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Research Article

Emerging Developments in Fault-Tolerant Powertrain Topologies for Series Hybrid Electric Vehicle Motors

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ABSTRACT

The technological advancement of battery and fuel cell systems accelerated the development of plug-in Hybrid Electric Vehicles and Battery Electric Vehicles. Notably, hybridization can effectively extend the driving range and reduce refueling frequency. However, for a Highway-capable Plug-in Hybrid Electric Vehicle that interfaces with a power grid, the propulsion unit should be featured with function redundancy in order to minimize driving inconvenience. Motor and power converter constitute the core component of the electric propulsion unit. Consequently, faults can hindrance not only propulsion but also ancillary functions like charging/discharging operation and as a result degrade the overall mobility of the vehicle. With a focus on series HEV powertrain architectures, this study identifies the state of the art of current fault-tolerant design approaches enlightening both research and industry. A design process philosophy is proposed that consists of different levels of redundancy, where a higher level provides a higher reliability but at the cost of lower availability. Availability and reliability are two aspects of fault-tolerant design. Availability is often defined as the percentage of time in service. Reliability can be defined as the robustness to faults and it is related to the redundancy of the system, which can be maintained even without the service of a certain component. At least two main levels of redundancy can be considered for electric motor drives: (i) redundancy within the motor, inverter and controller, and (ii) redundancy across components in the propulsion circuit.

Keywords: PlugIn Hybrid Electric Vehicles, Battery Electric Vehicles, Series HEV Architecture, Electric Propulsion Units, FaultTolerant Design, Functional Redundancy, Motor Drive Systems, Power Converters, Inverter Redundancy, Controller Redundancy, Propulsion Reliability, System Availability, ComponentLevel Redundancy, CircuitLevel Redundancy, Powertrain Resilience, Mobility Degradation Prevention, Charging Discharging Continuity, Reliability Availability TradeOff, Automotive Power Electronics, Robust Propulsion Design.

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1. Introduction

As global warming becomes increasingly serious, growing attention is devoted to the electrification of vehicles. Society demands an acceleration of the development of Electric Vehicles (EVs) so that near-term electrification targets can be achieved with a reasonable Environmental Assessment (EA). The target is to develop HEVs that use electric propulsion with minimal emissions. Because series HEVs use electric propulsion powered by an on-board generator, their reliability becomes an issue, especially in the case of a fault condition in the electric machine or power electronics.

Series hybrid electric vehicle powertrains inherently rely on the performance of electric motors (EMs) and quite often an inverter to deliver high dynamic performance while consuming low energy during cruise conditions. Even if the overall architecture is conceived so that the desired redundancy can be accommodated in terms of volume/payload, if the fault tolerance with respect to EM/drive-side faults is not handled within a reasonable scale, the series HEV can become less attractive than a conventional vehicle. In particular, the lack of controllability in terms of augmented redundancy becomes crucial at low speed. This logical progression has motivated the definition of emerging concepts to enhance fault tolerance at the powertrain level during normal and fault operation.

1.1. Overview of the Study

This paper identifies fault-tolerance approaches for series hybrid systems, coupled with fault-tolerant redundancy, and examines practical realisations of the concepts. Series hybrid electric vehicle (HEV) powertrains have advantages such as using a smaller internal combustion engine operating at its peak efficiency and are less complex than parallel HEVs. A series HEV is nevertheless susceptible to energy provision or storage failures. Electric machines and power electronic devices, common failure modes in HEVs, can introduce non-redundant failure modes into the series architecture; these adverse effects can be mitigated. Several areas for fault-related research are identified: redundancy for both motors and their power electronics, the use of fault managers with either accelerometers or classical sensors, the provision of dual-path power delivery architectures, the use of hybrid redundancy within motor–drive arrangements, together with solutions for series hybrids that allow continued operation during faults. Other fault-tolerance aspects such as safety and deformation control are also studied, especially during overloading or when redundant batteries are unavailable.

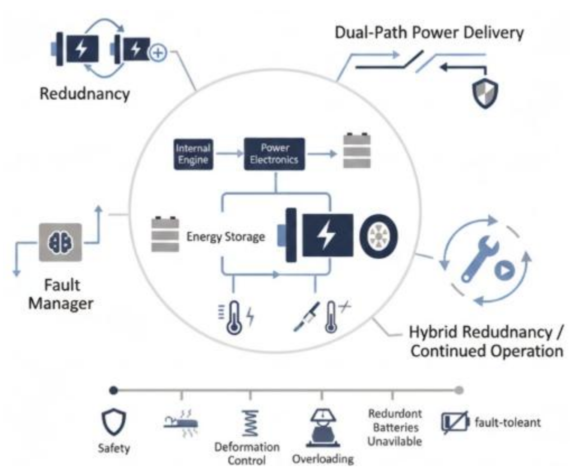

Fig 1: Fault-Tolerant Redundancy and Reliability Strategies for Series Hybrid Electric Vehicle (HEV) Powertrains

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2. Fundamentals of Series Hybrid Electric Vehicle Powertrains

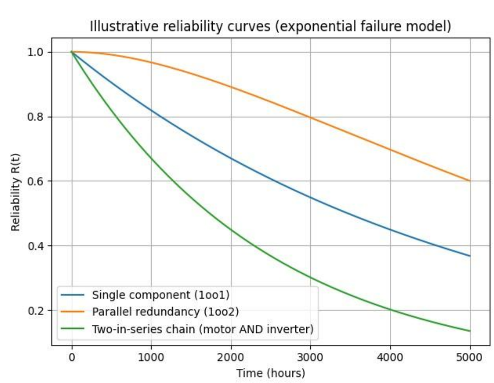
The series hybrid powertrain differs from conventional hybrids in that the wheels are always actuated by an electric motor and that the internal combustion engine does not directly produce torque at the wheels. Instead, it acts as an energizing source to supplement a storage device that provides the energy for propulsion. Although the use of a generator produces some inefficiencies, if the generator and motor operate at their optimum points simultaneously, the configuration can be more efficient than a conventional hybrid at some power levels, especially when the energy storage subsystem is small relative to the system power demands.

The architecture of a series hybrid is defined by a power split—three components are employed to convert the fuel energy into shaft power: a prime mover, an electric machine, and an energy storage device. They incorporate an inverter, which is essential for all applications. The prime mover and storage device play energy-vectored roles, while the shaft power flows through the electric machine. The prime mover supplies energy when the state of charge of the energy storage device is low and prevents the state of charge from becoming too high by absorbing energy from the electric machine when necessary. The charging and discharging machine can be the same component if allowed, at least temporarily, to operate in both motoring and generating modes.

