Solving The Crisis in Unscheduled Power

While NAESB and NERC struggle over the issue, North America steadily drifts toward unreliability.

BY ROBERT BLOHM

Time is running out. It's been more than two years since the North American Electric Reliability Council (NERC) Joint Inadvertent Interchange Taskforce (JIITF), on which I served, issued its white paper[1] proposing how to price the unscheduled power (inadvertent interchange)[1] flowing between NERC-certified balancing authorities (BAs). This was the first serious attempt ever to price the degree to which non-adherence to generation or load "schedules" helps or hurts keeping frequency within a reliable range of 60 Hz, which is the point where all the scheduled load exactly and instantly equals all the scheduled generation on an interconnected electric system.[2]

A year-and-a-half ago, NERC decided implementation and further development of the paper was a commercial matter and handed it to the North American Energy Standards Board (NAESB), which thus created the Inadvertent Interchange Payback Taskforce (IIPTF) on which I currently serve. But the IIPTF has made little progress in proposing a credible standard for paying for unscheduled power flows[3] between BAs because BAs will not or cannot override existing incentives for unscheduled behavior that is moving frequency away from, rather than toward, schedule (*see "Balancing Authorities: Caught in a Closing Vice," p. 66*).

The fundamental incompatibility between reliability and non-payment for unscheduled power is causing not only a reliability crisis in the form of upward frequency drift [2] and declining frequency support[3], but also a Sarbanes-Oxley financial reporting concern about unearned profit or unjustified costs due to taking or giving unscheduled power for free, which one big BA is already estimating the value of and deducting from its income statements. The total amount of scheduling error on the North American systems is worth many billions of dollars annually,[4] much of it never paid for but "accumulated" in BA accounts whose megawatt-hours are tracked by NERC. Less than a year from now, the Eastern interconnected system is set to violate NERC's upper average frequency limit and to experience widespread violation of the upper limit on BAs' control performance.

Not a Standard Commodity

Inadvertent interchange isn't a standard commodity transaction: It occurs without specific mutual consent. The total inadvertent interchange on an interconnected system always sums to zero because a single reading of a common meter on any tie-line is counted twice, once as one BA's outflow and again as the other BA's inflow. Since inadvertent interchange always clears, its price must be driven by something else. Furthermore, the NERC JIITF broke down unscheduled power into two parts: power at the hourly price of scheduled energy and an "unscheduled" part that is the average hourly contribution to frequency error, or the frequency contribution component (FCC). In the absence of an existing spot market, the cost basis of the BA's internal FERC Order No. 888/889 Schedule-4 "Energy Imbalance" tariff can serve as the energy price.[5]

If each BA pays or is paid its local energy price for the energy component of inadvertent interchange, under- or over-collection occurs. The price differences may tend to result in over-collection, because high price areas may tend to over-schedule generation or under-schedule load while low price areas may tend to under-schedule generation or over-schedule load. Occasional under-collection of revenue, like over-collection, would be redistributed by a NAESB-created settlement agent to all the interconnected system's BAs according to their share of inadvertent interchange. This ensures energy pricing that discourages congestion by inadvertent interchange [4].

True economic dispatch decisions for reliability are based not just on energy cost, but also on FCC cost (*see Table 1*). Two-part pricing of inadvertent interchange (into energy and FCC) makes the price of inadvertent interchange greater when there is under-frequency than when there is over-frequency (*see Table 2*).

Good FCC is the same as ancillary services deployed to offset bad FCC. The price and effectiveness of ancillary services reflects the speed at which they deploy, from the most expensive and most immediate—frequency response in seconds—to regulation in minutes, to operating reserves in 10 to 15 minutes, to load following in 30 minutes. Inadvertent interchange flows reflect the sudden loss of resources as well as the sudden deployment of resources.

TABLE 1 — ANCILLARY SERVICE DISPATCH DECISION

Table adapted from EnergyMark

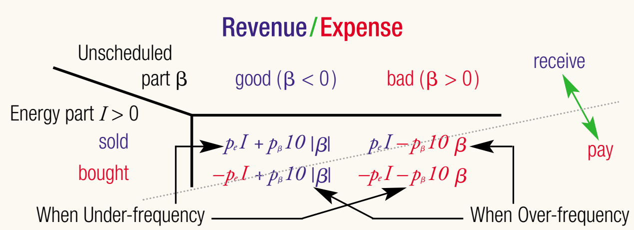
Marginal-Energy-Cost Not the Most Economic Basis for Reliability

