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Smart dispatch of variable-speed Pump Storage Plants to facilitate the insertion of intermittent generation

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SUMMARY

Renewable Energy Sources (RES) share in generating capacities has significantly increased the last decade, such a trend will continue in the coming years. However, the variability of some RES such as wind and solar generation is raising new challenges to operate the power system. In Europe, this new situation has to be managed in an energy market framework that is structured around the principle of BRPs (Balance Responsible Parties), where BRPs are financially responsible for keeping balanced over each Imbalance Settlement Period their contractual position (i.e. the sum of their injections, theirs withdrawals and theirs purchase and sale trades). More sophisticated optimization-based solutions are needed to determine the best very short term generation scheduling and dispatch strategy for a generation portfolio that could include intermittent, thermal, and hydro generation. In such a context, hydro generation valorization is increasing as hydro equipments such as dams and pumping storage facilities are seen as complementary to intermittent generation sources, such as wind and solar generation. Moreover, if flexibility brought by hydro generation and pumping is considered as key in the process of keeping the energy balance over each market period, and so to avoid deviation financial penalties, hydro assets are also critical for TSOs (Transmission System Operators) to procure the regulation and reserve services needed to operate the power system. However, if the flexibility provided by the hydro units is highly valuable, a special care must be taken in the water use and in hydro operations due to the energy-related limitations inherent to storage assets. This paper describes how a smart dispatch optimization of the hydro units for very short term scheduling can facilitate the integration of intermittent resources. Such an optimization allows the fine rescheduling of the units with regard to the latest operation conditions and managing extra flexibility that can be used to cope with the power system balance, especially in the situation of significant deviations identified in the intermittent generation forecasts. A special focus is given to the benefits obtained from the additional regulation capabilities offered to the TSO by variable speed pumped hydro storage and maximized through the implementation of the smart dispatch module. Such a work is done through the eStorage project which is carried out by a multidisciplinary consortium supported by the European Commission. eStorage aims to improve energy management by developing a solution for cost-effective integration of intermittent renewable energy generation into the electrical grid.

KEYWORDS

Variable Speed Pumped Storage - Hydro Optimization - Smart Dispatch - Renewable - Balancing Market - Short Term Scheduling - Balance Responsible Party

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The eStorage project

With the increasing deployment of intermittent generation such as wind and solar generation, the power system operation is becoming more and more complex. To manage appropriately the generation uncertainty inherent to wind and solar generation, making the best use of the balancing capacity is a major concern for TSOs (Transmission System Operators). In such a context, the fast response capabilities of the hydro plants are key assets for a reliable grid operation. However, the existing hydro technology cannot always address efficiently the operational issues raised by the massive insertion of intermittent generation in the power system. The maturity gained these last years by the variable speed technology offers additional flexibility by allowing the pumped hydro storage power plants to provide balancing energy and regulation services in pumping mode. This additional flexibility is particularly valuable during the off-peak hours when the intermittent generation becomes too large to be injected properly into the network.

Supported by the European Commission through the 7th Framework Programme for Research and Technological Development, the eStorage project [1] aims to improve energy management by developing a solution for cost-effective integration of intermittent renewable energy generation into the electrical grid. The eStorage consortium consists of a multidisciplinary team, gathering major European players from the entire electricity value chain. The eStorage project objectives are:

- Demonstrate technical and economic feasibility of upgrading an existing fixed speed pumped hydro storage to variable speed technology.
- Enhance the functionality of IT systems to develop grid management solutions in line with real-time market systems
- Quantify the benefits of an EU-wide rollout of variable speed pumped hydro storage's under alternative scenarios.
- Propose changes to the market and regulatory frameworks, to support appropriate business models for flexible energy storage in the EU.
- Develop and assess technology solutions allowing the upgrade of 75% of European pumped hydro storage to variable speed to obtain additional capacity for flexible load balancing.

In this context, IT tools are essential to support the BRPs (Balance Responsible Parties) in order to reach the following targets:

- Optimise their generation portfolio, reducing their operation and maintenance costs, and taking into account the ageing factors in their assets' operation.
- Balance the generation schedules according to their contractual position as notified to the TSO.
- Ensure the ancillary services supply (e.g. aFRR – automatic Frequency Restoration Reserve) that could have been contractualized with the TSO, acting as a BSP (Balancing Service Provider).

