International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

# Switching-Leg Redundancy in Power-Electronic Converters: Topologies, Strategies, and Emerging Directions

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**Abstract**

Switching-leg redundancy has become a key design philosophy for modern power-electronic converters, boosting reliability, fault resilience and uninterrupted service. This survey consolidates recent advances in redundant-leg concepts across multi-level inverters, modular multilevel converters (MMCs) and power-electronic building blocks (PEBBs). Redundancy schemes are reviewed from device to full-converter scale, alongside fault-detection, diagnostic and reliability-assessment methods, plus adaptive-control techniques. Results show leg-level redundancy offers the best cost-to-performance compromise relative to device- or module-level options. Contemporary fault-tolerant multi-level inverter configurations markedly raise system dependability; several render a converter immune to both single- and multi-switch faults. AI-driven diagnostics routinely exceed 95% accuracy under varied conditions. The review also highlights self-healing power architectures and reconfigurable topologies that autonomously restore operation with no human input.

**Keywords:** switching-leg redundancy, fault resilience, power-electronic converters, multi-level inverters, reliability analysis, fault diagnostics, modular systems

## 1. Introduction

Critical domains—aviation, medical instrumentation, industrial automation and renewable-energy grids—demand power converters that remain operational despite internal failures , . Fault tolerance denotes a system’s capability to function correctly when one or more elements malfunction . In power electronics the principal route to fault tolerance is redundancy, i.e., pre-provisioned backup hardware or pathways that immediately assume the workload when a primary element fails.

Unlike part-level redundancy that duplicates individual semiconductor devices, switching-leg redundancy addresses an entire leg of a converter bridge , . This strategy has proved especially valuable in high-power equipment, where downtime can cause large financial losses or create safety hazards. Implementations range from simple parallel legs to sophisticated modular assemblies with intelligent reconfiguration . Key technical hurdles include rapid fault detection, accurate fault isolation, balanced load redistribution and seamless mode-switching without degrading performance.

Wide-band-gap semiconductors and advanced digital control have opened new opportunities for economical, efficient redundant systems . Moreover, AI and machine-learning algorithms now enable predictive diagnostics and maintenance, pushing converter dependability well beyond traditional thresholds.

## 2. Fundamentals of Fault Tolerance in Power Electronics

### A. Redundancy Categories

Hardware redundancy—physical replication of critical components—remains the most prevalent route to tolerate faults. It appears at three principal granularities:

- **Device-level**: extra switches, capacitors or sensors inside one bridge-leg.
- **Leg-level**: entire additional legs connected so that any failed leg can be bypassed.
- **Converter-level**: duplicate full converters in parallel or N+1 arrangements.

Complementary forms include:

- **Time redundancy**—performing the same computation or switching action multiple times to detect transient errors.
- **Information redundancy**—embedding parity bits or checksums into control or communication signals.
- **Software redundancy**—adaptive algorithms that identify and mask abnormal behaviour without extra hardware.

### B. Passive vs. Active Approaches

**Passive tolerance** masks faults through built-in redundancy and voting logic (e.g., triple-modular redundancy) without explicitly identifying the defect . **Active tolerance** detects, localises and reconfigures around a fault in real time, typically with extra sensors and control logic . Although active schemes are more complex, they economise hardware and supply valuable diagnostic data.

## 3. Switching-Leg Redundancy Architectures

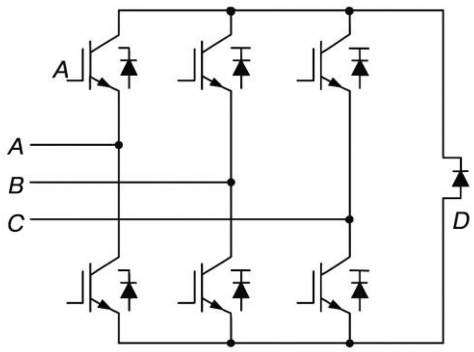
### A. Device-Level Redundancy

Here multiple semiconductor devices share current within one leg . Parallel devices carry the load jointly; if one opens, the remainder sustain the current but at higher stress. Series-connected devices, though rarer, help block voltage when a short circuit occurs . Equal current- or voltage-sharing circuitry is vital to avoid overstress.

