

Contents

| | |
|------------------------------------------------------------------------------|-------------|
| Abstract | v |
| 0.1 Motivation, Research Gap and Objectives of the Thesis | vi |
| 0.2 Contributions and Outline of the Thesis | vii |
| List of Tables | xiii |
| List of Figures | xv |
| Nomenclature | xxv |
| 1 Introduction | 1 |
| 1.1 Outline | 1 |
| 1.2 Literature Survey for Differential Protection of Transformer | 2 |
| 1.3 Motivation, Research Gap, Objectives and scope of the Thesis | 9 |
| 1.4 Outline of The Thesis | 10 |
| 1.5 Summary | 11 |
| 2 Development of Matched Wavelets for Differential Signals | 13 |
| 2.1 Outline | 13 |
| 2.2 Wavelets Families | 14 |
| 2.2.1 Wavelet Transforms [1] | 16 |
| 2.2.2 Refinement Relation | 17 |
| 2.3 Matched Wavelet Theory | 19 |
| 2.3.1 Motivation and Mathematical Foundation | 19 |
| 2.3.2 Filter Coefficients of Matched Wavelet : Problem Formulation | 22 |
| 2.4 Differential Evolution | 25 |
| 2.4.1 DE Algorithm | 26 |

| | | |
|----------|----------------------------------------------------------------------------------------------|-----------|
| 2.4.2 | Repairing Infeasible Solution in DE | 28 |
| 2.5 | Optimal Matched Wavelets using DE | 29 |
| 2.6 | Results and Discussion | 32 |
| 2.6.1 | Comparison with Existing Wavelets | 34 |
| 2.7 | Summary | 36 |
| 3 | Matched Wavelet based Protection of Power Transformers | 39 |
| 3.1 | Outline | 39 |
| 3.2 | System Model and Description | 40 |
| 3.2.1 | Magnetizing Inrush | 40 |
| 3.2.2 | Faults in Power Transformers | 47 |
| 3.2.3 | CT Saturation | 49 |
| 3.2.4 | Effects of CT Saturation on External and Internal Fault Signals | 55 |
| 3.2.5 | Transformer Ratings | 59 |
| 3.2.6 | Robustness | 59 |
| 3.3 | Transformer Differential Protection Scheme | 61 |
| 3.3.1 | Existing Transformer Differential Protection Scheme | 61 |
| 3.3.2 | Proposed Scheme for Transformer Differential Protection | 61 |
| 3.3.3 | Matched Wavelets for Inrush and Fault Waveforms | 63 |
| 3.4 | Results and Discussion | 66 |
| 3.5 | Summary | 70 |
| 4 | Hardware Implementation | 91 |
| 4.1 | Outline | 91 |
| 4.2 | Outline of the Hardware Implementation Studies | 92 |
| 4.3 | Hardware Simulation for Inrush- and Fault-Filter: (Stage-2) | 95 |
| 4.4 | Results of Hardware-Simulation Model (Stage 2): Testing Accuracy of Implementation | 96 |
| 4.5 | Hardware Implementation-I (Stage 3) | 98 |
| 4.5.1 | Waveform-Board Design | 102 |
| 4.5.2 | Filter-Board Design | 106 |
| 4.5.3 | Hardware Set-up (Stage 3) | 109 |
| 4.5.4 | Results and Discussion (Stage 3) | 111 |

| | | |
|----------|------------------------------------------------|------------|
| 4.6 | Hardware Implementation-II (Stage 4) | 112 |
| 4.7 | Hardware Results on a Physical Transformer | 124 |
| 4.7.1 | Inrush Conditions | 124 |
| 4.7.2 | In-zone Fault Conditions | 126 |
| 4.7.3 | External Fault under CT Saturation | 129 |
| 4.7.4 | Energizing Transformer under Faulted Condition | 130 |
| 4.7.5 | Inter-turn Faults | 131 |
| 4.8 | Summary | 132 |
| 5 | Conclusion and Future Scope | 153 |
| 5.1 | Conclusions | 153 |
| 5.2 | Future Scope | 155 |
| | Appendix I | 159 |
| | Appendix II | 161 |
| | References | 162 |

