COORDINATED CONTROL AND OPTIMIZATION OF VIRTUAL POWER PLANTS FOR ENERGY AND FREQUENCY REGULATION SERVICES IN ELECTRICITY MARKETS

A Thesis

by

FAN ZHANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Electrical Engineering

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Approved by:

Co-Chairs of Committee, Le Xie
Chanan Singh
Committee Members, Shankar Bhattacharyya
Marc G. Genton
Head of Department, Costas N. Georghiades

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ABSTRACT

Coordinated Control and Optimization of Virtual Power Plants for Energy and Frequency Regulation Services in Electricity Markets. (December 2011)

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Co-Chairs of Advisory Committee: Dr. Le Xie
Dr. Chanan Singh

With increasing penetration of intermittent resources such as wind and solar, power system operations are facing much more challenges in *cost effective* provision of energy balancing and frequency regulation services. Enabled by advances in sensing, control and communication, the concept of Virtual Power Plant (VPP) is proposed as one possible solution which aggregates and firms up spatially distributed resources' net power injection to the system. This thesis proposes a coordinated control and bidding strategy for VPPs to provide energy balancing and grid frequency regulation services in electricity market environment. In this thesis, the VPP consists of two energy conversion assets: a Doubly Fed Induction Generator (DFIG)-based wind farm and a co-located Flywheel Energy Storage System (FESS). The coordination of the VPP is implemented through power electronics–based controllers. A five-bus system test case demonstrates the technical feasibility of VPPs to respond to grid frequency deviation as well as to follow energy dispatch signals. To enable the participation of VPPs in electricity market, this thesis also proposes an optimization based bidding strategy for VPPs in both energy balancing and frequency regulation service markets. The potential economic benefits of this bidding strategy are demonstrated under Denmark wholesale electricity market structure. Four case studies show the economic benefit of coordinating VPPs.

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Finally, thanks to my family and my girlfriend for their encouragement and love.

NOMENCLATURE

ACE	Area Control Error
AS	Ancillary Services
DA	Day Ahead
DAB	Day Ahead Bidding
DAE	Day Ahead Energy service
DAR	Day Ahead (primary frequency) Regulation service
DFIG	Doubly Fed Induction Generator
DK1	Power System Operator in West Denmark
DOD, DoD	Depth of Discharge for the ESS
ESS	Energy Storage System
FC	Forecast
HA	Hour Ahead
HAB	Hour Ahead Bidding
HAE	Hour Ahead Energy (service)
LMP	Location Marginal Price
LP	Linear Programming (optimization problem)
MPC	Model Predictive Control
OPEX	Operating Expenses
SOC, SoC	State of Charge of the ESS
SMP	System Marginal Price

VPP	Virtual Power Plant
WPP	Wind Power Plant

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

1. INTRODUCTION

Intermittent Distributed Generation (DG) resources such as wind and solar are growing fast in electric power systems all over the world. Distributed renewable energy is predicted to become the second-largest source behind coal for generating electricity before 2015. Wind, as a major source of power in many countries across the world, has mushroomed into a mature global business. With the improvement in power control, efficiency and reliability as well as dramatically reduction of generation costs over the last 15 years, wind becomes a promising renewable source to replace conventional generators. Global installed wind capacity continued to grow at an average cumulative rate of over 30% and the total installed capacity reached to 120 GW in 2008. These distributed resources show obvious benefits comparing with conventional technologies such as high efficiency and flexibility of fuel usage, short construction time and relatively low emission, high power quality and energy independence [1].

However, with the wind and other DGs gradually replacing the capacity of conventional power plants, power system operators are facing difficulties in frequency control and other services which are essential to system reliability [2]. For example, it is possible to integrate 20% renewable energy into California electric system. However, the frequency regulation capacity needs to increase by 170 MW to 250 MW for “Up Regulation” and 100 MW to 500 MW for “Down Regulation” [3]. Due to their high inter-temporal

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variability and limited predictability, resources like wind typically are excluded from providing ancillary services. This, in turn, increases the burden of conventional generators for provision of ancillary services such as frequency regulation [4].

However, with the wind and other DGs gradually replacing the capacity of conventional power plants, power system operators are facing difficulties in frequency control and other services which are essential to system reliability [2]. For example, it is possible to integrate 20% renewable energy into California electric system. However, the frequency regulation capacity needs to increase by 170 MW to 250 MW for “Up Regulation” and 100 MW to 500 MW for “Down Regulation”. Due to their high inter-temporal variability and limited predictability, resources like wind typically are excluded from providing ancillary services. This, in turn, increases the burden of conventional generators for provision of ancillary services such as frequency regulation [2].

More recently, the concept of VPP is proposed as one possible approach to enhance the control and dispatch of intermittent resources. Through spatial coordination between intermittent and other distributed resources such as storage, the net VPP will have the same visibility, controllability and market functionality as the conventional power plants [5]. The combined production of VPPs can be sold in the electric market as a single market participant. Moreover, power system would benefit from more optimal use of available resources and the efficiency of operation would be improved [6].

The potential benefits of VPPs can be summarized as [1]:

- Facilitating the integration process of intermittent generations such as wind and solar.
- Providing more valuable services like ancillary services to power system which could help reduce the burden of system frequency through centralized control strategies.
- Reducing the energy losses during electricity transmission and distribution.

In order to implement these functions of VPPs, coordinated control and bidding strategies are required to dispatch the VPP assets in electricity market. The main contribution of this thesis is two-fold: First, the technical feasibility is shown for coordinating wind farm and flywheel energy storage system for both energy balancing and frequency regulation services. Second, an optimization-based bidding strategy is proposed to allow VPPs to participate across the energy balancing and frequency regulation markets.

This thesis is organized as follows. Section 2 presents the literature survey of existing dispatch methods for wind farms and energy storage systems. In Section 3, the proposed coordinated control and optimization of wind farms and co-located flywheel energy storage systems are presented. Numerical results based on realistic Denmark market data are discussed in Section 4. Conclusion remarks are drawn in Section 5.

2. LITERATURE REVIEW

With advanced turbine design, recent literature began to investigate the feasibility of allowing wind turbines to participate in frequency regulation. In [7-9], frequency response of DFIG based and fixed speed wind turbines has been studied. The result shows that fixed speed wind turbine generators can participate in primary frequency response. For DFIG based wind turbines, a supplementary loop is proposed to allow DFIGs to participate in frequency regulation. This method utilizes the kinetic energy stored in the rotating mass of wind turbines such that the additional amount of power supplied by the wind generator to the grid is proportional to the derivative of the system frequency. In [7], a control scheme is proposed to allow wind generators operate according to a deloaded optimum power extraction curve such that the active power provided by each wind turbine increases or decreased during system frequency deviations. For Variable Speed Wind Turbine Generators (VSWTG) to contribute to frequency control, it is necessary to operate the wind generator below the maximum power output, thereby creating a real power reserve that can be used for frequency control.

There has also been focus on the use of energy storage systems to provide the frequency regulation services [10], [11]. Energy storage systems can recycle electrical energy, in response to an Area Control Error (ACE) signal, by absorbing energy from the grid when it is in excess and then supplying it back to the grid when required. The use of

Flywheel Energy Storage Systems (FESS) in conjunction with wind generators to compensate for power variations caused by wind speed fluctuations has been proposed [12], [13]. In fact, FESS have already been used for the purpose of system frequency regulation [14]. However, the potential benefits of coordinating variable wind with energy storage for provision of both energy balancing and frequency regulation services, especially from a centralized VPP's perspective, has not been explored in detail.

The coordination of wind and storage system, or the so-called VPPs, has become an active area of research focus. According to [15], VPPs can be classified into two categories: Commercial VPP (CVPP) and Technical VPP (TVPP). CVPP aggregates the DGs in order to perform market related activities, such as energy trading in different markets from forward to spot, which aims to maximize the profit margins for the aggregated generation portfolio. For TVPP, the aggregation is normally directed to provide specific power system support services, which are essential in maintaining power quality, reliability and security of the grid. Sometimes, local network constraints and real-time local network status are also included in the TVPP portfolio to assure the seamless grid operation. Also, smart grid techniques such as distribution network management and multi-asset energy management system provide technical support for the realization of TVPPP. The challenge remains in the area of how to build a framework from both technical and commercial prospectives. In the next section, a control and optimization for co-located VPPs will be proposed.

Coordinated control of the assets of VPPs would lead to financial advantages to the plant owner compared to operating the assets separately. Depending on the configuration of the VPP, the aggregation can provide technical capabilities and a higher level of confidence to fulfill the commitments made to the electric market in terms of energy balancing and ancillary services.

3. COORDINATED CONTROL AND OPTIMIZATION FOR VPPS

3.1 Frequency Control Introduction

Grid frequency can represent the balance between generated power and consumed power. The small imbalance between generation and demand will cause the small frequency deviate from the nominal value while severe power imbalance due to generator outage or transmission line tripping may result in large frequency deviation. Frequency control should be applied to avoid such situations and to keep the power grid stable and secure [16].

Electrical energy cannot be stored in large quantities and thus the total demand should always be met by the corresponding generation. Normally, the combined load of the system is changing in a relatively predictable pattern even individual customer could vary in a large scale. This predictable load pattern allows the operators to schedule the daily generation to satisfy the load while to keep the system secure and secure through certain control actions. However, increasing penetration of intermittent renewable energy increases the difficulty of accurate prediction of the demand pattern.

Frequency controls are typically classified as:

- Primary Frequency Control
- Secondary Frequency Control
- Tertiary Frequency Control

3.1.1 Primary Frequency Control

Primary frequency control is immediate response to frequency change from generators that equipped with speed governor system. Frequency control regulates the generator's output power according to the frequency difference between grid frequency and a predefined frequency reference. The change of output power is proportional to the frequency deviation based on the droop characteristic of the generator. This control could stabilize the frequency quickly (within 15-30 seconds). However, it does not have the effect to bring the frequency back to nominal value and thus the secondary frequency control is needed. When the generation unit is operating at its rated value and has no ability to increase power output for frequency regulation, spinning reserve is required by the system operators and the activation of the reserve should not be longer than 15-30 seconds. This kind of reserve is also referred as primary reserve in European electric system.

3.1.2 Secondary Frequency Control

Secondary frequency control aims to bring the frequency back to the equilibrium point and to bring the tie-line to schedule through adjusting the frequency reference of the speed governor system. The frequency reference follows the Area Control Error (ACE) signal which is used to adjust control setting power of each area in power system corresponding to the change of scheduled tie-line capacity and change of system frequency. The control purpose is to drive ACE in all areas to zero. Physically, an integral controller is required to drive ACE to zero at steady state. Secondary control is also referred as Automatic Generation Control (AGC). The activation of this control is slower than primary control and must be within 15min.

The ACE for two areas is defined as [17]:

$$ACE_1 = \Delta P_{12} + B_1 \Delta\omega \quad (1)$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta\omega \quad (2)$$

where

B_i : frequency bias setting of area

ΔP: power flow between area 1 and area 2

$\Delta\omega$: frequency difference between two areas

3.1.3 Tertiary Frequency Control

Tertiary frequency control (economic dispatch) concerns about satisfying the overall demand with minimum cost by adjusting the power output levels of different generators. The system operators set the operating points of individual power plants based on the economic dispatch scheme subject to certain constraints so that the overall cost of system operating could be minimized. This control action is slower than primary and secondary control.

