

A Methodology for Sizing Primary Frequency Control in function of Grid Inertia

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Abstract—Large increase in wind and photovoltaics will lead to lower and more volatile grid inertia but also to the lack of primary frequency control, i.e. frequency containment reserve (FCR) providers in the Continental Europe Grid. This will therefore impact negatively the frequency dynamics. One potential solution for ensuring the frequency to stay in reasonable bounds is to take the dynamics of potential providers into consideration. From this observation, we develop a novel methodology for having a linear programming problem to select the most suited FCR providers. It is based on the minimization of the overall cost while respecting static and dynamic constraints which are respectively ensuring a sufficient amount of FCR and avoiding too large frequency deviations after a large disturbance. The methodology has been tested on a case with 200 potential FCR providers in function of various grid inertia and load damping factors.

Index Terms—Power System Modeling, Power System Dynamics, Power System Reserves, Frequency Containment Reserves.

I. INTRODUCTION

Various power grids and specifically the Continental Europe (CE) grid, are undergoing a transformation from a centralized generation mix to a distributed generation based on renewables. This change has drastic consequences on many aspects of the power sector. Amongst all of them, two aspects, grid inertia and lack of primary control, will be discussed altogether for the specific case of the CE grid.

Grid inertia is referred to as the rotational energy contained in the electrical machines, generators and motors, directly connected to the power system. Grid inertia is useful since it slows the frequency deviations and gives time to the system for reacting to imbalances. Since renewable generation such as wind power and photovoltaics is generally connected to the power grid through power electronics, grid inertia tends to decrease and become more volatile as the penetration of renewables increases [1]. Since the CE grid is very large, it is not yet concerned with ensuring a sufficient level of inertia. Nevertheless, other grids, generally much smaller, e.g. Ireland, are already facing some challenges regarding the penetration of non-synchronous generation [2], [3].

Primary frequency control is one of the major element for ensuring the safe operation of a power grid. In the CE grid spanning from Portugal to Poland, primary frequency control is realized through frequency containment reserves (FCR), formerly called primary reserves. These reserves must

fulfil specific criteria such as being able to be fully activated in less than 30 seconds [4]. They are mostly provided by large synchronous generators and the selection of participants is market-based in various countries, e.g. in Germany and Belgium. In 2014 the Belgian market for FCR has been marked by price peaks: from 34.74 €/MWh in February to 152.73 €/MWh in April [5]. This shows that at some moments there is a clear lack of FCR providers.

These two problematics are generally decoupled. Concerning inertia, various propositions have been made on providing virtual inertia, i.e. implementing controls to reproduce inertia [6]–[8]. Concerning the lack of FCR, various solutions have been proposed, e.g. storage [9]–[12], wind turbine control [13], [14], demand-side management [15], [16] or mutual support between AC grids via HVDC interconnectors [17], [18]. Nevertheless, FCR and grid inertia are related to each other. Indeed, for impeding the frequency to deviate too much, a decreasing grid inertia could be, up to some limits, compensated by faster FCR. Such improvement in speed reaction is generally achievable by new potential providers such as storage, renewable and demand-side management. Up to now, FCR requirements are not a function of the grid parameters but since grid inertia is fluctuating in function of the penetration of non-synchronous generation, there exists an interest to modify the minimal requirements in function of the situation.

In this article, we propose a methodology for selecting FCR participants in function of the grid state. The principle is that for a specific period of time, e.g. one hour or 15 minutes, all participants bid on the market and are selected as a result of a linear program minimising the overall provision cost while meeting defined performance criteria in terms of frequency deviations. This proposal has two main advantages. First, the FCR provision would better match the grid's actual needs and second, it will enable new entrants on the market, for example renewables. Finally, the hourly market enables participants to bid when they are actually generating power and consequently, must-run costs are avoided.

The article is organized as follows: a model for the frequency deviation is developed in section II, section III presents the ongoing trends in the power sector, section IV develops the problem formulation, i.e. the objective function with the constraints and finally, simulations are carried out and discussed in section V.

