System Security and Ancillary Services

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Introduction

• Electricity markets rely on the power system infrastructure
• Participants have no choice to use a different system
• Cost to consumers of outages is very high
• Consumer have expectations for continuity of service
• Cost of this security of supply must match its benefit
System security

• System must be able to operate continuously if situation does not change

• System must remain stable for common contingencies
  ♦ Fault on a transmission line or other component
  ♦ Sudden failure of a generating unit
  ♦ Rapid change in load

• Operator must consider consequences of contingencies

• Use both:
  ♦ Preventive actions
  ♦ Corrective actions
Preventive actions

- Put the system in a state such that it will remain stable if a contingency occurs
- Operate the system at less than full capacity
- Limit the commercial transactions that are allowed
Corrective actions

• Taken only if a disturbance does occur
• Limit the consequences of this disturbance
• Need resources that belong to market participants
  • Ancillary services that must be purchased from the market participants by the system operator
• When called, some ancillary services will deliver some energy
  • However, capacity to deliver is the important factor
• Remuneration on the basis of availability, not energy
Outline

• Describe the needs for ancillary services
  • Keeping the generation and load in balance
  • Keeping the security of the transmission network

• Obtaining ancillary services
  • How much ancillary services should be bought?
  • How should these services be obtained?
  • Who should pay for these services?

• Selling ancillary services
  • Maximize profit from the sale of energy and ancillary services
Needs for ancillary services
Balancing production and consumption

- Assume that all generators, loads and tie-lines are connected to the same bus
- Only system variables are total generation, total load and net interchange with other systems
Balancing production and consumption

• If production = consumption, frequency remains constant
• In practice:
  ◦ Constant fluctuations in the load
  ◦ Inaccurate control of the generation
  ◦ Sudden outages of generators and interconnectors
• Excess load causes a drop in frequency
• Excess generation causes an increase in frequency
Balancing production and consumption

• Generators can only operate within a narrow range of frequencies
  ✷ Protection system disconnects generators when frequency is too high or too low
  ✷ Causes further imbalance between load and generation
• System operator must maintain the frequency within limits
Balancing production and consumption

- Rate of change in frequency inversely proportional to total inertia of generators and rotating loads
- Frequency changes much less in large interconnected systems than in small isolated systems
- Local imbalance in an interconnected system causes a change in tie-line flows

Inadvertent flow
Balancing production and consumption

- Inadvertent flows can overload the tie-lines
- Protection system may disconnect these lines
- Could lead to further imbalance between load and generation
- Each system must remain in balance
Balancing production and consumption

- Minor frequency deviations and inadvertent flows are not an immediate threat
- However, they weaken the system
- Must be corrected quickly so the system can withstand further problems
Example: load over 5 periods
Example: energy traded
Example: energy produced
Example: imbalance
Example: imbalance with trend

Imbalance [MW]

Random load fluctuations

Slower load fluctuations

Outages

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Example (continued)

• Differences between load and energy traded:
  ♦ Does not track rapid load fluctuations
    • Market assumes load constant over trading period
  ♦ Error in forecast

• Differences between energy traded and energy produced
  ♦ Minor errors in control
  ♦ Finite ramp rate at the ends of the periods
  ♦ Unit outage creates a large imbalance
Balancing services

- Different phenomena contribute to imbalances
- Each phenomena has a different time signature
- Different services are required to handle these phenomena
- Exact definition differ from market to market
Regulation service

• Designed to handle:
  ◆ Rapid fluctuations in load
  ◆ Small, unintended variations in generation

• Designed to maintain:
  ◆ Frequency close to nominal
  ◆ Interchanges at desired values

• Provided by generating units that:
  ◆ Can adjust output quickly
  ◆ Are connected to the grid
  ◆ Are equipped with a governor and usually are on AGC
Load following service

• Designed to handle intra-period load fluctuations
• Designed to maintain:
  ♦ Frequency close to nominal
  ♦ Interchanges at desired values
• Provided by generating units that can respond at a sufficient rate
Reserve services

