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Review of the doctoral dissertation entitled :

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

developed by Frank Mieske

PhD Supervisor: Prof. Waldemar Rebizant, PhD, DSc

The basis for this review is the resolution of the Council of Discipline of Science: Automation, Electronic, Electrical Engineering and Space Technologies, Wrocław University of Technology of 2023-05-22 and the letter of the Head of this Council, Prof. dr hab. Andrzej Dziedzic of June 1st, 2023.

1. Choosing the topic of the dissertation

The reviewed doctoral dissertation is the result of several years of research by the author, Frank Mieske on the investigation of the behaviour of transformer differential protection and sensitive turn-to-turn fault (TTF) protection schemes in the inverter-based generation-dominated power system and to improve the sensitive TTF protection of power transformers. The author conducted research on this subject mainly in Poland (Wrocław) and in a German research centre (Berlin). Issues involving research in this area are currently very important, both for theoretical and practical reasons. The share of distributed generation in the power industry is increasing, which means that the previous paradigm regarding the operation of power protection devices has completely changed. This applies to all protection systems used in those areas where the share of production resulting from RES is increasing.

Internal short-circuits, are very dangerous for the transformer, since they cause serious damage to both the transformer windings and cores. They can also result in drastic increase of the internal pressure in the transformer tank. It is not always easy to make a post-fault analysis of what may have happened in a transformer based on disturbance recordings. Post-fault examination of the transformer which was disconnected due to a winding fault may not clearly indicate what was the initiation of the short circuit [206]. Quite a big number of authors say that the inception of turn-to-turn faults (TTFs) on the transformer winding is one of the most prominent reasons for transformer failure. The authors [1r] propose to analyse the influence of four variables: load, fault location, fault severity and load power factor in order to assess the transformer performance. Statistics of CIGRE report [2r] indicate load tap changer and winding are the most probable locations of transformer failure. The analysis of the characteristics of current during inter turn fault using Park's vector and symmetrical components approach is presented in [2r]. a comparison of two of the most sensitive methods to detect low-level turn-to-turn faults in the windings of three-phase transformers is presented in [3r]. Simulating turn-to-turn faults in power transformers is an arduous task. A method of modeling internal faults in a power transformer using a model entirely compatible with the EMTP software is presented in [4]. An EMTP/ATP power transformer model is presented in [5r]. This model was used for generating transient waveforms by means of ATP under different operating conditions. The generated waveforms were utilized to evaluate the performance of a transformer relay. A new method for simulating faulted transformers is presented in [6r]. The method uses the data obtained from any sound transformer simulation to obtain the damaged condition by simply adding a set of calculated currents. The technique used by authors [6r] avoids the use of complex routines and procedures devoted to specially simulate the internal fault.

[1r] [1]Guzmán D´ıaz González, Javier Gómez-Aleixandre Fernández, Pablo Arboleya Arboleya, Diagnosis of a turn-to-turn short circuit in power transformers by means of zero sequence current analysis, *Electric Power Systems Research*[2] 69 (2004) 321–329.

[2r] P. A. Venikar, M. S. Ballal, B. S. Umre and H. M. Suryawanshi, "Condition assessment of transformer by park's vector and symmetrical components to detect inter turn fault," *2013 IEEE 1st International Conference on Condition Assessment Techniques in Electrical Systems (CATCON)*, Kolkata, India, 2013, pp. 163-168, doi: 10.1109/CATCON.2013.6737491.

[3r] L.M.R. Oliveira and A.J.M. Cardoso. "Comparing Power Transformer Turn-to-Turn Faults Protection Methods: Negative Sequence Component versus Space VectorAlgorithms". In: *2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*. Sept. 2015, pp. 289–295. DOI: 10.1109/DEMPED.2015.7303704.

[4r] P. Bastard, P. Bertrand, and M. Meunier. "A Transformer Model for Winding Fault Studies". In: *IEEE Transactions on Power Delivery* Vol. 9 (no. 2 1994), pp. 690–699. DOI: 10.1109/61.296246.

[5r] Kezunovic M, Guo Y. Modeling and simulation of power transformer fault and related protective relay behavior. *IEEE Trans Power Deliv* 2000;15(1):44–50.

[6r] Diaz G, Gomez Alexandre J. Analytical approach to inter turn fault simulation in power transformers based on fault related incremental current. *IEEE Trans Power Deliv* 2006;21(1):142–9.

2. The dissertation argument

In the dissertation, the author put forward the following argument:

"The main task of this work was to show that an improved sensitive TTF protection based on incremental negative-sequence differential current offers high dependability and security in power systems with inverter-based resources. The proposed three new stabilisation criteria provide superior protection security under external faults with CT saturation and transformer inrush conditions.".

The PhD candidate author consistently strives to prove the above-formulated argument using analytical methods, computer simulation and experimental research on a laboratory model as a way to verify the results.

In order to prove this argument, the author methodically presented:

- A theoretical background of transformer differential protection, the state of the art of TTF protection and an insight into two established and two published protection schemes based on negative-sequence current. (Chapter 2).
- A simulation model of the converter transformer capable of simulating TTFs, and the Modular Multilevel Converter (MMC) for a High Voltage Direct Current (HVDC)

[1][*r] reference number used by the reviewer

transmission link (Chapter 3). The PhD candidate described again the existing transformer models and the selected saturable transformer model. Also his proposal of TTF model is developed. A Thévenin equivalent circuits employed to calculate the terminal currents and sequence components for TTFs is also introduced (a detailed description of this model is included in Appendix B.1)

