Electric motor design for steer-by-wire systems and functional safety analysis

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Abstract. Steer-by-Wire (SbW) systems are gaining significance in the automotive industry in response to growing demands for driving comfort and safety. By eliminating traditional mechanical steering column connections, SbW systems offer reduced power consumption and enhanced steering performance. This paper examines the design and functional safety requirements of feedback motors used in SbW systems. In SbW systems, feedback motors generate reactive torque to improve the driver's steering feel, requiring precise control. Brushless DC (BLDC) motors are emphasized as the preferred choice due to their high reliability and efficiency. This study outlines specific parameters for the selection and design of BLDC motors and identifies suitable options. The ISO 26262 functional safety standard is crucial for ensuring the safe operation of these systems. In compliance with the ISO 26262, the failure rates of electric motors must align with the associated risk levels. Additionally, these motors should incorporate safety mechanisms capable of detecting and isolating faults. In conclusion, adherence to the ISO 26262 standards in electric motor design for SbW systems is vital for vehicle safety and performance. This paper reviews studies aimed at developing safe, efficient, and reliable motors for modern automotive applications and offers recommendations.

Keywords: steer-by-wire, brushless dc motor, functional safety, electric motor design.

1. Introduction

In recent years, the rapid advancement of technology has led to an increase in complex systems in vehicles, driven by demands for greater driving comfort and safety in the automotive sector. X-by-Wire systems, where electronic units replace traditional mechanical or hydraulic linkages, serve as prominent examples of this shift. Among these systems, Steer-by-Wire (SbW), Brake-by-Wire, Throttle-by-Wire (Drive-by-Wire), and Shift-by-Wire are the most commonly implemented. Steer-by-Wire (SbW) systems are regarded as a groundbreaking innovation among X-by-Wire technologies in the automotive industry. Consisting of electronic control units, steering assist motors, and sensors, SbW systems replace the conventional mechanical steering column. The advantages of SbW systems include reduced power consumption, improved steering performance, and enhanced road handling [1]. From the perspective of driving experience and ergonomics, SbW systems offer several benefits over traditional steering systems, including weight reduction, vibration mitigation, and improved steering functionality. One of the primary challenges of SbW systems is creating an appropriate steering feel for the driver. Many studies propose various methods, including objective criteria for steering feel characterization and hysteresis steering feel models, to optimize the driving experience. Achieving optimal steering feedback is a critical control problem involving feedback motors, steering columns, steering wheels, angle, and torque sensors within the steering feedback module [2]. The implementation of SbW systems eliminates the mechanical connection between the steering wheel and wheels while fulfilling the specific tasks of the steering system. These systems translate the steering wheel's rotation into an electronic signal via sensors and execute the commands using an electric drive system, which is connected to the wheels either directly or via mechanical components.

Feedback torque, representing steering effort, is applied to the steering wheel through another electric drive system. The adoption of SbW systems in vehicles offers significant benefits in terms of active and passive driving safety, driving ergonomics, and environmental protection. Active safety is achieved through the adaptability of electronic steering commands to driving maneuvers, environmental conditions, and vehicle status. Passive safety is enhanced by removing the steering column, a potentially hazardous component in the event of a collision. Driving ergonomics benefit from increased space in the driver's area and improved design flexibility for the steering wheel [3]. Structurally, SbW systems may employ two or three motors. In addition to the motor at the steering wheel, each of the two front wheels may have its own motor for redundancy and enhanced driving safety. A three-motor system, illustrated in Figure 1, comprises a steering wheel module, a steering execution module, a controller module, a fault-tolerant module, and a power module. The primary components of the steering wheel module include the steering wheel, steering shaft, angle sensor, and road sense motor (referred to as the driver feedback motor). The steering execution module consists of the steering motor, rack and pinion mechanism, and front wheel angle sensor. The controller module serves as the core of the SbW system, analyzing and processing vehicle dynamic signals from various sensors, evaluating real-time driving conditions, and ensuring the proper operation of each actuator [4].

