Spectral Analysis of Energy-Constrained Reserves

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Abstract

The definition of a service is key to the ability to meter it, measure it, regulate it, price it, or otherwise take it into consideration. Reserves (a form of power supply insurance) are key to power system operability. Traditionally, reserves have been characterized in terms of time domain quantities such as ramping rate capabilities and the like. Also, traditionally such measures have not considered the possibility that some of the reserve services may be energy or otherwise time-limited. This paper illustrates how to take into consideration energy-constrained reserve services, and also how to classify and measure both the need for reserves as well as the ability to provide them in terms of frequency domain techniques. In a sense, the use of frequency domain quantities is more "natural" for this problem where the characterization of the speed of response is in fact quite important. The paper illustrates a number of numerical examples.

Introduction

The prevention of blackouts due to spurious incidents in the system has led over many years to the use of "reserves" of various "types" to prevent such occurrences. The objective of these reserves is to make the system resistant to failures of individual (and sometimes multiple) components. Of particular concern is the prevention of uncontrolled cascading outages. Reserves are thus a form of "insurance" that is paid to attain continuity of service and prevent major and unacceptable disruptions of service. How much is needed for reserves, who should provide them, and how much should one pay for "reserve services" have all become quite important questions in deregulated electricity markets.

Reserve capabilities are commonly classified according to the ability to respond of the unit serving as a reserve unit. Traditionally, the classification of reserves has been based on the capabilities of existing technologies. Conversely, reserve needs are often categorized in terms of the suddenness, size and frequency of the outages that lead to the need for having reserves in the first place. It is useful to start our discussion from NERC's [1] definitions of reserve services (emphases in these definitions are ours):

- Regulation and Frequency Response Service: Provides for following the moment-to-moment variations in the demand or supply in a Control Area and maintaining scheduled Interconnection frequency.
- Spinning Reserve Service: Provides additional capacity from *electricity generators* that are on-line, loaded to less than their maximum output, and available to serve customer demand *immediately should a contingency occur.*
- Supplemental Reserve Service: Provides additional capacity from electricity generators that can be used to *respond to a contingency* within a short period, usually *ten minutes*.
- Although not listed in the NERC definitions, others have also considered a category called "backup reserve service" to refer to reserves that can come on-line within a period of thirty minutes to one hour or more to replace for lost power due to a contingency.

Associated with the notion and classification of reserves is the notion of "ramping rates" of different generating units. It is standard terminology to say that a unit can offer x MW of spinning reserves if it is capably of increasing its output within the "spinning reserves" time frame (usually under one minute) by an amount x. Likewise, a unit is said capable of offering y MW of supplemental reserves if it can increase its output by y MW within the time frame suitable for supplemental reserves, say 20 minutes. Being able to raise one's output by a given amount requires not only the ramping rate capability, but also that the unit be operating at less than full power output at the time.

Historically, a variety of techniques have been used and proposed for the quantification of the reserves. The problem of reserves has also been commonly tied to the problem of Unit commitment. For numerous references and further references on the general topic, we suggest any of a number of additional readings such as those in references [5-15].

As an illustration of what reserve capabilities are about, consider figure 1, illustrating the time domain conventional definitions of three kinds of reserves. Essentially, a unit of regulation reserves is presumed to be able to deliver a unit of power instantaneously.

A unit of spinning reserves is supposed to deliver the same unit of power but it is "allowed" to take a little longer to ramp up. Finally, a unit of supplemental reserves is permitted to take even longer to respond to a given demand for additional power.

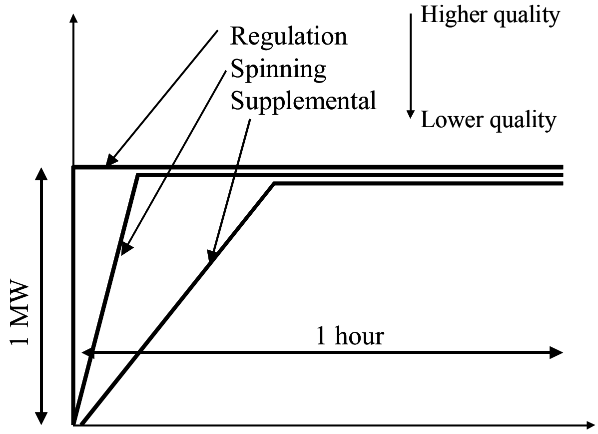


Figure 1: General structure of the conventional classification of reserves in the time domain.