- Three 500 MW Units with 5% Droop.
  - 5% Droop means
    - 100% of capacity needed to arrest freq. drop of 5% of 60 Hz = 3 Hz
    - Response Requirement of 10% of capacity (= 150 MW = 50 MW per gen.) to arrest conceivable .3 Hz freq. drop (= 0.5% of 60 Hz).
- Each Loaded to 425 MW
- Unit 1 – Incremental Price = $30/MWh
- Unit 2 – Incremental Price = $40/MWh
- Unit 3 – Incremental Price = $50/MWh
- How should a 75-MW increase in balancing energy be delivered?
- Alternative 1: Variable-cost Based Decision: load Unit 1 an additional 75MW.
  - Cost $2,250
  - Remaining resp. to next .3 Hz drop: 100 M ⇒
    - ⇒ only 2 available generators left @ 50 MW per generator = 1/3rd shortfall from response needed to arrest next frequency drop. Need to buy 500 MW of new excess capacity to make up the lost 50 MW of response
- Alternative 2: Capacity-cost Reliability Based Decision: load each unit an additional 25 MW.
  - Cost $3,000
  - Remaining resp. to next .3 Hz drop 150 MW ⇒
    - ⇒ all 3 generators available @ 50 MW per generator = No shortfall from the response needed to arrest next frequency drop

TABLE 2 — DUAL PRICING OF UNSCHEDULED ENERGY BETWEEN BALANCING AUTHORITIES:

-of energy, and
-of unscheduled part: contribution to control of frequency error

Ambiguity along the diagonal.
Diagonal occurs only when overfrequency.
Off-diagonals occur only when underfrequency.
This makes prices higher when underfrequency than when overfrequency.



Note $p_\beta 10\,|\beta| = |AVG(p_{I_t} I_t)|$, where I= Inadvertent Interchange

Proper pricing of FCC makes inadvertent interchange comply with good, random control and frequency performance inside the range allowed by NERC's control performance standard CPS1 (the "1" denoting 1-minute-average measurement of frequency).[6] That means a price that penalizes inadvertent interchange for making frequency deviate and rewards it for preventing frequency from deviating more. That price would be driven by the marginal cost of complying with CPS1.[7]

"-FCC" is the slope of a line summarizing the history of a BA's contribution to frequency. The NERC JIITF proposed this definition of FCC developed by Howard F. Illian [5], a member of the NERC JIITF and the NAESB IIPTF and a co-inventor of NERC's control performance standard CPS1. The line's slope is a frequency-error weighted two-dimensional average (*see Figure 1*) of the BA's hourly inadvertent interchange and the interconnected system's hourly frequency error as plotted in a two-dimensional scatter diagram of those points for all the hours in a month. The line is the ("regression") line ("forced") through the origin that is the least vertical-distance from those points. One month is chosen to get enough history and because the hourly data is all that is available to NERC and is reported to NERC only monthly. One month is also the interval at which NERC assesses CPS1 performance.

Since inadvertent interchange sums to zero across the interconnected system, the FCCs of all the BAs together sum to zero, which is the slope of a horizontal line through the origin that is the line whose slope is the entire system's FCC. That means the upward-sloping lines pay for each hour's[8] share of their positive slopes to the downward sloping lines (*see Figure 2*). Upward-sloping means inadvertent interchange (which is plotted along the y-axis) is more often than not in the same direction (positive or negative) as frequency error (which is

FIGURE 1 MEASURING A BA'S FCC

A Balancing Authority i's Frequency Contribution Component is the negative of a "2-dimensional average" of Inadvertent and Frequency-error each weighted by Frequency error.