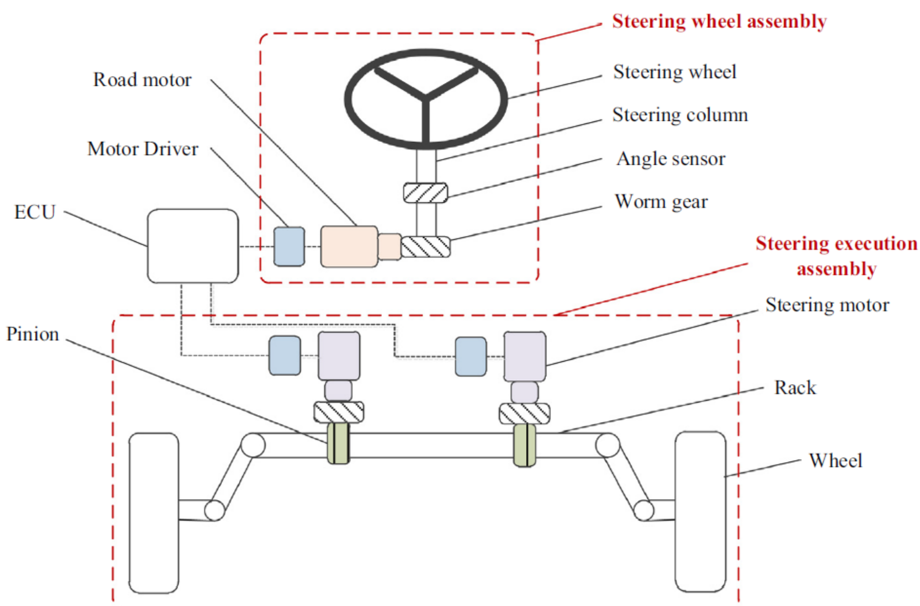

Fig. 1. Structure of an example SBW system [4]

The steering wheel controller detects the position of the steering wheel and transmits it to the wheel controller via the CAN interface every 250 ms. The steering module receives the actual wheel position and torque through the CAN interface, which is used to adjust the steering wheel to the position corresponding to the real position of the wheels. The wheel-side components include the wheels, rack and pinion gear, wheel actuator, pinion angle sensor, and wheel controller. The wheel controller uses the steering wheel position and vehicle speed received via the CAN interface to rotate the wheel motor to the required position corresponding to the steering wheel input [5].

2. Feedback motor and design parameters

This paper focuses on the selection, design, and functional safety evaluation of the feedback motor in the Steer-by-Wire (SbW) system, which generates reactive torque to enhance the driver's steering feel. In the SbW system, the steering wheel is also responsible for providing feedback to the driver. The SbW control module must determine the appropriate feedback and apply the resulting drive to the steering wheel via the driver feedback motor (road feel motor). For example:

1) Road surface and roughness can cause vibrations that should be transmitted to the steering wheel.

2) Mechanical failures in the steering system can result in changes to the steering feel.

3) When the front wheels reach their maximum steering angle, the steering wheel can stop rotating.

Positional feedback from the steering motor informs the SbW control module about road irregularities. This information, combined with data from other vehicle dynamics sensors, can be used by SbW control module algorithms to determine the feedback provided to the driver [6]. The feedback motor does not need to be as powerful as the steering actuator. In fact, it should require much less power to allow easy manual rotation by the driver. A motor that operates at 12V and draws less than 1.5 A is deemed sufficient [7]. Although traditional DC motors are highly efficient and suitable for use as servomotors, their main disadvantage is the wear and tear of commutators and brushes, necessitating regular maintenance. The advent of solid-state switches replacing the functions of commutators and brushes has led to maintenance-free motors, now known as Brushless DC Motors (BLDC motors). BLDC motors are ideal for applications requiring high reliability, efficiency, and torque per unit weight, making them the preferred choice in SbW systems [5]. BLDC motors are designed and manufactured for more efficient and flexible operation. Structurally, they consist of a rotor and a stator. The rotor, made of a magnetic material or permanent magnet, facilitates rotational movement. The stator, comprising a series of windings or coils, generates a magnetic field to induce rotation. Instead of sensors, feedback loops are used to detect the rotor’s position. Fig. 2 illustrates the structural and connection diagram of a BLDC motor [8].

