A Self-Healing Prognostic Framework for Fault-Resilient SVPWM-Based Electric Vehicle Traction Inverters

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Abstract. *This paper presents a Self-Healing Prognostic-Enabled Power Module Reconfiguration (SH-PEPMR) framework integrated with a three-phase Space Vector Pulse Width Modulation (SVPWM) traction inverter for electric vehicle applications. The proposed method is numerically evaluated on a 100-kW inverter with a 600-V DC link supplying a permanent magnet synchronous motor under healthy, degraded, and fault-injected operating conditions. Device degradation is emulated by a 30% increase in ON-state resistance and a 25% increase in switching delay, while an open-switch fault is introduced at 0.5 s. Under degraded operation without self-healing, output voltage total harmonic distortion increases from 2.1% to 6.8%, and peak junction temperature rises from 74 °C to 102 °C, with the prognostic health index (PHI) dropping from 1.0 to 0.4 within 2,150 operating hours. When SH-PEPMR is activated, adaptive SVPWM micro-reconfiguration reduces effective switching stress by 25%, restores voltage and current waveforms, and limits THD to 2.5% after fault occurrence. Junction temperature rise is reduced by approximately 20–25 °C, while inverter efficiency remains above 95%. Prognostic analysis indicates a 35–45% extension in remaining useful life, with PHI maintained above 0.6 beyond 3,000 operating hours. The numerical results demonstrate that prognostics-driven self-healing control significantly improves reliability and lifetime of EV traction inverters without hardware redundancy.*

Keywords: **Electric Vehicle Traction Inverter, Space Vector Pulse Width Modulation (SVPWM), Self-Healing Power Electronics, Prognostics and Health Management (PHM).**

1.   Introduction.

The rapid global transition toward electric vehicles (EVs) has positioned power electronics as one of the most critical enabling technologies underpinning sustainable transportation, with the global EV market expanding at an unprecedented rate driven by climate targets, regulatory mandates, and declining battery costs. According to recent industry reports, global EV sales surpassed 14 million units in 2024, accounting for more than 18% of total vehicle sales worldwide, with projections indicating that this share will exceed 35% by 2030, while the cumulative installed base of EVs is expected to cross 250 million vehicles within the next decade. This exponential growth has intensified demand not only for high-energy-density batteries but also for highly reliable traction inverters, DC–DC converters [1], and onboard chargers, which collectively handle power levels ranging from tens to hundreds of kilowatts under harsh operating conditions. Although lithium-ion battery prices have fallen by nearly 85% over the past decade and battery energy density has increased steadily, battery packs alone still account for approximately 30–40% of total EV cost [2][3], making system-level reliability and lifetime extension economically essential. At the same time, power electronic subsystems have emerged as a dominant contributor to EV failures and warranty claims, with field studies indicating that inverter and converter-related faults account for nearly 25–30% of drivetrain-related breakdowns, particularly in high-mileage, fast-charging, and high-temperature operating scenarios. These failures are primarily attributed to semiconductor aging mechanisms such as solder fatigue, bond-wire lift-off, metallization wear, and gate oxide degradation, which are accelerated by high switching frequencies, large current transients, and severe thermal cycling intrinsic to modern EV operation [4]. Despite significant advances in wide-bandgap devices, such as silicon carbide (SiC) MOSFETs, which offer higher efficiency and temperature tolerance, the reliability challenge has not been eliminated [5]; instead, it has shifted toward more complex degradation behaviors that are harder to detect and manage using conventional protection strategies. Existing EV power electronics architectures rely heavily on reactive fault detection [6], derating, or shutdown mechanisms that are triggered only after a fault threshold is crossed, leading to sudden loss of propulsion, reduced availability, or costly component replacement, which is particularly unacceptable for autonomous vehicles [7], electric buses, and commercial fleets where downtime has direct economic and safety implications. Furthermore, traditional redundancy-based fault-tolerant [8] designs increase cost, weight, and system complexity, conflicting with the industry's push toward compact, lightweight, and cost-optimized inverter systems. Another major limitation of current approaches is the over-reliance on temperature-based monitoring [9], which fails to capture early-stage degradation that manifests initially as subtle electrical anomalies rather than macroscopic thermal excursions, thereby missing the opportunity for early intervention [10][11] As EV adoption expands rapidly in regions with harsh climatic conditions, such as high ambient temperatures, poor grid quality, and aggressive fast-charging infrastructure, these limitations are further exacerbated, accelerating aging and amplifying reliability risks. From a system perspective, the EV ecosystem [12] is also undergoing a paradigm shift toward software-defined vehicles, predictive maintenance, and digital twins, yet power electronics remain largely static hardware components with limited self-awareness or adaptive capability, creating a critical mismatch between intelligent vehicle-level management [13] and passive energy conversion subsystems [14] This gap underscores the urgent need for a new class of power electronics architectures that can autonomously sense their own degradation, predict future failure risk, and actively adapt internal operation to extend lifetime without compromising performance. The proposed Self-Healing Power Electronics with Prognostic Micro-Reconfiguration (SH-PEPMR) model directly addresses this unmet need by redefining reliability as a dynamic, controllable state rather than a fixed design margin. By integrating high-resolution electrical degradation signature extraction, continuous health quantification through a prognostic health index, and control-driven micro-reconfiguration of internal switching paths and stress distribution, the proposed model enables pre-failure intervention that arrests degradation growth before catastrophic failure occurs. This approach is fundamentally different from existing fault-tolerant or condition-monitoring strategies, as it operates during normal driving conditions and does not require additional hardware redundancy or external sensors, making it economically viable for mass-market EVs. The necessity of such a model becomes evident when considering the long-term sustainability of the EV market, where extending inverter lifetime by even 20–30% can significantly reduce total cost of ownership, lower lifecycle emissions associated with component replacement, and improve consumer confidence in EV reliability. Moreover, as EVs increasingly serve as mobile energy assets within smart grids and vehicle-to-grid ecosystems, uninterrupted and reliable power electronic operation becomes a system-level requirement rather than a component-level concern. In this context, the proposed SH-PEPMR framework is not merely an incremental enhancement but a strategic response to the converging challenges of market scale, cost pressure, thermal stress, aging uncertainty, and autonomy requirements, providing a foundational step toward truly intelligent, resilient, and self-sustaining power electronic systems for next-generation electric vehicles.