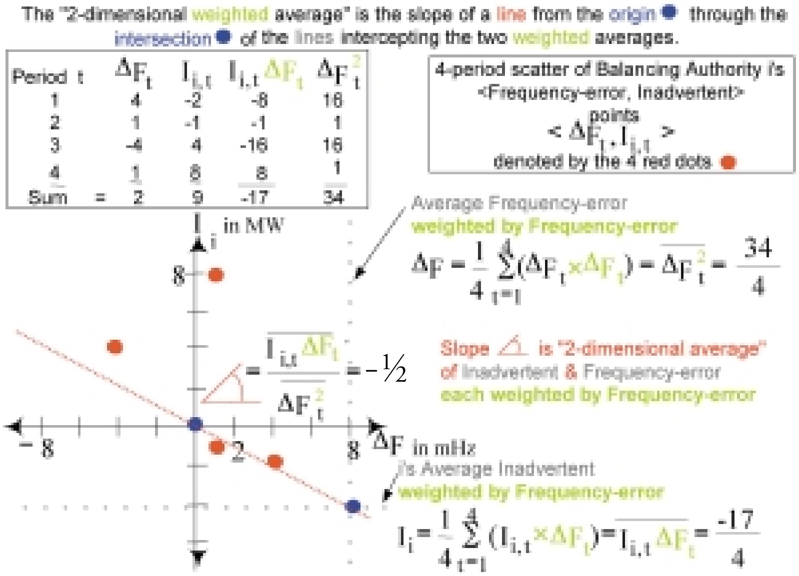
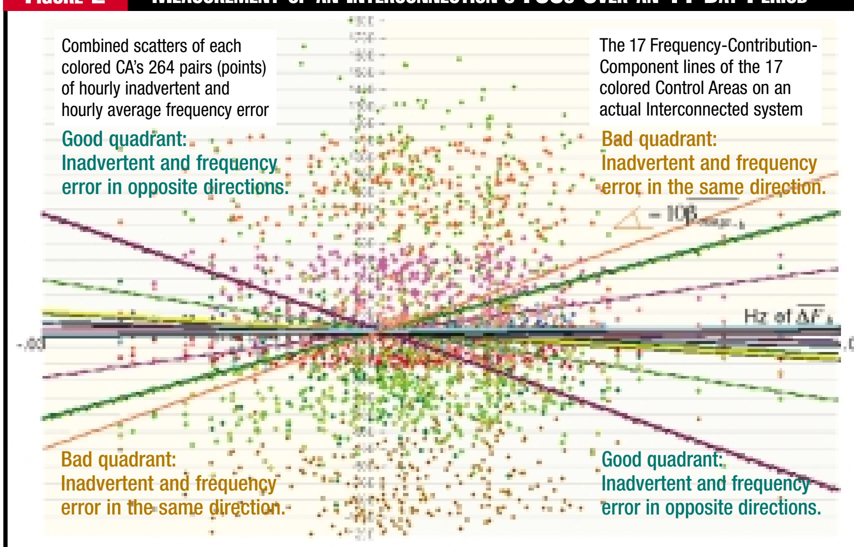


FIGURE 2 MEASUREMENT OF AN INTERCONNECTION'S FCCS OVER AN 11-DAY PERIOD



Upward slopes pay for their slopes to the Downward slopes and all lines' slopes add up to zero slope of horizontal line. Frequency Contribution Component always clears.

plotted along the x-axis) and, so, is contributing to the frequency error and is hurting frequency. Downward sloping means inadvertent interchange is on average in the direction oposite to frequency error and is preventing frequency error from being even larger; so, it is helping frequency.

The NERC control performance standard CPS1 measures individual BA performance (called ACE, for "Area Control Error") relative to the entire interconnected system's performance (measured by frequency error) by multiplying the two together and placing a limit on that product. CPS1 makes maximum efficient use of the benefit of interconnected operations [6-9]. ACE consists of the BA's inadvertent interchange (actually instantaneous "tie-line error" which is supposed to sum over an hour to inadvertent interchange) minus a "bias" obligation shared among all the BAs.[9] The red line in Figure 3 graphically depicts the limit set by CPS1 on the relationship between inadvertent interchange and frequency error.

Price Driven by NERC Compliance

Provided NERC has legislative power to levy a huge fine for noncompliance with CPS1, the price of FCC would be set by the procurement of good FCC to get compliant with CPS1. FCC exists either in the form of an ancillary services purchase on ancillary services markets, or as a component of the CPS1 equation.[10]

As an alternative to a huge NERC penalty at month's end, the trading of FCC to get compliant with CPS1 would drive a price for FCCs, just as the market for emission rights emerged as intended to avoid the huge Environmental Protection Agency (EPA) penalty for pollution that the EPA never actually collects. This makes a market for FCCs as much a NERC compliance mechanism as the SO_2 emission rights market is an EPA compliance mechanism. Controlled frequency, like clean air, is a public good needing a central authority to drive the market for error-rights.