II. MODELING

As stated in the introduction, the objective is to select the best candidates for FCR provision in function of the grid state. In order to be able to reach this objective, we develop a model of the frequency dynamics which will be the basis of the problem formulation. Since we are interested in frequency deviations, the model is based on the swing equation describing the frequency evolution in function of disturbances.

A. Swing equation

For a particular synchronous generator i , the swing equation is expressed in (1) with J_i the moment of inertia of the moving parts, ω_i the angular velocity and $P_{m,i}$ and $P_{e,i}$ respectively the mechanical and electrical torques.

$$J_i \frac{d\omega_i}{dt} = \frac{P_{m,i} - P_{e,i}}{\omega_i} \quad (1)$$

By expressing the constant of inertia $H_i = \frac{J\omega_n^2}{2S_i}$, the rated power S_i , the angular velocity $\omega_i = 2\pi f_i$, the nominal frequency f_n and by considering small frequency deviations, i.e. $\Delta f_i = f_i - f_n$ with $\frac{f_i}{f_n} \approx 1$, (2) is obtained.

$$\frac{2H_i S_i}{f_n} \frac{df_i}{dt} = P_{m,i} - P_{e,i} \quad (2)$$

We define the total power rating $S = \sum_i S_i$, the equivalent constant of inertia $H = \sum_i \frac{S_i H_i}{S}$, the equivalent grid frequency $\Delta f = \sum_i \frac{\Delta f_i S_i H_i}{H S}$ and $P_m = \sum_i P_{m,i}$ and $P_e = \sum_i P_{e,i}$ respectively the total mechanical and electrical powers.

In normal operation, the electrical and mechanical powers are equal and consequently, the frequency derivative is null, i.e. the grid frequency does not vary. When disturbances occur such as large power outages, the mechanical power is different from the electrical power, which makes the grid frequency deviate from its nominal value. Countermeasures should therefore be foreseen in order for the frequency to recover its nominal value. For the sake of clarity, we define the disturbance as $D(t)$ and all the countermeasures as $C(t)$ as well as the variable $I = \frac{2HS}{f_n}$. Relation (2) is then rewritten as $I \frac{d\Delta f}{dt} = C(t) - D(t)$.

B. Disturbance

Our interest lies in large frequency deviations resulting from a sudden worst-case mismatch between generation and consumption. In the CE grid, such worst-case is defined as the loss of two large nuclear power units or 3000 MW of generation [19]. This is described by $D(t) = D_{gen}H(t)$ with the Heaviside function H and the sudden loss of $D_{gen} = 3000$ MW at instant $t = 0$.

C. Load Reaction

One component of $C(t)$ is the load reaction, i.e. changes in power consumption in function of the grid frequency. These variations are mainly due to the fact that a proportion of the electrical power is consumed by motors directly connected to

the power grid. It is considered that the dynamics of such loads is fast enough to approximate this reaction by a proportional coefficient L .

D. Frequency Containment Reserves

In addition to the load reaction, frequency containment reserves are present in order to avoid the frequency to deviate too much after a major incident. These reserves are generally provided by large synchronous generators via a speed control, i.e. an adaptation of their power generation in function of the local frequency. In the CE grid, they must fulfil specific characteristics such as to saturate at ± 200 mHz, be proportional with the frequency deviation and be at least fully activated in less than 30 seconds [19]. It should also be noted that the total provision of FCR for the whole CE grid must be 3000 MW and corresponds to the largest considered incident.

In this article, we assume that each FCR provider j has the following characteristics: maximal FCR power P_j^{max} , a specific ramping rate R_j , a cost π_j and a zonal location Z_j . The ramping rate, expressed in MW/s is the maximal rate of change in power output. Fig. 1 presents the combination of three FCR providers, each with a different ramping rate. From this definition, the time required by a participant T_j to reach saturation is given by $T_j = \frac{P_j^{max}}{R_j}$.

