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Application of advanced fault-tolerant control techniques in the design of modern electric vehicles for increased reliability: a review

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ABSTRACT

Considering the increasing demand for environmentally friendly and economically viable transportation options, this in-depth analysis of fault-tolerant control (FTC) in the context of electric vehicles (EVs) covers all the latest developments and applications in the field. Maintaining vehicle stability and handling component failures with minimal or acceptable loss of performance are the primary goals of FTC systems in EVs. Thus, the FTC's crucial role in improving EV dependability is examined in this study. An explanation of the control strategies employed in EVs is followed by a description of the several types of FTC, including active, passive, and hybrid systems. The study aims to objectively evaluate advancements in tracking accuracy and robust performance by thoroughly reviewing FTC systems for modern EVs. This discusses various strategies as well as the challenges of integrating them into EV subsystems. Real-time deployment, validation against coupled failures, and the incorporation of learning-based FTC into safety-critical EV systems are some suggestions for future research. This study will help identify research gaps and topics that require additional investigation in order to advance the discipline.

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Electric vehicles; fault-tolerant control; vehicle-to-grid; motor control; battery management system; regenerative braking

1. Introduction

Electric vehicles (EVs) offer a development in the automotive industry by providing a cleaner substitute for automobiles that run on petrol and diesel, which cause pollution. Fault-tolerant control (FTC) is designed to maintain functioning in the event of a fault, such as a control system failure, for the stability and security of the vehicle. FTC and EVs are incredible industrial achievements in terms of producing automobiles and creating technology that benefits the environment and society [1]. The automobiles, led by Thomas Davenport and Robert Anderson, are prime examples of the first EVs to hit the market, powered by batteries that were not rechargeable [2].

Due to their low environmental effect and less noisy operation, electric cars became very popular in the 1800s and early 1900s [3]. They eventually overtook internal combustion engine cars, which had longer ranges and superior fuelling capabilities [4]. By the time EVs had lost market shares to gas-powered vehicles [5], the first electric cars had been effectively replaced with models powered by electric starters. So, EVs went back to serving only niche markets, such as golf carts. Late twentieth-century pollution and energy challenges revived EVs with hybrids and fully EVs. Li-Ion batteries [6] and large-scale charge stations boosted mobility, charging speed, and energy density, growing the EV industry. In the twenty-first century, the EV market has gained increased momentum with plenty of items like large SUVs, trucks, and compact city automobiles available. Economic growth has arisen from manufacturing, R&D, and infrastructure jobs at the vanguard of global warming, air quality, and energy independence [7]. Electric automobiles may improve city air quality, reduce CO2 emissions, and use renewable energy and smart grid technologies.

Fault tolerance, or EV technology, was created in the late 1970s and early 1980s for aircraft and nuclear power fail-safety. The first strategy was to create hardware redundancy devices that would function if the main ones failed. Intelligent control theory allowed FTC to diagnose, identify, and reconfigure following problems in the 1980s and 1990s, moving the focus to software and algorithmic solutions.

In the 1990s and 2000s, observer and Kalman filter observations increased detection and diagnosis, enabling exact localization. In the twenty-first century, FTC uses computing resources, big data analytics, and

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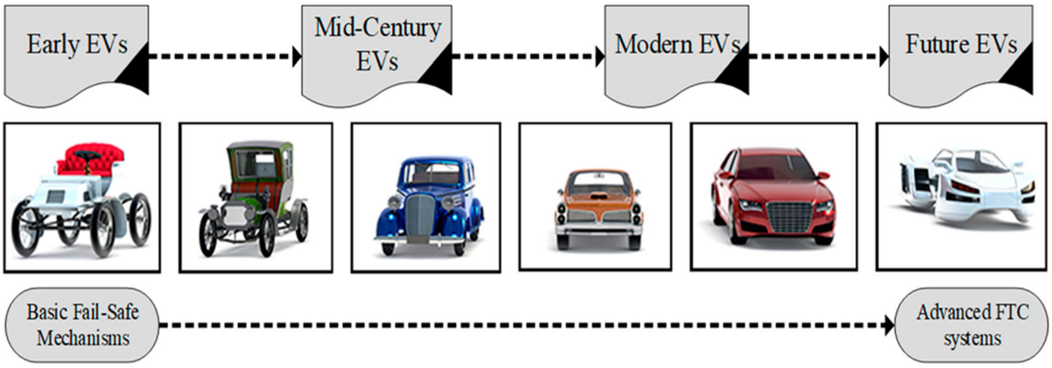

Figure 1. Evolution of EVs and FTC amid increased complexities.

AI to detect and forecast probable faults. Since the mid-2010s, Industry 4.0, IoT, and cyber-physical systems have presented new fault tolerance issues and possibilities.

EVs and FTC systems help with technological initiatives that save the environment. EVs emphasize vehicle dependability and safety, thus they should never fail as their usage grows. Engineering interventions are crucial to solving twenty-first-century challenges, showing the strong link between EVs and FTC. From simple fault-tolerant techniques to more advanced ones, FTC has advanced significantly. These modifications have improved the safety and dependability of EVs. Figure 1 below shows the evolution of FTC with EVs over time.

The increase in the application of FTC systems in EVs is caused by a concern for reliability and safety as these vehicles become popular. The latest research activities have been directed towards the enhancement of fault detection and diagnosis, and the recovery of FTC systems utilizing technologies such as artificial intelligence (AI), machine learning (ML), and cyber-physical systems (CPS) [8,9]. AI improves the precision of defect detection, even though CPS technologies are useful for tracking and managing car systems [10–12]. These improvements are an upgrade above the FTC's previous strategies, which mostly utilized hardware variation and basic fault tolerance measures [13].

Another topic that has been explored heavily over the past years is the use of predictive maintenance in FTC architectures for EVs. To avoid such faults, predictive models, sometimes enhanced by ML algorithms, have been employed to predict possible faults and mitigate their effects [14]. For example, the continuation of the work in FTC systems has been done with the incorporation of deep learning algorithms for enhanced fault prediction and real-time diagnosis of motors and batteries used in EVs [15]. These models use big data from the vehicle sensors to identify signs of faults and probable outcomes of a certain car part, and then organize ways and means of preventive action and adaptation to the given failure [16].

One of the other areas of interest highlighted in the recent research is that of a learning control system that is capable of adjusting to changes in fault conditions [17]. There is another form of FTC system primarily based on model predictive control (MPC) and reinforcement learning, which is more flexible and less sensitive to disturbances than classical FTCs [18,19]. It has been demonstrated that these techniques can enhance vehicle stability and handling in situations when multiple faults occur simultaneously [20]. Further, the integration of multiple sensors through sensor fusion has improved the reliability of fault detection because the data acquired from these sensors are fused to construct a more accurate representation of the automobile's current status [21,22].

Although there has been research done that has improved the implementation of the FTC approaches in EVs. Meanwhile, some studies are still lacking in providing real-time diagnosis of faults and identifying effective strategies for fault recovery. For example, numerous papers are devoted to control system redundancy, yet there is a scarcity of integrated approaches to proactive fault diagnosis and self-healing capabilities. Furthermore, there is a lack of focus on making fault tolerance complementary to novel applications, including AI-based control systems and Industry 4.0. This review points out these issues and seeks to inspire more literature studies to embrace the improvement of FTC systems in EVs using these advanced technologies.

2. Key contributions of this review

In this review, we specifically present the following primary contributions to the FTC research and development for EVs: Providing a systemic and comprehensive overview of the FTC systems studied in the last decade, as well as concentrating on the critical components of EVs, including motors, batteries, power electronics, and control systems. In this paper, FTC methods are classified into active, passive, and hybrid systems; advancement in vehicle safety and reliability is then discussed. This leads to the following realizations as

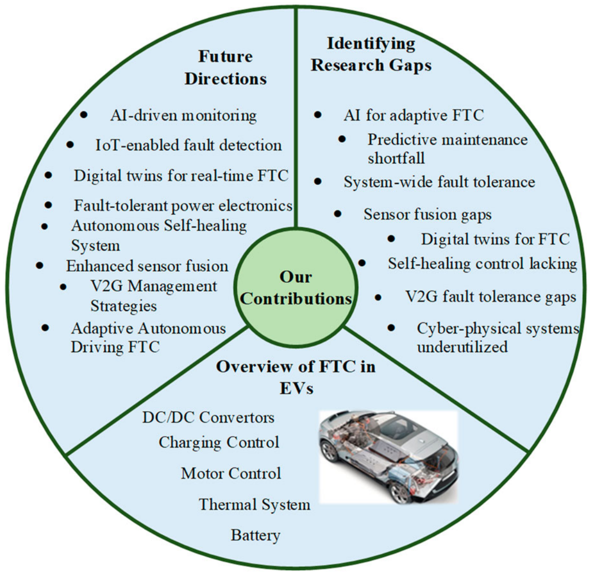

Figure 2. Key contributions of this paper.

major research gaps: the absence of complex predictive maintenance and real-time fault diagnosis systems. Most of the current FTC methods focus on the redundancy of the control system but do not incorporate the latest techniques for predicting potential faults or even preventing them from occurring in the first place. Even though there is research on fault detection using AI and ML, more research is needed on their application in real-time adaptive control systems. To fill these gaps, there is an approach based on using AI, ML, and CPS to create more flexible and reliable FTC systems. This includes the employment of real-time predictive fault diagnosis techniques and other control strategies following the data obtained from vehicle subsystems, for instance, motors and batteries. We also suggest the application of digital twins to model various aspects of vehicle behaviour in real-time so that any faults can be detected at an earlier stage; IoT-based technologies facilitate faster communication between the subsystems for identification and rectification of faults. These technologies increase the reactivity and the proactivity of the fault handling actions, enhancing the global system reliability and the vehicles' safety. At last, we discuss some real-world implications of this proposed methodology and further research areas like self-healing control systems, FTC systems with enhanced cybersecurity, and scale and real-time adaptively feasible battery management systems for new generation EVs, as they are increasing in complexity with the introduction of autonomous driving and vehicle-to-grid (V2G) facilities. The intended contribution of this paper is illustrated in the following graphical abstract in Figure 2.

The authors have conducted this review by searching for publications in the Scopus and IEEE Xplore databases. Research publications that met certain criteria were found that were published between 2014 and 2025. A selection of papers was made based on their relations to the field of FTC in EVs and their ability to provide proposals for effective control strategies, real-time fault detection, and fault prognosis. Some of the keywords used in the search were "Fault-Tolerant Control," "Electric Vehicles," "Active/Passive Fault-Tolerant Control," etc. Such a selection of articles ensures the review is comprehensive in covering concepts that are most recent and important in the field. Figure 3 depicts the corresponding Scopus and IEEE Xplore database retrieval results distribution for the years specified. Against each search string, the articles are classified into two categories: journal papers and conference papers. Table 1 displays the previous literature summaries reflecting the development trends in the FTC field.

Further contents of the paper are organized as follows: Section 2 describes the control of EVs, and Section 3 describes details of FTC, its components, and types. The use of FTC in EVs is explained in Section 4, and Section 5 discusses the Future Research direction. The conclusion is presented in section 6.

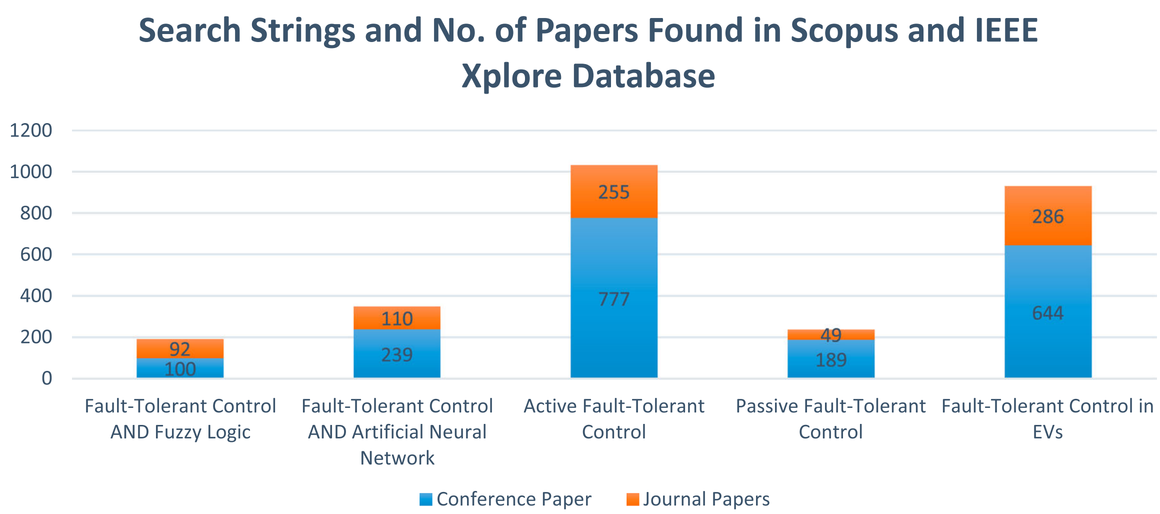

Figure 3. Breakdown of reviewed articles from 2014 to 2025.