The use of this general structure and classification of reserves is commonplace in markets such as those in California, where procurement of reserves is classified into Regulation, Spinning, Supplemental and Backup. Such a classification seems to imply that the faster-responding reserves should be more valuable ("higher quality") than the slower-responding ones, and thus can also substitute for slower reserves.

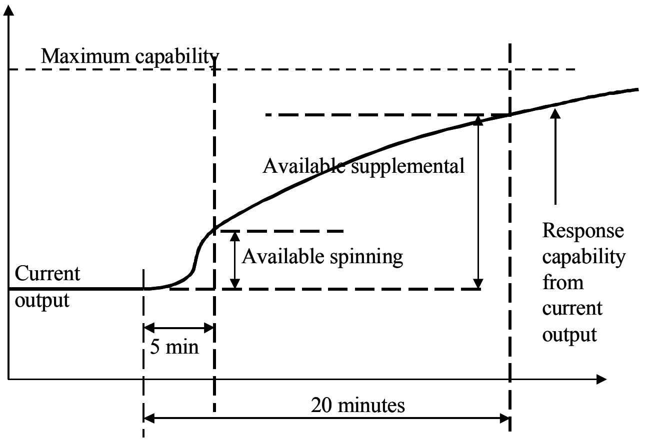


Figure 2: Determination of conventional reserve capabilities of a given generator.

As an example of how to "measure" the capability of a unit to provide reserve services, we can look into the features of the unit itself. Figure 2 illustrates the way in which the spinning and supplemental reserve capabilities of a given unit under given conditions could be defined. The available spinning and available supplemental capabilities are mutually exclusive: if a portion of the available ramping capability is used for spinning reserves, it is not available for supplemental reserves.

This conventional definitions and classification of reserve services may not be a good classification, in that it assumes that a reserve service, once activated, can continue to supply the power indefinitely and is able to do so at whatever market rates are in effect for the energy supplied. Reality, however, suggests that many means for providing reserves quite effectively (e.g., mechanisms that are fast-responding) may not be able (or willing) to sustain the called-upon level of output for very long periods. Examples include cases where reserves are provided by fuel or energy limited resources, or when reserves are provided by demand, but where the demand is willing to tolerate only a limited-duration interruptions or diminution of service. Figure 3 illustrates this point.

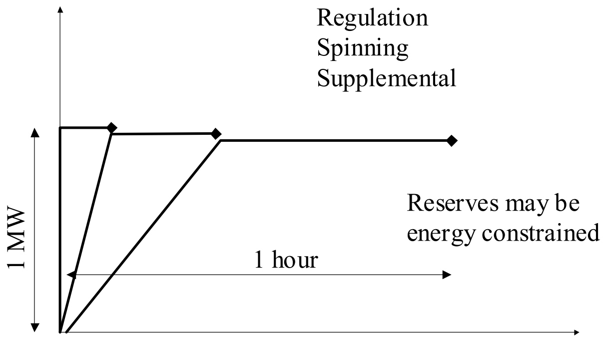


Figure 3: Alternative, energy constrained definition of reserves as non-overlapping services in the time domain.

The time-domain classification of reserves, particularly the conventional definitions that do not constrain reserves by time duration of the delivery period (or by an energy constraint) have led to some interesting problems and quandaries, the most interesting of which is that under some market designs it turns out that the "lower quality" reserves can end up selling for more than the "higher quality" reserves. This is in part a result of market designs that do not permit simultaneous clearing of energy and all types of reserves, and in part due to the overlapping nature of the reserves in the conventional definition. For more details on the quandaries that have resulted from such definitions, see [2,3,4].

