
- ω - the angular speed of the wheel rotor

In flywheels used for electrical energy storage, the rotating mass (called the rotor) is coupled with a motor-generator. This motor-generator converts electrical energy into rotational energy during charging and converts the rotational energy back into electrical energy during discharging. When charging, the motor accelerates the rotor to its maximum speed (approximately 17,000 rpm), and during discharging, the motor acts as a generator, converting the kinetic energy into electrical energy for external use.

A key advantage of flywheels is that they do not need to reach a full stop because the energy stored at low rotational speeds is minimal. When the flywheel is fully charged and waiting to discharge, the rotor spins at maximum speed. To minimize friction losses, the rotor operates in a vacuum and is supported by a magnetic levitation bearing.

The operating modes of a flywheel

Diagram 1: The operating modes of a flywheel

Although the flywheel may seem conceptually simple—essentially a "spindle with a motor"—developing such a system is a highly complex task filled with technical challenges, only some of which are described in this article. The focus here is mainly on the challenges related to the rotor, the bearing system, and the motor.

In the rotor of the flywheel, significant centrifugal forces are generated, which increase with the square of the rotational speed. These forces result in mechanical stresses. In a disk-shaped rotor, these stresses are two-dimensional (in the plane perpendicular to the axis of rotation) and are classified into circumferential stresses (hoop stresses) and radial stresses. The maximum stress, which is the combination of both, occurs at the rotor’s center and depends on the square of the speed.

Since both the stored energy and the stresses are proportional to the square of the speed, the energy content per unit mass of the rotor depends on a property known as *specific strength* (the ratio of maximum strength to density), which is a constant characteristic of the material. For this reason, flywheels are designed from materials with high specific strength.

In this system, the rotor is made from high-strength, fatigue-resistant steel and is constructed from laminated steel plates rather than a single solid body. This design allows for strict quality control of the individual plates before assembly and prevents the propagation of cracks between them. As a result, this unique structure, combined with the material's properties, ensures maximum safety.

Fatigue loads occur due to the changing speed of the flywheel, causing the forces acting on it to fluctuate multiple times a day. Fatigue is a critical safety concern because the energy stored in a single 400 kg rotor spinning at maximum speed is equivalent to the kinetic energy of a 40-ton truck traveling at 105 km/h. A rotor failure (disk burst) would have serious safety implications. In fact, earlier generations of flywheels were installed underground to mitigate this danger. However, the ZOOZ flywheel is designed using advanced methods from the aeronautics industry, including statistical calculation techniques and long-term endurance tests. These ensure that the chance of rotor failure is negligible, allowing for safe above-ground installation.

The bearing system of the flywheel is based on the physics of rigid bodies, similar to a spinning top. When a spinning top rotates above a certain speed (several thousand rpm in this case), it stabilizes vertically, and its center of mass aligns with the direction of gravity. Similarly, the flywheel is finely balanced. However, achieving absolute balance is impossible because, at maximum speed, the centrifugal forces cause the rotor to expand by about 1 mm from its resting diameter. For this reason, the system is designed to allow the rotor to "find" its natural balance point, stabilizing its movement. This design results in the rotor spinning smoothly without vibrations, and when you touch the flywheel housing, it feels like touching a stationary object.

The flywheel operates on a magnetic levitation bearing system, which supports the rotor without friction. In addition, the wheel axles are held by hybrid ball bearings that are flexibly coupled to the housing. These bearings experience no wear because no force is applied to them while the flywheel is operating within its normal speed range. They only come under load when the flywheel is spinning at low speeds, outside of its working range.

Motor and Vacuum Challenges

The flywheel motor is a permanent magnet synchronous motor (PMSM), known for its high efficiency over a wide range of speeds and well-developed control principles. However, the motor has several unique characteristics that require specialized design. Key challenges include operating in a vacuum, accommodating the floating motor shaft, and minimizing iron losses.

The flywheel operates in a vacuum to eliminate aerodynamic drag, as the peripheral speed of the rotor exceeds the speed of sound. This vacuum environment poses a challenge for the thermal management of both the motor's rotor and stator. In typical motors, airflow in the air gap helps cool these components. In a vacuum, however, the motor's rotor can only be cooled by radiation, while the stator is cooled externally (outside the vacuum). Maintaining safe operating temperatures is particularly important for the rotor, as its permanent magnets can weaken or even lose their magnetism if the temperature exceeds safe limits.

Unlike typical motors, the flywheel motor does not have its own bearing system but relies on the wheel's magnetic bearing system for support. As a result, the motor rotor "floats" on the same axis as the wheel rotor, and the motor’s air gap must accommodate this floating arrangement.

When the flywheel is fully charged and spinning at maximum speed, magnetic friction losses occur in the motor. These losses are caused by the rotating magnetic field of the motor rotor, which induces energy losses in the stator due to eddy currents and hysteresis (magnetic field behavior). To minimize these losses, the motor is constructed from thin laminations and high-quality magnetic materials.