Unlike primary and secondary frequency controls which are grid codes or requirements forced by the system operators, tertiary control is obtained via the energy market. Generator units could participate in this service optionally either through a centralized pool market or by bilateral contracts with particular customers. System operators should supervise all transactions between generators and customers and make sure that the transmission constraints are not violated and enough generation reserve is available in case of generator outage. In summary, tertiary control consists of following tasks:

- Automatic change of the set-points of individual units
- Automatic or manual connect/disconnect of generation units that are participating in reserve service

3.2 Wind Turbine Generator

Wind turbine generators could be generally divided into two categories: fixed-speed wind turbine generator and variable speed wind turbine generator. The detail descriptions are [16]:

- Fixed-speed wind turbine with induction generator

  This type of wind turbine generator is directly connected with the power grid. The rotor speed will be determined by the gearbox and the pole-pair number. It has strong coupling between the generator and the grid. The rotor speed is sensitive to the system frequency change due to this coupling.

- Variable-Speed Wind Turbine

  This type of wind turbine could either connect to a cage-bar induction generator or to a synchronous generator.

  - Variable-Speed Wind Turbine with multi-pole synchronous generator

To allow variable speed operation, a back to back converter is connected to the generator stator. The advantage of this type is the robustness in control and a wide range of operating speed which enhances generation efficiency.

- Variable-Speed wind turbine with Doubly Fed Induction Generator (DFIG)

  This type is one of the most popular and widely used wind turbine generators. The so-called “doubly fed” means that the stator is directly connected to the grid while the rotor is connected to the grid through a AC-DC-AC converter. Since power electronic converter only need to handle part of the total power (30%-40%), the power losses during converting process reduce.

3.2.1 Aerodynamic System of Wind Turbine

The aerodynamic system of wind turbine converts wind power into mechanical power through turbine blades. The available wind power can be expressed as [18]:

$$P_{wind} = 0.5\rho\pi R_w^2 V_w^3 \qquad (3)$$

The power captured by the wind turbine is:

$$P_m = 0.5\rho\pi R_w^2 C_p V_w^3 \qquad (4)$$

where

ρ: air density,

R_w: blade tip radius,

V_w: wind speed,

C_p: power coefficient, it is a function of the tip-speed ratio λ and pitch angle β(angle of the rotation of the blades around their main axis with respect to a reference position),

$$\lambda = \frac{R_w \omega_T}{V_w} \tag{5}$$

3.2.2 Drive Train of Wind Turbine

The drive train is the connection between aerodynamic system and generator. It consists of two main masses, turbine mass and generator mass. The two masses are connected to each other through a shaft which has stiffness and damping due to the physical structure of the turbine [19]. The equations for turbine side and generator side mass are:

$$2H_t \frac{d\omega_t}{dt} = T_t - K_S \theta_{tg} - D_s(\omega_t - \omega_g) \tag{6}$$

$$2H_g \frac{d\omega_g}{dt} = T_g + K_S \theta_{tg} + D_s(\omega_t - \omega_g) \tag{7}$$

where

H: inertia constant,

T: torque,

ω_g, ω_t: angular speed for generator and turbine,

K_S, D_s: shaft stiffness and damping constant,

θ_{tg}: electrical twist angle of the shaft, $\frac{d\theta_{tg}}{dt} = \omega_{base}\left(\omega_t - \omega_g\right)$

ω_{base}: base value of angular speed.

3.2.3 Generator of Wind Turbine

The detailed mathematical state space model of wind generator will be introduced in Section 3.3.1.

3.3 Coordinated Control Strategy for VPPs

In this section, we present the detailed coordination control formulation, which comprises of the following: (1) the model of the wind generator, (2) the model of the FESS, and (3) the detailed control formulation for the VPP to provide both energy balancing and frequency regulation services. Fig. 1 shows the schematic composition of VPP and its interconnection with the power grid.

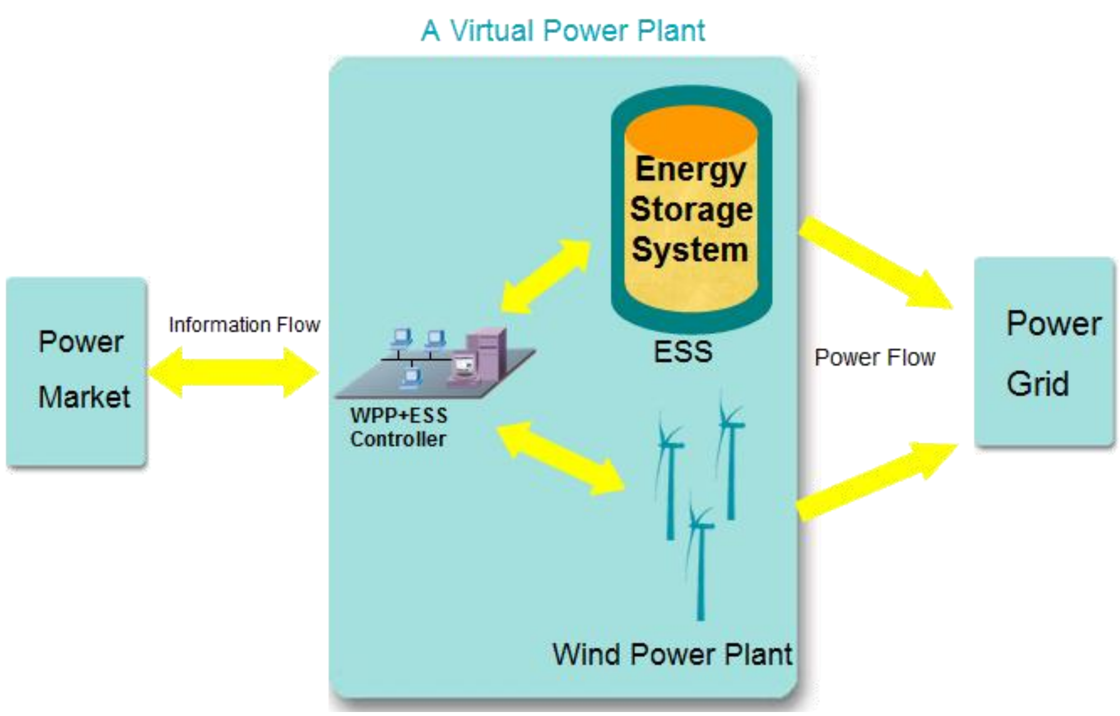

Fig. 1. Virtual Power Plant

A disturbance from either demand or supply in the power system results in a deviation in the frequency. Traditionally, conventional fossil fuel generators or hydro generators have been used to provide system frequency regulation. The primary frequency control action is carried out automatically by the governor systems of synchronous generator units, which stabilize the system frequency deviation. To return the frequency to the nominal value, a secondary control action known as Automatic Generation Control or Load Frequency Control (LFC) is required, in which the governor acts in response to an ACE signal [15]. In a multi-area power system the ACE is a combination of the frequency deviation from its nominal value and the tie-line power flow error.

The proposed control loops of the wind generator and FESS respond to the locally observed frequency deviation and provide primary frequency control actions. Additionally, based on the frequency deviation an ACE signal is fed to the wind generator and FESS. This results in a change in the induction machine controller set-points. These set-points are the reference electrical speed signals, which are fed to the power electronics based controllers in both the wind generator and the FESS. Based on the change in these set-points the controllers of both the machines adjust their power outputs, thereby providing secondary frequency regulation.

3.3.1 Linearized Wind Turbine Generator Control Model

A control scheme for the DFIG which comprises of primary, secondary and pitch control loops has been described in [9]. The primary frequency control loop generates a signalΔP_1, which is proportional to the frequency deviation. This control loop emulates the droop characteristic of synchronous generator governors. A reference signal P^{ref} is obtained from the deloaded power curve of the wind turbine. The wind farm supervisory system calculates a signalΔP_2, based on a system operator request. The combination of these three signals is fed to the rotor-side power electronics-based converter.

We suggest a modification to this scheme, where the supervisory system signal ΔP_2 is removed. Based on a grid frequency deviation, due to a disturbance, an ACE signal is fed to the wind generator. This signal acts to change the set-point ω_s^{ref} of the frequency control loop. Thus the signal ΔP_1 combines the primary and secondary frequency control signals. The power electronics converter then acts to change the real power output of the machine, thereby providing frequency regulation.

For completeness we restate the model of the induction machine and present the modified control scheme. The open loop model of the DFIG by Krause, with equations in flux linkage form is as follows [19]:

$$\dot{F}_{qs} = \omega_b\left[v_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{x_{ls}}\left\{x_{ml}\left(\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}}\right) + F_{qs}\right\}\right] \tag{8}$$

$$\dot{F}_{ds} = \omega_b\left[v_{ds} - \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{x_{ls}}\left\{x_{ml}\left(\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}}\right) + F_{ds}\right\}\right] \tag{9}$$

$$\dot{F}_{qr} = \omega_b\left[v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}F_{dr} + \frac{R_r}{x_{lr}}\left\{x_{ml}\left(\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}}\right) - F_{qr}\right\}\right] \tag{10}$$

$$\dot{F}_{dr} = \omega_b\left[v_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b}F_{qr} + \frac{R_r}{x_{lr}}\left\{x_{ml}\left(\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}}\right) - F_{dr}\right\}\right] \tag{11}$$

$$\dot{\omega}_r = \left(\frac{P}{2J}\right)(T_e - T_e) - \left(\frac{B}{J}\right)\omega_r \tag{12}$$

where

d: Direct axis,

q: Quadrature axis,

s: Stator variable,

r: Rotor variable,

F_{jk}, v_{jk}, i_{jk}: Flux linkages, voltages and currents (j = q or d and k = s or r),

R_r, R_s: Rotor and stator resistance,

x_{lr}, x_{ls}: rotor and stator leakage reactance,

x_m: Magnetizing impedance,

x_{ml}: Magnetizing leakage reactance, $\frac{1}{x_{ml}} = \frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}$

p: Number of poles,

J: Moment of inertia,

T_e, T_l: Electrical output and load torque,

ω_r, ω_e: Rotor and stator angular electrical speed,

ω_b: Machine angular electrical base speed.

The rotor side power electronics based converter regulates the voltage supplied to the DFIG rotor winding. The components of rotor voltage v_{qr} and v_{dr}, can be controlled independently to change the real and reactive power outputs, respectively. Two pairs of cascaded proportional-integral (PI) controllers are used for this purpose. The first pair of PI controllers regulate the rotor voltage components, whereas the second pair regulate the reference rotor current components. In this paper a trial and error method was adopted for determining the PI controller's gains. Fig. 2 shows the control scheme for wind turbine generator through power electronics devices.