A different classification of reserves is offered by the possibility of characterizing reserve services (both in capability and in actually measuring the performance to a reserve service request) using frequency-domain techniques. Frequency domain techniques can also be used to determine the reserve requirements imposed on the system by various events and/or power usage patterns. The remainder of this paper presents the foundations for a frequency-domain spectral classification of reserve services, needs and performance measures. It then applies these techniques to specific and hypothetical examples of reserve service provision and compares it with more traditional means for measuring and quantifying reserves. It illustrates how some of the problems of many present-day reserve tariffs are obviated and how a better overall market design can result.

The need for reserves

Both the trading of any commodity and the development of standards of service for any items or commodity depend on the ability to measure the quantity of the commodity or item prescribed or traded. One of the most important commodities in power systems is the requirement for reserves. Reserves refers to the requirement that the system be able to sustain any credible contingency or event without involuntary loss of load. An involuntary loss of load will occur under any of the following circumstances:

- Insufficient availability of generation system-wide (in some cases this refers to insufficiency of generation at or below a given price or under certain other restrictions).
- Availability of generation but inability to deliver the required generation into a given region either because of insufficiency of transmission or because of contractual arrangements that preclude such delivery in spite of available generation elsewhere and transmission capability.
- Insufficient reactive power within a portion of the system, leading to a voltage collapse problem. The threat of voltage collapse (or the occurrence of low voltages even in the absence of voltage collapse) can lead to involuntary loss of load.
- System separation leading to stability problems which result in the disconnection of load, either in a controlled manner by means of a load shedding program or (worse) by means of uncontrolled cascading failure resulting from a stability event.
- The overloading of a line of transformer, leading to its disconnection, followed by the cascading disconnection of other such components in rapid sequence after the loss of the first component, leading to loss of load.
- Misoperation of system relays or other components that directly result in involuntary loss of load.

Power systems are subject to failures of individual components due to a variety of reasons. Reliability criteria for system operation require that the failure of any single component in the system not create an involuntary loss of load. Toward this end, the notion of system reserves was developed and is used universally in all systems. Reserves represent excess capacity in the system, either in the form of excess available generation or excess available transmission, or both. NERC and other organizations generally prescribe by means of rules the amounts of reserves that are sufficient for adequate operation of the system. These rules require, at a minimum, that:

- The failure of any single generator in the system shall not cause loss of load.
- The failure of any single line or transformer shall not cause loss of load.

This is referred to as the “n-1” criterion for system operation. More stringent reliability criteria can be used, such as:

- The loss of no two components shall result in a loss of load (the “n-2” criterion).
- The system shall tolerate the complete loss of a substation without any other part of the system being affected except for possibly loads connected to the substation in question.

The criteria for meeting these objectives can be based on the establishment of rules for making a sufficient number of generating units available to the system in a time frame appropriate to respond to every contingency covered by the rules. For example, “every system area shall have generation reserves equal to 100% of the largest generating unit plus 50% of the next largest unit.” The rule can also permit or disallow the crediting of curtailable load and/or the us of transmission import capability in establishing reserve requirements.

If generators and lines never failed, reserves would not be required. If loads were known and given and sufficient generation to meet the loads was made available, again reserves would not be required. The need for reserves is tightly connected to the failure of generators and the failure of lines, as well as variations in load. Whether we choose to provide reserves to a system by market means (i.e., create an ancillary service market for reserves) or by mandatory means, it is necessary to be able to determine and quantify the reasons why reserves are needed in the first place and the manner in which the reserve needs are being met. A generating unit that has a low availability and where the failures of the unit happens suddenly and in an unannounced manner imposes a greater burden on the reserve needs that a unit that either both small or has high availability. Likewise, a demand that is constant and predictable imposes a lesser need for reserves that an highly variable and unpredictable demand. On the flip side, a unit capable of ramping its output rapidly to meet an increased demand that may result from either a generation unit outage or from a sudden load change is somehow providing a greater value in terms of its ability to supply reserves. We thus see the problem as one of creating a market that matches the nee for reserves (the reserve needs can be thought of as a "demand" for reserves that is established by the characteristics of the generators and loads connected to the system *and* by the specific system conditions at hand) to the "supply" of reserves (as determined by the capabilities of those generators and demands able to participate in the reserves market).