The charging accelerator system

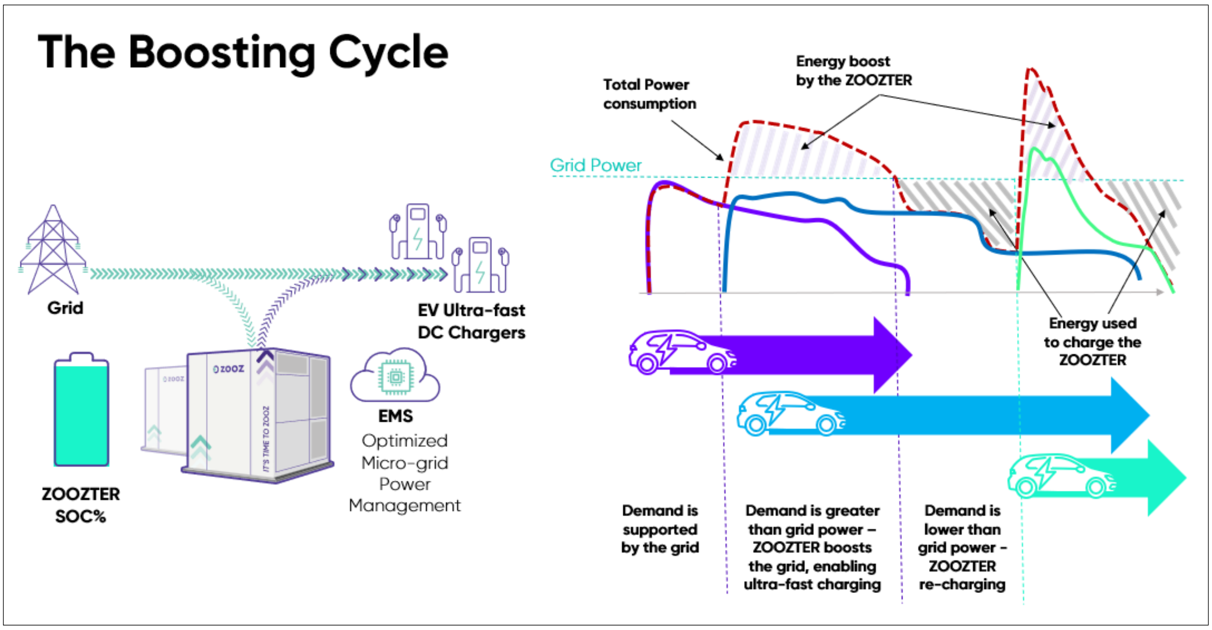

Diagram 2: The charging accelerator system

The charging accelerator system consists of eight flywheels, each capable of providing 12.5 kW for 15 minutes, allowing the entire system to supply approximately 100 kW for the same duration. During energy discharge, the system connects to the chargers and monitors the incoming power from the grid. It injects power into the grid when necessary while ensuring that the network does not exceed its maximum power limit. Typically, electric vehicle charging starts with high power, but as the battery heats up, the required power decreases. This creates a situation where the charging demand is lower than the available grid power. In this scenario, the charging accelerator recharges itself. As a result, the electric vehicle may be powered solely by the grid, while the charging accelerator also recharges. This method ensures that the charging accelerator is ready to support the next vehicles and optimizes energy use from both the grid and the accelerator.

"The Operation of the Charging Accelerator at a Real-World Site"

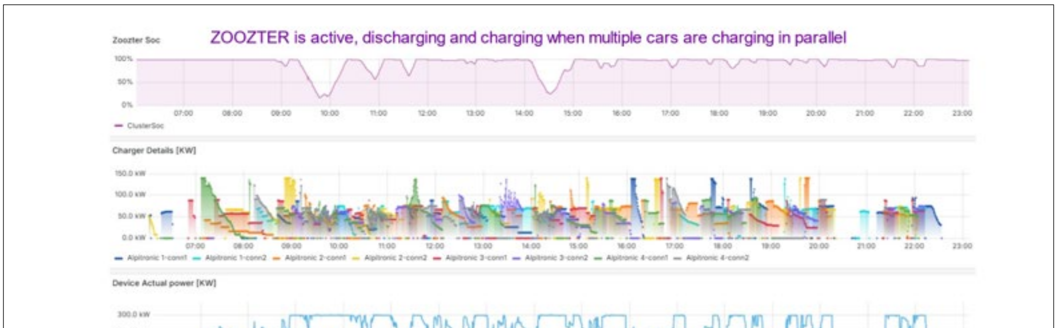

Diagram 3: Activity Graph of Electric Vehicle Charging at a Real-World Site

The graph in Figure 3 illustrates the electric vehicle charging activity at a real-world site. The site has a power input of 300 kW, and the owners aimed to upgrade from three chargers with a combined maximum output of 350 kW (two 100 kW chargers and one 150 kW charger) to four 150 kW chargers, totaling 600 kW, without upgrading the network.

The upper graph (in pink) shows the energy level in the storage system (State of Charge - SOC). The colored graph below represents the power output of each charging socket (each charger has two sockets). The lower graph illustrates the power levels of different elements at the station. The light blue line indicates the network power, which maxes out at approximately 300 kW. When the chargers draw more power than the network can provide, the charging accelerator activates. The brown line represents the charging accelerator's activity: when it dips below zero, the accelerator is discharging energy into the system, and when it rises above zero, the accelerator is recharging.

Summary

A charging accelerator based on flywheel technology provides an efficient, durable, and environmentally friendly solution for addressing power limitations at ultra-fast EV charging stations. This system significantly boosts the power and capacity of daily charging operations without the need for costly network infrastructure upgrades.

About the Author

Ilan Ben David is an entrepreneur and veteran executive with extensive technical and business experience. He co-founded ZOOZ and served as the company’s CEO from its inception in 2013 until 2020. Before that, he co-founded Genoa Color Technologies and served as its CEO. The company, which specialized in color processing chips for screens, was later acquired by Samsung. Additionally, he has held several senior positions in the electronic printing industry. Ilan served in the IDF's 8200 unit and is the inventor of more than 20 patent families. He holds a bachelor’s degree in mechanical engineering and a master’s degree in electrical engineering, both from Tel Aviv University, along with a microdegree in quantum computing from MIT.