The modified scheme for the real power control loop is described by:

$$\Delta P_1 = \frac{1}{R}\left(\omega_s - \omega_s^{ref}\right) \tag{13}$$

$$\dot{x}_1 = P^{ref} - \Delta P_1 - P \tag{14}$$

$$i_{qr}^{ref} = K_{p1}^{\omega}\dot{x}_1 + K_{i1}^{\omega}x_1 \tag{15}$$

$$\dot{x}_2 = i_{qr}^{ref} - i_{qr} \tag{16}$$

$$vi_{qr}^{ref} = K_{p2}^{\omega}\dot{x}_2 + K_{i2}^{\omega}x_2 \tag{17}$$

$$v_{qr} = K_{p2}\left[K_{p1}^{\omega}\dot{x}_1 + x_1 - i_{qr}\right] + x_2 \tag{18}$$

where

P^{ref}: Reference real power obtained from deloaded optimum power extraction curve,

P: Measured real power output of DFIG,

$K_{p1}^{\omega}, K_{p2}^{\omega}$: Proportional gains of the PI controllers of the wind generator,

$K_{i1}^{\omega}, K_{i2}^{\omega}$: Integral gains of the PI controllers of the wind generator,

i_{qr}: Rotor quadrature axis current,

i_{qr}^{ref}: Reference rotor quadrature axis current,

ω_s: Measured system frequency,

ω_s^{ref}: Reference system frequency,

R: Droop (emulated).

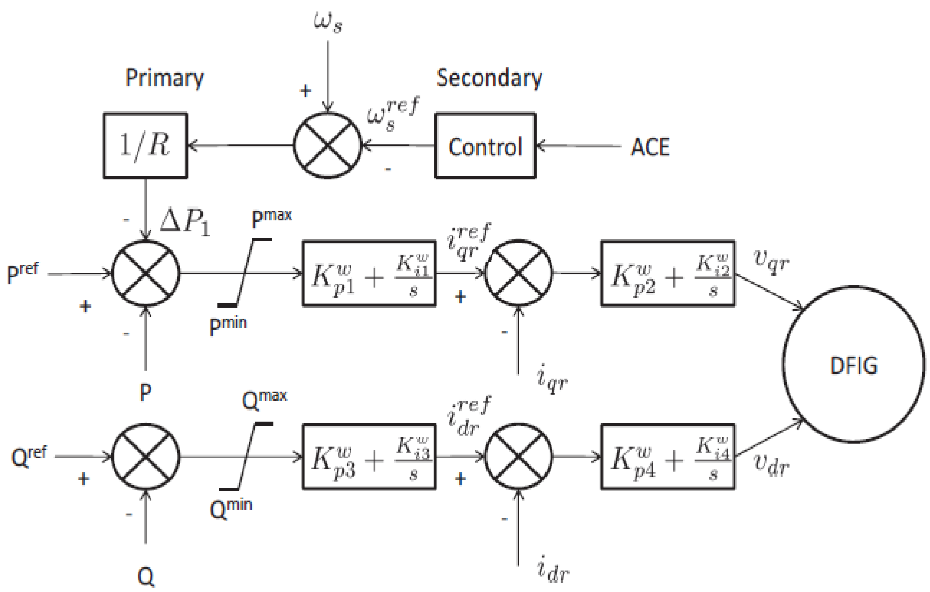

Fig. 2. Wind Generator Power Electronics Control

Thus the rotor side power electronics-based converter can control the amount of power injected by the DFIG into the grid. By adjusting its power output in response to frequency deviations, the wind generator can contribute to both primary and secondary frequency control action (6).

3.3.2 Linearized FESS Control Model

The FESS stores energy in the form of the kinetic energy of the rotating mass of the flywheel, which is given by:

$$E = \frac{1}{2} J \omega_m^2 \tag{19}$$

where ω_m is the mechanical speed of rotation of the flywheel. In this paper we assume that each unit of the FESS comprises of a flywheel coupled to a squirrel cage induction machine.

The inputs to the induction motor are the stator voltage, the stator frequency and the load torque. The outputs are the currents, the electrical torque and the rotor speed. There are various methods for the speed control of induction machine drives - which can be classified as open loop or closed loop, scalar or vector control [20]. Vector control, though considered complicated, enables good response to command input. For flywheel operation usually no load torque is applied, and for vector speed control the stator voltage and stator electrical frequency command inputs are described by [21], Fig. 3 shows the control scheme for flywheel system:

$$\frac{dv_{qs}^{ref}}{dt} = K_{p2}^{f}\frac{d}{dt}\left(i_{qs}^{ref} - i_{qs}\right) + K_{i2}^{f}\left(i_{qs}^{ref} - i_{qs}\right) \quad (20)$$

$$\frac{dv_{ds}^{ref}}{dt} = K_{p3}^{f}\frac{d}{dt}\left(i_{ds}^{ref} - i_{ds}\right) + K_{i3}^{f}\left(i_{ds}^{ref} - i_{ds}\right) \quad (21)$$

$$\omega_e = \omega_r + \omega_{sl}^{ref} = \omega_r + \frac{L_m R_r}{\psi_r L_r} i_{qs}^{ref} = \omega_r + \frac{1}{\gamma} i_{qs}^{ref} \quad (22)$$

where

$$i_{qs}^{ref} = K_{p1}^{f}\frac{d}{dt}\left(\omega_r^{ref} - \omega_r\right) + K_{i1}^{f}\left(\omega_r^{ref} - \omega_r\right) \quad (23)$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{1}{\omega_b}\left(F_{ds} i_{qs} - F_{qs} i_{ds}\right) \quad (24)$$

$$i_{qs} = \frac{1}{x_{ls}}\left[F_{qs} - x_{ml}\left(\frac{F_{qs}}{x_{ls}} - \frac{F_{qr}}{x_{lr}}\right)\right] \quad (25)$$

$$i_{ds} = \frac{1}{x_{ls}}\left[F_{ds} - x_{ml}\left(\frac{F_{ds}}{x_{ls}} - \frac{F_{dr}}{x_{lr}}\right)\right] \quad (26)$$

v_{qs}^{ref}: Reference stator quadrature axis voltage,

v_{ds}^{ref}: Reference stator direct axis voltage,

i_{qs}: Stator quadrature axis current,

i_{qs}^{ref}: Reference stator quadrature axis current,

i_{ds}: Stator direct axis current,

i_{ds}^{ref}: Reference stator direct axis current,

$K_{p1}^{f}, K_{p2}^{f}, K_{p3}^{f}$: Proportional gains of the PI controllers,

$K_{i1}^{f}, K_{i2}^{f}, K_{i3}^{f}$: Integral gains of the PI controllers,

L_m: Machine magnetizing inductance,

ψ_r: Rotor absolute flux value,

L_r: Rotor inductance,

ω_r^{ref}: Reference rotor angular electrical speed.

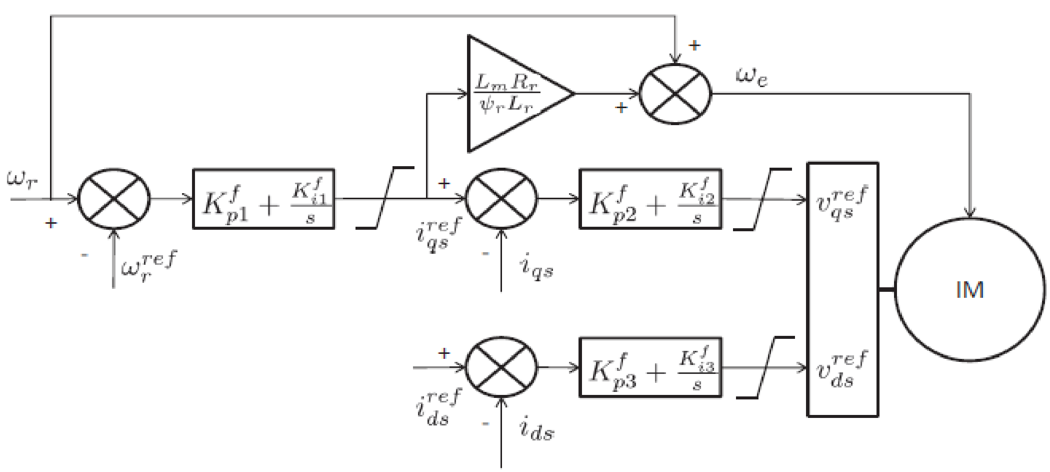

Fig. 3. Flywheel Power Electronics Control

The vector control scheme used to control the stator-side converter consists of a cascade of proportional-integral (PI) controllers, in which the outer PI block is driven by the speed error signal and the inner blocks are driven by the stator current reference signals.

Similar to the wind generator control scheme, the FESS is fed with an ACE signal. This results in a change in the speed reference input. The power electronics based controller compares the reference signal to the measured speed and changes the power output based on this error signal. The relationship between the rotor electrical speed ω_r (rad/s) and the rotor mechanical speed is given by

$$\omega_r = \frac{p}{2}\omega_m \tag{27}$$

By changing the rotor speed the amount of energy stored by the flywheel as kinetic energy can be controlled. When the speed of the flywheel is increased it draws energy from the grid whereas when the flywheel slows down it delivers this energy back to the system. Thus the FESS can provide regulation service to counter the mismatch between supply and demand of real power, by increasing or decreasing the speed of the flywheel.

3.3.3 Coordinated Control Scheme of Wind Generator and FESS

The power output of the wind generator, and the power output and energy storage level of the FESS obey certain constraints.

$$P_{\omega}^{rdn}(k) = \min\,(r_{\omega}\Delta t, P_{\omega}(k), \frac{\Delta\omega_{max}}{R_{\omega}} \tag{28}$$

$$P_{f}^{rdn}(k) = \min\,(r_{\omega}\Delta t, \frac{E(k-1)}{\Delta t}, \frac{\Delta\omega_{max}}{R_{\omega}}) \tag{29}$$

$$P^{rdn}(k) = P_{c}^{rdn}(k) + P_{\omega}^{rdn}(k) + P_{f}^{rdn}(k) \tag{30}$$

$$P_{\omega}^{rup}(k) = \min\,(r_{\omega}\Delta t, P_{\omega}^{max}(k) - P(k), \frac{\Delta\omega_{max}}{R_{\omega}}) \tag{31}$$

$$P_{f}^{rup}(k) = \min\,(r_{\omega}\Delta t, \frac{(E^{max} - E(k-1))}{\Delta t}, \frac{\Delta\omega_{max}}{R_{\omega f}}) \tag{32}$$

$$P^{rup}(k) = P_{c}^{rup}(k) + P_{\omega}^{rup}(k) + P_{f}^{rup}(k) \tag{33}$$

$$E(k) = E(k-1) - P_{f}(k)\Delta t - P_{f}^{l}(k)\Delta t \tag{34}$$

$$0 \leq P(k) \leq \hat{P}_{\omega}^{max}(k) \tag{35}$$

$$-P_{f}^{max} \leq P_{f}(k) \leq P_{f}^{max} \tag{36}$$

$$0 \leq E(k) \leq E^{max} \tag{37}$$

$$-r_{\omega}\Delta t \leq P_{\omega}(k+1) - P_{\omega}(k) \leq r_{\omega}\Delta t \tag{38}$$

$$\hat{P}_{\omega}^{max}(k+1) = f(P_{\omega}^{max}(k), P_{\omega}^{max}(k-1), \ldots, P_{\omega}^{max}(k-n) + e \tag{39}$$

where at time step k we have:

$P_{\omega}(k)$: Wind gen. power output to grid,

$\hat{P}_{\omega}^{max}(k)$: Predicted max. power capability of wind gen.,

$P_{f}(k)$: FESS power output to grid,

$P_{f}^{l}(k)$: FESS power loss due to friction, copper losses etc.,

$P^{rup}(k)$: System reg-up capacity requirement,

$P^{rdn}(k)$: System reg-down capacity requirement,

$P_c^{rup}(k)$: Reg-up capacity provided by conv. gen.,

$P_c^{rdn}(k)$: Reg-down capacity provided by conv. gen.,

$P_f^{rup}(k)$: Reg-up capacity provided by FESS,

$P_f^{rdn}(k)$: Reg-down capacity provided by FESS,

$P_\omega^{rup}(k)$: Reg-up capacity provided by wind gen.,

$P_\omega^{rdn}(k)$: Reg-down capacity provided by wind gen.,

$E(k)$: Energy level of FESS,

E^{max}: Rated energy storage capacity of FESS,

r_f: Ramping rate of FESS,

r_ω: Ramping rate of wind gen.,

$\Delta\omega_{max}$: Max. allowable grid frequency deviation,

R_ω: Wind gen. droop constant,

R_f: FESS droop constant.

