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# Hierarchical model-based predictive control of a power plant portfolio

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ABSTRACT

One of the main difficulties in large-scale implementation of renewable energy in existing power systems is that the production from renewable sources is difficult to predict and control. For this reason, fast and efficient control of controllable power producing units – so-called "portfolio control" – becomes increasingly important as the ratio of renewable energy in a power system grows. As a consequence, tomorrow's "smart grids" require highly flexible and scalable control systems compared to conventional power systems. This paper proposes a hierarchical model-based predictive control design for power system portfolio control, which aims specifically at meeting these demands.

The design involves a two-layer hierarchical structure with clearly defined interfaces that facilitate an object-oriented implementation approach. The same hierarchical structure is reflected in the underlying optimisation problem, which is solved using Dantzig–Wolfe decomposition. This decomposition yields improved computational efficiency and better scalability compared to centralised methods.

The proposed control scheme is compared to an existing, state-of-the-art portfolio control system (operated by DONG Energy in Western Denmark) via simulations on a real-world scenario. Despite limited tuning, the new controller shows improvements in terms of ability to track reference production as well as economic performance.

## 1. Introduction

With the recent (and ongoing) liberalisation of the energy market (Ringel, 2003), increasing fuel prices, and increasing political pressure towards the introduction of more sustainable energy into the market (Transport- og Energiministeriet, 2005; UCTE, 2007; United Nations, 1998), dynamic control of power plants is becoming highly important. Indeed, the incentives for power companies to adapt their production to uncontrollable fluctuations in consumer demands as well as in the availability of production resources, e.g., wind power, at short notice (UCTE, 2007), are stronger than ever.

Historically, static optimisation of load distribution among power production units, so-called *unit commitment*, has been the norm (Padhy, 2004; Salam, 2007). Unit commitment refers to determining the combination of available generating units and scheduling their respective outputs to satisfy the forecast demand with the minimum total production cost under the operating constraints enforced by the system under the given power company's jurisdiction (its *portfolio*) for a specified period of time—typically from 24 h up to a week. This optimisation problem is of high dimension and combinatorial in nature, and can thus be difficult to solve in practice. Results using Heuristic methods (Johnson, Happ, & Wright, 1971; Viana, de Sousa, & Matos, 2001), Mixed Integer Programming (Dillon, Edwin, Kochs, & Taud, 1978), Dynamic Programming (Ayuob & Patton, 1971) and Lagrangian Relaxation (Aoki, Satoh, Itoh, Ichimori, & Masegi, 1987; Shahidehpour & Tong, 1992) have been reported in the literature.

Once a solution to the unit comment problem, i.e., a static schedule, has been found, the production plans are distributed to the generating units, where local controllers track the plans while suppressing disturbances, etc.

However, with the aforementioned increasing impact of short-term fluctuations in the supply and demand, dynamic effects at the system level are becoming increasingly inconvenient to deal with for individual generating units. Various approaches to deal with these difficulties have been presented in the literature; Alvarado (2005) and Jokic (2007) deal with multiple area power system control through prices, where the network adds structure to the problem, while genetic algorithm-based (Ramakrishna & Bhatti, 2008) and fuzzy scheduling-based (Anower, Sheikh, Hossain, Rabbani, & Nasiruzzaman, 2006) solutions have been presented for single area problems.

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Yet another difficulty that will have to be faced in tomorrow's smart grids is the addition of many more power plants of various types, with different dynamics – e.g., decentralised bio-mass fired thermal units, solar farms, etc. – which means that *scalability* of the control system is set to become an important issue.

This paper presents a novel, object-oriented design for such a dynamic portfolio controller, which is able to handle dynamic disturbances at the system level as well as the non-static configuration of generating units, i.e., the fact that not all units are active at all times. It is based on model-based predictive control (see, e.g., Rawlings & Mayne, 2009; Rossiter, 2003 for a comprehensive review) and utilises a decomposed solution scheme tailored specifically to the problem at hand to solve the optimisation problem.

The objective of the proposed controller is to minimise deviations between sold and actual production. Furthermore, two main objectives are in focus in the design:

*Scalability* Future development of the power system will require the controller to be able to coordinate more units, therefore the method must be scalable in terms of computational complexity.

*Flexibility* The controller must be *flexible*, such that addition of new units and maintenance of existing ones is possible. This means that the design must have a modular structure that supports *information encapsulation* and clear *communication interfaces* between the modules.

