Full-Mode Control in Utilizing Stored Energy in Lithium-Ion Batteries Based on Forecasted PV Output Implemented for HEMS

(HEMSに用いる太陽光発電量予測に基づいたリチウムイオン電池に貯蔵されるエネルギー利用のフルモード制御)

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IBARAKI UNIVERSITY

DOCTORAL THESIS

Full-Mode Control in Utilizing Stored Energy in Lithium-Ion Batteries Based on Forecasted PV Output Implemented for HEMS

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Abbreviations

PV	Photovoltaic
GPV	Grid Point Value
MSM	Meso-Scale Model
ECMWF	European Centre for Medium-Range Weather Forecasts
NAM	North American Mesoscale
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
ANN	Artificial Neural Network
AR	Autoregressive
TCWB	Taiwan Central Weather Bureau
UTC	Coordinated Universal Time
JST	Japan Standard Time
JMA	Japan Meteorological Agency
NWP	Numerical Weather Prediction
HEMS	Home Energy Management System
RES	Renewable Energy Systems
BES	Battery Energy Storage
ESU	Energy Storage Units
SOC	State-Of-Charge
NID	Number of Insufficient Days
Ah	Ampere-hour
OCV	Open-Circuit Voltage
GRIB	General Regularly-distributed Information in Binary form
GRIB2	General Regularly-distributed Information in Binary form Edition 2
DOD	Depth Of Discharge

Symbols

S_i	hourly solar irradiance	MJm^{-2}
S_0	clear-sky solar irradiance on earth's surface	MJm^{-2}
z	solar zenith angle	rad
ϕ	geographic latitude	degree (°)
δ	solar declination angle	degree (°)
ω	hour angle	degree (°)
N	total number of days in 1 year	
D	single day in a year	
RH	relative humidity	%
P	precipitation	$10\times mm$
C_L	low-level cloud cover	%
C_M	middle-level cloud cover	%
C_H	high-level cloud cover	%
L	liquid water path	gm^{-2}
L_L	low-level liquid water path	gm^{-2}
L_M	middle-level liquid water path	gm^{-2}
L_H	high-level liquid water path	gm^{-2}
h	geopotential height	m
a	vapor density	gm^{-3}
T	temperature	°C
e_s	saturation pressure of water vapor	gm^{-3}
r	correlation coefficient	
$RMSE$	root mean square error	$MJm^{-2}day^{-1}$
MBE	mean bias error	$MJm^{-2}day^{-1}$
R^2	coefficient of determination	

S_m	measured solar irradiance	MJm^{-2}
S_c	estimated/calculated solar irradiance	MJm^{-2}
S_{avgm}	1-day average measured solar irradiance	MJm^{-2}
S_{avgc}	1-day average calculated solar irradiance	MJm^{-2}
S	one-day total solar irradiance	MJm^{-2}
Tdd	dew-point depression	°C (°K)
T_d	dew-point temperature	°C (°K)
N_{Tdd}	number of $Tdd \leq 3$°C	
G	generation	Ah
E	battery's storage level	Ah
C	consumption	Ah
G_i	generation on the i-th day	Ah
E_i	battery's storage level on the i-th day	Ah
C_i	consumption on the i-th day	Ah
E_{G_i}	storage level after generation process for the i-th day	Ah
E_{C_i}	storage level after consumption process for the i-th day	Ah
E_N	necessary energy to fully charge the batteries	Ah
E_0	initial storage level	Ah
E_{FULL}	full battery storage level	Ah
G_M	measured value of generation	Ah
G_C	measured value of generation	Ah

IBARAKI UNIVERSITY

Abstract

Industrial Science
Graduate School of Science and Engineering

Doctor of Engineering

Full-Mode Control in Utilizing Stored Energy in Lithium-Ion Batteries Based on Forecasted PV Output Implemented for HEMS

by AHMAD SYAHIMAN BIN MOHD SHAH

Renewable energy resources such as photovoltaic (PV) and wind energy are crucial to counter an incoming energy crisis in the near future. Nevertheless, an intermittent behavior of input energy that is generated through PV panels requires a proper battery energy storage system (BESS) in order to alleviate its output for the sake of the load. Moreover, when PV generators are integrated with storage batteries, a constructive mechanism needs to be well structured in order to securely control the flow of energy in the batteries during the charging/discharging process so that the risk of overcharge/over-discharge of the batteries can be significantly prevented. Furthermore, it is extremely essential to implement a control method that is capable to fully utilize a stored energy in the scope of small-scale BESS to the load regularly in the first place before it is further scaled up to a farm-scale or mega-structure. In this study, an energy control scheme that considers and executes a next-day forecast of generation as an input data has been proposed. Originally, numerical weather predictions of solar radiation are performed based on Grid Point Value (GPV) using relative humidity, precipitation and cloud cover parameterization. Main approach is to test how sensitive the proposed scheme works with the entire system, experimentally and how it deals with errors that caused by the forecast data. Thus, the charging (generation) and discharging (consumption) processes of the batteries were performed separately during the day and night, respectively. The amount of energy consumption determined by this control is the necessary amount of energy to fully charge the batteries on the next day based on the GPV-forecast data and the maximum storage size of the batteries used in here is 30 Ah. Basically, experimental equipment was structured to form a stable 100 V DC power supply for the load and the system's operation was completely administered by an RX621 microcontroller. As a result, the forecasting errors, if any, on the days when generation was less than 10 Ah or more than 30 Ah, were negligible since 10 Ah or 30

Ah of energy were supplied from the batteries to the load consistently during rainy or sunny days, respectively. Impressively, average energy consumption for January to June 2015 is considerably high with approximately 20.7 Ah, respectively, which suggests that the proposed control succeeded in utilizing energy corresponded to over 95.1% of the average G for 2011-2014. Thus, it is desirable if the entire proposed system might become a trigger for other researchers to structure more comprehensive EMS applications that are more reliable, efficient and sophisticated in the future.

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List of Publications

JOURNALS

1. **Ahmad Syahiman Bin Mohd Shah**, Hiroki Yokoyama and Naoto Kakimoto, "High-Precision Forecasting Model of Solar Irradiance Based on Grid Point Value Data Analysis for an Efficient Photovoltaic System," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 474-481, Apr. 2015.

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2. **Ahmad Syahiman Mohd Shah**, Yuki Ishikawa, Suguru Odakura and Naoto Kakimoto, "Numerical Model of Energy Control for Lithium-Ion Batteries Based on PV System," *Int. J. SIM. Syst. Sci. Technol.*, vol. 15, no. 6, pp. 67-74, Dec. 2014.

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CONFERENCE PROCEEDINGS

1. **Ahmad Syahiman Mohd Shah**, Yuki Ishikawa, Suguru Odakura and Naoto Kakimoto, "Power Control Modelling for Future Energy Management Based on Photovoltaic Integrated System with Lithium-Ion Storage Batteries," in Proc. *2014 8th Asia Modelling Symp. (AMS2014)*, pp. 187-192.

   DOI: 10.1109/AMS.2014.44

2. **Ahmad Syahiman Mohd Shah**, Yuki Ishikawa, Hiroki Takahashi, Suguru Odakura and Naoto Kakimoto, "Full Utilization Control of Stored Energy in Lithium-Ion Batteries Based on Forecasted PV Output for HEMS," in Proc. *2015 3rd International Congress on Energy Efficiency and Energy Related Materials (ENEFM)*, to be published.