After a technical description of variable speed pumping technology, the following sections will focus on the benefits offered by the smart dispatch function that copes with these targets. Moreover, the definition of new market products to facilitate the participation of storage assets in the balancing market will be discussed.

Variable speed pump storage power stations

With variable speed units the power absorbed in pumping mode can be varied over a certain range, depending on the given head, by approximately 30%. This gives the power station operator the possibility to contribute actively to grid frequency regulation in pump mode and therefore deliver services such as frequency regulation to the grid operator while filling the upper reservoir.

In variable speed power stations static frequency converters are used to vary the speed of the electrical machine. For installations with a power lower than approximately 100 MW, this is realized using conventional synchronous generators linked to the grid by a static frequency converter. In power stations with large variable speed units the double fed induction machines with a frequency converter feeding the rotor is today the preferred concept.

The operating mode of variable speed units is extended related to the normal operation (Figure 1) with respect to fixed speed units that can only regulate their power in generation mode and operate at fixed power in pumping mode.

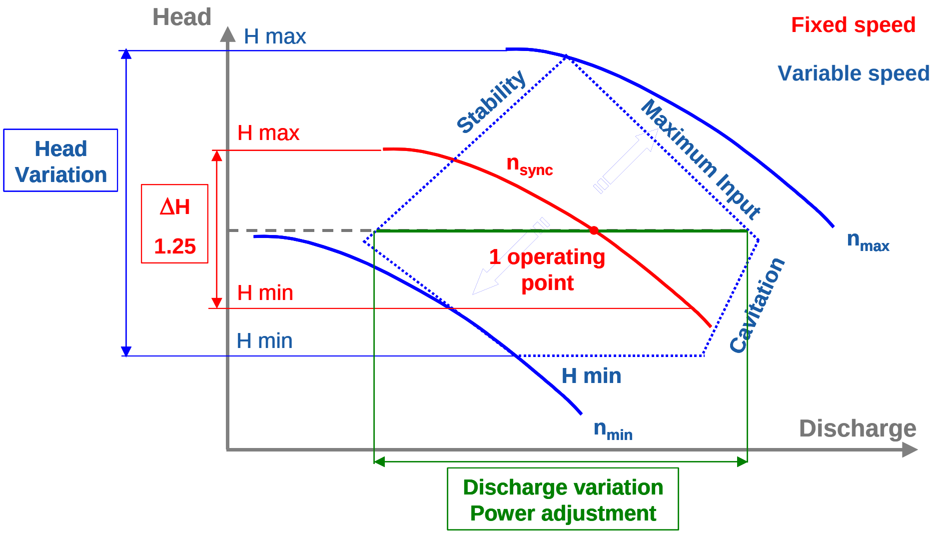

Figure 1: Operating domain for fix speed (in red) and variable speed (in blue)

For fixed operational speed, the top of the efficiency hill charts is generally not within the operating range. The Variable speed permits to have the optimal efficiency level at operating points in both turbine and pump modes. Generally higher efficiencies are achieved compared to the fixed speed and the same nominal speed, particularly at partial loads.

Variable speed systems can respond more dynamically to changes in power set point values. In conventional setups, power variation can be achieved only by changing the opening of the guide vanes of the hydraulic machine. This can only be done according to the defined opening and closing laws in order to avoid over or under pressures in the penstock and the draft tube. Using variable speed units, the same adaptations are done on the turbine side. However, during the slow reaction time of the hydraulic system, the power of the electrical machine can adapt to the new set point value respecting electrical time constants that are at least one order of magnitude lower. The difference between the power delivered to the grid (according to the new set point) and the power delivered by the turbine results in a speed change that can be corrected later on. In other terms the difference in power is temporarily stored or provided by the kinetic energy of the rotor.

Smart Dispatch to manage near real time and real time generation

An energy utility needs to operate its resources in the most profitable and sustainable way. In a deregulated context, profitability is obtained by applying an appropriate trading strategy on the energy markets, but also in respecting its contractual positions once the energy has to be delivered. Sustainability is ensured by a smooth real-time operation of the energy resources, taking into account their physical limits and the ageing factors such as the mechanical stress of the generating units.