### B. Leg-Level Redundancy

Leg-level redundancy offers the most attractive trade-off between hardware cost and reliability. The common four-leg topology adds a spare leg to a standard three-phase bridge, ready to replace any faulty phase leg.

Figure 1: Leg redundancy architecture with a redundant fourth leg for fault-tolerant power converters




The redundant fourth leg configuration represents a common implementation where a three-phase converter is equipped with an additional switching leg that can substitute for any failed main leg[15]. This configuration provides several advantages:

- Cost-effectiveness: Only one additional leg is required to protect against any single leg failure
- Simplified control: The redundant leg can use the same control strategy as the failed leg
- Minimal impact on efficiency: The redundant leg only operates when needed, avoiding continuous losses.

Advanced leg-level redundancy implementations include reconfigurable leg architectures where multiple redundant legs can be dynamically allocated to replace failed components[18]. These systems offer higher flexibility but require more sophisticated control algorithms and switching matrices.

Benefits include:

- **Low incremental cost**—only one extra leg protects all three phases.
- **Unified control**—the spare leg uses the same modulation as the failed leg.
- **Efficiency retention**—the redundant leg is usually idle, avoiding extra losses.

Advanced designs employ multiple spares and matrix switches so that any leg (or even half-bridge) can be re-allocated on the fly .

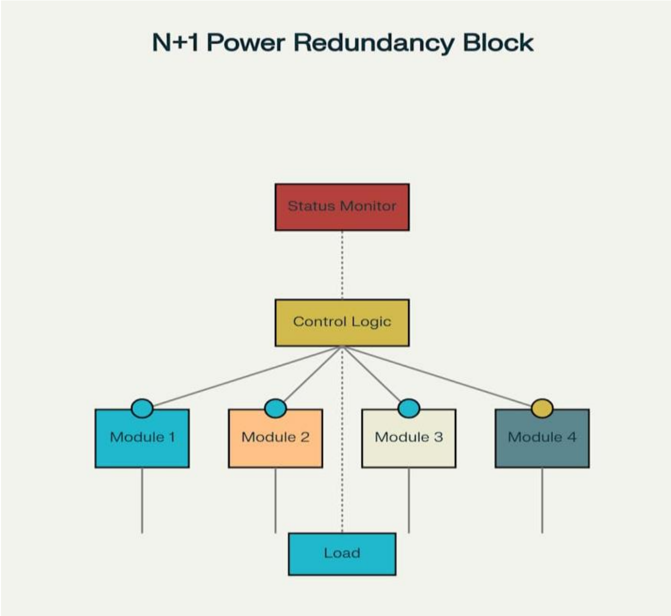
C. Module-Level Redundancy

Modular multilevel converters and cascaded H-bridge inverters naturally suit **sub-module redundancy** –. An N+1 policy—one spare for every N working sub-modules—allows a faulty unit to be bypassed with negligible performance drop . Graceful degradation enables continued operation, albeit sometimes at derated voltage.

D. Converter-Level Redundancy

Full-converter redundancy parallels or serialises complete power stages . Data-centre supplies often adopt an N+1 policy with hot-swap capability . Load-sharing controls distribute current during normal service; surviving converters automatically pick up the slack when one module fails.

Figure 2: N+1 redundancy configuration showing four power modules with Module 4 as backup