• Designed to handle large and unpredictable deficits caused by outages of generators and tie-lines

• Two main types:
  ♦ Spinning reserve
    • Start immediately
    • Full amount available quickly
  ♦ Supplemental reserve
    • Can start more slowly
    • Designed to replace the spinning reserve

• Definition and parameters depend on the market
Classification of balancing services

• Regulation and load following services:
  - Almost continuous action
  - Relatively small
  - Quite predictable
  - *Preventive* security actions

• Reserve services:
  - Use is unpredictable
  - *Corrective* security actions
  - Provision of reserve is a form of *preventive* security action
Example: Outage of large generating unit
Network issues: contingency analysis

• Operator continuously performs contingency analysis
• No credible contingency should destabilize the system
• Modes of destabilization:
  ♦ Thermal overload
  ♦ Transient instability
  ♦ Voltage instability
• If a contingency could destabilize the system, the operator must take preventive action
Types of preventive actions

• Low cost preventive actions:
  • Examples
    • Adjust taps of transformers
    • Adjust reference voltage of generators
    • Adjust phase shifters
  • Effective but limited

• High cost preventive actions:
  • Restrict flows on some branches
  • Requires limiting the output of some generating units
  • Affect the ability of some producers to trade on the market
Example: thermal capacity

- Each line between A and B is rated at 200 MW
- Generator at A can sell only 200 MW to load at B
- Remaining 200 MW must be kept in reserve in case of outage of one of the lines
Example: emergency thermal capacity

• Each line between A and B is rated at 200 MW
• Each line has a 10% emergency rating for 20 minutes
• If generator at B can increase its output by 20 MW in 20 minutes, the generator at A can sell 220 MW to load at B
Example: transient stability

• Assumptions:
  ♦ B is an infinite bus
  ♦ Transient reactance of A = 0.9 p.u., inertia constant H = 2 s
  ♦ Each line has a reactance of 0.3 p.u.
  ♦ Voltages are at nominal value
  ♦ Fault cleared in 100 ms by tripping affected line
• Maximum power transfer: 108 MW
Example: voltage stability

- No reactive support at B
  - 198 MW can be transferred from A to B before the voltage at B drops below 0.95 p.u.
  - However, the voltage collapses if a line is tripped when power transfer is larger than 166 MW
- The maximum power transfer is thus 166 MW
Example: voltage stability

- 25 MVAr of reactive support at B
  - 190 MW can be transferred from A to B before the outage of a line causes a voltage collapse
Voltage control and reactive support services

• Use reactive power resources to maximize active power that can be transferred through the transmission network

• Some of these resources are under the control of the system operator:
  - Mechanically-switched capacitors and reactors
  - Static VAr compensators
  - Transformer taps

• Best reactive power resources are the generators

• Need to define voltage control services to specify the conditions under which the system operator can use these resources
Voltage control and reactive support services

• Must consider both normal and abnormal conditions
• Normal conditions:
  ✷ 0.95 p.u. ≤ V ≤ 1.05 p.u.
• Abnormal conditions:
  ✷ Provide enough reactive power to prevent a voltage collapse following an outage
• Requirements for abnormal conditions are much more severe than for normal conditions
• Reactive support is more important than voltage control
Example: voltage control under normal conditions

- Load at B has unity power factor
- Voltage at A maintained at nominal value
- Control voltage at B?
Example: voltage control under normal conditions

**Active Power Transfer [MW]**

**Reactive Power Injection [MVAr]**

- **Voltage at B**
- **Reactive injection at B**

Voltage at B

Reactive injection at B
Example: voltage control under normal conditions

- Controlling the voltage at B using generator at A?

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- Local voltage control is much more effective
- Severe market power issues in reactive support
Example: reactive support following line outage

- Post-contingency reactive power injection at bus B
- Power Transfer [MW]
- Post-contingency reactive power injection [MVAr]
Example: pre- and post-contingency balance

Pre-contingency:

Post-contingency:
Other ancillary services

• Stability services
  ♦ Intertrip schemes
    • Disconnection of generators following faults
  ♦ Power system stabilizers

• Blackstart restoration capability service
Obtaining ancillary services
Obtaining ancillary services

• How much ancillary services should be bought?
• How should these services be obtained?
• Who should pay for these services?
How much ancillary services should be bought?

