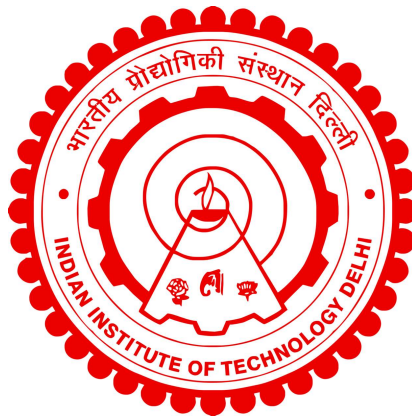


REAL-TIME MODELLING AND PROTECTION OF MICROGRID

RUCHI CHANDRAKAR



DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

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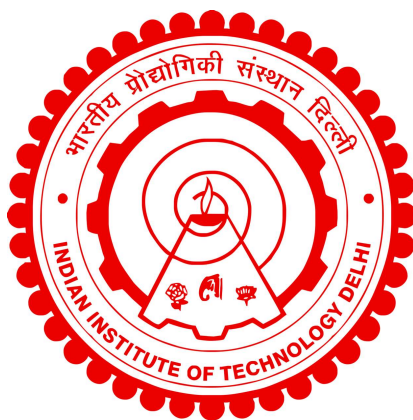
RUCHI CHANDRAKAR

Department of Electrical Engineering

Submitted

in the fulfillment of the requirements of the degree of Doctor of Philosophy

to the



Indian Institute of Technology Delhi

July 2024

Dedicated
to
My Family

Certificate

This is to certify that the thesis entitled “**Real-Time Modelling and Protection of Microgrid**”, submitted by **Ruchi Chandrakar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy (Ph.D.)** in Electrical Engineering, is a record of the original, bona fide research work carried out by her under our supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

Prof. Bijaya Ketan Panigrahi
Department of Electrical Engineering,
Indian Institute of Technology Delhi
New Delhi-110016, India.

Date:

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Ruchi Chandrakar

Abstract

The conventional distribution system is currently experiencing significant reconfiguration due to the penetration of distributed energy resources and energy storage systems. The microgrid operation in presence of distributed generation led to several technical challenges to the conventional control and protection methodologies. They are not applicable in a DG penetrated distribution system. This thesis first develops the microgrid system to analyze the phenomena of the power systems of a new era. Then, this work overcomes the unintentional islanding detection challenges of droop-controlled grid-forming inverters (GFMI). The conventional Islanding Detection Techniques (IDT) are ineffective in GFMI due to the impact of power control droop parameters on the Non-detection Zone (NDZ). Furthermore, the active IDTs may cause disturbances in the working operation of the GFMI due to their opposite functionality. Thus, there is a need to develop adequate IDTs which can perform robustly even with unconventional droop parameters and helps in maintaining the GFMI functions. The new methods developed for islanding detection are capable to detect even during the critical scenarios of weak-grid condition, nonlinear loading condition, and noise/distortion scenarios. The proposed methods are superior in accuracy and detection time (DT) compared to the other conventional techniques.

Furthermore, the conventional protection schemes such as over-current and earth-fault protections available in the distribution system usually fail to operate due to low magnitude of fault current (usually in the range of a few mA) during the High-Impedance Fault (HIF) condition and thus, HIF gets mostly undetected. These types of fault occur whenever an energized conductor makes contact with some high-impedance surfaces that are poor conductors such as asphalt, sand, concrete, etc. In order to overcome this challenge, this work develops a new high-impedance fault model that is able to demonstrate the HIF characteristics accurately even with DG penetration. A novel linear time-frequency-based tool is introduced for HIF identification. The main contributions of the proposed method are viz., it can correctly distinguish HIF from severe faults, switching events, energization scenarios, and noisy environments. The algorithm has been compared with the previously reported HIF detection techniques, and the efficacy of the method is presented through real-time simulation results. It has a fast detection time and less computational burden.

All propositions are validated from theory, by offline and real-time simulation case-studies as well as on the laboratory scale experimental setup. Real-time validation has been executed using hardware test bed setup, including the RTDS simulator, the SEL-relay, and the OPAL-RT simulator. The demonstrated real-time results validate the effectiveness of the proposed detection algorithms for the protection of complex DG-penetrated distribution systems.

Keywords: Islanding Detection Technique, Droop-controlled Inverters, Grid-Forming Inverter, Non-Detection Zone, Total Harmonic Distortion, Long-short-Term Memory network, High impedance fault, Distortion, Synchro-Squeezing Transform, Reconstruction Error, Phase current.

