A Novel Approach for Vehicle Parking: The Rotor Lock Module

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ABSTRACT: To reduce the complexity of modern electric drives, a holistic functional approach is essential. The function of preventing a parked vehicle rolling away is often realized by a mechanical park lock actuator with a pawl and ratchet wheel within the reducer: A solution that requires significant installation space and complicate assembly processes. The innovative rotor lock concept uses the possibility of precise rotor position control of the e-machine to engage the park lock with low forces. That allows the park lock function to be relocated from the reducer to the rotor shaft as it shrinks in size. This novel approach enables the integration of additional functions into a module like the rotor position sensor and the excitation system for EESM applications. Consequently, the Rotor Lock Module reduces weight, packaging and complexity which leads to a highly cost-effective system design.

KEY WORDS: Functional integration, complexity and cost reduction, Park Lock, Rotor Lock, iRPS, Brush transmitter

1. INTRODUCTION

One of the safety functions in a battery electric vehicle (BEV) is to ensure that the vehicle is secured in parking position. This function is often realized by a combination of park brakes and/or a park lock device to guarantee redundancy.

Park brakes often utilize the existing caliper of the service brake by adding an additional actuation mechanism generating the required brake force to hold the vehicle at slopes up to 30%. While featuring a smooth and comfortable engagement as well as potential wheel-individual redundancy, this approach, regardless of being hydraulically or electro-mechanically actuated, suffers from brake pad and disc cooling effects. These leads to brake force decrease during parking and requires additional functionalities to maintain the necessary brake force to hold the vehicle.

In contrast, the park lock approach is typically realized by an actuated form fit mechanism in the axle drive's gearbox of a BEV. Figure 1 depicts a classical pawl and locking wheel mechanism, integrated into the input shaft of the reducer gearbox. The system consists classically of an electromechanical actuator and mechanical lever with a spring, that guides the actuator rotation into a locking motion.

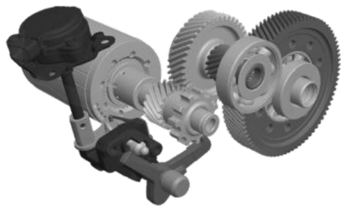

Fig. 1 State-of-the-art Park Lock system with pawl and locking wheel integrated into the reducer gearbox of a BEV

Comparing both solutions, the park lock device increases the reliability and safety of the parked vehicle. Firstly, it does not suffer from cooling effects of brake pad and disc and secondly, it does not limit the parking slope capability in the failure case, when the other securing device (e.g. a park brake) is not working.

However, this state-of-the-art approach, which is a carry-over from automatic transmissions, suffers from high cost and integration effort: High torque actuators with a weight of around 1.5kg are necessary for engagement and disengagement of the mechanism. Large forces are required to spring-load the pawl if there is a mismatch between parking pawl and the locking wheel (Fig. 2 left) for engagement. Even higher forces are required to pull out the pawl during disengagement process when the drivetrain and hence the form fit contact surface is loaded by the weight of the vehicle on the slope. Consequently, the actuators takes up a large space in a densely packed environment around the e-machine and reducer. In addition, the high load movements lead to a rough and noisy locking and unlocking process.

Furthermore, several steel parts for the locking mechanics need to be integrated into the gearbox. Due to packaging reasons, these steel parts often need to transfer and guide the actuation force through the gearbox. This leads to an increase of weight and additional package and, in terms of variations of the vehicle platform, to an inflexible integrated part.

