Multi-Motor Vehicular Systems

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With vehicle electrification, autonomous driving, and employment of X-By-Wire technology, mechanical systems are replaced by motor drives improving their efficiency and performance. Thus, vehicular systems are becoming multi-motor systems. In the following, the case of multi-motor systems in automotive applications is laid out by presenting the different vehicular systems comprising multiple motors.

motor drives multi-motor inverter topologies

1. Introduction

The four primary functions in a vehicle are traction, braking, steering and suspension. With vehicle electrification the mechanical actuators performing these functions are replaced by electric drives, thus, the vehicle becomes a system with multiple motors, and a multi-motor drive architecture may be beneficial. From another and more important aspect, due to the typical layout of a vehicle (two axles comprising two wheels each), each of these systems can be divided into sub-systems with a separate electric drive for each sub-system. This extends the operation domain of the system and allows for advanced technologies to be implemented. There are also cases where a modular approach is adopted where each motor is divided into multiple segments, either to enhance the performance or achieve fault tolerance. In both cases, each system (or sub-system) in the vehicle becomes a multi-motor system, and in each system the electric drives can have the same characteristics and perform the same functions, which further supports a multi-motor drive architecture design approach. In the following, examples from commercial vehicles and research portraying the prevalence of multi-motor systems in vehicular systems are presented. The examples are classified based on the vehicular function and other examples are presented separately.

2. Traction

Whether in a hybrid, battery or fuel-cell electric vehicle (EV), the traction function is carried out partially or fully by electric motors. The use of electric motors in EVs allows for the use of renewable energy sources, higher efficiency and reliability, wider operation range, improved dynamic performance and lower tailpipe emissions. Within the plethora of configurations proposed for these vehicles, two main categories can be identified: the “single-motor” and “distributed” configurations [1]. **Figure 1**a–f show the single motor and distributed 2-wheel-drive electric vehicle traction system configurations, respectively [2]. In the distributed approach, the traction system is a two-motor system. For all wheel drive vehicles, the same configuration can be duplicated for both vehicle axles or different configurations can be combined resulting in two-, three- or four-motor systems. Using multiple motors improves the vehicle performance and adds functionalities. Tesla models S 60D, S85D and P85D as well as Nissan's e-4ORCE powertrain have an all-wheel-drive two-motor traction system with the same configuration as in **Figure 1**c but duplicated for front and rear axles. An all-wheel-drive three-motor configuration is proposed in [3], where configurations in **Figure 1**c,f are combined for front and rear axles as shown in **Figure 1**g. The Audi e-tron S models have a similar three-motor configuration [4]. In [5], an all-wheel-drive four-motor configuration is implemented where a duplicate **Figure 1**d configuration is used. Hence, the distributed system for EVs with multiple motors is well researched and commercially employed.