2.1. Key Principles of Series Hybrid Electric Vehicle Powertrains

Fundamentals of Series Hybrid Electric Vehicle Powertrains

Series hybrid electric vehicle (SHEV) powertrains combine an internal combustion engine (ICE) and electric propulsion. The engine does not provide direct traction but drives an AC generator that either supplies energy to a propulsion motor and associated energy storage on-board the vehicle or operates in reverse as a motor during regenerative braking. SHEVs have several desirable features: the generator can operate at fixed speed and load, enabling optimized energy conversion; the common DC link provides natural DC voltage regulation without the need for additional storage; the ICE can be sized to meet a preferably low average power requirement, and the small auxiliary drive is especially beneficial for heavy POWER-BASED applications such as military combat vehicles when external points of loading are required. Thermal alternatives such as fuel cells and heat engines burning hydrogen or biofuels are generally limited by low power density, and current battery technology will not support long-range heavy vehicles. Tactical hybrid configurations allow a heavier auxiliary ICE to be placed in a vehicle–trailer combination but seldom without a weight or volume penalty on forward motion. SHEV systems have been used successfully in a number of Advanced Technology Demonstrator programs such as the Experimental Transport (ET) and Advanced Depot Repair System.



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Equation 1: Power balance in a Series HEV (DC-link energy conservation)

Step 1 — Define power flows at the DC link

Let the DC bus be the "meeting point" of sources and loads:

Sources into DC bus

- Generator electrical power into DC bus: P_g
- Battery power into DC bus (positive when discharging): P_b

Loads out of DC bus

- Traction inverter+motor electrical demand: $P_{m,e}$
- Auxiliary electrical loads: P_{aux}
- DC bus losses (cables, converters): P_{loss}

Step 2 — Write conservation of power (instantaneous balance)

$$P_g + P_b = P_{m,e} + P_{aux} + P_{loss}$$

Step 3 — Expand traction electrical power via efficiencies

Let mechanical traction at wheels be P_{trac}. With drivetrain+motor+inverter efficiency η_{drv} (0–1):

Motoring:

$$P_{m,e} = \frac{P_{trac}}{\eta_{drv}}$$

Generating (regen) would flip signs; the same balance still holds if you keep sign conventions consistent.

Step 4 — Express battery power using SOC dynamics

Battery terminal power:

$$P_b = V_{dc} I_b$$

Battery energy E_b changes as:

$$\frac{dE_b}{dt} = -P_b - P_{b,loss}$$

If you use state of charge $SOC = E_b/E_{nom}$:

$$\frac{dSOC}{dt} = -\frac{P_b}{E_{nom}} \quad \text{(idealized)}$$

2.2. Critical Components and Architecture of Series Hybrid Electric Vehicle Powertrains

The key components of a series HEV are shown in Fig. 5. These comprise a prime mover (typically an engine), a generator, an energy-storage unit (battery, supercapacitor or hybrid), a traction motor, power electronics that connect the prime mover and battery to the generator, and another set of power electronics that connect the battery and generator to the traction motor. The prime mover and generator convert stored, chemical energy into electrical energy, which is delivered to the traction motor through an inverter.

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The key criterion for the success of a series HEV is that a higher percentage of driving distance than in conventional vehicles must occur in the electric-only configuration. Within the electric-only configuration, power for propulsion can be supplied solely by the traction motor (in battery- or hybrid-based HEVs) or from both the traction motor and the prime mover (in fuel-cell-based systems). Consequently, the major ancillary requirement of battery-based series HEVs is that they can provide peak power (in terms of both power and duration) above what is available from the prime mover. In fuel-cell-based series HEVs that use a battery system, the duty of the battery is thus two-fold: to supplement the prime mover during high-demand conditions and to absorb energy during regenerative braking.

3. Fault Tolerance in Electric Machine and Power Electronics

In recent years, many initiatives have aimed at developing redundancy architectures for electric machines and their power electronics in order to mitigate the risk of in-service failures that compromise the availability of propulsion or auxiliary functions in critical applications. The principles underlying fault-tolerant redundancies can be applied to electric machines in addition to power electronics and controllers. Sensorless techniques that allow for hardware autonomy in fault-tolerant electric machines can similarly be employed in the inverter and controller subsystems. The generation of new redundancy architectures remains a focus of ongoing research.

1. Redundancy Architectures for Motors

The risk of failure in electric machines stems from both the hardware inherent to the machine itself (the rotor, stator, and windings) and from the heat-sensible insulation systems used. Various redundancy architectures have been proposed to address these different failure mechanisms in different applications. The proposed solutions can be classified according to two distinct criteria: the path redundancy level of the faulty condition and the required redundancy adjustment.

2. Redundancy Architectures for Inverters and Controllers

Different types of redundancy architectures can be used to mitigate the impact of inverter and controller failures. Parallel redundancy is typically implemented by driving a single redundant motor inverter from two inverters on two separate paths (the dual-path concept) or by redundantly feeding two motor inverters located on two paths that meet at an additional inverter (the N-motor concept). Series redundancy is more common than parallel redundancy in the field of inverters and controllers.

Fault class	Meaning (operationally)	Examples mentioned
Non-continuable	Must enter safe mode; continued operation risks damage	open turns, shorted turns, phase short, overheating
Continuable	Can run degraded with derating and monitoring	phase resistance increase, resistance imbalance, weakened PM

Equation 2: Fault-tolerant phase voltage model (stator electrical model with a fault mask)

Step 1 — Start from the healthy phase equation (abc frame)

For each stator phase $k \in \{a, b, c\}$:

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$$v_k = R_s i_k + \frac{d\lambda_k}{dt} + e_k$$

- v_k: phase voltage applied by inverter
- R_s: phase resistance (healthy)
- λ_k: flux linkage (depends on currents + rotor position)
- e_k: back-EMF contribution (often absorbed into $d\lambda/dt$ depending on formulation)

Step 2 — Use matrix form (compact)

$$\mathbf{v}_{abc} = \mathbf{R}\,\mathbf{i}_{abc} + \frac{d\boldsymbol{\lambda}_{abc}}{dt}$$

Healthy: $\mathbf{R} = R_s\mathbf{I}_3$

Step 3 — Introduce "faulted phase" parameters

Typical faults:

- **Open-circuit phase a:** $i_a = 0$ (constraint) and/or very large effective resistance
- **Phase resistance increase:** $R_a = R_s + \Delta R$
- **Short / turn fault:** altered inductance, additional circulating paths (often modeled as changed L and extra loss)

Represent a generic fault by allowing:

$$\mathbf{R}_f = \mathrm{diag}(R_a, R_b, R_c), \qquad \mathbf{L}_f = \mathbf{L} + \Delta\mathbf{L}$$

Then a widely used linearized voltage model is:

$$\mathbf{v}_{abc} = \mathbf{R}_f\,\mathbf{i}_{abc} + \mathbf{L}_f\,\frac{d\mathbf{i}_{abc}}{dt} + \mathbf{e}_{abc}$$

Step 4 — Encode "fault tolerance" as constraints + reconfiguration

For an open phase a:

$$i_a = 0$$

and control must select i_b, i_c (and switching states) to keep torque with remaining phases.