Table 1. Development trends in the FTC field.

Sr. No	Year	Aspects	Summary
1	1970s	Early beginnings[23]	The idea of fault tolerance develops, with an emphasis on redundant systems and manual backup procedures.
2	1980s	Theoretical Foundations[24]	Researchers have started to use the combination of classic control theory and fault detection and diagnosis (FDD) techniques. Here, systems are developed that can detect events of failures with the systems still maintaining service reliability.
3	1990s	Active FTC and Model-based Approaches[25]	Introduction of intelligent FTC strategies like prompt detection, isolation, and real-time fault accommodation. Both model-free and model-based detection and diagnostic methods have been subject to significant development. These techniques rely on the mathematical models of systems to predict how the machines and software will operate, and help to control the process accordingly.
4	2000s	Data-driven Approaches and Machine Learning[26]	The diffusion of computational power and data availability resulted in new data-oriented approaches, which have replaced traditional methods of FTC. These approaches are reliant on historical data and ML algorithms to optimize fault diagnostics and system adaptability.
5	2010s	Cyber-Physical Systems and IoT [27]	Systems are integrated more; thus, FTC concentrates on cyber-physical systems that combine computation, networking, and physical processes.
6	2020s	Advanced AI and Machine Learning [28]	Utilizing more advanced AI and ML approaches in FTC, and developing fault predictions, detection, and adaptive response features to the next level.

3. Control of EVs

Fault-tolerant and EV control are key factors in EVs' reliable, safe, and effective performance. EV dynamics simulations frequently use coupled longitudinal and drivetrain equations that take into account traction generation, resistive load effects, and rapid demand changes in order to develop and test FTCs and controllers. The standard longitudinal equation of motion in vehicle dynamics is written as:

$$m\dot{v} = F_{tractive} - F_{resistive} \tag{1}$$

where

$$F_{tractive} = \frac{\xi_o M_e n_t}{r} \tag{2}$$

$$F_{resistive} = f_r W + mgsin\theta + \frac{1}{2}\rho C_D A_f V_r^2 \tag{3}$$

The resistive dynamic load on the vehicle side is basically the sum of rolling, grade, and aerodynamic resistances in the equation, whereas the tractive effort is given as a relation of power transmission and tractive effort. In (1)–(3), vehicle mass is denoted by m, vehile speed in longitudinal direction is given by v, θ denotes road grade angle, f_r is rolling resistance coeficient, C_D is drag coefficient, $\xi_o$represents overall reduction ratio, M_e denotes torque (driving), and $n_t$denotes overall transmission efficiency.

Control techniques are crucial to the operation of EVs since they manage power flow, energy efficiency, and vehicle performance. So, here we describe some essential EV control techniques and their relation with FTC:

3.1. Motor control

Motor control systems in EVs are vital for boosting power delivery and vehicle performance. One major element of EVs is their potential to produce rapid and accurate torque via electric motors. To appropriately leverage this advantage, it's important to implement efficient control methods. Important references and their key considerations are shown in Table 2. Here are some standard motor control techniques used in EVs.

3.1.1. Field-oriented control (FOC)

Automotive and heavy equipment motor control use FTC and FOC, with FOC being crucial. As shown in Figure 4, FOC precisely adjusts motor-core rotation and speed by separating magnetic flux and torque-controlling currents [29,30]. The orientation angle that makes it possible to have a complete decoupling between two variables is the rotor flux angle. In this case, all the variables are controlled in the rotating coordinate frame (d-q frame), and electromagnetic torque T_e can be controlled through the virtual component of the stator's current i_d and i_q. Then, the stator flux can be expressed as a function of stator currents as

$$\varphi_s = \sqrt{(L_d i_d + \varphi_f)^2 + (L_q i_q)^2} \tag{4}$$

$$T_e = \frac{3}{2} P_n (\varphi_f i_q + (L_d - L_q) i_d i_q) \tag{5}$$

where φ_s is the stator flux, L_d and $L_q$are stator inductances, $\varphi_f$is the flux of the permanent magnet, and P_n is the pole pairs. This equation is used in a control system to help determine the disposition of the system towards such faults so that adjustments be made appropriately.

Because it is the only continuous actuator, the continuous voltage reference should be discretized using

Table 2. Motor control in EVs-references and key considerations.

Motor control in EV				
Aspects	Technique	References	Pros	Cons
Motor control	Modified Triple Modular Redundancy (MTMR)	[29]	(1) Enhanced reliability (2) MTMR increases the fault tolerance of the control system. (3) Maintained Control Precision (4) It allows automotive Fault recovery	(1) Increased system Complexity (2) Higher Cost (3) Potential for Redundant Failures
	Model Predictive Control (MPC)	[32]	(1) Smooth torque delivery (2) Optimized performance (3) Robustness to disturbances	(1) The effectiveness of MPC depends on Model accuracy and development time. (2) Tuning complexity
Motor efficiency	Field circuit coupled-finite element method (FEM)	[47]	(1) Enhanced optimization potential (2) Improved reliability	(1) High computational demand for detailed analysis. (2) Complex control algorithm
	Direct Torque Control (DTC)	[48]	(1) Fast Dynamic response (2) Simplified control structure (3) Energy efficiency	(1) Switching frequency variations (2) Torque ripple

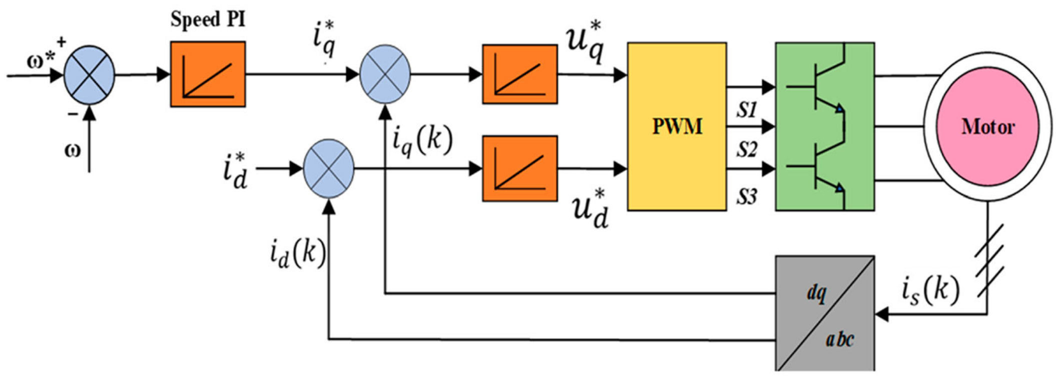

Figure 4. Control diagram of FOC [31].

the pulse width modulation (PWM) technology. When implementing three-phase PMSM, the space vector PWM or SVPWM is always employed by default. In Figure 4, we present the total process of FOC. The FOC controller is a cascade control loop of the second order, which includes two internal PI current controllers and the external speed PI controller. Internal PI controllers compute u_d^* and u_q^* regarded the error between the current reference $i_d^*$and i_q^*, and actual current $i_d(k)$ and $i_q(k)$, obtain from sampled stator current $i_s(k)$. The external PI controller estimates the current reference, which depends on the error between the rotor speed reference ω^* and real speed ω.This indicates that tuning the PI controllers is very complicated and should be reversed to the opposite when operating at varying conditions.

With FOC, encoders and resolvers determine rotor position and speed, boosting motor performance by increasing phase current. This improves efficiency, decreases heat, and simplifies operation [32–34]. Integrating FTC and FOC allows mistakes to be noticed and addressed to preserve performance despite faults.

It is possible to introduce FTC into FOC in several ways. One approach involves the use of multiple, different devices, like encoders and resolvers, for monitoring rotor position and speed. In the event of the failure of a particular sensor, the system can be programmed to use the secondary sensor to continue operation. This results in the estimation of the rotor position and speed, and if the measured inputs are significantly apart from the estimated data, the observer-based fault detection techniques, such as Luenberger observer or extended Kalman filter, predict faults. A self-tuning control system can change the controller parameters in response to fault identification, ensuring that the motor operates as designed, even if the structural dynamics change with time. Fault detection and diagnostic strategies aim at identifying the faulty part while reconfiguration strategies isolate the fault and change the control algorithm, e. g. switch to sensorless control in case of a failed resolver. Nonlinear control and advanced control structures, such as H-infinity control or sliding mode control, make control laws much less sensitive to parameter uncertainty, which in turn improves the fault tolerance of the FOC system. Finally, the FOC system's data is used in predictive maintenance algorithms to help identify upcoming issues that may cause problems and schedule them accordingly. By applying these integration methods, FTC can further improve the dependability of the FOC scheme with no interruption and steady and optimal motor working even with the fault.

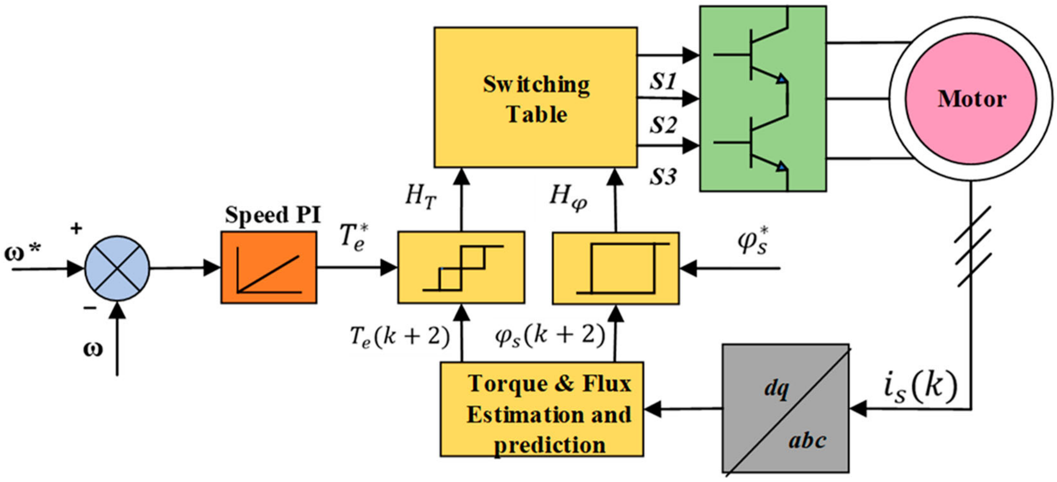

Figure 5. Control diagram of DTC [31].

Nevertheless, there are some drawbacks to FOC. Some of the challenges that make it difficult to implement the scheme include accurate sensing of the rotor position and real-time computation. This is further compounded by the need for highly advanced hardware and accurate calibration of control parameters. Moreover, the FOC systems get affected by the variation of the parameters, which may lead to deterioration of system performance and, therefore, need to be calibrated and maintained frequently. These factors may make the cost and design of the system more expensive and intricate.

3.1.2. Direct torque control (DTC)

DTC, another motor control method, is used in EV control. High-performance EVs rely on DTC algorithms to calculate voltage, current, torque, and flux control from immediate rotor speed and current data [35,36]. The main concept of DTC is the employment of two hysteresis controllers regulating electromagnetic torque as well as the stator flux. The torque hysteresis controller consists of three levels of comparators with one bandwidth, and the flux hysteresis controller consists of two levels of comparators with another bandwidth. The meaning of the output signals of hysteresis controllers is defined as:

$$H_T = \begin{Bmatrix} +1: & T_e \uparrow \\ 0: & T_e \rightarrow \\ -1: & T_e \downarrow \end{Bmatrix} \tag{6}$$

$$H_\varphi = \begin{Bmatrix} +1: & \varphi_s \uparrow \\ -1: & \varphi_s \downarrow \end{Bmatrix} \tag{7}$$

The basic DTC process is depicted in Figure 5, which illustrates the total process of basic DTC. According to the main frequency, the flux hysteresis bandwidth influences the current distortion only for low-frequency harmonics. Torque hysteresis bandwidth is the dominant factor that contributes to both the switching frequency and the switching losses. Here, the choice of hysteresis bandwidths is defined very deliberately. The switching table can be defined based on the electrical position and the hysteresis controllers used. The performance and lifespan of DTC systems decrease due to their vulnerability to sensor and other component failures. Overcoming these constraints and making the system more resilient in the event of failure is possible with a combination of the FTC and the DTC. The FTC and DTC are placed in a strategic way to handle component faults and to continuously change the speed and torque, which improves the usability and safety of EVs.

One method involves setting up an observer-based diagnostics and fault detection module that keeps constant monitoring on the motor's performance metrics.

Another option to improve the DTC system is to provide redundancy to its possible risk components. The FTC frequently uses this concept, in which the system grows with several actuators and sensors that can be utilized in an emergency. Additionally, by incorporating efficient adaptive control strategies, the DTC design can reduce faultiness. These algorithms have the ability to modify the online regulatory settings based on the type and severity of the problem. For instance, the adaptive control system may modify the torque and flux references if the motor has any problems, allowing it to continue operating safely without sacrificing performance.

