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Energy Management System for an Islanded Renewables-based DC Microgrid

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Abstract—DC microgrids are gaining attention of researchers and engineers due to the increasing deployment of renewable energy sources with energy storage systems, enhanced utilization of DC power electronics devices, and added advantages of no harmonics and synchronization issues. They are viable solutions for providing electricity to off-grid remote communities, like islands and remote areas. However, they need energy management systems for optimally scheduling the distributed energy generation and storage systems. Hence, this paper proposes a supervisory energy management system for optimal operation of islanded DC microgrid. Energy management system is responsible for determining optimal scheduling of each energy source and ensuring maximum utilization of renewable energy sources and supply demand balance. The proposed energy management model has been validated experimentally and practical results prove the effectiveness of the proposed method.

Index Terms—DC microgrid, tidal energy, battery degradation, energy management system, mixed integer linear programming.

I. INTRODUCTION

Renewable energy sources (RESs) have been globally deployed at large scale for environmental protection and sustainability. Moreover, they can provide electricity to off-grid areas as they can be installed locally, closed to load ends, with energy storage systems (ESSs). The interest for DC loads is also increasing due to technology enhancements in power electronic converters and devices. Hence, RESs, ESSs, and power electronic loads have paved way for DC microgrids [1]. Microgrids (MGs) are potential solutions for electrification of off-grid islands, rural villages, and remote areas [2]–[4].

Various RESs have been used for DC MGs in the literature. In [4]–[6], PV and battery potentials have been explored for applicability to DC MGs. In [7], a DC MG is investigated as a promising solution for solar and wind power integration. Wind and wave energy potentials are analyzed in [8] with DC MG

system. In [9], tidal energy based-hybrid renewable MGs are investigated for islands.

MGs face coordination and control challenges caused by ESS operation and intermittent nature of RESs, particularly solar and wind energy sources. Hence, energy management system (EMS) is needed to overcome these problems and optimally scheduling MG system against defined objectives [10]. EMS should operate at lower bandwidth than control and power management levels for robust and stable performance of MG system [11]. Control strategies are employed for current and voltage regulation, while power management approaches are related to managing line limits and losses. Instead, EMS schemes are deployed for ensuring supply demand balancing over longer time intervals in an optimal way, while satisfying economical, technical, and environmental requirements.

Few energy management systems for islanded DC MGs have been recently reported in the literature. For instance, in [12], a non-optimal rule-based energy management strategies are defined for power balancing of a standalone DC MG system. In [13], a nonlinear model predictive control based optimal EMS is formulated for battery management, voltage regulation, and proportional power sharing within a standalone DC MG. A priority-based EMS is formulated in [14] for energy balancing of an autonomous DC MG. Various optimization algorithms are analyzed and compared in [15] for offline multi-objective energy scheduling of hybrid power generation system. In [16], a two-level energy management strategy is defined for minimizing hydrogen consumption and ensuring generation demand balance of an isolated DC MG.

Furthermore, a real-time nonlinear EMS model is developed in [17], which performs economic dispatch for minimizing total generation cost of an islanded DC MG. In [18], a state machine control method is used for developing online EMS model that minimizes utilization cost of an islanded DC MG. However, most of these EMSs are not experimentally

tested. Furthermore, they have not developed optimal approach for realizing efficient operation of islanded DC MGs with maximum utilization of RESs and battery degradation cost consideration. This paper proposes an efficient EMS that optimally balances generation and demand with scheduled power generation of PV, wind, and tidal energy sources. The mathematical formulation of EMS optimization model is simple and reproducible and can be easily modified for other MGs.

The paper is organized as follows: Section II illustrates the case study of an islanded DC MG operation, Section III explains the EMS mathematical modeling in detail, Section IV presents the experimental results of the proposed EMS model, and Section V concludes the paper.