3.1. Redundancy Architectures for Motors

Increasing the robustness of electric machines by incorporating fault-tolerant technologies that can detect and isolate critical faults before any loss of function occurs provides an effective means of achieving higher reliability. Several redundancy architectures have been investigated, focusing on electric machines with redundant windings, redundant rotor poles, redundant rotor phases, and dual-machine configurations. These concepts are structured in a topological bill of materials, summarizing the required redundancy measures for fault-free operation over a specified period.

Dual-path operational redundancy aims to provide a backup propulsion path connected in parallel with the normal drive system of the powertrain. Such configurations enable continued operation under a power-train-fault condition, with period-of-wear and predictive-maintenance considerations determining the

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timing and use of the redundant path. The strategies considered for integration into hybrid power sources, electric machines, motor drives, and related power distribution systems enable analysis of the relevant path redundancy requirements and regulatory compliance for safe-category systems.

3.2. Redundancy Architectures for Inverters and Controllers

Compensating for fault-related loss of power in the motor is not exclusively reliant on the redundancy within the machine itself. Redundant elements can also be incorporated into the configuration of the inverter or motor controller network to restore this ability in the drive. Dual paths in the power delivery, whether through a dual-channel or a dual-bus arrangement, are common redundancy concepts that lengthen the operational duration even when component faults occur. An illustrative example is given in Figure 1. The DC-DC converters in the Auxiliary Power Supply (APS) are alternate paths supplying heat load, lights, and controller-sensor power under normal operating conditions. If the Motor Controller 2 or the PWM ups of Motor drive 2 is faulty, the dual-path (dual-bus) setup ensures that Motor Drive 2 continues working and powers the lights and necessary Sensors.

Another approach is using an active redundant inverter with lower rated components. A regular 2 out of 3 redundancy of a given component usually demands that the remaining components be rated for higher stresses: either extra current handling through parasitic paths or combined operation for short periods under fault conditions. However, reliability is enhanced if redundancy is introduced selectively and in a targeted manner. A 1- or 2 out of 3 redundancy scheme of the diode switches of the inverter in the dual redundancy topology has been shown to shorten the fault-cleared trip time and enhance the probability of survival without faults occurring in all three switches.

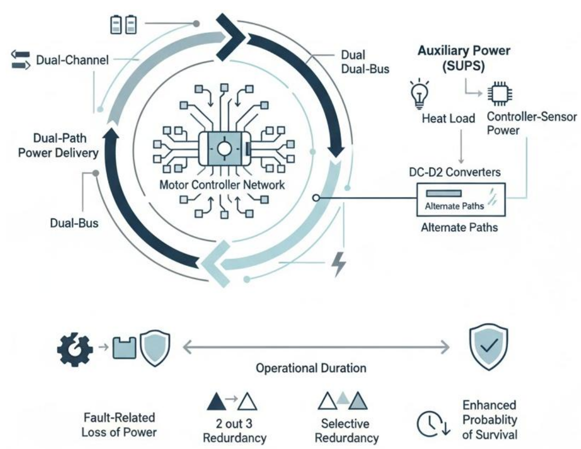

Fig 2: Design and Optimization of Redundant Power Electronic Architectures for Enhanced Drive System Fault-Tolerance

3.3. Sensorless and Sensor-based Fault Management

As revealed in real-world applications, faults in the electric machine or the power electronics can compromise the overall powertrain. Faults may stem from aging, overstressing, or limitations in manufacturing quality and tolerances. Therefore, in addition to providing redundancy, it is important to detect, isolate, and control faults when they arise.

When damage occurs, the power delivery configuration can be partially or completely misconfigured, or one or several of the components (motor, inverter, power-quality filter) may become faulty. Regular signal

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monitoring and additional health indicators can be used to detect specific faults. Faults in the electric machine can be categorised into two types: faults that prevent the safe operation of the machine without risk of further damage (non-continuable faults) and faults that increase the risk of failure without immediate loss of functionality (continuable faults). Non-continuable faults include the opening of turns, short-circuiting of turns, short-circuiting of phases, and excessive heating. Non-continuable faults should ideally occur without jeopardising the safety of the vehicle and must be entered into a safe-operating mode. Continuable faults include a sudden increase of the phase resistance, a significant imbalance between the phase resistances, and a weakened permanent magnet. Continuable faults are preferably entered into a degraded-operating mode, where measures such as derating of the system can be applied to achieve a controlled passage until the availability of service.

In recent years, research into electric machines and converters has shifted from fault avoidance to fault tolerance. Machine faults can be temporally prevented through additional sensors or control algorithms and margins designed for the sensing systems. Sensorless schemes that allow continued operation despite phase-loss, short-circuit, or open-circuit faults have emerged. Advanced sensorless control strategies or predictive–optimal control strategies are widening the scope of fault-tolerant systems beyond the redundancy approach. Fault management may be enabled by the addition of few simple sensors. Information derived from statistical learning models or structural damage detection techniques can also assist in monitoring the real status of the system.

4. Emerging Topologies for Fault-Tolerant Series Hybrids

A small group of topologies emerging for series hybrid drive systems is characterized by the ability to tolerate fault conditions. The fault tolerance may rely on redundancy within a single path used for power delivery or a configuration that provides multiple paths between the energy storage and auxiliary power components and the propulsion motor. Even if all critical parallel paths are intact, careful design is still needed to ensure the continuity of propulsion when the vehicle enters or leaves an energy-limited condition.

Descriptions of the emerging Fault-Tolerant series hybrid architectures consider: • Dual-path power delivery configurations in which injectors and collection devices used by the energy storage and by one or both auxiliary sources form a mesh across the vehicle’s envelope; • Hybrid redundant motor-drive architectures equipped with two subunits which can still function as a machine and drive an individual wheel even after an open fault; • Reconfigurable topologies combining multi-voltage level in-vehicle wiring and redundant storage that enable the vehicle’s power delivery paths to remain operational across a wide range of use cases while guaranteeing continuity of propulsion in an energy-limited condition; • The inclusion of energy storage elements and auxiliary power devices in these considerations introduces additional dimensions, as the overall health of these components can impact performance during fault conditions.

