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Wrocław University of Science and Technology

Study Committee B5

PROTECTION AND AUTOMATION

Paper 11091_2022

Advanced Transformer Protection to Secure Discriminating Internal Faults from Inrush Currents in Inverter-based Generation Networks

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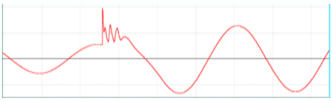
Motivation

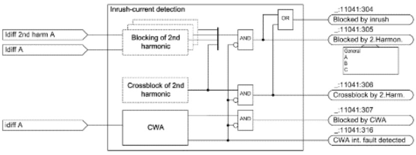


Fault current generated by VSC converter

- The effects of inverter-based fault current on transformer differential protection are investigated due to increasing renewables penetration and Inverter-based (IBG) networks
- Special focus on inrush stabilisation → Current Waveform Analysis (CWA), 2nd Harmonic, and improved CWA Internal Fault detection
- Previous study simulations of large motor drives with three-level neutral point clamped converters and testing results of converter transformer differential protection regarding the high content of higher harmonics (2nd, 5th) were presented.
- This study continues investigation at Adjustable Speed Drive (ASD) with Modular Multilevel Converters (MMC) Active Front End (AFE) with adequate control and Fast fault current injection control(Positive and negative-sequence reactive current injection) to fulfil Low Voltage Ride Through (LVRT) grid code requirements

Advanced Transformer Differential Protection with Combined CWA and 2nd Harm. Inrush Stab. CWA Internal Fault Detection

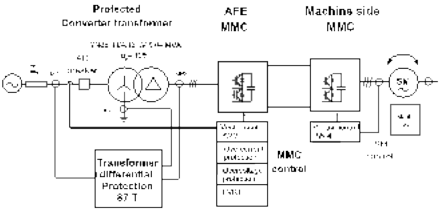
- CWA Method investigates flat areas in the current
- No flat areas precisely one period after fault inception → internal fault detected and the 2nd Harmonic is blocked



2nd Harmonic, CWA Inrush Stabilization, and CWA Internal Fault Detection [1]

Model Development / Simulation

- An EMT MATLAB/Simulink based on the «Specialized power system » of the ASD System was developed
- Half-Bridge MMC model contains 12 submodules (SM) and is operable in Switching Model PWM
- Inner control of the MMC is based on vector current control in the rotating state space vector *dq*-component reference frame.
- Extraction of the voltage *dq*-components quantities is done in a separate Double Decouple Synchronous Reference Frame PLL



Simulation and Protection Testing of Selected Disturbances

- Many simulations have been performed using MATLAB/Simulink → COMTRADE format
- MMC model verification based on reference data
- Transformer protection testing using simulated COMTRADE files

Results and Conclusion

- Advanced transformer differential CWA internal algorithm ensures stability and dependability of transformer protection in inverter-based networks
- Detailed, accurate, and grid code compliant model and control implementation necessary for protection testing in inverter-based power system
- The behaviour of protection depends on the settings of LVRT control and deadbands, the settings of PLL, PI control settings, MMC energy control and parameter

Further studies are recommended.

- No fast reactive negative sequence current injection (LVRT) at turn-to-turn fault because of inconsiderable voltage deviation
- Inrush effects at faults due to coherent voltage waves produced by control (Fast Fault Current Injection) and increased magnetising current

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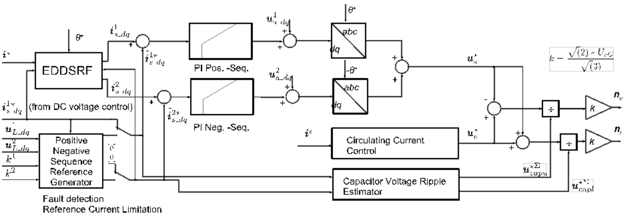
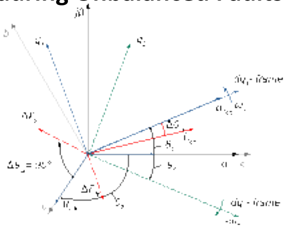
Modelling of the AFE MMC and Control

- Inner control of the MMC
    - Arm energy control
    - Circulating Current control
- positive and negative-sequence vector current control in *dq*-components
- Fault detection , reference generator and current limitation