To be consistent with CPS1, the price of FCC would vary as the square of frequency error. Equivalently, a frequency-contribution adder to the unit energy price of inadvertent interchange would vary as a fixed cash multiple of frequency error. This relationship, called "the Blohm formula"[11] in the NERC JIITF report ([1], pp. 8, 18), is required so that the FCC that is traded to be compliant with CPS1 can be considered "marginal" FCC. The relationship between FCC and CPS1, and the trading of FCC to get compliant with CPS1, are depicted graphically in Figure 4 for an interconnected system of 3 BAs identical to one another. The final equation in footnote 11 is also the monthly average of the hourly frequency-contribution value of inadvertent interchange and can be conveniently re-arranged[12] to get the hourly frequency-contribution unit price of inadvertent interchange: $p_{I_t} = -k\Delta F_t$, where p_{I_t} is the "frequency contribution price" per megawatt-hour of a BA's inadvertent interchange I_t at hour t, k is a monetary unit or alternatively some constant/fixed unit price per megawatt-hour-Hertz, and ΔF_t is the frequency deviation at hour t. This price is an "adder" to the hourly energy unit price of inadvertent interchange. No separate calculation or pricing of FCC is needed.

Before NERC gets legislative empowerment and a market emerges for trading FCC or inadvertent interchange, the NERC JIITF white paper recommends setting the FCC price by administratively applying the Blohm formula. This is equivalent to applying the simple formula above. But first constant monetary unit k needs to be estimated on some cost basis; then these formulas need to be tested in an economics laboratory simulation of actual trading of FCC or inadvertent interchange by control operators to ensure the formula mimics the actual price behavior in a market where FCC or inadvertent interchange is traded to get CPS1 compliant. There is strong mathematical reason to believe it would.

Trading of FCC or inadvertent interchange by BAs for CPS1 compliance serves as a reference point and guide to the emergence of markets for the trading of ancillary services as options where operators seek to set their optimum scheduling point between tending to underschedule and tending to overschedule. The NERC JIITF methodology is scalable to apply to the generating and load entities within BAs, and it sets the groundwork for a market in "control services" whereby good operators can market their capability. But the JIITF methodology is open enough that it doesn't require BAs to apply it to their own constituent generating or load entities.

No Real-Time Reliability Incentive From Spot-Energy Markets

Unscheduled power occupies the interface between markets and reliability; real-time is the proper domain for management of honest scheduling error, not for markets for energy. A market for FCC is the only market needed for incenting reliable behavior. Markets for energy alone do not efficiently

FIGURE 3 NERC'S CONTROL PERFORMANCE STANDARD USED FOR PRICING FCC

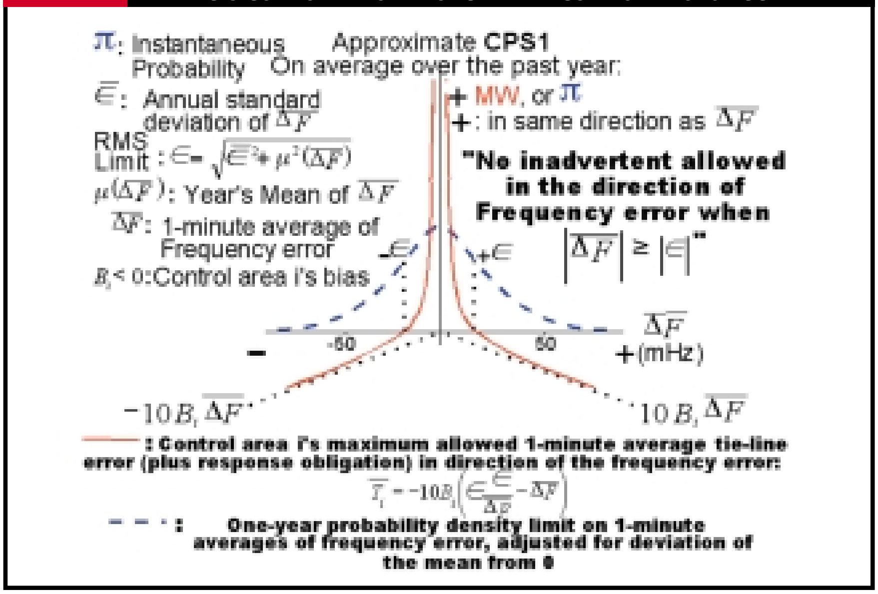
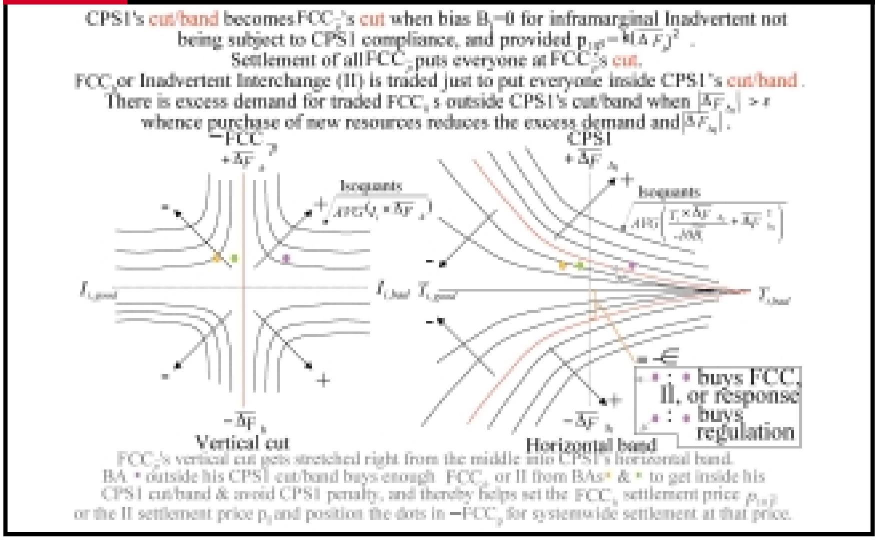


