Chain-Free Cycling

Serial hybrid drive for bicycles

Until now, almost all pedelecs (pedal electric cycles) have been equipped with parallel hybrid drives with a mechanical connection between the pedal and the drive wheel. Serial hybrid drives leave this high-maintenance coupling out, but give cyclists a very unnatural feel during the ride. The serial hybrid EE-SpeedBike by IAI GmbH overcomes this disadvantage. Thanks to the smart control strategy, developed with dSPACE tools, it delivers a highly authentic ride.

The market for pedelecs in Germany and Europe is booming, with an annual growth rate of almost 10%. Today's mid-priced pedelecs not only have a chain drive or a belt drive. They are also equipped either with a mid-drive motor near the pedals or with a rear hub motor. These drive concepts are commonly known as parallel hybrid drives.

Serial Hybrid Drives

For over 40 years already, engineers have been working on serial hybrid drives for bicycles. The original idea goes back to Augustus Kinzel, an American who was granted the first patent for this concept in 1975. Back then, the concept assumed that the pedals are connected directly to a generator. The pedaling power of the cyclist generated electric power which flowed through a cable to the front wheel motor. The design worked without the customary mechanic coupling between the pedals and the rear wheel. Many different bicycle models with serial hybrid drives were introduced in the years after that, but for various reasons, such as the unnatural feeling during the ride and the lack of counter torque at the pedals, to name a few, they did not reach market maturity.

The Road to the Future

The initial motivation for the first studies on serial hybrid drives at the Institut für Automatisierung und Informatik GmbH (Institute for Automation and Computer Science, IAI) came from discussions with a bicycle manufacturer. During this discussion, the wear and maintenance of parallel hybrid drive pedelecs, especially regarding the chain and derailleur, were seen as disadvantageous faults. These studies mainly consisted of analyzing the performance of various conventional bicycles. The development objective was to design a serial hybrid drive bicycle as an evaluation model that provides at least as much performance as a pedelec with a parallel hybrid drive and keeps the same pedal feel of a conventional bicycle. As part of one of the projects funded by the Federation of Industrial Research Associations (AiF), synchronous drives were developed on the basis of the driving performance analysis by using the associated measurement and control technology and power electronics that were first tested on a converted commercial bicycle. The torques demanded from the motor and generator are substantially different than for auxiliary drives available on the market. In serial hybrid drives, the drive motor must be able to translate all the drive power that the bicycle needs. In contrast, the generator must be able to produce adequate counter torque against the chain drive to give the cyclist haptic feedback that fits the particular ride. The first generation of drives did not fulfill these requirements completely, because the conflict of objectives between the required torque and the small size could only be solved with an optimized transmission. Nevertheless, this first model did prove that it is possible to emulate the chain drive with special control algorithms via software simulation.

The X-PESA Concept

Following the functional evidence, the drives were made smaller by integrating planetary gears, the torque was increased, and the concept was installed in a customized frame. A further functional model, the X-PESA, designed as a 25 km/h pedelec, measured up to the performance of parallel hybrid drive pedelecs that are currently available on the market. During an early development stage, though, it was clear that the generator was too large and too heavy to achieve the desired torques with a one-stage planetary gear.

The Next Generation

Funding from the State of Saxony-Anhalt as part of the state initiative ELISA (Electric Mobility and Lightweight Engineering) made it possible to resume re-engineering the drives. The gene-