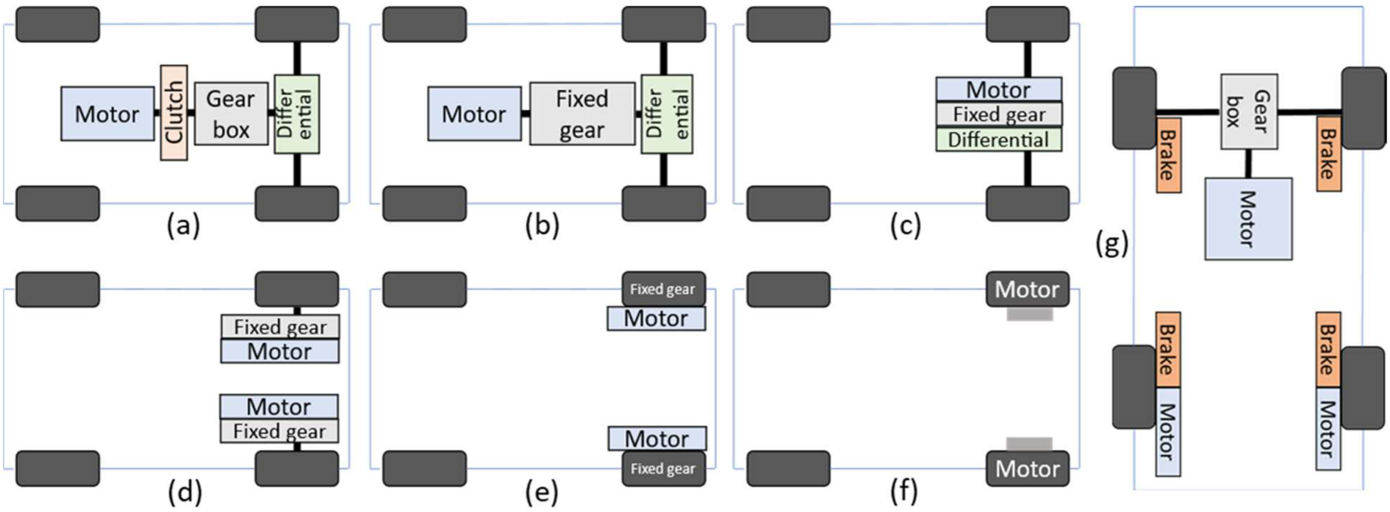

Figure 1. Various configurations of electric vehicle traction systems. (**a**) Conventional with clutch, (**b**) conventional without clutch, (**c**) conventional integrated, (**d**) close-to-wheel drive, (**e**) in-wheel indirect drive, (**f**) in-wheel direct drive [2], (**g**) Combined conventional without clutch and in-wheel motor drive [3].

3. Braking

While regenerative and plug braking are used in EVs to slow down the vehicle, friction braking is still needed to satisfy the high vehicle braking demands in more extreme braking conditions. Moreover, beyond slowing and stopping the vehicle, modern braking systems play an important role in the various vehicle stability control (VSC) systems such as anti-lock braking and traction control systems. Brake-by-wire (BBW) systems are characterized with accurate, rapid and dynamic control of the braking force and ease of design and maintenance compared to conventional braking systems. They allow for improvement of VSC systems and employment of new and more advanced control strategies [6]. They can also be implemented in both internal combustion engines and electric vehicles. BBW systems can be either electro-hydraulic (EHB), electro-mechanical (EMB) or a hybrid of both. In EMB and hybrid solutions an electric actuator/motor is used to generate the braking force. An example of the EMB is the Electronic Wedge Brake developed by siemens VDO shown in **Figure 2**a [7]. It houses two motors, one to generate the braking force and one for fail-safe and wear adjustment purposes.

The general structure of a BBW system is shown in **Figure 2**b where two electric actuators are used for each axle (one per corner). Combinations of an EMB based axle with conventional hydraulic brakes or EHB based axle are also possible. Therefore, an EMB BBW system is a four-motor system or a two-motor system if each axle is considered separately. The EHB system has been in commercial use since 1997 and one notable example is the Sensotronic Brake Control system developed and commercialized by Daimler and Bosch. However, aside from the electronic parking brake, the EMB technology is still under development, and it is not commercially employed yet, although many efforts are being made in that direction [8][9]. The EHB system comprises many hydraulic components, pipes and hydraulic fluid and is less performant than the EMB one. Therefore, it is thought that the EHB technology will be replaced by the EMB technology in future vehicles [10].

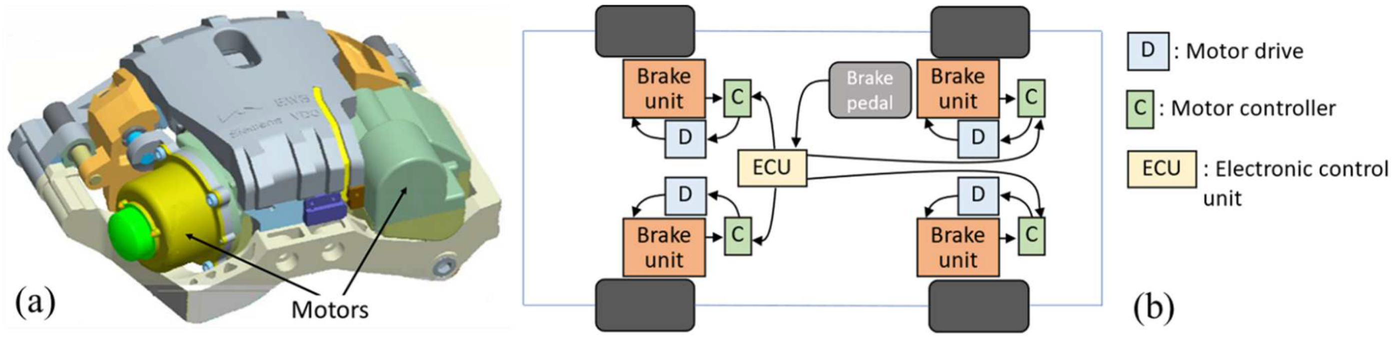

Figure 2. (**a**) A prototype of the electronic wedge brake by Siemens VDO [7], (**b**) General structure of a BBW system [10].

