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# Cutting plane approaches for frequency constrained economic dispatch problems

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ABSTRACT

Increasing the share of non-synchronous sources in the energy mix leads to a decline in the dynamic response of electrical systems. In particular, the performance of the primary frequency control may drop, increasing the risk of Under Frequency Load Shedding (UFLS) as a consequence of large power imbalances. This fact has drawn attention to the simplifications made when defining security constraints in generation schedule optimisation models. In this work we propose a new formulation of the security constraint in the economic dispatch problem. This formulation accounts for the diversity of the dynamic parameters of the reserve units in the optimal allocation of the frequency containment reserve. The approach may allow the development of renewable, but non-synchronous, sources while ensuring the power system security and generation schedules' optimality.



## 1. Introduction

The increasing share of variable renewable energy sources (V-RES), as a response to environmental concerns, brings new challenges to reconcile economics with security in the electricity supply. Nowadays, the most developed V-RES are wind power (WP) and photovoltaic (PV), which have low controllability and a variable power output that is only partially predictable. Moreover, these sources are often asynchronously connected to the system through power electronics, which prevents them from naturally providing inertial response or ancillary services [1–3]. These features entail a decline in the dynamic behaviour of electrical systems.

The impact of the hourly variability and increased uncertainty of V-RES generation has been widely addressed in literature. In this regard, some works propose the advanced calculation of conventional reserves [4], while others focus on stochastic or robust versions of unit-commitment [5–8] (see [9] for a survey).

Regarding the dynamic behaviour of the system, we have analysed the increase of the Under Frequency Load Shedding (UFLS) risk with the development of non-synchronous sources in an isolated power system [10]. This topic has also received some attention in the literature, especially regarding different European overseas territories (autonomous community or regions), such as the Canary Islands [11,12], the Madeira and Azores archipelagos [13], Sardinia as well as the DOM (French acronym for *Départements d'Outre-mer*) and Corsica [14] and even in larger systems such as Great Britain and Ireland [15,16], where load shedding may increase with the rapid development of non-synchronous V-RES, entailing economical losses that are hard to quantify.

Several mechanisms have been proposed to tackle this issue, from the revision of the classic security constraints [17–19] to the deployment of new technologies, such as battery storage systems [20,21]. In this work, we focus on the former approach. In general, classic security constraints consist of specifying a certain amount of connected available capacity called spinning reserves. They are commonly sized according to static reliability criteria in order to manage uncertainty while ensuring continuous electricity supply.

The most common criterion for the prescription of the primary or frequency containment reserve (FCR) is given by the $N-1$ rule, which establishes a fixed requirement as a function of the capacity of the largest generating unit (or import). This way, the system should be able to withstand the loss of the largest power input without load disconnection. Nevertheless, this solution becomes costly

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**List of symbols**

| | |
|---|---|
| $c_j$ | control signal for power generation of unit $j$ in MW. |
| $D_L$ | load self-regulation parameter in p.u. |
| $E_c$ | kinetic energy in MWs. |
| $f$ | system average frequency in Hz. |
| $f_n$ | nominal system frequency (50 Hz in Europe). |
| $(x, y) \mapsto f^{\circ}(x, y)$ | objective function. |
| $(x, y) \mapsto f_l^{i}(x, y)$ | function used in inequality constraints |
| $(x, y) \mapsto f_j^{e}(x, y)$ | function used in equality constraints |
| $g_j$ | instantaneous electrical power generation of unit $j$ in MW. |
| $g_{j,0}$ | scheduled power generation of unit $j$ in MW. |
| $G^{max}$ | power capacity vector in MW |
| $H_L$ | load inertial contribution in MWs |
| $h$ | time step index |
| $k$ | unit outage index |
| $\ell$ | iteration index for cutting plane model of the frequency nadir |
| $m$ | contingency index, linked to the loss of a (specific) unit $k(m)$ at a given time step $h(m)$ |
| $M$ | set of considered contingencies |
| $P_e$ | electrical power demand in MW |
| $\underline{q}$ | frequency security threshold in Hz. |
| $q_m$ | frequency minimum for contingency $m$ in Hz. |
| $\check{q}_m^L$ | cutting plane model of the frequency nadir $q_m$. |
| $\nabla_x q_m$ | frequency nadir gradient with respect to the generation dispatch in Hz/MW. |
| $R$ | power-frequency droop in p.u. |
| $R^{max}$ | frequency containment reserve capacity vector in MW |
| $s$ | laplace operator |
| $S_{n,j}$ | nominal apparent power of unit $j$ in MVA. |
| $t$ | (continuous) time (index). |
| $\tau_{rc,j}$ | lag time constant of unit $j$ control in seconds |
| $\tau_{ac,j}$ | lead time constant of unit $j$ control in seconds |
| $\tau_{rg,j}$ | lag time constant of unit $j$ process in seconds |
| $\tau_{ag,j}$ | lead time constant of unit $j$ process in seconds |
| $u_j$ | binary variable defining the state of unit $j$ (off-line = 0, on-line = 1). |
| $x$ | continuous decision vector, which includes the power output and reserve levels |
| $X$ | feasible set of $x$ |
| $y$ | binary decision vector, which includes state and on/off decisions |
| $\bar{y}$ | fixed binary decision vector, solution of the initial unit-commitment problem |