The ramping rate is then used to express $P_j(t)$ which is the power of participant j after a large disturbance in (3).

$$P_j(t) = H(T_j - t)R_j t + H(t - T_j)P_j^{max} \quad (3)$$

We consider m potential FCR providers, each of them having an associated binary variable δ_j enabling its selection or rejection. The swing equation can thus be rewritten as (4). Note also that some effects such as the damping of synchronous generator and the variability of the nature of the load have been neglected.

$$I \frac{d\Delta f}{dt} = -L\Delta f + \sum_{j=1}^m \delta_j P_j(t) - D_{gen}H(t) \quad (4)$$

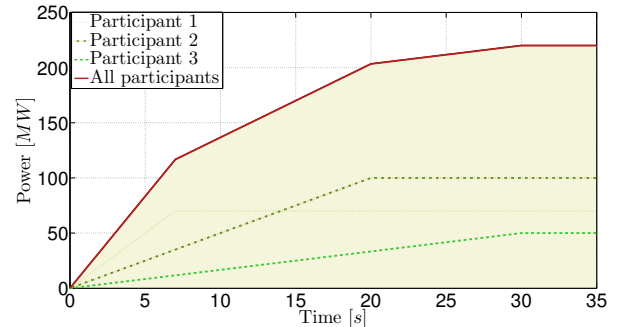


Fig. 1. Representation of three FCR providers having different ramping rates and maximal powers. The red line shows their combination.

E. Justification of the FCR modeling

It should be noted that two saturations are considered: first, the ramping rate is not sufficient for following the frequency drops and second, the frequency deviation exceeds the limit of -200 mHz. In (4) we make the hypothesis that FCR saturate as soon as the disturbance appears and continues until Δf reaches its extremal value. For the considered disturbance, the extremal value always exceeds -200 mHz. Therefore, the hypothesis is true if we show that FCR are saturated due to insufficient ramping rate at least until this limit. Since the frequency derivative before -200 mHz is in absolute term decreasing, the most critical point is at the limit and the condition for validating the hypothesis can be written as (5) for each participant.

$$\left| \frac{d\Delta f}{dt} \right|_{\Delta f = -0.2} \geq 0.2 \frac{R_j}{P_j^{max}} \quad (5)$$

The initial FCR ramping rate R_T , i.e. the total ramping rate before that any FCR providers saturate is expressed by $R_T = \sum_{j=1}^m \delta_j R_j$. The swing equation before any FCR provider is saturated, i.e. between $t = 0$ and $t = \min(T_j)$ is expressed in (6) and its solution in (7).

$$I \frac{d\Delta f}{dt} = -L\Delta f + R_T t - D_{gen} \quad (6)$$

$$\Delta f(t) = \left(\frac{D_{gen}}{L} + \frac{R_T I}{L^2} \right) \left(e^{-\frac{L}{I}t} - 1 \right) + \frac{R_T t}{L} \quad (7)$$

Finally, the time to reach the frequency deviation of -0.2 Hz, $T_{\Delta f = -0.2}$, can be expressed using the Lambert W_{-1} function as expressed in (8).

$$T_{\Delta f = -0.2} = \frac{I}{L} [W_{-1}(-k_1 e^{-k_2}) + k_2] \quad (8)$$

With $k_1 = \frac{D_{gen} L}{R_T I} + 1$ and $k_2 = \frac{-0.2 L^2}{R_T I} + k_1$. From there, we can find the expression of the frequency derivative at $\Delta f = -0.2$ Hz. Then, the condition (5) becomes (9) by using the property of the Lambert function $e^{W(x)} = \frac{x}{W(x)}$ if $x \neq 0$. In all simulations, each participant is required to have a T_j superior or equal to T^{min} expressed in (9) in order to validate the model used. This is illustrated in Fig. 2.

$$T_j \geq T^{min} = \frac{0.2}{\left| \frac{R_T}{L} (1 + W_{-1}(-k_1 e^{-k_2})) \right|} \quad (9)$$

III. PARAMETER VARIATION

The parameters of (4) are function of the grid situation and consequently variate from one moment to another. In the coming years, they are likely to variate even more with the increasing penetration of new technologies such as renewables and power electronics. Since power reserves and particularly FCR, are generally dimensioned to be constant over a long period, i.e. a month or a year, it should be more efficient and economical to assess what are the actual needs and to procure reserves in function of those needs. In this section, a brief introduction of the important trends is presented.

