OPERATION AND PROTECTION OF DC SHIPBOARD POWER SYSTEM

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Abstract

Marine vessels integrated with the electrical propulsion have conventionally been based on fixed voltage, fixed-frequency (50/60 Hz) ac generation and distribution system. In recent years, dc power system in the marine vessels has been proposed primarily to take advantage of the fuel-efficient operation which is enabled through the integration of the variable frequency diesel generators. Such emerging dc shipboard power system (SPS) also enables interconnection of the alternative power generation and energy storage technologies which helps in peak shaving of the generators in the event of wide load variation. In spite of the advantages, one of the impediments to the widespread adoption of dc SPS is the lack of comprehensive short-circuit fault management strategies. In such systems, the voltage source converter (VSC) based dc generation system is expected to be chosen as an interface between the generators and the marine loads owing to its improved operational benefits. During the fault, the dc-link the capacitor of the VSC will discharge rapidly, releasing high current. This rapidly rising capacitive discharge current poses a serious challenge in fault detection as the rate of rise and magnitude of the current profile depends on the fault resistance, fault location, and circuit parameters. Moreover, the time required to detect the dc fault current is very low. It is thus required to devise suitable protection algorithm to expedite the process of fault detection and isolation. The power system of such vessel is dominated by a significant number of active loads and a finite number of dc generation sources. As a result, the network configuration is expected to get dynamically altered to fulfill the required generation and load demands to cater for the desired marine mission. Such varying network configurations make the transient responses significantly different from the conventional ac grids and the prospective dc grids and hence making the fault management strategies more challenging. Thus, the modeling and control of the dc generation sources, loading scenarios, and the system operation become an important aspect to effectively understand and analyze the transient responses. The aim of this thesis is to address the modeling and control challenges of the dc SPS and systematically perform transient analysis to devise the protection algorithms to effectively detect short-circuit faults. This thesis considers the platform supply vessel (PSV) emulating the Rolls-Royce UT776 vessel as the target dc SPS. PSV is taken as an example, due to its complex operating scenarios and wider applicability in the marine industry.

The first part of the thesis proposes the real-time transient framework to understand the marine operation with the increased focus on the modeling and control of the dc generation system. Automatic flux regulator (AFR) based dc generation system has been proposed and has been compared in detail with the traditional automatic voltage regulator (AVR) based dc generation system. It is seen that the AFR is easier to implement, does not require bulky $LC-$ filters (hence lower footprint), easier to operate at variable operating speed and has lower

power consumption than the AVR based dc generation system. After the development of dc generation system, the operation of the dc SPS is studied with various contingency scenarios, such as the outage of the generation systems, abrupt load changes, the effect of the energy storage systems and so on, with the objective of operating at fuel-efficient operation. It is concluded that the coordinated treatment of the energy storage sources with the operation of diesel generator operating at optimized speed results in fuel-efficient operation with fuel savings of 19% when compared with the fixed frequency based ac SPS.

After the modeling and operation, this thesis covers systematic transient studies to devise the short-circuit fault detection technique for the target dc PSV. It is seen that the traditional time-domain based fault detection technique is not suitable for such applications as the magnitude and rate of rise of current is limited by varying network conditions of the dc PSV. On the other hand, the rapidly rising fault current is expected to have high-frequency components which could be an effective indicator of the transient condition. With this regard, this thesis considers the short-time Fourier transform (STFT) based quantitative analysis of the high-frequency components in the dc currents for the fault detection in the dc SPS. The operating principles, factors affecting the STFT operation and the sensitivity analysis are also discussed. For the enhanced selectivity, a novel directional protection is also proposed which uses directional zonal interlocking as a directional element and STFT as fault detector. The efficacy of this proposed directional protection is substantiated by confirming against a range of fault impedances initiated at the generator terminals, load terminals, lines and buses of the dc PSV.

The third part of the thesis discusses the fault tolerant dc generation system which is able to restrict the fault current in the event of the external short-circuit faults. The thesis is concluded by discussions and the future work recommendations.

