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Optimal Tertiary Frequency Control in Power Systems with Market-Based Regulation ⋆

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Abstract: The system frequency of a power systems is a good indicator of the networks resilience to major disturbances. In a completely deregulated setting, for example in the Nordic power system, the system operator controls the system frequency manually by calling-off bids handed in to a market, called the regulating market.
In this paper we formulate the problem of optimal bid call-off on the regulating market, that the system operator is faced with each operating period, as an optimal switching problem with execution delays.
As general optimal switching problems with execution delays are computationally cumbersome we resort to a recently developed suboptimal solution scheme, based on limiting the feedback information in the control loop.

Keywords: Delayed reaction, frequency control, optimal switching, power systems, stochastic optimal control.

1. INTRODUCTION

The worldwide deregulation of electricity markets has changed the operation of power systems and drawn attention to development of new operational strategies. A power system should be securely operated at all times whilst the operating conditions change over time. There are several states to keep track of which makes it challenging, in real-time, to monitor and perform countermeasures to prevent leaving the secure region of operation. In particular, a power system must, at all times, be operated close to its nominal frequency where the system inertia together with fast controlling reserves are able to decelerate frequency deviations following disturbances. A complicating factor is the random nature of power consumption and volatile production that brings stochastic variations into the frequency. With the increased integration of renewable production the challenge only seems to grow in the near future.

The deregulation has also often led to a more inflexible generation control as independent system operators do not, themselves, operate the production units. In many systems, regulating power is instead traded on a market, called the *regulating market*. A bid to the regulating market is a block-bid on alteration of injected power at a given price per MW of produced power, that is binding in a specific operation period. One example is the Nordic market with operating periods of one hour, where the regulating market for each operating period closes 45 minutes before the start of the period. During operation, the system operator can control the system frequency by and purchasing the energy specified

During operation, the system operator has the opportunity to, at any time, contact actors responsible for bids on the regulating market to purchase the power specified in the contract. This is referred to as calling-off the bid. Furthermore, the system operator can reverse any prior call-offs. Call-offs can does be made of several bids simultaneously and each bid can, due to the possibility of reversing call-offs, be called-off several times during one operation period.

In this setting the problem of finding an economically efficient frequency control scheme can be formulated as a multi-modes optimal switching problem. This problem is further complicated by the reaction times which, combined with ramp rates of power plants, lead to execution delays.

The general optimal switching problem (sometimes referred to as starting and stopping problem) has been thoroughly investigated in the last decades after being popularised in Brennan and Schwartz (1985). In Djehiche et al. (2009) existence of a solution to the multi-modes optimal switching problem was proved for constant switching costs. In El Asri and Hamadéne (2009) this result was extended to switching costs which depend on the state variable and uniqueness of the viscosity solution to the Bellman equation was shown. Since then, results have been extended to problems with negative switching costs in El-Asri and Fakhouri (2012), partial information in Li et al. (2015) and execution delays in Perninge (2016).

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Optimal switching problems with delayed reaction have been considered in a variety of different settings. Exact solution schemes are usually based on augmenting the state space with "time after intervention" (see Bertsekas (2005); Perninge and Söder (2014); Perninge (2016)). For some problems, such as the impulse control problem with uniform lag studied in Bar-Ilan et al. (2002), a more compact state space augmentation can give exact solutions, while for more general problems no tractable augmentation has been found for systems with multiple modes. Instead approximations, such as time separation in Carmona and Ludkovski (2008) and more recently limiting the feedback information in Perninge (2016), have been suggested.

On the topic of frequency control in power systems much work has focused on optimal bidding strategies for a producer participating in the regulating market (see Olsson and Söder (2005); Dai and Qiao (2015); Soares et al. (2016) and references therein) and demand side management for frequency control (see Gellings and Chamberlin (1988); Ma et al. (2013); Bagagiolo and Bauso (2014)). Although some work on optimal bid call-off in real-time operation of power systems exist (see Perninge and Söder (2014, 2012); Perninge (2015)). The main focus has been on maintaining power flow feasibility. One of the few exceptions is Perninge and Eriksson (2017), where the market model is limited by not allowing reversion of call-offs.

Little work thus focus on aspects and challenges faced by the system operator related to manual frequency control in real-time operation. The aim of the present article is to fill this gap.