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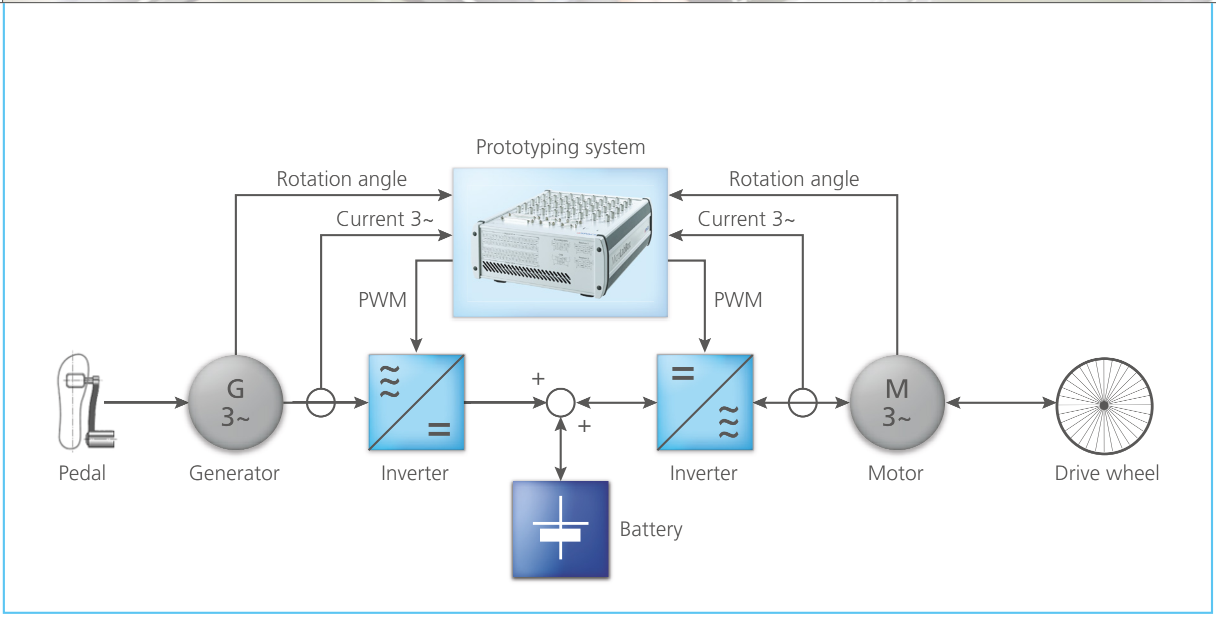

Figure 1: Power flow of a serial hybrid drive with the dSPACE MicroLabBox as a prototyping system.

rator, now equipped with a two-stage planetary gear, delivers a maximum torque of 180 Nm at a total weight of 2.9 kg, so a cyclist weighing 100 kg feels enough counter torque, even during more aggressive rides. The drive motor, using the installation space of the rear sprocket, reaches a peak torque of 120 Nm and temporarily generates 2 kW of power. With this performance, the motor is designed for use in the S-Pedelec category up to 45 km/h and can also be used by all types of bikes (city bikes, mountain bikes, cargo bikes, rickshaws, etc.) under a speed limit of 25 km/h. The motor and generator are completely maintenance-free. Despite the double energy conversion, the efficiency and costs of this drive system are, in principle, comparable to that of parallel hybrid drives, since the mechanical coupling between the pedal and rear wheel and the mechanical circuit are removed. In terms of its functionality, the serial hybrid drive is unique worldwide.

Convenient Control via Smartphone

The heart of the drivetrain is a 16-bit microcontroller that controls the motor and generator in real time, performs the monitoring tasks, and handles communication with the control display and the smartphone connected by Bluetooth. The smartphone displays all the ride parameters, such as the speed, battery level, and performance, with a specially developed app. In addition, the smartphone also sets the various operating modes. In manual switching mode, a control display operates the virtual 20-speed gearing, which represents a conventional derailleur. As an alternative option, the serial hybrid drive has a continuous automatic derailleur that lets cyclists set the desired stride rate via the control display. The variable setting of the battery support allows for adjustments of the cyclist`s electric "tailwind". With medium support, the battery pack gives the EE-SpeedBike a range of 80 km, which can be extended to any distance. If the cyclist generates more pedal power during the trip than the drivetrain requires, the excess power charges the battery. At a speed of 45 km/h, when a greater part of the drive power is provided by the battery pack, the range is still 45 km. As an alternative to reloading the battery via a power socket, the exercise bike mode allows charging the bicycle´s 850 Wh battery while it is standing still. During rear wheel braking, the motor is operated in a continuously controllable recuperation mode and transforms the kinetic energy back into electrical energy, which is fed into the battery before and while the mechanical brake engages.

Figure 2: The user interface of the smartphone, connected via Bluetooth.