By coordinating FESS with wind, the wind generator does not need to spill real power in order to provide regulation-up service. Therefore when coordinating wind with FESS, the control signals (frequency reference) for the wind generator and flywheel are:

$$\omega_{w-ref}(k) = \begin{Bmatrix} V_{reg}\dfrac{W_u(k)}{W_u(k)+S_u(k)} \ where\ V_{reg} > 0 \\ V_{reg}\dfrac{W_d(k)}{W_d(k)+S_d(k)} \ where\ V_{reg} < 0 \end{Bmatrix} \tag{40}$$

$$\omega_{s-ref}(k) = \begin{cases} V_{reg} \dfrac{S_u(k)}{W_u(k) + S_u(k)} \ where \ V_{reg} > 0 \\ V_{reg} \dfrac{S_d(k)}{W_d(k) + S_d(k)} \ where \ V_{reg} < 0 \end{cases} \quad (41)$$

where

$\omega_{w-ref}(k), \omega_{s-ref}(k)$: frequency reference for wind generator and flywheel,

V_{reg}: frequency regulation requirement for the whole virtual power plant,

$S_u(k), W_u(k)$: regulation up schedule for flywheel and wind generator, (given in optimization-based bidding part)

$S_d(k), W_d(k)$: regulation down schedule for flywheel and wind generator, (given in optimization-based bidding part)

3.4 Bidding Strategy for VPPs

3.4.1 Denmark Electric Market Introduction

In this thesis, we use West Denmark wholesale market (DK1) for case study and simulation. The DK1 market is classified in detail as [22]:

- Energy Market
    - Day-Ahead Market (Elspot)
    - Intraday Market (Elbas)
- Ancillary Service Market
    - Primary Reserve
    - Secondary Reserve
    - Tertiary (Manual) Reserve

- Balancing Market
- Other Ancillary Services

3.4.1.1 Energy Market

a. Day-Ahead Energy Market (Elspot)

In day-ahead market (Elspot), all power producers and consumers are trading their offers or bids for the operating day based on their forecast. The electricity price is determined by the supply and demand. Producers and customers inform system operators their bids (quantity of power and corresponding price) 12-36 hours in advance. The deadline for day-ahead energy bidding is 12 hours before deliver. One hour after deadline, system operators declare the generation schedule and the corresponding prices for each hour of the next deliver day. The market participants are usually big producers and consumers.

The detailed timeframe for the day-ahead market trading is [22]:

- By 10:00 AM, Nordic transmission system operators do analysis and calculation to ensure enough transmission capacity is available for the operation day.
- By 12:00 noon, system operators collect all the bidding information from producers and customers and close the day-ahead market.
- By 13:00 PM, system operators calculate the system price and generators' schedules based on the bidding information from generators and demands. If

there is sufficient transmission capacity and no transmission congestion, the system will share the same electricity price which is so-called System Marginal Price (SMP). Otherwise, there are different price zones due to the transmission congestion and the electricity price for each area is called Local Marginal Price (LMP).

b. Intraday Energy Market (Elbas)

Intraday Energy Market (Elbas) serves as an adjustment market after day-ahead market. This market provides power producers and consumers opportunity to trade their offers before the real time deliver and thus hedges the high risk of unsecure balancing market price. Comparing to day-ahead energy market, Elbas is a continuous cross border intra-day market that covers the Nordic countries, Germany, and Estonia until one hour before the delivery. At 08:00 CET the hour-contracts for the next day are opened for trading in Germany. At 14:00 CET the hour-contracts for the next day are opened in the countries Finland, Sweden, Norway, Denmark and Estonia.

3.4.1.2 Ancillary Service Market

Ancillary services are the necessary services in support of uninterrupted services of electricity, under normal and abnormal conditions. Reserve service is one important ancillary service and it ensures sufficient reserve capacity is available to cover the possible contingencies of generators. To encourage generators to participate in this market, system operators in Nordic Pool pay a fixed availability payment before actual activate the generator units for being available and submitting bids to the reserve service market. A generator has to bid for each hour of the month if it commits to participate into a particular reserve service market. This market could be classified as:

a. Primary Reserve

Primary reserve is automatically supplied by generators to ensure the balance between production and consumption. The activation of primary reserve is aiming to stabilize the frequency deviation. The primary reserve is requested as an up regulation reserve and a down regulation reserve [22].

Auctions are held once a day for the next operating day with the deadline at 12:00 noon of previous day. Each auction is divided into six blocks of four hours each:

- Block 1: 00:00--04:00
- Block 2: 04:00--08:00
- Block 3: 08:00—12:00
- Block 4: 12:00—16:00
- Block 5: 16:00—20:00
- Block 6: 20:00—24:00

Detailed requirements for bids in this market:

- Deadline for bidding is 15:00 the day before operation.

- Bids must contain both quantity [MW] and price information for each hour of the operation day. Changes in price and quantity will apply for the whole 4-hour block. The price or quantity of the first hour will apply for the whole bid if there are different prices or quantities within the 4-hour block.
- Each bid must be at least 0.3 MW. Quantity must be stated as MW with one decimal and price must be stated as DKK/MW without the use of decimals.

The reserve must be activated linear by a frequency deviation between 20 mHZ and 200 mHz. The first half of the activated reserve must be delivered within 15 seconds while the last part must be fully delivered within 30. This reserve must be maintained until the secondary reserve takes over.

b. Secondary Reserve

Secondary reserve aims to relieve primary reserve as well as to bring the imbalance cross different areas to schedule and bring the grid frequency to nominal value. Secondary reserve is activated automatically by responding to a dispatch signal from system operators and it consists of up and down regulation reserve. Both up and down regulation reserve could be provided by either generators or consumers. The secondary reserve is purchased on a monthly basis and the quantity of needed reserve is published at the 10^{th} day in the month before. The secondary reserve must be delivered within 15 minutes after activated by system operators.

c. Tertiary Reserve (Manual Reserve)

Tertiary reserve is the capacity reserve through manual activation up and down of generators' output power by system operators. It relieves the secondary reserve in case of large generator outage. This reserve is trading on a daily auction base with quantity needed for each hour.

The detailed requirements apply to bids:

- Bids must be submitted to system operators no later than 9:30 AM before the operating day.
- Bids must contain quantity [MW] and price for each hour for the operating day.
- Each bid must be at least 10 MW and maximum 50 MW. Quantity must be stated as MW and price must be stated as DKK/MW without using of decimals.

After 10:00 AM, system operators notify the generators that are accepted to supply tertiary reserve and they are paid an availability payment equal to the cost of the highest bid for up or down reserve. This reserve is activated by adjusting the supply or consumption schedules. The manual reserve must be fully delivered within 15 minutes after activation. If there is additional need for manual reserve than purchased, system operators will conduct an extra auction in the afternoon similar to the morning auction.

The requirements for this extra auction are:

- The auction for additional manual reserve must be announced to suppliers no later than 14:30.
- System operators must receive bids no later than 15:00.
- System operators must finalize the auction and inform suppliers no later than 15:30.

3.4.2 Bidding in Electric Market

This subsection illustrates the multi-service bidding approach proposed for VPPs. Multi-service bidding refers to allocating net available energy from the VPP to multiple services in an electricity market. The allocation can composed of both energy balancing and ancillary service markets. Numerical optimization methods are adopted for making the bidding decisions.

The following assumptions are made:

- The VPP consists of two generation assets:
  - Wind Power Plant (WPP)
  - Energy Storage System (ESS)
- The electricity market structure is selected to be Denmark wholesale Market
- The VPP participates in three different services:
  - Day Ahead Energy (DK1's ELSPOT) market: it requires bids to be submitted daily at 12:00 noon on the day previous to the operating day

for the full 24 hours in an hour-by-hour basis. The bid is submitted once a day and consists of 24 values – MWs and prices for each hour of the operating day. The market clears at 13:00 and system operators announce the generation schedules.

- Intra Day Energy market (DK1's ELBAS): it requires bids to be submitted one hour before the operating hour. Therefore, there are 24 possible bids and one for each hour of the day.
- Day Ahead Primary Reserve market: it belongs to Ancillary Service (AS) that requires bids to be submitted daily by 15:00 on the day previous to the operating day in four-hour constant blocks. There are 6 bids per day and the market clears at 16:00.

Fig. 4 depicts a schematic diagram of the bidding process as a function of time. The figure lists input and output signals from each stage in the process. By noon on the previous day, the DA Energy Bidding computes energy allocation to each hour of the operating day via optimization. Preliminary bids for DA Primary Reserve and HA Energy are also obtained as a by-product of this optimization. Final DA Energy prices are available after the market clears, around 13:00. At that point, DA Energy bids become commitments to be honored on the operating day.

