Optimal Control of Distributed Energy Resources using Model Predictive Control

Ebony Mayhorn, *Student Member, IEEE,* Karanjit Kalsi*, Member, IEEE,* Marcelo Elizondo, *Member, IEEE,* Wei Zhang, *Member, IEEE,* Shuai Lu, *Member, IEEE*, Nader Samaan, *Member, IEEE,* Karen Butler-Purry, *Senior Member*, *IEEE*

***Abstract* — In an isolated power system (rural microgrid), distributed energy resources (DERs), such as renewable energy resources (wind, solar), energy storage and demand response, can be used to complement fossil fueled generators. The uncertainty and variability due to high penetration of wind makes reliable system operations and controls challenging. In this paper, an optimal control strategy is proposed to coordinate energy storage and diesel generators to maximize wind penetration while maintaining system economics and normal operation performance. The problem is formulated as a multi-objective optimization problem with the goals of minimizing fuel costs and changes in power output of diesel generators, minimizing costs associated with low battery life of energy storage, and maximizing the ability to maintain real-time power balance during operations. Two control modes are considered for controlling the energy storage to compensate either net load variability or wind variability. Model predictive control (MPC) is used to solve the aforementioned problem and the performance is compared to an open-loop look-ahead dispatch problem under high penetration of wind. Simulation studies using different prediction horizons further demonstrate the efficacy of the closed-loop MPC in compensating for uncertainties in the system caused by wind and demand.**

***Index Terms*— model predictive control, coordination of distributed energy resources**

NOMENCLATURE

$C(P_{Gi}(k))$	fuel cost for diesel unit *i* at time step *k* ($)
$P_{Gi}(k)$	scheduled output level of diesel generator *i* at time step *k* (kW)
P_{Gi}^{min}	minimum rated power of generator *i*
P_{Gi}^{max}	maximum rated power of generator *i*
R_{Gi}^{max}	maximum ramp rate of generator *i*
G	set of all diesel generators
$C(P_s(k)$	cost of operating the Battery Energy Storage System (BESS)
$SOC(k)$	State of Charge of BESS at time step *k*
π_{SOC}	penalty factor on low State of Charge (SOC)
SOC_{ref}	reference state of charge
$P_s(k)$	BESS charge/discharge power level at time step *k* (MW)
E_{max}	energy capacity of BESS (kWh)
η	efficiency of BESS
SOC_{min}	minimum SOC of BESS
SOC_{max}	maximum SOC of BESS
$T(k)$	threshold used as control input to compensate for wind or net load variability
$P_L(k)$	actual load power at time step *k*
$P_w(k)$	actual wind power at time step *k*
$\hat{P}_{Gi}(k)$	predicted power of diesel generator *i* at time step *k*
$\widehat{SOC}(k)$	predicted SOC of BESS at time step *k*
$\hat{T}(k)$	predicted threshold value
$\hat{P}_L(k)$	forecasted load power at time step *k*
$\hat{P}_w(k)$	forecasted wind power at time step *k*
Gr	set of all wind generators

I. INTRODUCTION

ISOLATED power systems are typically small distribution systems in remote areas, which lack support from larger interconnected power grids. In these systems, electricity is often supplied by small fossil fueled generators that tend to be very expensive to operate. Integrating distributed energy resources (DERs), such as renewable resources and energy storage, can allow for economical and environmentally friendly operation. However, there is significant variability and uncertainty associated with high penetration of renewable resources like wind and solar. Energy storage devices have inter-temporal constraints associated with their operation, and it can be difficult to predict the state of charge (SOC) during operation of some energy storage devices. Due to these inherent characteristics of wind and energy storage, real-time operations and control coordination becomes challenging.

Many centralized/decentralized control strategies have been and are being developed to integrate DERs in power system operations. Examples of control strategies already proposed and/or developed such as the 'Grid Friendly Appliance' technology (decentralized) is given in [1]. A decentralized droop control is added to disaggregated loads using quasi-continuous control law to have a desired aggregated response for frequency and stability control in [2]. In [3], a decentralized control of voltage profile is proposed in the distribution system with DGs using reactive power control of inverters. A centralized AGC-type control of DGs is proposed in [4]. A combination of centralized and decentralized coordination strategies for a rural microgrid, containing wind and diesel generators, BESS, and demand response, were studied in [5]. The objectives for the coordination strategies were to maintain system frequency close to nominal and to reduce fossil fuel generator movement by allowing energy

---

This work was supported by the Laboratory Directed Research and Development (LDRD) program at the Pacific Northwest National Laboratory.

E. Mayhorn and K. Buttler-Purry are with Texas A&M University, College Station, TX.
K. Kalsi, M. Elizondo, S. Lu and N. Samaan are with Pacific Northwest National Laboratory, Richland, WA 99354 USA.
W. Zhang is with the Ohio State University, Columbus, OH

978-1-4673-2729-9/12/$31.00 ©2012 IEEE

storage devices to compensate wind variability. Arbitrary control inputs were selected only to show the effectiveness of the control coordination strategies. The authors recognized the need for an optimally coordinated control scheme between different DERs.