II. ISLANDED DC MICROGRID OPERATION

An islanded DC MG with tidal energy potential is shown in Figure 1. It consists of a PV system, wind turbine, tidal turbine, and Li-ion battery. Load is connected with DC/DC converter to emulate constant power load. All RESs, ESSs, and load are connected to DC bus using DC/DC converter. An EMS is used for supervisory control of DC MG. The principles task of EMS are data storage, data analytics, and power scheduling. It collects and stores data from energy sources and load for performing future forecasting and system analysis. It also determines a day-ahead optimal scheduling of energy sources and sends this information to local controllers of DERs. It is assumed that load demand is always met by RESs generated power and battery discharge power.

All local controllers of RESs operate in either MPPT mode or power limitation mode. These modes are defined by decision strategy of EMS obtained from the solution of the defined mathematical model and decision algorithms. Hence, all RESs either produce maximum power or limit power production according to EMS decisions. However, the RESs are intermittent in nature and they sometimes cannot generate scheduled power value in certain conditions. Hence, a simplified scheme is taken from [19], where minimum of scheduled power and MPPT power is selected as a power reference for RESs. Various MPPT strategies for PV, wind

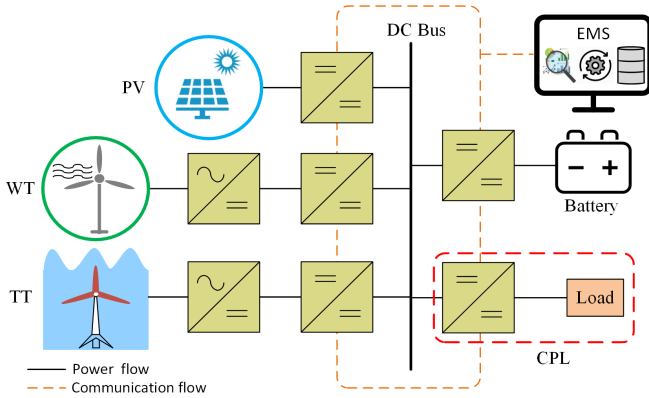


Fig. 1. Islanded DC MG Architecture.

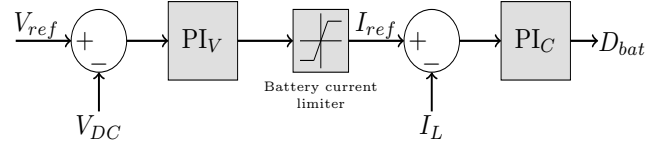


Fig. 2. DC bus voltage regulation based on battery connected DC/DC converter.

turbine, and tidal turbine generators are provided in references [20]–[23]. In this case study, all RESs local controllers are direct current controlled except local controller of ESS.

For ESS, battery storage system is considered [24]. A bidirectional DC-DC converter is used for controlling battery operation and it also acts as a grid-forming converter. In this case study, battery is solely in charge for voltage regulation of DC bus. Hence, it is used for bus voltage regulation as well as power imbalance compensation in real-time. A dual loop V-I controller is used for battery storage system [25]. The block diagram of V-I controller for a bidirectional converter of battery is shown in Fig. 2, where inner loop is used for current control and outer loop is used for voltage regulation of DC bus through proportional integral controllers. The state of charge (SoC) of battery is modeled using Columb counting method [26], as given by (1), and it is based on energy balance at DC bus.

$$SOC_k = SOC_0 + \frac{1}{E_r^b} \sum_{i=1}^k (PG_i - PD_i - PL_i)T_s \quad (1)$$

where SOC_k is battery SoC at index k and SOC_0 is initial battery SoC. E_r^b is the rated battery capacity. PG_i , PD_i , and PL_i are the total power generation, demand, and losses at index i , respectively. T_s is the sampling time in hour.