Most of the European markets are based on the principle of the Balance Responsible Parties (BRP). Any market player that becomes a Balance Responsible Party can create his own activity portfolio, carrying out all types of commercial transactions. Mixing within its domain of responsibility any type of (physical and/or financial) transactions allows the BRP to reduce its financial exposure to real-time imbalances. These transactions can be physical injections of its own production units or partner's production units, declared withdrawals for its large-size customers, aggregated withdrawals for its small-size customers, as well as sales and purchases with counterparts. The BRP must declare to the TSO (Transmission System Operator), usually first in day-ahead and then updated in intra-day, these physical and financial transactions, and in particular the generation schedules determined in the short-term planning phase, according to the ENTSO-E Scheduling System (ESS) implementation guide [3].

In a decentralized structure (i.e. when the generation company controls in real-time its generation assets), the goal of a BRP is not to ensure the power balance at any time – this is the role, at the system level, of the Transmission System Operator – but is to keep the energy balance over each trading interval at its portfolio level. If imbalance settlement rules vary from a country to another, the general concept is that the BRP will pay a financial compensation in case of a negative imbalance over the trading interval, while it will receive a financial compensation for any positive imbalance. Imbalance prices are usually derived from the costs occurred by the TSO on the balancing market to keep the power balance.

If avoiding any energy imbalance is, by essence, not an easy task for a BRP, having intermittent generation assets within its portfolio will even increase the balance position management complexity – and so raise the deviation penalty risk. In such a context, the flexibility offered by hydro generation and pumping facilities is a key advantage to avoid imbalances. Even more, this increases significantly the generation portfolio value through its contribution to ancillary services and balancing market.

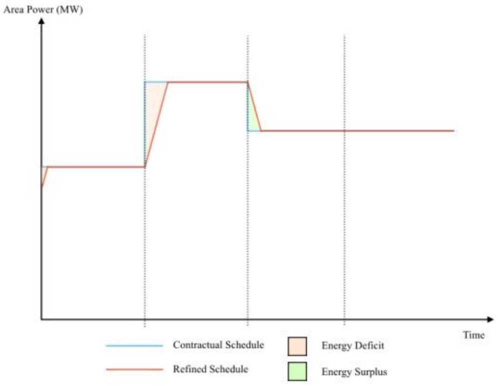

Figure 2
Passive balancing strategy

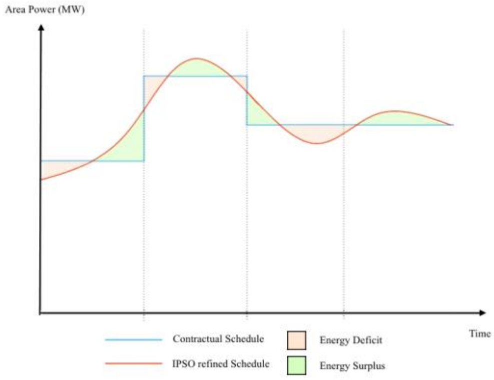

Figure 3
Smart balancing strategy

A smart dispatch function can help the BRP to valorize his hydro assets. In look-ahead, unit generation schedules can be converted, using an optimization-based application, into a smoothed ramping profile with 1-minute granularity, ensuring this energy balance over each trading interval. Figure 2 illustrates a basic passive strategy that consists in reaching the new schedule at the beginning of each imbalance settlement period. Such an approach results in some energy imbalances over each period. If more sophisticated strategy could be implemented based on some heuristics, applying an optimization-based function will define a smooth, smart balanced strategy as illustrated in figure 3. Moreover, contracted reserves and regulation can be allocated over the controlled units in terms of available capacity and associated ramp rate. This ensures the AGC (Automatic Generation Control) application to be able to react on the TSO aFRR signals, and as a consequence, to avoid penalties for not being able to deliver the contractualized service.

If these scheduling decisions are based on generation cost for thermal units, a special care must be given to hydro plants and pump storage facilities. While hydro generation costs are usually lower than any thermal costs, hydro generation schedules may be the most impacted, resulting potentially in inappropriate hydro conditions, both in terms of operational rules and security (such as large discharge rate-of-change), and in terms of daily strategy (overuse of water for balancing purpose during the beginning of the day, resulting in water deficit – and so energy imbalance – on the remaining hours of the day). As a consequence, the mathematical formulation used by the intra-day plant and storage optimization (IPSO) application must include hydro-related constraints aiming to tend towards an energy balance between initial and updated schedules for the hydro assets. Moreover, the hydro generation costs to be used in the objective function must reflect not only the real costs, but also fictive costs expressed as a function of the magnitude of the deviation between initial and updated schedules. Additional fictive costs can be also added in the objective function to prefer "smooth behaviors" that will reduce the mechanical stress of the machines or that will limit the discharge rate-of-change.