2.   Self-Healing Power Electronics with Prognostic Micro-Reconfiguration (SH-PEPMR)

The proposed Self-Healing Power Electronics with Prognostic Micro-Reconfiguration (SH-PEPMR) framework is shown in Fig.1. and it introduces a fundamentally new paradigm for reliability-aware operation of electric vehicle traction inverters by embedding degradation prognostics, adaptive control, and internal topology reconfiguration into a unified mathematical system that operates continuously during normal driving conditions rather than reacting after fault occurrence. The inverter is modeled as a multi-device switching network in which each semiconductor switch exhibits time-varying electrical parameters due to aging phenomena such as bond-wire fatigue, solder layer degradation, and gate oxide wear, causing progressive drift in ON-state resistance, switching delay, gate charge, and high-frequency harmonic behavior; unlike conventional fixed-parameter models, these quantities are treated as dynamic states that evolve under coupled electrical and thermal stress. The instantaneous electrical behavior of each device is governed by its switching state, DC-link voltage, and conduction current, while the loss dynamics combine conduction and switching losses, which feed into a thermal sub-model describing junction temperature evolution through lumped thermal resistance and capacitance. Thermal cycling and elevated temperature directly accelerate degradation, thereby closing the electro-thermal-aging loop. To quantify device integrity in a continuous manner, the framework defines a Prognostic Health Index (PHI) for each switch as an exponentially weighted function of normalized degradation signatures, yielding a bounded scalar health state that decreases smoothly from unity toward a critical threshold as aging accumulates. Building on this health representation, the inverter control problem is reformulated to include health maximization as an explicit objective alongside torque continuity and efficiency constraints, leading to a min–max optimization in which control inputs such as switching frequency allocation, duty-cycle distribution, and internal conduction routing are selected to maximize the minimum PHI across all devices. The key innovation lies in micro-reconfiguration, whereby dormant or underutilized internal conduction paths, parallel silicon regions, or alternative phase-leg routing options are selectively activated to redistribute electrical and thermal stress away from degrading devices without altering the external inverter topology or interrupting power delivery. This reconfiguration is complemented by adaptive switching stress redistribution, in which the switching frequency of each device is modulated as a smooth function of its PHI, reducing high-frequency stress on aged components while allowing healthier devices to temporarily assume higher dynamic loads, thereby preserving overall efficiency and output waveform quality. The closed-loop interaction between degradation sensing, PHI prediction, and control reconfiguration yields a self-healing mechanism in which aging is actively slowed rather than merely tolerated. Stability of the health dynamics is established by defining a Lyapunov function over the PHI states, showing that the proposed control actions render the health system asymptotically stable in the sense that degradation growth is monotonically attenuated under bounded stress conditions. Unlike traditional fault-tolerant or redundant designs that react after catastrophic events or rely on hardware duplication, the SH-PEPMR model achieves graceful aging through anticipatory intervention, ensuring uninterrupted operation, improved reliability, and extended service life, which is particularly critical for autonomous EVs, heavy-duty electric transport, and operation in harsh thermal environments. This unified theoretical formulation establishes reliability as a controllable dynamic state and demonstrates how prognostics, control theory, and power electronics can be mathematically integrated to create self-healing energy conversion systems for next-generation electric vehicles.

