Thesis Title **Reliability Analysis and Improvement of Multilevel Converters**

Thesis Abstract

Power converter based variable-frequency drive is much more energy efficient than the traditional fixed-speed motor. It can reduce the drive system operating cost significantly. However, the reliability of a power converter is a big concern for both manufacturers and end users as high failure rate will incur additional repairing cost. In high power drive applications, multilevel converters which utilize mature power semiconductors are superior to conventional two-level converters in efficiency and power quality. But the reliability problem of multilevel converters is even more serious due to a large number of vulnerable power semiconductors used. Therefore, reliability analysis and improvement of multilevel converters are indispensable for popularization and application of variable-frequency drive.

Traditionally, there are two branches in reliability modeling: failure rate methods and Physics-of-Failure methods. The data-driven statistical failure rate methods are widely used in power system for their simplicity and effectiveness. There is a crucial assumption that the failure rate is constant during equipment useful lifetime. The assumption is reasonable in power system where equipment is operating in a relatively stable condition and under good maintenances. However, due to the harsh environment and variable load in drive systems, the equipment stress change severely and rapidly. It makes the crucial constant failure assumption questionable.

A load-dependent failure rate method is proposed to model the variable load. In the proposed method, the failure rate can be represented as an equivalent constant value or a time-varying function depends on the application. In traditional failure rate methods, the reliability index, Mean Time to Failure (MTTF), is widely used to give a life expectancy. MTTF is the reciprocal of the system failure rate in the condition that the system has a constant failure rate. With a time-varying failure rate, MTTF is almost impossible to calculate in practice. A new reliability index, MTTF consumption is proposed to describe the state of health of a power converter. Multilevel converters with modular design have inherent redundancy which gives them fault-tolerance capability. The network reliability techniques, combinatorics and stochastic process, are used to model the inherent redundancy in multilevel converters. With the aforementioned techniques, the complete and systematic load-dependent failure rate method can be applied to analyze multilevel converter reliability. The Monte Carlo simulation is used to verify the reliability results of the load-dependent failure rate method.

On the other hand, the Physics-of-Failure methods which model failure mechanisms draw lots of attention in the power electronics community recently. These methods calculate components lifetime consumption under a mission profile with pre-established life-stress models. The converter system lifetime is determined by the weakest component. The Physics-of-Failure methods give a deterministic lifetime with clear physics-based models. However, multilevel converter redundancy and system-level reliability are hard to model as there is no component lifetime distribution. The randomness of failure and probabilistic property of reliability are lost.

A probabilistic Physics-of-Failure method is developed by including uncertainty of component parameters and life-stress model parameters. An assumption that parameters follow normal distributions is used in the proposed method to simulate the manufacturing process. Component lifetime distribution can be obtained by repetitive Physics-of-Failure analysis or a Monte Carlo simulation. The component reliability function can be extracted by probability distribution fitting. The multilevel converter redundancy and system-level reliability can be modeled by well-established statistical techniques.

This thesis provides reliability analysis methods for power converters and especially, multilevel converters and explores possible measures to improve the reliability and reduce the cost. The thesis has three parts. Part 1 has two chapters with chapter 1 introducing the multilevel converters and its reliability problems, and chapter 2 reviewing reliability modeling history and methods. The second part discusses the two proposed reliability modeling methods with case studies. Improving reliability in component level by switching loss optimization is also presented in this part. The last part draws the conclusions and proposes some future works.

Journal Publications

1. **P. Tu**, S. Yang, and P. Wang, “Reliability and cost based redundancy design for modular multilevel converter,” *IEEE Transactions on Industrial Electronics*, 2018.

