To the almighty,

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It is certified that the work contained in the thesis titled **Maximization of customer benefits and ancillary support to micro-grid through EV charging stations, and their de-energization under un-intentional islanding** by **Shailendra Singh** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Signature of Supervisor

Professor M.K. Verma
Department. of Electrical Engineering
IIT(BHU), Varanasi
Varanasi – 221005

आचार्य / PROFESSOR
विद्युतीय अभियांत्रिकी विभाग / Department of Electrical Engineering
भारतीय प्रौद्योगिकी संस्थान / Indian Institute of Technology
(काशी हिन्दू विश्वविद्यालय) / (Banaras Hindu University)
Varanasi, U.P. (INDIA)

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I, **Shailendra Singh**, certify that the work embodied in this thesis is my own bonafide work and was carried out by me under the supervision of **Prof. M.K. Verma** from July 2016 to December 2022, 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 on websites and have not included them in this thesis and have not cited as my own work.

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Shailendra Singh

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It is certified that the above statement made by the student is correct to the best of my/our knowledge.

Professor M.K. Verma

Department. of Electrical Engineering

IIT(BHU), Varanasi

आचार्य / PROFESSOR
विद्युतीय अभियांत्रिकी विभाग / Department of Electrical Engineering
भारतीय प्रौद्योगिकी संस्थान / Indian Institute of Technology
(काशी हिन्दू विश्वविद्यालय) / (Banaras Hindu University)
Varanasi, U.P. (INDIA)

12/06/2023

Signature of Head of Department/Coordinator of School

आचार्य व विभागाध्यक्ष / PROFESSOR & HEAD
विद्युतीय अभियांत्रिकी विभाग / Department of Electrical Engineering
भारतीय प्रौद्योगिकी संस्थान / Indian Institute of Technology
(काशी हिन्दू विश्वविद्यालय) / (Banaras Hindu University)
Varanasi, U.P. (INDIA)

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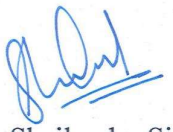

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Date: 12/06/23

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LIST OF ABBREVIATIONS

RES	Renewable Energy Sources
EVs	Electric Vehicles
TOU	Time of Use
LP	Linear Programming
V2G	Vehicle-to-Grid
G2V	Grid-to-Vehicle
CVR	Conservation Voltage Reduction
RTDS	Real-Time Digital Simulator
RTAC	Real-Time Automation Controller
SKT	Socket Protocol
DNP3	Distributed Network Protocol 3
GOOSE	Generic Object Oriented System-Wide Events
TFDI	Transient Frequency Deviation Index
DGs	Distributed Generators
IDS	Islanding Detection Scheme
M-SFS	Modified-Sandia Frequency Shift
FROCOF	Fast Rate of Change of Frequency
DERs	Distributed Energy Resources
ADN	Active Distribution Network
FCFS	First-Come-First-Serve
SOC	State of Charge
PEVs	Plug-in Electric Vehicles
DSM	Demand-Side Management

ISO	Independent System Operator
AGC	Automatic Generation Control
CS	Charging Station
LFC	Load Frequency Control
ESS	Energy Storage Systems
PI	Proportional-Integral
PVs	Photovoltaics
EVA	Electric Vehicle Aggregator
V2V	Vehicle-to-Vehicle
BE	Branch Exchange
VVO	Volt/Var Optimization
OLTC	On-Load Tap Changing Transformer
MV/LV	Medium/Low Voltage
PPSO	Pareto Particle Swarm Optimization
PMUs	Phasor Measurement Units
SCADA	Supervisory Control and Data Acquisition
PLCC	Power Line Carrier Communication
µPMU	Micro- Phasor Measurement Unit
AFS	Active Frequency Shift
SMS	Slip-Mode frequency Shift
SVS	Sandia Voltage Shift
SFS	Sandia Frequency Shift
NDZ	Non-Detection Zone
PQ	Power Quality
PCC	Point of Common Coupling