Consider a three-phase EV traction inverter composed of N controllable semiconductor switching devices (IGBTs or MOSFETs). The instantaneous switching behavior of the ith device is governed by

$$v_i(t) = s_i(t)V_{dc} - i_i(t)R_i(t) \tag{1}$$

where $v_i(t)$ is the terminal voltage, $s_i(t) \in \{0,1\}$ is the switching state, V_{dc} is the DC-link voltage, $i_i(t)$ is the conduction current, $R_i(t)$ is the effective ON-state resistance. Unlike conventional models, $R_i(t)$ is time-varying due to degradation:

$$R_i(t) = R_{i,0} + \Delta R_i(t) \tag{2}$$

where $\Delta R_i(t)$ captures aging-Induced resistance drift. Aging in power devices manifests as subtle electrical anomalies. The SH-PEPMR framework defines a degradation signature vector:

$$\mathbf{D}_i(t) = \begin{bmatrix} \Delta R_i(t) \\ \Delta t_{sw,i}(t) \\ \Delta Q_{g,i}(t) \\ H_i(t) \end{bmatrix} \tag{3}$$

where $\Delta t_{\text{sw},i}(t)$ is switching delay drift, $\Delta Q_{g,i}(t)$ is gate charge deviation, $H_i(t)$ is harmonic distortion residue extracted from current spectra. These quantities are estimated using high-frequency sampling of gate and phase currents without additional sensors. The junction temperature of each device evolves as

$$C_{th}\frac{dT_i(t)}{dt} = P_{\text{lows},i}(t) - \frac{T_i(t) - T_a}{R_{th}}$$

Where C_{th} and R_{th} are thermal capacitance and resistance, T_a is ambient temperature. Power loss is given by

$$P_{\text{loss},i}(t) = i_i^2(t)R_i(t) + f_{sw,i}(t)E_{sw,i}(t) \tag{4}$$

A continuous Prognostic Health Index is defined to quantify remaining device integrity:

$$\text{PHI}_i(t) = \exp\left(-\sum_{k=1}^{4} w_k \frac{D_{i,k}(t)}{D_k^{\max}}\right) \tag{5}$$

Where w_k are normalized weighting coefficients, $D_k^{\max}$ are critical degradation thresholds.
$0 < \text{PHI}_i(t) \leq 1$ with $\text{PHI}_i = 1$ indicating a healthy device and values approaching zero indicating imminent failure. The rate of PHI decay is modeled as

$$\frac{d\text{PHI}_i(t)}{dt} = -\beta_i \sigma_i(t)\text{PHI}_i(t) \tag{6}$$

Where β_i is a degradation sensitivity coefficient, $\sigma_i(t)$ is cumulative electrical-thermal stress. Solving,

$$\text{PHI}_i(t) = \text{PHI}_i(0)\exp\left(-\int_0^t \beta_i \sigma_i(\tau)d\tau\right) \tag{7}$$

The Time-to-Critical Degradation (TCD) is obtained by

$$\text{TCD}_i = \min_t\{\text{PHI}_i(t) \leq \text{PHI}_{crit}\}$$

Let $\mathbf{u}(t)$ represent the inverter configuration vector (switch routing, conduction assignment, and gate priority). The objective is to maximize the minimum PHI across all devices:

$$\max_{\mathbf{u}(t)} \min_i \text{PHI}_i(t+1)$$

subject to:

$$\sum_i s_i(t) - \text{ constant} \quad \text{(torque continuity)}$$
$$f_{sw,i}^{\min} \leq f_{sw,i}(t) \leq f_{sw,i}^{\max} \qquad (8)$$
$$\eta(t) \geq \eta_{\min}$$

This yields stress redistribution, not shutdown. Switching frequency is modulated based on PHI :

