To the one and all.

LORD RAMA

卐 एकं सत् विप्र बहुत वदन्ति 卐

CERTIFICATE

It is certified that the work contained in the thesis titled **Monitoring, Analysis, and Control of Integrated Transmission and Distribution System under the purview of ATC/ADC considering Blockchain based energy transaction** by **Devesh Shukla** 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 SOTA for the award of Ph.D. Degree.

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I, **Devesh Shukla**, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of **Prof. S. P. Singh** from July-2015 to September-2020, at the Department 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 research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, 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: -

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List of Abbreviations and Symbols

Ld	Be the set representing all the load buses in the system.
n_{sink}	Number of load buses in sink area.
l	Subset of Ld representing all the load buses in the sink area.
s	Subset of Gen representing gen buses in source area.
x_i	Load at i^{th} bus.
x_{oi}	Initial load at i^{th} bus.
x_{min}	Lower limit of the variable.
φ_i	Represents pattern set.
φ_i^l	Represents i^{th} pattern vector of pattern set.
φ_i'	Represents transpose of φ_i.
ζ	Mesh Size.
P_{gi}	Active Power injected at i^{th} bus.
P_{di}	Active Power drawn at i^{th} bus.
Q_{gi}	Reactive Power injected at i^{th} bus.
Q_{di}	Reactive Power drawn at i^{th} bus.
P_{ij}	Power flowing in line connecting buses i, j.
P_{ij}^{max}	Maximum permissible power flow through line connecting buses i, j.
Q_{gi}^{max}	Upper limit of reactive power generation of i^{th} generator.
Q_{gi}^{min}	Lower limit of reactive power generation of i^{th} generator.
V_i	Voltage of i^{th} bus.
V_i^{min}	Lower limit of voltage permissible at i^{th} bus.

V_i^{max}	Upper limit of voltage permissible at i^{th} bus.
N	Total number of bus in the system.
M	Total number of generator buses.
L	Total number of lines.
TTC	Total Transfer Capability.
CBM	Capacity Benefit Margin.
TRM	Transmission Reliability Margin.
ETC	Existing Transmission Commitments.
ATC	Available Transfer Capability.
ANN	Artificial Neural Network.
GPS	Generalized Pattern Search.
GTNET	Giga-Transceiver Network Communication Card.
SKT	Socket Protocol
GTSYNC	Synchronization Card.
RTDS	Real Time Digital Simulator.
TSO, DSO	Transmission, Distribution system operator.
TN, DN	Transmission, Distribution network.
TS, DS	Transmission system, Distribution system level.
DER	Distributed energy resources.
PV DER	Solar PV based distributed energy.
WIND DER	Wind based distributed energy.
VVC	Volt-VAR control devices.
ADN	Active distribution network.
ADS	Active distribution system.

TNO	Transmission network optimizer.
ITD	Integrated Transmission and Distribution framework
$T\&D$	Transmission and Distribution System
MAS	Multi-Agent System.
EV	Electric Vehicle.
MG	Micro-grid.
RTCA	Real-Time Contingency Analysis.
VVO	Volt-VAR Optimization.
EVSE	Electrical vehicle supply equipment.
$\mathcal{A}, \alpha$	Agent vector.
$\mathcal{A}_i^j$	j^{th} component of i^{th} agent vector.
na	Cardinality of agent vector.
na_i	Cardinality of i^{th} agent vector.
$\mathcal{A}gent2tr, tr2\mathcal{A}gent$ $\mathcal{A}gent2dn, dn2\mathcal{A}gent$	Subroutine protocols invoked by MAS.
$Pd_t^{pcc,i}$	Total load at i^{th} pcc node at time t.
α_{Pd}^{DN}	agent component containing the equivalent load of ADN
P_{PV}^i, P_w^i	Power output of PV and wind at i^{th} bus.
$P^{inv}, P_{losses}^{inv}$	PV inverter power output and losses.
ADS_{load}	Aggregated load of active distribution system.
$Q^{inv}, \eta_{inv}, S^{max}$	PV invertor reactive power, efficiency and maximum rating of smart inverter.
v, v_{ci}, v_{co}, v_N	Velocity, cut in, cut out, and nominal wind velocity
B_{svc}	Equivalent susceptance of SVC.
PD^{TS}	Load at transmission level.