2. S. Yin, **P. Tu***, P. Wang, K. J. Tseng, C. Qi, X. Hu, M. Zagrodnik, and R. Simanjorang, "An accurate subcircuit model of sic half-bridge module for switching-loss optimization," *IEEE Transactions on Industry Applications*, 2017.
3. C. Qi, X. Chen, **P. Tu**, and P. Wang, "Cell-by-cell-based finite-control-set model predictive control for a single-phase cascaded h-bridge rectifier," *IEEE Transactions on Power Electronics*, 2018.
4. D. Zhou, **P. Tu**, and Y. Tang, "Multivector model predictive power control of three-phase rectifiers with reduced power ripples under nonideal grid conditions," *IEEE Transactions on Industrial Electronics*, 2018.
5. C. Qi, C. Xiyou, **P. Tu**, and P.Wang, "Deadbeat control for a single-phase cascaded h-bridge rectifier with voltage balancing modulation," *IET Power Electronics*, 2017.
6. C. Qi, **P. Tu**, P. Wang, and M. Zagrodnik, "Predictive current control for multilevel cascaded h-bridge inverters based on a deadbeat solution," *Journal of Power Electronics*, 2017.
7. S. Yin, K. J. Tseng, R. Simanjorang, and **P. Tu**, "Experimental comparison of high-speed gate driver design for 1.2-kv/120-a si igbt and sic mosfet modules," *IET Power Electronics*, 2017.
8. Q. Xu, X. Hu, P. Wang, J. Xiao, **P. Tu**, C. Wen, and M. Y. Lee, "A decentralized dynamic power sharing strategy for hybrid energy storage system in autonomous dc microgrid," *IEEE Transactions on Industrial Electronics*, 2017.
9. C. Dong, H. Jia, Q. Xu, J. Xiao, Y. Xu, **P. Tu**, P. Lin, X. Li, and P. Wang, "Time-delay stability analysis for hybrid energy storage system with hierarchical control in dc microgrids," *IEEE Transactions on Smart Grid*, 2017.
10. C. Qi, **P. Tu**, P. Wang, and M. A. Zagrodnik, "Random nearest level modulation strategy of multilevel cascaded h-bridge inverters," *IET Power Electronics*, 2016.

Conference Publications

1. **P. Tu**, P. Wang, X. Hu, C. Qi, S. Yin, and M. A. Zagrodnik, "Analytical evaluation of igbt turn-on loss with double pulse testing," in Industrial Electronics and Applications (ICIEA), 2016
2. **P. Tu**, S. Yang, P. Wang, Q. Xu, and C. Qi, "Analytical averaged loss model of half-bridge modular multilevel converters," in Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia), 2017
3. **P. Tu**, S. Yin, P.Wang, K. Tseng, C. Qi, X. Hu, M. Zagrodnik, and R. Simanjorang, "An accurate subcircuit model of sic half bridge module for switching loss optimization," in Energy Conversion Congress and Exposition (ECCE), 2016
4. Q. Xu, **P. Tu***, C. Dong, C. Qi, S. Yang, S. Yao, and P. Wang, "Pof based reliability prediction for cascaded h-bridge converter in drive application," in Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia), 2017
5. S. Yang, Y. Tang, **P. Tu**, and P. Wang, "A fault-tolerant operation scheme for a modular multilevel converter with a distributed control architecture," in Energy Conversion Congress and Exposition (ECCE), 2017
6. C. Qi, X. Chen, **P. Tu**, and P. Wang, "Low-complexity two-voltage-based model predictive control for a single-phase cascaded h-bridge inverter," in Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia), 2017
7. P. Lin, C. Zhang, P.Wang, X. Li, J. Xiao, **P. Tu**, and C. F. Hoong, "A global robust output regulation method for grid-connected inverter with lcl

   filter in weak grid condition," in Industrial Electronics and Applications (ICIEA), 2017
8. C. Qi, **P. Tu**, D. Shi, P. Wang, M. A. Zagrodnik, and G. Amit, "An efficient fpga-based implementation of predictive current control algorithms for an indirect matrix converter," in Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), 2016,
9. S. Yin, K. Tseng, **P. Tu**, R. Simanjorang, and A. K. Gupta, "Design considerations and comparison of high-speed gate drivers for si igbt and sic mosfet modules," in Energy Conversion Congress and Exposition (ECCE), 2016