Energy Management of DC Microgrid considering Correlated Input Uncertainties

Thesis submitted in partial fulfillment
for the award of degree

Doctor of Philosophy

by

Abhishek Singh

DEPARTMENT OF ELECTRICAL ENGINEERING
Indian Institute of Technology
(Banaras Hindu University)
Varanasi

Roll No: 20081505

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Dedicated

To

My Parents, Teachers &
Lord Vishwanath Ji

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Supervisor
Dr. Avirup Maulik
Deptt. of Electrical Engg.
IIT(BHU), Varanasi
Varanasi, India - 221005

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Dr. Avirup Maulik

IIT(BHU), Varanasi

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Abhishek Singh

Place: Varanasi

(Abhishek Singh)

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Acronyms

μ**G** microgrid

H_2 Hydrogen

ADMM alternating direction method of multipliers

AE Alkaline electrolyzer

aFRR automatic frequency restoration reserve

air con air-conditioner

BESS battery energy storage system

CCP chance constrained programming

cdf cumulative distribution function

DC direct current

DCμ**G** DC-Microgrid

DCμ**GO** DCμG operator

DCSOP DC soft open points

DD Driven distance

DER distributed energy resource

DG distributed generation

DLC direct load control

DOC depth of charge

DOD depth of discharge

DoSA denial of service attack

DR demand response

DVs decision variables

EMPC economic model predictive control

EMS energy management scheme

ESS energy storage system

EV electric vehicles

FC fuel cell

FDIA false data injection attack

G-bus bus conductance matrix

G2V grid-to-vehicle

GA Genetic algorithm

GAMS General Algebraic Modeling System

GHG greenhouse gas

GIC grid-interlinking converter

GSDF Generation shift distribution factor

GT gas turbine

H2P hydrogen to power

HESS hybrid energy storage system

HSS H_2 storage system

IDR integrated demand response

IES integrated energy system

IQR inter-quartile range

KKT Karush-Kuhn-Tucker

LA load aggregator

LCOE levelized cost of energy

LP Linear programming

MCS Monte Carlo Simulation

MILP mixed-integer linear programming

MITM man-in-the-middle attack

MO multi-objective

MODA multi-objective dragonfly algorithm

MPC model predictive control

MPPT maximum power point tracking

MT microturbine

NSGA-II non-dominated sorting genetic algorithm-II

NT Nataf Transformation

OC operating cost

p.u. per unit

P2H power to hydrogen

P2P peer-to-peer

PALO parallel ant lion optimizer

pdf probability density functions

PE power electronic

PEM Point estimate method

PHEV plug-in hybrid vehicles

PI proportional integral

PSO particle swarm optimization

PVGIS Photovoltaic Geographic Information System

PVSA parallel vortex search algorithm

R-MPCE resilience oriented economic model predictive control based EMS

RES renewable energy sources

RPP retail power price

RV random variable

SG Stackelberg game

SOC state of charge

SOP soft open point

SPG solar photovoltaic generator

STD Subsequent trip distance

SW scheduling window

SWP social welfare problem

TCL thermostatically controlled load

V2G vehicle to grid

VSCs voltage source converters

WPG wind power generator

Nomenclature

Sets/Indices

$a \in \mathcal{A}$	Air-conditioner
$t/k \in \mathcal{T}$	Time
$\mathcal{T}^{a,v}/\mathcal{T}^{a,e}$	PHEV availability time for charging/discharging
Ξ	Set of load types (flexible, moderate, and critical loads)
$\{\mathcal{W}_1, \mathcal{W}_2\}$	Game objectives
$b/n/j \in \mathcal{B}$	Bus
$f \in \mathcal{F}$	Line
$v/e \in \mathcal{V}/\mathcal{E}$	PHEV

Parameters

α and β	Shape parameters
χ^{co2}	Interval length of carbon emission
Δ_c	Incremental carbon price
ϵ_A	Inertia factor
η_C^E/η_{ev}^C	PHEV charging efficiency
η_D^E/η_{ev}^D	PHEV discharging efficiency
η_A	air con coefficient of performance