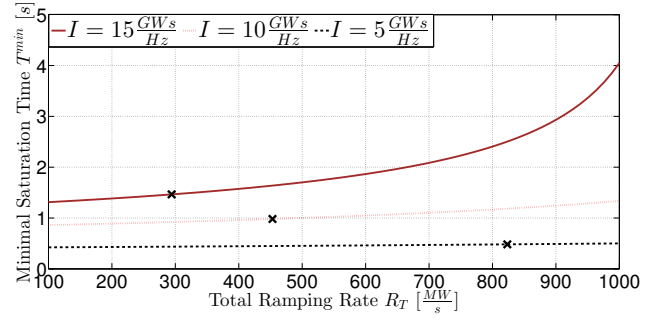


Fig. 2. Minimal saturation time admissible as expressed in (9) in function of R_T for $L = 3000$ MW and $I_{1,2,3} = \{5, 10, 15\}$ GWs/Hz. The crosses are the results of the simulations presented in Fig. 4 and validate consequently the model used since no selected FCR has a lower saturation time.

A. Grid Inertia

The grid inertia is directly related to the generation mix at a particular instant. With the increasing penetration of renewable generation that is connected to the power grid through power electronics such as wind and photovoltaic, there is a trend of decreasing and more volatile grid inertia. Some authors have already been studying the variation of inertia [1].

To exemplify this phenomena, Fig. 3 presents the penetration of solar and wind in the Belgian generation for one week of May 2015 with a precision of 15 minutes. It should be noted that this penetration does not directly give a correct estimation of I since generators can be running at different load level. Actually, the grid inertia can only be rightfully assessed by knowing exactly which generators are running. In addition, H_i can be different from one generator to another. Nevertheless, such general representation can quickly present an approximative approach for estimating I .

In the simulations of section V, we consider values for grid inertia I ranging from 4 to 15 GWs/Hz corresponding to equivalent constant of inertia H from 0.5 to 1.88 seconds if the total load is 200 GW. These values were up to now never reached for the whole CE grid. Nevertheless, they could be attained in the coming years or decades if generation from renewables still grow.

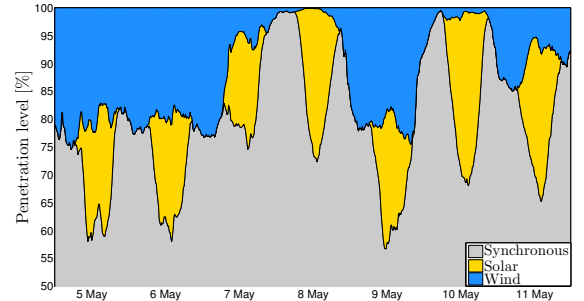


Fig. 3. Penetration of solar, wind and synchronous generation in the Belgian generation mix expressed as a percentage of the total generation with a precision of 15 minutes. Synchronous generation refers to all generation except wind and solar.

B. Load Reaction

The load reaction is determined by two factors : the total load and the load composition. The first component varies according to some factors including weather, seasonality and hour of the days. The second factor varies from one day to another. Indeed, the load is different from workdays when most industries are active from weekends when some industries are not active.

In addition, there is a global trend of decreasing load reaction. Indeed, an increasing amount of power electronics is introduced for controlling electric motors. This increase of power electronics is motivated by efficiency and controllability gains.

C. Disturbance

The size of disturbance that is considered represents the level of risk that the system operators are eager to take. Contrarily to what is currently done in the CE grid, one could imagine to variate D_{gen} in function of the grid situation. A first example for such variation is the generation mix that is currently running in the power system. Indeed, it could be possible that at some hours, the largest generators are smaller than in other hours or that they do not generate at their maximal output. A second example is the introduction of HVDC lines between synchronous zones. If in the future, such interconnections represent the largest possible disturbance, the risk level does depend on the level and the direction of power flowing in those.