Initial Commissioning

The commissioning and evaluation of the drive components was done with

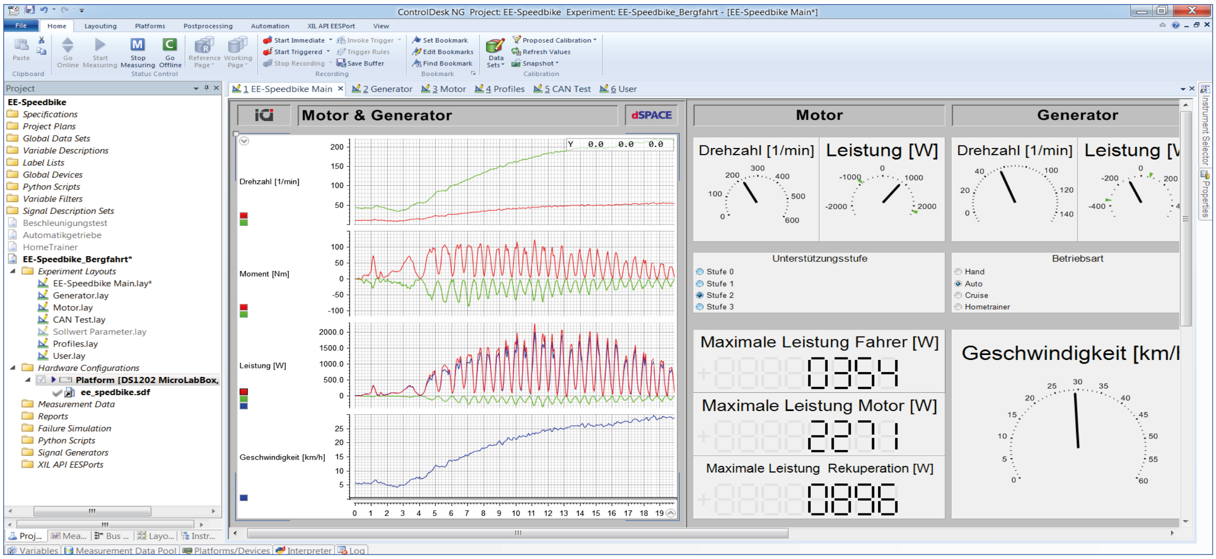

Figure 3: Torques, rotational speeds, and different levels of power from the motor and generator during a simulated mountain ride on a test bench.

> "The comprehensive I/O functionalities of dSPACE MicroLabBox gave us maximum flexibility for testing our new drive concept on the test bench."
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> *Steffen Braune, Institut für Automatisierung und Informatik GmbH (IAI)*

the help of a DS1103 PPC Controller Board. The performance of the prototyping system allowed real-time testing of even CPU-intensive control algorithms developed in MATLAB®/Simulink®, initially without considering runtime optimizations. The extensive peripheral functions of the DS1103 made it possible to perform fully comprehensive trial runs on a test bench for the motor or generator.

From the DS1103 to MicroLabBox

Recently, IAI has started using a MicroLabBox on the test bench. With higher computing power than the DS1103 and the extended peripherals, in particular multi-channel PWM signal generation, MicroLabBox made it possible to test the motor and generator simultaneously on the test bench. This enabled the researchers to reach a better understanding of how the two drives interact, and thus to continue improving both the ride feeling related to the generator and the motor's torque generation. The RTI USB Flight Recorder Blockset lets IAI record all relevant process data with a high sampling rate over a longer period and makes performing an analysis much easier. The extended features of ControlDesk 5.5, such as the new Variable Browser and the ability to save individual plotters as new measurements, enable the quick and efficient implementation and evaluation of test series.

Conclusion and Outlook

Together, the EE-SpeedBike and its predecessor X-PESA have put several thousand test kilometers on the road and on the test bench without any notable problems. In December 2015, the drive concept was honored with third place in the Hugo Junkers Award for Research and Development of the state of Saxony-Anhalt in the category "Most Innovative Projects in Applied Research". The next development step is to industrialize the current model in order to manufacture high numbers of bicycles through production technology. ■

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