Finally, the DTC system's reliability can be even higher with the addition of a predictive maintenance module. It attempts to forecast trends of fault occurrence using previous data and artificial neural networks. This is how it is possible to control the faults and ensure that they do not become critical by early scheduling of maintenance activities and continuous control strategies.

3.1.3. Pulse width modulation (PWM)

PWM is used to control motor voltage and to adjust the duty cycle of high-frequency pulses. It is a standardized component, which can be combined with both FOC and DTC as shown in Figure 3 [37]. Embedding FTC into the PWM method improves system dependability and reduces its vulnerability to failure or degradation of components [38].

One method of combining the FTC with the PWM is to incorporate redundancy in the PWM controllers. This is because the system can have multiple parallel controllers, in which a backup controller can always take over in the event of a failure, thus ensuring that the system runs uninterruptedly and with a stable and optimum performance. The other solution is the integration of control algorithms into the PWM strategy that involves the identification of faulty control factors and the dynamic modification of the corresponding duty cycles. This adaptive adjustment allows the motor to continue performing efficiently even under sub-optimal operating conditions.

Another critical component of FTC integration is the use of fault diagnostic technologies and real-time monitoring. These devices monitor the health and reliability of the motor. In the case that problems are detected, it is simple to alter the PWM control mechanism in order to prevent a cascade of problems or the motor's eventual failure. Improving the integration of FTC and PWM requires intelligent control approaches such as fuzzy logic and neural networks. Reliable control adjustments and explanations of complex faulting patterns are provided by this technology. For instance, fuzzy logic controllers can detect the severity of a defect and adjust the pulse width modulation (PWM) levels appropriately. Another option is to use neural networks; they can learn from past failure patterns and potentially adjust PWM signals proactively. Modern sensor technology allows FTC to incorporate PWM. Based on the accurate and real-time data acquired by high-precision sensors, the FTC system adjusts the PWM control parameters to ensure stable and economical operation by monitoring the motor's state.

However, many things should be considered within the boundaries of research. Electrical signals produced by PWM systems must be free of noise to avoid interfering with other parts that the PWM system communicates with. Two possible characteristics of PWM control are the resolution of the signal and the response rate of the regulating device.

Furthermore, when the basic principles of redundancy and advanced control algorithms are employed, this results in a higher cost and complexity of the system. However, in severe fault conditions or multiple fault occurrences, the capability of FTC strategies with high success may be compromised, needing a more advanced holistic approach at the system level. Considering these limitations and by the use of various methods to interface the FTC with PWM, the robustness and efficiency of a motor control system of EVs could be boosted.

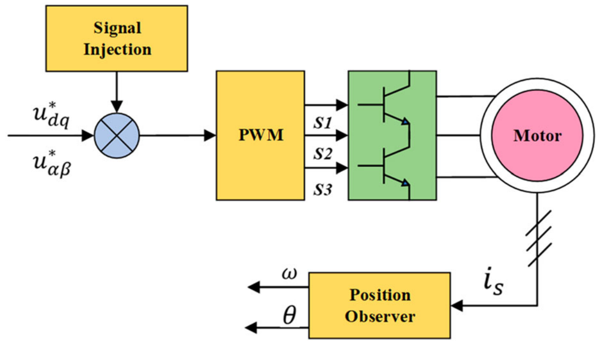

Figure 6. Block diagram of sensorless control [31].

3.1.4. Sensorless control

Some EVs apply sensorless motor control, which is accomplished through algorithms [39] without using traditional sensors. Generally speaking, sensorless control can be classified into two categories: The model observer-based method, which performs at a relatively high speed when compared to the injection-based method, and the low-speed method. Model observer-based sensorless control usually consists of two steps: the first one is back EMF or flux observation, and the second one is the position or speed estimation. Here, several control theories that can be used are linear observer, sliding mode observer (SMO), and extended Kalman filter (EKF) [40]. The injection-based methods usually consist of two kinds: The two categories included are rotating signal injection and pulsating signal injection. The former adds a continuous sinusoidal wave into the stator $\alpha\beta$ frame, while the latter adds a pulsating sinusoidal wave or pulsating square wave into the rotor dq frame. A typical block diagram is illustrated in Figure 6.

Figure 6 presents a sensorless control system diagram that employs PWM control, signal injection, and observer-based position in electric motors. This is done through the use of advanced estimation techniques that ensure the system does not need direct feedback from the sensors. The signal injection block embodies the two categories of injection methods, rotating and pulsating, where signals for detecting motor parameters are injected. The position observer uses these signals to estimate key motor parameters, including the rotor position (θ) and speed (ω) from the injected signal and the stator current feedback (i_s). Following this is the PWM block that modulates the input voltage signals ($u^*_{dq} and u^*_{\alpha\beta}$) for controlling the motors with optimal energy transfer towards the motor. Constantly, during the whole process, the performance of the motor is under observation, and the observer constantly fine-tunes the position and speed estimates of the system.

The FTC will only need to adapt sensorless control algorithms that can work even with motor or controller failures; therefore, it will be optimal to have a high available speed without unnecessary use of expensive

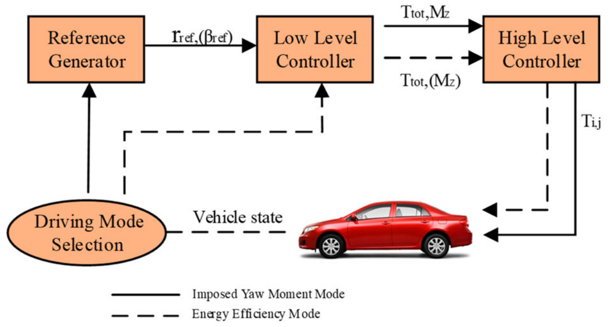

Figure 7. Block diagram of torque vectoring control [43].

sensors and equipment. When integrating FTC into this system, the following techniques must be employed to provide the necessary degree of fault tolerance.

First of all, observer-based approaches comprising Luenberger observers or Kalman filters can be employed to estimate the rotor position and speed and detect abnormalities that indicate faults. This makes it possible to take action to resolve the issue and prevent more attentional lapses by keeping a close monitoring on events. By altering control settings in response to potentially troublesome situations, feedback control techniques can sustain high performance even in the absence of additional sensors. Software redundancy improves the reliability of the suggested approaches by employing several redundant techniques to estimate the motor states of the model.

In most fault situations, conventional advanced control techniques like H-control or sliding mode control can offer enough performance and a reasonable level of protection against modelling errors and disturbances. Combining these technologies greatly increases the fault tolerance of sensorless motor control systems for EVs. This implies that even in the event of a motor or motor controller failure, performance and dependability are retained. However, sensorless control has its drawbacks, mainly at low speed, which produces small back-EMF, and it may need some tuning to give good results in different conditions. Nevertheless, incorporating FTC strategies strengthens the reliability and sturdiness of the sensorless motor control system.

3.1.5. Torque vectoring

Torque Vectoring in EVs with multiple motors employs torque redistribution techniques to each wheel to realize better traction as well as handling [41,42]. Figure 7 describes a simple torque vectoring control system for EVs using yaw moment (a torque that produces a rotational force around the vertical axis of the vehicle, affecting the turning and stability during cornering) as well as efficiency modes.

The system is initiated by the Driving Mode Selection that defines the current state of the car and its capabilities to switch from imposed yaw moment mode to energy efficiency mode. The Reference Generator generates the reference signals like the desired yaw rate (r_{ref}) and desired sideslip angle (β_{ref}), depending on the selected driving mode and the current state of the vehicle. These signals are then received by a component called the High-Level Controller and yield control outputs. In the imposed yaw moment mode, it controls the total torque (T_{tot}) and yaw moment (M_Z), and in the energy efficiency mode, it adjusts the torque distribution to minimize energy consumption. From these high-level commands, the Low-Level Controller is tasked with converting these commands into individual wheel torques ($T_{i,j}$) to achieve the desired results. The system additionally modifies the control signals based on the vehicle's current condition, including its speed and yaw rate, to ensure the vehicle proceeds as planned. Each mode has a different way of using the controls. While the enforced yaw moment mode prioritizes maintaining vehicle stability and control, the energy efficiency mode seeks to deliver the best torque distribution for increased energy economy. This system integrates time-based vehicle status observation, dynamic mode switching, and control hierarchy approaches to enhance the driving dynamics and efficiency of EVs.

When one of the motors is faulty, FTC uses force vectoring to keep the remaining, healthy motors operating at the necessary level while keeping control over the handling. A direct way to implement FTC in a torque vectoring system is the use of multiple motor and sensor setups. Continuous monitoring enables the system to detect if there is an issue or if it is faulty. When one of the motors has a fault, the other motor is triggered to replace the faulty one so that torque distribution is not affected and the vehicle's behaviour remains constant.

Another technique that also holds promise is MPC [44,45], which utilizes a predictive model of the vehicle's dynamics to determine optimal torque split to all the motors in real time. Using the fault detection algorithms as an add-on to the MPC makes it possible for the system to anticipate a future failure of the motor. This type of prevention reduces the adverse effects of motor failures because it allows for constant and reliable automotive operation.

Autonomous control techniques modify the control parameters if a fault affects the system operation. That way, the adaptive control system can change the algorithm for distributing torque in real-time in response to input from several sensors. Even in the event of an engine fault, this system uses torque vectoring control methods to alter the lost torque and maintain consistent vehicle handling. FTC integration also includes techniques like fault isolation and reconfiguration, which enable the elimination of faulty motors and the assignment of their corresponding functions to other motors. The combination of ML and AI allows the FTC to process huge amounts of data on vehicle performance and diagnose faults.

Over time, reliability and fault tolerance are increased via AI techniques that modify torque distribution in response to detected faults. Lastly, the goal of robust control design is to provide control algorithms that function well under different conditions, including motor faults. These methods ensure that the torque vectoring system will continue to function and be efficient during different operating states.

The theory behind torque vectoring is that control and tractive force can be enhanced by dynamically redistributing torque among the wheels. Numerous advantages are provided by this system's multi-component design, including improved dynamic performance and controllability (even in the event of motor failure), a greater range of control schemes (including adaptive and model predictive control), and more. The addition of additional motors and sensors has several drawbacks, including raising the complexity and cost of the system and requiring high computational power for real-time monitoring and fault detection. Combining FTC with torque vectoring requires extra hardware, real-time safety checking, perspective, and learning control techniques, AI, and ML to predict possible malfunctions, as well as reliable algorithms.

3.2. Battery management system (BMS)

Electric and hybrid EVs are viewed as viable alternatives to traditional automobiles powered by internal combustion engines since they do not need petrol. EVs and HEVs powered by batteries are commonplace due to their many benefits, such as high energy density, extended cycle life, and low environmental effects. However, if batteries aren't managed properly, they might catch fire or explode before their time, highlighting the importance of BMS, which includes battery modelling, internal state estimation, and battery charging [46].

3.2.1. Battery modelling

Battery Management Systems (BMS) use electric, thermal, and coupled electro-thermal battery models. The behaviour of electrochemical systems and their real-time applications is analyzed using equivalent circuit models. A careful compromise between minimal complexity and accuracy is required with reduced-order models. To represent the distribution and dissipation of heat, thermal models employ either complex three-dimensional geometry or approximation reduction modelling.

Combining electrical and thermal properties, electric-thermal models enhance charging efficiency [49]. These models support BMS development, control, and optimization [50,51] by considering computational load, operations, and battery system management. Real-time monitoring is necessary when applying FTC to the battery model and reinforcement.

To control and distribute heat in the battery system, thermal models with intricate 3D geometries or simplified models are required. By evaluating electrical and thermal characteristics and putting management techniques in effect that account for any anomalies discovered in integrated electro-thermal models, FTC seeks to maximize charge efficiency.

These models are beneficial for BMS development, control, and optimization since they provide a thorough insight into computational load, processes, and battery system management. A mathematical model is created for ML algorithms to employ for forecasting faults based on both historical data and real-time input in order to integrate FTC approaches. This predictive method guarantees that the system maintains operating performance by modifying operations in response to error detection. The implementation of FTC in battery models typically results in enhanced safety, performance, and extended battery life.

3.2.2. Battery states

BMS uses estimation approaches to monitor SOC (State of Charge), SOH (State of Health), and internal temperature because of their known effects on the battery's most interior features and critical operation zone. SOC measures a battery's present capacity as a percentage, SOH determines its long-term ability to provide constant power, and ambient temperature affects performance, security, and lifetime. The FTC in the BMS is constantly monitoring and modifying these settings to make sure the batteries can continue to operate efficiently and dependably, even when problems occur. The high-level algorithms and redundant features of the integration allow the system to continue operating normally even in the event of a fault. For instance, model-based SOC and SOH fault detection techniques are excellent at predicting battery performance problems so that repairs can be made before any damage has been done. In order to attain optimal battery conditions, cooling and heating systems can be adjusted or controlled using thermal models and real-time temperature data from the battery.