η_{bc} / η_{bd}	Charging/Discharging efficiencies of the BESS
η_{el}	Electrolysis efficiency of AE stack
η_{GT}	Efficiency of GT
$\mathcal{H}_p$	Prediction horizon
μ_d	Mean of daily drive distance
μ_g	Mean of grid power price
μ_l	Mean of load demand
μ_s	Mean of solar irradiance
$\overline{\mathcal{I}}$	Line rating (p.u)
$\overline{EB}$	Energy rating of the BESS (kWh)
$\overline{P^{grid}}$ / $\underline{P^{grid}}$	Upper/Lower limits of power exchange with upstream grid (kW)
$\overline{PA}$	air con power rating (kW)
$\overline{PBC}^c/\overline{PBD}^d$	Charging/Discharging power limit of BESS (kW)
$\overline{pls}^x$	Maximum load shedding allowed for different load types (kW)
$\overline{PS}$	SPG installed capacity (kW)
$\overline{PT}/\overline{PF}$	Installed capacities of the MT and the FC (kW)
$\overline{PW}$	Installed capacity of WPG (kW)
π^g	Cost of procuring power from the upstream grid (\$/kW)
π^s/π^{sc}	Generation cost and the power curtailment cost of SPG (\$/kW)
π^w/π^{wc}	Generation cost and the power curtailment cost of WPG (\$/kW)
π^{bes}	OM of the BESS (\$/kW)
π^{co2}	Base carbon trading cost (\$/kg)

π^{DR}	Bid offered by DR participator $(\$/kW)$
π^{ed}	Price at which DCMGO sells electricity to customers($\$$)
π^{ely}	OM of the AE($\$$)
π^{fc}	LCOE cost of FC $(\$/kW)$
π^{gas}	Gas price ($\$$/kW)
π^{H_2}	selling price of $H_2(\$/kg)$
π^{hr}	selling price of heat
π^{mt}	LCOE for MT $(\$/kW)$
π^{ur}/π^{dr}	Price of reservation of capacity for upward/downward provisions in the aFFR market $(\$/kW)$
σ_d	Standard deviation of daily driven distance
σ_g	Standard deviation of grid power price
σ_l	Standard deviation of load demand
σ_s	Standard deviation of solar irradiance
θ^{am}	Ambient temperature $(^{\circ}C)$
$\Theta^{co2,G}/\Theta^{co2,GT}$	Carbon intensity of upstream grid/gas for GT
θ^{des}	Desired indoor temperature $(^{\circ}F)$
θ^{el}_0	AE initial temperature $(^{\circ}C)$
$\underline{\theta}^{el}/\overline{\theta}^{el}$	Lower/Upper limit of AE stack temperature $(^{\circ}C)$
$\underline{\theta}^{A}_{a}/\overline{\theta}^{A}_{a}$	Min/max indoor temperature $(^{\circ}F)$
$\underline{E}^{E}_{v}/\overline{E}^{E}_{v}$	PHEV min/max energy levels (kWh)
$\underline{Pel}/\overline{Pel}$	Minimum/Maximum power consumption capacity of the AE (kW)
$\underline{PT}$	Lower limit of active power generated by MT (kW)

$\underline{VH}/\overline{VH}$	Minimum/Maximum limits of H_2 storage
ϱ^{co2}	Free carbon emission coefficient
ϱ_{H_2}	Hydrogen density (kg/m^3)
A^{cond}	Home thermal conductivity ($kW/^\circ F$)
AER	All-electric range
C_{lmp}^{el}	Lump heat capacitance of stack (J/K)
C_{lmp}^{el}	Lumped heat capacitance of electrolyzer ($kWh/^\circ C$)
C_{bat}	Energy rating of PHEV battery (kWh)
d	Daily driven distance (km)
d_s	Subsequent trip distance (km)
DOD	Depth of discharge of PHEV battery
E^{AE}/E_0^E	Energy of PHEV battery at arrival (kWh)
$E^{E,R}$	Energy required by the PHEV battery during departure (kWh)
EB_0	BESS initial energy (kWh)
F	Ambient temperature ($^\circ F$)
$G_{b,n}$	b^{th} row n^{th} column element of bus conductance matrix G (p.u.)
$GSDF_{l,b}$	GSDF (p.u.)
$m^{H_2,d}$	H_2 demand (kg)
N^{st}	Number of the stacks
P_{base}	Base power (kW)
P_{chg}	Charging rate of PHEV battery (kW)
PL	Electricity demand under the normal operating period (kW)

PL^0	Electricity demand before DR implementation (kW)
$PNFL$	Non-flexible load power (kW)
PS^{avl}/PW^{avl}	Available power from SPG/WPG (kW)
PS^{pu}/PW^{pu}	Solar/wind power available (p.u. of installed capacity)
$Q_{hhv}^{H_2}$	Hydrogen HHV (kWh/kg)
R	Number of intervals in the carbon emission ladder structure
R_{heat}^{EL}	Electrolyzer heat resistance ($^{\circ}C/kW$)
S_{phev}	State of charge of PHEV battery
T	Last time step
t_a/t_d	PHEV arrival/departure time
t_{dur}	Duration of charging of PHEV battery
t_{start}	Charging start time
v_{ci}	cut-in speed (m/s)
v_{co}	furling speed (m/s)
v_{wr}	rated wind speed (m/s)
v_w	wind speed in m/s
VH_0	Initial stored hydrogen (N/m^3)
x/c	shape/scale factor

