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Concepts and Practice Using Stochastic Programs for Determining Reserve Requirements

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SUMMARY

The use of intermittent resources, such as wind and solar power, can increase challenges in ensuring reliability and efficiency of power system operations. These challenges can become more difficult to manage with increased penetration of variable and uncertain resources beyond the capabilities of existing techniques. While procurement of Reserves is an effective technique at providing the flexibility necessary to protect against uncertainty, deterministic methods used today may fail to appropriately place Reserves such that they can be deliverable to address deviation events. Further, deterministic techniques used today procure suboptimal quantities of Reserve by failing to optimize with respect to multiple potential realizations. Static policies may be too conservative in the amount of procured Reserves at the expense of market efficiency. Therefore, we propose that stochastic optimization techniques can appropriately balance these competing interests to ensure reliable and economical operations with increased penetration of intermittent resources. In this paper, we describe, through a simple representative model, how to appropriately determine Reserve requirements. The model is designed to illuminate potential procurement issues for Reserve products that are dispatched in intra-hour market cycles to balance forecast deviations (Load-Following Reserves). First, we show the Reserve procurement results from a deterministic model where we have perfect foresight over several realizations of Net Load in the model. Then, we demonstrate a deterministic optimization case where the model procures an appropriate amount of Reserves relative to the utilized scenarios, but fails to place these Reserves in an area that allows for sufficient delivery. After that, we integrate the use of stochastic optimization over the same scenarios to show that, in absence of an appropriate formulation, it is possible to arrive at a commitment and dispatch solution that is feasible across all modelled scenarios, yet through use of Reserves established implicitly in available online generation capacity, such that there is insufficient information returned about the amount of Reserves which are needed. Finally, we show, through leveraging of modern power system optimization tools, that Reserve resources can be selected in a stochastic optimization process that appropriately addresses deliverability in an economically efficient manner. Conclusions are made from these observations.

KEYWORDS

Reserve requirements, stochastic optimization, renewable generation, grid operations

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1. Introduction

As power networks introduce more intermittent resources such as wind and solar, effectively managing the variability and uncertainty of these assets becomes more challenging. In classic power systems without modern renewables, continuous uncertainty is present in load forecasting and managed by Automatic Generation Control (AGC) using Regulation Reserves on a second-by-second basis [1]. However, on-going supply-side uncertainty events combine to pose a new operational challenge in the magnitude and rate of change of deviations from scheduled levels. This precipitates the need for establishing greater flexibility in advance of such events to ensure reliable operations of the power system.

In the California ISO, Load-Following Reserves may be as high as 4000 MW for Up and Down class Reserves [1][2][3], at a rate of approximately 200 MW/min in extreme cases [1]. However, while procuring amounts that protect against extremes at all times could enhance system reliability, these amounts are not always necessary, and over-procurement could affect market efficiency. Further, poor placement of such Reserves may not allow for their benefits to be realized should there be congestion that limits deliverability, and reliability issues may persist.

In order to balance the need for procuring Load-Following Reserves in amounts and locations as needed for enhancing the reliability and efficiency of real-time operations, we propose the use of stochastic programming. When combined with effective policies and modern power systems optimization tools, stochastic methods can increase penetration of renewable resources without sacrificing system reliability. In this paper, we describe a simple and transparent electricity dispatch model that can assist in decisions to appropriately place Reserves. The model exhibits potential procurement issues for local Reserves, in both deterministic and stochastic problem formulations, and helps schedule resources while addressing deliverability issues in an economically efficient manner.

1.1 Overview

A network diagram of the power system model is shown in Figure 1 having a single overall area (Wide Area) and two sub-areas (Cheap and Expensive) that are connected by a single transmission line. The generation costs are chosen so that the economic solution has a dispatch schedule that prefers to produce energy in the Cheap area and transfer power through the line for consumption (Net Load) in the Expensive area.

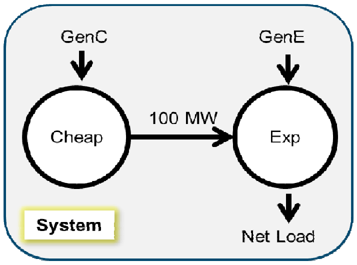

Figure 1. Two-area power network with single load center

There is also an area-level Reserve requirement, and the economically preferred source of Reserve is the Cheap area. However, the line has limited capacity and cannot carry both energy and Reserve, under some conditions. This is the crux of the deliverability matter, and these conditions will be used to investigate various heuristics for local Reserve requirements.