Keywords: DC Generation Systems, DC Power Systems, DC Protection, DC Power System Modeling, DC Fault Studies, DC Transient Analysis, Marine Vessels, Platform Supply Vessels, Directional protection, Shipboard power system.

List of Publications

- **As First Author**
  - ***Refereed Journal Publications:***
    1. **K. Satpathi**, A. Ukil, J. Pou and M. A. Zagrodnik, "Design, Analysis and Comparison of Automatic Flux Regulator with Automatic Voltage Regulator Based Generation System for DC Marine Vessels," *IEEE Trans. Transport. Electrific.*, 2018 (*In Press*).
    2. **K. Satpathi**, Y.M. Yeap, A. Ukil, and N. Geddada, "Short-time fourier transform based transient analysis of VSC interfaced point-to-point DC system," *IEEE Trans. Ind. Electron.*, vol. 65, no. 5, pp. 4080-4091, May 2018.
    3. **K. Satpathi**, A. Ukil, and J. Pou, "Short-circuit protection in DC electric ship propulsion system: Review of existing technologies and future research trends," *IEEE Trans. Transport. Electrific.*, vol. 4, no. 1, pp. 272-291, Mar. 2018.
    4. **K. Satpathi**, V. M. Balijepalli, and A. Ukil, "Modeling and real-time scheduling of DC platform supply vessel for fuel efficient operation," *IEEE Trans. Transport. Electrific.*, vol. 3, no. 3, pp. 762-778, Sep. 2017.

– ***Refereed Conference Publications:***

1. **K. Satpathi**, A. Ukil, S. S. Nag, and J. Pou, "Comparative Analysis of Directional Protection in AC and DC Power Systems," *Innovative Smart Grid Technologies (ISGT)*, Singapore, 2018. (*Accepted*)
2. **K. Satpathi**, A. Ukil, N. Thukral and M. A. Zagrodnik, "Modeling of DC Shipboard Power System," in *Proc. IEEE Int. Conf. on Power Electronics, Drives and Energy Systems (PEDES)*, Trivandrum, India, Dec. 2016.
3. **K. Satpathi** and A. Ukil, "Protection of MVDC Shipboard Power System using Rogowski Coil," in *Proc. IEEE Int. Conf. on Power Electronics, Drives and Energy Systems (PEDES)*, Trivandrum, India, Dec. 2016.
4. **K. Satpathi**, N. Thukral, A. Ukil and M. A. Zagrodnik, "Flux Estimation based DC Bus Voltage Control in Marine DC Power System," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Florence, Italy, Oct. 2016.
5. **K. Satpathi**, N. Thukral, A. Ukil and M. A. Zagrodnik, "Directional Protection Scheme for MVDC Shipboard Power System," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Florence, Italy, Oct. 2016.
6. **K. Satpathi** and A. Ukil, "Protection Strategies for LVDC Distribution System," in *Proc. IEEE PowerTech Conf.*, Eindhoven, Netherlands, Jun. 2015.

- **As Co-Author**

– ***Refereed Journal Publications:***

1. Y. M. Yeap, N. Geddada, **K. Satpathi**, and A. Ukil, "Time and frequency domain fault detection in VSC interfaced experimental DC test system", *IEEE Trans. Ind. Informat.*, 2018 (*In Press*).

– ***Refereed Conference Publications:***

1. A. Ukil, Y. M. Yeap, **K. Satpathi** and N. Geddada, "Fault Identification in AC and DC Systems Using STFT Analysis of High Frequency Components," in *Proc. Innovative Smart Grid Technologies (ISGT)*, Auckland, New Zealand, 2017.
2. S. S. Nag, **K. Satpathi**, A. Ukil, M. A. Zagrodnik and J. Pou, "An Isolated Bipolar DC-DC Converter for Energy Storage Integration in Marine Vessels," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Beijing, China, 2017.
3. D. Francis, Q. Zhengting, **K. Satpathi**, N. Thukral and A. Ukil, "Suitability of Rogowski Coil for DC Shipboard Protection," in *Proc. IEEE TENCON Conf.*, Singapore, Nov. 2016.