UV/UF	Under Voltage/Frequency
OV/OF	Over Voltage/Frequency
ROCOF	Rate of Change of Frequency
VU	Voltage Unbalance
THD	Total Harmonic Distortion
PJD	Phase Jump Detection
ROCOAP	Rate of Change of Active Power
RQs	Research Questions
IPM	Interior-Point Method
KKT	Kuhn–Tucker conditions
FLs	Fundamental Loops
RDS	Radial Distribution System
CHIL	Controller Hardware In Loop
TCP/IP	Transmission Control Protocol/Information Protocol
API	Application Programming Interface
IEDs	Intelligent Electronic Devices
RMS	Root Mean Square
ACE	Area Control Error
ITAE	Integral Time Absolute Error
IAE	Integral Absolute Error
ISE	Integral Square Error
ITSE	Integral Time Square Error
LFC	Load Frequency Control
STG	Steam Turbine Governor
C.B.	Circuit Breaker

PLL	Phase-Locked Loop
APM	Active Power Mismatch
RPM	Reactive Power Mismatch
ZPM	Zero Power Mismatch
I.M.	Induction Motor
HIF	High Impedance Faults
IoT	Internet of Things

LIST OF SYMBOLS

$(X^+)_k^n$	Charging rate of n^{th} PEV in k^{th} time interval
$(X^-)_k^n$	Discharging rate of n^{th} PEV in k^{th} time interval
C_k	Cost of energy in k^{th} time interval
N	Number of PEVs
K	Time intervals
T	Total time duration
L_{ET}	Energy throughput of the battery
L_c	Charge/discharge cycle life of the battery
E	Energy stored in the battery
DOD	Depth of discharge of the battery at specified L_c
c_d	Battery degradation cost
c_{bat}	Capital cost of the battery
c_d^n	Battery degradation cost of n^{th} PEV
T_a	Arrival time of PEV
T_d	Indicated departure time of PEV
$(X^+)_{max}^n$	Maximum charging rate of n^{th} PEV
$(X^-)_{max}^n$	Maximum discharging rate of n^{th} PEV
SOC^n	State of charge of the battery of n^{th} PEV
SOC_{min}^n	Minimum allowable SOC of the battery of n^{th} PEV
SOC_{max}^n	Maximum allowable SOC of the battery of n^{th} PEV
SOC_d^n	Indicated desired SOC of the battery of n^{th} PEV
SOC_i^n	Initial SOC of the battery of n^{th} PEV

$\eta_{charging}^{n}$	Charging efficiency of the battery of n^{th} PEV
$\eta_{discharging}^{n}$	Discharging efficiency of the battery of n^{th} PEV
E^{n}	Energy stored in the battery of the n^{th} PEV
V_t^i	Voltage at i^{th} bus at time instant, t
V_{min}^{i}	Minimum voltage limit at i^{th} bus
V_{max}^{i}	Maximum voltage limit at i^{th} bus
I	Total number of buses in the system
t	Time horizon variable covering the entire length of the day
c_{peak}	Price per kWh of energy consumed in the peak load period
$c_{off-peak}$	Price per kWh of energy consumed in the off-peak load period
$c_{load\ threshold}$	Cost for penalty imposed on consumers to discourage over-loading
T_s	Metered time period
[C]	Incidence matrix
b	Number of buses in the system
nb	Number of branches in the system
C_{ij}	Element of incidence matrix for i^{th} branch and j^{th} node
$CVR_{factor,i}$	CVR factor for constant impedance load connected at bus i
$\Delta E_i\%$	Percent reduction in energy consumed by constant impedance load at bus i
$\Delta V_i\%$	Percent reduction in voltage at bus i
$E_{CVR\ off,i}$	Energy consumed by the constant impedance load at bus i without CVR
$V_{CVR\ off,i}$	Voltage at bus i without CVR
$E_{CVR\ on,i}$	Energy consumed by the constant impedance loads with CVR
$V_{CVR\ on,i}$	Voltage at bus i in the presence of CVR

P_i	Power consumed by the loads at bus i
V_i	Voltage magnitude at bus i
V_{0i}	Rated voltage at bus i
Z_{pi}	Coefficient of the constant impedance component of load at bus i
I_{pi}	Coefficient of the constant current component of load at bus i
P_{pi}	Coefficient of the constant power component of load at bus i.
τ	Duration of each time step
s_k	Binary variable denoting the charging status of the connected PEV in k^{th} time interval
V_{var}	Voltage variability in the system
V_n	Voltage of the node supplying n^{th}PEV
SOC_k^n	State of charge of the battery of n^{th} PEV in k^{th} time interval
X^n	Nominal charging power of the n^{th} PEV charger
$-X^{n,min}$	Minimum charging power limit of the n^{th} PEV charger
$X^{n,max}$	Maximum charging power limit of the n^{th} PEV charger
SOC_k^n	State of charge of the n^{th} PEV battery in k^{th} time interval
SOC_0^n	Initial state of charge of the n^{th} PEV battery
$SOC_k^{n,min}$	Minimum permissible limits on the state of charge of the n^{th} PEV battery in k^{th} time interval
$SOC_k^{n,max}$	Maximum permissible limits on the state of charge of the n^{th} PEV battery in k^{th} time interval
P_k	Total power drawn from the grid in the k^{th} time interval
$P_{k,base\ load}$	Power drawn by the non-EV loads in the k^{th} time interval
V_k^j	Voltage at j^{th} bus in k^{th} time interval
V_{min}^j	Minimum permissible voltages at j^{th} bus