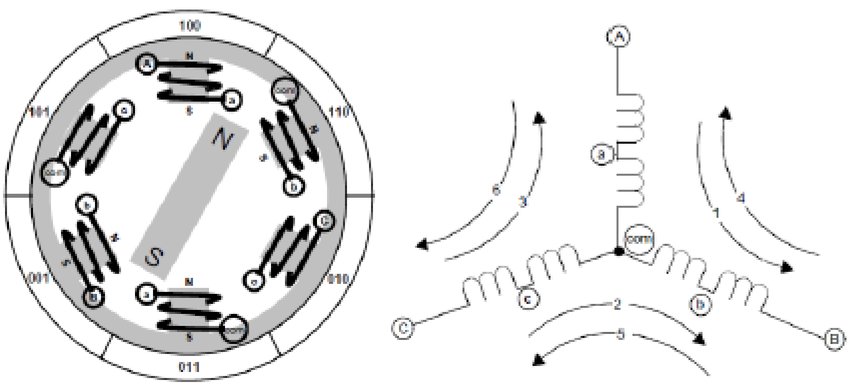

Fig. 2. BLDC motor diagram [8]

In Steer-by-Wire (SbW) systems, motor selection is primarily determined by system performance, reliability, and cost. Table 1 below compares the key characteristics of BLDC (Brushless DC) motors, brushed DC motors, and stepper motors. This comparison clearly demonstrates why BLDC motors are preferred in SbW systems. Their high efficiency, low maintenance requirements, long lifespan, and superior control precision make them more advantageous than brushed DC and stepper motors. Especially in the automotive industry, where reliability and performance are critical factors, BLDC motors stand out.

From a cost point of view, the cost-effectiveness of motors in SbW applications depends on several factors:

1) Initial Cost: Purchase price and manufacturing costs

2) Maintenance Cost: Frequency and cost of repairs or replacements.

3) Energy Efficiency: Power consumption, which affects long-term operating costs.

4) Durability and Lifespan: Longevity affects total cost of ownership.
5) Performance Efficiency: Affects driving safety and system reliability.
Table 2 provides a cost-effectiveness comparison based on these factors.

Table 1. Comparison of motor characteristics

Feature	BLDC Motors	Brushed DC Motors	Stepper Motors
Efficiency	Offers high efficiency	Exhibits low efficiency	Provides moderate efficiency
Maintenance requirement	Requires minimal maintenance due to its brushless design	Requires regular maintenance due to brush wear	Has a simple mechanical structure with low maintenance needs
Lifespan	Long lifespan	Shorter lifespan due to brush wear	Long lifespan
Control precision	Provides high-precision speed and position control	Less precise speed and position control	Offers high positioning accuracy with step-by-step movement
Torque and speed	Delivers constant torque over a wide speed range	Provides high torque at low speeds but experiences torque drops at high speeds	Provides high torque at low speeds, but performance drops at higher speeds
Reliability	High reliability due to electronic commutation	Lower reliability due to brush wear and spark generation	High reliability due to mechanical simplicity.
Electrical noise	Low	Produces high electrical noise due to brush contact	Low
Cost	High initial cost but offers long-term advantages due to low maintenance costs	Lower initial cost, but high maintenance and replacement costs can make it more expensive in the long run	Moderately priced

Table 2. Comparison of cost-effectiveness

Factor	BLDC Motors	Brushed DC Motors	Stepper Motors
Initial cost	High	Low	Moderate
Maintenance cost	Low	High (due to brush wear)	Low
Energy efficiency	High	Low	Moderate
Durability	Long lifespan	Short (brush wear)	Long lifespan
Performance	High precision & smooth control	Less precise control	Good position control but lacks speed control
Total cost of ownership	Cost-effective in the long run	Higher due to frequent maintenance.	Moderate