III. ENERGY MANAGEMENT SYSTEM

Energy management system supervises operation and control of DC MG system to achieve efficient energy transfer and balancing. In the proposed energy management optimization model, the only binary variable is associated with battery charging and discharging status. While, all the other decision variables are real variables. The time horizon for optimization is defined as T , which is sampled at the time interval Δt to have $N = T/\Delta t$ discrete time slots. K represents discrete time set such that $K = \{1, 2, 3, \dots, N\}$. The objective function and constraints of the mixed integer linear programming-based energy management optimization model are presented as follows:

$$\min \sum_{k \in K} \left\{ C_k^b \left(\eta P_k^{b+} - \frac{P_k^{b-}}{\eta} \right) \Delta t + \sum_{x \in X} \zeta_t^x (P_{f,k}^x - P_k^x) \Delta t \right\} \quad (2)$$

$$0 \leq P_k^x \leq P_{f,k}^x, \quad x \in X, k \in K \quad (3)$$

$$SOC_k = SOC_{k-1} + \frac{1}{E_r^b} \left[\eta P_k^{b+} - \frac{P_k^{b-}}{\eta} \right] \Delta t, \quad k \in K \quad (4)$$

$$0 \leq P_k^{b+} \leq \delta_k P_{max}^b, \quad k \in K \quad (5)$$

$$0 \leq P_k^{b-} \leq (1 - \delta_k) P_{max}^b, \quad k \in K \quad (6)$$

$$SOC_{min} \leq SOC_k \leq SOC_{max}, \quad k \in K \quad (7)$$

$$\sum_{x \in X} P_k^x - P_k^{b+} + P_k^{b-} = (1 + \alpha) P_k^d, \quad k \in K \quad (8)$$

$$\delta_k \in \{0, 1\}, \quad k \in K \quad (9)$$

Equation (2) presents the objective function, which aims to minimize the total operating cost of an islanded DC MG system over discrete time. C_k^b is battery degradation cost at discrete index k and it has been taken from the practical battery degradation cost model developed in [5]. ζ_k^x is defined as a penalization cost for each RES to have maximum utilization of its available generated power. The value of ζ_k^x is defined such that $\zeta_k^x > C_k^b$ to have maximum utilization of RESs. P_k^{b+} and P_k^{b-} are battery charging power and discharging power at index k , respectively. η represents battery round-trip efficiency. P_k^x is the decision variable for power produced by RES x at index k , while $P_{f,k}^x$ is its forecasted power. The set X defines the type of RESs; PV, wind, and tidal energy.

Equations (3)-(9) represents the constraints of EMS optimization model. Constraint (3) ensures that RES power remains within the limit of its forecasted power. The dynamic state of charge representation of battery is modeled in (4), where E_r^b is rated capacity of battery. d is depth of discharge of battery, which is equal to $d = SOC_{max} - SOC_{min}$. Constraints (5) and (6) restricts battery from charging and discharging at the same discrete time index k . Constraint (8) ensures power balancing of DC MG system, where α represents system losses in terms of percentage of total power demand. P_k^d is parameter that represents power demand at index k . The binary variable associated with battery charging and discharging status is presented in (9).

The day-ahead decisions of EMS optimization model are sent to all RESs to produce either maximum or reduced power accordingly. As battery is solely responsible for voltage regulation of DC bus, it shall continuously charge or discharge for ensuring continuous real-time operation of DC MG system.

IV. CASE STUDY AND EXPERIMENTAL RESULTS

An islanded DC MG of PV-wind-tidal and Li-ion battery is used as a case study for Ouessant island. The hardware-in-the-loop (HIL) experimental setup has been implemented using Danfoss converters and dSpace RTI 1006 platform at the DC Microgrid Research Laboratory in Aalborg University [26]. Four power electronic converters are used for representing PV, wind turbine (WT), tidal turbine (TT), battery, and constant power load (CPL). The converters of PV, WT, and TT have only current control loop, while battery converter has both inner and outer voltage control loops. The converter of CPL

TABLE I
SYSTEM PARAMETERS OF ISLANDED DC MG.