- Test results of transformer protection in inverter-based generation-dominated (IBG) power system are presented in Chapter 4. The author has emphasized the following points - inrush current phenomenon at fault inception due to the MMC control fast fault current injection, the behaviour of transformer differential protection, dependency of the operate quantities of the TTF protection schemes in different short-circuit levels of inverter-based generation and in pure synchronous machine power system. He has also analysed in more detail the negative-sequence current protection quantities of a TTF with a small number of shorted turns,
- The security of the investigated TTF protection schemes regarding adverse conditions such as external faults, energisation of transformers, and switching of loads are presented in Chapter 5. According to the PhD candidate statement the analysis developed in this stage of his research is an essential foundation for improving the TTF protection scheme. It encompasses, among others – establishment of a security margin as a criterion to evaluate the investigated protection schemes, analysing the security of the TTF protection schemes regarding current transformer (CT) errors and power system asymmetry at operating conditions, investigates the security of the TTF protection schemes regarding CT saturation at external fault. At the end the PhD candidate concluded that the TTF protection scheme with incremental negative-sequence differential current is a valid base for improvement because of its dependability for detecting TTFs with a small number of turns. However, it is shown that security needs to be improved.
- The conclusions of the thesis and recommended topics for subsequent research work are presented in Chapter 6. The essential test results of the transformer differential protection and TTF protection scheme dependability and security in the HVDC-MMC simulation model are summarised. The author also discussed both transferability of the results into practical implementation and the validity for more power transformer types.

In my opinion, the argument formulated by the author can be considered as original and has been fully proven. The author dealt with a particularly difficult issue, which is the non-linear analysis of transient phenomena in circuits arising during the occurrence of short circuits. The PhD candidate has worked out protection schemes based on negative-sequence current. He has developed a simulation model of the converter transformer capable of simulating TTFs, a Thévenin equivalent circuits was employed to calculate the terminal currents and sequence components for TTFs. At the end he has presented the essential test results of the transformer differential protection and TTF protection scheme dependability and security in the HVDC-MMC simulation model. The author also discussed both transferability of the results into practical implementation and the validity for more power transformer types. This is a significant scientific and research achievement, because on the basis of the above-mentioned literature, it is clear that the issue is valid and the solution proposed by the author is an important achievement in this field.

3. <u>The importance of the undertaken scientific issue</u>

In my opinion, the dissertation completes the current state of knowledge, showing detailed formulas and analytical calculations, defining the procedures aiming at the improvement of detection of turn to-turn faults in power transformers and the impact of inverter-based resources on the TTF protection scheme operation.

The importance of the dissertation for science lies in the presentation of two main aspects of the problem of detection of turn-to-turn faults in power transformers by protection algorithms – first of all, the fault currents observed at transformer terminals are very small, on the other hand, the demand for dependable TTF protection is very high because of the high fault currents inside the shorted turns and the resulting damage consequences. Both of those tasks were made with due scientific diligence and being a valuable source of knowledge for further scientific research in this area. The valuable achievements of the author include the following categories:

- Development of a method for creating a HVDC-MMC Power System Simulation Model;
- Development of a methodology for Transformer Differential Protection Behaviour in the HVDC-MMC Power System Simulation Model;
- Formulation of statements about the Dependability of TTF Protection Schemes in Power Systems with Inverter-Based Resources;
- Development of methodology for Improving the Security of Incremental Negative-Sequence Current Differential Protection;
- Sketch of an attempted transformation of the Research Results into a Practical Application.

The author also added at the end any Limitations on the Validity of the Thesis Statement and Recommendations for Future Research.

4. A Detailed Description of the Dissertation

The background of the dissertation is quite well presented. It encompasses, among others - Transformer Differential Protection, including the aspect of protection blocking such as Inrush Blocking. Most of the methods discussed in the world literature are briefly discussed here. We can enumerate among others Harmonic Restraint Blocking, Power differential protection, Voltage and Flux Restraint Methods based on Transformer Model, Wavelet based Techniques, Pattern Recognition, Stochastic Approaches, Fuzzy Logic and Artificial Neural Networks (ANN). The author also presented some methods like Ratio, Vector Group and Zero-sequence Compensation. A rather exhaustive presentation of the methods used in Vector Group and Zero-sequence Compensation used for the calculation of current vectors with consideration of the phase shift and transformer group connection are included in this preliminary part of the dissertation.

The background also contains a fairly exhaustive presentation of the literature relating to the main subject of the thesis. The main scientific positions relating to Turn-to-turn Fault (TTF) Protection Schemes are given here. We can distinguish among others the Negative-Sequence Current Differential Protection 87Q, the Sensitive Negative-Sequence Differential Protection (SNSDP), the Negative-Sequence Integral TTF Protection, the Percentage-based Fault-related Incremental Negative-Sequence Protection 87Q FRIC, which is quite an interesting protection technique quite well presented in the positions [46, 47] of the PhD student's dissertation literature.

Finally a very important subsection is devoted to the Protection Scheme of an Offshore WPP HVDC-MMC. This is quite a reliable example reflecting the method of setting the transformer protections in the case of a power system with a large share of RES, where the key role is played by power electronic systems, and the settings and coordination of protections will have to take into account their operation. Several WPPs are connected in a High Voltage AC (HVAC) offshore grid with the offshore HVDC converter Station. As the author indicates, for the offshore HVDC power transmission mainly Voltage Source Converters (VSC) are used, that are specified in the IEC TR 62543 [91].

Both the model and the protection scheme of the HVDC-MMC are well presented and a clear presentation of the datasheet is shown in Table 2.1 and Fig. 2.7. The protection set is divided into the conventional AC protection with standard protection relays and the non-conventional protection with converter specific protection.