BLDC motors do not have brushes that wear out over time. This significantly reduces maintenance and replacement costs. BLDC motors consume less power than brushed DC motors. Their robust design ensures longevity, leading to lower long-term costs. They provide precise speed and position control. This comparison shows that despite the high initial cost, BLDC motors are the most cost-effective choice for SbW systems in the automotive industry due to lower maintenance costs, higher energy efficiency, longer lifespan and performance. While brushed DC motors offer a lower initial cost, their frequent maintenance requirements and lower efficiency make them less viable in SbW systems. Stepper motors, while mechanically simple and reliable, lack the speed and torque characteristics required for SbW applications. BLDC motors, despite a higher initial investment, prove to be the most cost-effective choice over the life of the vehicle due to their efficiency, reliability, and low maintenance costs.

To select a suitable motor for the project, specific requirements and conditions must be considered. There are many BLDC motors available for SbW systems, and a systematic approach must be followed to identify the most suitable one. In the study “Selection and Design of BLDC

Motor for Different Applications” by Priti S. Manware et al., this process is described as follows.

For reliable and efficient motor selection, it is essential to know the operating conditions. In addition to specifying the output power in kW and speed, the following information must be known:

1) Torque at the shaft during operation, start-up, and under various loads.
2) Acceleration torque and braking torque.
3) Switching frequency.
4) Motor efficiency under different loads.
5) Other operational requirements.

When examining a motor’s performance for a specific drive unit, one criterion is determining whether the motor’s speed-torque characteristics align with the requirements set by the drive unit. The behaviour during start-up, braking, or speed variation depends on how the speed changes with the motor and drive unit. Hence, analyzing the speed-torque characteristics is crucial for selecting the right motor and achieving economic drive performance [9]. Adhering to these criteria, the following parameters define a suitable BLDC Feedback Motor for the SbW system:

1) Typically, 1-5 Nm torque is sufficient to ensure appropriate steering response and feel.
2) It should be compatible with high-resolution torque sensors for precise control.
3) 0-5000 RPM (rotations per minute) to ensure sensitivity at low speeds and stability at high speeds.
4) Torque response time should be < 5 ms to provide rapid feedback to the driver.
5) It should exhibit low torque ripple (< 1 %) under sudden load changes.
6) Nominal voltage should be 12V, adaptable to the vehicle’s electrical system.
7) Current range typically between 2-10 A.
8) Physically, it should have a compact design (motor diameter < 100 mm, length < 150 mm) and be lightweight (< 2 kg) to ensure easy installation and maintain weight balance in the steering column.
9) It should feature an ISO-compliant shaft diameter (e.g., 10-12 mm) and connection flange.
10) It must support precise feedback algorithms to simulate steering feel.
11) Compliance with Automotive Safety Integrity Level (ASIL) requirements is necessary.

Based on these specifications, motors such as the Maxon EC-i 40 High Torque Series, Kollmorgen CT Series BLDC Motor (CT03 or CT04), Nidec UQK Series, Allied Motion HeiMotion Compact HMC Series, and Faulhaber BP4 Series are suitable candidates. Alternatively, you can design your own motor with the specified parameters using programs such as ANSYS Motor-CAD, ANSYS Maxwell, Altair FluxMotor, JMAG Designer, or COMSOL Multiphysics to optimize and analyze electromagnetic, thermal, and other aspects.

3. Impact of functional safety on feedback motor design

To ensure sustainability, driver comfort, and safety, automotive electronics have gradually undertaken more control functions beyond mere computational tasks. Hybrid Electric Vehicles (HEVs) and X-by-Wire systems represent next-generation vehicles poised to become mainstream soon. As electronic control systems take over vehicle control functions, the functional safety concerns become critical, necessitating tight safety requirements during their development. Additionally, safety issues must be addressed with the utmost priority throughout the entire lifecycle of a safety-critical system. To facilitate the development of such safety-focused systems, the ISO 26262 functional safety standard has been established [10]. The ISO 26262 standard addresses potential hazards arising from faulty behaviour of safety-related electrical/electronic (E/E) systems, including interactions between these systems. The ISO 26262 standard provides guidance, and the concept phase recommends minimum requirements for the development of safety-critical products in a specific area [11]. The ISO 26262 [12] comprises 12 parts, as represented in Fig. 3, and significantly affects the design of electric motors in Steer-by-Wire (SbW) systems from various aspects. Particularly, this standard plays a crucial role in defining the safety and functional requirements of electric motors.