Formal quantification and classification of these loose and intuitive ideas has led to the classification of reserves into several types, depending on speed of response. These reserves include, for example, spinning and supplemental. The classification is generally done in the *time domain*. As defined above, spinning reserve may refer to generation that can respond to either frequency changes or signals sent to its prime mover in a time frame of seconds to minutes, while supplemental reserves refers to the ability to respond in several (say 20) minutes. It is common to also consider a faster time frame called "regulation" or "regulation reserves."

Spectral viewpoint of reserves

Rather that specification of reserves and reserve needs (demand) in term of ramping rates and time-domain ability to respond, the capabilities of reserve requirement imposed on a system by a generating unit or by a load may be quantified by means of a spectral analysis of the availability characteristics of the unit. Likewise, the ability of a unit to supply reserves can be based on a frequency domain analysis of the response capabilities of the unit. The methodology for reserve measurement and classification advocated here involves the following steps:

- Determine the time-domain characteristics of the "signal" associated with either the ability of a unit to respond to sudden changes, or the time-domain characteristics of the failure more of interest and responsible for the required level of reserves (for example, determine a curve illustrating the availability of a given unit).
- For each of these "signals", perform a numerical FFT transformation.
- By inspecting the frequency spectrum of each signal, aggregate the frequency domain components of the reserve needs to come up with "categorized" reserve needs (or categorized reserve provision capability).
- Within each category, match (either by market means or by mandatory "required" means) the reserve needs in each category to the reserve "supply."

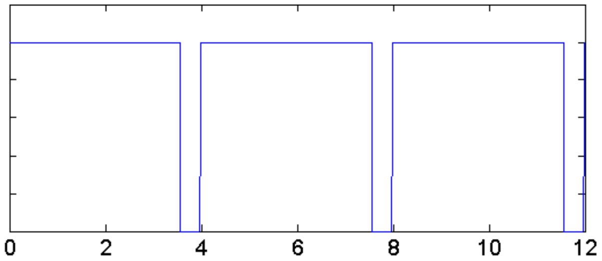
For purposes of this paper, once quantities are expressed in the frequency domain, the following tentative 3-way frequency-domain classification of reserves is used:

- Reserves in the spinning reserve time frame are assumed to be associated with variations with periods between under 5 minutes (frequencies between 0.2 Hz and ∞ Hz).
- Reserves in the supplemental time frame are associated with variations in the 5 minute to 20 minute time frame (frequencies between 0.05 Hz and 0.0067 Hz).
- Reserves in the backup time frame are associated with variations in the 20 minute to one hour, specifically excluding also "dc" components which are presumably to be handled by regular energy markets.

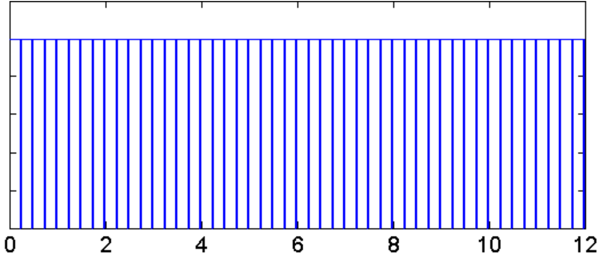
Examples of spectral reserve needs

We illustrate the spectral content of four types of needs. The four types of reserve need considered are:

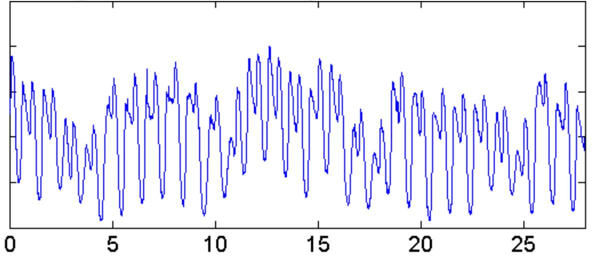
- Reserve requirements imposed on the system by a generator with 90% availability where the unavailability is characterized by a few sudden but extended outages with ramped restoration of service, Figure 4(a). For simplicity, these occur at regular intervals.
- Reserve requirements imposed by a generator with 90% availability where the unavailability is characterized by numerous and sudden outages and rapid restoration of service, Figure 4(b).
- Reserve requirement imposed by aggregate load variation over a one month period, Figure 4(c). The load patter was obtained from the PJM system load over a four week period.
- Reserve requirement imposed by an arc-furnace like device, Figure 4(d).