Seeking for size and cost reduction, a holistic approach was developed utilizing the e-drive and its control to facilitate the locking procedure for securing the vehicle in parking position

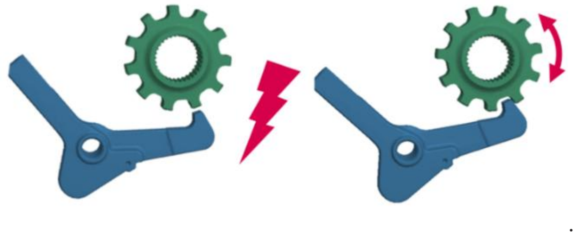

Fig. 2 Park pawl and locking wheel

2. FROM PARK LOCK TO ROTOR LOCK

The core function to enable cost and complexity reduction with Rotor Lock is to pre-align the locking elements prior to the engagement and disengagement process as depicted in the right-hand-side of Fig. 2. By a quick pre-positioning, introduced by a software feature of the HV-Drive, the rotor rotates to the form fit matching angle for pawl and locking wheel. The state-of-the-art rough activation of the park lock transfers to a seamless locking procedure while requiring only a few degrees of turning. This procedure leads to the general concept of function splitting between the HV drive and the locking actuator: All park lock-relevant sub-functions causing heavy actuator torques are covered by the HV drive (e.g. avoid mismatch between pawl and locking wheel) while the remaining functions, the movement of locking engagement, are handled by the lock actuation system.

Besides the already mentioned pre-positioning, the HV-Drive supports also further maneuver like the disengage and stopping of the vehicle: For the unlock procedure, the HV drives unloads the form fit during when the weight of the vehicle exerts a constant torque on the locking form fit depending on the road slope. The required rotor torque and movement to unlock is typically a function of slope, drivetrain stiffness and number of locking segments on the locking wheel. For the stopping maneuver, when the locking command is requested already a low vehicle speeds, the HV drives takes over the function of stopping the vehicle. In state-of-the-art park lock systems this function generates mechanical shocks with high dynamic torque and forces in the system, when the pretensioned pawl snaps into the ratchet wheel, thus requiring strong and heavy structures.

Hence, the locking element in the rotor lock approach needs to fulfill significantly reduced dynamic load requirements and can be smaller and lighter while providing the functionality of keeping the vehicle at up to 30% inclination. In addition, the pre-positioning/unloading facilitates the lock actuation to become a nearly frictionless movement to engage and disengage the locking element without high torque requirements. This results in a further reduction of required space, while providing engagement cycle times of less than 250 milliseconds and covering the main functional safety request for a locking mechanism.

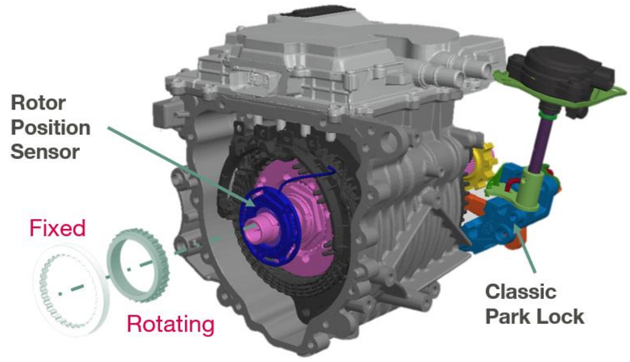

Fig. 3 Relocation of the park lock out of the reducer into the rotor shaft end by an axially moving multi-tooth locking element

As a consequence of this size reduction of actuator as well as the locking element, the mechatronic system for the new locking function can be removed from the reducer gearbox and integrated into the shaft end of the e-machine in the form of an axially-moving multi-tooth ring. This is shown in Figure 3. Thereby, it significantly increases cost-efficiency due to smaller and lighter parts as shown in Figure 4. But also, in the whole drivetrain context it brings big systemic advantages as it enables a smaller reducer gearbox package and can even reduce the number of reducer variants depending on the vehicle platform strategy.

Nevertheless, one of the biggest advantages of the rotor lock approach is the possibility for function integration. The shaft end of the e-machine is a very limited design space in axial direction as components are located here, that serve the e-machine functionality. Removing those components by integrating their functionality into the rotor lock device und thus removing component part redundancies brings further package and weight advantages but also improves cost efficiency even more. This will be detailed in the next section of this paper.

