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ADVANCEMENTS IN FAULT-TOLERANT POWERTRAIN TOPOLOGY FOR MOTORS OF SERIES HYBRID ELECTRIC VEHICLES

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ABSTRACT

In order to provide efficient and environmentally friendly transportation, a fault-tolerant hybrid electric vehicle (HEV) powertrain integrates electric motors with conventional engines. Rapid fault isolation and detection, as well as post-fault functioning at rated power throughput, are characteristics of the new topology. Detailed below are the procedures for fault diagnosis, the operating principle, and the control plan. The Markov reliability model confirms the significantly enhanced dependability compared to the conventional architecture. Excellent post-fault performance and a robust fault detection technique have been further proven by experimental findings from a prototype. Duplicated components and sophisticated control mechanisms ensure that these systems can continue to operate in the event of a failure. Reliability and uninterrupted operation are guaranteed by real-time defect detection and strong energy management. These powertrains are an important step towards a future of reliable and efficient transportation, especially with the automobile industry's emphasis on sustainability.

Keywords: Vehicle, Management, System, Hybrid, Power.

I. INTRODUCTION

In an increasingly environmentally concerned society, a fault-tolerant hybrid electric vehicle (HEV) powertrain combines state-of-the-art electrical systems with state-of-the-art automotive engineering to provide efficiency and dependability. It is vital to fulfill the performance and reliability requirements of current customers while simultaneously reducing dependency on fossil fuels and greenhouse gas emissions; this is the driving force behind the development of HEVs. The heart of a fault-tolerant hybrid electric vehicle's powertrain is an efficient integration of several power sources, usually an ICE with electric motors and a strong energy storage system like a battery pack or ultracapacitors. By combining the best features of electric and conventional propulsion systems, this hybrid setup optimises fuel economy while lowering pollutants. It also permits variable energy management. Making ensuring the system keeps running even when parts fail is one of the fundamental goals of building a fault-tolerant HEV powertrain. Redundant systems, smart control techniques, and sophisticated diagnostics all work together to find, identify, and fix problems without affecting the vehicle's performance or safety too much, which is how fault tolerance is done. Several kinds of powertrain redundancy exist, such as parallel battery modules, duplicate inverters, and multiple motor-generators, each of which may get the vehicle to a safe condition or keep it running normally in the event of a failure. A degree of dependability essential for customer trust and regulatory compliance is provided by these redundancies, which make sure that a malfunction in one part does not render the whole system useless. An HEV powertrain that can withstand faults is an architectural marvel, with mechanical, electrical, and control systems all working in perfect harmony. The internal combustion engine (ICE), which is usually tuned to minimize emissions and maximize efficiency, works in conjunction with the electric motors to provide thrust. By converting kinetic energy during deceleration into usable battery energy, the electric motors may double as both driving units and regenerative braking systems. In addition to reducing wear on conventional braking systems, this feature improves the vehicle's overall energy economy. Furthermore, the powertrain has an advanced energy management system (EMS) that, depending on driving circumstances, battery charge, and driver inputs, dynamically modifies the power distribution between the internal combustion engine (ICE) and electric motors. By controlling the thermal loads on the components, the EMS avoids overheating and prolongs their lifetime, in addition to ensuring maximum performance, fuel economy, and emissions management.

Integrating sophisticated control algorithms that can identify and react to errors in real-time is a crucial part of fault tolerance in HEV powertrains. Critical factors including motor speed, torque, temperature, and battery voltage are monitored by a network of sensors spread throughout the powertrain using these algorithms. The control system has pre-programmed procedures to reorganize the powertrain in the event of a malfunction, allowing it to isolate the problematic part and keep the car running by modifying the power flow. For example, in the event of an inverter failure, the system may transfer power to the other motors, deactivate the one that is malfunctioning, or use a backup inverter if one is available. To keep the vehicle safe and usable, especially in situations when fixing it right away isn't an option, real-time problem management is essential. The durability and dependability of the energy storage system is of utmost importance in the construction of a fault-tolerant HEV powertrain. There are several safeguards and redundancies built into HEV batteries since they are both an essential and potentially vulnerable component. As an example, BMSs keep tabs on each cell's status and performance in real time, adjusting the charge and discharge rates to avoid thermal runaway and maximize battery life. The ability to separate and replace broken battery pack modules in some designs prevents system-wide damage. In addition, the energy storage system is continuously being upgraded to be more durable and fault-tolerant by incorporating new battery technologies including solid-state batteries and better thermal management materials. Software is just as important as hardware when it comes to making sure the HEV engine can withstand any kind of failure. The development of control software is usually done in accordance with strict standards, including ISO 26262, which regulates the functional safety of electrical and electronic systems in automobiles. Throughout the development lifecycle, this standard requires a methodical approach to hazard identification, risk assessment, and safety measure implementation. The software is validated and tested thoroughly throughout this process to make sure it can manage various operating settings and fault situations. This includes hardware-in-the-loop (HIL) simulations as well as real-world driving scenarios.