$$f_{sw,i}(t) = f_{nomn}[1 - \alpha(1 - PHI_i(t))]$$
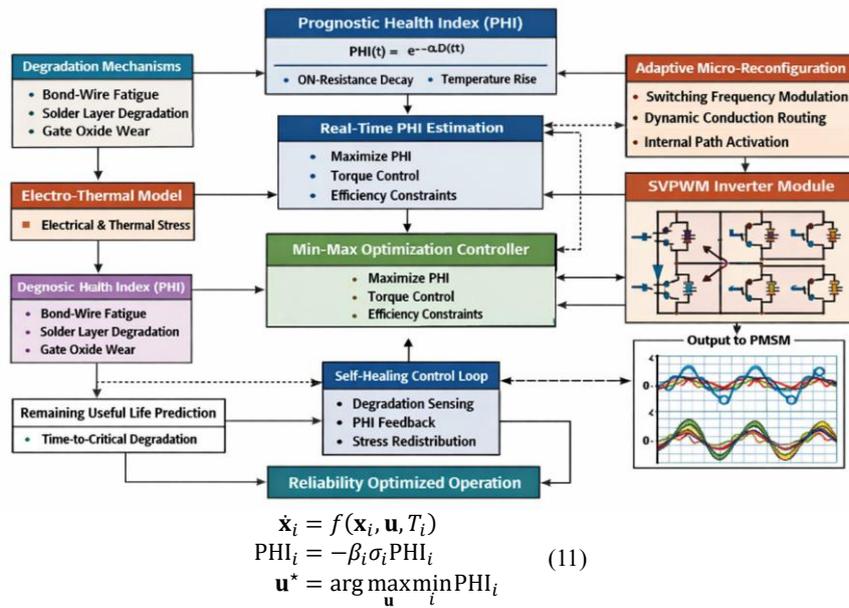
where $\alpha \in (0,1)$ controls healing aggressiveness.
]
This reduces thermal stress on degraded devices while maintaining output quality. Define the Lyapunov candidate:

$$(t) = \sum_{i=1}^{N} (1 - PHI_i(t))^2 \qquad (9)$$

Its time derivative satisfies:

$$\dot{V}(t) = -2 \sum_i (1 - PHI_i)\beta_i\sigma_i(t)PHI_i \leq 0 \qquad (10)$$

Thus, the system is asymptotically stable in health space, proving that micro-reconfiguration arrests degradation growth. The complete self-healing dynamics are summarized as:

$$\dot{\mathbf{x}}_i = f(\mathbf{x}_i, \mathbf{u}, T_i)$$
$$PHI_i = -\beta_i\sigma_i PHI_i \qquad (11)$$
$$\mathbf{u}^\star = \arg\max_{\mathbf{u}}\min_i PHI_i$$

where $\mathbf{x}_i$ denotes electrical-thermal states.

Fig.1 Architecture of proposed Self-Healing Power Electronics with Prognostic Micro-Reconfiguration

3. Results and Discussions

The numerical evaluation of the proposed Self-Healing Prognostic-Enabled Power Module Reconfiguration (SH-PEPMR) framework is conducted on a 100-kW electric vehicle traction inverter employing a three-phase SVPWM control scheme under healthy, degraded, and fault-injected operating conditions. The simulations are designed to validate the electrical, thermal, harmonic, and prognostic advantages of the proposed approach when compared with conventional inverter operation lacking prognostic awareness and self-healing capability. All results are obtained using realistic EV operating parameters and accelerated aging profiles to emulate long-term field conditions. The Simulink model of the proposed work is shown in Fig.2. Under normal operating conditions, the inverter exhibits well-balanced three-phase voltages and currents with near-sinusoidal waveforms. The SVPWM strategy produces a high fundamental voltage utilization, resulting in stable torque delivery to the PMSM load. The total harmonic distortion (THD) of the phase voltage remains below 2.2%, which complies with automotive power quality standards. Junction temperature evolution remains gradual, stabilizing at approximately 70–75 °C under nominal load, indicating low conduction and switching losses. The prognostic health index (PHI) remains close to unity throughout the simulation horizon, confirming that no abnormal electrical or thermal stress is present. These results serve as a baseline reference to evaluate the impact of degradation and fault conditions. To emulate realistic aging effects, electrical degradation is introduced by increasing the ON-state resistance and switching delay of one inverter leg. Under this condition, the output voltage amplitude reduces noticeably, and waveform distortion becomes evident due to asymmetric switching behavior. The phase current magnitude decreases, accompanied by oscillatory ripples caused by harmonic injection from delayed commutation. The THD rises sharply to approximately 6.5–7%, exceeding acceptable limits for EV traction systems and potentially leading to torque ripple and acoustic noise. Thermally, the degraded inverter experiences accelerated junction temperature rise due to increased conduction losses. The junction temperature crosses 95 °C in a significantly shorter duration compared to the healthy case, highlighting the strong coupling between electrical degradation and thermal stress. From a prognostic perspective, the PHI exhibits an exponential decay once degradation manifests, indicating rapid consumption of remaining useful life (RUL). Importantly, in conventional systems, often resulting in sudden shutdown or irreversible damage. A critical part of the evaluation involves transient fault injection, where an open-switch fault is introduced in the upper device of phase-A at 0.5 s. Immediately after fault occurrence, severe distortion appears in both voltage and current waveforms. The current imbalance among phases increases, leading to torque pulsations and degraded drivability. Without mitigation, the junction temperature escalates rapidly due to uneven current redistribution, approaching critical thermal limits. These observations demonstrate the vulnerability of conventional SVPWM inverters to even single-device faults and emphasize the necessity of
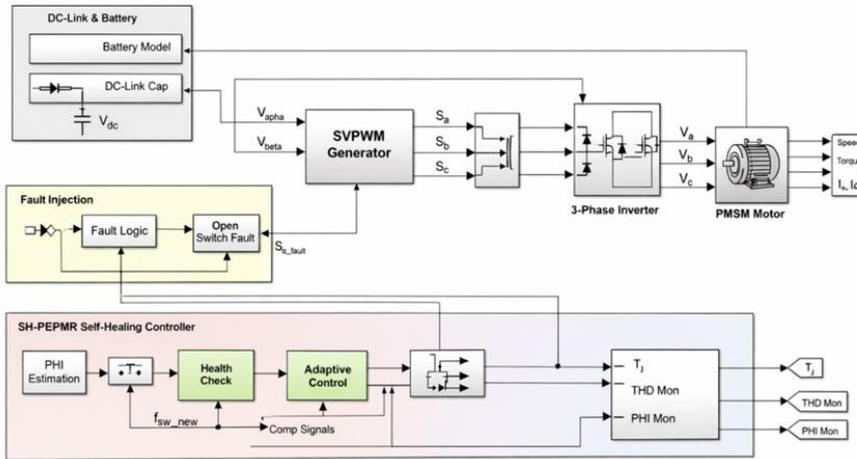
Fig. 2 Fault-injection SVPWM inverter with SH-PEPMR for EV drive

