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Improved Turn-to-turn Fault Protection for Power Transformers in Power Systems with Inverter-Based Resources

Summary of the Doctoral Dissertation

The dissertation addresses two complex areas of research: improvement of the procedures for the detection of turn-to-turn faults (TTFs) in power transformers and the impact of inverter-based resources (IBRs) on the TTF protection scheme operation. Detecting turn-to-turn faults in power transformers by protection algorithms is challenging since the fault currents observed at transformer terminals are very small. Yet, the demand for dependable TTF protection is very high because of high fault currents inside the shorted turns and the resulting damage consequences. On the other hand, for such sensitive protection, adverse conditions such as transformer inrush currents or CT errors may lead to protection maloperation. Installing more and more IBRs to meet global climate targets increases the share of inverter-based generation in the power system. The fault current characteristics of the IBR infeed are very different compared to the synchronous machine infeed, particularly regarding the negative-sequence current characteristics of the TTF protection schemes.

The literature study on transformer TTF modelling, TTF protection schemes and modelling of IBRs have been conducted. The simulation test power system model with a Modular Multilevel Converter (MMC) for a High Voltage Direct Current (HVDC) link and its appropriate control was developed. The Low-Voltage-Ride-Through (LVRT) control to comply with grid code requirements for reactive positive- and negative-sequence fault current contributions has been adequately implemented and validated.

The HVDC-MMC model was employed to simulate transients with varying degrees of inverter-based infeed and to assess the dependability of the transformer differential protection and four other selected TTF protection schemes. It was observed that the protection schemes based on negative-sequence differential current are, in principle, suitable for detecting TTFs with IBR infeed, but that direction-dependent protection schemes based on negative-sequence current are undependable. It has also been observed that the magnitude of the vectorial sum of the negative-sequence currents at both transformer sides is the same for the synchronous machine and inverter-based infeed, independently of the degree of inverter-based generation and LVRT reactive fast fault current characteristic and current control design.

It was found that the investigated incremental negative-sequence differential current protection (87Q FRIC) provides much higher sensitivity than the negative-sequence differential current protection (87Q) and the standard transformer differential protection (87T), with comparable security. However, some areas for improvement have been identified in the security examination of the 87Q FRIC protection. The directional negative-sequence differential protection (SNSDP) and the negative-sequence integral TTF protection provided inherent security in case of external faults. Yet, for inverter-based generation and SCR greater than 1, both protection methods were found to have poor dependability for TTFs.

The Author's proposal is the new *Zero-Sequence Stabilised Incremental Negative-Sequence Current Differential (ZSINSD)* protection scheme that has been developed as an improvement of the 87Q FRIC protection. Three new stabilisation criteria have been introduced based on the vectorial similarity of the incremental positive- and negative-sequence differential currents and the ratio and angle of the zero-sequence to the negative-sequence differential currents. The validity of the new stabilisation criteria has been analytically verified by correlation analysis of the sequence components using the equations obtained from the derived TTF Thévenin equivalent circuits. The introduced protection stabilisation criteria guarantee high security under adverse conditions such as transformer inrush currents and external faults with CT saturation. The developed protection scheme has been extensively tested in the power system model without and with IBR, proving superior dependability and security as compared to the other protection schemes.

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