1.2 Generation

Parameters for electricity generation units are shown in Table I. GenC has a maximum dispatch of 200 MW and costs 10 $/MWh. GenE has a Maximum Dispatch of 50 MW and costs 40 $/MWh. Both generating units have a Minimum Dispatch near 0 MW, in order to make the solution results more transparent. Likewise, the Cold Start Cost for each unit is near zero to promote transparency.

Table I. Generation parameters

Name	Area	Minimum Dispatch	Maximum Dispatch	Energy Cost	Cold Start Cost
GenC	Cheap	ε MW	200 MW	$10 /MWh	$(2ε)
GenE	Exp	ε MW	50+ε MW	$40 /MWh	$(3ε)

GenE has a Maximum Dispatch of 50+ε MW, so that it can freely provide 50 MW of Reserve when its Unit Commitment is on and it produces Energy at its Minimum Dispatch of ε MW and so that the Reserve price will not reach a penalty value under normal conditions.

1.3 Reserve Requirements

The Reserve requirement for deterministic versions of the electricity dispatch model is 50 MW at the level of the Wide area, which means that GenC or GenE can satisfy the requirement in any combination. The nominal model input is designed to have a surplus of Reserve supply from the generating units, which will result in a zero Reserve price under nominal conditions.

Table II. Reserve requirement

Area	Mode	Reserve Requirement
Wide	Deterministic	50 MW
N/A	Stochastic	0 MW

1.4 Network

The area interchange connection between subareas Cheap and Exp (short for expensive) has been set to 100+ε MW, where ε prevents multiple dual solutions and to avoid small differences leading to energy or Reserve violation penalties.

Table III. Network parameters

Source	Sink	Capacity
Cheap	Exp	100+ε MW
Exp	Cheap	100+ε MW

To further improve transparency, the ε values will be left out of in the rest of this paper.

1.5 Net Load Scenarios

Net Load is defined as the average energy consumption over the given interval (ID 15-minute, RT 5-minute) subtracting the average energy supply that is not controlled, like from photovoltaic and wind generation sources. The Net Load value is that which the controllable energy supplies must follow in order to maintain an energy balance.

Table IV contains the values of three Net Load scenarios used to elicit various conditions in the solution of this simple power system model. The Expected Net Load scenario is defined to be the average of the Low Net Load and the High Net Load scenarios and to be satisfied completely (and myopically) from GenC. The Low Net Load scenario is designed to be satisfied completely by GenE. The High Net Load scenario is designed to require foresight of all potential scenarios in order to preposition the system to respond appropriately.

Table IV. Net Load scenarios

Scenario	Probability	Load
Low Net Load	1/3	50 MW
Expected Net Load	1/3	100 MW
High Net Load	1/3	150 MW

While the ID cycle has one Net Load schedule for 15-minutes, there are actually three RT Net Load schedules. For transparency, we assume that these three schedules are constant over the 15-minute period. In the next section, we describe the prepositioning process, which is followed by the recourse response.

1.6 Two-Cycle Operational Process

The operational process for this simple model involves two cycles called Intraday (ID) and Real Time (RT) as seen in Table V. The RT cycle length (period of time over which it is active) is 5 minutes, and the ID cycle length is 15 minutes. As a result, the operational process solves the ID cycle model first in order to preposition the system, and then it solved three of the RT cycle models, covering the same 15-minute period, as recourse responses to forecast errors in the ID cycle. Different decisions are made in each cycle, leading to two different model types. The main difference between the two models is that the ID model is used to determine Unit Commitments and Reserve procurements based on the Expected Net Load scenario, which does not occur in the RT models. The RT model takes the Unit Commitment and Reserve decisions as given and utilizes these resources to meet the RT Net Load schedule.

Table V. Decisions and tasks in each decision cycle

Cycle	Commitment Decisions	Settlement Decisions
ID	Unit On/Off Reserve Schedule	Reserve Schedule ID Energy Schedule
RT	Release Reserve	RT Energy Schedule

The ID Commitment Decisions are those that remain fixed across multiple RT Net Load scenarios. The ID Settlement Decisions are those that we treat as being compensated for scheduling in the ID cycle. Recall that Unit Commitment is assumed to have no cost, for transparency purposes. Thus, the schedules for Reserve and ID Energy are determined and settled in the ID cycle to meet the Expected Net Load and Wide Area Reserve requirement. As will be seen, the release of Reserve procurements for RT recourse (conversion to energy) is critical for addressing Net Load forecast uncertainties.

2. Electricity Dispatch Model Results

This section describes a series of examples, based on the given model setup, that vary according to what information is available during the operational process at the time of making an electricity scheduling decision and how those decisions are being made.

