Why and How of Power System Frequency Control

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Rotating System Dynamics and Kinetic Energy Exchange

How does a load get served, on being connected

- At the instant of connection (gen dip), load exceeds generation
- The energy consumed by this new load is served from the Kinetic Energy of the rotating system, slowing the system
- The frequency of the system dips, losing Kinetic Energy

Reverse happens when generation added (load is lost)

- At the instant of generation addition, generation exceeds load
- Surplus energy gets stored as Kinetic Energy in the rotating system by way of its increased speed (frequency)
- The frequency of the system increases, gaining Kinetic Energy

With no other corrective dynamics the change in frequency would be perpetual!
Load Power
Dependence on Frequency

- Each load device has a definite relationship of its power consumption to the supply frequency
  - The drive speed the varies in direct relation to frequency.
  - Power consumption in some loads are immune to frequency, e.g. incandescent lamps, resistance heaters, VFD

- Power consumption in various motive loads is dependent on frequency, to varying degree
  - Let us take for instance, the agricultural pump set.
  - An induction motor driven, centrifugal pump, with no control
  - Discharges into an open channel
Load Power Dependence on Frequency

Pump power variation with frequency:

**Output Power 'P' of the pump = k x H x Q,**

Where,

\[ H = k_1 x N^2 \quad \& \quad Q = k_2 x N \]

Hence,

\[ P = k k_1 k_2 x N^3 \]

Thus, the pump power varies as the 3\(^{rd}\) power of speed or frequency

\[ P = k' k_1 k_2 x f^3 \]
Changing the Generated Power with Frequency

- Load is perpetually changing and is not controllable
- Load generation balance achieved only by real time corrections in generation
  - To be more accurate, specify at the “target frequency”!
  - Physics relating to energy balance will be satisfied naturally!
- The simple and reliable indicator (in real time!) of this balance is thus \textit{frequency constancy}
  - Generation control must correct any frequency change
- Two types of load / generation mismatch events
  - Slow and small load changes are perpetually present
  - Large mismatches created by say, generating unit trip out
Changing the Generated Power with Frequency

- The slow changes best addressed by modulating a few generating units carrying reserve for this purpose
  - Controlled by the LDC pulse tele-command by operator or automated by AGC/ALFC
  - Every Generating Unit has provision for accepting remote “raise” / “lower” pulse commands for this purpose
  - Can maintain frequency constant, under normal operation
  - Such a control, known as ‘Supplementary’ or ‘Secondary’ Control, acts perpetually to maintain frequency constant.
  - Machines carrying Governor Control margin preserve the same for the other kind of large load / generation mismatch
Changing the Generated Power with Frequency

Dealing with large and abrupt frequency changes:

- Secondary Control too slow and ineffective for the urgent need of quick delivery of large quantum of generation.
- The requirement can only be met by globally increasing the output of all the machines in the system automatically.
- All / most of the generating units to perpetually carry this control margin.
- Quick delivery is achieved by the Governor Control.
- Once this control margin is delivered, it has to be withdrawn, thus reclaiming the control margin for the next event.
- This restorative correction is also by Secondary Control, acting to restore frequency to the original (target) value.
Why Constant Frequency?

- Constant Frequency does not mean a loose band!
- Constancy, within the Governor Dead Band (± 0.015Hz), prevents oscillatory “racing” of generators
- Oscillatory interaction caused by the governors responding at different speed to frequency change
  - Steam machines (non-reheat type) are fastest
  - Propeller type hydro machines are slowest
  - All other types fall in between
- In hydro machines, initial response to valve opening is reduction in power output!
  - Till penstock flow readjusts, overcoming hydraulic inertia
Why Constant Frequency?

Let us examine what happens in an 80,000 MW two utility power pool if target frequency is not stipulated!
SAMPLE TWO UTILITY POWER POOL, 80,000MW

STATE: NORMAL, 
Freq. = 49.80Hz

UTILITY
“ALPHA”
\[ P_L = 50,000 \text{ MW} \]
\[ P_G = 49,000 \text{ MW} \]

UTILITY
“BETA”
\[ P_L = 30,000 \text{ MW} \]
\[ P_G = 31,000 \text{ MW} \]
STATE: NORMAL,  
Freq. = 49.85Hz

SAMPLE TWO UTILITY POWER POOL, 80,160MW

UTILITY
“ALPHA”
$P_L = 50,100 \text{ MW}$
$P_G = 49,000 \text{ MW}$

UTILITY
“BETA”
$P_L = 30,060 \text{ MW}$
$P_G = 31,160 \text{ MW}$

$1,100\text{MW}$
Why Constant Frequency?

- The pool load grows to 80,160MW (with frequency)
  - Alpha serving 50,100MW and Beta serving 30,060MW.
- Operating frequency change marginally to 49.85Hz.
- Generation becomes 49,000MW and 31,160MW
- The net exchange 1,100MW. (Is it over-drawal?)
- Assuming the incremental cost of generation in Beta as Rs 1/kWh and the UI rate as Rs 3.93/kWh,
  - Beta earns Rs 233,000/- each hour (Rs 5,592,000/- per day)
  - Alpha, pays Rs 393,000/- each hour (Rs 9,432,000/- per day).
- What benefit has accrued to the pool and to Alpha in particular?
  - Frequency changed from one target frequency of 49.80Hz to another target frequency of 49.85Hz!
SAMPLE TWO UTILITY POWER POOL

STATE: NORMAL,
Freq. = 49.80Hz

UTILITY
“ALPHA”
\[ P_L = 50,000 \text{ MW} \]
\[ P_G = 49,000 \text{ MW} \]

UTILITY
“BETA”
\[ P_L = 30,000 \text{ MW} \]
\[ P_G = 30,000 \text{ MW} \]
STATE: NORMAL,
Freq. = 49.85Hz

SAMPLE TWO UTILITY POWER POOL

UTILITY
“ALPHA”
\( P_L = 50,100 \text{ MW} \)
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UTILITY
“BETA”
\( P_L = 30,060 \text{ MW} \)
\( P_G = 30,000 \text{ MW} \)

IPP

\( 1,160 \text{ MW} \)

\( 1,100 \text{ MW} \)
Why Constant Frequency?