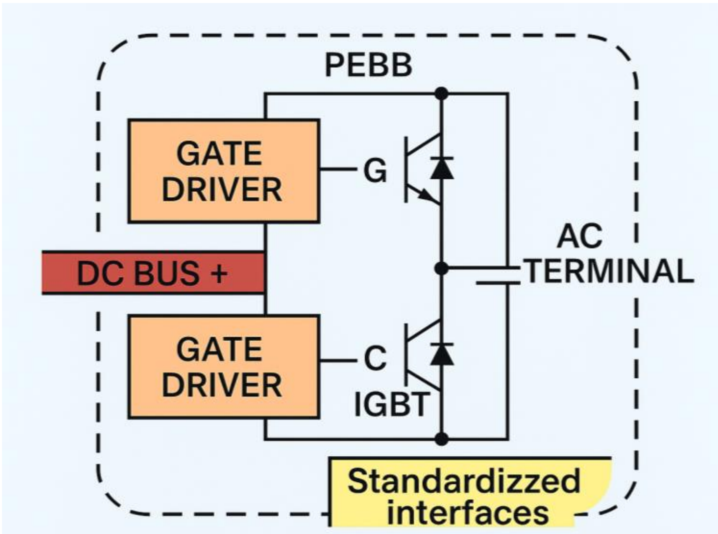



## 4. Power-Electronic Building Blocks (PEBBs)

A. Architecture and Standardization

The PEBB initiative, first promoted by the U.S. Office of Naval Research, pursues plug-and-play power-conversion bricks with uniform electrical, thermal and control interfaces.

Figure 3: Power Electronic Building Block (PEBB) standardized structure for modular systems




Salient traits include:

- **Commonality**—one footprint suitable for multiple converter roles.
- **Scalability**—larger ratings obtained by paralleling blocks.
- **Intrinsic redundancy**—faulty blocks can be isolated and swapped quickly.
- **Maintainability**—modularity simplifies upgrades and repairs , .

B. Redundant PEBB Operation

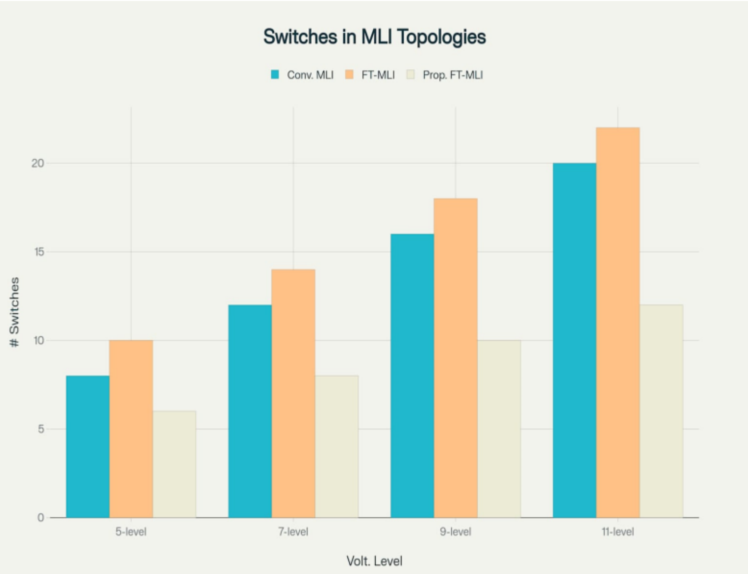
PEBB clusters may run in *stand-by*—where spares are cold until failure—or *power-sharing* mode that spreads load among all bricks . Reliability can be enhanced by reserving one or more bricks, or by operating all bricks below full rating to tolerate additional failures.

## 5. Multilevel-Converter Fault Tolerance

### A. Fault-Tolerant Topologies

Multilevel inverters inherently provide extra switching states, making reconfiguration straightforward , . Cascaded H-bridge arrays can bypass a single faulty cell and retune modulation to hold the output voltage . Neutral-point-clamped and active-NPC converters exploit alternative conduction paths to survive single- or double-switch defects.

Figure 4: Comparison of switch requirements across different multilevel inverter topologies




### B. Redundant Switching Cells

Instead of full sub-module spares, some designs add a small number of redundant switching cells that engage only after a fault , . FPGA-based controllers detect the anomaly, actuate SPDT relays and restore operation within microseconds . Flying-capacitor inverters, thanks to multiple capacitor charge routes, can also self-reconfigure after a device failure , .

## 6. Reliability Assessment and Diagnostic Advances

Classical mean-time-to-failure (MTTF) calculations are being augmented with Markov models, wear-out data and real-time health indicators –. AI classifiers now identify open- or short-circuit faults from tiny waveform deviations, reducing false positives and maintenance cost –. Optimisation frameworks even size the ideal redundancy level for a target availability and budget.