Another subsection is devoted to the Impact of Inverter-Based Resources on Power System Protection. Two aspects of this problem are presented in this subsection – The Fault Current Characteristic of Inverter-Based Resources (IBR) and the comparison of situations in which the transient of a short-circuit current is generated by a synchronous generator to a situation when the transient is generated by an Inverter-Based Resource (IBR) for a metallic fault is depicted (Fig. 2.8) and commented. Next, the Enhanced Voltage Support by IBR during unbalanced AC Faults is presented. the examples given are illustrated with figures from different positions of the literature included in the dissertation. This subsection also encompasses Grid Codes Requirements for Reactive Fault Current Contribution and Requirements for Transient Behaviour of Fast Fault Current Injection (FFCI).

Finally a separate subsection is devoted to the Challenges of Transformer Differential Protection of Converter Transformers. This subsection is limited to a short presentation of the main literature positions on the subject and a Figure showing the Field transient of phase-to-ground fault recorded at an Offshore WPP HVDC-VSC, where the transformer differential protection quantities are presented.

Chapter 3 contains more detailed information relating to the Development and Validation of the Converter Transformer Model for Protection Studies. This subsection encompasses the following points : Transformer Model Development, Transformer Model for Turn-to-turn Faults, Current Transformer Modelling, and finally the Modelling of the HVDC-MMC, the Modelling of the MMC Control, LVRT Reactive Positive- and Negative-Sequence Current Injection. At the end of this subsection a Test Power System Model with Inverter-Based Resources is included. All of the above mentioned are quite well described in the dissertation. they also include relevant references to the literature. Therefore, their detailed description is omitted in this review. Comments on the dissertation contents are included in the section entitled "Detailed Comments".

Chapter 4 contains a detailed description of the Results of testing the Transformer Protection in the HVDC-MMC Test Power System Model. This chapter contains a few main sections : Simulation of Selected Faults and other Disturbances. The simulation model in question contains among other things the developed saturable CTs and converter transformer, as described in Section 3.1. The next section is devoted to the Results of Transformer Differential Protection Operation. A few set of tests described in different subsections are included here: the Analysis of Transformer Differential Protection regarding Security for External AC Faults, the Analysis of Transformer Differential Protection regarding Dependability at AC Internal Faults. The following point is devoted to the Analysis of Sensitive TTF Protection Schemes regarding Dependability. Simulation results regarding the sensitivity of different TTF protection schemes for the MMC converter compared to the synchronous machine (SM) infeed are included in this subsection. A few influencing parameters such as Short-circuit Ratio (SCR) of Infeed, short-circuit resistance and short-circuit location in either star or delta transformer winding were systematically varied in order to get meaningful results. Another aspect of the conducted analysis is the dependency of the

TTF Protection Quantities on SCR and Inverter-Based Resources. The last three points of this subsection are devoted to the following analyses:

- Analysis of the Negative-sequence Current for TTFs with a Small Number of Shorted Turns and IBR infeed;
- Analysis of the Negative-sequence Current for TTFs with a High Number of Shorted Turns and IBR infeed;
- Dependability of TTF Protection Schemes in Power Systems with IBR.

Chapter 5 devoted to the Zero-Sequence Stabilised Incremental Negative-Sequence Differential Current Protection is the most important part of this dissertation. The maloperation of the TTF protection schemes must be kept to a minimum since it affects the system reliability of the power grid. Improving the sensitive TTF protection scheme can be obtained by analysing adverse conditions such as external faults, transformer switching, and load switching. The negative-sequence differential current not caused by internal faults is termed a false negative-sequence differential current.

Differential protection is used for detecting internal faults. The Negative-Sequence Differential Current can be used as a parameter for a differential protection. Unfortunately The negative-sequence differential current can appear not only in case of internal faults but during such other phenomena as external faults and increased transformer magnetising current due to overexcitation or switching operations. A distinction is then necessary because a percentage stabilisation is provided for the linear steady-state load flow range, and additional stabilisation criteria or algorithms are necessary for the adverse conditions. The negative-sequence differential current not caused by internal faults is termed *a false negative-sequence differential current*.

The next subsection is devoted to TTF Protection Schemes Security in Steady-State Operating Conditions. Except some preliminary information about the security itself (Definition of Security Margin) some examples of sources of False Negative-Sequence Differential Current such as False Negative-Sequence Differential Current Caused by CT Accuracy, also a few conclusions resulting from the Comparison of Negative-sequence Differential Current and Incremental Negative-sequence Differential Current in Presence of Transducer Errors and Power System Asymmetry are included in this subsection.

A separate subsection is devoted to TTF Protection Schemes Security at External faults with CT saturation. An example presenting the behaviour of the sensitive TTF protection schemes is evaluated on a case of a field transient shown in Fig. 5.7. This case concerns a maloperation of the generator differential protection. Another example is devoted to Percentage-based Sensitive Negative-Sequence Differential Current Protection Schemes. The influence of different types of differential current protections reacting to (a) standard current (b) negative-sequence current and (c) incremental negative-sequence current have been presented. The last case analysed in this subsection is the Directional-based Sensitive Negative-Sequence Current Protection Scheme. Trajectories of negative-sequence current of the HV and the LV side of the transformer during external generator-close fault with CT saturation are depicted and commented.

The subsequent subsection encompasses a few Considerations for the Improvement of the TTF Protection Scheme. Taking into account the results of analyses carried out previously, the author comes to the conclusion that significant improvements and enhancements of the 87Q FRIC protection lead to an new protection scheme called Zero-sequence Stabilised Incremental Negative-Sequence Differential Current Protection (ZSINSD protection). Moreover, this type of protection will be analysed in detail in subsection 5.8.