IV. PROBLEM FORMULATION

A. Minimization of FCR provision cost

As stated in section II, each FCR provider is bidding at a particular price π_j . Therefore, the objective is to select, for each time step, i.e. each market clearing, the best candidates j minimizing the overall procurement cost as expressed in (10). Since the candidates are either selected or not selected, the problem is defined as a binary programming problem.

$$\min \sum_{j=1}^m \delta_j \pi_j \quad (10)$$

This optimization could be at any time interval, e.g. one hour or each 15 minutes. A shorter time interval is synonym of a better estimation of the grid parameters but would require more calculations per day.

B. Static Constraints

At any moment, a sufficient amount of FCR, 3000 MW in the CE grid, should be foreseen. It also corresponds to a specific damping, i.e. the relation between frequency deviation and power imbalance. This condition is expressed in (11) with P_{sys}^{tot} the minimal amount of FCR that should be foreseen for all zones.

$$P_{sys}^{tot} \leq \sum_{j=1}^m \delta_j P_j^{max} \quad (11)$$

The localization of such reserves could potentially be important in order to ensure sufficient damping in all zones. Consequently, a static inequality is added per zone for ensuring such sufficient damping. These inequalities are expressed in (12) with P_k^{tot} the minimal amount of FCR that should be foreseen in zone k and $Z_{k,j}$ the binary variable describing the presence or not of FCR participant j in zone k . It should be noted that the sum of all minimal amount for FCR should be less or equal to the total amount for all zones, i.e. $\sum_{k=1}^{N_z} P_k^{tot} \leq P_{sys}^{tot}$ with N_z the number of zones.

$$P_k^{tot} \leq \sum_{j=1}^m \delta_j P_j^{max} Z_{k,j} \quad (12)$$

C. Dynamic constraints

The aim of the dynamic constraint is to ensure that the frequency deviation always remains within defined boundaries. Since the risk of large generation loss is much greater than large load loss, only negative power disturbance is considered in this paper and the frequency deviation limit is consequently expressed by $\Delta f(t) \geq \Delta f_{lim}$.

In order to have a linear formulation of this inequality, we express the frequency derivative of (4) by a forward difference and we obtain (13) by expressing the time interval $\Delta T = t_{i+1} - t_i$ and the other variables at instant i .

$$I \frac{\Delta f_{i+1} - \Delta f_i}{\Delta T} = -L \Delta f_i + \sum_{j=1}^m \delta_j P_{i,j} - D_{gen} \quad (13)$$

By defining the variables $d = D_{gen}/L$, $\tau = L\Delta T/I$, $p_{i,j} = P_{i,j}/L$ and by imposing the initial condition of $\Delta f_0 = 0$, we can retrieve all frequency deviations by iterations which leads to (14).

$$\frac{\Delta f_{i+1}}{\tau} = \sum_{j=1}^m \delta_j \left(\sum_{k=0}^{i-1} (1-\tau)^k (p_{i-k,j} - d) \right) \quad (14)$$

Finally, by combining (14) with $\Delta f(t) \geq \Delta f_{lim}$, we find one inequality per discretization timestep representing the minimal dynamic capability as stated in (15). These inequalities in combination with the static inequalities form the constraints of the minimization problem expressed in (10).

$$\frac{\Delta f_{lim}}{\tau} \leq \sum_{j=1}^m \delta_j \left(\sum_{k=0}^{i-1} (1-\tau)^k (p_{i-k,j} - d) \right) \quad (15)$$

D. Comparison with present FCR selection

Currently, the shortest contractual period for FCR provision is one week, e.g. in Germany. To the best of author's knowledge, providers complying with required dynamic criteria defined in the grid code are selected based solely on their price offer. The proposed methodology is original for two reasons. First, the contractual period is greatly reduced in order to take the variability of grid parameters into account. Second, the selection is not only based on the price but is the result of an optimization.

V. SIMULATIONS

A. Description

Since the CE grid is the case considered, the disturbance taken is the one of the European grid code, i.e. 3000 MW and consequently, $P_{sys}^{tot} = 3000$ MW. In the simulations presented here, we do not consider different zones and only one static constraint is present. In further studies, a division of the CE grid could be undertaken in order to take the geographical constraints into account.