Fig. 4 Cost comparison of Classic Park Lock vs. Rotor Lock

3. THE ROTOR LOCK MODULE

Evolved from the previously described development process the locking element has moved from the reducer gearbox to the free rotor end of the e-machine. Here, it enables function integration of the rotor position sensor and excitation system for externally excited synchronous machines (EESM) [1], both functions are typically localized in this design space. The concentration of active components into a module reduces cost and frees-up drivetrain package by sharing common component structures as housing, PCB and interfaces, like the electrical connector and the mounting points. Following this approach the Rotor Lock Module has become a highly integrated and easy-to-mount HV drive component which overcomes the major pain points of state-of-the-art park lock systems, being large, heavy, drivetrain-specific and thus costly.

The Rotor Lock Module is shown in Figure 5. The view from the e-machine housing direction reveals the axially moving locking element, that transfers the holding torque during parking from the rotor shaft to the e-machine housing. The multi-tooth geometry on the outside (housing interface) enables a good load distribution for durability whereas the high number of teeth on the inside (shaft interface) ensures a fast lock engagement and small vehicle movement after engagement, when the service brake is released.

The locking element is axially actuated by a DC-motor with a worm gear driving a spur gear segment on a spindle. It is a self-locking mechanical gear system, that keeps the states of locking element stable without consumption of energy.

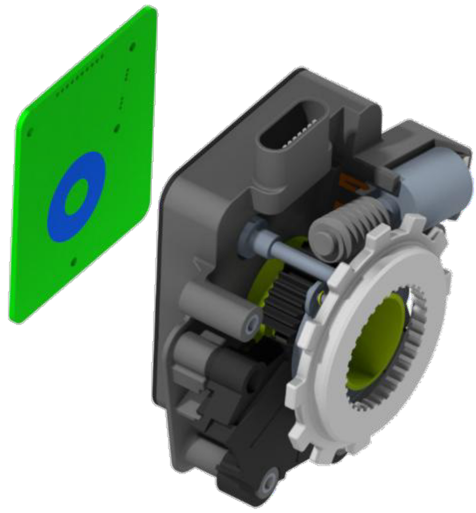

Fig. 5 Rotor Lock Module integrating rotor locking, position sensing as well as current excitation for EESM applications.

Besides being engaged or disengaged, the locking mechanics includes also a spring-pretensioned state. This acts like the classical park lock state for passive engagement but here in the Rotor Lock Module as a safety fallback in case the active prepositioning by the HV drive is not functioning properly. Thus, it needs not be designed to withstand thousands of high dynamic load engagements. Furthermore, the module includes a linear position sensor for direct measurement of the locking element state being engaged, disengaged, pre-tensioned or stuck in-between.

For being small, lightweight and cost effective, an inductive rotor position sensor (iRPS) is integrated. The robust and highly accurate system requires a coil system, a rotating electrically conductive target and signal processing electronics which have been deeply integrated into the Module's PCB and rotor interface. Figure 5 also depicts how the iRPS sensing coils are integrated, sharing space on the PCB with the motor electronics as well as iRPS target on the rotor shaft adapter. For low latencies, the rotor position signal is transmitted via analogue differential sine and cosine voltages to the inverter, which need to calculate the rotor actual rotor angle e.g. by a tracking loop algorithm.

Since the rotor position and hence the speed signal could be calculated also within the Rotor Lock Module by the integrated microprocessor, this speed information can be used to act as functional safety feature in the context of unintended locking, e.g. by a plausibility check for vehicle standstill. The additional source of speed itself within the vehicle system could furthermore act as redundancy for other subsystems, e.g. vehicle stability.

For axle drive variants with externally excited rotor (EESM), the mounting position of the Rotor Lock Module supports the integration of a conductive transmission system. The housing provides a mounting platform while the mechanical locking concepts leaves integration space for a set of brush pairs and slip rings to transmit current in and out of the rotor, powering the field coils.