In addition, it is common practice to include fail-safes and fallback modes into software architecture. These features allow the vehicle to safely transition to a safe state in case of a major malfunction. Another factor contributing to the fault tolerance of newer HEVs is the incorporation of networking and telematics. Connected to the internet and other devices, HEVs may get diagnostic information and software upgrades via vehicle-to-everything (V2X) communication networks. Remote monitoring and predictive maintenance are made possible by this connection, allowing for the identification and resolution of potential faults before they cause breakdowns. For instance, the car may notify the driver to arrange for a repair appointment or install a software update to fix the problem if it detects a pattern of diminishing battery performance. Another way that HEVs may improve energy economy and safety is via V2X communication. This allows them to take part in coordinated driving techniques like platooning. An impressive feat in automotive engineering, a fault-tolerant hybrid electric vehicle powertrain integrates mechanical resilience, electrical innovation, and sophisticated control systems to provide an efficient and dependable propulsion system. These powertrains improve vehicle dependability and customer trust by including redundant components, real-time fault management algorithms, and strict safety regulations. This allows the powertrains to continue operating even when a component fails. The ideas and technology of fault-tolerant HEV powertrains will be essential in determining the direction of transportation in the future as the car industry moves towards more electrification and sustainability.

II. REVIEW OF LITERATURE

Cheng, He et al., (2020). More and more people are taking an interest in plug-in hybrid electric vehicles (PHEVs) due to its many advantages, such as minimal carbon emissions, great fuel economy, and extended driving range. The integrated switching reluctance motor (SRM) powertrain architecture for plug-in hybrid electric vehicles (PHEVs) is introduced in this study. It has various driving and battery-charging functionalities while using less power electronic components compared to the conventional scheme. Depending on the road conditions, four driving modes may be reached in motor driving mode. Both the driving and braking processes are feasible. There are three different charging modes that may be used for the battery without the need for additional chargers. Charging the traction battery from the grid is accomplished using an integrated converter circuit and SRM windings, resulting in a three-channel interleaved boost converter with power factor correction (PFC) capabilities. To charge the auxiliary battery from the generator or traction battery, an integrated half-bridge isolation DC/DC converter is used. In order to confirm that the suggested integrated drive architecture and associated control techniques work, a proof-of-concept prototype platform is constructed and trials are conducted on a three-phase 12/8 poles SRM.

Singh, Krishna et al., (2019). An important driving force behind the expansion and improvement of fuel-efficient automobiles is the rising demand for fossil fuels and the corresponding rise in environmental harm. From its embryonic stage, hybrid electric vehicles (HEVs) have emerged as a potential answer to the grave existential threat that our world faces. In addition to meeting environmental regulations with their reduced emissions and improved fuel efficiency, HEVs help customers weather the storm of ever-increasing gasoline costs. Hybrid electric vehicles (HEVs) use engine power in conjunction with electric propulsion. Electric vehicles primarily consist of an energy storage system, a motor, a bidirectional converter, and, in the case of solar-powered HEVs, maximum power point trackers, or MPPT. These parts and their design are crucial to HEV performance. Choosing a bidirectional converter to achieve high efficiency, extending the battery life by combining an ultracapacitor with the battery, the role of traction motors, and their suitability for a particular application are just a few of the important components covered in this paper's comprehensive review of HEVs. The idea of using photovoltaic cells into HEVs is very recent and has been the subject of much discussion. This study also discusses the various MPPT approaches and how well they work for solar-driven HEVs.