• System Operator purchases the services
  ◆ Works on behalf of the users of the system
• Services are used mostly for contingencies
  ◆ Availability is more important than actual usage
• Not enough services
  ◆ Can’t ensure the security of the system
  ◆ Can’t maintain the quality of the supply
• Too much services
  ◆ Life of the operator is easy
  ◆ Cost passed on to system users
How much ancillary services should be bought?

• System Operator must perform a cost/benefit analysis
  - Balance value of services against their cost
• Value of services: improvement in security and service quality
• Complicated probabilistic optimization problem
• Should give a financial incentive to the operator to acquire the right amount of services at minimum cost
How should services be obtained?

• Two approaches:
  ♦ Compulsory provision
  ♦ Market for ancillary services

• Both have advantages and disadvantages

• Choice influenced by:
  ♦ Type of service
  ♦ Nature of the power system
  ♦ History of the power system
Compulsory provision

• To be allowed to connect to the system, generators may be obliged to meet some conditions

• Examples:
  ♦ Generator must be equipped with governor with 4% droop
    • All generators contribute to frequency control
  ♦ Generator must be able to operate from 0.85 lead to 0.9 lag
    • All generators contribute to voltage control and reactive support
Advantages of compulsory provision

• Minimum deviation from traditional practice
• Simplicity
• Usually ensures system security and quality of supply
Disadvantages of compulsory provision

• Not necessarily good economic policy
  ♦ May provide more resources than needed and cause unnecessary investments
    • Not all generating units need to help control frequency
    • Not all generating units need to be equipped with a stabilizer

• Discourages technological innovation
  ♦ Definition based on what generators usually provide

• Generators have to provide a costly service for free
  ♦ Example: providing reactive power increases losses and reduces active power generation capacity
Disadvantages of compulsory provision

• Equity
  ♦ How to deal with generators that cannot provide some services?
    • Example: nuclear units can’t participate in frequency response

• Economic efficiency
  ♦ Not a good idea to force highly efficient units to operate part-loaded to provide reserve
  ♦ More efficient to determine centrally how much reserve is needed and commit additional units to meet this reserve requirement

• Compulsory provision is thus not applicable to all services

• How to deal with exceptions that distort competition?
Market for ancillary services

• Different markets for different services
• Long term contracts
  - For services where quantity needed does not change and availability depends on equipment characteristics
  - Example: blackstart capability, intertrip schemes, power system stabilizer, frequency regulation
• Spot market
  - Needs change over the course of a day
  - Price changes because of interactions with energy market
  - Example: reserve
• System operator may reduce its risk by using a combination of spot market and long term contracts
Advantages of market for ancillary services

• More economically efficient than compulsory provision
• System operator buys only the amount of service needed
• Only participants that find it profitable provide services
• Helps determine the true cost of services
• Opens up opportunities for innovative solutions
Disadvantages of market for ancillary services

• More complex
• Probably not applicable to all types of services
• Potential for abuse of market power
  ♦ Example: reactive support in remote parts of the network
  ♦ Market for reactive power would need to be carefully regulated
Demand-side provision of ancillary services

• Creating a market for ancillary services opens up an opportunity for the demand-side to provide ancillary services

• Unfortunately, definition of ancillary services often still based on traditional practice

• In a truly competitive environment, the system operator should not favour any participant, either from the supply- or demand-side
Advantages of demand-side provision

• Larger number of participants increases competition and lowers cost

• Better utilization of resources
  
  ♦ Example:
    
    • Providing reserve with interruptible loads rather than partly loaded thermal generating units
    
    • Particularly important if proportion of generation from renewable sources increases

• Demand-side may be a more reliable provider
  
  ♦ Large number of small demand-side providers
Opportunities for demand-side provision

- Different types of reserve
  - Interruptible loads
- Frequency regulation
  - Variable speed pumping loads
Who should pay for ancillary services?