Several coordination strategies of DERs, to provide ancillary services (i.e., scheduling, dispatch, balancing, contingency response, etc.) have been explored in [6]-[11]. In [12], an energy management system is proposed that is divided into several modules: forecasting, energy storage management, and an optimization module. The optimization module performs day-ahead unit commitment that uses information from load and distributed generation (DG), power forecasting module, market information, and energy storage management system to economically allocate generation in a microgrid. A power management strategy for wind-diesel-BESS systems is presented in [13]. Diesel and energy storage power setpoints are dispatched, using day-ahead wind and load forecasts, to minimize diesel generator operating costs, as well as, costs related to battery lifetime. A conceptual idea for multi-stage economic load dispatch in island microgrids is presented in [14]. To address the issues of variability and uncertainty, in [15]-[18], a model predictive control (MPC) approach is introduced. The strategy is based on dispatching power at minimal cost, assuming that energy storage is not available, that renewable sources are dispatchable, and that only short term wind forecasts are reliable.

In this work, a centralized MPC based coordination strategy is proposed for dispatch of DERs in an isolated system. One key difference between this work and that proposed in [15]-[18] is that performance objectives are incorporated in addition to economics. The goal of this work is to maximize the amount of wind generation in the system while considering system economics and the individual controls of the DERs. This can be done by formulating a look-ahead dispatch problem and casting it in a multi-objective framework. The objectives are to: minimize fuel costs of diesel generators, minimize changes in power output of diesel generators (reducing wear and tear), minimize costs associated with low battery life of energy storage, and to maximize the ability for generators to provide real-time balancing. Two control modes are adopted depending on whether the energy storage system used to compensate for wind or net load variability. Simulation studies are used to evaluate the performance of the different control strategies and to demonstrate the effectiveness of the closed loop MPC in compensating for uncertainties in wind and load forecasts.

This paper is organized as follows. In Section II, a brief description of the standard look-ahead dispatch problem is given. An optimal control coordination scheme using MPC is presented in Section III. In Section IV, case studies are presented that demonstrate the effectiveness of the optimal control coordination strategy. Finally, conclusions are given in Section V.

II. CLASSICAL DISPATCH PROBLEM FORMULATION

In a typical dispatch formulation with conventional generation, wind generation, and BESS, the objectives are to: 1) minimize fuel costs of diesel generators and 2) minimize operating costs of energy storage. The power outputs of the diesel generators and energy storage are dispatched based on wind and load forecasts over an entire horizon. The optimization problem is formulated as follows:

$$min_{P_{Gi}(k),P_s(k)} \sum_{k=1}^{N}\sum_{i=1}^{G} C\big(P_{Gi}(k)\big) + \sum_{k=1}^{K} C(P_s(k)) \quad (1)$$

subject to

$$\sum_{i=1}^{G} P_{Gi}(k) + \sum_{j=1}^{Gr} \hat{P}_{wj}(k) + P_s(k) = \hat{L}(k) \quad (2)$$

$$SOC(k) = SOC(k-1) - \alpha\, P_s(k-1) \quad (3)$$

$$P_{Gi}^{min} \leq P_{Gi}(k) \leq P_{Gi}^{max}\ , i = 1, 2, \dots G \quad (4)$$

$$|P_{Gi}(k+1) - P_{Gi}(k)| \leq R_{Gi}^{max}\ , i = 1, 2, \dots G \quad (5)$$

$$SOC_{min} \leq SOC(k) \leq SOC_{max} \quad (6)$$

The above constraints (2-6) are calculated for $k = 1, \dots, N$, where N is the length of the prediction horizon. The fuel cost of each generator $C(P_{Gi}(k))$ is assumed to be linear and is given by

$$C\big(P_{Gi}(k)\big) = a_i + b_i P_{Gi}(k) \quad (7)$$

where, a_i, b_i are the fuel cost coefficients. The cost associated with operating the BESS, $C(P_s(k)$, is given by the following expression which is adapted from [13]:

$$C(P_s(k) = \pi_{SOC} SOC(K) C_p V_{max} \quad (8)$$

In (3), α is a constant given by $\alpha = \eta/(E_{max})\,\Delta t$ where, Δt is the time step duration (hr). The objective function defined in (1) is convex, and hence, any standard quadratic programming solver can be used to obtain the optimal solution. The decision variables in the optimization problem are the power setpoints of energy storage and generators. The basic power balance equation is given by (2), which must be satisfied at every time step over the prediction horizon. The evolution of the state of charge at every time step is given by (3). Furthermore, at every time step, the current state of charge is a function of the state of charge of the previous time step, the storage charge/discharge power, and the energy capacity. The output power of the generators and state of charge of the storage are constrained with the limits defined in (4), (5) and (6).

III. OPTIMAL CONTROL OF DISTRIBUTED RESOURCES USING MODEL PREDICTIVE CONTROL

The look-ahead dispatch problem discussed earlier has inherent increased uncertainty with high penetration of renewable energy resources in the system and is implemented in an open-loop manner. The optimization problem is solved over an entire horizon once and the resulting sequence of control inputs are implemented at the corresponding time steps. Even though day-ahead forecasts for load demand are reliable, day-ahead forecasts for wind are not. One possible technique to solve this problem is to use MPC, where at every step a finite horizon optimal control problem is solved using feedback from the system. However, the control sequence is implemented for only one step ahead. In this manner, MPC is considered closed-loop and has the ability to compensate for additional uncertainty in demand variability caused by high penetration of renewable energy resources. The MPC based optimal control problem can be viewed as a multi-objective optimization problem with goals to: 1) minimize fuel costs of diesel generators, 2) minimize changes in power output of diesel generators reducing mechanical wear and tear, 3) minimize costs associated with low battery life of energy storage, and 4) minimize the inability of isochronous generators to provide real-time balancing. Isochronous control