List of Tables

| | | |
|-----|---------------------------------------------------------------------------------------------------------------------|----|
| 2.1 | DE Parameter Values | 29 |
| 3.1 | CT parameters for transformer | 56 |
| 3.2 | Transformer Model Parameters for MATLAB | 59 |
| 3.3 | Transformer Model Parameters for PSCAD Simulator | 59 |
| 3.4 | Threshold and Worst Case Detection Scenario for Inrush Wavelet Filter (K=12, Number of Constraints=14) | 67 |
| 3.5 | Summary Results for Inrush Detection | 70 |
| 3.6 | Summary Results for Fault Detection | 70 |

List of Figures

| | | |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.1 | Taxonomy of literatures on Harmonic Restraint methods. | 4 |
| 1.2 | Taxonomy of literatures on Wave shape methods. | 4 |
| 1.3 | Taxonomy of literatures on Fuzzy Logic Methods. | 5 |
| 1.4 | Taxonomy of literatures on ANN methods. | 6 |
| 1.5 | Taxonomy of literatures on DT based method. | 6 |
| 1.6 | Taxonomy of literatures on Wavelet Analysis (WA) based method. | 8 |
| 2.1 | Matched wavelet (solid line) versus desired signal(dotted) from ref. [2]. Y-axis: Wavelet coefficient values/signal, X-axis: Sample index. | 21 |
| 2.2 | A function close to a ramp function (left) and its matched wavelet(right) taken from ref. [3]. Y-axis: Wavelet coefficient values (right)/signal (left), X-axis: Sample index. | 22 |
| 2.3 | Sequence of operations in DE | 26 |
| 2.4 | Illustration of crossover process for $D = 5$ | 28 |
| 2.5 | Flowchart for DE algorithm | 31 |
| 2.6 | Signal(db6) and its corresponding matched wavelet for $N = 6$ | 33 |
| 2.7 | Signal(db6) and its corresponding matched wavelet for $N = 5$ and 2 constraints | 34 |
| 2.8 | Inrush waveform and matched inrush wavelets | 35 |
| 2.9 | Fault waveform (L-G fault) and matched fault wavelets | 36 |
| 2.10 | Comparison of detection efficiency of wavelets. (a) Normalized differential current waveform (b) Matched wavelet based inrush filter response (c) db4 wavelet based inrush filter response (d) db5 wavelet based inrush filter response (e) db7 based inrush filter wavelet response | 37 |

| | | |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.1 | Differential protection of transformer | 41 |
| 3.2 | Flux produced in the core is in quadrature with applied voltage | 42 |
| 3.3 | Transformer circuit | 42 |
| 3.4 | Primary voltage and flux for one cycle of operation | 43 |
| 3.5 | Inrush current phenomena [4] | 44 |
| 3.6 | Test system for inrush and in-zone faults (source impedance $Z_s = 0.0318\angle -88.1759$) | 45 |
| 3.7 | Test system for generating over-excitation condition (source impedance $Z_s = 0.0318\angle -88.1759$) | 46 |
| 3.8 | Test system for generating sympathetic inrush current (source impedance $Z_s = 0.0318\angle -88.1759$) | 48 |
| 3.9 | Circuit for external fault with CT saturation (source impedance $Z_s = 0.0318\angle -88.1759$) | 50 |
| 3.10 | Test system for inrush and internal faults (source impedance $Z_s = 0.0318\angle -88.1759$) | 51 |
| 3.11 | Circuit for internal fault with CT saturation at 60% winding (source impedance $Z_s = 0.0318\angle -88.1759$) | 52 |
| 3.12 | CT drawing | 53 |
| 3.13 | B-H curve example for different core materials | 53 |
| 3.14 | Primary currents, secondary currents, and magnetic dipoles in the core during symmetrical saturation | 54 |
| 3.15 | Primary currents, secondary currents, and magnetic dipoles in the core during asymmetrical saturation | 55 |
| 3.16 | CT currents for external fault: (a) Primary and secondary CT (LT side) currents (b) Primary and secondary CT (HT side) currents (c) Differential current of the transformer | 57 |
| 3.17 | (a) Zoomed portion of CT secondary differential current (with and without noise) pertaining to in-zone fault (b) CT primary and CT secondary differential current (with and without noise) pertaining to in-zone fault | 58 |