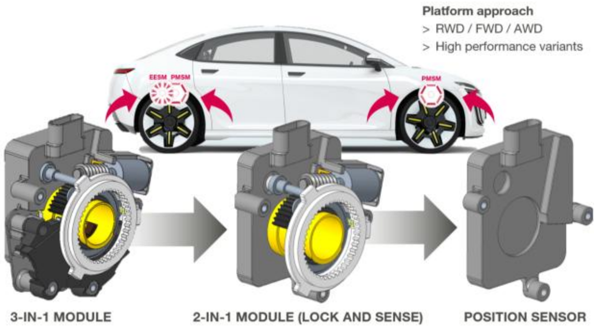

Fig. 6 Rotor Lock Module Platform Approach

From a vehicle platform perspective, that needs to provide different drivetrain variants (RWD, FWD, AWD plus high performance), the functional content of the Rotor Lock Module can be tailored to fulfill the specific motor application requirements. In addition to the already mentioned EESM, which requires the three module functions (3-in-1), a 2-in-1 module that includes locking and rotor position sensing could serve a permanent magnet synchronous machine (PMSM) on the rear axis as shown in Figure 6.

The cost advantage of the rotor lock concept resulting in actuator size reduction in combination with function integration resulting in the reduction of redundancies described before is shown in Figure 7. A 2-in-1 Rotor Lock Module can save up to 16% of total cost against the sum of all individual components to fulfill the required functions of locking and position sensing. In case of the 3-in-1 module advantage increases to even 19%.

Furthermore, reusing the same tooling and stripping down the functionality of the module to position sensing only, PMSMs on the front axle could be served. This could enable further cost improvements considering a holistic platform approach using as many equal parts as possible on the e-machine variants.

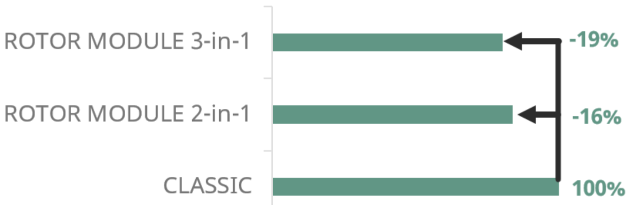

Fig. 7 System cost advantages for a 2-in-1 and 3-in-1 Rotor Lock Module compared to the sum of all required components of a classical system

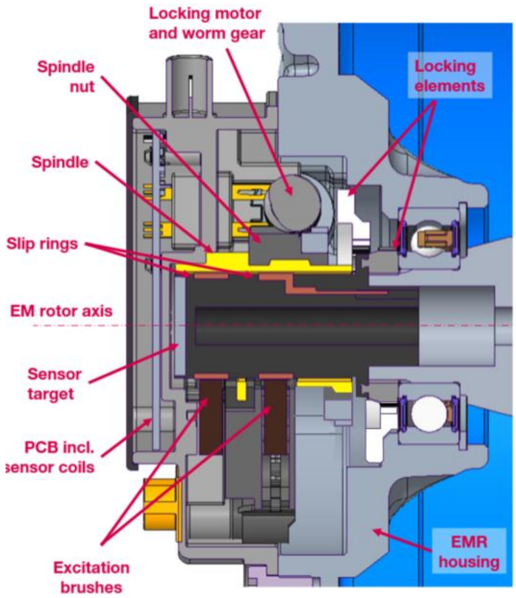

Fig. 8 Cross-section of the 3-in-1 rotor lock module integrated into the free end of an EESM

But cost is not the only advantage of the Rotor Lock Module. Figure 8 shows a cross-sectional view of the Rotor Lock Module installed into the e-machine housing at the free end of the rotor, opposite to the reducer gearbox. The deep integration of the compact design shows the efficient utilization of the available design space, which is very limited due to vehicle architectures.

Above the rotor axis of the e-machine, the position of the locking element (white part) indicates the unlocked state as the locking element on the shaft (dark grey) can freely turn. Driven in the direction of the e-machine axis by the motor with worm gear via spindle nut and spindle, the locking element is pushed via three annular distributed springs into the locked state.

This is shown in the lower part of Figure 8 where both locking elements are interlocked providing a direct torque path from the rotor into the housing of the e-machine. Hence, no parking torque is transferred through the rest of the Park Lock Module structure. Furthermore, it reveals the encapsulated PCB with the iRPS sensing coils shielded by the housing from inside of the e-machine and located close to the speed sensor target on the shaft adapter. The excitation system is integrated opposite to the locking mechanics with gaps in the central spindle to realize an access for the brushes to the two slip rings (plus and minus pole of excitation current).