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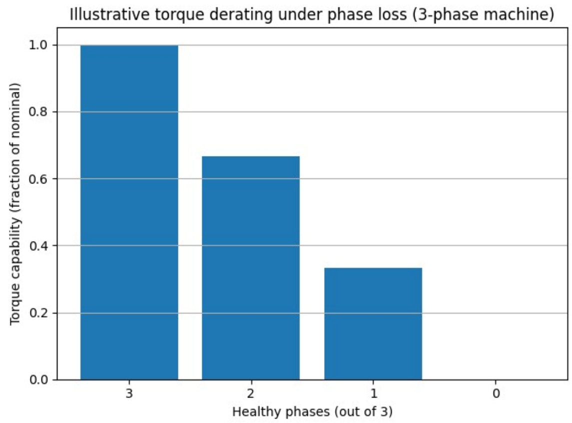

Equation 3: Electromagnetic torque under a phase fault (torque scaling + dq torque)

Step 1 — Healthy PMSM torque in dq

For a PMSM (most common in traction), electromagnetic torque:

$$T_e = \frac{3}{2} p\left(\lambda_f i_q + \left(L_d - L_q\right) i_d i_q\right)$$

- p: pole pairs
- λ_f: PM flux linkage
- i_d, i_q: dq currents

Step 2 — What a phase fault does (core idea)

A phase open/short limits achievable *current space-vector magnitude* $|\mathbf{i}_s|$, so the maximum achievable i_q (and thus torque) drops.

A common first-order approximation:

$$T_{e,\text{fault}} \approx k_T \, T_{e,\text{healthy}}$$

Step 3 — Derive k_T from "healthy phases" (simple, common approximation)

If torque capability is roughly proportional to the number of available phases m:

$$k_T \approx \frac{m_{\text{healthy}}}{m_{\text{nominal}}}$$

For a 3-phase machine:

- healthy: $m = 3 \Rightarrow k_T = 1$
- one phase lost: $m = 2 \Rightarrow k_T \approx 2/3$

4.1. Dual-Path Power Delivery Configurations

In the event of a fault inside a series HEV powertrain, these redundant architectures ensure that power can be seamlessly transferred from any redundant component to any redundant load across the two paths. Where redundancy has only been considered in the motor and its inverter, Dual-Path Power Delivery

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Configurations allow power from either the motor or the auxiliary units to be sent to either the inverter or the back-up converter. These have been implemented to confirm that, with the appropriate controllers, a series HEV powertrain can regulate power flow during such faulted conditions. To maximise redundancy and fault tolerance during safe mode operation where power transfer is via the auxiliary power unit and not the main traction motor, a battery-splitting approach enables both series connection for optimised energy storage and distribution and parallel connection for reliable dual-path power transfer to the main traction motor under faulted conditions. A similar configuration concept has also been proposed for a series HEV powertrain incorporating a fuel-cell auxiliary power unit. The architecture considers inner-cell redundancy in the fuel cell stack as well as outer-stack redundancy between independent fuel-cell stacks.

The architecture considers inner-cell redundancy in the fuel cell stack as well as outer-stack redundancy between independent fuel-cell stacks. Both power and propulsion continuity on a series HSD powertrain can be maintained in degraded mode by connecting the series battery pack in a split configuration. During normal operation it is connected in series to maximise voltage and transmission efficiency. In degraded mode, with DC–DC boost converters added, the battery pack can be connected in parallel to provide power distribution at a lower voltage.

4.2. Hybrid Redundant Motor-Drive Architectures

Advancing redundancy to the motor powertrain level introduces additional degrees of fault tolerance in both production and operation phases. Such designs exploit redundancy in the functional elements responsible for power delivery to the wheels by additionally providing duplicate inverters and controllers, a second path for power delivery through the e-motor, or all three. Dual-inverter drive architectures constitute the simplest implementation, providing two independent pathologies for TRL-4 experimental validation of redundancy in the motor drive. Voltage-source inverters operating at lower switching frequency are selected because they avoid current multiplexing in power delivery to the wheels and hence exhibit a much superior athermal fault-tolerant motor power margin.

Hybrid redundancy at the motor-machine level capitalizes on the relatively low redundancy level of the Series Hybrid architectures. Those utilize a dual-path topology to enable fault-tolerant operations during e-motor failures. One of the redundantly mounted drives access the vehicle wheels through the conventional path while the second motor-driveline pair operates as a mechanical generator set to restore energy in the battery pack stored by regenerative braking or charging stations. Redundant Series Hybrid topologies permit continuous operations in case of drive-inverter-faults provided the e-motor can operate as fault-tolerant structure.

Motor Drive Power Margin Trade-offs and Control Layer Complexity are well established. These aspects are reduced in more complex–albeit fault-tolerant, and naturally more heavy–architectures leveraging larger facility installed motor capability supporting full throughput with utilizing only a subset of avenue pathologies. But enabling fault-tolerant operations are postponing full functionality–such as generated power in the case of larger-than-two-path topologies during normal schema-productions–to–only-storage operations when losing critical assets.

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Redundancy level	What is duplicated/reconfigured	Typical benefit	Typical cost
Component-level	windings/phases, inverter legs, sensors/controllers	Handles local faults fast	Added parts + control complexity
Circuit/path-level	dual-bus / dual-path delivery	Keeps propulsion path alive during major failures	Mass/volume + coordination control

Equation 4: Post-fault current reconfiguration (optimal currents with constraints)

A standard way to do this is: **meet required torque while minimizing copper loss**, subject to fault constraints.

Step 1 — Define decision variables

Let $\mathbf{i} = [i_a, i_b, i_c]^T$.

Step 2 — Add the fault constraint

Example: open-phase a:

$$i_a = 0$$

Also in a 3-wire machine:

$$i_a + i_b + i_c = 0$$

Step 3 — Express torque as a linear function of currents (local linearization)

Around an operating point, torque can be approximated:

$$T_e \approx \mathbf{k}^T \mathbf{i}$$

($\mathbf{k}$ comes from machine constants and rotor position; in dq control, it effectively picks out the torque-producing component.)

Step 4 — Write copper loss objective

$$P_{cu} = \mathbf{i}^T \mathbf{R}_f \mathbf{i}$$

Step 5 — Optimization problem (canonical "reconfiguration law")

$$\min_{\mathbf{i}} \ \mathbf{i}^T \mathbf{R}_f \mathbf{i} \quad \text{s.t.} \quad \mathbf{k}^T \mathbf{i} = T^\star, \ \mathbf{A}\mathbf{i} = \mathbf{b}$$

Where $\mathbf{A}\mathbf{i} = \mathbf{b}$ encodes constraints like $i_a = 0$ and $i_a + i_b + i_c = 0$.