| | |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.18 (a) Zoomed portion of CT secondary differential current (with and without noise) pertaining to internal fault (b) CT primary and CT secondary differential current (with and without noise) pertaining to in-zone fault at 60 % of transformer winding | 58 |
| 3.19 Simulink test system | 60 |
| 3.20 A schematic logic set-up for relay operation (Existing Scheme) | 62 |
| 3.21 A schematic logic set-up for relay operation (Proposed Scheme) | 63 |
| 3.22 Inrush waveform and matched inrush wavelets | 64 |
| 3.23 Fault waveform (L-G fault) and matched fault wavelets | 65 |
| 3.24 (a) Normalized differential current waveform (b) Response of inrush-filter (c) Response of fault-filter | 66 |
| 3.25 Case of magnetizing inrush and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 70 |
| 3.26 Case of over-excitation current and its noisy version for 315 MVA transformer, angle of inception 180° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 71 |
| 3.27 Case of sympathetic inrush current and its noisy version for 315 MVA transformer, angle of inception 180° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 72 |
| 3.28 Case of sympathetic inrush current and its noisy version for 315 MVA transformer with load, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 73 |
| 3.29 Case of magnetizing inrush current and its noisy version for 25 MVA transformer (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 74 |

| | | |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.30 | Case of L-G fault current and its noisy version for 315 MVA transformer, angle of inception 0° with fault resistance 0.01 ohm (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 75 |
| 3.31 | Case of L-G fault current and its noisy version for 25 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 76 |
| 3.32 | Case of 25 MVA transformer energized under fault (L-G fault) at 0° and its noisy version (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 77 |
| 3.33 | Case of L-G fault current and its noisy version for 315 MVA transformer with fault resistance 0.1 ohm , angle of inception 180° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 78 |
| 3.34 | Case of L-G fault current and its noisy version for 315 MVA transformer with fault resistance 0.5 ohm , angle of inception 180° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 79 |
| 3.35 | Case of L-G fault current and its noisy version for 315 MVA transformer with fault resistance 1 ohm , angle of inception 180° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 80 |
| 3.36 | Case of external fault current and its noisy version for 315 MVA transformer, angle of inception 10° (a) Zoomed portion of CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 81 |
| 3.37 | Case of L-G fault current and its noisy version under moderate saturation for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT primary and CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 82 |

| | | |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.38 | Case of inter-turn fault current at 60% of winding and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT primary and CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 83 |
| 3.39 | Case of inter-turn fault current at 20% of winding and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT primary and CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 84 |
| 3.40 | Case of inter-turn fault current at 10% of winding and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT primary and CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 85 |
| 3.41 | Case of inter-turn fault current at 5% of winding and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT primary and CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 86 |
| 3.42 | Case of inter-turn fault current at 2% of winding and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of CT secondary differential current (b) CT primary and CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 87 |
| 3.43 | B-H curve | 87 |
| 3.44 | Case of in-zone fault current where detection fails due to poor CT (CT under high saturation) and its noisy version for 315 MVA transformer, angle of inception 0° (a) Zoomed portion of poor CT secondary differential current (b) CT secondary differential current (c) Response of inrush-filter (d) Response of fault-filter | 88 |
| 4.1 | Details of software implementation (stage 1) | 92 |
| 4.2 | Details of hardware simulation model (stage 2) | 93 |
| 4.3 | Hardware implementation-I (stage 3) | 94 |
| 4.4 | Hardware implementation-II (stage 4) | 94 |
| 4.5 | Schematic diagram for filter unit | 96 |
| 4.6 | Inrush-filter/fault-filter hardware simulation model for two samples | 97 |