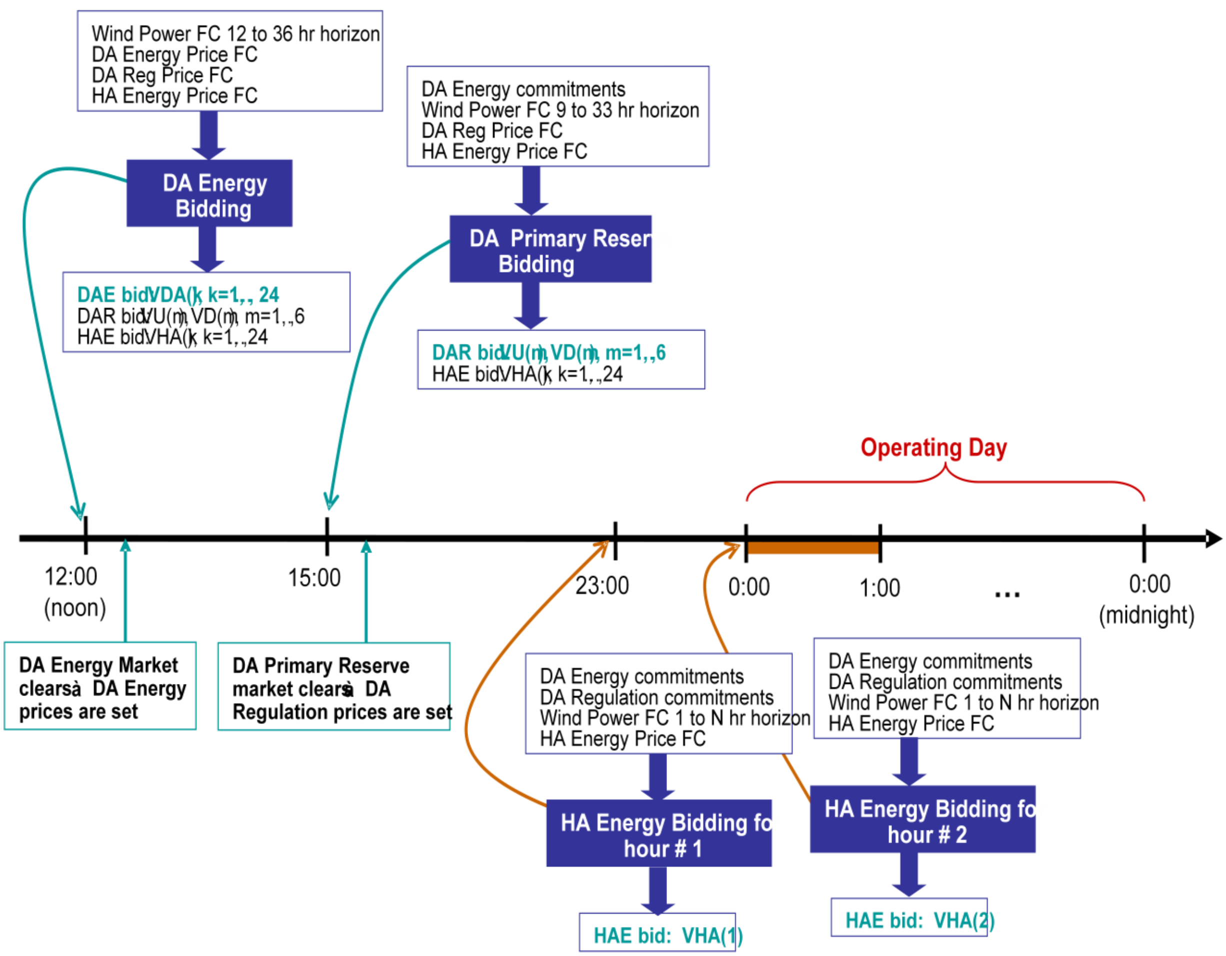

Fig. 4. Optimization-Based Bidding

By 15:00 on the previous day, the DA Primary Reserve Bidding assigns the primary frequency reserve quantities for up and down regulation for each 4-hour block of the operating day. Preliminary HA Energy bids come as by-products of this optimization. The market clears at around 16:00 and the VPP primary reserve bids become commitments. DA Energy Bidding and DA Primary Reserve Bidding are consolidated into one single process referred as Day Ahead Bidding.

A preliminary estimate of the energy available for HA Energy market is obtained while computing the DA Primary Reserve bid. As time progresses, the WPP power forecast is updated (and improved) and therefore this estimate should be modified. If the updated forecast wind power is more than previous forecast, the extra energy could be sold to the HA Energy market. If the updated forecast wind power is lower than previous forecast, the missing energy should be bought from the HA market and/or obtained from the ESS, depending on what is economically more convenient. This HA bidding is repeated 24 times throughout the operating day with each bidding process to be completed earlier than one hour before the start of the operating hour.

3.4.2.1 Optimization-Based Day-Ahead Bidding

Day Ahead Bidding (DAB) refers to the allocation of the expected VPP production in DA energy market and DA primary reserve AS market. This allocation attempts to maximize the expected VPP profit over the entire operating day, and therefore relies on forecasted values for WPP production and electricity prices for energy and ancillary services. It also requires estimated operating costs for WPP and ESS. The ESS is used to increase, as well as to firm the capacity that WPP offers into the AS market with respect to wind power forecasting errors.

- Goal: Computation of the VPP bids for the DA Energy market and DA Primary up/down Reserve AS market, such that the expected VPP profit is maximized over the operating day
- Inputs: Forecasted wind power and electricity prices, estimated costs for operating the assets, ESS parameters and initial SoC
- Outputs: VPP bids (MWs offered and duration) for DA Energy and for DA Primary Reserve up/down.

The optimization problem can be formulated as:

$$Maximize \sum_{k=1}^{24} \{\pi_{DA}(k) * W_{DA}(k) + \pi_{HA}(k) * W_{HA}(k) + \pi_{PRU}(k) * [W_u(k) + S_u(k)] + \pi_{PRD}(k) * [W_D(k) + S_D(k)] - CE_{WPP} * [W_{DA}(k) + W_{HA}(k)] - CR_{WPP} * [W_u(k) + W_D(k)] - CR_{ESS} * [S_u(k) + S_D(k)]\}$$

Subject to

$$0 < W_{DA}(k) < \widehat{W}(k)$$

$$0 < W_{HA}(k) < \widehat{W}(k)$$

$$0 < W_u(k) < \widehat{W}(k)$$

$$0 < W_D(k) < \widehat{W}(k)$$

$$0 < S_u(k) < S_{max}$$

$$0 < S_D(k) < S_{max}$$

$$W_{DA}(k) + W_{HA}(k) + W_u(k) < \widehat{W}(k)$$

$$W_{DA}(k) + W_{HA}(k) - W_D(k) > 0$$

$$E_{min} < E_{init} - \frac{1}{\eta} * S_u(1) + \eta * S_D(1) < E_{max}$$

$$E_{min} < E_{init} - \frac{1}{\eta} * [S_u(1) + S_u(2)] + \eta * [S_D(1) + S_D(2)] < E_{max}$$

...

$$E_{min} < E_{init} - \frac{1}{\eta} * [S_u(1) + \cdots + S_u(24)] + \eta * [S_D(1) + \cdots + S_D(24)] < E_{max}$$

$$W_u(1) + S_u(1) = W_u(2) + S_u(2) = W_u(3) + S_u(3) = W_u(4) + S_u(4)$$

$$W_D(1) + S_D(1) = W_D(2) + S_D(2) = W_D(3) + S_D(3) = W_D(4) + S_D(4)$$

...

$$W_u(21) + S_u(21) = W_u(22) + S_u(22) = W_u(23) + S_u(23) = W_u(24) + S_u(24)$$

$$W_D(21) + S_D(21) = W_D(22) + S_D(22) = W_D(23) + S_D(23) = W_D(24) + S_D(24)$$

The following are the decision variables in the optimization:

- $W_{DA}(k)$: WPP power bid for the DA Energy market, in MW
- $W_{HA}(k)$: WPP power bid for the HA Energy market, in MW
- $W_u(k)$: WPP power for the Primary Reserve up-regulation, in MW
- $W_D(k)$: WPP power for the Primary Reserve down-regulation, in MW
- $S_u(k)$: ESS power for the Primary Reserve up-regulation, in MW
- $S_D(k)$: ESS power for the Primary Reserve down-regulation, in MW

Therefore, VPP bids can be written in terms of the decision variables as follows:

- VPP DA Energy bid = $W_{DA}(k)$

- VPP HA Energy bid = $W_{HA}(k)$
- VPP Primary Reserve Up-regulation bid = $W_u(k) + S_u(k)$
- VPP Primary Reserve Down-regulation bid = $W_D(k)$+$S_D(k)$

The ESS model parameters of interest are:

- S_{max}: power rating, in MW
- E_{max}: energy rating, in MWh
- SOC_{max} and SOC_{min}: operational limits for SOC, dimensionless
- η: charge/discharge efficiency, dimensionless

Other parameters are:

- CE_{WPP}: cost of using WPP for energy, in $/MW
- CR_{ESS}: cost of using ESS for regulation, in $/MW
- CR_{WPP}: cost of using WPP for regulation, in $/MW
- E_{init}: initial ESS Energy, in MWh

Optimization input signals (problem input data):

- $\widehat{W}(k)$: WPP power forecast, in MW. This is the WPP power forecast available at time k
- $\pi_{DA}(k)$: DA Energy price forecast, in $/MWh
- $\pi_{HA}(k)$: HA Energy price forecast, in $/MWh
- $\pi_{PRU}(k)$: DA Primary Reserve up-regulation price forecast, in $/MWh
- $\pi_{PRD}(k)$: DA Primary Reserve down-regulation price forecast, in $/MWh

The optimization objective is to maximize the profit given the forecasted data over the 24 hour horizon cross different markets. For day-ahead bids, the hour-ahead bids are computed and estimated as a by-product.

The optimization constraints can be divided into 4 categories:

- Capacity constraint for decision variables. Some decision variables are limited by the forecasted values such as wind power and some are bounded by the actual capacity such as ESS power and energy.
- Constraints related with the WPP variables. The combination of energy allocated to day-ahead, hour-ahead and primary reserve markets cannot exceed the forecasted wind power.
- Constraints related with ESS variables. ESS energy must be limited by E_{min} and E_{max}. The power of ESS must be limited between S_{min} and S_{max}.
- Constraints related market requirements. Every bid of primary reserve must be constant over a 4-hour period.

3.4.2.2 Optimization-Based Hour-Ahead Bidding

Hour Ahead Bidding (HAB) refers to the computation of VPP bids for the intraday energy market. HAB needs to take into account that a portion of the VPP production is already committed on the DAB. Two situations can be encountered:

1. The hour-ahead wind power forecast indicates there will be enough production to cover DAB commitments, and any excess production is therefore bidding at the HA Energy market
2. The hour-ahead wind power forecast indicates there will not be enough production to cover the DAB commitments, and therefore the deficit portion must be covered by buying energy on the HA market and/or by discharging the ESS

- <u>Goal:</u> Computation of the VPP bids for the HA Energy market (buy and sell) such that the expected VPP profit is maximized subject to the constraint that a portion of the available production is already committed to the DA Energy and Reserve markets.
- <u>Inputs</u>: Forecasted wind power and HA energy prices, estimated costs for operating the assets, ESS parameters and initial SoC.
- <u>Outputs</u>: VPP bid (MWs offered and duration) for HA Energy for a given hour of the operating day.