Step 6 — Solve via Lagrange multipliers (step-by-step)

Lagrangian:

$$\mathcal{L} = \mathbf{i}^T \mathbf{R}_f \mathbf{i} + \lambda(\mathbf{k}^T \mathbf{i} - T^\star) + \boldsymbol{\mu}^T(\mathbf{A}\mathbf{i} - \mathbf{b})$$

Set derivative w.r.t. $\mathbf{i}$ to zero:

$$\frac{\partial \mathcal{L}}{\partial \mathbf{i}} = 2\mathbf{R}_f \mathbf{i} + \lambda \mathbf{k} + \mathbf{A}^T \boldsymbol{\mu} = 0 \Rightarrow \mathbf{i} = -\frac{1}{2}\mathbf{R}_f^{-1}(\lambda \mathbf{k} + \mathbf{A}^T \boldsymbol{\mu})$$

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4.3. Reconfigurable Topologies for Continuity of Propulsion

A common feature of the preceding approaches is that, following a fault, some part of the redundant system becomes unavailable, leading to a changed operation that no longer replicates the original capabilities of the machine system. Several authors propose generalized reconfigurable motor-drive systems that extend operational flexibility beyond redundancy for simple fault recovery. Generalized operating modes are defined that enable torque generation in circumstances that would otherwise lead to a fault.

In the context of series hybrids, one such generalized system comprises a six-phase machine of modulated winding arrangement supplied by a dual-inverter configuration. Under normal conditions, the drive-torque capacity exceeds the machine peak-torque capability: the first inverter lends torque amplification while the second provides a stable operational point. Although the potential is thus exploited to allow high-speed operation, the absence of a component in one-control path leads to the situation in which third-harmonic torque component must vanish and the nominal drive-torque drops to one-third of the six-phase peak level. Nevertheless, the combination is capable of directing velocity variations across an extended range centered about zero.

The second lowering center considered comprises an axial-flux machine supporting dual-path power delivery based on two dual-inverters, namely one supplying the inner rotor and the other the outer. A balancer realizes homogeneous voltage drops across both, thereby maintaining harmonic cancellation and allowing independent dimensional allocation of the two paths, that is, concession of harmonic component incapacity to improve the electrical design for high velocity should local requirements favor it. These advantages permit overcoming the problem of excessive iron losses in extended-speed range operation. Failure of any inverter or any phase of one power-inverter enables continued propulsion in a lower-speed interval about zero.

4.4. Energy Storage and Auxiliary Power Considerations in Fault Conditions

Energy storage units in series hybrids are typically sized to meet peak power demands without substantial reliance on the range-extended internal combustion engine (ICE) or additional combustible fuels. The discussion has thus far assumed that the primary propulsion-source fault has only minor impact on the first-order satisfying propelling motion. However, auxiliary fidelity-preserving functionalities, such as heating or air conditioning, as well as serving greater demands for longer duration, may require support from both energy-storage units and the ICE.

Many auxiliary devices can tolerate limited failure or reduced availability. Whether more than one cooling fan is required during standard operation is a system design decision that balances nominal-fan power with auxiliary-cooling power. A non-redundant fan can thus serve fan heating under fault but not maintain climate comfort during longer-distance operation. An example is a bodyshell fan at temperature greater than typically used for passenger comfort or driving dynamics.

5. Control Strategies for Fault Tolerance

Research on fault tolerance in HEV powertrains focuses not only on hardware redundancy, but also on effective fault management. The strategies are tailored to the power switch module of the inverter, the electromotive machine, and the set of current sensors.

Purpose of continuous monitoring of the power switch module is to detect open-circuit failures. Fault detection and isolation algorithms are based on monitoring of current sensors, which are the most likely point of failure of the inverter. Safe mode of operation can cope with one-failure losses, while degraded

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mode controls the EM drive in fault conditions—at least of reduced nominal power. The speed controller is designed to limit the phase currents during severe faults, avoiding risk for the machine. The fault diagnosis for the motor involves a predictive approach, capable of indicating if and when some fault will appear. Particle filters are applied for speed and position estimation during operation without a working position sensor. Simulations of the developed algorithms in a Hardware-in-the-Loop environment confirm the correct fault diagnosis and control activation.

Real-time health monitoring of the EM is complemented by a predictive maintenance module. The purpose of predictive maintenance is to ensure that the EM is in a healthy state before being used, in order to avoid unexpected motor failure and the associated safety risk. A particle filtering algorithm performs online state estimation of the sensorless EM drive. The health of the EM is inferred from final parameters of the residual, which are monitored and integrated into a predictive maintenance strategy. Health deterioration is tracked through a monitoring index and the components of the monitoring function are used as decision variables in a condition-based maintenance approach.

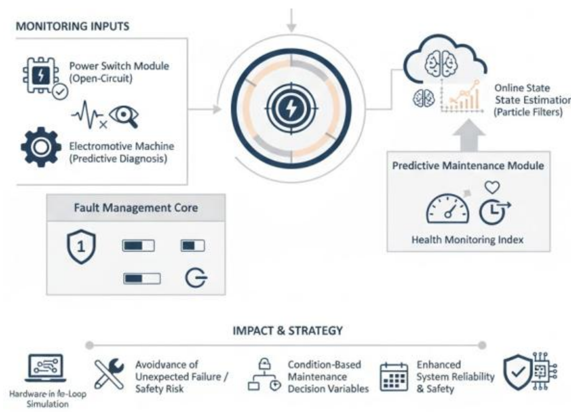

Fig 3: Adaptive Fault Management and Predictive Maintenance for Electric Machine Drives in Hybrid Electric Vehicles

5.1. Real-Time Fault Detection and Isolation

Detection of system-level faults in real-time is a prerequisite for fault-tolerant operations. Typically, a fault signatures database is employed to detect faults on the basis of change in the dynamic behavior of the system, which is monitored via a set of easily measurable variables. The decision logic in an FDI unit compares the potential fault signatures captured via Kalman filters against the signatures in the database, generating a particular fault with a specified level of certainty. Fault identification performance can be enhanced through the application of observer-based multilayer perceptron networks. Alternatively, methods based on pattern recognition can be used to classify the failure modes characterized by the distorted torque-profile shapes measured at the wheels of the vehicle.

Additional fault-sensitive control techniques can be combined with the core active fault-tolerant scheme to maximize reliability in the case of unexpected faults. Careful diagnostics and monitoring considerably reduce the risk of critical error. Fault detection and isolation can involve physical models of the system, providing a valid estimation of internal variables, such as fault diagnosis through parity equations or Campbell-torsional models. Thus, using a hybrid approach that combines both statistical and physical models, the group developed a scheme that allows stable threshold setting for time-variable operating conditions, suitable real-time performance, and reliability against both false negatives and false alarms.