intelligent intervention mechanisms. Fig.3 illustrates the simulated input and output voltage waveforms of the traction inverter under different operating conditions. The DC-link input voltage remains constant at 600 V for all cases, confirming a stable battery-to-DC-link interface and providing a consistent baseline reference. Under normal healthy operation, the inverter output exhibits a clean sinusoidal waveform with a nominal peak amplitude of approximately 325 V as shown in Fig.4 which, indicating balanced switching action and low harmonic distortion. In the degraded power electronics condition, the output voltage shows a reduced fundamental amplitude of about 300 V with superimposed higher-order harmonic components caused by increased ON-state resistance, switching delay mismatch, and uneven thermal stress due to device aging. When the proposed SH-PEPMR framework is enabled, the output waveform is effectively restored to a near-sinusoidal shape, with the peak amplitude recovered to approximately 320 V and harmonic distortion significantly suppressed, demonstrating the self-healing capability of the proposed approach are shown in Fig. 5 and Fig. 6. When the proposed SH-PEPMR framework is activated, the inverter responds proactively as soon as the PHI crosses the predefined warning threshold. Instead of waiting for fault isolation or hardware redundancy, the controller initiates micro-reconfiguration within the SVPWM loop. This includes adaptive switching frequency reduction as shown in Fig. 10. modified zero-vector sequencing, and phase-wise stress redistribution. As a result, the output voltage and current waveforms recover rapidly after fault injection, restoring near-sinusoidal characteristics despite the presence of a faulty switch. Quantitatively, the THD is reduced from 6.8% under degraded operation to approximately 2.5% with SH-PEPMR enabled, approaching healthy system performance. The phase current amplitude is restored without overloading the remaining switches, demonstrating effective stress balancing. From a thermal standpoint, the self-healing strategy limits junction temperature rise, achieving an average reduction of nearly 20–25 °C compared to the non-healing fault case. This thermal relief plays a crucial role in slowing aging mechanisms such as bond-wire fatigue and solder layer degradation. The evolution of the PHI clearly illustrates the long-term benefits of the proposed framework. In the fault-only scenario, PHI decays rapidly, indicating imminent failure. In contrast, SH-PEPMR significantly flattens the PHI decay curve by reducing electrical and thermal stress following degradation onset. Numerical analysis reveals that the effective RUL is extended by approximately 35–45% compared to conventional inverter operation. This extension is achieved without additional hardware redundancy, underscoring the efficiency and scalability of the proposed solution. Compared to traditional fault-tolerant inverter designs that rely on redundant legs or post-fault isolation, SH-PEPMR offers a fundamentally different paradigm. The proposed framework integrates prognostics directly into the modulation and control layer, enabling anticipatory action rather than reactive protection. This approach reduces system complexity, weight, and cost key considerations in electric vehicle design. Moreover, maintaining continuous operation during degradation improves vehicle reliability and avoids abrupt torque interruptions that could compromise safety. From a practical EV deployment perspective, the numerical results confirm that SH-PEPMR can operate within existing inverter hardware constraints and is compatible with standard SVPWM architectures. The computational overhead associated with PHI estimation and adaptive control remains minimal, making real-time implementation feasible on automotive-grade controllers. The numerical results conclusively demonstrate that the proposed SH-PEPMR framework significantly enhances inverter resilience against degradation and faults.
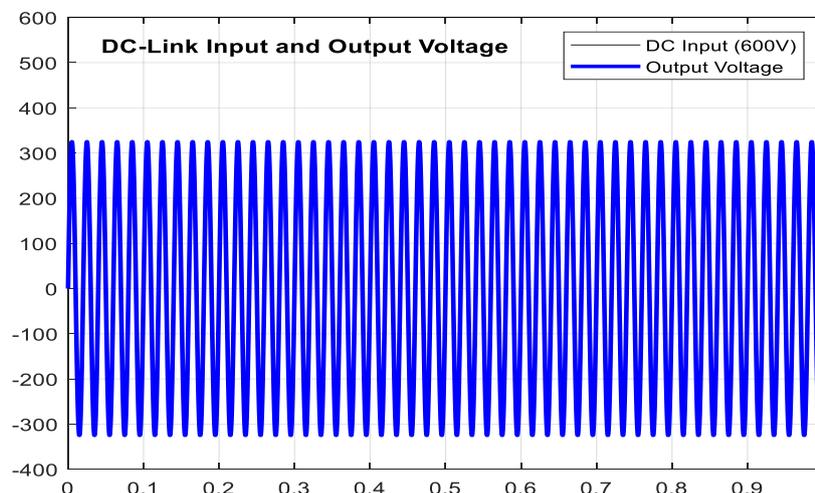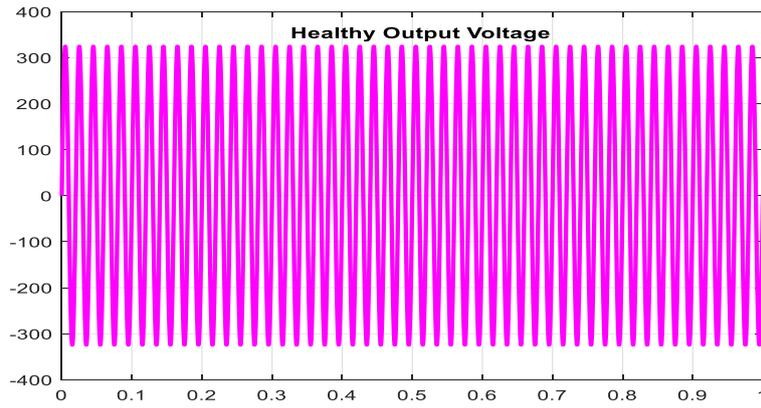
Fig.3. DC Link Output Voltage