  The optimization problem can be formulated as:

$$Maximize \sum_{k=1}^{24} \{\pi_{HA}(k) * W_{HA}(k) - CR_{WPP} * [W_u(k) + W_D(k)] - CR_{ESS} * [S_u(k) + S_D(k)]\}$$

Subject to

$$-W_{max} < W_{HA}(k) < +W_{max}$$

$$0 < W_u(k) < \widehat{W}(k)$$

$$0 < W_D(k) < \widehat{W}(k)$$

$$0 < S_u(k) < S_{max}$$

$$0 < S_D(k) < S_{max}$$

$$\widehat{W}(k) - V_{DA}(k) < W_u(k) + W_{HA}(k)$$

$$\widehat{W}(k) > W_u(k) + W_D(k)$$

$$E_{min} < E_{init} - \frac{1}{\eta} * S_u(1) + \eta * S_D(1) < E_{max}$$

$$E_{min} < E_{init} - \frac{1}{\eta} * [S_u(1) + S_u(2)] + \eta * [S_D(1) + S_D(2)] < E_{max}$$

...

$$E_{min} < E_{init} - \frac{1}{\eta} * [S_u(1) + \cdots + S_u(24)] + \eta * [S_D(1) + \cdots + S_D(24)] < E_{max}$$

$$V_u(k) = W_u(k) + S_u(k)$$

$$V_D(k) = W_D(k) + S_D(k)$$

The following are the decision variables in the optimization:

- $W_{HA}(k)$: WPP power bid for the HA Energy market, in MW. It can be positive or negative

- $W_u(k)$: WPP power for the Primary Reserve up-regulation, in MW
- $W_D(k)$: WPP power for the Primary Reserve down-regulation, in MW
- $S_u(k)$: ESS power for the Primary Reserve up-regulation, in MW
- $S_D(k)$: ESS power for the Primary Reserve down-regulation, in MW

Therefore, VPP bids can be written in terms of the decision variables as follows:

- VPP power available for Up-regulation bid = $W_u(k) + S_u(k)$
- VPP power available for Down-regulation bid = $W_D(k)$+$S_D(k)$

The ESS model parameters of interest are:

- S_{max}: power rating, in MW
- E_{max}: energy rating, in MWh
- SOC_{max} and SOC_{min}: operational limits for SOC, dimensionless
- η: charge/discharge efficiency, dimensionless

Other parameters are:

- CR_{ESS}: cost of using ESS for regulation, in $/MW
- CR_{WPP}: cost of using WPP for regulation, in $/MW
- E_{init}: initial ESS Energy, in MWh
- W_{max}: WPP power rating, in MW

Optimization input signals (problem input data):

- $\widehat{W}(k)$: WPP power forecast, in MW. This is the WPP power forecast available at time k
- $\pi_{HA}(k)$: HA Energy price forecast, in $/MWh

- $V_{DA}(k)$: VPP commitment for DA Energy, in MW
- $V_u(k)$, $V_D(k)$: VPP commitment for up/down regulation, in MW

The optimization objective is to maximize the VPP profit from selling or buying energy in the HA energy market. This optimization is executed one hour before the operating hour. The constraints of the optimization are similar to DA bidding except extra commitment in DAB.

4. SIMULATION RESULTS

4.1 Coordinated Control Result

We illustrate the proposed control scheme under the Denmark wholesale electric market. The wind power plant power capacity is 30 MW and the power capacity of ESS is 3 MW with energy capacity 1.5 MWh. The performance of the coordinated control is displayed as following:

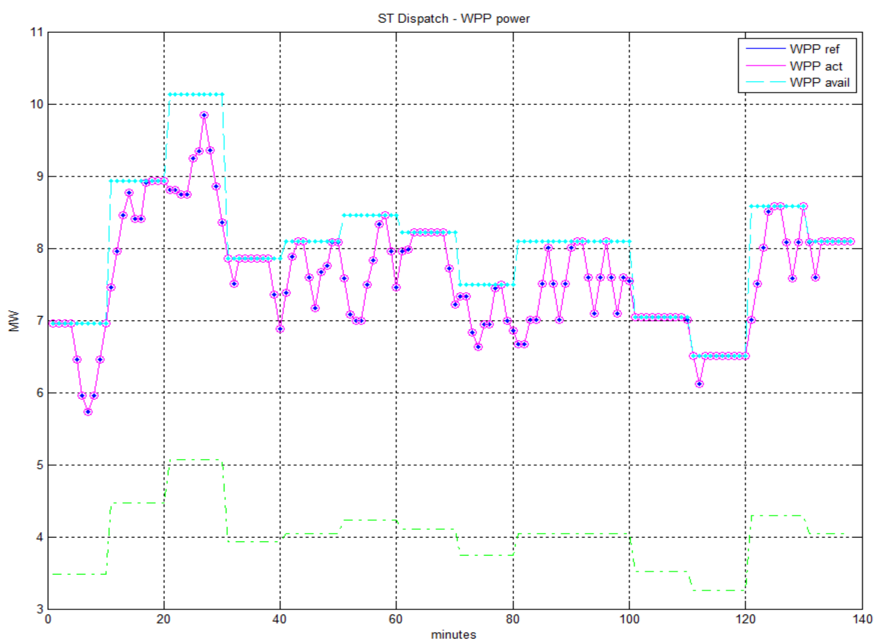

Fig. 5. WPP Power Available, WPP Power Command, WPP Actual Power

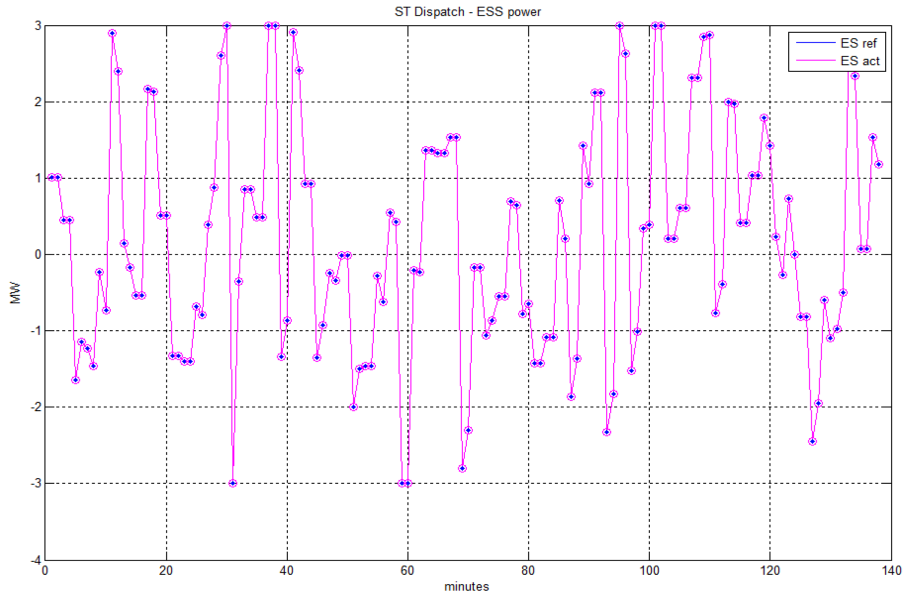

Fig. 6. ESS Power Command and ESS Power Response

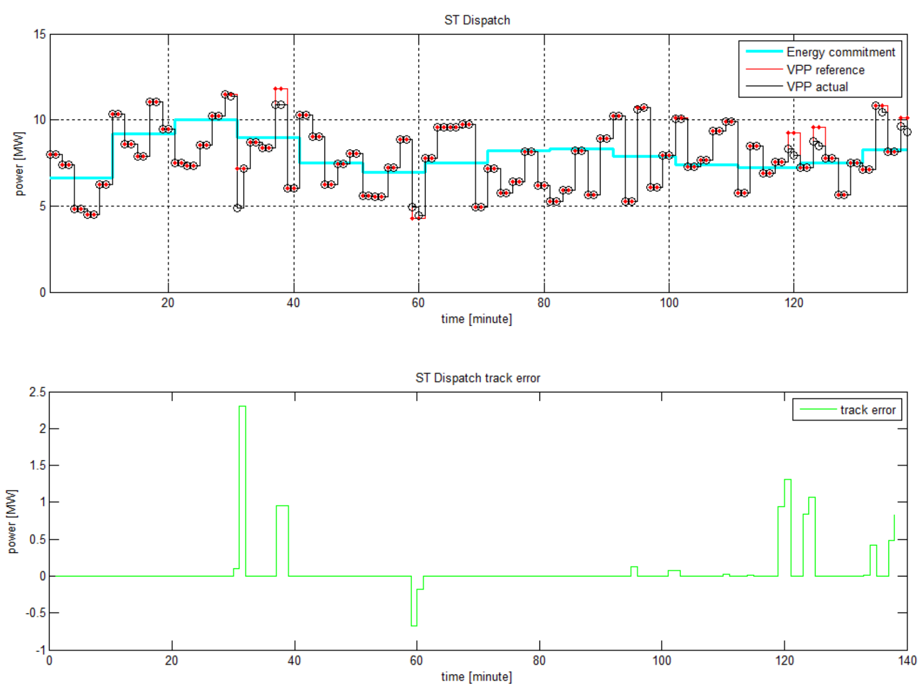

Fig. 7. VPP Power Request and VPP Output Power, VPP Tracking Error

Fig. 5 shows the relation among WPP power reference, WPP actual power, and WPP available power. The wind turbine tracks the reference power curve very well and regulates up and down according to the specified requirements through power electronics based controller. The power ramping rate of WPP power is limited to 0.5 MW/minute to emulate the practical control action of a wind turbine generator.

Fig. 6 shows the relation between ESS power reference and ESS actual power over the simulation period. ESS tracks the power reference well. The energy of ESS could vary between lower and upper energy limit to provide the regulation service to grid.

Fig. 7 shows the VPP tracks the requested power dispatch signals. The requested dispatch signals are proportional to grid frequency changes which are simulated as uniformly distributed signals. The VPP output power tracks the requests fairly well with only a few exceptions. Better tracking can be achieved by better WPP ramping ability and better forecast of wind power.

4.2 Optimization-Based Bidding Result

4.2.1 Day-Ahead Bidding Result

Wind power forecast and electricity price forecast are shown in the Fig. 8. The electricity price forecast includes both energy price and primary reserve up/down price. From the forecast price, we could observe that for the first 5 hours of the day, HA energy price is higher than DA energy price while for the last 5 hours of the day, the situation is opposite. Expect for 8:00-12:00, the regulation price curves are below energy price curves.

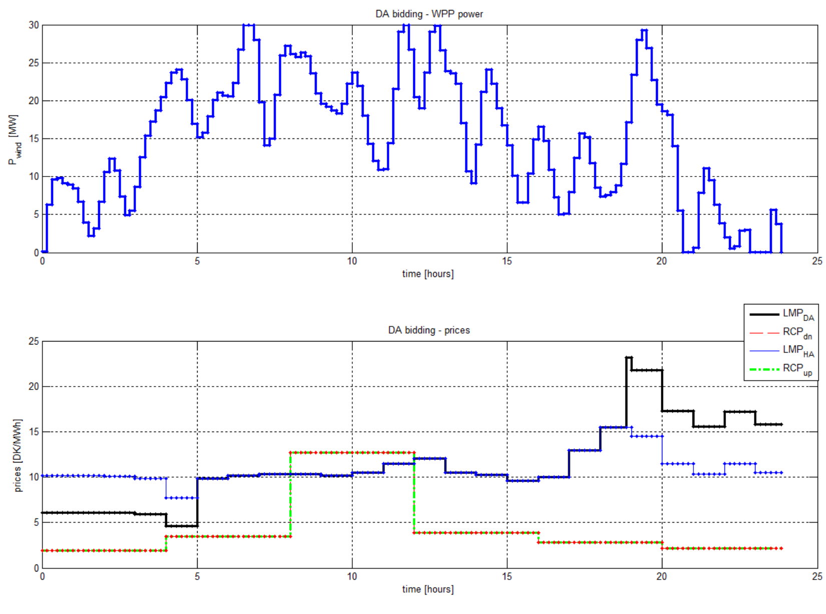

Fig. 8. Wind Power Forecast and Electricity Price Forecast

The bidding results are shown in Fig. 9. We can observe: Before 5:00, major wind power is allocated to DA energy market due to the higher DA energy forecast price. Also, during 8:00 to 12:00, the WPP is de-rated by roughly 3MW (forced requirement) to take advantage of the favorable primary reserve price during that interval. The primary reserve bids are shown explicitly in the mid-lower subplot. We limit the primary reserve maximum value up to 6 MW for up and down over a 4-hour interval. The reason of zero bid quantity for the first and last four hour block is due to the zero wind power forecast during these intervals.