Raisemche, Aziz. (2014). Automakers are compelled by different international regulations to optimize traditional power trains and, more importantly, to create alternate forms of transportation, with electric vehicles being among the most promising. But you can be sure that the new drives will provide the same performance and security as the old ones.There are a lot of moving parts in an electric power train—the electrical machine, the sensor, the converter, the power electronics, etc.—and any one of them may fail. While finding and fixing these problems is important, it isn't enough to guarantee the system will work as expected. Degraded mode functioning can only be guaranteed with fault tolerant control (FTC) architecture. Our primary goal in writing this thesis was to identify different kinds of mechanical sensor failure and then suggest novel fault tolerant control architectures for the electric vehicle's induction machine power train. The structure of this thesis consists of four sections.

Song, Yantao & Wang, Bingsen. (2013). In this study, we provide a powertrain architecture for SHEVs that can withstand powertrain failures. Optimal reliability improvement with lowest part-count increase is achieved with the use of a redundant phase-leg shared by three converters in a typical SHEV engine. Hence, the rise in cost is also maintained to a minimal. Quick fault isolation and detection, as well as post-fault functioning at rated power throughput, are characteristics of the new architecture. Along with a detailed explanation of the operating principles, control systems, and techniques for fault diagnostics, two examples of the fault-tolerant design are also provided. Examining the Markov reliability model proves the powertrain's far higher dependability compared to conventional SHEVs. The suggested SHEV drive system has been tested and shown to work via time-domain simulation using a Saber model. Experiments on a reduced laboratory prototype have confirmed the reliability of the system's fault detection/isolation mechanism and its unaltered functioning after a failure.

Song, Yantao & Wang, Bingsen. (2012). In this study, we provide a powertrain design for series hybrid electric vehicles (SHEVs) that is resilient to failure. A design with minimum cost increase has been obtained by introducing a common redundant phase leg for the rectifier, inverter, and buck/boost converter of the typical drive system. Better fault management, post-fault functioning at rated power throughput, and enhanced dependability are all characteristics of the new architecture. The fault-tolerance's control approach and operational philosophy are laid forth. In order to objectively evaluate the proposed powertrain's dependability, a Markov reliability model is built. The proposed fault-tolerant SHEV drive system has been validated using numerical simulation using a Saber model. The findings show that the system is both feasible and performs well.

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III. EVALUATING THE HAIL-TOLERANT SHEV POWERTRAIN'S RELIABILITY

The reliability of the system has a direct correlation to the amount of time and money needed for repairs. In this part, we quantitatively assess the reliability of both the suggested and the standard SHEV drive systems. The new drive system may easily include more passive components, but the assessment for reliability enhancement is focused on semiconductor devices such as relays, IGBTs, diodes, and TRIACs.

A. Components Failure Rates

The MIL-217F reliability handbook contains a comprehensive database of different parts. Which is why it's used so often to find out how reliable different kinds of electronics are. We have assumed the following operating conditions so that you can use the component failure rate models from the handbook.

1. The temperature at which semiconductor devices and relays have a junction is 150 °C and 100 °C, respectively.

2. When components are passive, their failure rates are zero. In order to find the TRIAC reliability model,

$$\lambda_{TRIAC} = \lambda_b * \pi_T * \pi_R * \pi_S * \pi_Q * \pi_E \quad (1)$$

When trying to predict how often IGBTs will fail, the following criteria are considered: λb represents the base failure rate, πT the temperature factor derived from the device's junction temperature, πR the current rating factor derived from the device's rated current, πS the voltage stress factor derived from the ratios of the applied block voltage to the rated block voltage of TRIAC, πQ the quality factor, and πE the environmental factor that emulates the impact of environmental stresses. There is a lack of information on IGBT dependability in the MIL-HDBK-217F. It is possible to predict the failure rates of IGBTs using the failure rate model of MOSFETs due to the similarities in their internal architecture. Therefore, the IGBT failure rate may be represented as

$$\lambda_{IGBT} = \lambda_b * \pi_T * \pi_A * \pi_E * \pi_Q \qquad (2)$$

according to the TRIAC reliability model, with the exception of the application factor πA, all of the other parameters having the identical values. A model for the diode's failure rate is derived from

$$\lambda_{diode} = \lambda_b * \pi_T * \pi_S * \pi_C * \pi_Q * \pi_E \qquad (3)$$

the contact construction factor is denoted as πC, and the other variables are identical to those in the TRIAC and IGBT failure models. A model for the failure rate of the solid-state relay is used.

$$\lambda_{relay} = \lambda_b * \pi_Q * \pi_E \qquad (4)$$

where πQ and πE are quality factor and environmental factor, respectively.