We formulate the frequency control problem as an optimal switching problem, where we assume that frequency deviations are penalized by adding an operation cost that is quadratic in the power imbalance. Building on the work in Perninge (2016) we then apply a numerical solution scheme based on limiting the feedback information available when making decisions. According to numerical experiments in Perninge (2016) this leads to a drastic improvement in computational efficiency (12 times faster already for a small system with just 3 bids) without sacrificing too much in terms of optimality (a maximal relative error around 1-3%).

2. FREQUENCY CONTROL

The objective of this article is to facilitate the frequency control in power systems operation. We compute a strategy for trading on the regulating market that minimizes a cost functional over an operating-period, $[0, T]$, that includes cost of called-off bids and penalizes deviation from the nominal frequency. In this section we start by presenting some background on frequency control and then move on to define the frequency control problem.

2.1 System frequency and primary frequency control

In a power system it is at all times necessary to maintain a balance between production and consumption. To this end, there are certain power plants in the system whose steady state production depends linearly on the frequency. When the consumption increases energy is initially taken from the large rotating masses in generators, which constitute the main inertia of the system. This causes the system frequency to drop. As a consequence the frequency responding power plants will increase their production, and vice versa in case of a frequency increase. This is called the primary frequency control of the system (more information on frequency control can be found in *e.g.* Wood and Wollenberg (1996)). The primary frequency control is the fastest part of the frequency control and will act in a time frame of a few seconds. The primary control of a system is a proportional controller with a total gain (referred to as the primary control droop) K_P [MW/Hz] that is constant under normal operation conditions.

The steady state system frequency at time t can be calculated through

$$f(t) = f_0 + \frac{1}{K_P}(P_G(t) - P_L(t)) \qquad (1)$$

where f_0 is the nominal frequency (usually 50 or 60 Hz), $P_G(t)$ is total generation (not including primary control) and $P_L(t)$ is the aggregate load.

Many systems also have an automatic secondary control, referred to as automatic generation control (AGC) that participates in the frequency control to relieve the primary control and restore the frequency.

The activation of regulating bids is called tertiary frequency control. The main objective of the tertiary frequency control is to relieve the primary (and/or secondary) control while performing an economically efficient generation-dispatch.

2.2 Planned production and demand modelling

We consider a power system with an aggregate load described by the stochastic process $(P_L(t) : 0 \leq t \leq T)$ on the filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{0\leq t\leq T}, \mathbb{P})$ and a deterministic production plan $(p_G(t) : 0 \leq t \leq T)$. Due to physical limitations in production units the planned production will constitute a continuous function. We will let $(X_t; 0 \leq t \leq T)$ denote the net power imbalance, *i.e.* the difference between aggregate demand and planned production. Hence, we have $X_t := P_L(t) - p_G(t)$.

We will assume that X_t is the strong solution to a stochastic differential equation (SDE) as follows

$$\begin{aligned} dX_t &= a(t, X_t)dt + \sigma(t, X_t)dW_t, \quad t \in [0, T], \\ X_0 &= x_0 \end{aligned}$$

where $(W_t; 0 \leq t \leq T)$ is a one dimensional Brownian motion that generates the completed filtration $(\mathcal{F}_t; 0 \leq t \leq T)$, $x_0 \in \mathbb{R}$ and $a : [0, T] \times \mathbb{R} \to \mathbb{R}$ and $\sigma : [0, T] \times \mathbb{R} \to \mathbb{R}$ are two continuous functions that satisfy

$$|a(t, x)| + |\sigma(t, x)| \leq C(1 + |x|)$$

and

$$|a(t, x) - a(t, x')| + |\sigma(t, x) - \sigma(t, x')| \leq C|x - x'|,$$

for some constant $C > 0$.

For all $t \in [0, T]$ and $x \in \mathbb{R}$ we define the process $(X_s^{t,x}; t \leq s \leq T)$ as the strong solution to

$$\begin{aligned} dX_s^{t,x} &= a(s, X_s^{t,x})ds + \sigma(s, X_s^{t,x})dW_s, \quad \forall s \in [t, T], \\ X_s^{t,x} &= x, \quad \forall s \in [0, t]. \end{aligned}$$