Grid Code Compliant Modeling and Control of the MMC during Unbalanced Faults

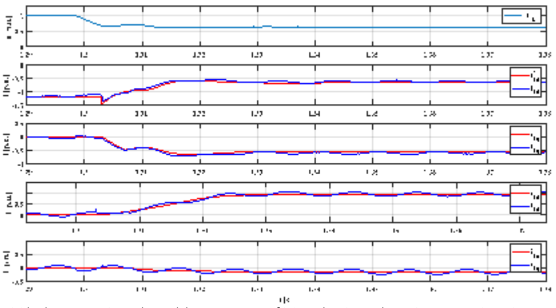
- Implementation of Fast Fault Current Injection according to VDE-AR-N 4120 with separate positive- and negative-sequence reactive current infeed (Low Voltage Ride Through LVRT capability)
- voltage deviation at the point of common coupling (PCC) is measured, and separate droop factors k_1 for positive-sequence and k_2 for negative sequence reactive current are applied
- In this study, the droop factors of $k_1 = 2.5$ and $k_2 = 2.5$ are applied, which emulate the behaviour of a synchronous machine. Additional, a 10% Deadband is used.
- Extraction of the PCC sequence components in Enhanced Decoupled Double Synchronous Reference Frame (DDSRF) PLL



Vector diagram of the positive and negative dq-components voltages and current references for fast fault current contribution

Model Verification and Control Setup during Unbalanced Faults

- Transient shows line voltage, set points and actual *dq*-components of injected active and reactive currents during an external phase-to-phase fault in motor mode
- before fault inception, only active current component i_{1d} of ca. - 1.1 p.u. (ASC)
- Measure rise time for injected positive-sequence reactive current and negative-sequence reactive current is around 12 milliseconds
- VDE AR-N-4120 requires a rise time (90% value) smaller than 30 milliseconds.
- Priority of reactive current injection, the active current i_{1d} drops close to 0.5 p.u.

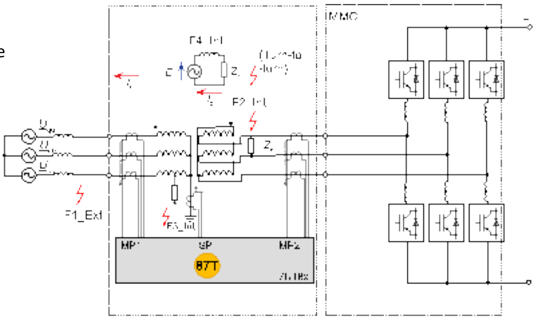


Grid voltage, set point and actual dq-components of injected active and reactive currents in DDSRF ($|u_L|$;i_{1d}, i_{1q}, i_{2d}, i_{2q}) phase-to-phase external fault (4 Ohm) in motor mode

- the delay of fault detection and delay of set point command generates the distorted waveforms in the differential current, which can be wrongly identified as the second harmonic component

Simulation of selected disturbances

- fault resistance: from 0.01 Ω to 20Ω,
- fault location (Extern F1, Intern Converter Side F2, Grid side F3),
- fault type: two-phase and three-phase, at grid side single-phase-to-ground at terminal and 50 % of winding, turn-to-turn faults in star and the delta winding,
- point-on-wave: $V_{L1-L2}=V_{DC}$, $V_{L1-L2}=V_{DC}/2$, $V_{L1-L2}=0$, $V_{L1-L2}= -V_{DC}/2$, $V_{L1-L2}= -V_{DC\ ful}$
- turn-to-turn faults: short-circuit of all parallel conductors or in one of the parallel conductors
- turn-to-turn fault simulation for a small number of turns with fictitious winding
- generator operation mode/ motor operation mode,
- variation of LVRT droop factors (typically k_1,k_2 = 2.5).