Variables

ΔV	Per unit voltage deviation from nominal value
δ^G	Binary variable for GT on/off status
$\delta^{bat,c,I}$	Binary variable indicating BESS charging after islanding

$\delta^{bat,c}$	Binary variables indicating the charging of the BESS
$\delta_{ev}^{c}/\delta_{ev}^{D}$	Binary variable for PHEV charging/discharging
$\delta^{E,C}/\delta^{E,D}$	Binary variable indicating charging/discharging status of PHEV
$\delta^{mt}/\ \delta^{fc}$	Binary variables denoting the ON status of the MT and the FC
δ^{u}/δ^{d}	Binary variable of BESS for regulation
δ^{x}	Binary variable for load shedding
$\hat{\Psi}_1$	$DC\mu GO$ objective
$\kappa^{co2,G}/\kappa^{co2,GT}$	Free carbon quota of the upstream grid/GT
$\mathcal{I}$	Line current (p.u)
$\mathcal{I}^{I}$	Line current after islanding (p.u)
$\mathcal{I}^{u}/\mathcal{I}^{d}$	Line current when the upward/downward reserve is activated (p.u)
$\mathcal{W}^{co2}$	Carbon trading cost of the DC microgrid (\$)
$\mathcal{W}_{2b}$	Objective of the consumer
$\overline{PEV}^{C}$	Maximum charging power of PHEV (kW)
$\overline{PEV}^{D}$	Maximum discharging power of PHEV (kW)
π^{R}	Retail power price (\$$/kW$)
θ^{el}	Temperature of the AE stack ($^\circ C$)
θ_a^{A}	Smart house indoor temperature ($^\circ F$)
$\varepsilon^{co2,G}/\varepsilon^{co2,GT}$	Carbon emissions due to power procurement from the upstream grid/power generated by the GT (kg)
$\varepsilon_0/\varepsilon_r$	Carbon emission of the DC microgrid in the interval $0/r$
$\{\pi^{s}\}/\{PFL\}$	$DC\mu GO$/consumer strategies
E^{E}	PHEV battery energy (kWh)

EB	BESS energy (kWh)
H^{loss}	Heat lost to the ambient (kW)
hr	Heat recovered (kW)
$m^{H_2,sh}$	H_2 demand shedded (kg)
P^{gen}	Net generation at a bus (kW)
$P^{grid,u}$ / $P^{grid,d}$	GIC power when the upward and downward reserves are activated (kW)
P^{grid}	Power from the upstream grid (kW)
P^{heat}	Heat produced by electrolyzer stack (kW)
$P^{inj}/P^{inj,I}$	Nodal power injection before/after islanding (kW)
PA	air con power consumption (kW)
PBC/PBD	Charging/discharging power of BESS(kW)
PBC^d	Reduction in charging power of BESS (kW)
PBC^r/PBD^i	Decrease/Increase in battery energy storage system (BESS) charging/discharging power after islanding (kW)
PBD^d	Reduction in discharging power of BESS (kW)
PBD^u	Increase in discharging power of BESS (kW)
Pel	Power produced from AE(kW)
Pel^r	Reduction in electrolyzer power after islanding (kW)
Pel^u / Pel^d	Increase/Decrease in AE power consumption for downward and upward regulation (kW)
PEV^C/PEV^D	PHEV charging/discharging power (kW)
PF	Power produced from FC(kW)
PF^i/PGT^i	:Increase in FC/GT power output after islanding (kW)

PF^u / PF^d	Increase/Decrease in power output of the FC for provisioning upward and downward reserves (kW)
PFL	Flexible load power(kW)
PGT	Power produced by GT (kW)
PL	Total load at a bus (kW)
pls	Electrical load curtailment(kW)
PS	Power generated by SPG (kW)
PSC	SPG power curtailment (kW)
$PSOP$	Active power injected by the SOP in to a bus (kW)
$PSOP^l$	Active power loss in the DC-DC converter of the SOP (kW)
PT	Power generated by the MT(kW)
PT^u / PT^d	Increase/Decrease in the MT power output from the initial operating points for upward and downward reserves (kW)
PW/PWC	Generated power and curtailed power of WPG(kW)
r^u/ r^d	Amount of upward/downward reserve (kW)
$SSOP$	Apparent power rating of the DC-DC converter of the SOP (kW)
V	Bus voltage (p.u)
V^I	Node voltage after islanding ($p.u.$)
V^{st}	Voltage setting of ST (p.u)
V^u/V^d	Bus voltage during the upward/downward reserve activation (p.u)
VH	volume of H_2 in the HSS (Nm^3)
m^{Ely,H_2}	Mass of H_2 produced by AE stack(kg)
m^{FC,H_2}	Mass of H_2 required by FC(kg)