The parameters of all the participants used for the simulations are fictional ones and could be retrieved in Fig. 4. It should be noted that the total power P_j^{max} ranges from 10 MW to 200 MW. The saturation time T_j spans from 1.5 to 30 seconds, i.e. from very fast to the maximal admissible time. Concerning the cost, it is expressed in €/MWh, i.e. the cost to provide one MW of FCR during one hour. The cost is likely to be higher for faster FCR.

B. Selection of the bidders

In this section, we present on Fig. 4 the selection of FCR bidders for three different level of inertia $I = \{5, 10, 15\}$ GWs/Hz and for a load reaction of $L = 3$ GW and a maximal admissible frequency deviation of $\Delta f_{max} = -0.5$ Hz. We observe that for high inertia, most of the bidders do not depend on T_i because the dynamic constraint is not decisive. Alternatively, reaction time becomes critical with lower grid inertia.

It should also be noted that for all scenarios, the condition expressed in (9) is respected for all three cases. Indeed, the minimal admissible saturation times are $T_{1,2,3}^{min} =$

$\{0.48, 0.98, 1.47\}$ seconds, all lower than the faster FCR provider.

C. Total power and cost

In this part, we have run several optimization problems in function of the grid inertia and for two levels of load reaction $L = \{2, 3\}$ GW and two frequency limits $\Delta f_{max} = \{-0.5, -0.8\}$ Hz. The total power selected and the total cost are shown respectively on Fig. 5 and Fig. 6. The total power selected is increasing when dynamics is becoming problematic, i.e. low inertia, low Δf_{max} and low L . It means that the static constraint is less binding than the dynamic constraints or in other words, the ramping of the fastest 3000 MW of FCR is not enough to meet the dynamic criteria. In Fig 6, we also see that for high Δf_{max} and L , the total cost does almost not

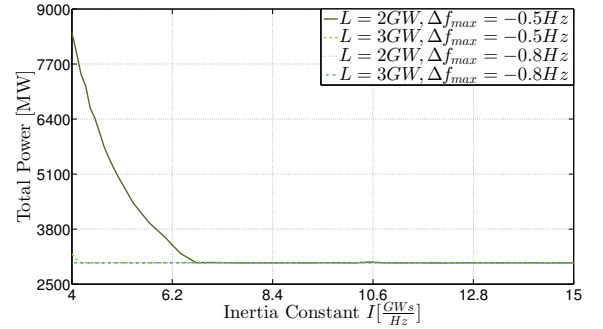


Fig. 5. Total power selected in function of I for four different cases with $L = \{2, 3\}$ GW and $\Delta f_{max} = \{-0.5, -0.8\}$ Hz.