Furthermore, FTC can use fuzzy logic-based charging and discharging control algorithms that modify their profiles in real-time according to the battery's performance by continuously monitoring the battery's health and charge. By using ML techniques, the BMS can improve the accuracy of failure predictions and identify patterns in previous information, allowing for proactive fault control. This helps to improve the reliability of the BMS because even though the primary control may be damaged, other equally effective mechanisms, such as backup sensors and other control pathways for the same component, will have been implemented. This begins with the early signs of deteriorating health or reduction in the overall lifetime of a battery, which is essential for safety and performance, keeping batteries within safe operating limits, and extending their lifetime.

3.2.3. Battery charging

There are a number of methods that have been proven effective for charging the batteries of EVs. Three examples of these are constant-voltage (CV), constant-current (CC), and multi-stage constant-current (MCC). The primary aims of developing these technologies are to achieve precise temperature control, speed up charging, and improve energy efficiency. Evolutionary algorithms, dynamic programming (DP), pseudo-spectral optimization, and MPC [52] are only some of the computational intelligence techniques used in advanced charging systems. Evolutionary algorithms enable the study of various charging patterns, DP offers a degree of freedom, and MPC accurately adheres to the battery limits. To overcome challenging charging conditions, pseudo-spectral optimization requires both theoretically solid and battery-specific knowledge.

The FTC system can improve the safety and dependability of the previously described charging systems. The implementation of FTC cannot be achieved without protocols that allow for real-time monitoring and feedback on measures taken to address any issues that may arise during charging. In order to prevent the battery from being overcharged or overheated, the FTC system constantly adjusts the charging algorithm based on the inputs from the voltage, current, and temperature sensors.

Modern charging systems use a wide range of AI methods, including DP, MPC, evolutionary algorithms, pseudo-spectral optimization, and many more. Integrating with the FTC may lead to an improvement in these strategies. Evolving algorithms can optimize the profiles in the absence of issues or anomalies, preventing the battery from being overcharged. The best approach to charging procedures that respect the battery's safety limits is to combine MPC with FTC, which incorporates fault detection algorithms into control operations. In order to achieve fault-specific flexibility in real-time, DP can keep its charge decision-making skills with FTC. By minimizing the possibility of unexpected behaviour, the system can remain stable and secure when the FTC is included in the pseudo-spectral optimization for the charging condition. Battery control systems are made more dependable, secure, and efficient with the addition of FTC to these cutting-edge technologies.

The block diagram of BMS is shown in Figure 8 below, which depicts the general architecture and operation of the BMS. The measurement block comprises sensors that record individual cell voltages, battery current, battery temperature at different sections of the battery bank, and ambient temperature digital data sets. All of this data is then used to estimate the battery status in later stages. Battery Algorithm block (SOC Estimation block, SOH Estimation block): SOC and SOH Estimation are conditional status blocks of the battery. One main purpose is to calculate SOC and SOH based on several battery variables such as voltage, current, and temperature. After SOC and SOH have been identified, the maximum allowable charging and discharging currents are regulated with the help of a capability assessment block. The cell balancing block utilizes the findings of what is wrong and how to fix it; it might be relevant to have a sound and efficient automated information analysis technique. The controller block assesses the voltage levels of each cell and determines the variation between the maximum voltage and the minimum voltage of the cells. If the difference is more than the threshold, then the charging is stopped, and the highest voltage cell is put to discharge through the discharge resistor.

The operator shall receive this information on an interface that is easy to understand and control. Essentially, the ground fault set of appropriate systems is safer. The thermal control module constantly checks the battery's temperature to prevent any risk to it and switches on the cooling or heating process if the temperature rises to an abnormal level. To address the control input and output, the following transceiver is employed. Because in communication, high-volume data are transmitted and received, hence, a high-speed regulated transmitter.

3.3. Battery thermal management system (BTMS)

With tough environmental restrictions, the world has welcomed EVs. Thus, demand for advanced energy storage technologies like lithium-ion batteries increased [54]. This battery degrades significantly with temperature, requiring refrigeration for efficient thermal management. Battery Thermal Management Systems (BTMS) manage battery heat (cooling, heating, insulation, and ventilation) to minimize imbalance, deterioration, and thermal runaway. As EV batteries increase energy density and charging speed, a reliable BMS is more vital than ever for their safety, efficiency, and lifespan.

3.3.1. Battery thermal management system with VCC

BTMS is essential for EVs to keep battery temperatures at ideal levels. This has led to the creation of three major cooling systems [55]. Cabin air conditioning systems in which excessive energy consumption and noise difficulties are two problems that utilize outside air, preconditioned cabin air, or extra evaporators. Improved airflow and temperature models are the end goal of this study. The secondary loop liquid cooling system, with its refrigerant and liquid coolant loops linked by a chiller, provides efficient temperature management, despite its added complexity and potential for leaks.

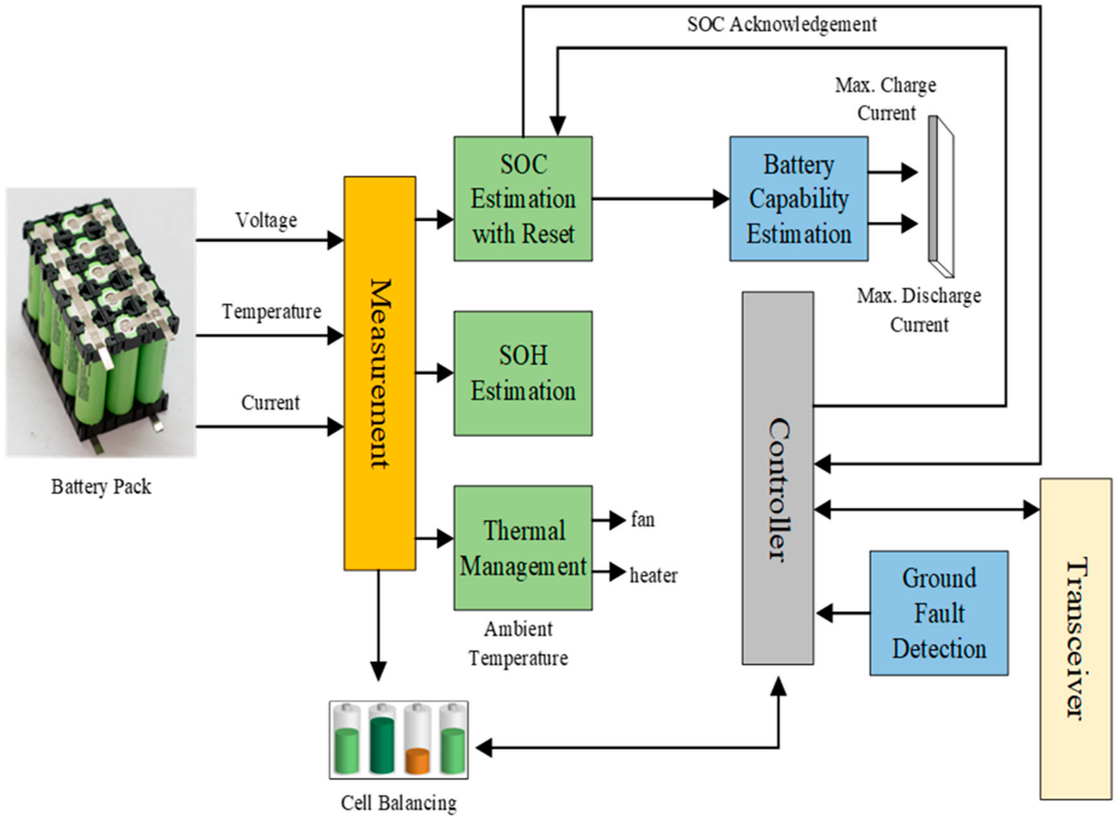

Figure 8. Block diagram of BMS [53].

Both fin cooling and mini-channel cold plate cooling systems use channel geometry as their key optimization objective. Recently developed, the direct refrigerant two-phase cooling system integrates battery cooling and the vehicle's HVAC systems into a single unit. The use of refrigerants reduces both mass and complexity, but it is important to manage the AC and BTM demands in tandem. It shows hope for the future of EVs despite numerous obstacles.

3.3.2. Battery thermal management system without VCC

BTMS employs a variety of cooling strategies to maintain optimum temperatures in the batteries of EVs. Energy-efficient cooling is made possible by phase change material (PCM) cooling systems, which use PCMs to store and release heat during phase transitions. A promising alternative to PCMs is heat pipe cooling systems, which employ phase-change principles to convey heat effectively without the need for external power. They efficiently cool the battery by integrating with the battery cells.

Thermoelectric element cooling systems are small in size, need little maintenance, and utilize semiconductor matrices to control the temperature of the battery. But they face challenges due to their poor efficiency. The purpose of research in these technologies is to improve the functionality of BTMS in EVs, leading to more effective temperature regulation and longer battery life. Figure 9 below shows the classification of BTMS.

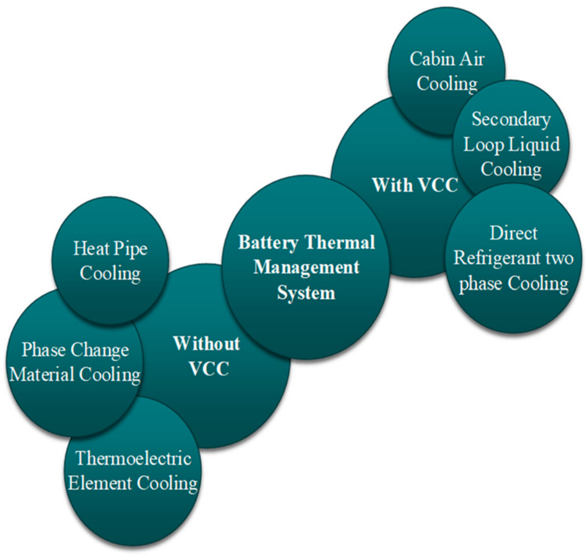

Figure 9. Classification of BTMS [56].

The integration of FTC within BTMS can contribute to enhancing its reliability and robustness to a greater extent. As indicated earlier, it will be possible to integrate FTC techniques at different types of points within BTMS to ensure that the system will continue to operate regardless of fault or failure occurrence. One way of incorporating FTC into BTMS is by incorporating spare elements, such as extra sensors and actuators. These components actively keep track of the temperature of the battery system and other parameters of the system. In case a primary sensor or actuator gets damaged, the backup units are available to support the requisite operations of the BTMS without any interference. This redundancy can be especially beneficial in systems where the use of both refrigerant and liquid coolant loops connected by a chiller is required, as it enables objects to detect a fault at once and switch to backup components to continue providing proper thermal control.

Adaptive control and MPC are two concepts from modern control theory that can be used to improve BTMS fault tolerance. These algorithms can detect faults before they happen and adjust the parameters to correct them. In the case of direct refrigerant two-phase cooling, for example, MPC can adjust cooling and control the flow of refrigerant in real-time according to process parameter conditions for steady operation. In adaptive control, adjustments can be made with the change-of-behaviour of the system, like the ageing of components or even changes in the environment, to meet optimal performance and avoid thermal runaway.

Furthermore, adopting diagnostic and prognostic techniques will help in enhancing the fault tolerance of BTMS greatly. While there are diagnostic methods that detect faults at the onset of failure, prognostic methods are those that estimate the occurrence of faults based on historical data and system operating conditions. For instance, in phase change material (PCM) cooling systems, these methods can determine the effectiveness of phase change and predict the times at which the system may not be able to store heat or release heat anymore. With the help of these methods, the BTMS can proactively manage to avoid fault progression, for instance, by changing cooling approaches or notifying the maintenance team for intervention.

Compact and low-maintenance thermoelectric element cooling systems can have their efficiency problems fixed with FTC. The system may modify control strategies permanently by using ML techniques to analyze historical performance data. Algorithms can monitor for signs that could indicate when faults are about to occur. If they do, they can adjust the temperature control settings to extend battery life and ensure appropriate operation.

3.4. Power electronics

3.4.1. Inverter control

EV power electronics depend on the power inverter, which transforms direct current (DC) from the battery into alternating current (AC) so that the motor can turn. Utilizing energy and frequency modulators, inverters provide fine control of the motor's torque and speed [57,58]. Because of their high power conversion efficiency, fast switching speed, insulated gate bipolar transistors (IGBTs), and silicon carbide (SiC) are widely used in current inverters. Several cutting-edge methods are utilized to incorporate FTC, guaranteeing that inverter systems will continue to operate normally in the event of any faults or anomalies.

One strategy is to duplicate the hardware and subcomponents, for instance, parallel inverters that can assume the duty if the main inverter breaks down. Further, observer-based FTC methods can be used for supervising the inverter operation and detecting anomalies in real-time. For example, Luenberger observers or Kalman filters can approximate the inverter's condition and check the difference with the overall outcomes to detect deviations that signify faults. Depending on the detected fault, the FTC system may be able to rearrange the control algorithms online, either modifying the modulation strategy or redistributing the load of faulty components to another functional part for motor running. Other forms of control, like the MPC, can be applied to improve the inverter's operation during faulty circumstances, as it involves analysis of future states of a system and control actions. Moreover, to enhance the accuracy of fault detection and diagnosis, ML algorithms can also be incorporated into the FTC system, which allows the FTC system to continuously learn from historical data and discover the tendencies leading to failures. These efficient techniques of FTC minimize the impact of faults on the inverter operation and thereby make the overall operation of EVs more reliable.