The next subsection (5.6) contains some considerations relating to Operating and Restraint Quantities. Several types of quantities can be used as restraint quantities for differential protections. The basic case presented by the author is that one where the only operating quantity is the absolute value of the incremental negative-sequence differential current, since the similarity stabilisation criterion checks its equality with the incremental positive sequence differential current. The original 87Q FRIC method proposes the formation of the restraint quantity as the maximum value of the sum of the incremental positive- or negative-sequence currents of the two transformer sides. Two variants of quantities that can be used to form the restraint quantity from the true RMS phase currents are presented in this subsection. More information about the analysis conducted are in the dissertation. This part of the dissertation is quite important, *but I think the way how the PhD student explains the theory is nor so clear, so I will probably ask him to give more clarification about the way how the mathematical process included in the text was constructed.*

The subsection (5.7) contains a few case studies aimed at a Qualitative Analysis of Incremental Zero-Sequence Differential Current as Stabilisation Criterion. The first one deals with the case of External Phase-to-Ground Fault and a TTF. This analysis allows to determine the incremental positive- and negative-sequence differential current and the magnitude of the zero-sequence differential current depending on the transformer leakage impedance, the system impedance, the fault resistance, and the infeed ratios. The second case was aimed at determining the Generalised Correlations between the Incremental Zero-, Positive-, and Negative-Sequence Differential Current for TTFs. This case allowed to determine the ratio between zero-, positive-, and negative-sequence current depends on the transformer leakage impedance (ZTC) and the source impedance (ZQ2), according to the author's nomenclature (Eq. 5.20). Also the generalised relation between the sequence components could be determined and given by the Eq. 5.21.

The determination of the above-presented parameters allowed to determine the relationships between those quantities and ratio of source and transformer leakage reactance Q_2 for different R/X ratios of transformer k_{TC} and power system k_{Q2}. An example of such relationship is shown in Fig. 5.14.

The three last cases were aimed at the determination of the following parameters:

- Incremental Zero-Sequence Stabilisation Criterion (5.7.3). The ratio of incremental zero-sequence and incremental negative sequence differential currents is given by Eq. 5.22, and the phase displacement between the incremental zero-sequence and negative-sequence differential current by Eq. 5.23. The quantity calculated using Eq. 5.22 is used as the incremental zero-sequence stabilisation criterion.

- Correlations of Incremental Zero-sequence, Positive-, and Negative-Sequence Differential Currents for External Faults with CT saturation (5.7.4). The minimum thresholds of the stabilisation criteria can be determined through the calculation of ratio of incremental zero-sequence to the negative-sequence differential current at external faults with CT saturation of modelled iron-core CT. Two cases where analysed in this case (1) the case of no remanence induction in the CT when the fault occurs and (2) the case when there is remanence induction in the CT before fault inception. Unfortunately the illustration (Fig. 5.15) is not clear enough in order to come to the conclusions included in the description of this case. All the three stabilisation criteria, i.e. similarity C_{D12}, zero-sequence ratio C_{D02} and angle α_{D02} were verified by applying different external fault types, with low and medium CT saturation in HV and XV CT. The results are presented in Table 5.1 and 5.2.

- Correlations of Incremental Zero-sequence, Positive-, and Negative-Sequence Differential Currents during Inrush (5.7.5). The inrush transient currents and the stabilising criteria for energising the investigated converter transformer are from a non-inverter-based power source. The waveforms depicted Fig. 5.17 made come to the conclusions that the stabilisation criteria similarity C_{D12} of around 2.7 and the angle α_{D02} securely block the incremental negative-sequence differential current protection.

The author has conducted further simulations during which the transformer was energised on the XV (delta) and the HV (star) side, varying the point-on-wave switching time so that the reliability of the above-assumed stabilisation criteria were confirmed (Fig. 5.18). Another simulation was conducted where a transformer sympathetic inrush current is a consequence of a sympathetic interaction between two or more transformers after the energisation of one of them (Fig. 5.19). the last simulation was a case where the stabilisation during fault-recovery inrush is caused by voltage recovery after clearance of an external fault in the AC network connected to the HVDC MMC (Fig. 5.20). The last case analysed in this subsection concerns an external phase-to-phase fault where the Fast Fault Current Injection in the LVRT control of the MMC generates two coherent voltage waves immediately after the fault has occurred (Fig. 5.21). One general conclusion has been drawn for all the cases - the vectorial stabilisation criterion and the angle criterion block the incremental negative-sequence differential current protection securely for quite a large number of contingencies.

The next subsection (5.8) can be considered as the clou of this dissertation. The details about the Zero-sequence Stabilised Incremental Negative-sequence Current Differential (ZSINSD) protection scheme are presented here, including a few case studies.

First a list of the subroutines of which the algorithm is composed is presented: they are - Measurement preprocessing, Fault detection and incremental quantities calculation, Pickup characteristic, Stabilisation criteria calculation, Trip decision logic. More details about each subroutine are included in the dissertation.

The Incremental sequence-components differential current calculation and update logic based on *Moving Window Variance* (MWV) as presented in Chapter 2 (Eq. 2.14) is developed. The calculation is based on the positive-sequence differential current I1D, according to a method presented in references [47, 46]. As the acronym MWV indicates the accuracy of the results depends on the length N of the moving window. In the analysed case this length is equal to a power system frequency half cycle and is equivalent to a time delay TD (Fig. 5.22). Fig. 5.2.2 depicts the Incremental sequence-components differential current calculation and update logic based on Moving Window Variance (MWV). As the author wrote in this subsection, no proposal is made for the MWV update threshold in [47, 46]. The threshold must be set high enough to avoid updating for distorted signals and, on the other hand, be sensitive enough to update for TTFs. The simulation carried out by the author made come to the conclusion that the waveforms and signals of the update algorithm for a TTF with an incremental positive-sequence differential current of 0.02 p.u. (Fig. 5.23). The Fault Detection and Incremental Quantities Calculation takes place as follows - The MWV update threshold of 1 x 10-5 is exceeded after approx. 8 milliseconds after fault inception. Incremental quantities are formed with latch signal, which makes half-cycle pre-fault phasors are latched. After two more cycles, the system drop-outs to the measured phasors, and the incremental quantities fall back to zero.