सार

पारंपरिक वितरण प्रणाली वर्तमान में वितरित ऊर्जा संसाधनों, साथ ही ऊर्जा भंडारण प्रणालियों के प्रवेश के कारण महत्वपूर्ण पुनर्संरचना का अनुभव कर रही है। वितरित पीढ़ी की उपस्थिति में माइक्रोग्रिड संचालन ने पारंपरिक नियंत्रण और सुरक्षा पद्धतियों के लिए कई तकनीकी चुनौतियों का सामना किया। वे डीजी प्रवेशित वितरण प्रणाली में लागू नहीं हैं। यह थीसिस सबसे पहले नए युग की बिजली प्रणाली घटना का विश्लेषण करने के लिए वास्तविक समय माइक्रोग्रिड विकसित करती है। फिर, यह कार्य डूप-नियंत्रित ग्रिड-फॉर्मिंग इनवर्टर (जीएफएमआई) की अनजाने द्वीपीकरण पहचान चुनौतियों पर काबू पाता है। नॉन-डिटेक्शन जोन (एनडीजेड) पर पावर कंट्रोल ड्रॉप पैरामीटर्स के प्रभाव के कारण पारंपरिक आइलैंडिंग डिटेक्शन तकनीक (आईडीटी) जीएफएमआई में अप्रभावी हैं। साथ ही, सक्रिय आईडीटी अपनी विपरीत कार्यक्षमता के कारण जीएफएमआई के कामकाज में गड़बड़ी पैदा कर सकते हैं। इस प्रकार, पर्याप्त आईडीटी विकसित करने की आवश्यकता है जो अपरंपरागत डूप मापदंडों के साथ भी मजबूती से प्रदर्शन कर सके और जीएफएमआई कार्यों को बनाए रखने में मदद कर सके। आइलैंडिंग का पता लगाने के लिए विकसित की गई नई विधियां कमजोर-ग्रिड स्थिति, गैर-रेखीय लोडिंग स्थिति और शोर/विरूपण परिदृश्यों के महत्वपूर्ण परिदृश्यों के दौरान भी पता लगाने में सक्षम हैं। प्रस्तावित विधियां अन्य पारंपरिक तकनीकों की तुलना में सटीकता और पता लगाने के समय (डीटी) में बेहतर हैं।

इसके अलावा, वितरण प्रणाली में उपलब्ध पारंपरिक सुरक्षा योजनाएं जैसे कि ओवर-करंट और अर्थ-फॉल्ट सुरक्षा आमतौर पर हाई-इम्पीडेंस फॉल्ट (एचआईएफ) के दौरान फॉल्ट करंट के कम परिमाण (आमतौर पर कुछ एमए की सीमा में) के कारण संचालित होने में विफल रहती हैं। स्थिति और इस प्रकार, एचआईएफ का अधिकांशतः पता नहीं चल पाता है। इस प्रकार की खराबी तब होती है जब एक ऊर्जावान कंडक्टर कुछ उच्च-प्रतिबाधा सतहों के साथ संपर्क बनाता है जो डामर, रेत, कंक्रीट इत्यादि जैसे खराब कंडक्टर होते हैं। इस चुनौती को दूर करने के लिए, यह कार्य एक नया उच्च-प्रतिबाधा गलती मॉडल विकसित करता है जो डीजी प्रवेश के साथ भी एचआईएफ विशेषताओं को सटीक रूप से प्रदर्शित करने में सक्षम है। एचआईएफ पहचान के लिए एक नया रैखिक समय-आवृत्ति-आधारित उपकरण पेश किया गया है। प्रस्तावित विधि का मुख्य योगदान यह है कि यह एचआईएफ को गंभीर दोषों, स्विचिंग घटनाओं, ऊर्जा परिदृश्यों और शोर वाले वातावरण से सही ढंग से अलग कर सकता है। एल्गोरिदम की तुलना पहले रिपोर्ट की गई एचआईएफ पहचान तकनीकों से की गई है और विधि की प्रभावकारिता वास्तविक समय सिमुलेशन परिणामों के माध्यम से प्रस्तुत की गई है। इसमें तेजी से पता लगाने का समय और कम कम्प्यूटेशनल बोझ है।

सभी प्रस्तावों को सिद्धांत से, ऑफ़लाइन और वास्तविक समय सिमुलेशन केस-स्टडी के साथ-साथ प्रयोगशाला-पैमाने पर प्रयोगात्मक सेटअप द्वारा मान्य किया जाता है। आरटीडीएस सिमुलेटर, एसईएल-रिले और ओपीएल-आरटी सिमुलेटर सहित हार्डवेयर परीक्षण बेड सेटअप का उपयोग करके वास्तविक समय सत्यापन निष्पादित किया गया है। प्रदर्शित वास्तविक समय के परिणाम जटिल डीजी-प्रवेशित वितरण प्रणालियों की सुरक्षा के लिए प्रस्तावित पहचान एल्गोरिदम की प्रभावशीलता को मान्य करते हैं।