Table 1 displays the results of an evaluation of the failure rates of IGBT, diode, TRIAC, and relay under the previously described operating settings, as well as recognized environmental and application circumstances.

Table 1. Ratios of component failure

Component	Failure Rate	Unit
IGBT	39.8	Failure per 106 hours
TRIAC	4.7	
Diode	4.10	
Relay	0.7	

B. Reliability Evaluation of the SHEV Driving System

A useful method for assessing the dependability of fault-tolerant systems at the system level is the Markov chain. Sequence of failures, failure coverage, and state-dependent failure rates are only a few of the redundant system aspects that this technique can handle. A number of dependability indicators, including availability, failure rate, and mean time to failure (MTTF), may be estimated using a Markov model. In this case, the fault-tolerant SHEV drive system's dependability is evaluated using the Markov reliability model. All devices that have the same operational states and transition processes are considered as one subsystem to simplify the analysis and lower the order of the state equation. One part of the system has all the diodes and IGBTs, while the other part contains the TRIACs. This study has not taken repair processes into account.

The system has three states:

State 0: With the exception of the redundant and connecting devices, which are inactive, all devices function properly;

State 1: The redundant leg and corresponding linking device TRIAC are engaged in the event that one switch (IGBT, diode, or both) fails;

State 2: The system turns off when either the IGBTs or the TRIAC fail, or both fail at once.

Figure 1 shows the system's state transition diagram.

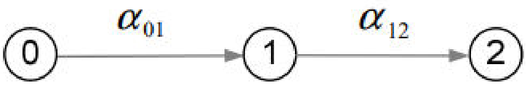


Figure 1. Diagram depicting the states of transition for the SHEV powertrain

From state 0 to state 1, the system transitions when an IGBT in the rectifier, inverter, or dc/dc converter fails, either open-switch or short-switch. The total of the failure rates of all operational IGBTs, diodes, and relays is the transition rate α01, which may be represented as

$$\alpha_{01} = 14(\lambda_{IGBT} + \lambda_{diode}) + 7\lambda_{relay} \quad (5)$$

If the redundant legs or the active TRIAC fail to keep one IGBT healthy, the system will transition to state 2. Included in the failure rates of operational IGBTs, diodes, TRIAC, and relays is the transition rate α12. One thing to keep in mind is that in state 1, there is only one TRIAC. The value of α12 may be found via

$$\alpha_{01} = 14(\lambda_{IGBT} + \lambda_{diode}) + 6\lambda_{relay} + \lambda_{TIRAC} \quad (6)$$

The state equation of the SHEV system can be obtained

$$\begin{bmatrix} -\alpha_{01} & 0 & 0 \\ \alpha_{01} & -\alpha_{12} & 0 \\ 0 & \alpha_{12} & 0 \end{bmatrix} * \begin{bmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \end{bmatrix} = \frac{d}{dt} \begin{bmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \end{bmatrix} \quad (7)$$

The system's reliability function may be calculated by adding up the probability that the system is in each functional state at time t, which is the reliability of the system.

$$R(t) = P_0(t) + P_1(t) \quad (8)$$

Table 2. Test Run Time (MTTF) of the Standard and Proposed SHEV Powertrain

Topology	MTTF

Standard powertrain	1597 hours
Proposed powertrain	3160 hours

The proposed and standard SHEV drive trains' reliability functions are shown in Fig. 2. The proposed drive system clearly outperforms the standard one in terms of reliability, thanks to the redundant phase leg.