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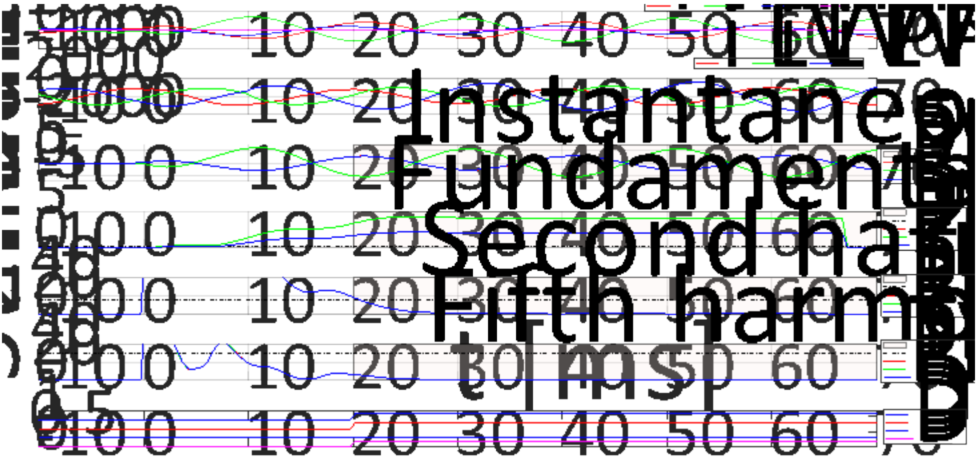
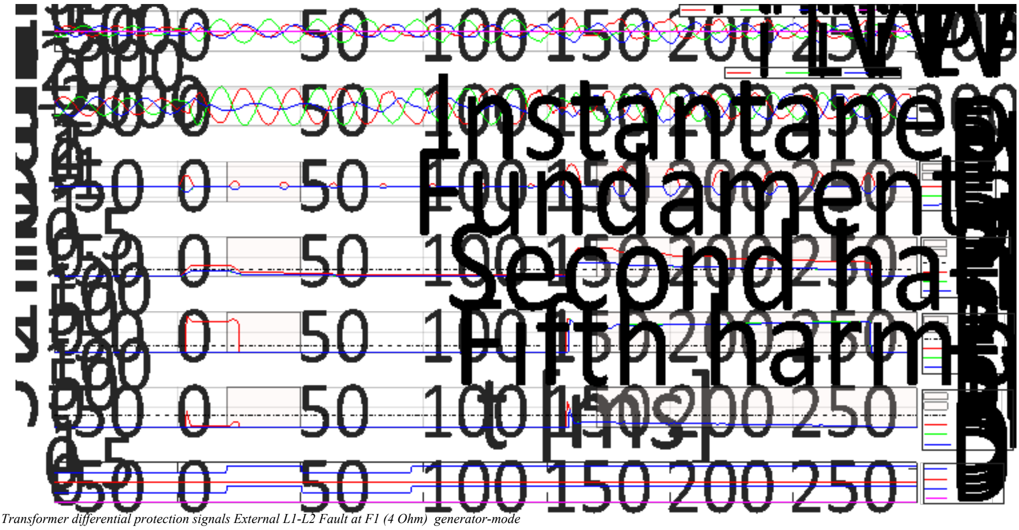
Transformer Differential Protection – Internal Fault



Transformer differential protection signals Internal L1-L2 Fault at F2 (converter side, 0.3 Ohm) Fault

- Differential protection evaluates the differential current precisely one cycle after fault inception. (Shaded rectangle in the above figure)
- At this time point 2nd Harmonic content in differential current at around 20 per cent
- However, because of the sinusoidal waveform „CWA Internal Fault“ is detected, 2nd Harmonic Blocking is blocked, and the „Diff> Operate „ signal is generated as expected

Transformer Differential Protection –External Fault with Fault-recovery and MMC Control-generated Inrush



Transformer differential protection signals External L1-L2 Fault at F1 (4 Ohm) generator-mode

- After 150 milliseconds, the external phase-to-phase fault is cleared, and due to the voltage recovery, fault-recovery inrush occurs
- In the instantaneous differential current, the flat areas are significant, and therefore “Diff> CWA” is detected and Operate blocked
- at the beginning of external fault occurs, an inrush due to coherent voltage waves generated by the MMC current control
- Accordingly. the “Diff> CWA” is detected, and the Operate is blocked

[1] SIEMENS AG, *Numerical Differential Protection Relay for Transformers, Generators ,Motors and Mini Busbars Instruction Manual Siprotec 5 7UT8x*. V6.0 and higher, 2015.