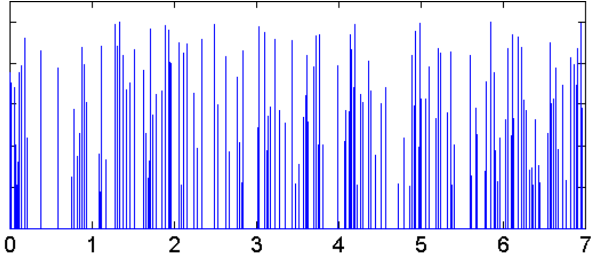
(a) Status of a generator with 90% availability, infrequent but extended outages. Time in months.



(b) Status of a generator with 90% availability, frequent but short outages. Time in months.



(c) Demand variation (taken from a four week period of actual PJM demand)..

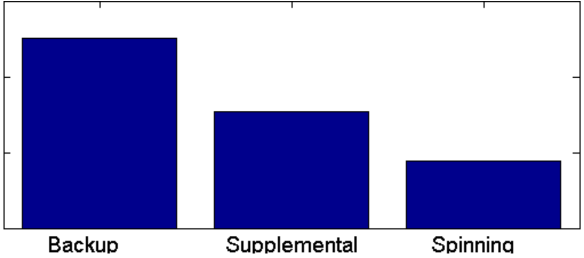


(d) Simulated arc furnace load over one week period.

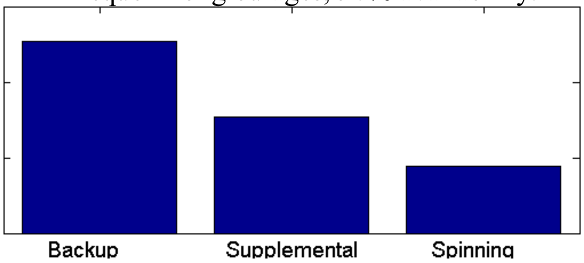
Figure 4: Time domain signals of interest.

It would be difficult to ascertain just how much reserves would be needed to meet each of these cases. In the simplest case, one could assume that one would need to be able to meet a “spinning reserve” capability sufficient to accommodate the loss of the larger generator. Likewise, one may need to keep enough spinning reserves to accommodate the largest excursion due to the arc furnace load. However, an alternative approach is to find the Fourier spectrum for each of these “signals” and to then determine which portion of the spectrum lies within the “range” of each specific reserve service category. For a regular periodic signal, analytic studies are possible. For the other signals, a numeric Fourier transform can be used.

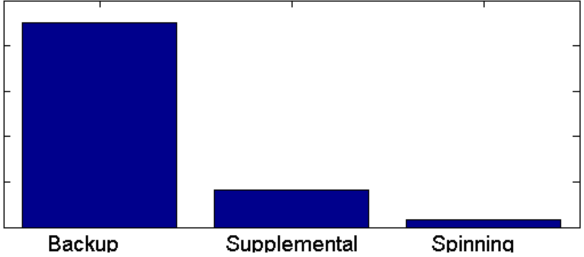
Once the spectrum if obtained it must be classified according to the energy content in each “frequency band.” Let Δt be the sampling rate of a signal and T be the total period of the signal. For the first two signals, T is 12 months. The sampling used was one minute. For the PJM demand the period T was four weeks and the sampling rate Δt 5 minutes. For the arc furnace, T is one week and Δt was 0.2 minutes. Let each sampled time domain signal be x. Let y=fft(x). The value $2\pi/T$ corresponds to the frequency of the second entry of y, y_2.