3.4.2. DC–DC converter control

To operate auxiliary systems, such as lighting, infotainment, and HVAC, a DC–DC converter is required to convert high-voltage DC power from the main battery into lower-voltage DC power [59]. By preventing the main battery from experiencing excessive deep discharges while the vehicle is operating on low power, this converter maximizes the use of the main battery and increases its lifespan [60]. FTC guarantees a continuous power supply in EVs, externalizing anomalies in DC–DC converters, and adopting certain security strategies to ensure optimal performance of the system.

Another aspect that can be implemented to incorporate FTC into the DC–DC converter control is through redundant conversion systems, where backup conversion systems are always on standby in case of a converter failure, so that power is not interrupted. Furthermore, dynamic model-based diagnosis can be applied in real-time to identify faults and isolate them, so that corrective measures can be quickly taken. For example, some state estimators, such as the Kalman filter-based ones, can observe the converter parameters and identify anomalies that are associated with faults.

It is possible to dynamically modify the system's performance in reaction to fault events by integrating adaptation capabilities that control the conversion duty cycles and power delivery rates. The system employs a neural controller to handle newly produced fault

Table 3. AC charging vs. DC charging [64].

	AC charging	DC charging
Power Levels	Level 1 (up to 120 V, 12 A or 16 A) Level 2 (up to 240 V, 60 A, 14.4 kW) Level 3 (Over 14.4 kW)	Level 1 (up to 450 V, 80 A, 36 kW) Level 2 (up to 450 V, 200 A, 90 kW) Level 3 (600 V, 400 A, 240 kW)
Charging Speed	slower than DC charging	Faster than AC charging
Charging Locations	This can be done at home with regular 110 V outlets and Level 2 stations	Typically, available at specialized charging stations and garages
Equipment	Requires an AC-to-DC converter for on-board chargers	Uses EV Service Equipment (EVSE) hardwired into the charging infrastructure
Time to Charge EV	Takes longer (0.5-12.5 h) for small EVs; suitable for overnight charging.	Generally faster; Level 3 chargers can charge a typical EV battery pack in under 30 min.
Charging Efficiency	Typically, less efficient due to the AC-to-DC conversion	Generally, more efficient, especially for fast-charging
Cost of Installation	Relatively low cost; can be done at home with standard outlets	Higher installation costs due to EVSE and specialized infrastructure
Safety and Compatibility	Safer and more widely compatible with existing electrical systems	May require specific wiring and installations for compatibility

scenarios in an online setting, hence increasing its resilience. Sliding mode control (SMC) is one of these; it safeguards the converter by keeping the control variable settings when a specific failure happens. The battery thus lasts longer, the car's electrical systems are safer, and gas mileage increases, due to the FTC. In the end, this method makes EVs safer, more efficient, and more dependable by increasing the DC–DC converter's accuracy and performance.

3.5. Charging control

Algorithms regulate the charging rate to protect the battery and prolong its life, whether high-speed DC fast charging or standard AC charging. An AC or DC socket can be used to charge EVs. For charging, a variety of voltage and current configurations, or "levels," are available. The amount of time needed for charging depends on the amount of employment. Table 3 shows the comparison of AC vs. DC charging. Incorporating the FTC into a system that has multiple approaches is necessary for consistent and efficient charge control. One of the control strategies for the charging system that has been studied by researchers is adaptive control algorithms, which allow the charge parameter to be adjusted using data gathered from the system.

To reduce the risk of overcharging or overheating the battery, MPC can be utilized to select the optimal charging profile in the context of battery health management, taking into consideration the future state space and control inputs [61,62]. Reducing the tolerance levels of the actuators and heat sensors is also a potential approach. In this manner, the system can continue working without compromising safety even if one of them fails to operate. On the other hand, advanced diagnostic models powered by ML can anticipate issues with charging equipment, enabling accurate localization and breakdown avoidance. These technologies simplify the process of converting an AC system to a DC system and vice versa while maintaining system functionality by increasing the charging control system's precision and adaptability. The combination of these FTC techniques assists in the pinpoint detection and avoidance of improper or unstable power connections, thus enhancing the efficiency and conformity of the charging process [63].

3.6. Drive modes

EVs have multiple driving modes to meet driver demands and increase energy economy. Sport Mode powers the wheels for high-speed driving, while Economy Mode saves fuel and reduces CO2 emissions. The vehicle accelerates quickly in sporty mode. The mode option affects dynamic braking, which may consume less energy in Sports. Additionally, temperature control, steering, and suspension parameters may be modified to improve performance. Applying FTC techniques in these drive modes increases the dependability and security of EV operations.

For example, FTC systems could use the MPC to enhance the performance of diverse driving modes by predicting and mitigating faults in real-time. In applications such as the Sport Mode, which requires high power and fast response, FTC can assess the state of the drivetrain components using sensor fusion and/or neural networks to detect signs of distress [65]. While the vehicle is in Economy Mode, FTC can adjust the power setting and regenerative braking system to optimize energy capture and prevent any detected issues from compromising the vehicle's overall performance and safety. On top of that, the FTC can alter a vehicle's steering, suspension, and temperature control if it finds it is not performing safely, regardless of whether a system is malfunctioning or not, by utilizing self-suspending and self-consuming control regulations [66]. As FTC is further integrated into the drive modes, electric vehicles are able to adapt to different driving conditions, consider the driver's desires, and maintain optimal efficiency and safety.

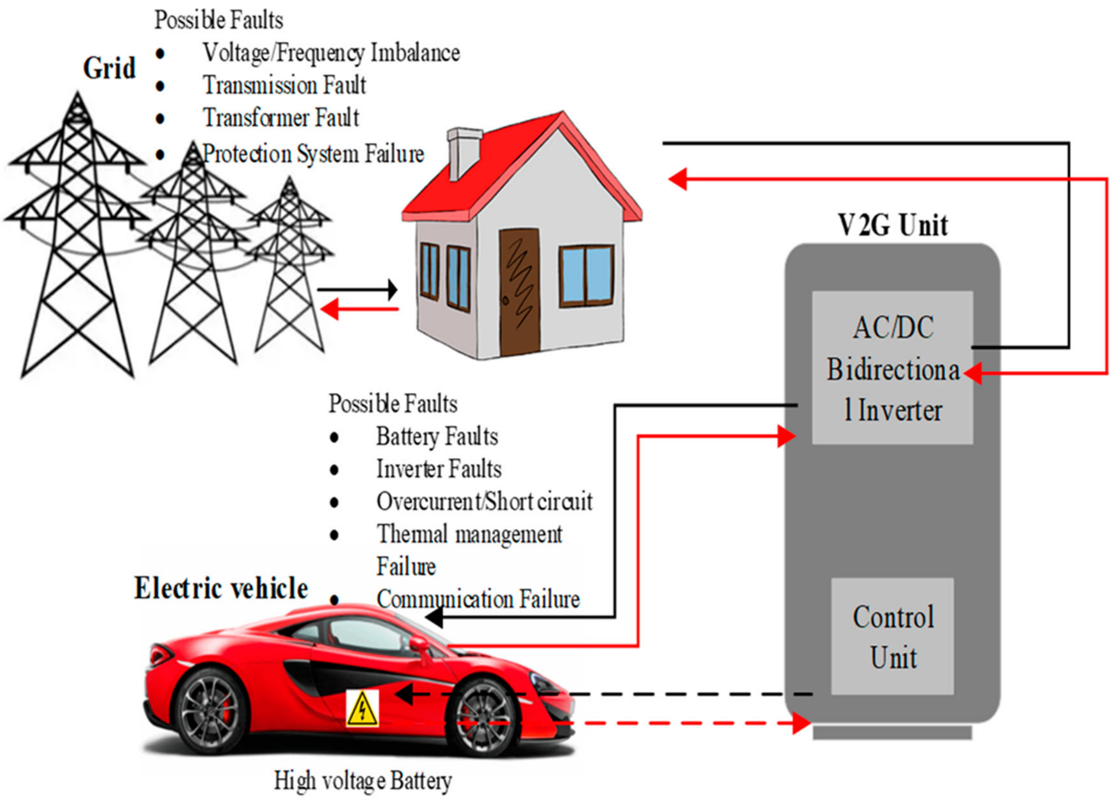

Figure 10. Vehicle to grid (V2G).

3.7. Vehicle-to-grid (V2G)

Concerns about rising pollution and greenhouse gas emissions have led to an increase in the use of EVs. It offers a versatile energy storage option, particularly during times of high demand after Vehicle to Grid (V2G) technology was implemented. EVs can function as power generators through V2G if they are parked and connected to the grid via bidirectional charging stations, as shown in Figure 10. When demand isn't as high, EV batteries are recharged. When the car is parked, the battery can provide power to utility companies to help optimize energy flow. This system incorporates a smart grid, an electricity network that can manage the flow and the communication of electricity from the generation sources through to the consumers, depending on the ever-changing demand for electricity. This is an efficient approach to addressing future challenges in energy by utilizing the storage capacity of power cables in EVs for the benefit of both the vehicle owners and the power grid. Additionally, the figure illustrates possible grid or vehicle faults, highlighting the importance of robust FTC techniques in these systems.

Figure 10 vividly explains the functioning of V2G technology; this is a scenario whereby EVs are both consumers and sellers of electricity. The EV is connected to the grid through a bidirectional inverter, which can convert the AC to DC and vice versa. When connected to the grid, the EV uses the battery to either store energy during off-peak hours or discharge energy during peak hours to support the grid. The control unit in the system controls the flow of power between the vehicle and the grid. The smart grid illustrated in the figure ensures interconnectivity between the energy suppliers (grid and EVs) and the energy users (such as households) in managing the flow of electricity depending on consumer demand. This transfer capability also helps in dealing with the decentralized connection of the grid and Energy resources more efficiently.

The incorporation of FTC strengthens V2G against grid disturbances in terms of frequency control, peak trimming, and load levelling [67,68]. Dynamically regulating the power flow between EVs and the grid using FTC approaches like adaptive control and robust control helps assure system stability and reliability in the case of a malfunction. In order to mitigate the effects of grid instability on model accuracy and uncertainty, robust control strategies can ensure that system performance remains within a predetermined range.

It is possible to use predictive control approaches to estimate not only the load requirements, but also the charging and discharging of EV batteries. In instance, predictive control anticipates possible defaults and makes adjustments accordingly to ensure the efficient and consistent supply of energy and services [69]. The FTC integration also incorporates redundancy strategies to prevent a single failure and conduct the necessary actions, such as combining several power converters and multipath communication systems. The integration of real-time monitoring and diagnostic systems aids in the detection and correction of problems before they can affect the whole system. Taken as a whole, these strategies improve the reliability, efficiency, and safety of EVs, which in turn boosts their popularity and helps build a stronger electrical grid.

4. Fault-tolerant control

In different sectors, such as aerospace, automotive, and industrial applications, engineers use FTC to ensure a system remains operational even if a component becomes faulty and stops performing consistently. Fast fault detection, issue identification, and resolution are FTC's strengths, improving crucial system safety [70]. FTCS defines a family of closed-loop systems, comprising subsystems that can maintain stability during component faults, for nonlinear, MIMO processes with offsets and delays [71]. FTC solutions reduce production losses and improve system reliability, availability, and performance in essential sectors like oil, gas, and fertilizers.

4.1. Components of FTCS

Fault-tolerant control systems (FTCS) are high-tech systems that guarantee essential components remain running and operating even if there are malfunctions or malfunctioning parts. Four main components collectively make FTCS.

4.1.1. Fault detection

The initial step of FTCS is fault detection, which includes constant monitoring of all system components, such as sensors, actuators, and subsystems, for indications of abnormal behaviour. This is often achieved by analyzing data in real time and comparing it to established norms or models [72]. The presence of a variance could mean the system has a fault. The early identification of problems is very critical for the success of the FTCS because it provides the opportunity to take quick corrective actions [73].

4.1.2. Fault diagnosis

With the FTCS, the company diagnoses the nature and the underlying root cause of a defect once it has been noticed. A fault diagnostic's purpose is to determine the faulty components and to specify the nature of the problem [74,75]. To find the nature and place of the problem, diagnostic procedures are used, most of which are based on system modelling and information analysis. This data is critical as different vulnerabilities require different preventative measures [76].

4.1.3. Fault accommodation

Once the problem has been detected, the FTCS primarily uses fault accommodation techniques to weaken its influence and to maintain the system's operation without disruptions or failures. Controlling the process modes, setting the control parameters, and using control systems properly is what is called "fault accommodation." The actions of repairing may be changing algorithms, adding redundancy, activating backup components, or even replacing the complete control system. The aim is to ensure the fault-tolerant and secure function of the system, irrespective of whether an error occurred [77].