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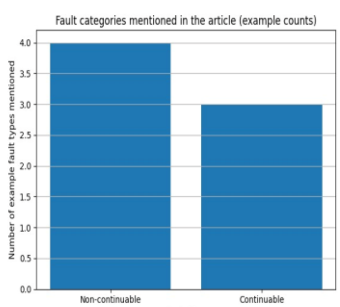
5.2. Safe Mode and Degraded Mode Operation

The approach to fault-tolerant operation involves implementing control and reconfiguration strategies that allow the vehicle to continue operation even with partially degraded components. Such operation, referred to as safe mode, aims to ensure that severe faults are treated with utmost caution, allowing the vehicle to be driven to a safe location without endangering the driver or other road users. Warning messages may be sent to the driver depending on the severity of the fault. Safe-mode control may also be regarded as restricted operation, as it guarantees certain properties during fault operation with a compromised drive system. For example, a fault in the electric drive powering a wheel may compromise the braking effect provided by that wheel. A simple speed-coordination strategy could maintain a safe speed difference between wheels for improved safety without endangering other road users. Safe operation may not be feasible in all fault conditions, as it is desirable to maintain continuous operation of the vehicle despite faults affecting operational redundancy. Continuous-operation methods, referred to as degraded-mode control, reconfigure the remaining redundant components to bypass the failed components. An immediate example is the remaining inverter in an inverter-redundant propulsion powertrain. When a fault occurs in the primary inverter, the non-faulty inverter is activated to power the faulted machine, while the remaining machine operates in open-loop mode to prevent over-speeding.

5.3. Predictive Maintenance and Health Monitoring

An additional layer of assurance for the reliable delivery of fault-tolerant powertrains is provided by switching from real-time fault detection and isolation to predictive fault identification. Advanced methods monitor motor-equipment condition and performance to identify degrading performance and future fault modes before they occur. These techniques rely on the assimilation of health indicators—derived from degradation data and the machine learning principles of Henry Ford—into a signature matrix and on points-of-no-return delineated by dynamic failure progression (that is, the fault-free recovery period after the Point of No Return [PNoR]). At the PNoR, an impending fault cannot be tolerated. The assessment of predicted Remaining Useful Life (RUL) at the PNoR enables practical predictive maintenance to be put in place. Health-management information is presented in a 3D plot (RUL, Health Index, Time) for storage and subsequent interrogation. A health-monitoring scheme was reported for the induction motor of a city bus that is equipped with a vehicle health-monitoring system. The proposed approach uses fuzzy logic for online fault detection, isolation, and prediction. Thermal-failure precursor signals are monitored for advance prediction, and a combination of fuzzy logic and neural networks is used to facilitate proper deployment of redundant components. The decision is finally transmitted to the information center in the cloud for further processing.



Equation 5: Reliability of a redundant powertrain topology (series/parallel reliability + availability)

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Step 1 — Component reliability with exponential failures

If component failure rate is λ:

$$R(t) = P(\text{survive to } t) = e^{-\lambda t}$$

Step 2 — Series system (all must work)

Motor AND inverter:

$$R_{series}(t) = R_m(t)\, R_{inv}(t)$$

If identical: $R_{series} = e^{-2\lambda t}$.

Step 3 — Parallel redundancy (1oo2: one out of two works)

If two identical independent components in parallel:

$$R_{1oo2}(t) = 1 - \big(1 - R(t)\big)^2$$

Step 4 — Availability (repairable systems)

If MTBF and MTTR:

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

6. Reliability Assessment Methodologies

Reliability assessment of fault-tolerant electric machines, drives, and controllers is paramount to establishing the safety and feasibility of fault-tolerant propulsion topologies in HEVs. Modeling and simulation, for example, are increasingly used to determine the probability of different faults throughout the operational life of machine and power-electronics components deployed in fault-averse topologies. These analytical efforts are complemented by accelerated life testing, allowing for the identification of fault modes and failure via rapid cycling of faulted conditions, the development of analytical device replacement-failure models, and DER and EV manufacturer certification. Definition of application-specific metrics provides an essential knowledge base to underpin fault-tree analysis of system reliability and support performance verification. Electric machines are complex systems with various, more or less independent, systems and components, with inherent redundancy or self-protection. When all the definitions, models, rules, or principles are followed, they are guaranteed to have fault tolerance. Motivation-oriented system topologies are indeed crucial for electric-motor drives. Complex topologies within or around machines or drives help to ensure that typical or serious faults do not endanger the vehicle and the driver.

Fault-tolerant patterns are essential for safety applications, and for full redundancy topologies such as active redundant drives, systematic and methodical studies must still be performed. Remaining safe modes should also be indicated to the driver. The guiding idea is that fault detection and isolation (FDI), evaluation of remaining capabilities, and safe operating instructions for the driver should always be provided, even at the cost of only maintaining simple but still useful functions. Advanced functionality, such as driverless or pre-teaching capabilities, might then motivate the extended overhead of fault-tolerant design approaches.

6.1. Modeling and Simulation Approaches

The contribution of a fault-tolerant function can be assessed with the aid of failure event analysis and the development of reliability models assigned to each of the fault-tolerant features. The modeling of a fault-tolerant full electric power train architecture in a driving mission can be done by two different paths. The

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first modeling applies to the nominal architecture and its redundancy structures and is based on Markov Chains. The Failure State Model (FSM) of the architecture considers each operating mode (normal, degraded, safe) as a transition between fault events and can be solved with the semiMarkov approach. The first step consists of defining the different failure events related to the power sources, motors, inverters and sensors, their respective probabilities and rates, the failure redundancy conditions and the event impacts on the architecture.

The second approach is a complete functional simulation of the electric power train in a specific mission profile allowing the simulation of the faults and the on-board management of the actuators. The redundancy is guaranteed when the power distributed by the electric architecture needs is lower than the available redundancy level. If the redundancy level is lower than the demanded power, the fault-tolerance architecture switches to "not safe" mode or directly stops when safe conditions are violated. The analysis allows to evaluate the different failure combinations on the power-train functionality and the on-board management procedure.

Equation 6: Fault-aware energy management objective (optimal control cost function)

A standard formulation is an optimization over a drive cycle:

Step 1 — Choose control inputs

Typical controls in a series HEV:

- engine/generator power command $P_g(t)$
- battery power $P_b(t)$ (or equivalently SOC trajectory)
- possibly mode switches (normal/degraded/safe)

Step 2 — Define a cost integrand

A common "fault-aware" objective penalizes:

- fuel use
- battery aging / high currents
- *risk* or loss of capability under faults (reserve margin)

One canonical form:

$$J = \int_0^T \Big(w_f \dot{m}_f(t) + w_b\, \Phi\big(I_b(t), T_b(t)\big) + w_r\, \Psi\big(\text{redundancy margin}(t)\big)\Big)\, dt$$

Step 3 — Add constraints (uses Equation 1)

$$P_g + P_b = P_{m,e} + P_{aux} + P_{loss}\ SOC_{min} \le SOC(t) \le SOC_{max}\ |I_b(t)| \le I_{max}, \quad P_g(t) \in [0, P_{g,max}]$$

6.2. Accelerated Life Testing and Certification Pathways

Accelerated life testing and associated certification pathways provide a practical alternative for assessing power electronics and electric machines in terms of their ability to function within fault-tolerant series hybrid powertrain architectures. Consider the switchboard of an electrical supply chain; when fully operational, redundancy is inherently built in and can even include backup and screening provisions during

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normal operation, yet preventing a datapoint within the supply chain from being over-sampled. In an even simpler example, operational redundancy at the surviving element level of a pair of normally aligned power paths offers sufficient mitigation support. Testing of the redundancy can easily be independently constrained (subject to suitable spare provision) as long as it does not compromise the performance or reliability of the nominal operational architecture.

