# Islanding and Faults Detection in Utility Grid Integrated With Solar Renewable Energy Source Using Signal Processing and Machine Learning Algorithms

*A Thesis submitted by*
**Mahmood Shaik**

*in partial fulfillment of the requirements for the award of the degree of*
**Doctor of Philosophy**




॥ त्वं ज्ञानमयो विज्ञानमयोऽसि ॥

**Indian Institute of Technology Jodhpur**
**Department of Electrical Engineering**
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# Declaration

I hereby declare that the work presented in this Thesis titled "*Islanding and Faults Detection in Utility Grid Integrated With Solar Renewable Energy Source Using Signal Processing and Machine Learning Algorithms*" submitted to the Indian Institute of Technology Jodhpur in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Dr. Sandeep Kumar Yadav. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.



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# Certificate

This is to certify that the thesis titled "*Islanding and Faults Detection in Utility Grid Integrated With Solar Renewable Energy Source Using Signal Processing and Machine Learning Algorithms*", submitted by *Mahmood Shaik (P15VSS005)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



*Dr.Sandeep Kumar Yadav*
*Ph.D.Thesis Supervisor*

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# List of Symbols

| | |
|---|---|
| $Z(t)$ | Analytic function. |
| $\phi(t)$ | Angle of rotation in positive direction. |
| $\psi(t)$ | Angle of rotation in negative direction. |
| $\Theta(t)$ | Angular coordinate of normal polar coordinate system. |
| $\theta_s$ | Angle of symmetry. |
| $a(M, N)$ | Alienation coefficient of two matrices $M, N$. |
| $D_{Actual}$ | Actual fault distance from the substation. |
| C | Cost Parameter. |
| $\mathrm{E}_{cv}(\mathrm{c})$ | Cross validation error. |
| $\hat{x}_k$ | Current state estimate. |
| $I_{DG}$ | Current contributed by Distributed Generation. |
| $I_A$, $I_B$, $I_C$ | currents in Phases A,B and C respectively. |
| $I_{UG}$ | Current contributed by Utility Grid. |
| $r(M, N)$ | Correlation coefficient of two matrices $M, N$. |
| $A, B, b$ | Constants. |
| $\sigma(f)$ | Control parameter of the Gaussian window. |
| $P_{correct}$ | Correct predictions. |
| $\{u_{ts}, v_{ts}\}$ | DT Training samples. |
| $d_i$ | Dilation parameter of the wavelet. |
| $d$ | Delayed samples. |
| $E_{Signal}$ | Energy of the signal. |
| $E_{Noise}$ | Energy of the random noise. |
| $ds$ | Estimated fault location. |
| $Z_{m-n}$ | Equivalent impedance between nodes $m$ and $n$. |
| $D_{Estimated}$ | Estimated fault location. |
| $I_F$ | Fault current. |
| $I_A^{'}$, $I_B^{'}$, $I_C^{'}$ | Fault currents entering the phases A,B and C through neutral N. |
| $\mathrm{IMF}_1$ | First level intrinsic mode function. |
| $\mathrm{R}_1$ | First level residue. |
| $F(s)$ | Fourier transform for any function of $f(x)$. |
| $T_F$ | Fault threshold. |
| K | Gain parameter in SDP. |
| $S(\tau, \omega)$ | Gabor transform signal. |
| $\mu_t$, $\Delta_t$ | Gabor transform center and radius parameter. |
| $T_G$ | Ground fault threshold. |
| $H(t)$ | Hilbert transform of the residue $\mathrm{R}_1(\mathrm{t})$. |
| $Amp(t)$ | Instantaneous amplitude. |
| $\theta(t)$ | Instantaneous phase. |
| $\omega(t)$ | Instantaneous frequency. |
| $K_f$ | Kernel Function. |
| $\gamma$ | Kernel Parameter. |
| $K_k$ | Kalman gain. |
| $Zl$ | Line Impedance Matrix. |
| $I_L$ | Load current. |
| $L_l$ | Line length. |
| $M_s$ | Margin. |

| | |
|---|---|
| $h$ | Mother wavelet. |
| $\bar{M}$, $\bar{N}$ | Mean of the matrices $M, N$ |
| $S_{max}$, $S_{min}$ | Maximum and minimum values of signal. |
| $Z_k$ | Measurement value in Kalman Filter. |
| $I_n$ | Neutral current. |
| $V_n$ | Nominal Voltage. |
| $f_n$ | Nominal frequency. |
| $N_o$ | Number of observations. |
| $f(n)$ | One-dimension signal with domain $D[f] \subset E$. |
| $V_m$ | Pre-fault Voltage at node $m$. |
| $I_{m-n}$ | Pre-fault current between nodes $m$ and $n$. |
| $R^n$ | Real Numbers. |
| $A(t)$ | Radial coordinate. |
| $E(c)$ | Redistribution error. |
| $re, im$ | Real and Imaginary parts. |
| $\{x_p, y_p\}$ | SVM Training samples. |
| $\alpha$ | Scale parameter of the wavelet function. |
| $sgn$ | Signal function. |
| $\omega(\tau, d_i)$ | Scaled replica of the fundamental mother wavelet. |
| $g(n)$ | Structure element with domain $D[g] \subset E$. |
| $V_s$ | Sending end voltage. |
| $\tau$ | Translation parameter of the wavelet function. |
| $f(t)$ | Time-varying signal. |
| $t_P$ | Travel time from $P$ to fault. |
| $t_Q$ | Travel time from $Q$ to fault. |
| $t_d$ | Time delay. |
| $I_s$ | Upstream current vector. |
| $\alpha_p$ | Variable of Cost Parameter. |
| $w_{ts}$ | Value of the weighting variable for case $ts$. |
| $v_{ts}$ | Value of the response variable. |
| $f_{ts}$ | Value of the frequency variable. |
| $w$ | Vector of weights. |
| $v$ | Velocity of travelling waves. |
| $T_w(n)$ | Weighted number of cases in node $n$. |
| $\overline{v}$ | Weighted mean for node $n$. |
| $WT(\alpha, \tau)$ | Wavelet function. |
| $g(t)$ | Window function. |