| | | |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.7 | (a) Magnetizing inrush current waveform given as input to inrush- and fault- filters (b) Response of inrush-filter (c) Response of fault-filter | 99 |
| 4.8 | (a) Over fluxing current waveform given as input to inrush- and fault-filters (b) Response of inrush-filter (c) Response of fault-filter | 99 |
| 4.9 | (a) In-zone fault without CT saturation given as input to inrush- and fault- filters (b) Response of inrush-filter; the quantization errors in digital im- plementation are evident for very small values of responses (c) Response of fault-filter | 100 |
| 4.10 | (a) In-zone fault (L-G fault) with CT saturation given as input to inrush- and fault-filters (b) Response of inrush-filter; the quantization errors in digital implementation are evident for very small values of responses (c) Response of fault-filter | 101 |
| 4.11 | (a) External fault (L-G fault) with CT saturation given as input to inrush- and fault-filters (b) Response of inrush-filter (c) Response of fault-filter . . | 102 |
| 4.12 | The complete flow of process | 102 |
| 4.13 | Hardware simulation model for creating Input | 103 |
| 4.14 | Recorded simulation waveform for magnetizing inrush using hardware sim- ulation model | 105 |
| 4.15 | Recorded simulation waveform for over-flux inrush waveform using hard- ware simulation model | 107 |
| 4.16 | Recorded simulation waveform for in-zone fault without CT saturation us- ing hardware simulation model | 107 |
| 4.17 | Recorded simulation waveform for in-zone fault (L-G fault) with CT satu- ration using hardware simulation model | 108 |
| 4.18 | Recorded simulation waveform for external fault (L-G fault) without CT saturation using hardware simulation model | 108 |
| 4.19 | Hardware set-up | 110 |
| 4.20 | (CH2) Magnetizing inrush current. (CH1) Response of inrush-filter indi- cating inrush. | 112 |
| 4.21 | (CH2) Magnetizing inrush current. (CH1) Response of inrush-filter indi- cating inrush. | 113 |

| | |
|-----------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.22 (CH2) Magnetizing Inrush current. (CH1) Response of fault-filter indicating no fault. | 114 |
| 4.23 (CH2) In-zone fault (L-G fault) current with low CT saturation. (CH1) Response of fault-filter indicating fault. | 115 |
| 4.24 (CH2) In-zone fault (L-G fault) current with low CT saturation. (CH1) Response of inrush-filter indicating no inrush. | 116 |
| 4.25 (CH2) Over fluxing current. (CH1) Response of inrush-filter indicating inrush. | 117 |
| 4.26 (CH2) Over fluxing current. (CH1) Response of fault-filter indicating no fault. | 118 |
| 4.27 (CH2) External fault (L-G fault) current with CT saturation. (CH1) Response of inrush-filter indicating inrush. | 119 |
| 4.28 (CH2) External fault (L-G fault) current with CT saturation. (CH1) Response of fault-filter indicating no fault. | 120 |
| 4.29 (CH2) In-zone fault (L-G fault) current with moderate CT saturation. (CH1) Response of inrush-filter indicating no inrush. | 121 |
| 4.30 (CH2) In-zone fault (L-G fault) current with moderate CT saturation. (CH1) Response of fault-filter indicating fault. | 122 |
| 4.31 Hardware set-up | 123 |
| 4.32 (CH2) Inrush current. (CH3) Response of inrush-filter indicating inrush. | 125 |
| 4.33 (CH2) Inrush current. (CH3) Response of fault-filter indicating no-fault. | 126 |
| 4.34 (CH2) Inrush current with load. (CH3) Response of inrush-filter indicating inrush. | 127 |
| 4.35 (CH2) Inrush current with load. (CH3) Response of fault-filter indicating no-fault. | 128 |
| 4.36 (CH2) Sympathetic inrush current. (CH3) Response of inrush-filter indicating inrush. | 129 |
| 4.37 (CH2) Sympathetic inrush current. (CH3) Response of fault-filter indicating no-fault. | 130 |
| 4.38 (CH2) Sympathetic inrush current with load. (CH3) Response of inrush-filter indicating inrush. | 131 |