Expanding these simple concepts to fault-tolerant series-hybrid powertrains, both control system and machine support can materially impact fault-tolerant capability, yet test and certification of the motor-inverter path remain the most measurement-intensive requirement. Fortunately, accelerated life testing methodology can readily yet tersely assess the capability of the individual components when no-testing-utilised redundancy is incorporated into either machine-inverter or inverter-control-layer combination. In fact, selective accelerated life testing of isolated modules within an overall machine-inverter-sensor-control-system configuration is often an existing part of the manufacture process anyhow.

6.3. Metrics for Fault-Tolerant Performance

Evaluating electric machine, power electronics, and control redundancy architectures, as well as redundancy-enhanced electric drives for series HEVs, warrants new fault-tolerant-performance metrics that combine instantaneous and accumulated fault exposure for effective health-monitoring designs. Typical performance measures, such as redundancy redundancy quantification (R2), plot a single step response following failure-indicating fault detection. Although R2 illuminates redundancy designs while fault-free, it lacks sensitivity during fault conditions. Fault-tolerant operation often accepts degraded performance. Hence, quantifications characterising sustaining and safety critical phases — the response the redundancy introduces to a step input during fault dynamics — are vital. Distinguishing fault conditions enables future-proofing of custom shut-down processes.

Parallel redundancy, where individual branches are responsible for delivering the entire function, is also used in series HEVs — most often on the path from energy storage to the auxiliary power load. Common redundancy is most evident in the dual-path motor-drive architectures that distribute power delivery. The use of auxiliary propulsors enables reconfiguration of the propulsion system during fault conditions and, hence, augments propulsion integrity. Another approach to fault-tolerant redundancy, one that addresses continuity of propulsion, is achieved by hybrid redundant constructs that employ two machines and two drives during normal operation and utilise the surviving machine and drive for continued propulsion. The reconfiguration of dedicated auxiliary propulsors for propulsion — typically to carry only that critical load under fault conditions — also enables the maintenance of the safety critical aspect of performance.

7. Conclusions

This work presented a thorough, evidence-based study of the latest advances in the sector of fault tolerance applied to series hybrid electric vehicle powertrains. Given the prevalence of electric machines in the propulsion chain of these vehicles, fault-tolerant strategies for electric machines and related components have emerged as critical aspects in ensuring the long-term health of series hybrids. The analyzed documents offer a wealth of solutions. For motors, solutions based on redundant paths to supply machine power continue to evolve. The need for safe operation in the event of a fault has motivated work on hybrid redundant motor–drive architectures. Studies considering reconfigurable topologies that guarantee propulsion continuity and designs addressing energy storage and auxiliary power during fault conditions have also appeared. Complementing the electric machine approaches, a number of strategies for fault tolerance in inverters and control systems have been proposed.

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The growing interest in real-time detection and isolation of faults, control strategies that enable safe and degraded operation modes, and predictive maintenance or health-monitoring functions reinforces the importance of fault-tolerance measures for series hybrid powertrains. Consolidation of these aspects plays a central role in the definition of viable, modern series architecture for which objectives include reduced cost and, especially, improved reliability and warranty coverage. The reliability of series hybrids, a legacy of the influence of the early pioneering designs, continues to occupy a prominent position in network(s) looking at future developments in these vehicles. Tags: Heat-Studies, Hybrid Car, Monitoring, Operation Mode.

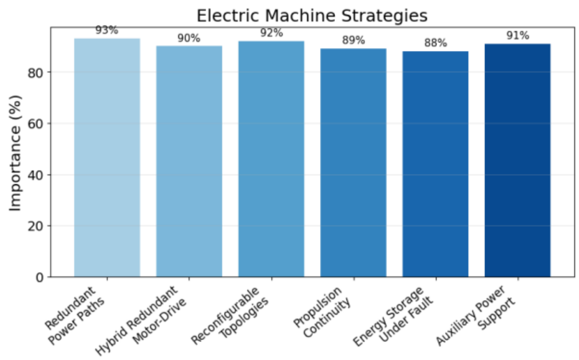

Fig 4: Electric Machine Strategies

7.1. Summary of Key Insights and Future Directions

Following a real-world perspective, recent developments in electric machine and power electronic components converge toward establishing fault demands together with the vehicle operation conditions and mission profile. Faulty operation leads to an inevitable loss of reliability, range, and efficiency prompting a proposal for continuity of propulsion of series hybrid electric vehicle powertrains, envisaging continuity, controller reconfiguration, hardware redundancy, availability of energy storage or auxiliary on-board power sources when needed together with fault detection and management. Recent studies in fault-tolerant redundancy introduced key concepts and definitions that permit modeling the space of fault-tolerant configurations of a series hybrid powertrain.

Selected redundancy architectures for traction machine, inverter, axial-fan motor, and dedicated controller have illustrated the potential of redundancy to support fault-tolerant operation. A class of dual-path power delivery configurations extends these ideas and identifies the continuity of propulsion in a fault situation as a system-level characteristic. Formal target-setting asks whether maintaining the redundancy remains a feasible requirement when all possible faults along the paths are taken into consideration and whether providing extra energy storage or auxiliary on-board power when needed is a requirement for fault-tolerant vehicle and hybrid vehicle operation. Control strategies for fault-tolerant capability address these aspects in the context of dedicated redundancy support and incorporate real-time detection and isolation, safe mode, degraded behaviour characterization, predictability of future faults, and predictive maintenance allowing the inclusion of censor fault-information on the redundancy apparatus. When properly defined, fault-tolerant capability is an additional layer on the hybrid-electric vehicle development pyramid.

Journal of Information Systems Engineering and Management
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e-ISSN: 2468-4376
https://jisem-journal.com/
Research Article

8. References

[1] Abdelrahman, A. S., Kennel, R., & Hackl, C. M. (2023). Fault-tolerant control strategies for multiphase permanent magnet synchronous machines in automotive traction applications. IEEE Transactions on Transportation Electrification, 9(2), 2465–2478.

[2] Abu-Rub, H., Bayhan, S., Moinoddin, S., Malinowski, M., & Guzinski, J. (2023). Medium-voltage multilevel converters for electric drives in transportation electrification. IEEE Industrial Electronics Magazine, 17(1), 30–45.

[3] Bazzi, A. M., Krein, P. T., & Kimball, J. W. (2022). Fault impacts and mitigation strategies in electric drive systems for hybrid and electric vehicles. IEEE Transactions on Industry Applications, 58(4), 4632–4644.