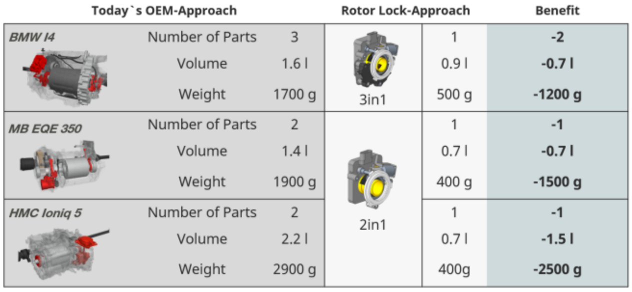

Fig. 9 Summary of space and weight savings for the 2-in-1 and 3-in-1 variants

With this compact design, utilizing the limited space in axial direction in an optimal way, large overall volume and weight savings can be achieved. Figure 9 gives some examples for specific state-of-the art applications where more than 700 ml and 1.2 kg can be saved for a 3-in-1 module compared to function realization by individual components. Even up to 1500 ml and 2.5 kg savings are feasible for the 2-in-1 module in an Ioniq 5.

4. VALIDATION AND TESTING

Key specifications for each product function as well as for the whole 2-in-1 Rotor Lock Module are given in Table 1. These were determined for the prototype development phase representing a typical BEV application in the D-segment.

The locking capability shall be designed to withstand 450 Nm steady locking torque and 1050 Nm dynamic torque for transient loads e.g. rotor shock. The whole system shall realize a locking and unlocking event within a duration of 300 msec including the HV-drive prepositioning and unloading. The rotor position sensing system shall be designed for a 4-pole pair e-machine with an accuracy of ±0.5° electrically in an 90° sensor segment resulting in a mechanical accuracy of ±0.125° at a rotor speed up to 17.000 rpm which largely covers market applications

Table 1 Key function specifications for the Rotor Lock Module

Function	Key Requirement	Value
Drivetrain Locking	Static torque	450 Nm (3.5t @ 34% slope)
	Dynamic torque	1050 Nm (rotor shock)
	Time to lock/unlock	< 300 ms
Rotor Position Sensing	Number of segments	4 per revolution (4 pole pair machine)
	Accuracy	±0.5 deg electrical (per segment)
	Maximum speed	17.000 rpm
2-in-1 Rotor Lock Module	Communication	CAN protocol
	Volume	< 0.7 liter
	Weight	< 400 gr

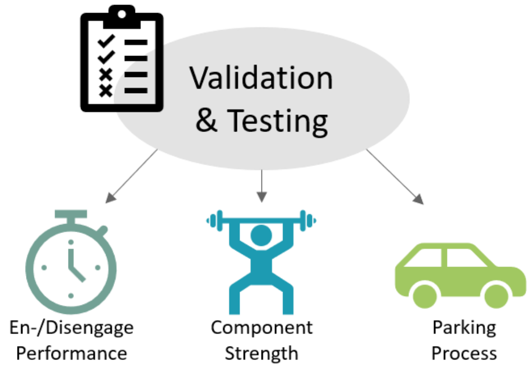

Fig. 10 Overview of implemented testing to validate the module requirements

The module shall be integrated into the vehicle's communication system via CAN interface. Total volume and weight shall be below 700 ml and 400 grams, respectively, for the 2-in-1 Rotor Lock Module prototypes to be tested.

The module testing has been conducted in three different focus areas to validate the requirements as depicted in Figure 10. System testbench measurements have been performed to measure the performance of the actuation system to engage and disengage the locking element. To ensure the mechanical strength of the locking element in all lifetime conditions, structural simulations and mechanical load testing have been performed. And finally, the whole parking process including the e-machine prepositioning has been tested and validated in a vehicle. Figure 11 shows a prototype of the 2-in-1 Rotor Lock Module on the system test bench. The bench consists of a shaft representing the e-machine rotor, which can be controlled by a motor for continuous turning and prepositioning.