To meet these objectives, the problem is formulated as a *linear program* and solved using the so-called *Dantzig–Wolfe decomposition* (Dantzig & Thapa, 2002; Dantzig & Wolfe, 1960; Lasdon, 2002), which is a very efficient algorithm for solution of linear programs of the type considered here. Dantzig–Wolfe decomposition breaks a linear program into a number of independent subproblems and a Master Problem that coordinates the subproblems. The Master Problem sends a "price" on a shared resource to each of the subproblems. Subject to this "price", the optimal solution to each of the subproblems is individually computed and returned. This interchange of information continues until convergence. The Dantzig–Wolfe decomposition algorithm always converges in a finite number of iterations to the solution of the original linear program if a feasible solution exists (Dantzig & Thapa, 2002). In predictive control applications, this implies that stability can be guaranteed under mild conditions even if the algorithm has to be stopped prematurely to maintain a constant sample rate (Scokaert, Mayne, & Rawlings, 1999). That is, assuming the problem is feasible in the first place, it is always possible to forcefully truncate the number of iterations in case the computations are taking too long for online usage; a solution to the problem is ensured after the first iteration, although it is likely suboptimal. This is a distinct advantage over other, similar solution strategies such as Lagrange relaxation; see also Gunnerud, Foss, Nygreen, Vestbø, and Walberg (2009) and Gunnerud and Foss (2009). Dantzig–Wolfe decomposition has also been used successfully in model predictive control of chemical plants, see Cheng, Forbes, and Yip (2008).

Venkat, Hiskens, Rawlings, and Wright (2008) use more traditional distributed MPC to solve a similar portfolio control problem (more precisely, an Automatic Generation Control problem). However, it is not clear how the Scalability and Flexibility objectives can be managed efficiently by the approach presented in that paper. These issues are addressed directly by the Dantzig–Wolfe approach presented here.

Other related solution approaches to decentralised and/or hierarchical control can be found in, e.g., Rantzer (2009), Beccuti, Geyer, and Morari (2004), Picasso, De Vito, Scattolini, and Colaneri (2010), and Scattolini (2009), amongst others.

The design is initially developed for the Western Danish power system, since it already exhibits some of the traits outlined above: on average, about 20% of the electrical energy is supplied by wind, while the rest is supplied by a mixture of fossil fuel, bio-fuels, etc. The Danish power system currently has one of the highest ratios of renewable energy in the world; however, other countries are expressing their interests towards similar introduction of renewables. As a consequence, the design presented here can be likely used with minor modifications for various other systems in the future.

The outline of the rest of the paper is as follows. In Section 2 an overview of the Danish power system is given, including a brief account of the system services the producers must provide. For comparison purposes, the existing portfolio controller will also be discussed briefly. Next, Section 3 presents the proposed control design method and Section 4 uses the design method for designing a controller for the current portfolio. Section 5 presents a comparison of control performances based on simulations of the actual portfolio, whereupon Section 6 sums up the contributions of this work.

The notation is mostly standard. Scalars are written in normal font, while vectors and matrices are written in boldface. $(\cdot)^T$ indicates the transpose of a matrix or vector, while $\mathbf{v} \perp \mathbf{w}$ indicates that the pair of vectors $\mathbf{v}$ and $\mathbf{w}$ is orthogonal. If $\alpha = \{\alpha_i\}$ and $\beta = \{\beta_j\}$ are ordered sets of the same cardinality $n$, the notation $\alpha_i \perp \beta_i,\ i = 1,2,\ldots,n$ indicates that $\alpha_i\beta_i = 0$ for each $i$, even if $\alpha_i \neq 0$ and $\beta_j \neq 0$ for some $i,j = 1,2,\ldots,n$. Finally, $\Delta$ is the backward difference operator, i.e., $\Delta\mathbf{u}_k = \mathbf{u}_k - \mathbf{u}_{k-1}$, where $k-1$ and $k$ are consecutive sample numbers and $\mathbf{u}$ is a signal vector.

## 2. System description

The Danish power grid is a part of the ENTSO-E, which is the electrical grid covering the mainland of Europe, from Portugal in the west to Romania in the east; within this grid, consumption and production must be balanced at all times. Roughly speaking, if the consumption is larger than the production, energy will be drained from the system, making the generators slow down, and vice versa. Such imbalances manifest themselves as deviations from the usual 50 Hz grid frequency. In order to maintain the overall balance between production and consumption, ENTSO-E is split into several regions, each governed by a Transmission System Operator (TSO) responsible for matching production with consumption and import/export into/out of the region.

### 2.1. Western Denmark

The major production units of the Western Danish region are shown in Fig. 1.

Maintaining balance between production and consumption within Scandinavia is managed via energy markets such as Nord Pool (2010); contracts closed on the relevant energy markets yield an hourly amount of energy that suppliers must produce within each region. The amount of energy sold is passed to a *Short-Term Load Scheduler* (STLS), which solves a *Unit Commitment problem* as mentioned in the introduction.[1] The result is a load schedule with a time resolution of 5 min for each individual producing unit, as shown in Fig. 2.

However, even though the market provides a good estimate of the demand for the following day, there will be deviations during the day due to disturbances, inaccurate predictions, weather, etc.

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[1] A more detailed description of the Short-Term Load Scheduler used in Western Denmark can be found in Jørgensen, Mortensen, Mølbak, and Nielsen (2006).