4.1.4. Fault recovery

After the problem has been solved, step three of the FTCS consists of fault recovery, which involves returning the system to its normal or optimal operating conditions. With a fault-tolerant system, the system would either return to its initial level of function or the control parameters of the system can be made to gradually reset to their initial values [78,79]. Recovery from a fault means that the performance won't be interrupted, even though the reliability and security of the system will be maintained.

4.2. Types of FTCS

FTCS are of diverse forms, each to address unique problem areas of fault detection, diagnosis, and reconfiguration. It is classified into two main categories: As a result, active fault-tolerant control systems (AFTCS) and passive fault-tolerant control systems (PFTCS). Once they are integrated, however, they form Hybrid Fault-Tolerant Control Systems (HFTCS) [80].

4.2.1. Active FTCS (AFTCS)

AFTCS uses real-time FDI device data to construct its failure case algorithm. The most critical aspects of this process are precision in detecting, addressing, and managing the system to maintain dependability and stability [81], and resilience to erroneous readings or early error alarms. The FDI unit of an AFTCS monitors plant data to detect actuator or sensor faults that might cause an unintended system shutdown. It modifies control rules, identifies issues in real-time, and takes relevant operator actions [82], maintaining stability under intense computing. With AFTCS, multiple issues may be addressed at once [83].

AFTCS has three key subsystems: the FDI module, the reconfigurable controller, and the reconfiguration mechanism.

The FDI module continuously transmits fault information to the controller, allowing quick problem response [84,85]. Its rapid response to faults makes AFTCS dynamic and able to manage various mistakes and boost performance. However, planning for nonlinear systems that are both volatile and vulnerable to the effects of FDI might be difficult [86,87]. The structure of an AFTCS is described in the following figure, Figure 11. The main components within this system

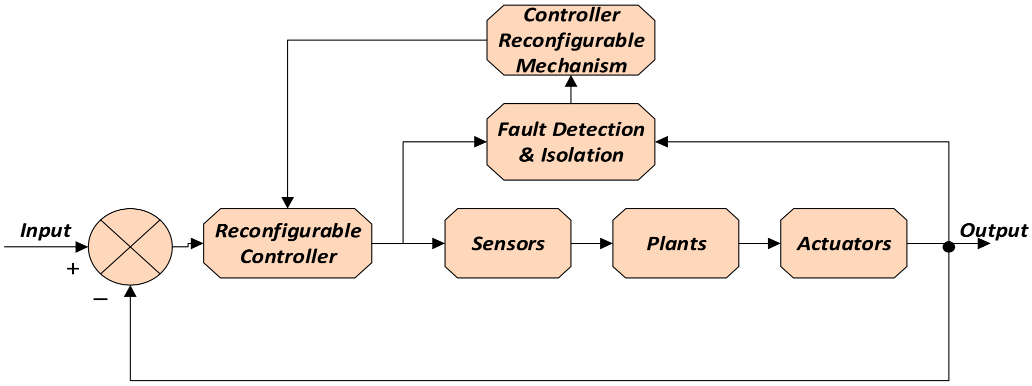

Figure 11. Active fault tolerant control structure [89].

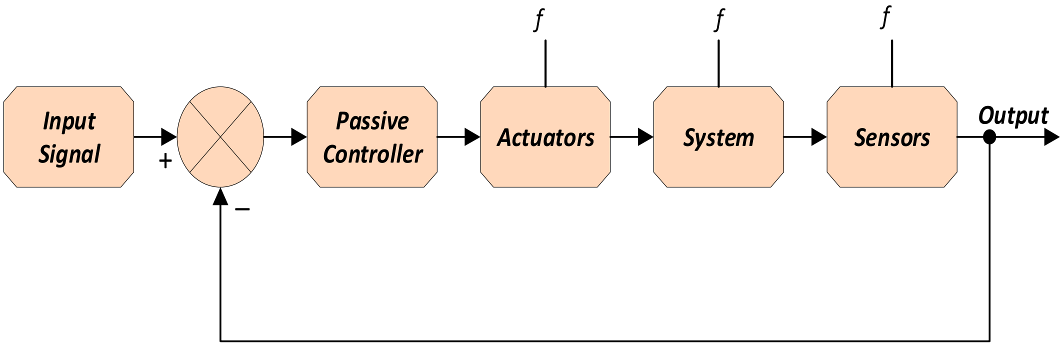

Figure 12. Passive fault tolerant control structure [89].

are the Fault Detection and Isolation (FDI), the Reconfigurable Controller, and the Reconfiguration Mechanism. In particular, the FDI unit is responsible for controlling the data of the sensors, plants, and actuators. It analyses real-time operational data with values of operations desired behaviour, usually with the help of model chequers or other observer-based techniques. These discrepancies are what are termed or seen as potential faults or defects. On detection of a fault, the FDI unit locates it to determine the type of fault that occurred [88].

This is where the Reconfigurable Controller takes the stage. Taking into account the fault information received from the FDI unit, it changes the control strategy in real-time to reduce the impact of the fault. This guarantees the overall functionality of the system without requiring a complete system shutdown. The Reconfiguration Mechanism is useful in making sure that the control laws have been altered to affect the fault condition, whereby only the inputs that are estimated rather than actual are affected [89,90].

4.2.2. Passive FTCS (PFTCS)

Passive fault-tolerant control systems (PFTCS) are based on the concept of redundancy and can function normally even in the absence of fault information as shown in Figure 12 where for clarification the symbol f is used to represent faults insertion in the actuators, system, and sensors, lacking both the FDI and the reconfiguration unit for the controller settings with preset conditions for all circumstances which indeed makes response time faster but very specific for fault detection. The elements in the system are an Input Signal, which initiates the flow; these elements include a Passive Controller. It implements pre-defined control rules and has no provision for dynamically adjusting according to the fault information.

The system components comprise Actuators, Sensors, and the System itself to sustain functionality. In PFTCS, hardware redundancy means comparing multiple signals in components to the primary input; the system can switch to backup actuators as soon as performance becomes inferior [91,92]. There is a redundant design of sensors, actuators, and controllers for a smooth switchover during a failure. The maneuvering capability of limited FTC uses methods such as SMC [93], linear quadratic, fuzzy logic [94,95], and Lyapunov-based control [96] for fault accommodation with a reduced processing burden.

PFTCS ensures fault tolerance; however, Hardware Redundancy increases cost and space. The model's premise of asymptotic stability may fail under unanticipated fault circumstances, causing system collapse. Second, performance conservatism prioritizes stability over efficiency in emergencies. Unlike PFTCS, which is simple and eliminates network connection but cannot manage simultaneous faults, AFTCS is recommended for its flexible and thorough problem-solving.

Table 4. Overview of FTC techniques with focus on EVs.

EV subsystem	Fault type	Some FTC techniques studied in the literature	Core focus	Key remarks	Some relevant references
Traction Motor	Actuator faults, parameter/ uncertainty faults	SMC, HOSMC, Adaptive FTC, Observer-based FTC	• Robust torque/speed tracking	• Widely used for motor drive robustness	[104–106]
Inverter & Power Electronics	Component/switch faults, current/voltage sensor faults	MPC-FTC, Reconfigurable FTC	• Safe power conversion	• Emphasis on post-fault reconfiguration	[107–110]
Battery Management System	Sensor faults, estimation faults (SOC/SOH drift)	Observer-based FTC, Kalman-FTC, AI-based FTC	• SOC/SOH reliability	• Critical for EV safety	[111–113]
Steering & Braking	Sensor faults, actuator faults, and communication faults	Adaptive FTC, Redundant FTC, Sliding-mode FTC	• Vehicle stability	• Safety-critical subsystems	[114–116]
Integrated EV Control	Multiple/Combined faults	AI-based FTC, Hybrid FTC	• System-level fault handling	• Emerging research trend	[117–119]

4.2.3. Hybrid FTCS (HFTCS)

In a hybrid approach formed by combining both AFTCS and PFTCS, the shortcomings of each are addressed, which results in fast fault analysis and improved system performance [97].

This method is helpful for some critical systems, solving problems such as sensor faults [98], actuator saturations [99], and parameter uncertainties [100,101]. It guarantees great performance and system stability in the face of various faults. This approach works particularly well for nonlinear systems, flight control systems, and aerospace vehicles [102,103]. FTC is a multidisciplinary field that uses control theory, fault detection, AI, and engineering principles to guarantee the safety and security of complex systems. The needs and limitations of a given application determine the best FTC method to use.

Table 4 provides comprehensive details about the FTC application in EVs. This part covers the fundamentals of fault-tolerant control specifically for EVs. Common FTC methods, control reconfiguration suggestions, and fault classification for the primary EV subsystems are among them. Many FTC solutions in the literature address sensor, actuator, and component failures; however, some more recent research is examining system-level fault scenarios with coupled faults.

5. Fault-tolerant control in EVs

FTC systems are crucial to improving the reliability, performance, and safety of EVs by reducing the impact of probable faults and failures in different vehicle components. These innovations are crucial as the automotive industry moves towards greater use of EVs. The following is an overview of FTC in EVs.

5.1. Fault detection and diagnosis

Continuous fault detection and diagnosis are the keys to quick failure identification in electric cars' components, batteries, motors, power electronics, and sensors. The fault diagnosis structure for an EV's power train has been illustrated in Figure 13. The diagram highlights the major parts necessary for detecting the faults in the EV system and diagnosing them. The Controller obtains input signals (r) and produces control signals (u) to control the Actuator that is regulating the monitored Process, e.g. motor or battery. The Sensor collects the information (y) of the process and takes it back into the loop to compare it with the pattern.

At the bottom of the diagram, Diagnostic Logic is constantly assessing system performance by comparing results to an ideal model of how the system is expected to behave given certain inputs and data from the sensors. If disparities are identified, the Fault Diagnosis unit determines the kind of fault and where it occurred. This process aids in determining faults in critical components, including the motor, battery, or power electronics, on the grounds of deviations arising due to faults (f), disturbances (d), or noise (n).

In [121], paper, the authors offer a comprehensive and up-to-date survey of Fault Detection and Diagnosis (FDD) techniques for EV motor and battery systems, focusing on new approaches such as ML and deep learning as a more sophisticated and data-driven approach to the previous model- and signal-based approaches [122]. In the case of motor drives such as Permanent Magnet Synchronous Motors (PMSMs) [123,124], deep learning algorithms such as CNNs have positive impacts in reducing the detection time and increasing the coverage of the faults; however, there are open issues in distinguishing different faults and real-time detection. Battery FDD methods, which were originally linked to Kalman Filters, are gradually shifting towards data-driven ones; however, this field is still under investigation. However, some of the limitations are as follows: the models are not accurate for a longer period, and computational methods of AI may consume more time and resources; hence, future studies should be directed towards the extent of deep learning applications, other fault indicators, and efforts to reduce the time and cost of the methods while addressing the hardware constraints. The paper provides useful information on the development of FDD in EV

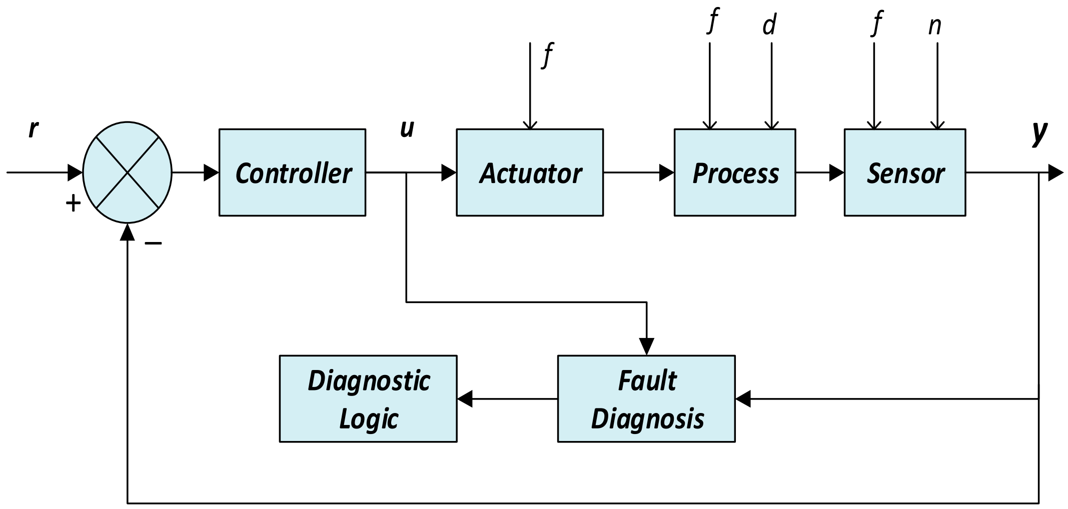

Figure 13. Fault diagnosis in an EV [120].

systems for improving the reliability and safety of such systems.