कीवर्ड: आइलैंडिंग डिटेक्शन तकनीक, डूप-नियंत्रित इनवर्टर, ग्रिड-फॉर्मिंग इनवर्टर, नॉन-डिटेक्शन जोन, टोटल हार्मोनिक डिस्टॉर्शन, लॉन्ग-शॉर्ट-टर्म मेमोरी नेटवर्क, हाई इम्पीडेंस फॉल्ट, डिस्टॉर्शन, सिंक्रो-स्क्वीजिंग ट्रांसफॉर्म, रिकंस्ट्रक्शन एरर, फेज़ प्रवाह ।

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Abbreviations

THD	T otal H armonic D istortion
VTHD	V oltage T otal H armonic D istortion
ITHD	C urrent T otal H armonic D istortion
RMS	R oot M ean S quare
PCC	P oint of C ommon C oupling
IDT	I slanding D etection T echnique
IDF	I slanding D etection F actor
IDX	I slanding D etection I ndex
FFT	F ast F ourier T ransform
DT	D etection T ime
PI	P roportional I ntegral
UVP	U nder V oltage P rotection
OVP	O ver V oltage P rotection
UFP	U nder F requency P rotection
OFP	O ver F requency P rotection
GFMI	G rid F orming I nverter
GFLI	G rid F ollowing I nverter
NDZ	N on D etection Z one
PWM	P ulse W idth M odulation
IBR	I nverter B ased R esources
AWF	A daptive W eighing F actor
RLC	R esistance I nductance C apacitance
CB	C ircuit B reaker
UDP	U nconventional D roop P arameter
ROCOV	R ate O f C hange O f V oltage
ROCOF	R ate O f C hange O f F requency

P-IDT	Proposed Islanding Detection Technique
RT	Real Time
LSTM	Long Short Term Memory
P-IDM	Proposed Islanding Detection Method
RNN	Recurrent Neural Network
ANN	Artificial Neural Network
UDP	Unconventional Droop Coefficients
MSO	Mixed Signal Oscilloscope
ELM	Extended Learning Machine
NB	Naive Bayes
SVM	Support Vector Machine
LR	Logistic Regression
EC	Ensemble Classifier
DT	Decision Tree
KNN	K-Nearest Neighbour
HIF	High Impedance Fault
SST	Synchro Squeezing Transform
STFT	Short Time Fourier Transform
CWT	Continuous Wavelet Transform
DWT	Discrete Wavelet Transform
EV	Electric Vehicle
SOC	State Of Charge

Symbols

R	Resistance
L	Inductance
C	Capacitance
P	Active Power
Q	Reactive Power
δV	Change in Voltage
δP	Change in active power
δQ	Change in reactive power
δf	Change in frequency
ΔP	Active power mismatch
ΔQ	Reactive power mismatch
Z_G	Grid Impedance
M_p	Active droop-coefficient
M_q	Reactive droop-coefficient
Z_L	Load Impedance
T_f	Time-frequency
u	Dilation parameter
v	Time shift
ω	angular frequency
ω_l	center frequency
E	Reconstruction Error
M	Overlapping Number
R_g, L_g	Grid equivalent impedance
R_f, L_f, C_f	RLC filter
θ	angular displacement
V_{oc}	Open-circuit voltage

I_{sc}	Short-circuit current
$\frac{dP}{dt}$	Rate of Change of Active Power
$\frac{dQ}{dt}$	Rate of Change of Reactive Power
$\frac{df}{dt}$	Rate of Change of Frequency
$\frac{dV}{dt}$	Rate of Change of Voltage
Q_f	Quality Factor
V_1	Fundamental component of voltage
I_1	Fundamental component of current
V_h	Harmonic component of voltage
I_h	Harmonic component of current
I_t	Input gate
F_t	Forget gate
H_t	Hidden gate
O_t	Output gate
c_t	Memory cell
x_t	Input function
H_{t-1}	Previous hidden state
C_{t-1}	Last memory cell
H_t	New hidden state
b_i, b_f, b_o, b_c	Bias vectors
Y	Target response
$\hat{Y}$	Predicted response
t_o	Observation time
t_{LSTM}	LSTM test time
V_{rms}	RMS Voltage
I_{rms}	RMS Current
R_f	Fault resistance