FIGURE 4 PRICING FCC BY TRADING CPS1 DEVIATION RIGHTS.



Balancing Authorities:
Caught in a Closing Vice

In its *1999-2008 Reliability Assessment*, the North American Electric Reliability Council (NERC) documented how a power marketer (Enron) had purchased more than 20 power plants in the Southeastern United States. Enron wanted to form 3 "generation only" control areas so the company could deliberately create unscheduled power and benefit commercially from the NERC rule allowing a control area or balancing authority (BA) to pay back only in-kind accumulations of unscheduled power it has taken from the rest of the interconnected system. Unscheduled power taken when price and frequency are high may be paid back when price and frequency are low but, since payback is not enforced, unscheduled power tends to be "parked" and not even paid back. NERC admitted that market pricing of scheduled energy thereby made payback-in-kind, let alone parking, untenable both from an equity point of view and from a reliability point of view.

Some Midwestern BAs several times have taken unscheduled power at high-price periods from other BAs that were never paid back the economic value of that power. Indeed, the California market meltdown may be attributed in significant part to improper pricing of unscheduled power in regulators' very poorly thought-out "spot-energy" market design and crisis management, as may the legal effort to nullify subsequent imprudent contracts governments signed with Enron, which elected to take unseemly advantage, rather than complain, of the pricing flaws that shouldn't have been there in the first place.

From Bad Connections to Worse

BAs signed bad connection agreements with independent power producers (IPPs) and merchant generators, drafted by lawyers only and sanctioned by FERC, that specify energy only, none of the ancillary services that support frequency, no ramping rate, no charge for hurting frequency, and no payment for supporting frequency. As a result, merchants and IPPs, now accounting for 20 percent of this country's power, chronically disable governors, generate to a constant thermal rate, and over-generate in early morning hours for as little as -$100 a MWhr for a few hours to avoid $20,000-$30,000 in startup costs. This is reflected in chronic overgeneration such as by the Mid-Atlantic Area Council (MAAC) and Southwest Power Pool (SPP).

Also, the asymmetry of NERC-sanctioned payback-in-kind itself, like energy-only pricing, upward-biases frequency by rewarding over-frequency through both rewarding the over-generation that drives over-frequency and penalizing the under-generation that counters over-frequency. At the same time, it doesn't penalize under-frequency: It neither penalizes the under-generation or over-consumption that drives under-frequency nor rewards the over-generation that counters under-frequency. [NERC hasn't helped matters any by making its Disturbance Control Standard (DCS) since 1997 unidirectional to require deployment of reserves to recover only from under-frequency events, thereby incenting BAs to overgenerate to make the unidirectional recovery easier. DCS is mercifully being superseded in NERC's new draft Balancing Standard.]

Passing the buck to the interconnection creates a vicious reliability and financial/accounting circle. Rather than override the incentives for their constituent entities to over-generate, or bear the economic consequence of mindless IPP and merchant interconnection agreements, BAs "push" unscheduled power for free onto other BAs that are forced to take it for free by under-generating to keep frequency from drifting even higher and to keep their control performance from violating the NERC limit on frequency-deviation-weighted average contribution to frequency deviation. As a result either (A) inadvertent interchange accumulates as frequency creeps upward because the other BAs don't under-generate enough to keep up, or (B) inadvertent interchange stops accumulating but frequency creeps upward even more because BAs hurt their control performance by stopping frequency support or by unscheduled payback in kind of the accumulated power (notably in the Southeastern Electric Reliability Council). The Midwest ISO's Control Area Working Group has vigorously complained recently to NERC about this [11].