• Not all users value security and quality of supply equally
  • Examples:
    • Producers vs. consumers
    • Semi-conductor manufacturing vs. irrigation load

• Ideally, users who value security more should get more security and pay for it

• With the current technology, this is not possible
  • System operator provides an average level of security to all users
  • The cost of ancillary services is shared by all users on the basis of their consumption
Who should pay for ancillary services?

• Sharing the cost of ancillary services on the basis of energy is not economically efficient

• Some participants increase the need for services more than others

• These participants should pay a larger share of the cost to encourage them to change their behaviour

• Example: allocating the cost of reserve
Who should pay for reserve?

• Reserve prevents collapse of the system when there is a large imbalance between load and generation
• Large imbalances usually occur because of failure of generating units
• Owners of large generating units that fail frequently should pay a larger proportion of the cost of reserve
• Encourage them to improve the reliability of their units
• In the long term:
  - Reduce need for reserve
  - Reduce overall cost of reserve
Selling ancillary services
Selling ancillary services

• Ancillary services are another business opportunity for generators

• Limitations:
  ♦ Technical characteristics of the generating units
    • Maximum ramp rate
    • Reactive capability curve
  ♦ Opportunity cost
    • Can’t sell as much energy when selling reserve
    • Need to optimize jointly the sale of energy and reserve
Example: selling both energy and reserve

- Generator tries to maximize the profit it makes from the sale of energy and reserve

- Assumptions:
  - Consider only one type of reserve service
  - Perfectly competitive energy and reserve markets
    - Generator is a price-taker in both markets
    - Generator can sell any quantity it decides on either market
  - Consider one generating unit over one hour
    - Don’t need to consider start-up cost, min up time, min down time
  - No special payments for exercising reserve
Notations

\( \pi_1 \) : Market price for electrical energy (£/MWh)

\( \pi_2 \) : Market price for reserve (£/MW/h)

\( x_1 \) : Quantity of energy bid and sold

\( x_2 \) : Quantity of reserve bid and sold

\( P^{\text{min}} \) : Minimum power output

\( P^{\text{max}} \) : Maximum power output

\( R^{\text{max}} \) : Upper limit on the reserve (ramp rate x delivery time)

\( C_1(x_1) \) : Cost of producing energy

\( C_2(x_2) \) : Cost of providing reserve (not opportunity cost)
Formulation

Objective function:

\[ f(x_1, x_2) = \pi_1 x_1 + \pi_2 x_2 - C_1(x_1) - C_2(x_2) \]

Constraints:

\[ x_1 + x_2 \leq P^{max} \]

\[ x_1 \geq P^{min} \]

\[ x_2 \leq R^{max} \] \hspace{1cm} \text{(We assume that } R^{max} < P^{max} - P^{min} \text{)}

Lagrangian function:

\[ \ell(x_1, x_2, \mu_1, \mu_2, \mu_3) = \pi_1 x_1 + \pi_2 x_2 - C_1(x_1) - C_2(x_2) \]

\[ + \mu_1 (P^{max} - x_1 - x_2) + \mu_2 (x_1 - P^{min}) + \mu_3 (R^{max} - x_2) \]
Optimality conditions

\[ \frac{\partial l}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \]

\[ \frac{\partial l}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \]

\[ \frac{\partial l}{\partial \mu_1} \equiv P^{\text{max}} - x_1 - x_2 \geq 0 \]

\[ \frac{\partial l}{\partial \mu_2} \equiv x_1 - P^{\text{min}} \geq 0 \]

\[ \frac{\partial l}{\partial \mu_3} \equiv R^{\text{max}} - x_2 \geq 0 \]
Complementary slackness conditions

\[ \mu_1 \cdot (P_{max} - x_1 - x_2) = 0 \]

\[ \mu_2 \cdot (x_1 - P_{min}) = 0 \]

\[ \mu_3 \cdot (R_{max} - x_2) = 0 \]

\[ \mu_1 \geq 0; \mu_2 \geq 0; \mu_3 \geq 0 \]
Case 1: $\mu_1 = 0; \mu_2 = 0; \mu_3 = 0$