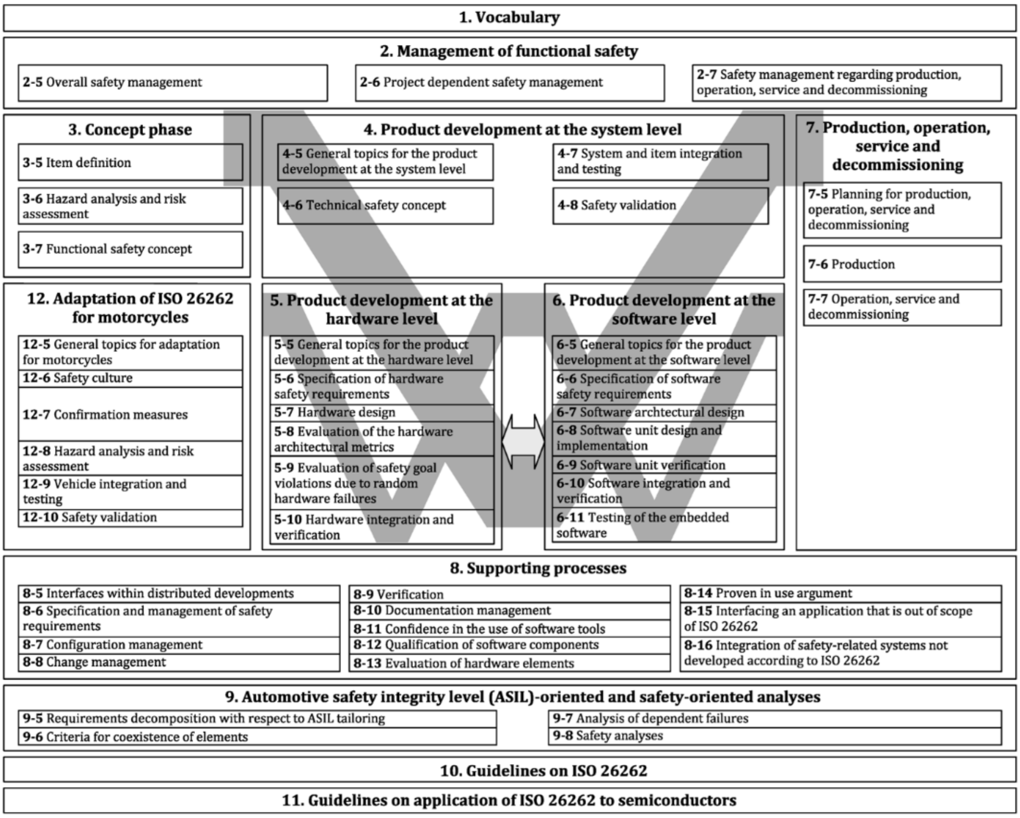

Fig. 3. V Cycle of the ISO 26262 [12]

4. Functional safety process for feedback motor

The functional safety process for the feedback electric motor designed for the Steer-by-Wire (SbW) system begins with identifying and categorizing hazardous events, defining safety goals, and determining the Automotive Safety Integrity Level (ASIL) [12]. To achieve these safety goals and prevent unreasonable risks, the Hazard Analysis Risk Assessment (HARA) method recommended by the ISO 26262 is used. The HARA study details potential motor failures and operational conditions or modes where the feedback motor's faulty behaviour might lead to a hazardous event. Risk assessment for identified hazardous events is based on severity (S), probability of exposure (E), and controllability (C) [12]. Depending on these factors, the appropriate risk level is determined, ranging from ASIL A to ASIL D (increasing risk level). For each hazardous event associated with a specific risk level, safety goals must be defined. In practical terms, consider an example where an electrical short circuit occurs in the feedback motor, resulting in partial or complete loss of functionality. On a rainy, slippery highway, if a vehicle traveling at high-speed experiences a short circuit in the feedback motor, leading to loss of functionality, it is a hazardous scenario. The risk level is determined based on the controllability, occurrence rate of this event, and the magnitude of potential harm to individuals involved, typically categorized as ASIL D. The primary safety goal in this scenario is to ensure that the feedback motor does not lose functionality.