and even ineffective as the operational environment of power systems continues to evolve. Therefore, in recent years some works dealing with the FCR optimisation following dynamic criteria have been published [22–25].

In this paper we propose a new formulation of the Economic Dispatch (ED) problem which includes explicit security constraints on the frequency nadirs following unit outages. This problem will be referred to as the Frequency Constrained Economic Dispatch (FCED). The originality of our work lays in the consideration of a detailed model of the primary frequency control at the short-term optimisation stage (some hours ahead). This model is able to account for the deployment dynamics of the FCR in order to avoid UFLS.

The paper is organized as follows. Section 2 discusses the interest of accounting for frequency within unit-commitment or dispatch models and provides an overview of the literature on the topic. We also illustrate how existing indirect methodology may fall short of identifying a "safe" dispatch solution. In Section 3 we provide the model of frequency response that we would like to add within the nominal unit-commitment or economic dispatch model. The latter model is given in a high-level abstract formulation. Section 4 explains the approach proposed in this work to integrate the frequency nadir constraints in the FCED model. Several numerical experiments are discussed in Section 5 showing the efficiency of the suggested method. The paper ends with Section 6 wherein conclusions and perspectives are provided.

## 2. Accounting for frequency regulation in optimisation

### 2.1. A brief discussion of primary frequency regulation

In an electrical system the frequency must remain around its nominal value. However, it may suffer significant excursions during certain events, such as the loss of a generating unit. In this case, the system frequency drops as illustrated in Fig. 1.

The initial rate of change of the frequency (ROCOF) is limited by the inertia of the synchronous units connected to the network. Thereafter, the primary regulation control increases automatically and locally the power output of the units providing this service [26]. This mechanism should enable the power balance to be restored and the system frequency to be stabilised before the security threshold is reached, as represented by the solid blue line in Fig. 1.

If the primary frequency regulation fails to maintain the frequency within the acceptable range, the under frequency relays located in some substations may disconnect part of the consumers in order to avoid the system collapse. This action, called the UFLS [27], is meant to face events that are more severe than a predefined reference incident. However, in small systems with low inertia, an insufficient deployment rate of the FCR may prevent the restoration of the power balance before the security threshold is reached, entailing an unexpected supply interruption (see the dotted green line in Fig. 1).

This undesirable behaviour may be strengthened as the conventional generation is substituted by non-synchronous sources, which decreases the system equivalent inertia and may reduce its regulating power (see the dashed violet curve in Fig. 1).

The objective of the optimisation of the FCR, following dynamic considerations, is then to prevent the activation of the UFLS following contingencies of an equivalent size to the reference incident. Nevertheless, the accurate evaluation of dynamic constraints may be time consuming, while generation schedules must be computed in a time compatible with power system operation.

### 2.2. Overview of the literature

A first contribution on this topic proposed an iterative approach where the FCR prescription was sequentially increased in a discrete manner, until dynamic simulations showed that a certain security level was reached (see [17]). However, this approach acts exclusively on the FCR volume, while the consideration of other parameters, such as the inertia, could provide lower cost solutions with the expected dynamic performance.

Subsequently, more sophisticated methodologies, based on the off-line simulation of several scenarios, were proposed [18,19]. They allow the construction of linear approximations of the security constraints from a database, which could then be easily included in ED models. These works revealed the interest of including enhanced FCR constraints, representing the transient response and regulation capability of committed units, in optimisation models to compute a secure and economic schedule. However, the