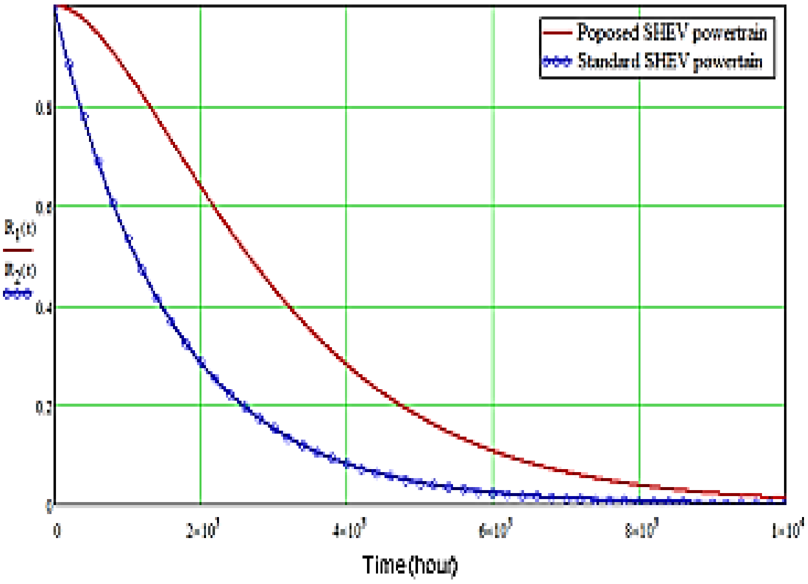


Figure 2. Comparison of planned and standard SHEV powertrain reliability.

Another crucial indicator of a system's dependability is its mean time to failure (MTTF), which is related to the reliability function via the following:

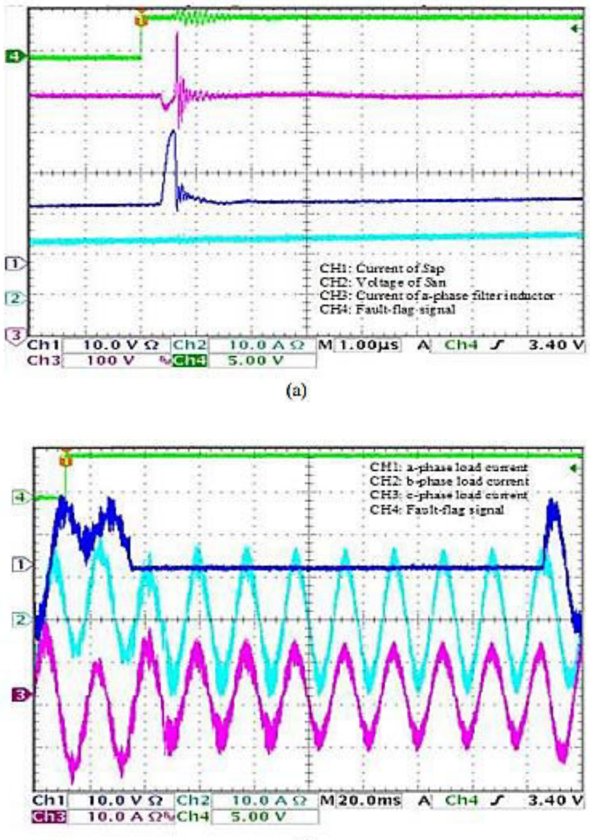
$$MTTF = \int_0^\infty R(t)dt \qquad (9)$$

The new fault-tolerant SHEV drive trains and the standard SHEV drive trains are listed in Table 2 along with their MTTFs. The new topology's super reliability performance is demonstrated by the significantly improved MTTF, which is twice as long as the standard one and operates without disturbance for twice as long.

IV. EXPERIMENTAL RESULTS

The dc-link voltage is set up by a dc power source. To power the inverter, three electronic loads are used. The regular operation of the electrical load is ensured by inserting an LC filter, which absorbs switching-frequency ripple.

As a fault-isolating component, a relay with a release time of around 24 ms is used in IGBT modules with anti-parallel diodes, which also include primary switches and connecting devices.



(a)

(b)

Fig. 3. Experimental findings for Sap short-switch fault: (b) the fault signal, switch San voltage, faulty switch Sap current, and faulted phase load current; (a) fault signal and three-phase currents.