The Pickup percentage characteristic of the ZSINSD protection scheme is depicted in Fig. 5.24. *Unfortunately I must say that apart from the enumeration of the various faults which could trigger the action of the protection*, as well as two examples of faults to which the device would react, *there is not much information which would help to understand how this curve was constructed. This will need more clarification.*

The decision logic of the ZSINSD protection scheme is depicted in Fig. 5.25 (not Fig. 5.24 as it is written in Paragraph 1 – Page 105). The logic itself is pretty clear, so I have no comments to say about it.

The evaluation of the ZSINSD Protection Scheme is presented in subsection (5.9). as the author wrote "*The performance analysis focuses on reviewing the setting values of the stabilisation criteria parameters to find a reasonable balance between the dependability and security of the ZSINSD protection scheme.*" A few parameters have been established to be analysed so that their influence on the security and dependability are shown. The results are presented in Table 5.4. the author has analysed the performance of the ZSINSD protection scheme is analysed regarding dependability for TTFs and security at external faults and recovery inrush in the study case test bench for the protection of the HVDC-MMC converter transformer.

The analysis was based on the performance evaluation with regard to security in the event of external faults with CT saturation, the model of which was presented in subsection 5.7 (the configuration of the synchronous machine infeed). Moreover the restraining True RMS size was introduced to increase security in the presence of external disturbances. One of the conclusion which was drawn by the author is that at CT saturation, the Operate indication is not issued, but "*one can observe a spurious Operate indication immediately after fault clearance when the circuit breaker opens*". This observation made the author come to the conclusion that "*improvements in the update logic are required. Additionally, in the performance evaluation below for dependability, a potential increase of the percentage characteristic slope is considered.*"

Another simulation in which inverter-based power source, as for the investigated MMC-HVDC configuration was used, the security for slight transformer inrush conditions is relevant. The observation was as follows: "*incremental negative-sequence differential current does have a security margin factor of three to the restraint quantity*" and the ZSINSD protection does not pick up. The conclusion is that "*the simulated inverter-based generation transient shows the effectiveness of the percentage characteristic and the use of the True RMS value as the restraining quantity.*"

With regard to the evaluation of the ZSINSD protection scheme in terms of dependability, an analysis was performed by investigating the performance of the protection by verifying the operating characteristic's safety margin and parameters of the stabilisation criteria during TTFs with the influencing variables. The results of the investigation are listed in Table 5.4. The model takes into account a restraining quantity ΔI_r based on the True RMS currents and therefore includes DC component and harmonics in contrast to the operate quantity, and the negative-sequence current increment I_{2D} is based on the fundamental frequency component. Results of the primary analysis have shown that "*Regardless of the DC component, the operate quantity of 0.18 p.u. is six times higher than the restraining quantity ΔI_{R2} multiplied by the slope.*" A few parameters of the TTFs and the power system have been systematically varied in order to assess the dependability of the ZSINSD protection scheme. Operating points in the percentage characteristic for TTFs in the delta or the star winding with one-sided fault current injection (SCR = 0), fault inception at zero crossing, and thus a high DC component in the fault current for synchronous machine and HVDC-MMC infeed are presented in Fig. 5.29.

The last item in this subsection is for Issues Encountered of Incremental Quantities. The author wrote that it can be difficult in some cases to correctly determine the incremental quantities from section 5.8.2 that can be attributed to the TTF current. We have to ensure that the threshold value is not constantly triggered with fluctuating phasors. Also another issue relating to the decaying differential current resulting from the inrush current can also permanently trigger the latching of the pre-fault phasors. The author has suggested to introduce a useful modification of the algorithm for calculating the increment by excluding the switched-off negative sequence current by only evaluating the magnitude of an increase in the negative-sequence current. This solution is given by the Eq. 5.28 in the dissertation. More information about the usefulness of this operation is included in the dissertation – subsection 5.9.4. The author added that the proposed solution is just experimental and further research to improve this SOTF case described in the subsection is recommended.

Chapter 6 contains the conclusions. According to their contents two complex areas of research have been involved in this work: improvement of the procedures for the detection of turn to-turn faults in power transformers and the impact of inverter-based resources on the TTF protection scheme operation. A big challenge that the author has to face is the detection of turn-to-turn faults in power transformers by protection algorithms. There are two main aspects of this problem – first of all, the fault currents observed at transformer terminals are very small, on the other hand, the demand for dependable TTF protection is very high because of the high fault currents inside the shorted turns and the resulting damage consequences. Moreover, adverse conditions such as transformer inrush currents or CT errors may lead to protection maloperation. Another problem the author had to face is the fault current characteristic of the inverter-based resource infeed which is very different compared to the synchronous machine infeed, particularly the negative-sequence current used in the TTF protection schemes. This question requires a completely new philosophy of protection parameters, and new research is mandatory.

5. <u>The scientific workshop</u>

The author of the dissertation shows good orientation in the field of power system protection and control, renewables, power electronics, protection algorithms. The reviewed dissertation is analytical and experimental in nature. The great care he took in the selection of analytical equations proves a thorough understanding also from the mathematical side of the issues in the presented research area. In my opinion the reviewed dissertation is a valuable scientific achievement in this area, and is among the most up-to-date approach to the presented subject. The dissertation contains a lot of original content, formulations and valuable results, which only confirms the good preparation of the PhD student to independently conduct scientific and research work in the future.