## 7. Conclusion

Switching-leg redundancy has evolved from rudimentary parallel legs to intelligent, modular, self-healing networks. Among available schemes, leg-level redundancy supplies the most favourable cost-versusresilience balance. MMCs extend this flexibility through inherent sub-module spares, while AI-enhanced diagnostics further elevate reliability. Anticipated research avenues include predictive maintenance, cyber-secure redundancy control and bio-inspired self-repair mechanisms. Continuous innovation will be indispensable for upcoming electric-aviation, renewable and telecom applications that cannot tolerate power interruptions.

**References**

1. Mahafzah KA, Obeidat MA, Mansour AM, Al-Shetwi AQ, Ustun TS. "Artificial-Intelligence-Based Open-Circuit Fault Diagnosis in VSI-Fed PMSMs and a Novel Fault Recovery Method, Sustainability Method," Sustainability, 2022, vol. 14, pp. 24.
2. C. Chen, Y. Chen, X. Yang, S. Gao and B. Zhang, "Inverter Fault Detection Method Based on Park Transformation and K-means Clustering Algorithm," 2021 CAA Symposium on Fault Detection, Supervision, and Safety for Technical Processes (SAFEPROCESS), Chengdu, China, 2021, pp. 1-6.
3. S. Wang, A. M. Massoud and B. W. Williams, "A T-Type Modular Multilevel Converter," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 1, pp. 843-857, Feb. 2021
4. Rehman, H.; Tariq, M.; Sarwar, A.; Alhosaini, W.; Hossain, M.A.; Batiyah, S.M., "Single-Phase Fault Tolerant Multilevel Inverter Topologies—Comprehensive Review and Novel Comparative Factors," Energies, 2022, vol. 15, pp. 9319.
5. Rehman, H.; Tariq, M.; Sarwar, A.; Alhosaini, W.; Hossain, M.A.; Batiyah, S.M. Single-Phase Fault Tolerant Multilevel Inverters Topologies. Encyclopedia. Available online: https://encyclopedia.pub/entry/38774 (accessed on 04 July 2025).
6. R. Khanaki, G. R. Walker, G. F. Ledwich and M. A. H. Broadmeadow, "Impact of Inverter Distribution and Redundancy on Reliability of Battery-Integrated-Converter Systems," 2019 29th Australasian Universities Power Engineering Conference (AUPEC), Nadi, Fiji, 2019, pp. 1-6
7. Nguyen, M.H.; Kwak, S. "Enhance Reliability of Semiconductor Devices in Power Converters," Electronics, 2020, vol. 9, pp. 2068.
8. Dr. K. Vasudevan, "Applications of Artificial Intelligence in Power Electronics and Drives Systems: A Comprehensive Review," Journal of Power Electronics (JPE), 2023, vol. 1, pp. 1–14.
9. Deye Jiang, Shuting Huang, Juan Guo, "Fault diagnosis of power electronic circuits using optimized BP neural networks," MATEC Web of Conf., vol. 399, 2024, pp. 16.
10. A. Sangwongwanich and F. Blaabjerg, "Reliability Assessment of Fault-Tolerant Power Converters including Wear-Out Failure," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), Houston, TX, USA, 2022, pp. 300-306
11. Dhananjay Kumar, Rajesh Kumar Nema, Sushma Gupta, "Development of a novel fault-tolerant reduced device count T-type multilevel inverter topology," International Journal of Electrical Power & Energy Systems, vol.132, 2021, pp. 107185.
12. R. Emamalipour and J. Lam, "Built-in Circuit Redundancy and Fault-tolerant Operation of a New Multi-Mode Hybrid String Inverter/Rectifier Leg," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), Phoenix, AZ, USA, 2021, pp. 626-631
13. Y. Song and B. Wang, "Survey on Reliability of Power Electronic Systems," in IEEE Transactions on Power Electronics, vol. 28, no. 1, 2013, pp. 591-604.