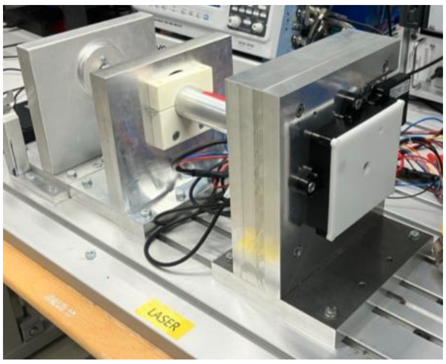

Fig. 11 2-in-1 Rotor Lock Module prototype on the system test bench for locking and unlocking performance measurements

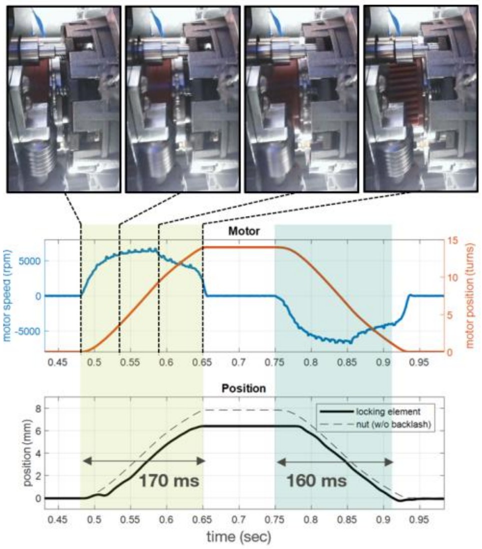

Fig. 12 Measurement results of prepositioned engagement (left) and disengagement (right) movement including resulting motor position and speed, as well as the position of the locking element

The prototype is mounted on the flange carrying the rotor bearing. For performance analysis, locking element engage and disengage cycles have been performed. The locking element position was determined by the integrated Hall-effect position sensor as well as an external laser sensor. Furthermore, the actuating DC-motor has been measured by an integrated multi-turn Hall-effect sensor, to analyze rotation speed and backlash in the lock actuation system. A typical engagement and disengagement cycle at nominal operation voltage of 12 V is displayed in Figure 12. The engagement process takes 170 ms, clearly visible in the motor speed profile (blue line, upper graph). Disengagement is even faster and takes 160 ms due to the pretension in the actuation system, that eliminates the backlash and helps in accelerating the locking element into the backward motion.

The performance of the module regarding the rotor position sensing function was confirmed to comply existing stand-alone applications. However, tests for quantification of functional crosstalk, especially for the position sensing accuracy, have been conducted and showed unobtrusive results.

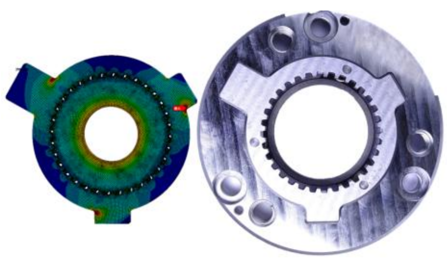

Fig. 13 Structural strength analysis of the locking element by finite elements simulation (left) and testing (right)

Once the locking element has engaged, it transmits the torque in the drivetrain from the rotor into the e-machine housing via its mechanical interfaces on the inner and outer diameter. As shown in the structural analysis plots in the left-hand side of Figure 13, the multi-tooth geometry on the outside (housing interface) enables a good load distribution for durability whereas the high number of teeth on the inside (shaft interface) ensures a fast lock engagement and small vehicle movement after lock engagement, when the service brake is released. The simulations have been validated with strength tests on real parts, which can be seen in the right-hand-side of Figure 13.

For the validation of the whole park lock functionality the Rotor Lock System has been integrated into a test vehicle. This included the mechanical integration of the rotor lock actuator into the e-machine of a Peugeot e-208, the function development of the inverter software for prepositioning, unloading and park lock management and finally the integration of all components including the human machine interface. Focus of testing was on the normal operation with prepositioned locking and unloading. The locking and unlock process was silent and could hardly be felt on flat terrain or low road slopes. At higher slopes, a little vehicle movement of a few millimeters could only be felt during parking.