4. Steering

The steering system in the vehicle has transitioned from a purely mechanical system through a hydraulic and electrohydraulic power-assisted system, to an electromechanical power-assisted system (EPS). The main reason behind this transition is that it reduces the driver's steering effort and improves the efficiency, stability and safety of the system. With EPS the design is simplified and has more flexibility. Additionally, the environmental concerns due to hydraulic fluids are eliminated [11]. Of the various EPS configurations, the superimposed EPS system comprises two motors; one on the steering column and one on the steering rack and enjoys more steering functionalities than single motor EPS systems. An example is the Audi A8 Dynamic all-wheel steering system, shown in **Figure 3**a, where an additional motor is used for rear wheel steering [12]. With steer-by-wire the mechanical connection between the steering wheel and the steering gear is eliminated. This improves the steering system response (handling) and vehicle and steering system design flexibility, reduces the space, cost and weight of the system and also improves the passive and active safety [11].

The simplest form of an SBW involves two motors: one motor on the steering rack providing the steering force and a motor on the steering hand wheel providing steering feedback to the driver as shown in **Figure 3**b. Often two motors are employed on the steering rack whether for design purposes or to provide fault tolerance [13]. The direct adaptive steering (DAS), shown in **Figure 3**c, system is the first commercially employed SBW system provided by Infinity on their Q50 and Q60 vehicles. It employs two motors on the steering rack mainly for design/cost purposes, and fault tolerance is realized with a backup mechanical steering column normally disconnected via a clutch [14]. The DAS system is a good testimony for the feasibility and high performance of SBW systems, however, the full potential of SBW is yet to be unlocked. Wheel individual SBW (WI-SBW) promises optimal performance in terms of package and assembly, cost and additional functionalities [15]. In WI-SBW each wheel is steered individually and separately from other wheels as shown in **Figure 3**d, thus two motors are needed per axle. WI-SBW is still under development; the SpeedE project at RWTH Aachen University [15] and Schaeffler Group wheel module concept [16] are examples of research and industry efforts into realization of WI-SBW systems.