14. Shuai Xu, Hao Chen hchen@cumt.edu.cn, Feng Dong, “Converter-level reliability prediction and analysis in switched reluctance motor drive,” IET Electric Power Applications, vol. 14(3), 2022, pp. 500-511.
15. Sharayu Raut, Sonal Pandey, Vaishnavi Bhonde, Switi Rangari, Soumya Hakke, Bhushan Warjurkar, Ruchi Pajai, “Reliability improvement in Z-source inverter with redundancy,” International Journal of Advance Research, Ideas and Innovations in Technology, 2021, vol. 7(3).
16. B. N. Reddy, K. B. Shetty, R. Jalli, K. Akhila, K. S. Prudhviraj and V. Jagan, "Reduced Redundant Power Processing in DC-DC Converters: A Comprehensive Review," 2024 3rd International conference on Power Electronics and IoT Applications in Renewable Energy and its Control (PARC), Mathura, India, 2024, pp. 361-365
17. Kumar, D., Nema, R. K., Gupta, S., Nema, S., & Dewangan, N. K., “A New Fault-Tolerant Multilevel Inverter Topology with Enhanced Reliability for PV Application,” Arabian Journal for Science and Engineering, 2022, vol. 47(11), pp. 14841-14858.
18. Narender Reddy Kedika, Srinivasan Pradabane, “Fault-tolerant multi-level inverter topologies for open-end winding induction motor drive,” International Transactions on Electrical Energy Systems, 2020.
19. Nor Shahida Hasan, Norzanah Rosmin, Dygku. Asmanissa Awg. Osman, Aede Hatib Musta’amal@Jamal, “Reviews on multilevel converter and modulation techniques,” Renewable and Sustainable Energy Reviews, Vol. 80, 2017, pp.163-174
20. T. Heath, P. R. Green, M. Barnes and D. Kong, "Design, construction and testing of a modular multilevel converter with a distributed control architecture," 15th IET International Conference on AC and DC Power Transmission (ACDC 2019), Coventry, UK, 2019, pp. 1-6
21. T. -Y. Nam, D. -I. Cho, W. -S. Moon, J. -C. Kim and J. -W. Shin, "MVDC MMC Redundancy Design Based on Availability and Cost Considering Submodule Degradation," in IEEE Access, vol. 11, 2023, pp. 101890-101903.
22. Henry Zhang, Wei Chen, “Low Voltage, High Current DC/DC Power Supply with Load Sharing and Redundancy,” Analog Devices, 2022.
23. K Xing "Power Electronics Building Blocks - VTechWorks." Virginia Tech, 2024.
24. T. Ericsen, N. Hingorani and Y. Khersonsky, "PEBB - Power Electronics Building Blocks from Concept to Reality," 2006 Record of Conference Papers - IEEE Industry Applications Society 53rd Annual Petroleum and Chemical Industry Conference, Philadelphia, PA, USA, 2006, pp. 1-7.
25. Z. Chen, H. S. Rizi, C. Chen, P. Liu, R. Yu and A. Q. Huang, "An 800V/300 kW, 44 kW/L Air-Cooled SiC Power Electronics Building Block (PEBB)," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, Toronto, ON, Canada, 2021, pp. 1-6.
26. Abarzadeh, M., Peyghami, S., Al-Haddad, K., & Blaabjerg, “Power electronics building blocks: Control and applications,” Control of Power Electronic Converters and Systems, Vol. 4, 2024, pp. 155-180.
27. "10 kV, 120 A SiC MOSFET Modules for a Power Electronics Building Block (PEBB)." CPES Virginia Tech, 2015.
28. Deshpande, Amol & Chen, Yingzhuo & Narayanasamy, Balaji & Yuan, Zhao & Luo, Fang, “Modular Three-level T-type Power Electronics Building Block for Aircraft Electric-Propulsion Drives”, AIAA Propulsion and Energy 2020 Forum, 2020.