Parameters	Value
Nominal DC bus voltage	380 V
Sampling frequency	10 kHz
Inverter inductor	1.8 mH
DC bus capacitance	3.3 mF
Proportional gain of current loop	5E-3
Integral gain of current loop	0.5
Proportional gain of voltage loop	0.62
Integral gain of voltage loop	0.06
Proportional gain of power loop	5E-5
Integral gain of power loop	5E-3
Load	33 Ω

have only power loop that is used to generate real-time power demand profile. The system parameters are provided in Table I. The battery rated capacity is taken as 20 kWh and the maximum limit on battery charge (discharge) power is assumed to be 2 kW. The round-trip efficiency is considered as 0.95. The maximum and minimum limits on battery SoC are defined as 0.9 and 0.4, respectively. The initial SoC of battery is 80%. The penalization cost of each RES is taken as 1 €/kWh and battery degradation cost is considered as 0.02 €/kWh.

The PV, wind, tidal, and load power profiles of Ouessant island are taken from [2], [9] for 24h period and they are scaled down for the experimental case study. The system losses are considered as 5% of load demand. The EMS optimization model considers sampling time equal to 1h for 24h scheduling horizon, thus takes 24 discrete time indices. The prediction errors in PV power, wind power, tidal power, and load demand are taken as 5% of their forecasted values. All local controllers are running in real-time but the scheduling profiles are scaled from hours to seconds (1 h: 60 s).

Both forecasted and real-time load demand profiles are shown in Fig. 3. The forecasted load demand are used in

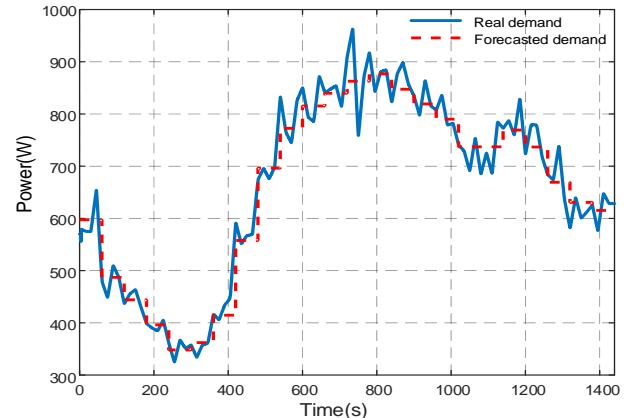


Fig. 3. Real and forecasted power demand profiles of islanded DC MG.

EMS optimization model for determining scheduling decisions of RESs. In real-time, generated power and load are continuously changing and their forecasted profiles have prediction errors. Hence, real-time power generation and load profiles are generated from normal distribution of mean value equal to their forecasted values and standard deviation equal to prediction errors in these forecasted values. The prediction errors are introduced after every 15 seconds and they are linearly interpolated to represent real-time scenarios of power generation and load profiles.

Figures 4 and 5 graphically represent the MPPT and real-time power production of RESs. As RESs produce more power than the required load demand, RESs local controllers follow scheduled power decision forwarded by EMS. They operate in power limitation mode or MPPT mode when needed. Figure 6 illustrates battery charge(discharge) power and SoC. Final SoC of battery is higher than initial SoC as shown in Fig. 3(d). Battery is charging when RESs generate more power than load and it is discharging when power generation of RESs is lesser than the load demand and real-time losses. Figure 7 shows that DC bus voltage always remains within $\pm 5\%$ limit of referenced DC bus voltage and islanded DC MG is performing stable operation.

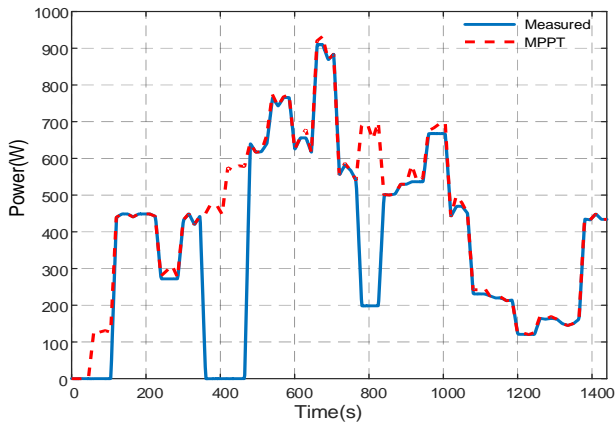


Fig. 4. Measured and MPPT power profiles of combine PV and WT.