Another work [125] proposes an FTC approach for EVs with an emphasis on the FDD of four in-wheel motor drive systems. It uses a hierarchical controller over MPC and reinforcement learning (REDQ deep Q-learning) for controlling and balancing the torque outputs of the motors to enhance vehicle stability when a motor fails. Subsequent simulations conducted on a CarSim EV model display enhanced stability, decreased driver workload, and minimized power usage. Some of the major contributions are implementing reinforcement learning for the real-time detection of faults. The main limitations of the study include a lack of experimental validation of the results, limited consideration of fault coverage and extent of the study, as well as consideration of only one fault type in future investigations.

Additionally, in [126], the authors intend to use a ML approach for fault diagnosis in EVs, with emphasis on faults between the 3-φ inverter and the BLDC motor. When models are combined by voting like KNN [127,128], Decision Tree, and XGBoost, it yields better precision, recall, F1 score, and accuracy than the individual classifiers. Despite the ability to detect electrical faults, the study was also limited in the failure to include inverter and mechanical faults. The above review depicts a list of issues that future work should address to fill these gaps.

The paper [129] proposes a composite learning adaptive intelligent self-triggered FTC for autonomous surface vehicles (ASVs) to track a desired trajectory while dealing with unknown actuator failures. An integration of fixed-time performance functions and a Fuzzy Wavelet Neural Network (FWNN) enhances the solution convergence accuracy and insensitivity to unknown disturbances. The self-triggered technique allows for optimized control update intervals with frequent tracking performance and stability, independent of abrupt actuator failure. However, the proposed approach only depends on the performance of a single vehicle, and future work will be devoted to the investigation of cooperative control strategies for a team of ASVs. This research helps in the future progress of the auto-steer control of such vehicles, especially in fault-tolerant systems, due to the potential of providing a route towards highly accurate, stable, and efficient tracking of the target. These developments can be used to improve FTC scheme development techniques in addition to improving EV performance and reliability. This is particularly crucial when handling unknown system dynamics or real-time actuator failures.

5.2. Battery management

EV batteries must be monitored frequently; thus, FTC devices aid in cell failure management, which prevents unexpected drops in performance and reduced range [130]. In [131], the author presents an online technique for detecting various problems in EV battery packs. In order to distinguish between cell, sensor, and connection faults, all without the need for extra hardware, it employs a non-redundant crossed-style measuring circuit. An alternate method that is typically adaptive to variations in temperature, state of charge, and health is the increased correlation coefficient approach, which can be used to detect faults and evaluate their severity. Despite experimenting, the presence of large inconsistencies has been found difficult to handle. The future work includes developing a more complete battery health management system in detail [120].

The paper [132] focuses on external short circuit (ESC) faults in Li-ion batteries used in EVs and proposes a model-based fault diagnosis algorithm. The proposed method, based on an equivalent circuit model modified with dynamic-neighborhood particle swarm optimization (DPSO), proved that ESC faults can be detected in a time of up to 5s with a high degree of accuracy, even when there is a 10%

error in state-of-charge (SOC) estimation. The two-layer fault diagnosis policy is effective, efficient, and provides good results when it comes to diagnosing faults. Although the conclusions are only applicable to ESC faults, the positive outcomes indicate the possibility of extending the method to other fault types and conditions. Hossain Lipu et al. [133] also present and discuss intelligent algorithms and control strategies for battery management systems (BMS) in EVs and their contribution towards the improvement of battery performance, safety, and reliability. Notable algorithms enhance calculations of SOC, SOE, SOH, and RUL with control techniques, such as fuzzy logic and model-based predictive control for temperature control, fault detection, and charge equity. The limitation associated with it is computational complexity and feature selection. Discussed possibilities for further research include implementing advanced sensors, hybrid algorithms, and cloud computing.

Beyond that, in [134], a paper analyzing the susceptibility of EV battery management systems to cyber threats where the improvement of the battery "State of Charge" (SOC) is achieved using a "Back Propagation" (BP) "Neural Network" (NN). Based on the experimental data, the performance of the proposed BP NN was established and proved the utility of the model in detecting false entries due to cyber-attacks, with mean absolute percentage error (MAPE) values being an indication of proper prediction under various attacks. This research can therefore be said to add an aspect to predicting SOC that has not been studied before, with EV SOC by discussing cybersecurity. Nevertheless, the investigation is only focused on SOC-related attacks while ignoring other significant EV systems, including brake and autopilot systems, which can be studied in the future. Future work will involve improving the security performance of NNs in estimating SOC and expanding this to other systems used in EVs, such as steering and locking systems. As more integration of EVs into smart grids happens, this work has had a remarkable influence on improvements in EV fault tolerance concerning cybersecurity threats and challenges in integrating more secure, reliable EV control systems.

5.3. Redundancy and backup systems

Several EV FTC strategies include backup systems and redundancies. The vehicle's control system may automatically switch to a backup motor in case one of the vehicle's motors or inverters fails [135]. The paper introduces the Double Redundant Electro-Hydraulic Brake (DREHB) system for AVs, which will provide fail-safe and fail-operational braking to autonomous EVs. It has a three-layered, modular design with redundancy designed to improve braking in different situations, such as AEB and ACC. Supported by specific simulations and hardware-in-the-loop (HIL) tests, the system shows high-performance hydraulic control. Although very useful, the current work is only based on simulation, and future work will be dedicated to real-vehicle implementation and improved control approaches. It develops fault tolerance in EVs by offering a reliable braking system for autonomous vehicles in the presence of a fault.

Reference [136] proposes the design of a human–machine redundant braking system (HMRBS) for low-speed electric vehicles (LSEVs), which combines electro-hydraulic braking with manual braking for the improvement of safety and reliability. By employing adaptive fuzzy-PID and double closed-loop PI control strategies, the system enhances the braking performance by minimizing deceleration irregularities and braking range in contrast to conventional techniques. Also, through simulation and experimentation, the HMRBS has been found suitable for use in aftermarket LSEVs. The present system focuses on low-speed vehicles; thus, the study may examine the effectiveness of an adaptive model for other types of EVs.

Reference [137] suggests a redundancy dual-backup system to meet the power supply needs of two-wheeled self-balanced vehicles and improve safety in battery failure conditions. The system identifies faults and transfers them to the backup battery to avoid long-term impairment of the loads. As indicated in Figure 14, a battery monitoring system (microcontroller and diode) is responsible for the control and monitoring of the power supply from both batteries. This provides constant operation and safety by switching between the batteries, based on voltage and fault detection. In the attention to battery reliability, the study overlooks other intricate components, such as control circuits, that may also benefit from redundancy. So, in future research, this approach should be applied to different vehicle systems. EVs' control and fault tolerance are both improved by this study's method for managing batteries; thus, EV safety and dependability are increased.

5.4. Regenerative braking

By monitoring the battery and braking systems, FTC systems can adjust the braking force to fine-tune EV braking. This optimization aims at maximizing range and increasing battery life by utilizing energy recovery during braking, potentially reducing energy usage by 20–30%. According to the article [138], integrating flywheels and ultracapacitors can also extend the range by up to 16.25%, in addition to voltage boosting at low speed and fuzzy logic [139] control strategies.

In the paper [140], an improved Active Fault Tolerant Control (AFTC) system used in the regenerative Anti-lock Braking System (ABS) of EVs is proposed, especially for wheel speed sensor failures. With the PID controller, the highest overshoot is 19%, the lowest settling time is 0.1 s, and the steady-state error is

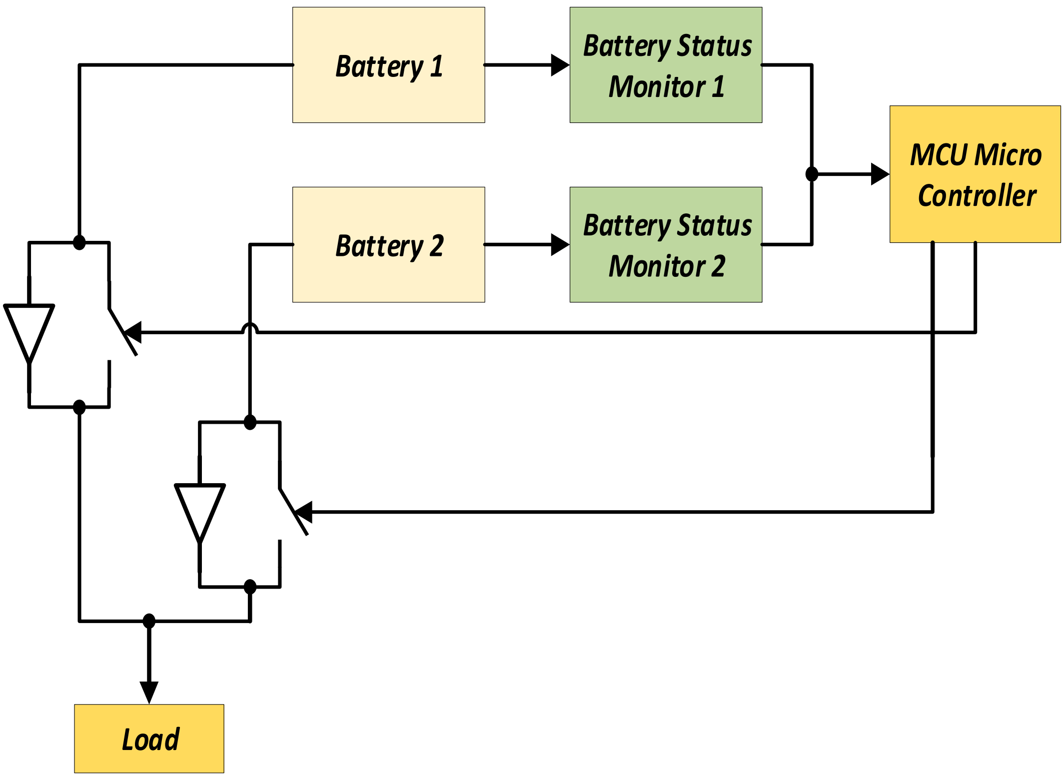

Figure 14. Redundancy dual-backup strategy [137].

zero, which outperforms the AFTC scheme using the SMC.

The incorporation of an Extended State Observer (ESO) helps in the fast and precise estimation of faults while guaranteeing system stability despite sensor faults such as bias and sensitivity. However, the study restricts itself to single sensor faults only, while there exists potential for analyzing multiple sensor faults at a time and for field implementation. This work contributes much to the future development of EV control and fault tolerance in the areas of AFTC and SMC, as well as its application on brake control and vehicle safety under sensor faults, as the EV system is more complicated and more reliant on sensor data for optimum operation.

Further in [141], a data-driven finite-state deterministic fully intuitionistic fuzzy automata (FDFIFA) approach for fault diagnosis of HEV regenerative braking system is proposed. Combining both the hardware and software aspects, along with communication concerns, enables it to handle parametric, sensor, and logic errors more effectively than conventional approaches. This is because Intuitionistic fuzzy sets (IFS) are more capable of handling uncertainties, hence enhancing the accuracy of fault detection. Thus, based on the algebraic properties of FDFIFA, a good inference system can be designed for the diagnosis of faults and their intensity. Thus, despite the clear diagnostic framework the model provides, it is too complicated and therefore not efficient in practical work. Further studies should be conducted with more real-time adjustments and extensions to other EV systems.

In the paper [142], a fuzzy control approach is employed for selecting the regenerative braking strategy of an EV to maximize energy feedback from both the front and rear brake tractions. Results under six driving conditions are depicted and coupled with fuel economy, revealing the possible 40% reduction under the NYCC conditions. Some of the notable contributions of the invention include: the ability to increase energy recovery and decrease parts wear. However, the study lacks consideration of other types of drivetrains and ignores the influence of the environment. This work also contributes to fault tolerance as it proposes a concept of EV control that increases energy efficiency as well as battery life.

5.5. Human–-machine interface (HMI)

The FTC systems in EVs with HMIs provide drivers with instantaneous monitoring and approval of the problems, as well as prompt solution suggestions. Dvorak et al. [143] introduces an improved thermal management (TM) system for Battery Electric Vehicles (BEVs), which involves both convective air conditioning and infrared heating panels (IRPs) alongside an HMI. The system enhances energy management practices in HVAC systems by employing a user-HMI, which eliminates flaws in conventional input panels. While the new HMI improved objective task completion in user studies, users also reported lower satisfaction levels with the new HMI because of its unfamiliarity. This includes the enhancement of HVAC efficiency, the increase in the driving range, and the minimization of range anxiety. They include a lack of willingness from the users to change from the conventional HMI since they are used to it. Further studies should focus on the optimization of the control strategy for the improvement of the comfort level of the passengers, and more extensive research should be conducted concerning the users' adaptation to the newly developed HMI.