The PhD candidate Frank Mieske has been dealing with this research area for many years, as evidenced by his numerous original and co-authored publications in Germany and abroad.

6. <u>Original achievements</u>

The elements of novelty, which are the original and most important results of the dissertation and the achievements of its author, include the following:

- A very carefully conducted analysis of the research area based on the latest scientific world literature, which is confirmed by the list of 3 journal papers, 4 conference papers, 7 patents and 4 submitted patent applications,
- The development of an adequate digital simulation model of the HVDC-MMC converter transformer with converter control and LVRT capability in the MATLAB/Simulink environment;
- The development of Zero-Sequence Stabilised Incremental Negative-Sequence Current Differential (ZSINSD) protection scheme as an improvement of the 87Q FRIC protection;

- Performance of deep analysis of general aspects of the impact of inverter-based generation on protection with fault characteristic transients from the implemented HVDC-MMC simulation model;
- Deep investigation of the security in the event of external faults and transformer inrush transients, as well as the dependability of the transformer differential protection in the event of internal high-current transformer faults;
- Performance evaluation of the proposed stabilisation criteria with regard to CT saturation;
- Analysis of protection stability during transformer energisation and examination of auto-recovery and sympathetic inrush cases.

7. Polemical, discussion and editorial remarks

a. General remarks

There is a general point that I would like to make. I see the author is trying to write everything in British English. Only I see that from time to time he puts American accents in it and even sometimes he uses a kind of mixture. Of course everything is understandable and lately there is even a kind of tolerance towards the mixed use of the two versions of English, which are still a bit different. The author generally uses the expression "***phase-to-ground***" which is typically American. The British English expression is "**line-to-earth**" (but lately also the term **line-to-ground** is more often used). The author uses also this later (page 92).

b. Particular remarks

After reading the doctoral dissertation, I had critical remarks that should be discussed during the defence of the doctoral thesis, i.e.:

Remark 1. Page 9 – You wrote « The authors of [20] improved the EII method. The fixed EII threshold is challenging to obtain for different transformer types, so they proposed using the ratio of average EII during the inrush transient. In the case of inrush, the EII consecutively changes between the non-saturation and the saturation zone and the magnitude of change is then expressed as a ratio. A further improvement is suggested in [21] by the same authors. The authors emphasise the sensitivity of this algorithm to detect small TTFs covered by the inrush current. »

How come [21] is an improvement of [20] since it has been published earlier?

Remark 2.

[145] F. Naseri et al. "Fast Discrimination of Transformer Magnetizing Current From Internal Faults: An Extended Kalman Filter-Based Approach". In: IEEE Transactions on Power Delivery Vol. 33 (no. 1), pp. 110–118. ISSN: ITPDE5 ISSN 0885-8977.

The publication year of the above-mentioned paper is 2018.

Remark 3. Page 13 - The way how the equations (2.6) (2.7) were obtained is not very clear. The Fortescue transformation itself is clear, ***but then the author doesn't give any definition/explanation of some of the symbols he uses in the formulas.***

Remark 4. Page 26 - You wrote "The linkage flux at rated voltage is calculated with"

Can you explain how the expression

$$\psi_r = \frac{U_{rTCH}\,\sqrt{2}}{2\,\pi\,f_n\,\sqrt{3}}$$

was obtained?

Remark 5. Page 28 (paragraph 3) - the sentence "*The effective short-circuit impedance Zsc is defined in p.u. with respect to the measured current at the terminal, like the short-circuit impedance of the transformer, and*" **is not finished**.

Remark 6. Pages 39-40. The way how the variables are displayed is a little bit confusing. All the variables were first indicated *using a regular way*, because the author dealt with scalars. Then he introduced some matrices **displayed as bold**, but at the same time *the currents and voltages were also displayed using bold character*, which would also be equivalent to saying that **they are matrix-type variables. There was no explanation why the convention of representing the currents and voltages was changed in the meantime.** I think the bold expressed currents and voltages are at least vector of these quantities? **If so a small explanation or legend could be included.**

Starting from formula 3.23 the author reverted to representing the case of currents using a standard font, *which is a bit confusing in reading and understanding the mathematical demonstration of the formulas.*

Remark 7. Page 40. You write as follows "The left part of Eq. (3.21) represents the imbalance of DC input and zero-sequence voltage source of converter equivalent Eq. (3.16)"

I think **there are no left/right parts in Eq. (3.21)**. There are only *upper and lower part*, if we refer to the "geographical" representation of the formula. The whole expression was set equal to zero, so the right part is zero.

Remark 8. Page 40 – The passage from Expression 3.14 and 3.20 is too fast. You should add some explanation where the different new variables (*R, L, U* and *I*) come from.

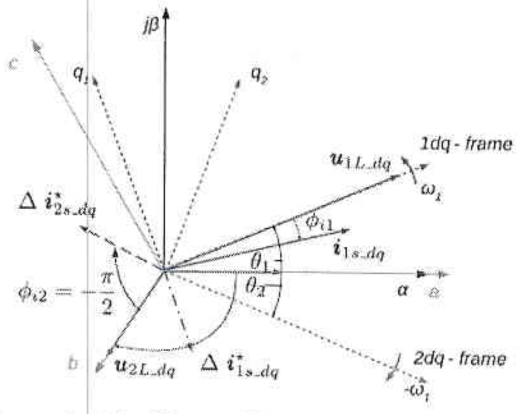
Remark 9. Page 42. You made such a statement "Since the displacement angle is small in regular operation and the sine is linear at a small angle, the proportional term $U_{1s} \sin \delta = I_{1s} \cos \phi X_c$ determines the active power that is delivered to the grid." **It is better to show it in a vector diagram.**

You also wrote "The phasor diagrams of the four-quadrant operating modes of the power and reactive power control of the MMC in Active Sign Convention (ASC) are shown in Fig. A.2 with load angle ϕ_L". **I don't see this angle anywhere in A.2. May be you meant φ_L ???**

Remark 10. Page 47. It seems to me that the currents in Fig. 3.22 are different from the currents in the description "The Fig. 3.22 shows the positive-sequence space vectors and the negative-sequence space vectors of grid voltage u_{1L_dq}, u_{2L_dq} and converter current control reference values $i^*_{1L\_dq}, i^*_{2L\_dq}$ in the two $1dq, 2dq$ synchronous reference frames."