V_{max}^{j}	Maximum permissible voltages at j^{th} bus
e_d, e_q, e_0	Stator voltages in *dq0* components
i_d, i_q, i_0	Stator currents in *dq0* components
e_{fd}	Field voltage
i_{fd}, i_{kd}, i_{kq}	Field and amortisseur circuit current
R_{fd}, R_{kd}, R_{kq}	Rotor circuit resistance
L_{aa}, L_{bb}, L_{cc}	Self-inductances of stator windings
L_{ab}, L_{bc}, L_{ca}	Mutual inductances between stator windings
$L_{afd}, L_{akd}, L_{akq}$	Mutual inductances between stator and rotor windings
$L_{ffd}, L_{kkd}, L_{kkq}$	Self-inductances of rotor windings
R_a	Armature resistance per phase
p	Differential operator, $\frac{d}{dt}$
P_t	Three-phase power output of synchronous generator
T_e	Developed electrical torque in synchronous generator
SOC_k	State of charge of k^{th} class of vehicles
$N_{bcars\,k}$	Number of EVs in k^{th} class of vehicles
P_{charg}	Total power available in charging mode
N_{bcharg}	Number of grid-connected EVs in charging mode
P_{reg}	Power injected/absorbed by the EV fleet in regulation mode
K_D	Gain of the derivative controller
K_P	Gain of the proportional controller
ω_{ref}	Nominal system frequency
ω_{sys}	Actual system frequency

$P_{max\,reg}$	Maximum power limit of the EV fleet in regulation mode
η	Transient Frequency Deviation Index
t_{cr}	Time duration for which observation is made
t_b	Time interval for which frequency is less than the critical value
f_{min}	Minimum system frequency
f_{cr}	Critical system frequency
f_N	Nominal system frequency
ACE_i	Area Control Error of Area-i
ΔP_i	Net change in the power injected from Area-i to all other areas
β_i	Frequency bias of Area-i
Δf_i	Frequency deviation in Area-i
D_i	Damping coefficient for the power system in Area-i
R_i	Governor droop for Area-i
ACE_1	Area Control Error for Area-1
ACE_2	Area Control Error for Area-2
ΔP_{12}	Power injected to the tie-line from Area-1
ΔP_{21}	Power injected to the tie-line from Area-2
Δf_1	Frequency deviation in Area-1
Δf_2	Frequency deviation in Area-2
β_1	Frequency bias factor for Area-1
β_2	Frequency bias factor for Area-2
ΔP_{tie}	Change in the tie-line power
K_{Pmin}	Minimum limit of the gain of the proportional controller
K_{Pmax}	Maximum limit of the gain of the proportional controller

K_{Dmin}	Minimum limit of the gain of the derivative controller
K_{Dmax}	Maximum limit of the gain of the derivative controller
cf_0	Initial chopping fraction of the SFS method
k	Positive-feedback gain of the SFS method
R_G	Grid resistance
L_G	Grid inductance
R_f	Filter resistance
L_f	Filter inductance
K_i	Gain of the integral controller
I_d	Inverter d-axis reference current
I_q	Inverter q-axis reference current
cf	Chopping fraction of the SFS method
f	Islanded PCC voltage frequency
f_{nom}	Nominal frequency in grid-connected mode at PCC
$\delta_{i,DG}$	Phase angle for the inverter output current
δ_{load}	Phase angle of the load current
Q_f	Load quality factor
f_0	Load resonant frequency
β	Rate of change of frequency relay threshold
$I^*_{d,ref}$	Inverter d-axis reference current after phase-angle transformation
$I^*_{q,ref}$	Inverter q-axis reference current after phase-angle transformation
k_{M-SFS}	Positive feedback gain for the M-SFS method