Fig. 14 Test vehicle with integrated Rotor Lock Actuator (RLA) on front axle e-drive parked on the edge of a curb stone (no ground level wheel contact)

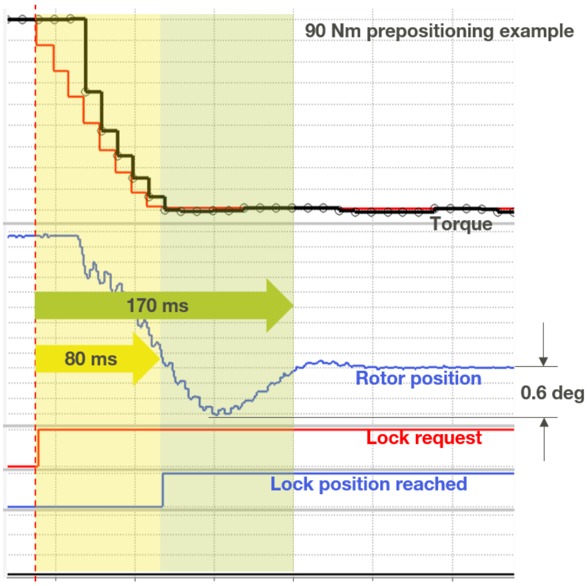

Fig. 16 Example of rotor prepositioning by inverter control against up to 90Nm torque

Drive-off was smooth and anything unpleasant was not perceptible. Beside the silent actuator mechanics, this was also due to the implementation of prepositioning and unloading function in the inverter. Even parking and drive-off on a curb stone edge, which leads to heavy torque conditions in the drivetrain and shown in the picture in Figure 14, was exceptionally inconspicuous.

Figure 16 exemplifies the rotor pre-positioning process up to 90 Nm which happens within 80 ms. After this time the form fit matching rotor position is reached, and the engagement can happen without friction. This prepositioning phase is emphasized by the yellow background color. Nevertheless, there is a slight position overshoot and after further 90 ms the rotor comes to rest, but due to the play in the locking elements, this does not affect the engagement process (green background).

Thus, in total the system can lock and unlock the vehicle within a timeframe of 250 ms at 90 Nm prepositioning torque, being well below 300 ms and providing 20% safety margin for extreme parking conditions where even more torque is required. However, these are highly dependent on vehicle weight, drivetrain stiffness, number of locking element teeth as well as preposition/unloading function implementation and need to be validated in the specific target application.

As the preposition/unloading function cannot be guaranteed in all failure cases of the vehicle, springs have been implemented in the locking mechanics. They provide a fallback solution, such that the system behaves like a normal park lock. Thus, the locking element will be pretensioned and pressed against the counterpart by the actuator when not prepositioned and snaps in, once the vehicle starts to roll after the service brake is released. Furthermore, unintended locking at higher shaft speeds is prevented by locking element design. Due to the tooth shape the locking element cannot engage above a vehicle speed of 4kph, in case any malfunction causes the actuator to engage.

5. CONCLUSIONS

This paper presents the Rotor Lock Module, a compact, leightweight and cost effective solution for locking the e-machine rotor during parking, determining the rotor position for efficient motor control and providing a conductive current transmission interface for EESM applications. It integrates the e-machine functionality into the park locking process by rotor pre-alignment for parking and lock unloading for drive-off. Hence, reducing dynamic loads on the structural components it enables significant packaging and weight advantages compared to state-of-the-art park lock solutions, validated by component and vehicle testing. Besides the directly accompanied cost benefits, also the elimination of redundancies through function integration improves cost efficiency of the novel product. It carries even more potential for further cost reduction on vehicle or even platform level as it can reduce the number of reducer variants in the HV drive, for instance, and guarantees simple mounting on the rotor free end of the e-machine.

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