In [144], the paper presents a novel strategy to enhance HMIs for smart EVs by integrating brain-computer interfaces (BCIs), deep neural networks (DNNs), and genetic algorithms (GAs). When the real-time EEG data were incorporated into the model, the DNN-GA achieved the lowest mean squared error (MSE) and mean absolute error (MAE) for predicting the driver's cognitive states compared to the other models, like the SVM-GA and PSO-GA, with comparably low accuracy and high computational time. The contributions of the proposed techniques are the significant enhancement of HMI performance, response time, and flexibility for users. Drawbacks discussed include limited participants, no field tests, and the exclusion of factors such as environmental characteristics and driver preferences, which are worth considering in subsequent studies for more general use of the research. In order to enhance the system's efficacy, safety, and adoption, this study contributes to the current information on EV control by proposing a method to install and modify the HMI control in real-time. On the same front, it alters fault tolerance by enabling EVs to adapt the driving experience to the driver's cognitive condition, which may avoid mishaps or operational breakdowns. There is a need for other future studies to include a massive sample population and a real-world context to support its application. Table 5 shows the summary comparison of existing studies in FTC for EVs with our paper.

In general, the analyzed articles reveal the progress, present issues and prospects of applying FTC for EVs according to recognized academic sources. In the multiple studies discussed, there is the idea of improving the reliability, safety, and efficiency of complex EV systems through new FTC approaches.

Collectively, all these studies demonstrate a shift in trend towards the adoption of high-end technologies, including AI, ML, as well as real-time monitoring of the FTC systems of EVs. Recent studies are focused on enhancing the accuracy of fault detection, increasing system availability by making it more robust with backup systems, and reducing energy consumption. However, the focus is on the practical applicability of these technologies and on presenting the complete datasets, validation of the results, and approaches to problems concerning the accuracy of the models and their computational complexity. Further developments are required to fine-tune these methodologies, adapt them to various EV components, and integrate them into currently implemented vehicle structures, opening the path to improved EVs.

6. Future research directions

The area of FTC for EVs is still growing, and there are still several unaddressed issues concerning more intelligent, robust, and autonomous systems.

6.1. *Application of AI and ML for real-time EV fault diagnostics and adaptive control*

The first aspect of the investigation looks at the possibility of applying AI and ML methodologies to fault diagnosis and real-time system monitoring. Despite AI being implemented to some extent in predicting maintenance schedules and identifying anomalous conditions, the possibilities to build further effective adaptive FTC systems with the ability to adjust on the fly to unpredictable situations haven't been extensively researched. Prior research has shown that AI is effective in fault predictions; still, the previous integrations of AI are particular to certain sub-systems and not for a system-level integration as required in today's sophisticated EVs. However, more work is needed to develop models that can operate in real-time to analyze a huge number of inputs from various sensors and varying environmental conditions of an entire EV system. Further, these systems must go beyond fault detection and diagnosis based on non-holistic data as well as pre-fault detection, where the vehicle is aware of potential faults that could occur shortly and be prepared to deal with them, as applies specifically to self-driving cars.

6.2. *Integrating cyber-physical systems and the internet of things to improve EV FTC*

Opportunities arising from the integration of cyber-physical systems and IoT with EVs for implementing FTC, although promising, are not sufficiently developed. Previous studies on cyber-physical systems for use in EVs have mainly been directed towards data acquisition or transmission and not on the usage of cyber-physical systems in fault resilience. While current trends incorporate IoT technologies in automobiles for real-time health checks of cars, it is seen that there is not much concern given to the adaptability of FTC systems towards faults in real-time. Future studies should focus on the ways of providing robust and trustworthy wide-area communication for IoT-integrated EV systems to achieve fast fault recovery at the system level and guarantee safety in the context of more integrated vehicle networks. Therefore, considering the growing complexity of the powertrain, battery management, and sensor array, and their increased dependence on real-time data transfer, future research is needed to investigate how IoT can be optimally used for fault

Table 5. Summary comparison of existing papers.

Study	Contributions	Methodology	Findings	Strength	Weakness
[125]	FTC for in-wheel motor drive systems	Model predictive control (MPC) and reinforcement learning (REDQ deep Q-learning)	Increased vehicle stability, reduced workload for drivers, and reduced power use	Real-time fault detection based on reinforcement learning	Requires validation in the real world and the inclusion of a wider range of faults.
[126]	Fault detection and analysis between the 3-φ inverter and the BLDC motor	Voting classifier integrating KNN, Decision Tree, and XGBoost	Precise and accurate for fault detection of electrical systems	High-performance rating of the voting classifier	Exclusion of inverter and mechanical faults
[132]	ESC fault diagnosis for lithium-ion batteries	Fault diagnosis based on a model with dynamic-neighborhood particle swarm optimization	Accurate identification of ESC faults within the 5-second window	Robust detection could be achieved with a 10% error in SOC estimation.	Applicable only for ESC faults and should be expanded to other types of battery faults
[134]	Cybersecurity for battery SOC estimation in EVs	Back Propagation (BP) Neural Network	Effective identification of false SOC entries due to the involvement of cyber threats	New perspective on tackling cybersecurity in SOC prediction	Focuses only on the SOC-related attacks while ignoring various other crucial EV systems
[135]	Double Redundant Electro-Hydraulic Brake (DREHB) for EVs	Modular three-layer architecture with dual redundancy	Higher braking safety in such circumstances as AEB and ACC.	Hydraulic control with high-frequency and low-latency confirmed in HIL tests	Needs real-car testing and enhanced control actions
[136]	Human–Machine Redundant Braking System (HMRBS) for LSEVs	Adaptive fuzzy PID as well as the double-closed-loop PI controllers	Greater braking precision and fewer fluctuations in deceleration	Suitable for low-speed EVs	Restricted to low-speed vehicles, it requires expansion to other EV types.
[140]	AFTC system in the scenario of regenerative ABS in EVs	Sliding Mode Controller (SMC) with Extended State Observer (ESO)	Better stability compared to the PID controller, with less overshoot and higher settling time	Fault estimation using AFTC and ESO integration with high efficiency	Concentrated on the single sensor fault, but the complex fault model considering multiple sensors and the real-world case study is missing.
[142]	A novel regenerative braking strategy for EVs based on fuzzy control	Fuzzy control of the braking force ratio between the front and rear axles	Under NYCC conditions, energy efficiency was enhanced up to 40%.	Promotes energy regeneration and reduces mechanical stresses.	It is applicable only to front-wheel drive systems and does not look at other types of drive-train systems or conditions.
[143]	Battery thermal management system combined with an HMI in BEVs	Application of convective air conditioning in combination with infrared heating panels (IRPs)	Higher efficiency of HVAC and driving range, reduced inefficiencies in conventional input panels	Improved objective task execution, Human–Machine Interface design	It was rated lower by users because it was unfamiliar, and it needs custom tuning of the control strategy to increase comfort.
This paper	A comprehensive review of FTC in EVs	The current and future application of the FTC to EVs	Emphasizes the gaps in the existing literature and recommends the use of AI	Offers an extensive introduction to the topic and suggests areas that need further study	Demands testing of recommendations and the feasibility of proposed approaches

detection and remediation across these and other sub-systems.

6.3. EV reliability through the integration of digital twins, predictive maintenance, and FTC

As far as Industry 4.0 is concerned, digital twins and predictive maintenance concepts have been applied partially in EV systems, but not in FTC. Digital twins have great potential to improve fault-tolerant systems through the creation of digital tools for modelling and monitoring physical systems. Yet, present implementations are limited to predictive maintenance and not actual faulty condition detection or FTC. To fill this gap, further research should consider the application of Digital Twins integrated with FTC systems to provide a real-time data-based decision-making process for fault identification, prognosis, and compensation. This integration is particularly important as the complexity of EVs increases to comprise many more interdependent sub-systems that need a high level of Integrated fault-tolerant systems. Furthermore, there is research conducted regarding predictive maintenance methods in isolation from FTC, and thus incorporating enough sophisticated predictive models together with real-time control approaches that would significantly help improve the system's robustness is still lacking.

6.4. Energy efficiency and lifespan in BMS improvement using real-time FTC

The safety and efficiency of EVs are dependent on the BMS. Although there has been a lot of study on BMS fault tolerance, real-time reconfigurability is an area that needs some development. Despite redundancy and monitoring, fault tolerance in most modern BMS designs is inadequate for efficient energy management in the case of a system breakdown or for preventing problems from propagating across the system. A more sophisticated BMS connected to FTC systems that operate in real-time is essential for overcoming these challenges. Future research should focus on creating adaptable BMS systems that can use guided models to proactively identify the sources of energy management problems and make the required adjustments. The main objectives of developing a BMS that can identify issues and prevent power outages caused by fault-related scenarios are to optimize the vehicle and increase the battery's lifespan.

6.5. Developing self-healing FTC systems for EVs

By contrast, smarter FTC systems, whereby systems are capable of diagnosing and correcting faults independently of the operator, are still in their experimental stage. Thus, the general idea of self-healing is studied in diverse fields and extended to different domains, but is not sufficiently investigated in the context of EV FTC systems. The current FTC systems are typically implemented such that fault handling is pre-scripted or pre-designed for specific or known faults and are not capable of excelling in handling new or unknown fault conditions. For future work in this direction, the realization of more complex systems that are self-healing and autonomous will require the advancement of improved control algorithms that will allow systems to gain knowledge from these fault events and potentially change their fault tolerance strategy in real time. Such systems would have to use AI, sensor fusion, ML, and other methods to self-learn how to adapt their fault handling and keep their performance up to par in single faults and multiple concurrent faults. This direction has enormous potential, especially for future fully self-driving cars that will have to navigate roads without human intervention.

6.6. Enhancing EV FTC through sensor fusion and redundancy

Redundancy and sensor fusion are known methods for improving FTC, even though they have not been investigated enough to address fault-tolerant systems in EVs. It is found that sensor fusion enhances the reliability of collected data, as well as can signify fault occurrence in autonomous driving; however, its application in the general framework of FTC is still not fully realized. Today's researchers are more likely to explore subsystems in the abstract without the need to consider a total failure in the area of fault tolerance that may affect car braking, steering, etc. Research should focus on the experimental advancement of what emerges from the sensor redundancy across different sub-systems to ensure both fault detection and the proposed response strategy for faults are well-integrated in the automotive systems. This is especially important for the new and expanded sensor suites used in contemporary EVs, where the data collected from them must be combined into a single holistic view of the state of operation of the vehicle.

Thus, in the context of autonomous driving, FTC systems are much more challenging than traditional control systems. Recent studies are focused on the use of FTC approaches to essential safety intrinsic systems like brakes and steering, but concerns regarding completely self-organizing, fault-tolerant vehicles are still in the distant future. Intelligent driving systems also require constant error recognition and handling in addition to being safe and efficient. Small advancements have been made in the design of FTC systems for autonomous driving; however, these FTC systems are developed to cope with pre-designated fault conditions only. To progress beyond this, future work should consider the design of self-learning FTC systems that can detect new fault modes and update the control strategy in real time so that the safe operation of the vehicle is maintained.

6.7. Improving the fault tolerance in power electronics for EVs

Another application where fault tolerance is essential is power electronics as EVs shift to SiC and GaN transistors. Generalized approaches for fault tolerance in power electronics have been carried out in terms of individual building block components rather than at the system level for multiple power subsystems. The applications of modern control methods, which include adaptive modulation methods and the real-time detection of faults within power electronics, should be studied to determine whether the systems can withstand component-level faults. The development of such general FTC power electronics architectures will benefit future EV systems because they address the rising demand for more economical and dependable systems.

6.8. Advancements in FTC and V2G technology integration

Subsequently, the integration of V2G technology increases complexity because the vehicle must manage its own FTC systems in addition to communicating with external systems. Despite V2G's applicability in settings like energy management and grid interfaces, fault tolerance has received very little focus in research. Further research should focus on FTC solutions that address both internal vehicle and grid-side concerns in order to provide safe and efficient EV charging and discharging without endangering the vehicle's systems. It will be particularly beneficial if renewable energy systems see a rise in the use of EVs and V2G technology. Consequently, though general advancements in the application of FTC for EVs have been made, there are numerous research gaps, especially in AI, IoT, self-healing control systems, and V2G functions. These future directions provide possible paths towards improving the safety, dependability, and efficiency of EVs in the future years.

7. Conclusion

This paper reviewed the FTCS, EV control, and FTCS variations and applications. The transition from traditional robust approaches to adaptive and modern FTC frameworks is addressed in this review of FTC mechanisms employed in modern EV research. The goal of FTC is to ensure minimal or acceptable performance degradation while keeping the vehicle stable and efficiently dealing with any component failures that might occur. The evaluation of FTC techniques in modern EVs in this research focused on improved dependability and safety. FTC systems had a significant impact on EVs' long-term operation and user confidence because of their growing significance in the sustainable transportation industry. An analysis of the current and potential applications of FTC in the EV sector was the focus of the study. This aids in highlighting topics that need more investigation and pointing out knowledge gaps. The study's most important contribution is its potential usefulness as a resource for experienced and aspiring FTC researchers. This review will help determine key areas to concentrate efforts towards the development of next-generation EVs with deployable, system-level FTC solutions based on the findings. This review will be helpful to researchers in this field because it attempts to provide insight into current developments and real-world applications.

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