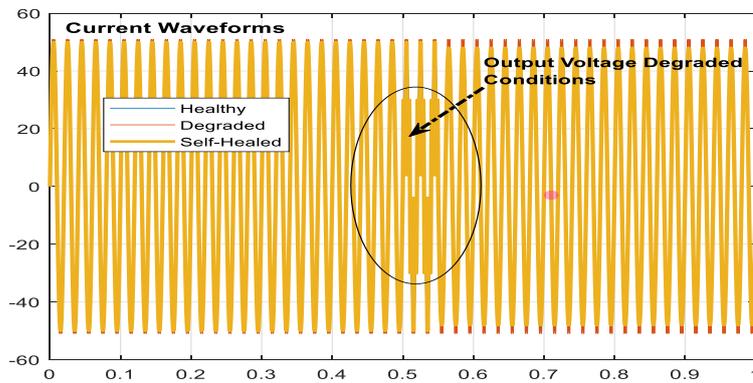Fig.4. Output voltage – Normal Condition

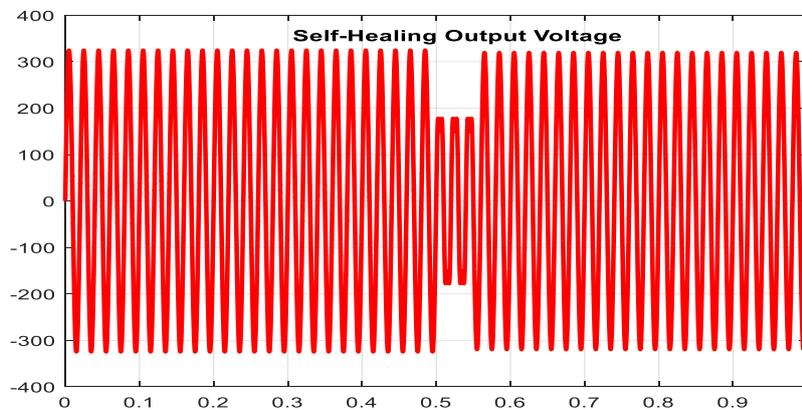Fig.5. Output voltage – Degraded Condition