29. Kumar, D., Nema R. K., & Gupta S., “Investigation of fault-tolerant capabilities of some recent multilevel inverter topologies,” International Journal of Electronics, vol. 108(11), 2021, 1957–1976.
30. Jih-Sheng Lai and Fang Zheng Peng, "Multilevel converters-a new breed of power converters," in IEEE Transactions on Industry Applications, vol. 32, no. 3, 1996, pp. 509-517.
31. Zhang, L, Waite, MJ and Chong, B, “Three-phase four-leg flying-capacitor multi-level inverter-based active power filter for unbalanced current operation”, IET Power Electronics, vol. 6, no. 1, 2013, pp. 153-163.
32. Wang, Y., Zhang, H., Lai, J. et al. “Extendable space-type switched-capacitor multilevel inverter with fault-tolerant capability,” Journal of Power Electron, vol. 22, 2022, pp. 923–934.
33. "Modular-Multilevel-Converters Family - A Survey." CPES Virginia Tech, 2013.
34. J. Huang, T. Wu and K. Wang, "Modular Multi-level Converter Control Method Based on CPS - PWM," 2017 International Conference on Computer Systems, Electronics and Control (ICCSEC), Dalian, China, 2017, pp. 1528-153.
35. Sang-Jung Lee, KiRyong Kim, Dae-Wook Kang, Jaesik Kang, Jee-Hoon Jung, “Phase-leg power equalization method of modular multilevel converter with APOD strategy under unbalanced fault condition,” International Journal of Electrical Power & Energy Systems, Vol. 153, 2023, pp. 109176.
36. S. V. Dhople, A. Davoudi, A. D. Domínguez-García and P. L. Chapman, "A Unified Approach to Reliability Assessment of Multiphase DC–DC Converters in Photovoltaic Energy Conversion Systems," in IEEE Transactions on Power Electronics, vol. 27, no. 2, 2012, pp. 739-751.
37. A. A. Tawfiq, M. Osama abed el-Raouf, A. A. El-Gawad, M. A. Farahat, “Reliability assessment for electrical power generation system based on advanced Markov process combined with blocks diagram,” International Journal of Electrical and Computer Engineering (IJECE), vol. 11, no. 5, 2021, pp. 3647-3659.
38. A. L. Sweet, Y. Lam and J. Bott, "Computation of Mean Time to Failure for a System with Simple Redundancy," in IEEE Transactions on Reliability, vol. 35, no. 5, 1986, pp. 539-540.
39. James Li, “Reliability Calculation for Dormant k-out-of-n Systems with Periodic Maintenance,” International Journal of Mathematical, Engineering and Management Sciences, vol. 1, no. 2, 2016, pp. 68–76.
40. Radmehr, M. and Mojibi, M. “Reliability Assessment and Thermal Consideration of a Step-down DC/DC Converter,” International Journal of Industrial Electronics Control and Optimization, vol. 2, no. 3, 2019, pp. 247-256.
41. Seolhee Cho and Ignacio E. Grossmann, “An Optimization Model for the Design and Operation of Reliable Power Generation Systems,” International Symposium on Process Systems Engineering, Kyoto, Japan.
42. Mohammad Mojibi, Mehdi Radmehr, “Reliability evaluation of buck converter based on thermal analysis,” Journal of Microelectronics, Electronics Components and Material, vol. 48, no. 4, 2018.
43. Hasan Mohammadi, Afshin Goldani, Ali Goudarzi Amlashi, Reza Moradpour, “Reliability Evaluation of a Buck Converter Based on Thermal Analysis,” Specialty Journal of Electronic and Computer Sciences, vol. 4, no. 3, 2018, pp. 1-11.
44. Ran Han, Rongjie Wang, Guangmiao Zeng, “Fault Diagnosis Method of Power Electronic Converter Based on Broad Learning,” Complexity, 2020.

45. Rachna Vaish, U.D. Dwivedi, Saurabh Tewari, S.M. Tripathi, "Machine learning applications in power system fault diagnosis: Research advancements and perspectives," Engineering Applications of Artificial Intelligence, vol. 106, 2021, pp. 104504.
46. Hamzah Abdulkhaleq Naji, Rashid Ali Fayadh, Ammar H. Mutlag, "Artificial intelligence-based fault classification for distribution line power cable," AIP Conference Proceeding, 2024.
47. Atanov I.V., Khorolsky V.Y., Shemyakin V.N., Yarosh V.A., "Optimum Redundancy of an Independent Power Supply System and Comparative Analysis of Its Solutions," Russian Electrical Engineering, vol. 90. No. 3. 2019, pp. 187-190.
48. Meseret Nasir Reshid, Mohd Amin Abd Majid and Masdi Muhammad, "Evaluation of Redundancy for Power Generating Unit in a Cogeneration Power Plant." MATEC Web of Conferences, vol. 13, 2014.