ADS_{Pd}^{DS}	Agent component containing aggregated load of ADS.
$X_C, X_L, \alpha_f, X_{TCSC}$	Capacitive, inductive reactance, firing angle and equivalent reactance of TCSC.
Pd^{DS}	Net load of active distribution feeder.
τ	The number of active distribution feeders.
SoC	The state of Charge.
ρ	Probability of requesting connection by EV from charging station.
η_{sk}	Skewness factor.
E^{EV}, P^{EV}	EV energy, Power absorbed or injected.
l_{oc}, v_{id}	Location of EV, vehicle identity.
c^r, d^r	Charging/Discharging rate of EV.
t_{start}, t_{stop}	EV charging/discharge start and stop time.
P^{MG}, Q^{MG}	Active and reactive power injected/drawn by MG.
θ_{ij}	Admittance angle of the line connecting buses $i \rightarrow j$.
δ_i, δ_j	Voltage angle of buses i and j.
$Pd_{i,t}^{TN}, Pg_{i,t}^{TN}$	Active power demand and injections of transmission level at i^{th} bus.
$Qd_{i,t}^{TN}, Qg_{i,t}^{TN}$	Reactive power demand and injection of transmission level at i^{th} bus.
$Pd0_{i,t}^{TN}$	Base Case Active power demand in transmission level of i^{th} bus at time t.
$P_{L,t}^{i}$	Load at i^{th} node in the ADN at time t.
c, C	Set of credible contingencies.
$V_{i,t}^{DN}, V_{i,t}^{TN}$	Voltage at DN and TN levels of i^{th} bus.
$V_{i,t}^{min,DN}, V_{i,t}^{min,TN}$	Minimum voltage at DN and TN levels of i^{th} bus.

$V_{i,t}^{max,DN}, V_{i,t}^{max,TN}$	Maximum voltage at DN and TN levels of i^{th} bus.
$P_{i,j}^{min,TN}, P_{i,j}^{TN}, P_{i,j}^{max,TN}$	Power flowing through line $i \rightarrow j$ and its minimum and maximum values at TN.
q, F	Feeder number and last feeder.
ζ	Acceleration factor.
$G_{q,t}^{DN}, B_{q,t}^{DN}, Y_{q,t}^{DN}$	Conductance, susceptance, and admittance of feeder q in p.u.
$g_{ij,t}, b_{ij,t}$	Conductance and susceptance matrix between nodes $i\ and\ j$ of feeder q.
$Q_{i,t}^{cb}, \beta_{i,t}^{cb}$	Capacitor bank (CB) capacity, integer value for capacitor bank unit.
cb	capacitor bank setting.
$\Delta q_{i,t}^{cb}$	VAR value of each capacitor in CB.
$\gamma_{tr,t}$	Off-nominal turn ratio of OLTC and voltage regulator.
$\Delta V_{tr,t}$	Voltage change for tap position.
t, T	Time interval, last time interval.
tap	Transformer tap.
SI, DI	Static and Dynamic information.

PREFACE

The nascent advances in technology and the global emphasis on sustainable development through clean and green power sources are transmuting the conventional analysis, monitoring, and control aspects of the power sector. Traditionally, the power system was mainly comprising of generation utilities, transmission utilities, and distribution utilities vertically integrated with centralized generation and unidirectional power flow. The power flow was primarily directed from Power generating sources to industrial, residential, commercial, or agricultural loads through the transmission network. Later, with the introduction of open access and deregulation, the monopolistic and centralized system transformed into a decentralized and horizontally integrated system. This enabled the independent power producers to inject and sell Power to the grid.