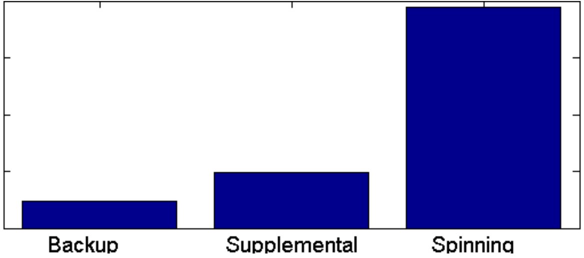
(a) Comparative reserve needs of generator with infrequent long outages, 90% availability.



(b) Comparative reserve needs, generator with frequent short outages and 90% availability.



(c) Reserve needs of a variable demand. In absolute terms, the values of these reserve needs are also smaller than those for a comparably sized generator.



(d) Comparative reserve needs for an arc furnace load.

Figure 5: Classified spectral content for the signals illustrated in Figure 4.

Let the number of samples x be $n=T/\Delta\tau$. The Nyquist (sampling) frequency corresponds to the mid-point of the spectrum of y with y_1 discarded since it corresponds to the dc bias of the signal. The bands for each reserve service are determined as a range of frequencies corresponding to a range of entries of y, according to the following criteria:

- Spinning reserves correspond to values of y from a sampling interval of 5 minutes all the way up to the sampling. The starting entry corresponds to a radian frequency 2π/5 Δτ. The final entry is the mid-point of y.
- Supplemental reserves range from a value of y corresponding to a radian frequency 2π/20 Δt up to the spinning reserve frequency.
- Backup reserves range from a sampling interval of 60 minutes to a sampling interval of 20 minutes.

To find the specific spectral content of the signal in each range, a summation is performed:

$$E = \sum_{i=w_{\min}}^{w_{\max}} |y_i|^2$$

The spectral content associated with each reserve band for each of the four sample signals is illustrated in Figure 5.

We thus observe that, comparatively speaking, the spinning reserve needs imposed on the system are relatively large and the supplemental and backup reserve needs are relatively modest. Conversely for the case of demand variation and for generation outages. In particular, ordinary demand variation requires very little spinning reserve.

Keep in mind during these observations that a generation outage requires a nontrivial amount of spinning reserve plus even larger amounts of supplemental and backup reserves. In other words, it is not enough to have reserves capable of meeting the initial needs of the generator outage, but also they must be sustainable over longer periods to be useful. This is not the case for the arc furnace load.

The values illustrated are only comparative values. The absolute values of the numbers also matter: the larger the generation unit, the larger all entries in all three bands get, and the same occurs for the other three types of reserve demand.

Spectral Analysis of Capabilities

In order to satisfy the needs for reserves as measured in the previous section, it is necessary to match each of the components of the spectral characteristics of every spectral demand component with a component capable of serving that need. That is, there must be sufficient ability to meet the reserve requirements. We consider six cases:

1. A unit capable of providing instantaneous response of 1 MW with arbitrary speed, and able to sustain the increased level of output indefinitely (or at least for one hour). This corresponds to the case of "regulation reserves" in Figure 1. In the frequency domain, such a unit is characterized as able to provide one unit of frequency response support in either the regulation, spinning or supplemental time frames. This is illustrated in Figure 6, left bars.
2. A unit capable of supplying 1 MW of response within the time designated for spinning reserves (in our case, 5 minutes) and sustaining this level of output indefinitely. This corresponds to the supplemental reserved trace in Figure 1. Such a unit is, in theory, unable to provide any regulation reserve, but can readily provide supplemental reserves. The frequency domain characteristics of this type of unit response are illustrated in Figure 6, middle bars.
3. A unit capable of supplying 1 MW of response in the time designated for supplemental reserves, in our case assumed to be 20 minutes. In addition to providing 1 MW of response in the supplemental time frame, this unit can in theory also provide 0.25 MW or reserves in the spinning time frame, but nothing in the regulation time frame. Also illustrated in Figure 6, right bars.
4. A unit capable of supplying 1 MW with arbitrary speed, but unable to sustain the output level into the spinning time frame (the case corresponding to Figure 3). Such a unit can provide 1 MW in the regulation time frame and nothing in the other two time frames. If we assume that the constraint is one on energy, however, in principle such a unit can provide up to 0.2857 MW of spinning reserve (a number that can be arrived at by comparing the "square area" of providing 1 MW for 5 minutes with the trapezoid defined by ramping up for 5 minutes followed by a sustained output for an additional 15 minutes). Likewise, the unit should be capable of providing an equivalent 0.1 MW of supplemental reserves. This frequency domain capability is illustrated in Figure 7, left bars.
5. A unit capable of supplying 1 MW within 5 minutes, and sustaining it up to 20 minutes. This unit cannot provide any regulation reserves, but can in principle provide 0.35 MW of supplemental energy. This is illustrated in Figure 7, middle bars.
6. Finally, a unit capable of providing 1 MW within 20 minutes and sustaining its output for one hour cannot provide any regulation, and in principle can provide up to 0.25 of pure spinning reserves. This is illustrated in Figure 7, right bars.