In the eStorage project, the IPSO hydro plant model has been extended to deal with variable speed pumping. More particularly, this extension includes an efficiency model received in input of the optimization application that is defined for the current hydro plant control configuration, as illustrated in figure 4. Several operating points are defined, each of them being characterized by an efficiency factor, a maximum contribution to upward aFRR and a maximum contribution to downward aFRR. This detailed model allows the optimizer to make a tradeoff between increasing the supply of aFRR services (but thus operating at a lower efficiency ratio) and operating at the best efficiency ratio (but thus having limited aFRR services). For instance, in case the TSO expects to be short and would need additional upward aFRR, the hydro plant may be controlled at a lower efficiency operating point, while still producing the expected amount of power (i.e. increasing the discharge flow), but offering additional upward aFRR to the TSO.

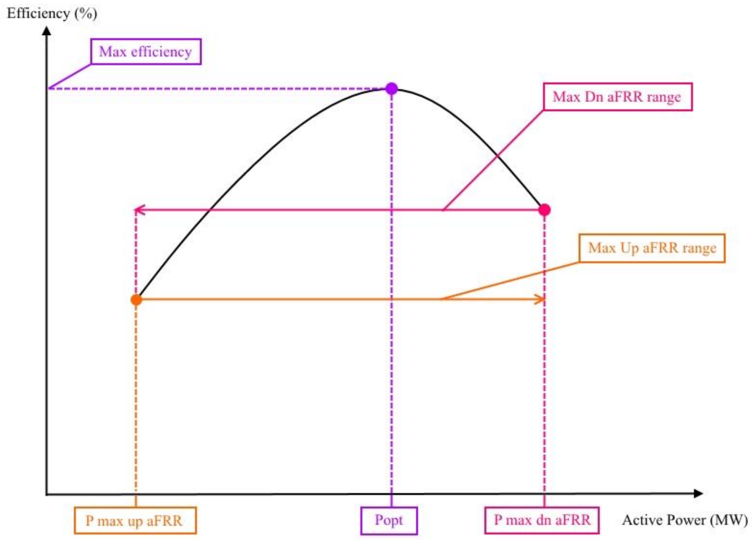

Figure 4: Efficiency model for a given hydro plant control configuration

Moreover, the hydro energy model of IPSO has been adapted and includes energy related constraints to reflect some hydro-related limits. For instance, the reservoir constraints are implicitly modeled with minimum and maximum energy limits (representing minimum and maximum elevations).Water flows (inflows, outflows, discharge and pumping flows) are expressed as energy-equivalent flows. A reservoir capacity target at the end of each period can be expressed in MWh-equivalent and may vary within a defined range. This hydro energy model allows IPSO to ensure the consistency between medium-term hydro scheduling strategy and very short term energy balancing strategy.

Such a look-ahead function replaces the traditional Economic Dispatch to address the economic dispatch calculations with a special focus on the energy balance requirement on each imbalance settlement period. Its integration in the generation portfolio management chain is depicted on figure 5. It typically runs each five minutes or on event (such as an asset sudden outage), over a horizon of one to several hours. Running over several hours allows the application to define the best strategy on units having inter-temporal constraints (such as ramp rate for thermal units, water storage for hydro). It receives from the SCADA (Supervisory Control And Data Acquisition) system the current unit condition, the imbalance that already occurred in the current imbalance settlement period, and can use the latest available forecast data (such as load forecast, and wind/solar generation forecast). Resulting 1-minute schedules are provided to and used by the AGC as base-points.