| | | |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.39 | (CH2) Sympathetic inrush current with load. (CH3) Response of fault-filter indicating no-fault. | 132 |
| 4.40 | (CH2) Fault (L-G fault) current under low CT saturation. (CH3) Response of inrush-filter indicating no-inrush. | 133 |
| 4.41 | (CH2) Fault (L-G fault) current under low CT saturation. (CH3) Response of fault-filter indicating fault. | 134 |
| 4.42 | (CH2) Fault (L-G fault) current under moderate CT saturation. (CH3) Response of inrush-filter indicating no-inrush. | 135 |
| 4.43 | (CH2) Fault (L-G fault) current under moderate CT saturation. (CH3) Response of fault-filter indicating fault. | 136 |
| 4.44 | (CH2) Fault (L-G fault) current under high CT saturation. (CH3) Response of inrush-filter indicating no-inrush. | 137 |
| 4.45 | (CH2) Fault (L-G fault) current under high CT saturation. (CH3) Response of fault-filter indicating fault. | 138 |
| 4.46 | (CH2) Fault (L-G fault) current with fault resistance = 0.1 <i>ohm</i> . (CH3) Response of inrush-filter indicating no-inrush. | 139 |
| 4.47 | (CH2) Fault (L-G fault) current with fault resistance = 0.1 <i>ohm</i> . (CH3) Response of fault-filter indicating fault. | 140 |
| 4.48 | (CH2) Fault (L-G fault) current with fault resistance = 0.5 <i>ohm</i> . (CH3) Response of inrush-filter indicating no-inrush. | 141 |
| 4.49 | (CH2) Fault (L-G fault) current with fault resistance = 0.5 <i>ohm</i> . (CH3) Response of fault-filter indicating fault. | 142 |
| 4.50 | (CH2) Fault (L-G fault) current with fault resistance = 1 <i>ohm</i> . (CH3) Response of inrush-filter indicating no-inrush. | 143 |
| 4.51 | (CH2) Fault (L-G fault) current with fault resistance = 1 <i>ohm</i> . (CH3) Response of fault-filter indicating fault. | 144 |
| 4.52 | (CH2) External fault (L-G fault) current. (CH3) Response of inrush-filter indicating inrush. | 145 |
| 4.53 | (CH2) External fault (L-G fault) current. (CH3) Response of fault-filter indicating no-fault. | 146 |
| 4.54 | (CH2) Transformer fault current when energized under in-zone fault (L-G fault). (CH3) Response of inrush-filter indicating no-inrush. | 147 |

| | | |
|------|------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 4.55 | (CH2) Transformer fault current when energized under in-zone fault (L-G fault). (CH3) Response of fault-filter indicating fault. | 148 |
| 4.56 | (CH2) Inter-turn fault current at 80% of winding. (CH3) Response of inrush-filter indicating no-inrush. | 149 |
| 4.57 | (CH2) Inter-turn fault current at 80% of winding. (CH3) Response of fault-filter indicating fault. | 150 |
| 4.58 | (CH2) Inter-turn fault current at 50% of winding. (CH3) Response of inrush-filter indicating no-inrush. | 151 |
| 4.59 | (CH2) Inter-turn fault current at 50% of winding. (CH3) Response of fault-filter indicating fault. | 152 |