

To the almighty,

महादेव

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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.

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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Date: 12/06/23

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



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## LIST OF FIGURES

Fig. 1.1 Structural transformation of conventional power system into the smart grid.....	2
Fig. 2.1 Time of use (TOU) based electricity pricing.....	24
Fig. 2.2 Schematic of the IEEE 33-bus distribution system.....	27
Fig. 2.3 Single line diagram of the test system.....	30
Fig. 2.4 Power generated by the DERs with a 15% penetration level.....	30
Fig. 2.5 Voltage distribution in the system without PEVs.....	31
Fig. 2.6 Voltage distribution in the system with PEVs in TOU-based tariff structure.....	32
Fig. 2.7 (a) Charging/Discharging rate of PEVs, (b) Active power load in the system without and with PEVs, (c) SOC of the PEVs battery in TOU-based tariff structure.....	33
Fig. 2.8 Cost of charging of PEVs in the system without re-configuration.....	34
Fig. 2.9 Voltage distribution in the system without PEVs in the re-configured network.....	35
Fig. 2.10 Voltage distribution in the system with PEVs in TOU-based tariff structure in the re-configured network.....	36
Fig. 2.11 (a) Charging/Discharging rate of PEVs, (b) Active power load in the system without and with PEVs, (c) SOC of the PEVs battery in TOU-based tariff structure in re-configured network.....	36
Fig. 2.12 Cost of charging of PEVs in re-configured network.....	37
Fig. 2.13 Power requirement by the loads while performing voltage reduction.....	38
Fig. 2.14 Cost of energy consumed by loads before and after deployment of CVR.....	38

Fig. 2.15 Cost of charging of PEVs in three different simulated cases.....	40
Fig. 2.16 Cost of charging of PEVs discarding battery degradation cost under TOU-based tariff with network re-configuration.....	41
Fig. 2.17 Cost of charging of PEVs with initial SOC near the battery capacity under TOU-based tariff with network re-configuration.....	42
Fig. 3.1 Single-line diagram of the test system.....	49
Fig. 3.2 Voltage profile of the system in Case I.....	54
Fig. 3.3 Load multiplier factor for 24h period.....	54
Fig. 3.4 TOU-based tariff structure.....	55
Fig. 3.5 Case I (a) SOC profiles of PEVs battery, (b) Charging/Discharging profile of PEVs, (c) Voltage profile of the system, and (d) Load profile of the system.....	58
Fig. 3.6 Cost of charging of PEVs for Case I.....	59
Fig. 3.7 Voltage profile of the system in the absence of PEVs Case II.....	60
Fig. 3.8 Case II (a) SOC profiles of PEVs battery, (b) Charging/Discharging profile of PEVs, (c) Voltage profile of the system, and (d) Load profile of the system.....	61
Fig. 3.9 Cost of charging of PEVs for Case II.....	62
Fig. 3.10 Case III, Test System I (a) SOC profiles of PEVs battery, (b) Charging/Discharging profile of PEVs, (c) Voltage profile of the system, and (d) Load profile of the system.....	63
Fig. 3.11 Cost of charging of PEVs for Case III (Test System I).....	64
Fig. 3.12 Voltage profile (surface plot) of the system for Case III (Test System II).....	65

Fig. 3.13 Case III, Test System II (a) SOC profiles of PEVs battery, (b) Charging/Discharging profile of PEVs, (c) Voltage profile of the system, and (d) Load profile of the system.....66

Fig. 3.14 Voltage profile (surface plot) of the system after PEVs voltage support for Case III (Test System II).....67

Fig. 3.15 Cost of charging of PEVs for Case III (Test System II).....68

Fig. 3.16 IEEE 34-node test feeder with EV charging stations.....70

Fig. 3.17 Controller Hardware In Loop (CHIL) simulation of PEVs charging schedule with Real-Time Digital Simulator.....71

Fig. 3.18 DNP3 controller in SEL AcSELeRator RTAC.....73

Fig. 3.19 GTNETx2 DNP and GOOSE component configuration in RSCAD draft.....74

Fig. 3.20 EV charging station status in RSCAD runtime at 1700hrs.....76

Fig. 3.21 EV charging station voltages from RSCAD runtime at the time of PEVs connection at 1700hrs (time-scaled).....76

Fig. 3.22 GOOSE packets from RTAC received over Wireshark.....77

Fig. 3.23 EV charging station power from RSCAD runtime at the time of PEVs connection at 1700hrs (time-scaled).....77

Fig. 4.1 Evolution of power systems from conventional energy sources to the integration of renewable energy sources.....81