Patch-Up "Solutions" Backfire

ERCOT (the Electric Reliability Council of Texas) attempted to avert this problem by "killing the patient" only to create a new problem. The moment Texas introduced its market in August 2001, ERCOT centralized control by simply eliminating control areas (and therefore inadvertent interchange but not scheduling error) and thereby eliminating the frequency-stabilizing benefit of multiple entities' mutually offsetting control efforts. Average frequency deviation quickly widened in violation of ERCOT's ±23 mHz limit, forcing NERC to grant an indefinite waiver to ±30 mHz over some objections including mine, and ERCOT is now close to exceeding that limit, having experienced a May 2003 blackout along the way.

Meanwhile the Western Electricity Coordinating Council (WECC) through Bonneville has attempted a non-pricing "technical" solution to the problem of accumulation of unscheduled flows between BAs by invoking "automatic time-error correction" or immediately prompting extended unilateral payback of inadvertent interchange in staggered small increments. The small size of these increments keeps them from overly disturbing frequency but bears no relation to economic value. This automatically creates new inadvertent interchange to pay back the old inadvertent interchange, doubling the errors while removing only the accumulation motivation behind the frequency deterioration trend. The Western "solution" is a "best efforts" voluntary unaudited frequency control regime that unnecessarily overrides and is much costlier than and mathematically inconsistent[1] with NERC's control performance standard CPS1, and this has already led one complaining Western BA to be granted occasional exemption. It still leaves opportunity for unfair financial gain from unpriced unscheduled power.

Furthermore, the NERC Resources Subcommittee is in the process of confirming whether correcting time-error is an obsolete service in the contemporary world of DC digital clocks. It's become just unfeasible in the Eastern Interconnection[2] where it used to be done only monthly, then became weekly, and now has to be done daily by NERC, soon becoming the proverbial boy without enough fingers to plug the holes in the dyke fast enough.

Meanwhile, the indiscriminate FERC energy-imbalance tariff on BAs' constituents worsens frequency performance. The NERC JIITF white paper [1] does not prescribe pricing for the energy part of inadvertent interchange, other than to specify including a "transmission loading (congestion) component." But it does reject the old FERC Order No. 888/889 Schedule 4 & 5 "energy imbalance" tariffs for prescribing a single percentage penalty on the energy price both to the provider and to the taker of all "imbalance energy" regardless of whether the "imbalance energy" helps or hurts frequency. The JIITF rejected the FERC tariffs also for applying only outside a megawatt deadband where clearing is often mathematically impossible, or outside a frequency deadband that contains practically all the inadvertent that continues to accumulate or be paid back in kind inequitably and unreliably and to fuel the upward-frequency-drift crisis.

A WECC representative reported to me that the indiscriminate penalty of the FERC energy imbalance tariffs has been prompting generators in the Western Interconnection to disable the governors on their units, thereby actually exacerbating the West's governor response deterioration and the high cost to BAs of complying with auto time-error correction. One big Eastern BA formally has asked NERC for relief from high control costs due to the ineffectiveness of the FERC energy imbalance tariff on the behavior of its constituent generators.—***R.B.***

Endnotes

1. See end of endnote 9 on p. 68.
2. See end of endnote 1 on p. 67.

incent behavior that is compatible with good frequency control. Moreover, allowing suppliers to increase real-time risk by taking real-time energy delivery risks in an energy-only spot market winds up unfairly penalizing customers if there are no resources available.

Robert Blohm, a co-author of the NERC Joint Inadvertent Interchange Payback Taskforce's White Paper on pricing unscheduled power, has also contributed to NERC's current draft "Balancing Resources and Demand" frequency control standard. He is listed in "Who's Who in America." His Web site is http://www.geocities.com/blohm_r. Contact him at rb112@columbia.edu.