There are i_{1s_dq} but no $i^*_{2L\_dq}$

Whereas Fig. 3.22 is shown as follows



Remark 11. Plage 48. Please explain **why do you use squares in the left side of the formulas (3.47), since we don't have them in (3.46).**

Remark 12. Page 57. **I can't see the infeed you indicate** "*The type of Infeed Q1 in the case study is either a synchronous generator or the MMC-HVDC converter.*". Is it the generator at the left side of the Figure 3.29?

Remark 13. Page 77. You wrote "As observed, both configurations' differential current in phase A I_{Da} and the negative-sequence differential current I_{2D} are nearly the same." Is I_{2D} and $(\Delta)I_{2D}$ the same ?. **I ask because you use one symbol in the text and a different one in the Fig. 4.14.** I have the same remark for the explanation in Page 79 and the Fig. 4.15.

Remark 14. Page 86. You made such a statement "As can be seen in Fig. 5.6, for simultaneous tap-change operation, the fundamental positive-sequence differential current is about 0.06 p.u. and the negative-sequence differential current is about 0.15 p.u." **I think it's the other way around, or the negative-sequence of the differential current is about 0.015p.u.**?

Remark 15. Page 87. You wrote "As can be observed in Fig. 5.4a, there is no security margin for the 87Q for 5 Ω fault resistance and CT error." **I can't see it. Please explain it better.** I would rather say that this statement applies to Fig. 5.5.a.

Remark 16. Page 87 – last paragraph. The statement is as follows "Fig. 5.8 presents the incremental positive and negative-sequence differential currents and the operate-to restraining ratio of the incremental negative-sequence current differential protection 87Q FRIC for the generator close external fault with CT saturation in Fig. 5.7 ." **I think you mean Fig. 5.9**?

Remark 17. Page 87. You also say "As observed, the incremental restraining current is increased at fault inception but very low for the slight CT saturation." **I don't see this incremental restraining current here** (Fig. 5.9).

Remark 18. Page 88. The clarification of Fig. 5.10 is not good enough. First of all, when you say "After fault inception and before CT saturation, the relative phase angle between these two phasors is 180 degrees. The phase angle during CT saturation drops down to 90 degrees for a very short time." **I don't really see it.** Secondly you should start *the explanation by saying what is what.* There are a lot of symbols in this Figure. I_{1TCX}, I_{2TCH}, **some colours symbolising ... exactly symbolizing what**?

Remark 19. Page 88. Then you write "In the Sensitive Negative-Sequence Differential Protection (SNSDP) the Relay Operate Angle, which determines the boundary between the internal and external fault region, is set to 60 degrees [50]. Accordingly, the angle difference between the negative-sequence current phasors is a reliable criterion to discriminate between external and internal faults." **I understand that, but what is the relationship between this statement and want you drew in Figure 5.10**?

Remark 20. Page 88 - fault currentś negative (**Polish s**)

Remark 21. Page 90. Please explain **how the mathematical process leading to the formulas (5.13) – (5.17) included in the text was constructed.**

Remark 22. Page 91 – First paragraph – you wrote "After vector group compensation, the absolute values and phase angles of the incremental positive and negative sequence transformer sides currents are identical for TTFs in the transformer:" **Could you refer to the part of the previously presented text where this compensation was done**?

Remark 23. Page 91 – You write „As can be observed, the vector percentage deviation is 2 p.u. for a phase displacement of 180 degrees and 0.2611 p.u. for a phase displacement of 15 degree." **Is this calculation made based on (5.19) and (5.18) expressions**?

Remark 24. Page 93. I think Figure 5.13 **needs a more detailed clarification.**

Remark 25. Page 95. I wrote in the description of the case "the clarification of the case (Fig. 5.15) **is not good enough to understand the case**".

Remark 26. Page 95. About the case entitled "Correlations of Incremental Zero-sequence, Positive-, and Negative-Sequence Differential Currents for External Faults with CT saturation" **I can't really see where is case 1 and case 2 in the depicted** Figure 5.15 because you wrote "These two cases are illustrated by the transient shown in Fig. 5.15 of an external single line-to-ground fault with unsuccessful automatic reclosing." **Can you explain the figure better**?

Remark 27. Page 100. There are two affirmations against which *I don't really understand how to assess them*. The first one is "the stabilisation criterion zero-sequence ratio C_{D02} during the fault-recovery inrush is greater than three at 120 milliseconds, and thus stabilisation is secure." and the second one "At the fault-recovery inrush, the stabilisation criterion zero-sequence ratio C_{D02} during the fault-recovery inrush is around two at 120 milliseconds, and thus stabilisation is secure."