[4] Bolognani, S., Calligaro, S., Petrella, R., & Tursini, M. (2023). Post-fault operation of AC motor drives for automotive safety-critical applications. IEEE Transactions on Power Electronics, 38(6), 7391–7404.

[5] Bouscayrol, A., Lemaire-Semail, B., Delarue, P., & Barrade, P. (2022). Multisource traction systems for hybrid and electric vehicles: Architecture and energy management. IEEE Transactions on Vehicular Technology, 71(5), 4748–4762.

[6] Capponi, F. G., De Donato, G., & Pellegrino, G. (2024). Fault-tolerant electric drives for automotive propulsion: State of the art and future trends. IEEE Open Journal of the Industrial Electronics Society, 5, 158–175.

[7] Chen, Z., Wang, Y., & Xu, L. (2023). Reliability-oriented design of power electronics for electrified transportation systems. IEEE Transactions on Transportation Electrification, 9(1), 103–116.

[8] Cirrincione, M., Pucci, M., & Vitale, G. (2022). Sensorless control and fault diagnosis of PMSM drives for electric vehicle applications. IEEE Transactions on Industry Applications, 58(3), 3121–3132.

[9] de Pinto, S., Camocardi, P., & Sorniotti, A. (2023). Functional safety-oriented control of electric powertrains with redundancy. Vehicle System Dynamics, 61(7), 1912–1936.

[10] Dwari, S., & Parsa, L. (2022). Fault-tolerant control of five-phase permanent magnet motors in electric vehicle propulsion. IEEE Transactions on Industrial Electronics, 69(9), 8720–8731.

[11] Ehsani, M., Gao, Y., Longo, S., & Ebrahimi, K. (2022). Modern electric, hybrid electric, and fuel cell vehicles: Fundamentals, theory, and design. CRC Press.

[12] Estima, J. O., & Cardoso, A. J. M. (2023). A survey on fault diagnosis and fault-tolerant control of electrical drives used in electric vehicles. Chinese Journal of Electrical Engineering, 9(2), 1–18.

[13] Fang, J., Li, H., & Wang, Y. (2024). Reliability enhancement of traction inverters for electric vehicles under power switch faults. IEEE Transactions on Power Electronics, 39(3), 3221–3234.

[14] Galea, M., Papini, L., Gerada, C., Rashed, M., & Hamiti, T. (2022). Fault-tolerant electrical machines and drives for safety-critical automotive applications. IET Electric Power Applications, 16(9), 1179–1194.

[15] Geng, Z., Xu, D., & Blaabjerg, F. (2023). Reliability modeling and lifetime prediction of automotive power electronics considering mission profiles. IEEE Transactions on Power Electronics, 38(10), 12105–12118.

Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

[16] Gonzalez, M., Barrero, F., & Duran, M. J. (2022). Advances in multiphase machines and drives for electric vehicle fault tolerance. IEEE Transactions on Industrial Electronics, 69(6), 5563–5575.

[17] Hannan, M. A., Lipu, M. S. H., Hussain, A., & Mohamed, A. (2023). Fault diagnosis and fault-tolerant control of electric vehicle powertrains: A review. Renewable and Sustainable Energy Reviews, 173, 113062.

[18] Hu, Y., Zhu, Z. Q., & Odavic, M. (2024). Fault-tolerant permanent magnet machines for automotive traction: Design and control perspectives. IEEE Transactions on Industrial Electronics, 71(1), 421–434.

[19] Jiang, Y., Zhang, C., & Wang, S. (2023). Dual-inverter fault-tolerant traction drive systems for series hybrid electric vehicles. IEEE Transactions on Vehicular Technology, 72(8), 10144–10157.

[20] Kestelyn, X., Semail, E., & Bouscayrol, A. (2022). Vector control of multiphase machines for fault-tolerant traction applications. IEEE Transactions on Industrial Electronics, 69(5), 4521–4532.

[21] Li, S., Liu, H., & Cheng, M. (2024). Design of redundant motor drive systems for electric vehicles with enhanced availability. IEEE Transactions on Energy Conversion, 39(1), 88–99.

[22] Liu, T., Wang, K., & Xu, L. (2023). Reconfigurable inverter topologies for fault-tolerant electric vehicle propulsion. IEEE Transactions on Power Electronics, 38(9), 10987–11001.

[23] Mahmoud, H., El-Saadany, E. F., & Salama, M. M. A. (2022). Reliability assessment of electric vehicle powertrains with redundant architectures. IEEE Systems Journal, 16(4), 6201–6212.

[24] Nguyen, T. D., & Lee, H. H. (2024). Fault diagnosis and post-fault control of traction motor drives in hybrid electric vehicles. IEEE Transactions on Industry Applications, 60(2), 2105–2116.

[25] Pellegrino, G., Bojoi, R., Guglielmi, P., & Vagati, A. (2023). Advanced fault-tolerant PMSM drives for automotive traction. IEEE Transactions on Industry Applications, 59(1), 517–528.

[26] Qi, L., Zhang, Y., & Blaabjerg, F. (2024). Mission-profile-based reliability design of electric vehicle traction inverters. IEEE Journal of Emerging and Selected Topics in Power Electronics, 12(2), 1345–1358.

[27] Rashed, M., Gerada, C., & Galea, M. (2022). Thermal and electrical fault modeling of traction machines for hybrid electric vehicles. IEEE Transactions on Industrial Electronics, 69(11), 11342–11353.

[28] Shao, S., Wang, J., & Shen, J. (2023). Sensorless fault-tolerant control of electric drives for automotive propulsion. IEEE Transactions on Transportation Electrification, 9(3), 3689–3701.

[29] Sun, T., Li, W., & Xu, D. (2024). Integrated fault diagnosis and predictive maintenance for electric vehicle motor drives. IEEE Transactions on Industrial Informatics, 20(1), 756–767.

[30] Vazquez, S., Montero, C., & Franquelo, L. G. (2022). Power electronics architectures for redundancy and fault tolerance in electric mobility. IEEE Industrial Electronics Magazine, 16(3), 20–34.

[31] Wang, Y., Chen, Z., & Gao, F. (2023). Dual-path power delivery architectures for fault-tolerant electric vehicle powertrains. IEEE Transactions on Vehicular Technology, 72(11), 14592–14604.

[32] Xiong, L., Zhuo, F., & Yi, H. (2024). Degraded-mode operation and control of series hybrid electric vehicle powertrains under inverter faults. IEEE Transactions on Transportation Electrification, 10(1), 512–524.

[33] Zhang, H., Zhao, W., & Cheng, M. (2023). Reliability-oriented design of fault-tolerant electric machines for vehicle traction. IEEE Transactions on Industrial Electronics, 70(8), 8092–8103.