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Endnotes

1. Inadvertent interchange is the unscheduled power flowing between BAs. Some of the BA's unscheduled power that is caused by the BA is immediately "countered" by energy the BA is obligated to provide in the opposite direction (called "bias" or a fixed percent share of the combined BAs' scheduling errors at that moment) by instantaneous response by governors that instantaneously change the generator speed, or by instantaneous adjustment by non-resistive loads. This response (called "primary response") limits the size of the frequency error but does not correct the frequency error. The BA's "net inadvertent interchange with the rest of the interconnected system" is the amount by which the BA's scheduling error differs from the BA's instantaneous or "primary" response to the frequency error provided the BA is exactly meeting the BA's primary response obligation. Inadvertent interchange that later corrects the frequency error is called "secondary response." The secondary response normally would be provided by the BA that made the scheduling error, but often never is. When it isn't it is socialized among all the BAs in interconnected systems except the Western in a procedure called "time-error correction," in which performance is measured against "scheduled frequency" that is temporarily shifted away from 60 Hz in the direction of the desired response.
2. Why is unscheduled power a reliability issue? Because momentary errors in the schedules which balance supply and demand are unavoidable and occur only in electricity, unlike any other commodity. The sum of all the BAs' scheduling errors at any moment is reflected in the deviation of the interconnected system's electrical frequency from target, normally 60 Hz, and is "made up for" by unscheduled power provided to the BAs by themselves or by other BAs. Too much frequency deviation can harm equipment and make blackouts more likely. Scheduling errors used to be more like random noise, but market pricing of scheduled power, while unscheduled power is given/had "for free," makes them occur deliberately and makes them occur more when they contribute to frequency error, than when they correct frequency error.
3. The NAESB IIPTF has correctly agreed to settlement only of a BA's net inadvertent interchange with the rest of the interconnected system over all the BA's tie-lines, not the flow on an individual tie-line. This means that only inadvertent interchange that a BA is the physical generator of or consumer of is counted for settlement purposes, not inadvertent interchange that is "passed through" from a second party to a third

party. In other words, only "source" or "sink" inadvertent interchange is explicitly settled, not unscheduled loop flow, which is more of a transmission usage issue than a frequency control issue but whose cost does get reflected in the energy/congestion part of the price of "source" or "sink" net inadvertent interchange. This both is economical in terms of the number of settlements to consider but also conforms to the inadvertent interchange data collected by NERC.

4. The annual "energy" value alone is over a third of a billion dollars but the reserve/control cost (discussed later) is many times that. The energy value for the Eastern Interconnection is derived from an average frequency error of 11.76 mHz converted to 353 MW. That's a "variance" of 353^2. Divided by a simplifying assumption of 20 large BAs, that's 6,230 MW^2 per BA, or a mean absolute error of 79 x .85=67 MW per BA. Times 20 BAs, times the hours in a year, times $25 per MWh, we get $293 million. This calculation was suggested by Howard Illian. The Western Interconnection is a quarter the size of the Eastern with fewer BAs and a smaller average frequency error, while ERCOT is less than half the size of the Western Interconnection with one BA and double the frequency error of the Eastern Interconnection. Utilities typically value reserve for control operations at nearly 20 percent of capital cost.

5. The NERC JIITF actually decomposed the energy price into an uncongested price and a "transmission loading component" price for congestion, with both prices usually combinable into a single locational energy price. It is not the role of inadvertent interchange pricing to mandate the formation of markets for scheduled energy or congestion, but simply to use whatever local/native scheduled-energy price/cost information is available to settle the energy component of inadvertent interchange.

6. Inadvertent interchange must be priced when performance is inside the CPS1 limit. Otherwise, once the energy component is priced, there's no incentive to help frequency, nor disincentive from hurting frequency, by scheduling or not within the range CPS1 allows for unscheduled power, and there's a disincentive from providing governor response that limits the amount of frequency error per megawatt of aggregate scheduling error on the system. (The steady decline in governor response in the North American interconnections since deregulation has been documented in [3].) Unless inadvertent interchange is subject to compliance-driven pricing/settlement, then everyone allows the amount of frequency error per megawatt to increase to the point where everyone drifts toward the edge of the allowable performance range (where compliance becomes increasingly expensive) and average frequency error continues having a tendency as it has today, when it should have no tendency: drifting toward the upper bound of its CPS1 limit (±18 mHz on the Eastern Interconnection, ±30 mHz in ERCOT).

7. All FCC shares the price of getting compliant with CPS1. If all BAs are near their CPS1 limits enabling one BA to tip the entire interconnected system over the frequency limit, then the FCC of the inadvertent interchange of all the BAs that put the interconnected system near the frequency limit should be assessed the price the tipping BA had to pay to bring his performance into CPS1 compliance.