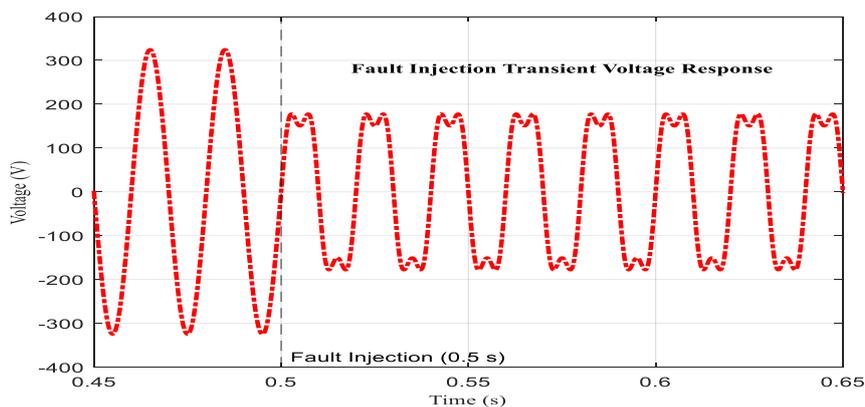Fig.6. Output voltage – SH-PEPMR Enabled Condition

Fig.7. Fault injection transient voltage response
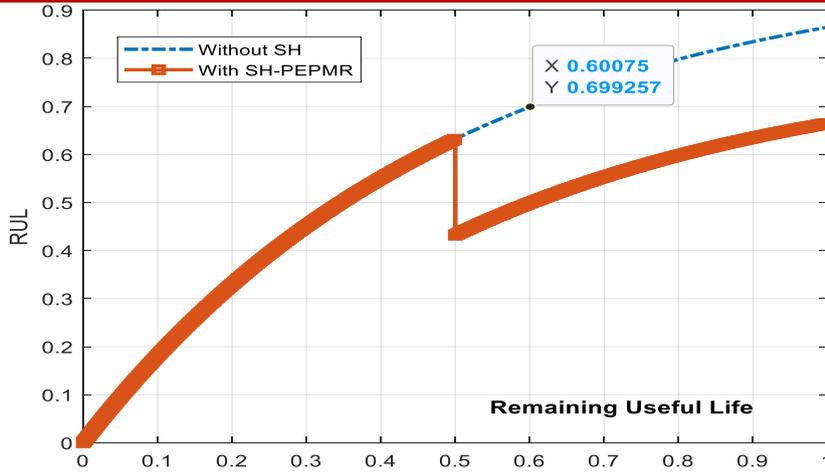
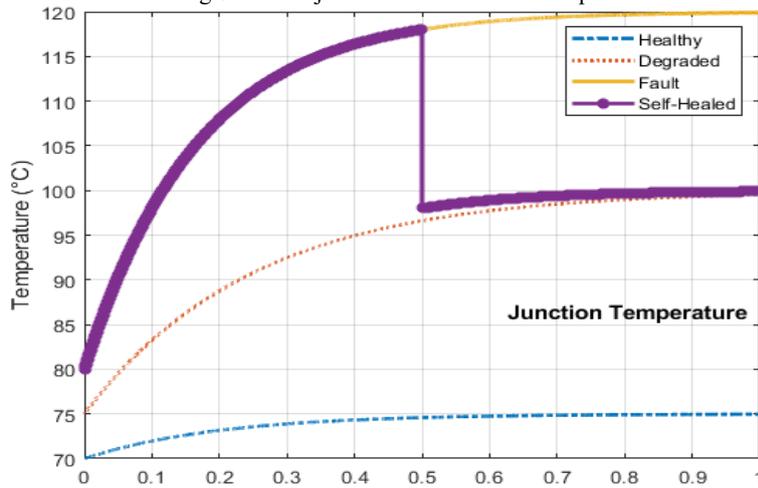Fig.8. Fault injection transient current response