Table VI. Description of example electricity dispatch models

Name	Number of Process Runs	ID Net Load Forecast	RT Net Load Outcome
Perfect Foresight Deterministic	3	3 Net Load	Same as ID Net Load
Myopic Foresight Deterministic	3	Expected	3 Net Load scenarios
Stochastic w/ Implicit Reserve	1	Expected w/ RT foresight	3 Net Load scenarios
Stochastic w/ Explicit Reserve	1	Expected w/ RT foresight	3 Net Load scenarios

The first example forecasts perfectly the Net Load in the ID cycle, and realizes that outcome in the RT cycle. The three operational process runs are independent, because each is run with one choice of Net Load in each cycle as specified in Table VI. The processes are deterministic, because each scheduling problem is solved under the assumption that the given Net Load scenario will be the actual outcome.

2.1 Perfect Foresight Deterministic Example

The second example forecasts and uses only the Expected Net Load scenario in the ID cycle, while the RT Net Load outcomes can be any one of the three scenarios. The three operational process runs are independent, because each is run with one choice of Net Load in each cycle as specified in Table VI. The processes are deterministic, because each scheduling problem is solved under the assumption that the given Net Load scenario will be the actual outcome. By definition, all negative aspects of deterministic modeling are mitigated when the Net Load forecast turns out to be correct. The ID cycle prepares properly, and the RT Energy dispatch is correct, without unserved energy.

The ID cycle prepares by scheduling the GenC Unit Commitment on coincidentally in each scenario and the GenE Unit Commitment on only in the High Net Load scenario. It also schedules GenC to provide Reserve in each scenario, which can be seen in Table VII. The indication that a generator has Unit Commitment off is that it provides neither Reserve nor Energy, as is the case for GenE in the Low Net Load and the Expected Net Load scenarios.

Table VII. Schedules for three perfect-foresight, deterministic scenarios

ID Scenario	ID Reserve		ID Energy		RT Scenario	RT Energy	
	GenC	GenE	GenC	GenE		GenC	GenE
Low Net Load	50 MW	0 MW	100 MW	0 MW	Low Net Load	50 MW	0 MW
Expected Net Load	50 MW	0 MW	100 MW	0 MW	Expected Net Load	100 MW	0 MW
High Net Load	50 MW	0 MW	100 MW	0 MW	High Net Load	100 MW	50 MW

The table contains the three solutions of these independent process runs and is a template for reporting subsequent examples. The ID cycle has GenE Unit Commitment on only in the High Net Load scenario, because it needs to dispatch 50 MW of Energy in RT. GenC provides Reserve coincidentally across all scenarios, because it is the least expensive (lower opportunity cost) to do so.

2.2 Myopic Deterministic Example

Significant forecast errors raise issues with the myopic nature of deterministic. In the Myopic Deterministic example, the ID-cycle foresight is limited to the Expected Net Load scenario, and depending on the scenario outcome in the RT cycle, there may be a problem with the prepositioning of the system. This process is much the way that present-day power system operations are scheduled.

Table VIII shows the schedules for three process runs where the ID cycle always uses the Expected Net Load of 100 MW, which always results in the same Unit Commitment (GenC on and GenE off) and Reserve schedule (GenC at 50 MW).

Table VIII. Schedules for three myopic, deterministic scenarios

ID Scenario	ID Reserve		ID Energy		RT Scenario	RT Energy	
	GenC	GenE	GenC	GenE		GenC	GenE
Expected Net Load	50 MW	0 MW	100 MW	0 MW	Low Net Load	50 MW	0 MW
Expected Net Load	50 MW	0 MW	100 MW	0 MW	Expected Net Load	100 MW	0 MW
Expected Net Load	50 MW	0 MW	100 MW	0 MW	High Net Load	100 MW	0 MW

As a result, the recourse decision in the RT cycle for the Low Net Load scenario is to reduce output from GenC. However, there is insufficient recourse for the High Net Load scenario, because GenE has Unit Commitment off and the transmission line can deliver only 100 MW. As a result, there is 50 MW of unserved energy, because the system was not prepositioned to respond properly to this scenario. In the following, we investigate how Reserve is defined and used to accommodate appropriate recourse decisions, the main topic of this paper.

2.3 Two-Stage Stochastic Program with Implicit Reserves

To determine for the ID cycle a Reserve schedule and a Unit Commitment that is both consistent and sufficient for every scenario in the RT cycle, we formulate the ID cycle as a Stochastic Program. This formulation includes both the model for the ID cycle and those for each RT scenarios. It need not explicitly represent Reserve in the ID cycle, because the Unit Commitment is required to be consistent across all of the RT scenarios. Thus, the Unit Commitment decisions are Stage 1 variables in a 2-Stage Stochastic Program. As such, the Reserve procurement is implicit and, depending on its definition, it can be deduced from the resulting ID and RT Energy dispatches.