The bidding table is listed as Table. 1. DA energy bid plus the expected HA bid and the primary reserve equal to the total forecasted wind power.

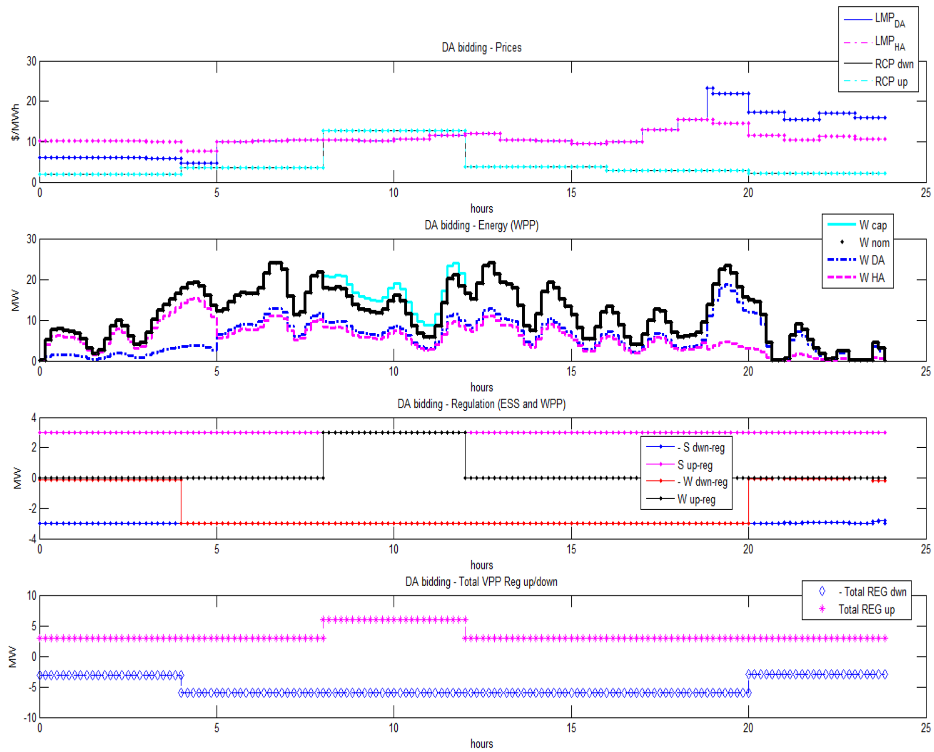

Fig. 9. DA Bidding Results

Table 1 DA bidding results, forecasted wind power, and preliminary HA energy bid

Hour starting at	Wind Power - DA forecast (MW)	DA Energy Bid (MW)	HA Energy expected bid (MW)	Regulation up bid (MW)	Regulation down bid (MW)
0:00	5.9	1.2	4.7	3.0	3.1
1:00	4.2	0.8	3.3	3.0	3.1
2:00	6.9	1.4	5.5	3.0	3.1
3:00	12.4	2.5	9.9	3.0	3.1
4:00	17.3	3.5	13.9	3.0	6.0
5:00	14.8	7.9	6.8	3.0	6.0
6:00	21.0	11.3	9.7	3.0	6.0
7:00	16.4	8.8	7.6	3.0	6.0
8:00	19.8	9.1	7.7	6.0	6.0
9:00	15.7	6.9	5.8	6.0	6.0
10:00	13.5	5.6	4.8	6.0	6.0
11:00	17.7	7.9	6.8	6.0	6.0
12:00	19.8	10.6	9.2	3.0	6.0
13:00	14.2	7.6	6.6	3.0	6.0
14:00	15.7	8.4	7.2	3.0	6.0
15:00	8.4	4.5	3.9	3.0	6.0
16:00	7.9	4.3	3.7	3.0	6.0
17:00	9.5	5.1	4.4	3.0	6.0
18:00	8.1	4.9	3.1	3.0	6.0
19:00	20.0	16.0	4.0	3.0	6.0
20:00	7.5	6.0	1.5	3.0	3.0
21:00	5.3	4.2	1.1	3.0	3.0
22:00	1.2	1.0	0.2	3.0	3.0
23:00	1.3	1.0	0.3	3.0	3.0

4.2.2 Hour-Ahead Bidding Result

Fig. 10 shows the wind power forecast for DA and HA bidding comparing with the actual wind power. We could observe that HA wind forecast is more accurate than DA forecast.

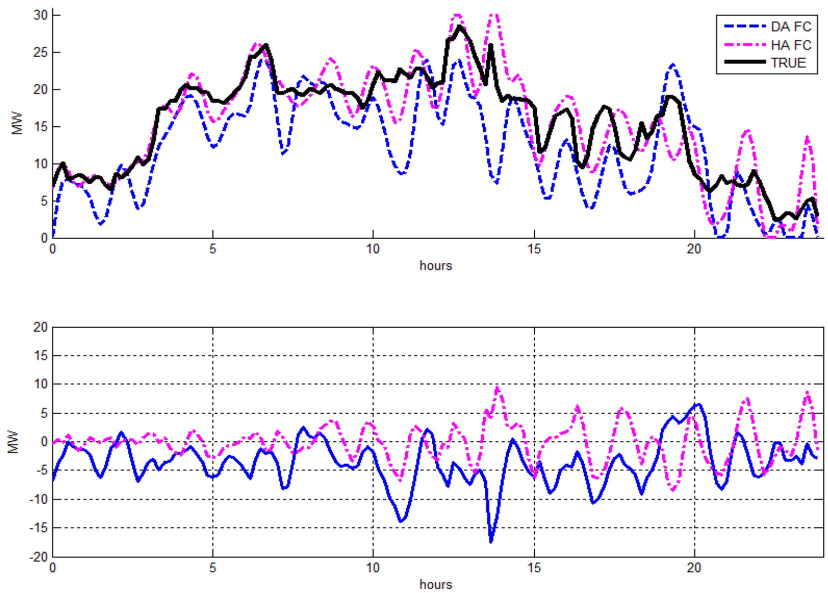

Fig. 10. Power Forecast vs. True Wind Power, Forecast Errors

Fig. 11 shows the DA and HA wind power forecast as well as the DA energy bids. Those points where the DA energy bids are above the HA power forecast (e.g., around hour 19:00) are very likely to be required to buy energy in the HA market to honor the DA Energy commitments.

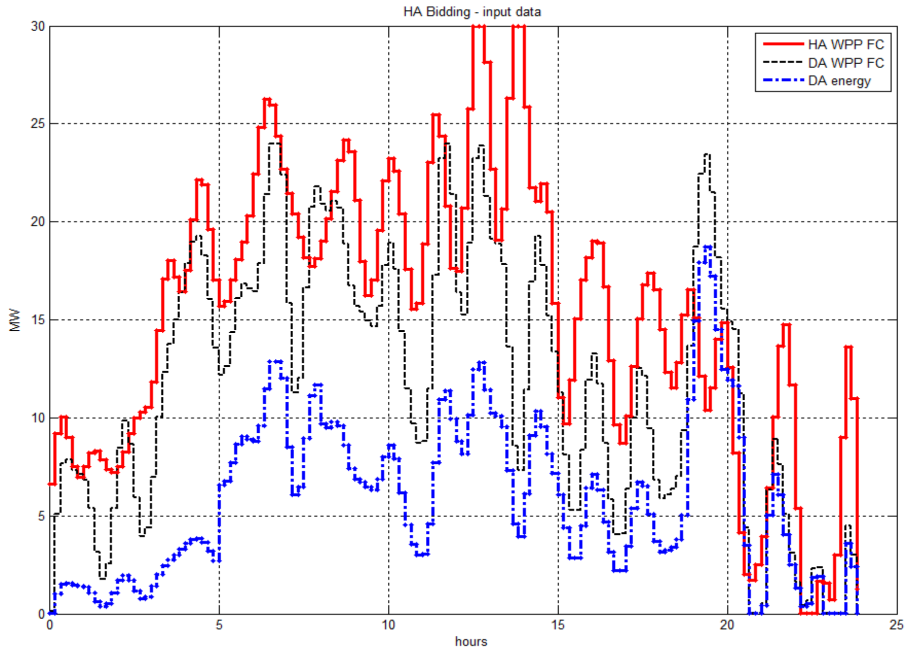

Fig. 11. Wind Power Forecast for DA and for HA, DA Energy Hourly Bid

Samples where DA Energy bids exceed the HA forecast indicate that it is required to buy energy in the DA market. The HA bidding information is summarized in Table. 2. The actual HA energy bids are different from expected HA bidding in DA market due to the update wind power forecast. Two negative HA bids are indicating that the VPP is buying energy from market. The negative bids correspond to hours 19:00-20:00 when DA energy bids above HA wind power forecast.

Table 2 Final bids for HA and DA markets

Hour starting at	Wind Power - DA forecast (MW)	Wind Power - HA forecast (MW)	DA Energy Bid (MW)	HA Energy expected bid (MW)	HA Energy final bid (MW)	Regulation up bid (MW)	Regulation down bid (MW)
0:00	5.9	8.2	1.2	4.7	7.1	3.0	3.1
1:00	4.2	7.8	0.8	3.3	6.9	3.0	3.1
2:00	6.9	9.3	1.4	5.5	7.9	3.0	3.1
3:00	12.4	15.8	2.5	9.9	13.4	3.0	3.1
4:00	17.3	19.7	3.5	13.9	16.2	3.0	6.0
5:00	14.8	17.7	7.9	6.8	9.7	3.0	6.0
6:00	21.0	24.4	11.3	9.7	13.1	3.0	6.0
7:00	16.4	19.2	8.8	7.6	10.4	3.0	6.0
8:00	19.8	22.0	9.1	7.7	9.9	6.0	6.0
9:00	15.7	19.0	6.9	5.8	9.1	6.0	6.0
10:00	13.5	19.2	5.6	4.8	10.6	6.0	6.0
11:00	17.7	21.7	7.9	6.8	10.8	6.0	6.0
12:00	19.8	25.3	10.6	9.2	14.7	3.0	6.0
13:00	14.2	24.8	7.6	6.6	17.2	3.0	6.0
14:00	15.7	21.2	8.4	7.2	12.8	3.0	6.0
15:00	8.4	13.8	4.5	3.9	9.3	3.0	6.0
16:00	7.9	14.3	4.3	3.7	10.0	3.0	6.0
17:00	9.5	14.7	5.1	4.4	9.6	3.0	6.0
18:00	8.1	13.8	4.9	3.1	8.9	3.0	6.0
19:00	20.0	13.0	16.0	4.0	**-3.0**	3.0	6.0
20:00	7.5	5.2	6.0	1.5	**-0.8**	3.0	3.0
21:00	5.3	10.1	4.2	1.1	5.9	3.0	3.0
22:00	1.2	1.4	1.0	0.2	0.5	3.0	3.0
23:00	1.3	6.4	1.0	0.3	5.4	3.0	3.0

4.3 Optimization Bidding Case Study

Services the VPP participates in are: DA Energy (ELSPOT), DA Primary and Frequency Reserve (regulation up and down), HA Energy (ELBAS).