I rechecked again the definition of the "stabilisation criterion" for the case of zero-sequence ratio, but I don't know what are the appropriate values. So **would you please comment on these two cases?**

Remark 28. Page 100 – last paragraph – you say "The restraint value multiplied by the characteristic slope exceeds the operating value, and thus the operating point is not above the operating characteristic." **How do we know how the operating characteristic looks like in order to believe that this statement is true**? Of course the Figures 5.20 and 5.21 contains some characteristics like "(c) the incremental zero-, positive-, and negative-sequence differential current absolute value and restraint quantity multiplied by slope ΔI_{2R} k_{2R}", **but they don't allow us to say the above-mentioned statement is true.**

Remark 29. Page 101 – first paragraph - I don't know if I understand well but **once you use the expression vectorial stabilisation criteria similarity C_{D12} and another time vectorial similarity stabilisation criterion C_{12}.**

Remark 30. Page 101. Is the vectorial similarity stabilisation criterion indicated by C_{D12} or C_{12} the same because **once you use the first expression (5.19) and another time the second one (Fig. 5.20 and 5.21).**

The same situation is with the incremental zero-sequence and incremental negative sequence differential currents. **One you use the symbol C_{D12} (5.22) and another time C_{02} (Fig. 5.20 and 5.21).**

Remark 31. Page 104. In the description of the dissertation I wrote: "The Pickup percentage characteristic of the ZSINSD protection scheme is depicted in Fig. 5.24. Unfortunately I must say that apart from the enumeration of the various faults which could trigger the action of the protection, as well as two examples of faults to which the device would react, there is not much information which would help to understand how this curve was constructed. **This will need more clarification.** "

Remark 32. Page 105. The decision logic is presented not in Fig. 5.24 but Fig. 5.25.

Remark 33. Page 110. Probably the way how to derive the errors given in Eq. 5.26 has been shown somewhere (may be some related factors which could be derived numerically with the Fortescue transformation?), **anyway it would be better to give the reference in the text.**

Remark 34. Page 113. I think one of the statements to be explained well is the following:

"In the first case, the transformer is de-energised, and a transformer inrush current occurs. In this case, due to the superposition of a large inrush current and a small fault current in the case of TTFs with a small number of shorted turns, it is impossible to use the incremental quantities for discrimination.

In the other case, the transformer is already energised. In this case, the TTF current is superimposed with the false differential current due to measurement errors. Consequently, in this SOTF case, it may lack dependability due to blocking caused by the vectorial similarity stabilising criterion."

Please explain using the appropriate formulas those two statements.

Remark 35. Page 116 – Second paragraph - You said « On the other hand, the magnitudes of the negative-sequence transformer side currents as a function of the SCR behave oppositely for the infeed from the HVDC-MMC compared to the infeed from the synchronous machine." Unfortunately you didn't indicate which part of the work you refer to (a figure? Some preliminary conclusions?)

The same situation is here. You wrote "The negative-sequence currents on both sides of the transformer are almost equal when feeding only from the HVDC-MMC (SCR=0). From an SCR greater than one, the negative-sequence current at the MMC converter side decreases as the SCR increases and falls below the minimum threshold for the directional-based negative-sequence protection." **The same as before, there is no reference to the part of the text from which you drew this conclusion.**

Remark 36. In page 118 you wrote "In the future, a small signal current transducer, such as the Rogowski coil, will also become established." I think you know quite well the advantages and drawbacks of non-conventional instrument transformers. In your opinion, if you use their mathematical models in the models you have presented in this thesis, **will the algorithms you have developed still be valid and will there be necessary modifications to be introduced**?

Remark 37. Page 118 again – there is another statement I don't see the justification in the text : "In the case of an external fault with a high through-fault current in the transformer, there is an increased probability of an evolving TTF. Therefore stabilising, in this case, may lead to a lack of protection dependability. Consequently, the topic of evolving faults needs particular consideration." **Can you explain it better**?

The above remarks and comments are debatable and *do not diminish the scientific value and practical significance of the reviewed dissertation.* Editorial errors doesn't significantly lower the evaluation of this work. **In short, my overall assessment of the submitted dissertation is positive.**

8. <u>Detailed and editorial notes</u>

The reviewed doctoral dissertation is written in English. The doctoral thesis has a total of 167 pages. The bibliography contains 221 items..

The work contains 6 chapters and 4 appendices, where the first 5 main chapters are divided into several subchapters.

The drawings included in the work are made with due care and are sufficiently legible together with their captions.

The editorial layout of the work does not raise any objections. The editorial work can even be considered exemplary, taking into account its editorial side.

The above comments are debatable and do not diminish the scientific value and practical significance of the reviewed dissertation. Editorial errors doesn't significantly lower the evaluation of this work. In short, my overall assessment of the submitted dissertation is positive.

9. <u>Final conclusion</u>

The reviewed dissertation of Frank Mieske entitled " Improved Turn-to-turn Fault Protection for Power Transformers in Power Systems with Inverter-Based Resources", regardless of the comments given in this review, is a serious and independent contribution of a PhD student to the research area of protection and control of the electrical system taking into account the high penetration of RES.

The author performed a comprehensive theoretical and experimental research, and demonstrated the ability to formulate and solve difficult and current scientific problems.

The author has also demonstrated the ability to cooperate with scientists from renowned foreign research centres, as evidenced by his co-authored foreign publications.

The obtained results are of significant cognitive and application importance, and can be used in further research in power electronics and power engineering.

I rate the doctoral dissertation of Frank Mieske very highly as "*extremely good, deserving of distinction*". This assessment consists of: the innovativeness of the topic, the rich content of the dissertation, the scale of the analyses carried out and the mature manner of presentation.

I believe that the work with a clear excess meets the requirements of the Act of 20/07/2018 Law on Higher Education and Science (Journal of Laws of 2018, item 1668, as amended).

Considering the above, I state that the doctoral dissertation of Frank Mieske meets the requirements specified in the above-mentioned act on academic degrees and academic titles I therefore request that its author be admitted to public defence.

At the same time, **I am applying for the dissertation to be distinguished** due to its merits, as well as the research and publishing activity of the PhD student.

Prof. Désiré Dauphin Rasolomampionona, PhD, DSc.