Fig. 4.2 Structure of grid with an attached EV charging station.....83

Fig. 4.3 Single-line diagram of the modified two-area system.....84

Fig. 4.4 Control logic for the charge-discharge decision of EVs.....	87
Fig. 4.5 Control block-diagram for power regulation through EV fleet.....	89
Fig. 4.6 Frequency response curve having intersection with line $f = f_{cr}$ .....	92
Fig. 4.7 Frequency response curve having no intersection with line $f = f_{cr}$ .....	93
Fig. 4.8 Block diagram of the two-area power system with frequency controls from EV.....	95
Fig. 4.9 Disturbance created using LG fault in the two-area system.....	96
Fig. 4.10 Disturbance created using change in reference power in the two-area system...97	
Fig. 4.11 Flowchart showing the process flow for EV's contribution in frequency regulation.....	98
Fig. 4.12 Frequency deviations for disturbance without EV.....	99
Fig. 4.13 Frequency deviations for a disturbance with EVs in frequency regulation mode.....	100
Fig. 4.14 Voltage, current and power of the EVs in frequency regulation mode.....	100
Fig. 4.15 SOC of the various EV profiles while performing frequency control.....	101
Fig. 4.16 Frequency deviations for disturbance without EV.....	102
Fig. 4.17 Frequency deviations for a disturbance with EVs in frequency regulation mode.....	103
Fig. 4.18 Voltage, current and power of the EVs in frequency regulation mode.....	103
Fig. 4.19 SOC of the various EV profiles while performing frequency control.....	105
Fig. 5.1 Single-line diagram of the test system.....	108

Fig. 5.2 Conventional SFS block diagram in the control interface scheme.....	111
Fig. 5.3 FROCOF element characteristics.....	114
Fig. 5.4 Block diagram of the proposed hybrid IDS.....	116
Fig. 5.5 PCC frequency for the system under different APM conditions equipped with the proposed hybrid method.....	118
Fig. 5.6 PCC frequency for the system under different RPM conditions equipped with the proposed hybrid method.....	119
Fig. 5.7 PCC frequency for the system without the proposed hybrid method.....	120
Fig. 5.8 PCC frequency for the system under load switching with proposed hybrid IDS.....	121
Fig. 5.9 PCC frequency for the system under capacitor switching and I.M. starting with proposed hybrid IDS.....	121
Fig. 5.10 PCC frequency for the system under different types of faults with proposed hybrid IDS.....	122
Fig. 5.11 PCC frequency for the system under LLLG fault with different fault impedance with proposed hybrid IDS.....	123
Fig. 5.12 PCC frequency for the system under different X/R ratios with proposed hybrid IDS.....	124
Fig. 5.13 PCC frequency for the system under different $Q_f$ values with proposed hybrid IDS.....	125
Fig. A.1 Single-line diagram of the IEEE 33-bus radial distribution system.....	142
Fig. B.1 Single-line diagram of the IEEE 34-node test feeder.....	146



## LIST OF TABLES

Table 2.1 Fundamental loops of the modified IEEE 33-bus system.....	28
Table 2.2 ZIP model coefficients for residential customers.....	37
Table 2.3 Comparison of charging cost of PEVs and minimum system voltage in three different simulated cases.....	39
Table 3.1 Test system line parameters ( $0.446 + j0.071\Omega/\text{km}$ ).....	50
Table 3.2 Comparison of charging cost of PEVs and voltage variability in different simulated cases.....	69
Table 3.3 Charging station Voltage (V) and Frequency (f) check.....	72
Table 4.1 Parameters of the power system network.....	84
Table 4.2 Parameters of the EV fleet.....	90
Table 4.3 Characterization of the EV fleet.....	91
Table 4.4 Frequency Nadir, ROCOF and TFDI without and with EVs for the different contingencies.....	106
Table 5.1 Test system parameters.....	109
Table A.1 Line and load data for IEEE 33-bus radial distribution system.....	141
Table B.1 Line segment data for IEEE 34-node test feeder.....	143
Table B.2 Overhead line configurations (Config.) of IEEE 34-node test feeder.....	144
Table B.3 Distributed load data of IEEE 34-node test feeder.....	145
Table B.4 Spot load data of IEEE 34-node test feeder.....	146



## 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
$\mu$ PMU	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 $i$ .
$\tau$	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
$\omega_{ref}$	Nominal system frequency
$\omega_{sys}$	Actual system frequency

$P_{maxreg}$	Maximum power limit of the EV fleet in regulation mode
$\eta$	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
$\Delta P_i$	Net change in the power injected from Area-i to all other areas
$\beta_i$	Frequency bias of Area-i
$\Delta f_i$	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
$\Delta P_{12}$	Power injected to the tie-line from Area-1
$\Delta P_{21}$	Power injected to the tie-line from Area-2
$\Delta f_1$	Frequency deviation in Area-1
$\Delta f_2$	Frequency deviation in Area-2
$\beta_1$	Frequency bias factor for Area-1
$\beta_2$	Frequency bias factor for Area-2
$\Delta P_{tie}$	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
$\delta_{load}$	Phase angle of the load current
$Q_f$	Load quality factor
$f_0$	Load resonant frequency
$\beta$	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