The introduction of deregulation and open access brought a competitive environment among the generation and distribution sector and complicated the task of independent system operators. The enhanced emphasis on distributed generation with high dependence on PV and Wind-based sources under both grid-connected and off-grid modes provided the consumers with the ability to meet their requirements and sell back locally or to the grid. Such consumers are being termed as prosumers.

Under the prevalence of Distributed Energy Resources (PV and Wind) and Virtual Power Plants (Electric Vehicles), there are chances of a reversal of Power from Active Distribution Networks to the transmission and sub-transmission levels. In such circumstances, the conventional notion of segregated analysis of transmission and distribution would not remain viable. The authenticity of the T&D system's segregated analysis could be challenged because the phenomena happening at the transmission level would now be affected by those occurring at the distribution level and vice versa. Thus, adequate frameworks for analyzing the integrated analysis of T&D systems need to be developed.

The overall power system's exact situational awareness has always been vital for adequate power system operation. Available Transfer Capability (ATC) is an indicator of the remaining transfer capability in the system. The availability of information pertinent to ATC would empower the system operator to take the most techno-economically feasible decision. In this research work, we have promulgated: -

- ATC assessment and enhancement methodology.
- The Pseudo-PMU (PPMU) emulation for quasi-static analysis and offline data generation of power systems has been developed.
- A framework for real-time ATC assessment has been proposed.
- ATC assessment of Integrated Transmission and Distribution.
- ATC assessment of Integrated Transmission and Distribution (ITD) considering Electric Vehicles and Microgrids as an element of Active Distribution System (ADS).
- Energy transaction using the blockchain-based framework and its impact on Aggregated Load Profile and Available Distribution Capability has been discussed.

The first part presents a method for ATC assessment and enhancement. The problem of ATC assessment has been solved by using pattern search optimization. The Flexible AC Transmission System (FACTS) devices can modulate the power flow through the lines and be optimally tuned to enhance the system's ATC. The devices, namely TCSC and SVC, have been considered and modeled, and the method for determining optimal operational strategies for maximizing the ATC of the system has been inked.

To develop the real-time ATC assessment technique based on Artificial Neural Networks (ANN), extensive training and testing data sets would be required. The synchrophasor measurement devices are capable of providing time-synchronized measurements across the grid. Such information could be considered as a first information report of events happening in the system. The measurement information could be directly utilized for various monitoring, control, and protection applications. Thus, for offline simulation gathering, PMU data was an issue; a pseudo-PMU emulation method has been developed and presented in the second part to tackle this issue.

In the third part, an ANN-based ATC estimator has been developed. The proposed method employs the radial basis neural network for estimating the ATC. The methodology involves feature extraction and linear state estimation. The developed method has also been tested on a real-time testbed using a Real-Time Digital Simulator (RTDS). The OPENECA software has been used to acquire the PMU measurement from the 'GTNET PMU' available in RTDS to MATLAB script, where the developed ATC estimator is employed to estimate the ATC.

Understanding the effect of large-scale deployment of distributed energy resources requires the development of a framework for integrated analysis of T&D analysis. Therefore, a multi-agent-based framework for integrated analysis of transmission and distribution systems has been propounded in the fourth section. The developed technique has been to assess the effect of ADN on the ATC of the system. The ADN employs CVR as a Volt-VAR optimization tool, and the impact of the same has also been assessed.

Advancing the research further, in section fifth, the effect of the presence of Electric Vehicles (EVs) capable of acting as Virtual Power Plants (VPP's) and microgrids capable of withdrawing/injecting Power to the ADN have been considered. Two indices, namely

ATCVR and ATCE factor, have been proposed as measures to assess the overall impact of considering the ADN on the ATC of the System.

The advent of the decentralized ledger and computing technology with cryptographic security paves the way to a new market structure where the various market participants could bid and actively participate in the bid settlement process. The sixth part of the work is dedicated to assessing the application of blockchain-based energy trading in IoT (Internet of Things) rich ADS and its probable impact on ADC as well as aggregated load profile of the ADS.