In Fig. 3, we can see how the inverter handles the short-switch problem in Sap. A short-switch fault happens to Sap when the fault signal rises because the gate-to-emitter voltage of the higher switch is continually driven high. Figure 3(a) shows that the fault current flowing through the faulty switch Sap grows substantially after a 400 ns turn-on delay, and that a short-circuit route emerges consisting of the dc-link capacitor and two switches in the wronged leg. The next step is to locate the broken leg and block the gating signals that were sending signals to the switches there. Consequently, the fault is resolved and the fault current vanishes. There is a short-switch current of around 31 A flowing through the faulty switch, and the fault itself only lasts about 200 ns. It provides more evidence that the suggested fault detection approach responds quickly.

We include a 35 ms delay between diagnosing the short-switch defect and activating the redundant leg to prevent a short-circuit route from forming between the failed switch and the complementary switch in the backup leg. This is necessary since the relay takes around 24 ms to completely disconnect. According to Figure 3(b), the load currents return to their usual operating state after about 100 ms. Rather than the control method, the electronic load connection time is the primary culprit in the disturbance time. When it comes to motors, the time it takes to detect a short-switch defect and enable the redundant leg determines the disturbance time, which may be significantly reduced.

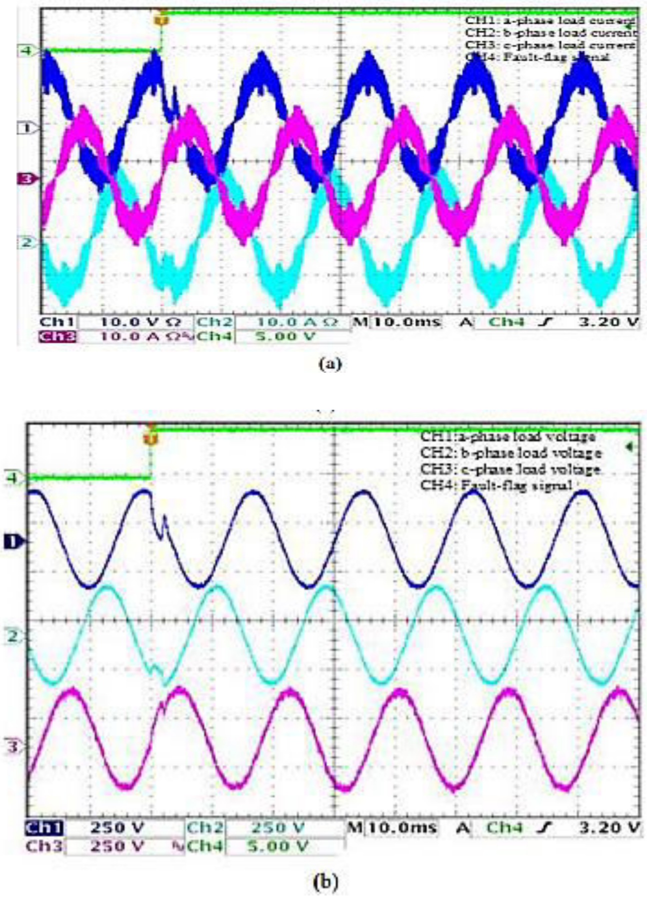


Fig. 4. Experimental findings for Sap open-switch faults: (a) fault signal and three-phase currents; (b) fault signal and three-phase voltage.

In the event of an open-switch defect to the top switch Sap of the inverter a-phase leg, the fault transition mechanism is shown in Fig. 4. After a disruption of around 1.8 ms caused by the fault, the system switches to the post-fault operation, which is identical to normal operation.

V. CONCLUSION

The powertrain of a fault-tolerant hybrid electric vehicle (HEV) is a prime example of how state-of-the-art electrical technology and sophisticated automotive engineering work together to provide dependable efficiency. These powertrains provide uninterrupted operation in case of component failures by combining several power sources, redundant systems, and sophisticated control algorithms. Thanks to strict attention to safety regulations, real-time defect detection and response, and advanced energy management, this resilience is realized. A more dependable and efficient transportation future will be shaped in large part by the advancements and concepts of fault-tolerant HEV powertrains as the automobile industry strives for more electrification and sustainability.

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