After defining safety goals, functional and technical requirements are written with the inclusion of safety mechanisms, fail-safe mechanisms, and safe states. A warning and degradation strategy should be established to notify the driver of faults and mitigate hazardous conditions to the extent possible. Safety mechanisms should involve monitoring the signals and status of sensors and actuators. As a safety measure, monitoring the signals of circuit components can prevent an electrical short circuit or mitigate potential hazardous scenarios caused by a short circuit. Providing limited operation capacity by lowering the motor's performance in the context of safety is a degradation mode. Notifying the driver of faults through indicator lights on the dashboard is part of the warning and degradation strategy.

After defining requirements, design verification is performed using safety analyses such as Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Failure Modes, Effects, and Diagnostic Analysis (FMEDA). To meet the ISO 26262's safety goals, the Hardware Failure Rate should be below a specific threshold [12]. The failure-in-time (FIT) rate, which defines the number of failures of an actuator over a certain period (usually 10^9 hours), should comply with the ASIL risk levels. From a safety perspective, the designed or selected electric motor should:

1) Operate with a minimal or negligible failure rate suitable for the specified ASIL risk levels.

2) Possess safety mechanisms to detect steering motor faults.

3) Be designed and installed to work flawlessly with sensors, maintaining specific positional attributes.

4) Define a safe state to detect and isolate the initial electronic fault in the SbW system's actuator group and notify the driver.

5) Validate the structural integrity of the mechanical part of the SbW system at specified frequencies.

6) Be designed to prevent loss or delay in steering response.

7) Prevent sudden voltage drops or surges within the nominal voltage.

8) Be designed to prevent performance and overheating issues caused by overcurrent or insufficient current.

To ensure the desired functionality of the feedback motor, additional measures can be taken. Redundancy involves adding supplementary tools to the existing system to achieve the required functionality. If redundancy is implemented, the system's design should consider a redundant item to quickly switch to a backup motor in case of a primary feedback motor failure, reducing the likelihood of hazardous scenarios. Even with redundancy, scenarios where both motors fail should not be overlooked.

5. Conclusions

This paper thoroughly examines the design and functional safety requirements for feedback electric motors to be used in Steer-by-Wire (SbW) systems. By ensuring compliance with the ISO 26262 standard, the technical requirements and solutions for potential faults are addressed to guarantee the motor's safe and efficient operation. The paper focuses on the selection, design, and functional safety compatibility of driver feedback motors used in SbW systems. Feedback motors generate reactive torque to improve the driver's steering feel and must be compatible with high-resolution torque sensors for precise control. Upon reviewing the studies, it is found that BLDC motors are the most suitable for providing feedback torque to the steering wheel. The selection criteria for these motors, emphasizing parameters such as reliability, efficiency, and torque-to-weight ratio, are discussed. The advantages of BLDC motors, including high reliability, high efficiency, and greater torque per unit weight, make them a preferred choice. The motor design must feature low torque ripple and support precise feedback algorithms. Furthermore, designing the electric motors used in SbW systems per the ISO 26262 standards is crucial for vehicle safety and performance. The ISO 26262 standard defines the safety and functionality requirements of the electric motor, including failure rates (FIT rate) and safety mechanisms based on ASIL risk levels. Motors developed according to these standards offer a safer and more comfortable driving experience for the driver. In conclusion, the design of electric motors used in steer-by-wire systems to the ISO 26262 standards is of vital importance to ensure vehicle safety and performance.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Mehmet Duran Menekşe: drafted the article. Mustafa Caner Aküner: supervised the article, reviewed it and indicated the parts to be added.

Conflict of interest

The authors declare that they have no conflict of interest.

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