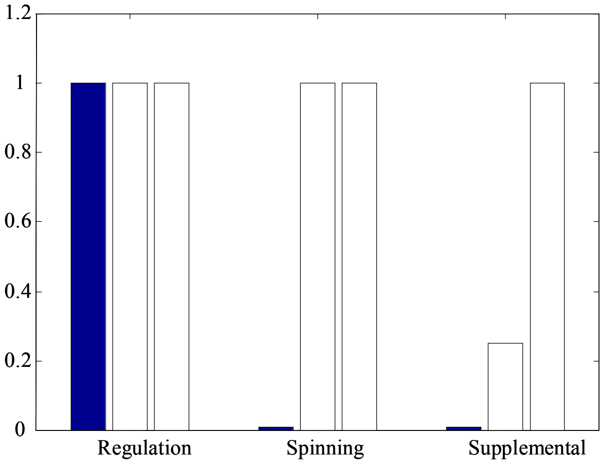


Figure 6: Spectral capabilities of three units based on a conventional characterization of reserve types.

The problem in the frequency domain then becomes one of matching the characteristics of the various units capable of providing reserve service with the requirements for reserves in the various portions of the frequency spectrum.

The above capabilities for reserve provision can be readily extended to take into consideration the role that demand can play in reserve provision.

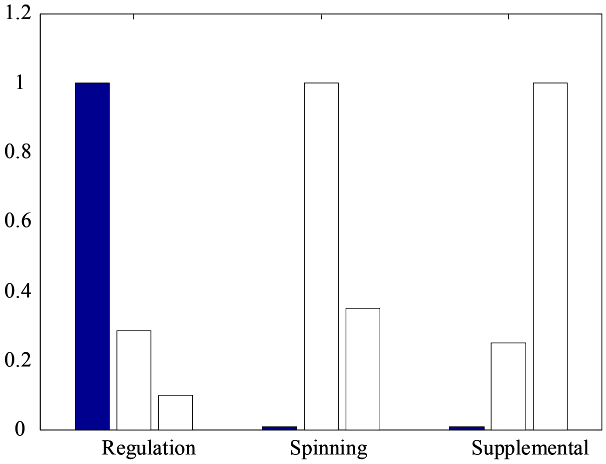


Figure 11: Spectral capabilities of three units based on energy-constrained characterization of reserve types.

Conclusions

The overall conclusions of this paper are:

- The distinction between backup, supplemental, spinning reserves and regulation depends on the nature of the variations.
- A complete non-overlapping separation among the various reserve types is possible by means of frequency domain (Fourier) techniques.
- Although the same methods are used for both generators and loads, the spectral characteristics of each are different.
- Availability alone is not sufficient to determine spectral content (and thus reserve type required). Mean time to failure information is also important.
- Changes in repair time (availability) have a significant effect on the need for backup reserves but have a negligible effect on the need for spinning reserves. Spinning reserves depend more on the failure rate.
- Reserve needs can be matched to reserve capabilities also in the frequency domain.

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