# List of Abbreviations

| | |
|---|---|
| AM | Absolute Mean |
| ANN | Artificial Neural Network |
| AFD | Active Frequency Drift |
| ANFIS | Adaptive Neuro Fuzzy Inference System |
| AIS | Artificial Immune System |
| BELM | Bidirectional Extreme Learning Machine |
| CIGRE | International Council on Large Electric Systems |
| CERTS | Consortium for Electric Reliability Technology |
| CVR | Core Vector Regression |
| CWT | Continous Wavelet Transform |
| CEEDMAN | Complete Ensemble Empirical Mode Decomposition with Adaptive Noise |
| CNN | Convolutional Neural Network |
| CT | Current Transformer |
| DG | Distributed Generator |
| DFT | Discrete Fourier Transform |
| DWT | Discrete Wavelet Transform |
| DM | Data Mining |
| DT | Decision Tree |
| DTC/R | Decision Tree Classification/Regression |
| DEDF | Dilate Erode Difference filter |
| DFST | Discrete Fast S-Transform |
| EMD | Empirical Mode Decomposition |
| ELM | Extreme Learning Machine |
| ETC | Ensemble Tree Classifier |
| FT | Fourier Transform |
| FFNN | Feed Forward Neural Network |
| FDST | Fast Discrete S-Transform |
| FIA | Fault Incidence Angle |
| FDT | Fault Detection Time |
| FLT | Fault Location Time |
| FI | Fault Index |
| FPI | Faulty phase Indices |
| FJ | Frequency Jump |
| FPGA | Field Programmable Gate Array |
| FTT | Fourier Taylor Transformation |
| FTU | Feeder Terminal Unit |
| GPS | Global Positioning System |
| GA | Goertzel Algorithm |
| GWT | Gabor-Wigner Ville Transform |
| GA | Genetic Algorithm |
| GDI | Gini Diversity Index |
| GEFS | General Electric Frequency Schemes |
| HHT | Hilbert-Huang Transform |
| HPI | Healthy Phase Indices |
| HST | Hyperbolic S-Transform |
| HIF | High Impedance Fault |

| | |
|---|---|
| IEEE | Institute of Electrical and Electronics Engineers |
| ICT | Interconnecting Transformer |
| IF | Instantaneous Frequency |
| IA | Instantaneous Amplitude |
| IDM | Islanding Detection Method |
| IDT | Islanding Detection Time |
| KF | Kalman Filter |
| LG | Line to Ground |
| LLG | Double line to Ground |
| LLLG | Triple Line to Ground |
| ML | Machine Learning |
| MM | Mathematical Morphology |
| MI | Mutual Information |
| NC | Not Considered |
| NDZ | Non Detection Zone |
| OSD | Optimal Steepest Descent. |
| 1D | One-Dimensional |
| p.u | Per Unit |
| PCC | Point of Common Coupling |
| PNN | Probabilistic Neural Network |
| PFD | Post Fault Data |
| PSO | Particle Swarm Optimization |
| PQ | Power Quality |
| PQD | Power Quality Disturbance |
| PV | Photovoltaic |
| PJD | Phase Jump Detection |
| PMU | Phasor Measurement Unit |
| PLCC | Power Line Carrier Communication |
| PT | Potential Transformer |
| PC | Personal Computer |
| RES | Renewable Energy Source |
| ROCOP/F | Rate Of Change Of Power/Frequency |
| ROCOFOP | Rate Of Change Of Frequency Over Power |
| RF | Random Forest |
| RBFNN | Radial Basis Function Neural Network |
| ReLU | Rectified Linear Unit Function |
| RTDS | Real TIme Digital Simulator |
| RAM | Random Access Memory |
| SP | Signal Processing |
| STFT | Short Time Fourier Transform |
| ST | S-Transform |
| SVM | Support Vector Machine |
| SVR | Support Vector Regression |
| SDP | Symmetrical Dot Pattern |
| SD | Standard Deviation |
| SDIF | Standard Deviation of Instantaneous Frequency |
| SDIA | Standard Deviation of Instantaneous Amplitude |
| SNR | Signal to Noise Ratio |
| SF | Sampling Frequency |
| SEIG | Self Excited Induction Generator |
| SVS | Sandia Voltage Shift |
| SMS | Slip Mode frequency Shift |
| SHD | Selected Harmonic Distortion |

| | |
|---|---|
| SVD | Singular Value Decomposition |
| TTT | Time-Time Transform |
| THD | Total Harmonic Distortion |
| TKEO | Teager-Kaiser Energy Operator |
| 2D | Two-Dimensional |
| VSC | Voltage Source Control |
| WT | Wavelet Transform |
| WPT | Wavelet Packet Transform |
| WBELM | Weighted Bidirectional Extreme Learning Machine |
| WSEI | Wavelet Singular Entropy Index |
| WFNN | Wavelet Fuzzy Neural Network |