By definition, the Stochastic Program formulation has foresight of the Unit Commitment needs across all of the RT scenarios. As such, the least-cost ID Unit Commitment is to have both GenC and GenE on, which is the correct, implementable solution. It also turns out that, the least-cost ID Energy schedule (subject to the expected cost of the RT cycle across equally weighted scenarios) is to produce 100 MW from GenC and 0 MW from GenE, as can be seen in Table IX. If the definition of Reserve is the ability of a generator to increase its dispatch from the ID Energy schedule, then GenC has 100 MW of Reserve and GenE has 50 MW of Reserve. These are the amounts of extra energy production that these generators can produce up to their Maximum Dispatch, based on their ID Energy schedules.

Table IX. Schedules for a Stochastic Program with implicit Reserves

ID Scenario	ID Reserve		ID Energy		RT Scenario	RT Energy	
	GenC	GenE	GenC	GenE		GenC	GenE
Expected Net Load	100 MW	50 MW	100 MW	0 MW	Low Net Load	50 MW	0 MW
					Expected Net Load	100 MW	0 MW
					High Net Load	100 MW	50 MW

The table also includes the least-cost RT Energy schedules for each scenario (given the ID Unit Commitments schedule). These Energy schedules are identical to those seen in the Perfect Foresight, Deterministic example. This is because the Stochastic Program formulation includes all of the scenario information. The difference here is that the Unit Commitment in the ID cycle is required to be consistent across all scenarios, whereas the three Perfect Foresight, Deterministic operational processes have different Unit Commitments, depending on the actual outcome.

The implicit Reserve, present in the Stochastic Program formulation, is optimal and sufficient for all RT scenarios. However, such a formulation is not used as a market-clearing model (for many practical reasons) and can only initially be used for off-line decision support to determine Reserve requirements. In an advisory role, it is clear that the implicit Reserve of the Stochastic Program formulation is not sufficient, because it is ambiguous about how to much reserve is actually needed.

We know from Table IX that the maximum increase in generator production from the ID cycle to any RT scenario is 50 MW for GenE in the High Net Load scenario, and this can help indicate the Reserve need. It cannot however indicate whether a Wide Area requirement is sufficient.

2.4 Two-Stage Stochastic Program with Explicit Reserves

Another way to formulate the Stochastic Program is to add a Reserve decision variable for each generator, as in the deterministic formulation that appears in a constraint that defines the amount of positive change between the ID Energy schedule and the RT Energy schedule.

The Energy schedules in this example are identical to those from the prior example, because the Reserve schedule is merely defined in their terms and does not affect the objective function value. Under these conditions, the schedules are summarized in Table X.

Table X. Schedules for a Stochastic Program with explicit Reserves

ID Scenario	ID Reserve		ID Energy		RT Scenario	RT Energy	
	GenC	GenE	GenC	GenE		GenC	GenE
Expected Net Load	0 MW	50 MW	100 MW	0 MW	Low Net Load	50 MW	0 MW
					Expected Net Load	100 MW	0 MW
					High Net Load	100 MW	50 MW

Adding this definition is helpful, because it makes the Reserve schedule explicit and transparent. In a more complex model formulation, such transparency is very important. Further, it can be used to support decisions for determining Reserve requirements in actual market clearing model formulations. This initial indication is that the Wide Area requires 50 MW of Reserve, but the actual market-clearing model for the ID cycle is the Myopic Deterministic formulation.

Recall that the Myopic Deterministic ID-cycle formulation with a 50 MW Wide Area Reserve requirement and Expected Net Load has GenE Unit Commitment off and that it provides no Reserve, which will result in unserved Energy under the High Net Load scenario. This is too risky and cannot be acceptable and must be resolved. One resolution of the unserved Energy in the Expensive area is to have a local requirement for Reserve only in that area, but how much is sufficient? To answer this question, more information must be derived from the Stochastic Program to help resolve this issue.

2.5 Need for Local Reserve

To determine a sufficient local Reserve requirement for the Expensive area we impose a cost for Reserve from GenE, which could be considered as an offer price from the owner for providing Reserve services. The effect on the Stochastic Program formulation is to add a term for the explicit Reserve into the objective function. When the GenE Reserve offer price is sufficiently high, the amount of explicit Reserve provided by GenE goes to 0 MW, and Table XI shows the result.