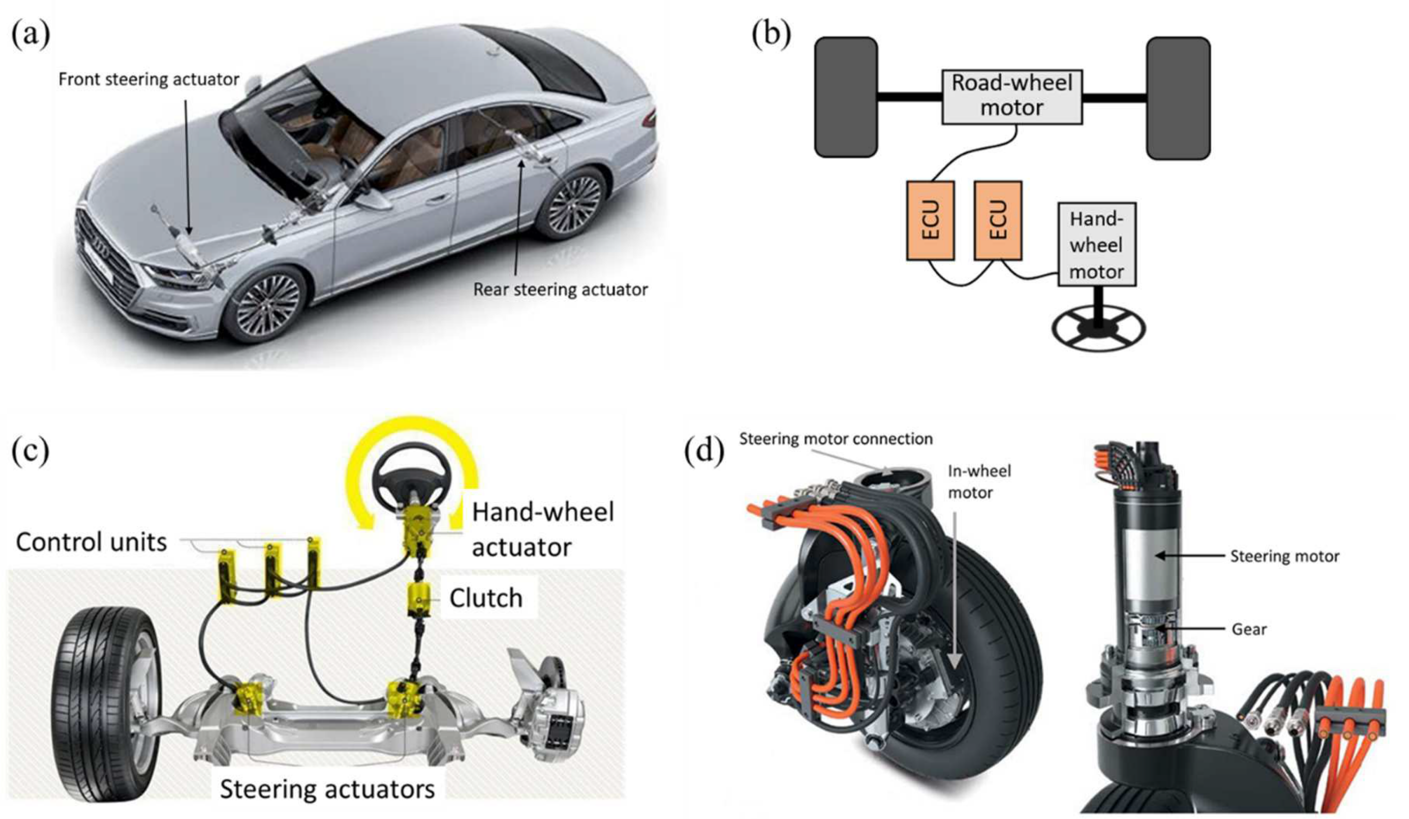

Figure 3. Various configurations of SBW systems. (**a**) Audi A8 Dynamic all-wheel steering [12], (**b**) General structure of a SBW system [11], (**c**) Infinity's DAS system [14], (**d**) Schaeffler Group wheel module concept [16].

5. Suspension

In passive suspension the movement of the vehicle chassis relative to the wheels and the road is dictated by the road. Active suspension utilizes actuators to control the motion of the vehicle chassis, allowing vehicles to achieve a greater degree of comfort and handling, thus improving ride quality and safety. Most active suspension systems in commercial vehicles currently are based on hydraulic or pneumatic operation [17] such as the hydro-pneumatic Active Body Control (ABC) system of Mercedes-Benz, although later in the E-ABC system a separate motor-pump unit is used at each corner [18]. However, hydraulic and pneumatic suspensions are complex, costly and take a lot of space and weight while not achieving the best performance. On the other hand, electromagnetic active suspensions (EAS) are more simple, less costly and can achieve better performance. Additionally, they have the inherent capability of regenerating energy from vehicle motion. However, the technology has not achieved commercial maturity yet [17].

EAS uses electric actuators and various configurations are possible. The 4th generation of Audi A8 cars incorporates an active suspension comprised of an adaptive air suspension and an EAS, as shown in **Figure 4**a [19]. The Active Wheel concept of Michelin houses an in-wheel suspension motor, as can be seen in **Figure 4**c [20]. Both of these are indirect drive active EAS. Direct drive EAS are also possible where a linear motor is used, as in the experimental EAS developed by Bose [21] or the EAS developed at the Eindhoven University of Technology [22], which are shown in **Figure 4**b,d, respectively. Other suspension motions can also be actuated like camber and toe as proposed in [23] for high performance sports cars and shown in **Figure 4**e. In all these configurations, one motor is needed for each corner/action. Thus, EAS forms a two-motor (per axle) or a four-motor system if active suspension is considered for all vehicle corners.