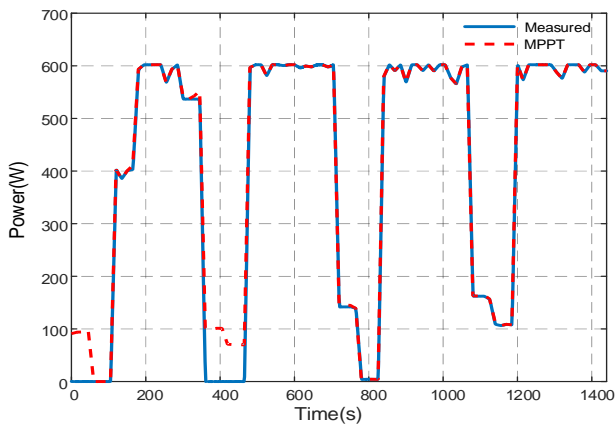


Fig. 5. Measured and MPPT power profiles of a tidal turbine.

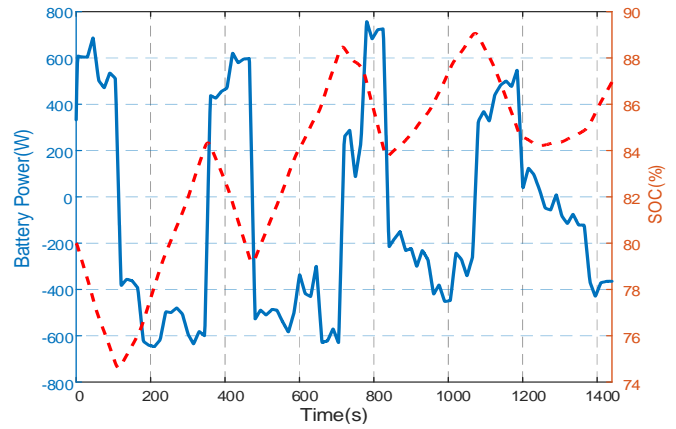


Fig. 6. Charge(discharge) power and SoC profiles of a Li-ion battery storage system.

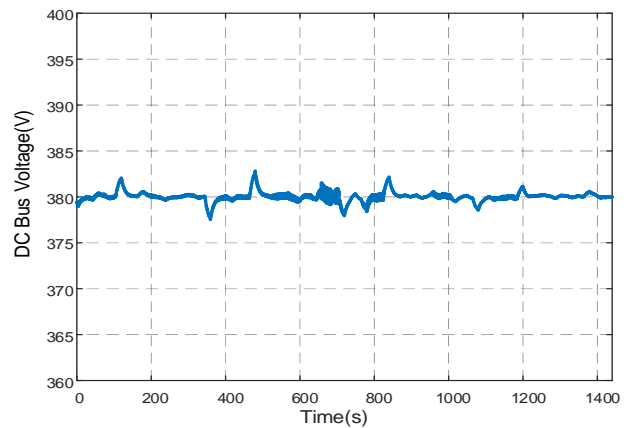


Fig. 7. Voltage profile of DC MG bus.

V. CONCLUSION

In this paper, an optimized energy management system is proposed for achieving stable operation of an islanded DC microgrid with the objectives of maximum utilization of renewable energy sources and supply demand balance. The optimization strategy has been defined as a mixed integer linear model to set optimal power references for the renewable energy sources of the DC microgrid. The proposed energy management system is validated by hardware-in-the-loop based experimental setup. The behavior of the variables obtained in real-time simulation follows the decision strategies given by the optimization stage. Experimental results prove the effectiveness of proposed energy management system approach of islanded DC microgrids.

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