- No binding constraints

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \Rightarrow \frac{dC_1}{dx_1} = \pi_1
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \Rightarrow \frac{dC_2}{dx_2} = \pi_2
\]

- Provide energy and reserve up to the point where marginal cost is equal to price

- No interactions between energy and reserve
Case 2: $\mu_1 > 0; \mu_2 = 0; \mu_3 = 0$

- Generation capacity fully utilized by energy and reserve:

$$x_1 + x_2 = P^{\text{max}}$$

$$\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0$$
$$\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0$$

$$\pi_1 - \frac{dC_1}{dx_1} = \pi_2 - \frac{dC_2}{dx_2} = \mu_1 \geq 0$$

- Marginal profit on energy equal to marginal profit on reserve
Case 3: $\mu_1 = 0; \mu_2 > 0; \mu_3 = 0$

- Unit operates at minimum stable generation

\[ x_1 = P_{\text{min}} \]

\[ \frac{\partial l}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \quad \Rightarrow \quad \frac{dC_1}{dx_1} - \pi_1 = \mu_2 \]

\[ \frac{\partial l}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \quad \Rightarrow \quad \frac{dC_2}{dx_2} = \pi_2 \]

- Marginal profit on reserve
- Marginal loss on energy minimized by operating at minimum
- KKT conditions guarantee only marginal profitability, not actual profit
Cases 4 & 5: $\mu_1 > 0; \mu_2 > 0; \mu_3 = 0$ \hspace{1em} $\mu_1 > 0; \mu_2 > 0; \mu_3 > 0$

$\mu_1: x_1 + x_2 \leq P^{max}$

$\mu_2: x_1 \geq P^{min}$

$\mu_3: x_2 \leq R^{max}$

Since we assume that $R^{max} < P^{max} - P^{min}$ these cases are not interesting because the upper and lower limits cannot be binding at the same time.
Case 6: $\mu_1 = 0; \mu_2 = 0; \mu_3 > 0$

• Reserve limited by ramp rate

$$x_2 \leq R^{\text{max}}$$

$$\frac{\partial l}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \quad \Rightarrow \quad \frac{dC_1}{dx_1} = \pi_1$$

$$\frac{\partial l}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \quad \Rightarrow \quad \pi_2 - \frac{dC_2}{dx_2} = \mu_3$$

• Maximum profit on energy

• Profit on reserve could be increased if ramp rate constraint could be relaxed
Case 7: \( \mu_1 > 0; \mu_2 = 0; \mu_3 > 0 \)

- Maximum capacity and ramp rate constraints are binding

\[
\begin{align*}
x_1 + x_2 &= P_{\text{max}} \\
x_2 &= R_{\text{max}}
\end{align*}
\]

\[
\begin{align*}
\pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 &= 0 \\
\pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 &= 0
\end{align*}
\]

- Sale of energy and sale of reserve are both profitable
- Sale of reserve is more profitable but limited by the ramp rate constraint
Case 8: $\mu_1 = 0; \mu_2 > 0; \mu_3 > 0$

- Generator at minimum output and reserve limited by ramp rate
  
  $$x_1 = P^{\text{min}}$$
  $$x_2 = R^{\text{max}}$$

\[
\frac{\partial \ell}{\partial x_1} \equiv \pi_1 - \frac{dC_1}{dx_1} - \mu_1 + \mu_2 = 0 \quad \Rightarrow \quad \pi_1 - \frac{dC_1}{dx_1} = -\mu_2
\]

\[
\frac{\partial \ell}{\partial x_2} \equiv \pi_2 - \frac{dC_2}{dx_2} - \mu_1 - \mu_3 = 0 \quad \Rightarrow \quad \pi_2 - \frac{dC_2}{dx_2} = \mu_3
\]

- Sale of reserve is profitable but limited by ramp rate constraint
- Sale of energy is unprofitable
- Overall profitability needs to be checked