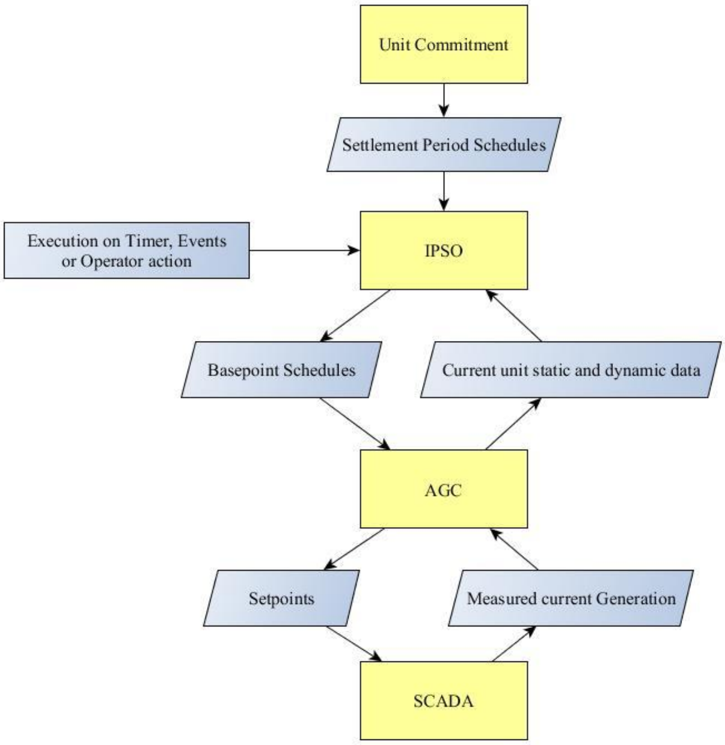

Figure 5: High level IPSO business integration

Then, in real-time, the AGC aims to define set-points to be sent via SCADA for controlled units, correcting the base-points with the unit contribution to the TSO's aFRR signal, as well as the imbalance reduction signal calculated by the AGC application.

Using such a smart dispatch application on a generation portfolio that includes variable speed pumped hydro storage will be particularly valuable to manage intermittent generation. Indeed, in case of a significant delta between the intermittent generation schedules as notified to the TSO and the latest intermittent generation forecast, the smart dispatch application will be able to adjust the variable-speed pumped hydro storage power plants dispatch, even when the assets are in pumping mode. For instance, if the wind generation will be significantly higher than initially forecasted, the optimization application may decide to increase the pumping level and to "absorb" this additional wind power. This definitively offers an economic and ecologic alternative to wind curtailment that could apply to wind generators in case of an excess of generation during the off-peak periods while a minimum number of conventional generators are required to maintain the system inertia and to provide the ancillary services needed to operate the power system [4].

Facilitating the use of storage assets in the balancing markets

As described in the previous sections, the use of the smart dispatch module combined with variable speed pumped hydro storage enable BRPs to fully take advantage of the good responsiveness of hydro plants. This additional flexibility is becoming more and more valuable for the TSOs as installed intermittent capacity continues to increase. In order to maximize the value offered by the storage assets, new market products could be proposed to promote this flexibility into the market in a fair and transparent means while being compliant with the ENTSO-E network code for electricity balancing [5].

Currently, pumped hydro storage plants participate to the balancing effort by providing ancillary services such as aFRR when operated in generation mode. However, the trading strategy in the energy market is constrained due to the energy limitation inherent to the storage assets. Such a status is shared not only with hydro storage, but also with any other storage technology such as CAES (Compressed Air Energy Storage) and Electrochemical storage solutions. Indeed, the market products usually do not allow dependencies between bids and/or do not offer a convenient means to deal with energy inter-temporal characteristics. The way storage assets are currently being used in the market does not therefore reflect all their dynamic potential, and even tends to stiffen the markets through block offer submission (all-or-nothing offers). However, proposing an appropriate market framework to facilitate the participation of storage to ancillary services such as FCR (Frequency Containment Reserve), aFRR (automatic Frequency Restoration Reserve), and mFRR (manual Frequency Restoration Reserve) could benefit to the TSO in its power system operation. For instance, results from a study on the Le Cheylas hydro plant (based in France) described in [6][7] showed that variable speed pumping technology can increase the participation to ancillary services (FCR and aFRR) up to 57%, but the market accessibility must be developed to valorize such flexibility.