- In this case, both Alpha and Beta suddenly find themselves over-drawing 100MW and 60MW respectively;
- Was the change desirable?
  - The frequency increases marginally from one acceptable operating frequency (49.80Hz) to another acceptable operating frequency (49.85Hz)!
- Alpha and Beta end up paying to the IPP Rs 393,000/- and Rs 235,800/- respectively, in each hour,
- The IPP pockets Rs 468,800/- each hour! In one day the IPP pockets Rs 11,251,000/-
- Who benefitted? Who lost?
Why Constant Frequency?

- What if Beta decides to make its UI zero?
  - It can either increase generation or reduce load, both acceptable, as there is no target frequency
  - If Beta increases generation, the quantum required is far in excess of 60MW
    - Alpha will find itself drawing more and more UI without having done anything to be so penalized!
  - If Beta were to shed load, it will have to shed far in excess of 60MW!
    - Alpha finds itself drawing more UI without having done anything at all!
Load / Generation / Frequency
Integrated Dynamics

Load Governing

- In steady state, power released by the existing loads alone serves the newly connected load.
- Kinetic energy exchange limited to the transient period alone.
- This effect is sometimes referred to as “Load Governing” denoted as a parameter “D” having units of MW/Hz.
- By rule of thumb,
  \[ 1\% \Delta f \approx 1 - 2\% \Delta P_L. \]
- 1.0Hz frequency change will result in 2 – 4% Load power change.
- The exact value is of no great significance!
Supplementary Control (Secondary Control)

- The perpetual small changes in frequency corrected by delivering (or withdrawing) Secondary Control Margin
- Can be manually ordered or automated as Automatic Generation Control (AGC)
- LDC operator delivered control impossible in multi utility pools, due to the additional control need of net exchange
- Single utility systems like England and South Africa use manual control but power pools in USA and Europe use AGC
- Supplementary Control Margins can be exhausted; can be replenished by quick starting generators (e.g. Gas Turbines) or by Demand Side Management (DSM)
Governor Control (Primary Control)

- Governor control is a proportional control which changes its output in the inverse linear proportion of change in frequency.
- Governor control margin is carried on as many machines as possible (*disregarding economics*).
- Incapable of restoring the frequency to the target value.
- The control margin remains delivered so long as the frequency error ($\Delta f$) exists.
- Machines with smaller speed regulation (droop) will share relatively larger proportion of the change, in steady state.
Governor Control (Primary Control)

- Speed Regulation (droop) is represented as “(-) $1/R$”, a characteristic parameter of the generating unit / system.
- Negative sign signifies the decrease of generated power with increase in frequency.
- "$R" has the unit Hz/MW.
- Speed regulation (droop) defined as the change in Frequency required for causing 100% change in MW output.

$$\Delta P_G = (-) \frac{1}{R} \times \Delta f$$
GOVERNOR CHARACTERISTICS

Diagram depicting the governor characteristics with axes for frequency (Hz) and power (% MCR). The graph shows multiple lines indicating different power levels at various frequency points.
Complementary Effect of Frequency Response: Area Frequency Response Characteristic (AFRC)

\[ \beta = D + \frac{1}{R}, \]

Where, \( \beta \) is the AFRC (composite Area Frequency Response Characteristic).

In the case of our sample system,

\[ \beta = (3200 + 32000) = 35200 \text{ MW/Hz} \]

The steady state frequency decline following the 800MW unit tripping event would be:

\[ \Delta f = - \frac{800\text{MW}}{35200\text{MW/Hz}} = -0.02273\text{Hz} \]

The corresponding Governor control delivery is

\[ \Delta P_G = (-) \frac{1}{R} \times \Delta f = (-) 0.02273\text{Hz} \times (-) 32000\text{MW/Hz} \]

\[ = 727.4\text{MW} \]
Governor Control Margin for the next event?

- Governors act to deliver the margin carried and holds
- The slow Supplementary Control (Automatic or otherwise) commences delivery restoring the frequency to target value
- As frequency starts moving towards its target value, the governor control margins, starts being withdrawn, as the frequency error ($\Delta f$) decreases
- As the supplementary control restores frequency to the target value, the frequency error ($\Delta f$) becomes zero and the delivered governor control margins are fully withdrawn.
Typical time frame of delivery of control margins

- Typically 100% governor control margin is delivered within the first 60 seconds of the event
- Some Grid Codes mandate 66.6% in 30 seconds
- Expected to hold up to 15/30 minutes (allows boiler firing to be changed)
- Supplementary control in contrast is expected to deliver 100% margin, during the same event within 15/30 minutes
Ideal Frequency Control Strategy

Reproduced from the report datelined December 2002
“Frequency Control Concerns In The North American Electric Power System”
by CERTS on behalf of the California Energy Commission
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Thank You!