The following 4 cases are considered:

- Case 1: the VPP consists of WPP only, and it participates only in the real time electricity market. All the WPP production is sold at real-time energy prices. This case attempts to reflect the most prevailing WPP operating practice.
- Case 2: the VPP consists of WPP only, and it participates in multiple electricity markets. The WPP provides DA Energy and HA Energy services but does not

provide primary reserve services, since its production cannot be fully guaranteed due to wind forecast errors without ESS.

- Case 3: the VPP consists of WPP plus ESS, and it is traded in multiple electricity markets. The VPP provides DA Energy, HA Energy, and primary reserve up/down services. However ESS and WPP do not act under a "coordinated" strategy – WPP is not utilized for regulation. This case reflects the simplest integration of WPP and ESS.
- Case 4: Same as Case 3, but with WPP and ESS under a "coordinated" strategy. This case reflects integration of WPP and ESS under optimization based bidding strategy.

We first illustrate the case study through one day simulation. The wind power and price data for this day are shown in Fig. 12.

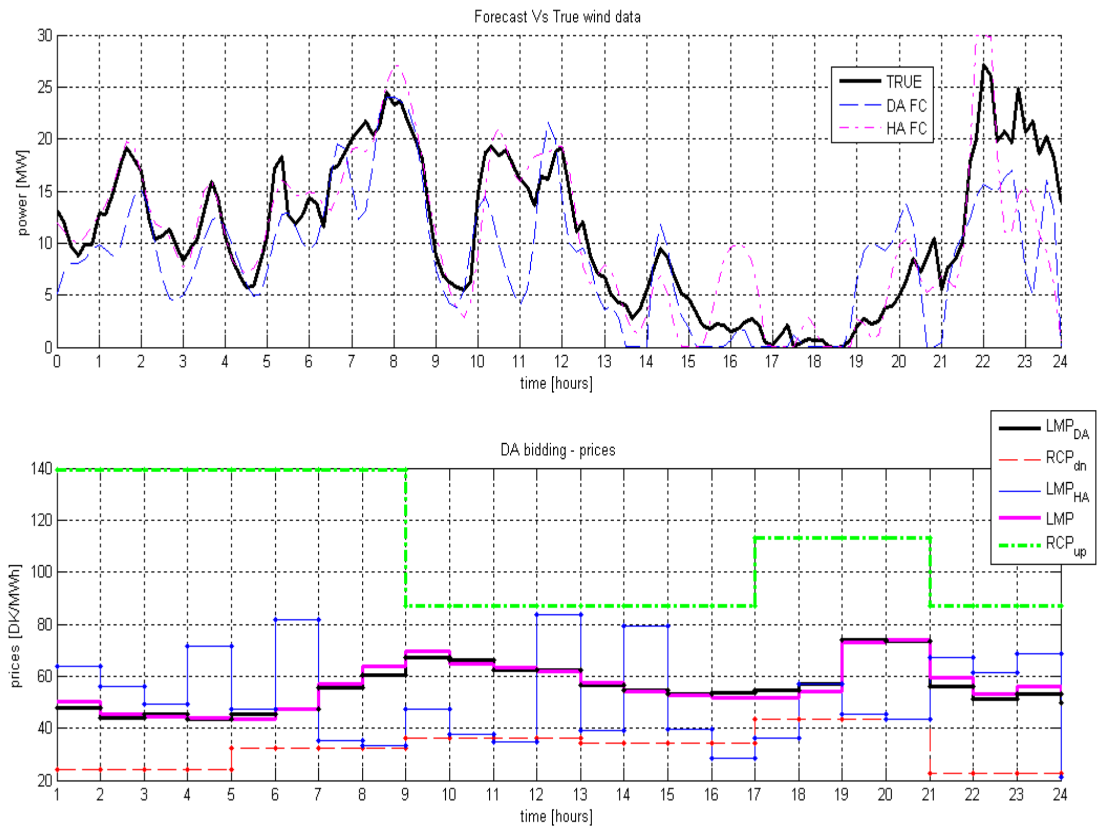

Fig. 12. Wind Power DA and HA Forecasts, Electricity Prices for All Services

Table 3 Profit comparison for different cases of one day ($ = USD)

Case No.	**DA Energy ($)**	**DA Primary Reserve ($)**	**HA Energy ($)**	**Real Time Energy ($)**	**Total ($)**
Case 1	0	0	0	19603	19603
Case 1	11310	0	8301	0	19611
Case 3	11310	46581	8301	0	66192
Case 4	10504	69585	7182	0	87271

The profit table is shown in Table. 3, we can conclude from the Table 3:

- Case 3 shows same DA/HA energy revenue as case 2 while with extra profit comes from primary reserve market.
- Compared with case 3, case 4 allows WPP to participate in primary reserve. This will increase its bids in primary reserve market and corresponding profit. Energy profit goes down since part of the energy is allocated to primary reserve up service.
- By bidding cross different markets rather than in single real-time market, the VPP increases profit by approximately 15%. (Case 2 compared with Case 1)
- By allowing WPP to participate in primary reserve market, the VPP increases profit by around 5%. (Case 4 compared with Case 3)

Then, we conduct the simulation which is based on actual wind and price data for one year of a wind farm in Denmark. Power forecast error and price forecast error are considered in the simulation. The actual wind and forecast wind for a typical day is show in Fig. 13. The final profit of each case is shown in the following Table. 4:

Table 4 Bidding strategy case study profit for one year

	Generation Assets		Operat-ion	Service				
Case NO.	WPP	ESS	Coordin ation	Elspot (Day-Ahead)	Elbas (Hour-Ahead)	Primary Reserve	Real Time	Total Profit($)
Case 1	✓						✓	5.62 million
Case 2	✓			✓	✓			6.39 million
Case 3	✓	✓		✓	✓	✓		9.0 million
Case 4	✓	✓	✓	✓	✓	✓		9.1 million

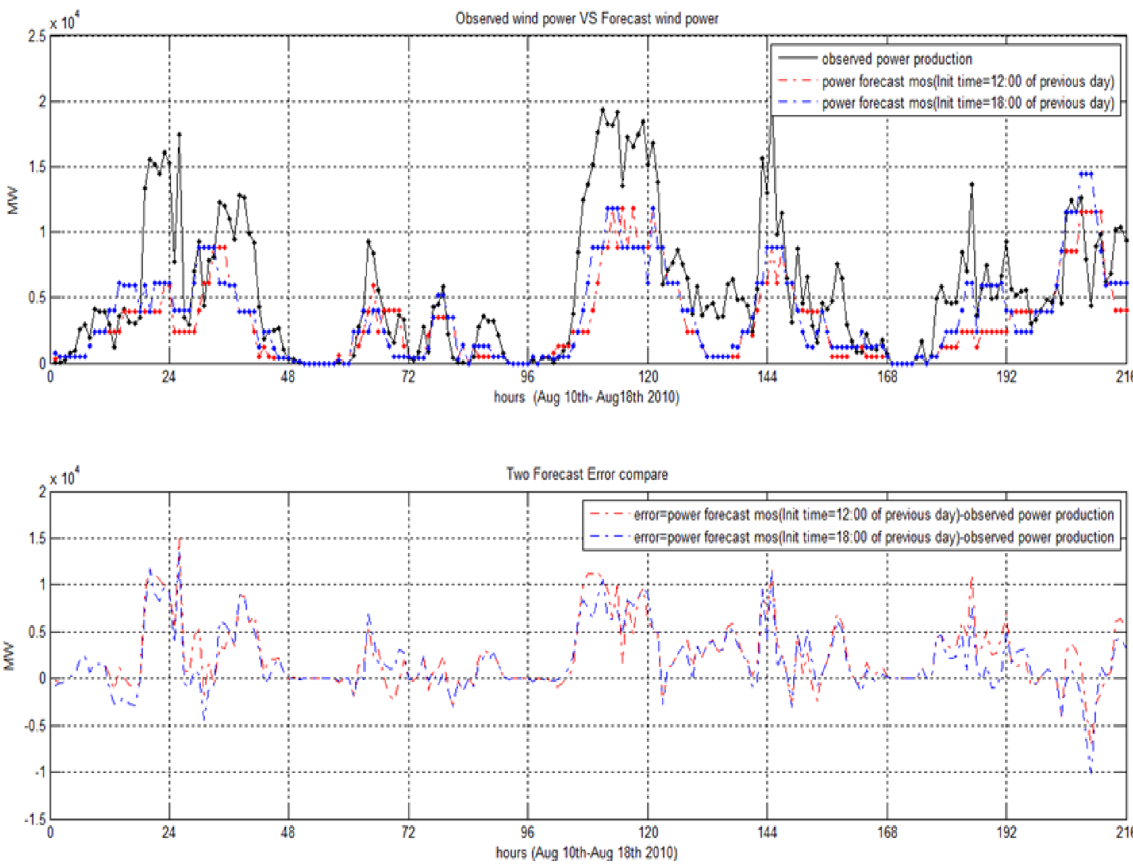

Fig. 13. Actual Wind Power and Forecast Wind Power

As shown in Table. 4, the potential benefits of allowing wind farms to participate in more than just real time market is 14% increase (comparing case 2 with case 1). The benefit of allowing coordination of wind farms and flywheels is 1% increase (comparing case 4 with case 3). It could be observed from this case study that the potential benefits of coordinating energy storage with wind farms for both energy balancing and regulation services in electricity market.

5. SUMMARY

This thesis presents a coordinated control scheme for VPPs to provide energy balancing and frequency regulation services. The proposed scheme uses power electronic converters to control the net power output from wind generation and storage systems in order to provide both energy balancing and grid frequency regulation services. To enable the participation of VPPs in multi-service electricity market operations, this thesis also proposes an optimization based bidding strategy for VPPs to participate in both energy balancing and reserve services. One year simulation of one Denmark virtual power plant data shows promising economic benefits through utilizing this optimization-based bidding strategy.

In this thesis, the wind farms and storage devices are assumed to be co-located. Future work could be extended to study the coordination of wind farms and geographically dispersed storage devices. Also, the impact of power system transmission capacity should also be investigated in future study.

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