8. While FCC is a one-month average, it is decomposable to an hourly amount thus:

$$FCC_i = -\frac{AVG(I_i \times \Delta F)}{AVG(\Delta F)^2} = AVG\left(-\frac{I_i \times \Delta F}{AVG(\Delta F)^2}\right), \text{ where}$$

$-\frac{I_i \times \Delta F}{AVG(\Delta F)^2}$ is BA i's actual hourly FCC amount.

9. The CPS1 equation. BA i's bias obligation $10B_i$ is to instantaneously respond to (mainly by governor action) and contain a given amount of frequency error ΔF by instantly providing a given amount of megawatts in the opposite direction determined by $10B_i\Delta F$, which is a negative number times the frequency error.

BA i's CPS1: On average over a year, $\frac{ACE_i}{-10B} \times \Delta F \leq \frac{B_i}{B} \epsilon^2$, where
- dividing BA i's ACE by minus the system "bias" -10B converts megawatts to Hertz,
- B_i/B is BA i's obligation's percentage share of minus the system bias, and therefore
- $\frac{B_i}{B} \epsilon^2$ is BA i's share of the ϵ^2 limit that is placed on system frequency error $\pm\Delta F$ when all the BAs' CPS1 equations are summed up into the entire interconnected system's CPS1.

The interconnected system's CPS1: On average over a year $(\Delta F)^2 \leq \epsilon^2$, where
- ϵ is ± 18 mHz on the Eastern interconnected system,
- since all the inadvertents sum to zero. [*Mathematical violation by Western Interconnection*. This "summability of ACEs" is violated by the Western Interconnection's "automatic time-error correction" explained in the sidebar.]

10. The CPS1 equation can be rearranged (per [10], section 9, pp. 7-9) to show FCC as a component of it thus:

$\frac{\beta_i - b_i}{-b} AVG(\Delta F)^2 \leq \epsilon^2$, where
- $-\beta_i$ is BA i's FCC in MW per 10th of a Hertz
- $-b_i$ is a least-squares estimator of minus BA i's bias obligation $-B_i$ (in MW per tenth of a Hertz).

11. "The Blohm formula" estimate of price of FCC in order for FCC settlement to be consistent with CPS1. Since it's not being directly subject to compliance, the non-marginal ("infra"-marginal) FCC is not directly subject to the bias obligation b_i and the frequency band $\pm\epsilon$ that the marginal is. Therefore, for the non-marginal FCC, $-b_i = 0$ and the rearranged CPS1 equation in footnote 10 above collapses to: $\beta_i AVG(\Delta F)^2 \leq 0$.

Expanding $10\beta_i$ into its definition [Figure1] makes the CPS1 equation for infra-marginal FCC become:

$$\frac{AVG(T_i \times \Delta_F)}{\cancel{AVG}(\Delta_F)^2} \cancel{AVG(\Delta} F)^2 \leq 0$$

$$AVG(T_i \times \Delta_F) \leq 0, \qquad (1)$$

where T_i is BA i's tie-line error. If the FCC price (by "the Blohm formula")

$p_{10\beta} \overset{?}{\approx} k \times (\Delta F)^2$, with some constant monetary unit k>0, then the monthly-average of the hourly *value* of FCC is

$$FCC \times p_{10\beta} = -10\beta_i \times p_{10\beta} = -\frac{AVG(I_i \times \Delta F)^2}{\cancel{AVG(\Delta} F)^2} \times k \times \cancel{AVG(\Delta} F)^2 = FCC_p$$

which reduces to $-k \times AVG(I_i \times \Delta F) = FCC_p$, (2)

where I_i is BA i's inadvertent interchange. In other words, when a BA i's non-marginal FCC is good on average, $FCC_p \geq 0$, which is equivalent to compliance with the CPS1 equation (1) above for infra-marginal FCC. Those with $FCC_p < 0$ are paying to those whose $FCC_p > 0$ to get into compliance with the CPS1 equation (1). Indeed, even if BA i is CPS1 compliant at the margin but its $FCC_p < 0$ because the BA is hurting frequency on average, the BA is contributing infra-marginally to any other BA's non-compliance with CPS1 and should therefore bear a cost.

12. While FCC_p is a one-month average, it is decomposable to an hourly amount thus: By equation (2) in footnote 11 above

$FCC_p = -k \times AVG(I_i \times \Delta F) = AVG_t(I_{i_t} \times -k\Delta\bar{F}_t)$,

where $I_{i_t} \times -k\Delta\bar{F}_t$ is BA i's actual FCC_p for hour t.