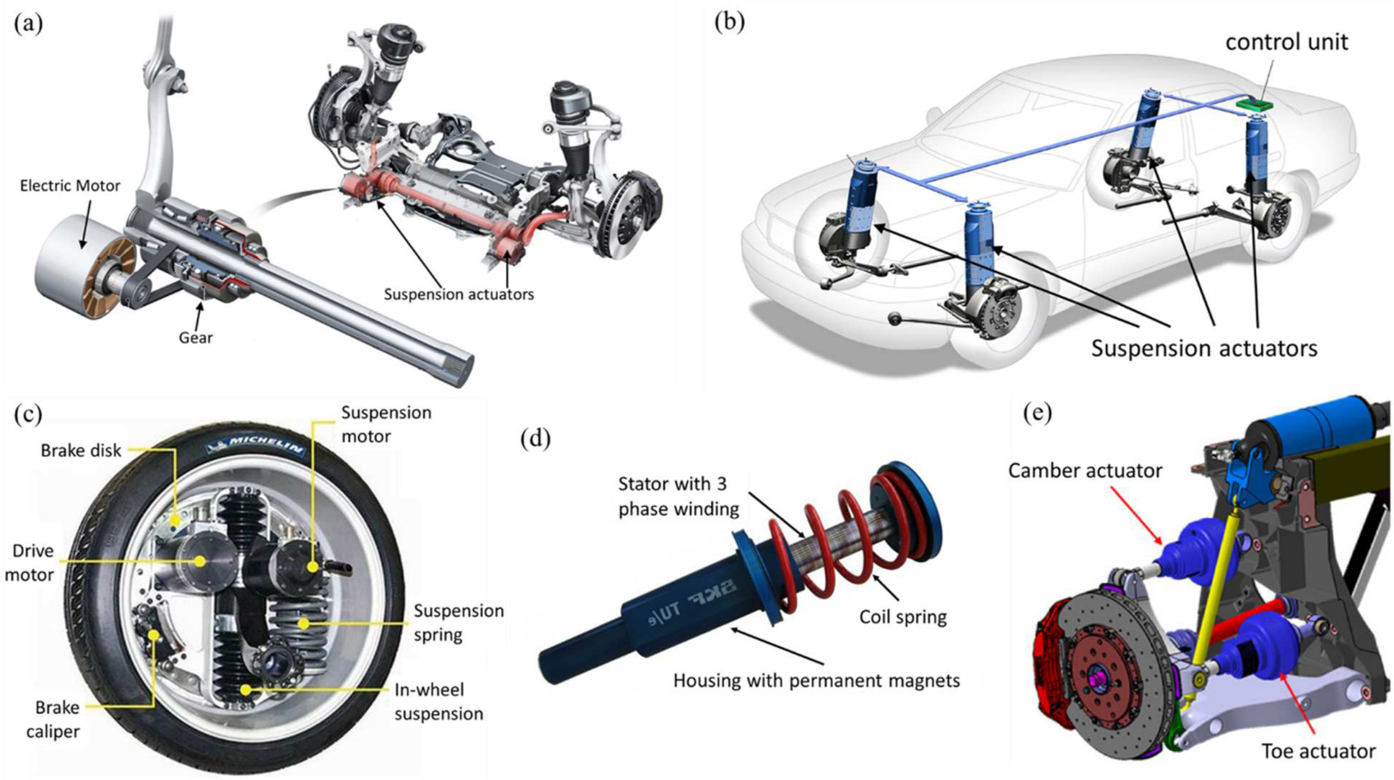

Figure 4. Examples of electromagnetic active suspension systems. (**a**) Audi active suspension system [19], (**b**) Bose active suspension [21], (**c**) Michelin active wheel [20], (**d**) EAS system of TU/e [22], (**e**) camber and toe actuators [23].

6. Other Examples

Other ways in which multiple motors and motor drives may be used in vehicular systems is the use of multiphase machines (more than three) and modular motors. These designs may be used to improve the performance of the system and grant it fault tolerance capabilities. For instance, increasing the number of phases in a motor reduces its torque ripple. Additionally, the power rating per phase is reduced allowing for an increase in power density which makes multiphase motors attractive for automotive applications [24]. With the modular design, a cascade motor design is used to lower the energy consumption of an EV drivetrain by increasing the high efficiency region of the operation range [25]. Different motor types can also be used to additionally combine advantages of different types and reduce the amount of rare earth permanent magnets used [26]. Multiple motors connected through gears is another approach employed to optimize the efficiency and dynamic performance of multiple speed-transmission heavy duty EVs [27] and extend the use of permeant magnet motors for high power applications (above 100 kW) [28].

These designs require a higher number of components in the system which increases the probability of a fault occurring, however, they allow fault tolerance and eliminate single point failures as they feature redundancy. This is important and required for safety critical applications as in the case of Protean IWM where the motor is divided into four sub-motors, each powered and controlled separately [29]. These designs are not only applicable for traction in vehicles as shown in the examples but can be used for the other vehicular systems depending on the requirements of those systems.

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