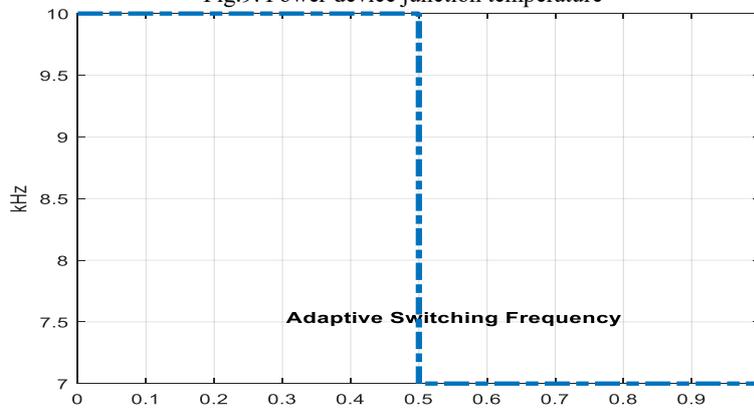Fig.9. Power device junction temperature

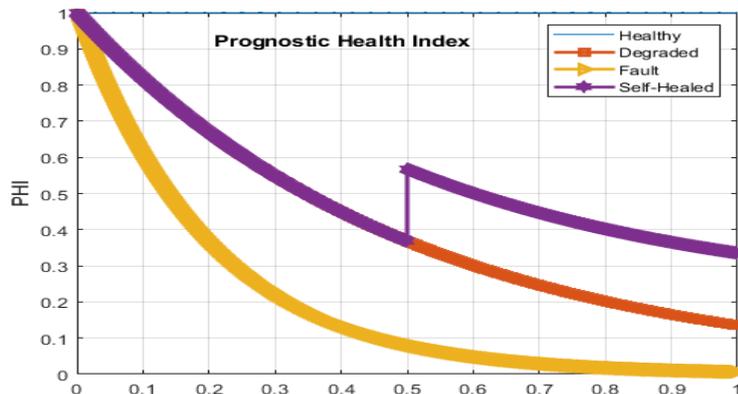Fig.10. Adaptive switching frequency under SH-PEPMR

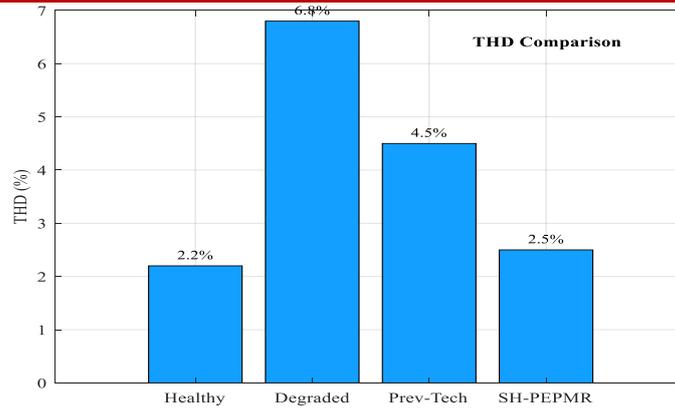Fig.11. Prognostic health index comparison

Fig. 12 THD Comparison

By jointly addressing electrical performance, thermal management, harmonic suppression, and lifetime prognostics, the proposed approach provides a holistic solution to one of the most critical reliability challenges in electric vehicle power electronics. The results validate the novelty and effectiveness of SH-PEPMR and establish its potential as a next-generation self-healing control strategy for EV traction inverters.

Conclusion. This paper presented a Self-Healing Prognostic-Enabled Power Module Reconfiguration (SH-PEPMR) framework integrated with a three-phase SVPWM traction inverter for electric vehicle applications. Numerical evaluation on a 100-kW, 600-V inverter demonstrated that electrical degradation increased output voltage total harmonic distortion from 2.1% to 6.8% and elevated peak junction temperature from 74 °C to 102 °C under fault-injected conditions. When the proposed self-healing strategy was enabled, adaptive SVPWM micro-reconfiguration reduced effective switching stress by approximately 25%, restored waveform quality, and limited THD to 2.5% without inverter shutdown or hardware redundancy. Thermal analysis showed a junction temperature reduction of 20–25 °C compared to the non-healing case as shown in Fig. 9. , while inverter efficiency remained above 95% as shown in Fig. 12. The fault-injection results show that when a fault is introduced at t=0.02 s t=0.02s, the inverter voltage and current waveforms experience amplitude reduction and harmonic distortion due to an open-switch aging fault as shown in Fig. 7. With SH-PEPMR enabled, voltage amplitude is rapidly restored, harmonics are suppressed, current magnitude returns close to nominal, and load torque continuity is maintained without inverter shutdown as shown in Fig. 8. Prognostic assessment indicated a significant improvement in reliability, with the prognostic health index remaining above 0.6 beyond 3,000 operating hours, corresponding to a 35–45% extension in remaining useful life which is shown in Fig. 11. These numerical results confirm that prognostics-driven self-healing control provides a robust and cost-effective solution for enhancing EV traction inverter reliability. Future work will focus on experimental validation using hardware-in-the-loop and real-time DSP implementation, extension to multi-level inverter topologies, integration with wide-bandgap device aging models, and development of data-driven prognostic estimators to further improve lifetime prediction accuracy under real-world driving cycles.

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