To cope with such a goal, new Flexible Energy Market products could be proposed. These new types of products would concern any storage asset type : pumped hydro, electrochemical batteries, Compressed Air Energy Storage, …. These market products could be structured as an energy volume expressed in MWh that could be used – totally or partially – at anytime within an availability period. They could be declined into three different products:

- A pure-supply flexible energy market product which would be expressed as a maximum supply energy volume in MWh and a maximum supply level in MW, with a given supply price in €/MWh, offered during a specified period of time, for purchase only.
- A pure-demand flexible energy market product which would be expressed as a maximum demand energy volume in MWh and a maximum demand level in MW, with a given demand price in €/MWh, offered during a specified period of time, for sale only.
- A combined flexible energy market product which would be expressed as a maximum supply or demand energy volume in MWh, a maximum supply level in MW with a given supply price in €/MWh, a maximum demand level in MW with a given demand price in €/MWh, available during a specified period of time. The product attributes would be completed with a supply/demand efficiency ratio. Then the balancing market operator would be allowed to call for supply and demand energy over the period of time as long as the energy balance remains lower than or equal to the maximum (supply or demand) energy. The efficiency ratio would be applied in the energy balance calculation. It can be noted here that the first two products could be seen as sub-products of the combined flexible energy market product.

While these flexible energy market products are expressed in terms of MWh, an alternate or complementary approach may consist in offering the possibility to link bids. Actually, the concept of link bids would allow the storage asset operator to define a market strategy that would guarantee to reach the targeted MWh equivalent storage level at the end of the market day. Two configurations could be proposed:

- Individual asset linked bids: a supply bid could be linked with a demand bid, both of them belonging to a same asset, but offered on different time periods. Then a bid can be selected only if its linked bid is also selected. As an example, a pump storage operator could define a strategy composed with a demand bid (i.e. storing water through pumping) and a supply bid (i.e. using water through generation). Linking bids would guarantee the pump storage operator to reach a situation where the reservoir conditions at the end of the market day will be close to the expected one, and so will not jeopardize the medium term water usage strategy.

- Multiple assets linked bids: two bids of the same type (supply/demand) from two different assets could be linked together, and offered on different or similar time periods. Here again, a bid can be selected only if its linked bid is also selected. As an example, this feature could be used to offer more flexibility from two cascading hydro plants using the same water resource: a supply bid from the upstream plant could be linked with a supply bid from the downstream plant. Offering these bids on different time periods could allow for taking into account the water traveling time if relevant.

The link bid concept could apply for both traditional and specific market products (supply or demand flexible energy MWh).These bidding strategies would however require the balancing market business process to allow for clearing decision to be taken not only for the coming periods, but also on longer horizon, such as the entire market day.

Conclusion

ENTSO-E has proposed a new framework for the procurement and the activation of balancing services in Europe through the Network code on electricity balancing. The main idea is to harmonize and to coordinate the exchange of balancing services between TSOs in order to increase operational security and market flexibility. The concepts of standard product and specific product have been introduced with the objective to facilitate TSO cooperation (with standard products) while keeping compatibility with local market (with specific products) and allow the participation of a wide range of service providers: load entities, energy storage facilities, renewable resources… In an evolving context driven by the increasing intermittent generation capacity, the eStorage project aims to facilitate TSOs in their power system operation, while helping BRPs to optimize their mixed resource portfolio management. A special focus is offered to hydro due to their dynamic properties which can be even more valuable with the rise of enhanced variable speed pumping technology. The associated benefits for both BRPs and TSOs are explored by the eStorage project, and some of the conclusions were presented in this paper.

First how IT tools can support BRPs in their day to day portfolio operation has been discussed. The use of a smart dispatch tool integrated into the traditional energy management chain has indeed shown to be beneficial to BRPs, providing strategies able to perform a trade-off between the supply of ancillary services and the hydro plant efficiency operating point. Then, new market products specifically designed for storage assets (including pumping hydro plants) in order to help the TSO in its balancing effort have been proposed. Flexible energy offers and linked bids could indeed bring additional flexibility to the TSO, while promoting the participation of storage assets within the balancing and ancillary services markets.

The ambition of the eStorage project for the coming two years is to experiment the smart dispatch tool in a production environment in order to validate the tool extensions. At the same time, the proposed market products will be prototyped on a balancing market clearing engine in order to simulate and evaluate their impact in balancing market operation.

ACKNOWLEDGMENTS

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