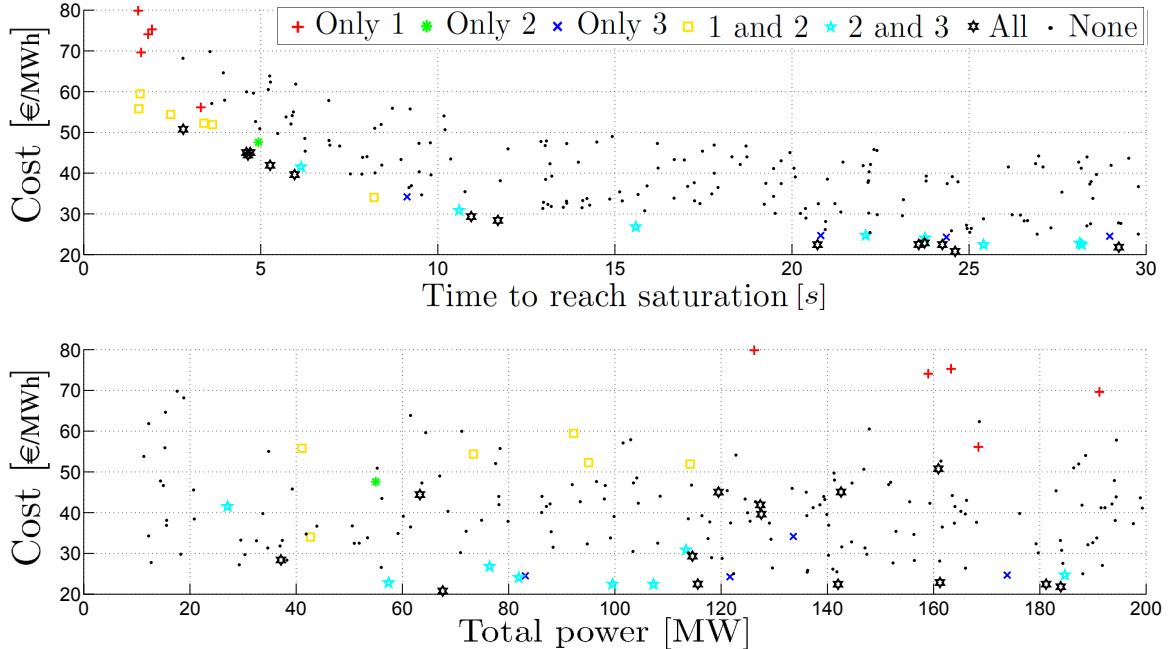


Fig. 4. Representation of the selected bids in function of T_i , P_i^{max} and the cost for three different level of inertia $I_{1,2,3} = \{5, 10, 15\}$ GWs/Hz and with $L = 3$ GW and $\Delta f_{max} = -0.5$ Hz. The selected bids are either for one, two or all cases. The non-selected bids are also represented by black dots.

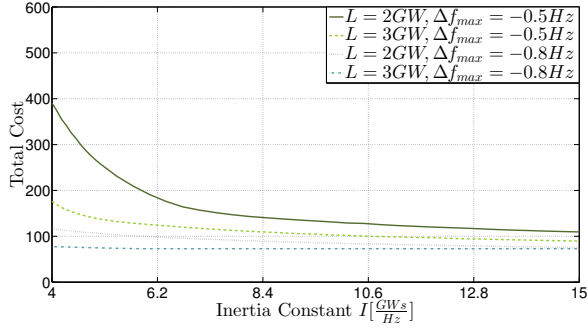


Fig. 6. Total Cost in k€ in function of I for four different cases with $L = \{2, 3\}$ GW and $\Delta f_{max} = \{-0.5, -0.8\}$ Hz.

depend on I meaning that the dynamics is never a constraint and consequently the bids selected are always similar.

VI. CONCLUSION

Grid characteristics such as inertia and load damping are important parameters for assessing the actual needs of FCR characteristics. With the large introduction of renewables and power electronics, these characteristics are likely to be more volatile and to decrease in average. In order to avoid too large frequency deviations after a large disturbance, FCR characteristics should be adjusted to meet an objective of maximal frequency deviation.

In this paper, we have presented a novel methodology to develop a linear programming problem for selecting FCR providers in function of the grid parameters. It is based on the minimization of the total provision cost while respecting static constraints, i.e. minimal amount of FCR power and dynamic constraints ensuring the frequency to remain in acceptable bounds. These dynamic constraints are based on the discretization of the swing equation and on a relatively simple characterization of the FCR reaction. The originality of the paper is to take the dynamics of the potential providers into consideration for selecting the most appropriate FCR providers.

With the model developed, simulations have been carried out on the selection of 200 FCR bidders. It has been shown that the selected bidders differ in function of the grid situation. Since faster FCR providers have a higher cost in the simulations, they are only selected when dynamics become problematic. In addition, for very low inertia, the program selects even more FCR than needed for the static constraint only to be able to respect the dynamic constraints.

Further research should focus on the determination of the different potential FCR bidders. Indeed, the study could be improved by assessing what are the real possibilities of faster FCR providers such as storage, wind turbines or demand-side management and what are the associated costs. In addition, special attention should be given to the determination of the grid parameters such as grid inertia and load reaction and to the improvement of the modeling. Also, the practical consequences of short-term provision such as the increased financial risk for power plant operators should carefully be considered.

Finally, the aim of the paper is actually to introduce the concept of selecting the best reserves in function of the grid situation. It is becoming clear that the grid should not be controlled similarly, i.e. with the same reserves, when renewable penetration is low or when it is high. It should certainly be better to adapt the reserves in function of the grid situation instead of having the exact same amount of reserves independently of the grid parameters.

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