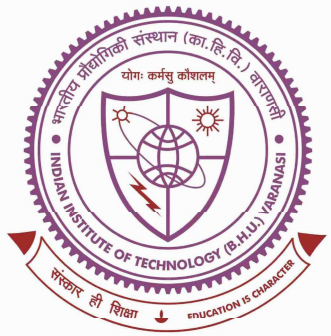
Traveling wave based protection and fault localization scheme for multi terminal HVDC grid and converter interfaced HVAC network



Thesis submitted in partial fulfillment
for the award of degree

Doctor of Philosophy

by

Mahitosh Banafer

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2023

Dedicated

To

My Parents &
Lord Vishwanath Ji

CERTIFICATE

It is certified that the work contained in the thesis titled **Traveling wave based protection and fault localization scheme for multi terminal HVDC grid and converter interfaced HVAC network** by **Mahitosh Banafer** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree. It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and State of the Art (SOTA) for the award of Ph.D. Degree.

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DECLARATION

I, **Mahitosh Banafer**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. Soumya R. Mohanty** from 01-Jan-2019 to 20-October-2023, at the Departement of Electrical Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the researchers wherever their works have been cited in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, thesis, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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Date: 21-02-2024 Mahitosh Banafer

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Nomenclature

Abbreviations

ACCB	AC circuit breaker
ADC	Analog to digital
AFL	Actual fault location
AT	Arrival time
CHIL	Control hardware in loop
CFL	Calculated fault location
CTD	Coordinated time delay
CWT	Continuous wavelet transform
DFR	Digital fault recorder
DPU	Data processing unit
EPT	Electric potential transducer
FCL	Fault current limiter
FLE	Fault location error
GTDI	Giga-transceiver digital input
GPIO	General purpose input/output
GTAI	Giga-transceiver analog input
GTAO	Giga-transceiver analog output
GOOSE	Generic object oriented substation event
HDCCB	Hybrid DC circuit breaker
HVDC	High voltage direct current
HVAC	High voltage AC
IGBT	Insulated gate bipolar transistor
IMF	Intrinsic mode function

LCC	Line commutated converter
LG	Line-to-ground fault
LL	Line-to-line fault
LLL	line-to-line-to-line (three phase fault)
LVRT	Low voltage ride through
MTDC	Multi terminal high voltage direct current
MMC	Modular multilevel converter
MUDW	Morphological un-decimated wavelet
MMG	Mathematical morphological gradient
NPG	Negative pole-to-ground
OCT	Optical current transducer
OHTL	Overhead transmission line
OCCO	Opening-closing-closing-opening filter
PTP	Precision time protocol
PCA	Principal component analysis
PP	Pole-to-pole fault
PPG	Positive pole-to-ground fault
PMU	Phasor measurement unit
PCC	Point of common coupling
ROCOV	Rate of change of voltage
RTDS	Real time digital simulator
SE	Structure element
STDFT	Short time discrete Fourier transform
SVD	Singular value decomposition
SNR	Signal-to-noise-ratio
SATD	Surge arrival time difference
SMPM	Sliding matrix pencil method
TW	Traveling wave
TWAT	Traveling wave arrival time
VSC	Voltage source converter
VMD	Variational mode decomposition
VF	Velocity factor

WABPS	Wide area backup protection scheme
ZCP	Zero crossing point

Symbols and variables

$\psi_i^{\uparrow}$	Signal analysis operator
$\psi_i^{\downarrow}$	Signal synthesis operator
$\omega_i^{\uparrow}$	Detail analysis operators
δ	Dilation operator
ε	Erosion operator
γ	Opening operator
i_d	Identity operator
ϕ	Closing operator
$\oplus$	Dilation operation
$\ominus$	Erosion operation
$\circ$	Opening operation
$\bullet$	Closing operation
Z_{in}	Internal zone
Z_{fe}	Forward external zone
Z_{be}	Backward external zone
x	per unit length of transmission line
ζ	Threshold value
Δt	Sampling time period
M	length of SE
α	Damping factor
β	Phase constant
α_S	Skin-effect loss in TW
α_D	Dielectric loss in TW
α_G	Conductivity of dielectric loss in TW
α_R	Radiation loss in TW
Σ	Diagonal matrix containing the singular or eigenvalues of Matrix in SVD
p	Filtering parameter
L	Pencil parameter

σ	Singular value
R	Left side unitary matrix of SVD
S	Right side unitary matrix of SVD
b	Regression coefficient
n	Nodes of graph theory
b	Branches of graph theory
w	Weight of branches in graph theory
$P^{min}_{n_1,n_2}$	Shortest path between two nodes n_1 and n_2
g	Graph network
D_{n_1,n_2}	Distance between nodes n_1 and n_2
l_x	length of x transmission line
t_x	TWAT at bus x
v_{TW}	velocity of traveling wave
v_{m0}	mode-0 DC voltage
v_{m1}	mode-1 DC voltage
i_{m0}	mode-0 DC current
i_{m1}	mode-1 DC current
v_p	Positive pole DC voltage
v_n	Negative pole DC voltage
i_p	Positive pole DC current
i_n	Negative pole DC current
P_x	Polarity of traveling wave at x
f_1	Sampling frequency is 500 kHz (High)
f_2	Sampling frequency is 50 kHz (Low)
u_α	Aerial mode signal of Karenbauer transformation
u_β	Aerial mode signal of Karenbauer transformation
u_0	Ground mode signal of Karenbauer transformation