Table XI. Schedules for a Stochastic Program with high-cost explicit Reserves at GenE

ID Scenario	ID Reserve		ID Energy		RT Scenario	RT Energy	
	GenC	GenE	GenC	GenE		GenC	GenE
Expected Net Load	50 MW	0 MW	0 MW	50 MW	Low Net Load	0 MW	50 MW
					Expected Net Load	50 MW	50 MW
					High Net Load	100 MW	50 MW

The GenC and GenE Unit Commitments are both on. The GenC ID Reserve is 50 MW and ID Energy is 0 MW. The GenE ID Reserve is 0 MW and Energy is 50 MW (Maximum Dispatch). In the RT cycle, GenC moves up and down for the High Net Load and Low Net Load scenarios, respectively, while GenE remains at Maximum Dispatch. The conclusion is that a local Reserve requirement in the Expensive area is not absolutely necessary and that it is sufficient to have a Wide Area requirement for 50 MW Reserve, only if the definition of Reserve is explicit. That is, a generator can only be expected to respond to positive changes from its ID Energy schedule if it has been scheduled for ID Reserve.

Figure 2 shows the effect of steadily increasing the GenE Reserve offer price on its Reserve and Energy schedules. At a low value, Reserve is the preferred choice, because providing Energy in every scenario is more expensive than providing it from GenC. This logic continues as the GenE Reserve offer price rises, until the total cost reaches a point where switching GenE from Reserve to Maximum Dispatch of Energy is equivalent (see Figure 3).

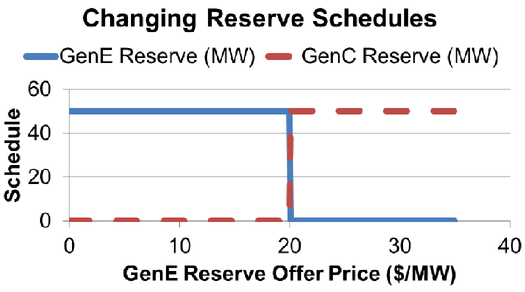

Figure 2. GenE Reserve and Energy schedules versus GenE Reserve offer price.

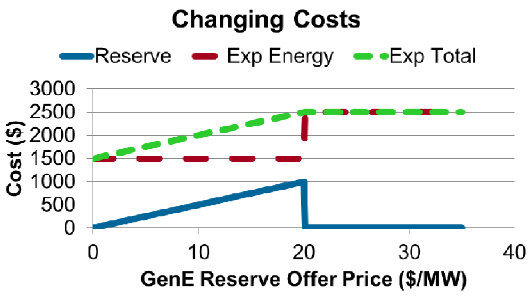

Figure 3. Reserve, expected Energy, and total costs versus GenE Reserve offer price.

Because this power system model is simple and linear, the transition from one regime to the other is immediate. In a more complex system the transition is likely to be more gradual. The key to obtaining sufficient reserve in this system is for GenC and GenE to have Unit Commitments on. A local reserve requirement in the Expensive area will have this effect for any value above 0 MW. The added cost is negligible, in this case, because the Unit Commitment cost for both generators is assumed to be negligible. The conclusion is that a negligible local Reserve requirement provides sufficient Reserve, only if Reserve is implicit, and that the added cost is also negligible. Similarly, a 50 MW Reserve requirement in the Expensive area would cause GenE to have Unit Commitment on, and it would satisfy the Reserve need, whether implicitly or explicitly, with negligible extra cost.

3. Conclusions

Through a simple electricity dispatch model, we have reviewed how to provide sufficient Reserve in forward decision cycles. The challenge is to determine Reserve schedules without perfect foresight of the actual Net Load in Real Time. This uncertainty can be anticipated by using a Stochastic Programming formulation as a decision support tool for dynamically determining Reserve requirements.

We conclude from the exposition above, in the context of the Simple Electricity Dispatch model, the following points.

- A local reserve requirement in the Expensive area is not absolutely necessary and that it is sufficient to have a Wide Area requirement for 50 MW Reserve, only if the definition of Reserve is explicit.
- A negligible local reserve requirement provides sufficient Reserve, only if Reserve is implicit.
- A 50 MW Reserve requirement in the Expensive area would cause GenE to have Unit Commitment on, and it would satisfy the Reserve need, whether implicitly or explicitly.

Not discussed in this analysis is the impact of economic choices on Reserve requirements and unserved Energy. For instance, the Stochastic Program may serve as a tool to determine demand curves for local and Wide Area Reserve requirements. This has yet to be analyzed.

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