Preface

Generation sources near the customer location in an active distribution network, known as distributed generation, help to reduce transmission losses and costs. Increasing greenhouse gas emissions and environmental degradation due to fossil-based sources have paved the way for renewable sources like solar photovoltaic and wind power. Also, plug-in hybrid vehicles are replacing conventional internal combustion engine vehicles. The change of the original power flow pattern due to the penetration of distributed generation and plug-in hybrid vehicles, as well as the variability of renewable sources, makes operation and planning challenging. Further, the DC-microgrid architecture is becoming popular for serving remote rural households and facilities, community buildings, data centres, etc. Since the capacity of controllable power generation facilities is limited in a DC-microgrid, a high proportion of renewable energy sources, like solar and wind, introduces volatility and uncertainty in maintaining the generation-demand balance. This thesis deals with the energy management scheme for a DC microgrid from different perspectives.

The second chapter of this thesis addresses the challenges of modelling the correlation between input random variables while formulating the energy management scheme of a DC-microgrid. Correlation between input random variables is modelled using an Inverse Nataf transformation-based approach. Previous studies used an empirical formula to map the correlation between the normal and arbitrary marginal distributions, limiting the approach's applicability to those marginal distributions for which empirical formulae existed. By contrast, Newton's Interpolation-based technique is used instead of empirical formulae for correlation mapping between normal space and arbitrary marginal distributions in this work. Newton's interpolation-based technique allows the Inverse Nataf transformation-based approach to be applied to any marginal distribution describing the behaviour of the correlated input random variables, which obviates the limitations of previous studies. Also, a multi-objective energy management scheme is formulated for a

DC-microgrid by modelling and incorporating uncertainties of renewable energy sources, load demand, plug-in hybrid vehicles load, and grid power price. The energy management scheme strategy envisages coordination between power procurement from various sources (renewable energy sources, grid, dispatchable unit), demand response implementation, battery energy storage system, and soft open point scheduling.

In the third chapter, a privacy-preserving energy management scheme with a retail-power price-based decentralized demand response program is proposed for a DC-microgrid with sectoral coupling between electricity and hydrogen, aiming to maximize the profit of the DC-microgrid operator and reduce consumer energy costs. The retail power price is established on a theoretical foundation using the concept of competitive equilibrium, considering the DC-microgrid network model and constraints. Operational flexibilities of plug-in hybrid vehicles and battery energy storage system, building thermal inertia, and the demand-shifting potential of hydrogen storage system are coordinated into an "integrated demand response scheme" to enhance the techno-economic performance of the coupled electricity-hydrogen DC-microgrid. Additionally, uncertainties, including correlations among input random variables, are modelled using probabilistic Copula models and integrated into the energy management scheme to mitigate risks in dispatch strategies under uncertainty.

In chapter four, a bi-level probabilistic Stackelberg game-based energy management scheme is proposed for a grid-connected electricity-hydrogen DC-microgrid with a hybrid energy storage system incorporating islanding constraints and with coordination between the operation of the DC-microgrid and demand response participators. The uncertain input random variables are modelled in the probabilistic domain using a copula-embedded Monte Carlo dynamic averaging approach and incorporated into the energy management scheme module. The objective of the DC-microgrid operator is to maximize the day-ahead profit for grid-connected operations using available generation sources and grid power, a hybrid energy storage system (battery energy storage system and hydrogen storage system), and controllable loads subject to equipment and network operating constraints. On the other hand, the objective of flexible consumers is to minimize the cost of day-ahead electricity usage. The demand response participation is coordinated with the DC-microgrid operation using a bi-level Stackelberg game.

In the fifth chapter, a resilience-oriented economic model predictive control-based energy management scheme is proposed for a DC-microgrid, enabling the co-optimization of hydrogen and electrical systems to ensure economical operation with automatic frequency restoration reserve market participation during normal periods, proactive preparation before extreme events, and reliable critical load supply with minimal non-critical load curtailment during emergencies. Designed with the DC-microgrid network model and incorporating equipment and network-level constraints, the resilience-oriented economic model predictive control-based energy management scheme ensures operational feasibility. Additional constraints are integrated to support automatic frequency restoration reserve market participation during grid-connected operation without violating system limits. Probabilistic Copula models address uncertainties in renewable energy sources generation and load demand and their correlations, mitigating the risks of dispatching under uncertainty.

Finally, the sixth chapter concludes the thesis by summarizing key findings and suggesting directions for future research.