Power Management issues in Smart Grid

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Outline

- What is SmartGrid?
- Need of SmartGrid
- Research areas in SmartGrid applied to distribution system
- Research areas in SmartGrid applied to Transmission system
- Optimal placement of PMU
- Introduction to electricity market
- Energy Management Systems (EMS)
What is SmartGrid ?...
What is SmartGrid ?...

**Definition from IEEE Website**

- The smart grid has come to describe a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy.

**Electrical power grid consist of:**

- Transmission network (High Voltage like 400kV, 220kV, 132kV etc)
- Distribution network (Low Voltage like 33kV, 11kV, 440V)

**What is "Smart Grid" from the perspective of distribution system ?**

- A two way digital communication to facilitate the delivery of power to users and control the appliances at home to save electricity and manage peak demand.
- Presence of smart meter and sensors in the network to monitor the various parameters of the distribution network
What is Smart Grid?

Characteristics of smart grid:

- Integrated, automated communication between components of the electric grid.
- Sensing and measurement technologies.
- Automated controls for distribution and repairs.
- Improved management dashboards and decision support software.
Why we need SmartGrid?

We need SmartGrid to address the problems associated with:

- Complexity of modern distribution and transmission systems
- Integration of renewable source of energies
- Optimal operation of distribution and transmission systems
- Distributed storage of electrical energy such as Electric Vehicle etc
Smart Grid for Distribution Systems
Empowering the customer with choice and control:

- Demand based traffic
- Choice to utilize the distributed/renewable energy sources
- Prepaid metering
- Optimal scheduling and control of the operation of home appliances
- Monitoring and mitigating the power quality

Providing security and safety management:

- Energy Theft
- Tamper detection
- Monitoring and estimating the average energy requirements
- Analysis the interruption and usage pattern to know and forecast the load profile
- Remote isolation of supply to insure safety
Incorporating distributed storage:

- Li-ion battery
- Fuel cell
- Plasma/ thermal storage
- Plug in Hybrid Electric Vehicle

Facilitating new program and capabilities:

- Demand response program
- Load management program
- Distributed generation (solar, wind, etc)
- Automatic meter reading (AMR)
- Remote Service Switch
- System Cyber Security
What is SmartGrid ?...
Important research areas in SmartGrid (Distribution Systems)

- Advanced metering infrastructure & Meter data management
- Geographical information systems (GIS)
- Customer Relationship management, Utility portals and Demand response
- Distributed storage such as electric vehicle
- Modulation of power requirements of large customer to improve the stability of Grid
- Power line communication
- Design of Intelligent Terminal Unit (ITU)
- Integration of renewable energy and Micro-Grid
- Reconfiguration of Grid to improve its reliability and performance
- Distribution Automation and Cyber security
Wide area monitoring systems (WAMS) provides the smartness to the transmission systems
Why we need GPS Synchronized time pulse?

- Common Reference Signal at remote locations possible due to GPS synchronization.
Wide Area Monitoring Systems (WAMS)(Contd...)

Load Flow Analysis:
- offline method of calculating the voltage and angle at the bus
- solve the set of nonlinear power balance equations
- Supervisory Control and Data Acquisition (SCADA):

Estimated voltage phasors are available with the time interval of about 5 minutes.
- Not suitable for observing the system under transient conditions.
Wide Area Monitoring Systems (WAMS) (Contd...)

- Phasor Measurement Units (PMUs) based WAMS

- Time synchronized phasor data with very high accuracy
- Provides the phasor with a interval down to 20 ms
- Suitable for observing the system under transient conditions
- Applicable for real time control and protection
PMU provides, time sampled phasor data with a phasor rate of 25 or 50 phasors/second for a 50 Hz System.
**IRIG-B**: The IRIG-B signal is a time code containing the 1PPS signal, second minute and hours of the day, the day of the year, the year and the time of the day.
Wide Area Monitoring Systems (WAMS) (Contd...)

<table>
<thead>
<tr>
<th>FORMAT</th>
<th>SIGNAL NO.</th>
<th>TIME FRAME RATE</th>
<th>CARRIER FREQUENCY F</th>
<th>SIGNAL BIT RATE ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A130,132 133</td>
<td>10 per sec.</td>
<td>10 kHz</td>
<td>1 kpps</td>
</tr>
<tr>
<td>B</td>
<td>B120,122 123</td>
<td>1 per sec.</td>
<td>1 kHz</td>
<td>100 pps</td>
</tr>
<tr>
<td>D</td>
<td>D111,112 121,122</td>
<td>1 per hr.</td>
<td>100 Hz 1 kHz</td>
<td>1 ppm 1 ppm</td>
</tr>
<tr>
<td>E</td>
<td>E111,112 121,122</td>
<td>6 per min.</td>
<td>100 Hz 1 kHz</td>
<td>10 pps 10 pps</td>
</tr>
<tr>
<td>G</td>
<td>G141,142</td>
<td>100 per sec.</td>
<td>100 kHz</td>
<td>10 kpps</td>
</tr>
<tr>
<td>H</td>
<td>H111,112 121,122</td>
<td>1 per min.</td>
<td>100 Hz 1 kHz</td>
<td>1 pps 1 pps</td>
</tr>
</tbody>
</table>
Wide Area Monitoring Systems (WAMS)(Contd...)
Wide Area Monitoring Systems (WAMS) (Contd...)

- Research in synchrophasor based WAMS
  - Protection and Control
  - Voltage Stability Prediction
  - Frequency Stability Prediction
  - Rotor Angle Estimator
  - Transient Angular Stability Prediction
  - Small Signal Stability Analysis
  - Wide area based control design
  - Dynamic Phasor Estimation
  - State estimation and bad data processing
  - Optimal PMU placement
Power system consists of large number of buses, the measurement quantities associated with them are voltage, current, power and frequency.

Observability of system requires, that the estimation of voltage and angle of each bus using these measurements. One way is to place the PMU at each bus, but since, PMU is a costly device, hence, it is required to be placed optimally to make system observable:

- Measurements can be made on the same bus
- Measurements of the bus can be made by its neighboring buses which are connected directly hence estimation can be made
Let us first define the observability of system.

A system is called observable when its states can be determined uniquely by given set of measurements.

Two types Observability can be defined for analyzing power systems:

**Topological:** In this type of observability, the system is observable topologically.

**Numerical:** In this type of observability, the system is observable in topology as well as have numerical observability.

For example: A linear state estimation model is given as

\[ z = Hx + e \]

If H is a singular matrix then the system is numerically unobservable.
Optimal PMU placement problem can be solved by graph theoretic approach along with observability index. The methods for PMU placement are based on:

- **Exhaustive search:** In this method all combinations are tested and then minimum number of PMUs are selected to make system observable, but this method is not suitable for a vast interconnected power system due to large number of buses involved in a power system, resulting in huge computational complexity.

- **Conventional techniques for optimization in another way for placing PMUs and which utilizes integer programming, linear programming and quadratic programming.**

- **Use of computational intelligence in PMU placement.**
Most of the old power systems are equipped with SCADA systems, which can be used along with PMUs measurements to get more information about systems. System measurements are of two types

- PMU measurements which consists of voltage magnitude and angle of buses and current injection and outgoing currents of buses with phase information. These measurements are also used to estimate the voltages of neighboring buses. With this type of measurements, the system state estimator will be linear.

- Conventional SCADA measurements are such as active and reactive powers and voltage magnitude.
In literature, several methods have been proposed for placement of PMUs in a power system.

We will look at a method in which we first find the theoretical upper bound on the number of PMUs in a system required for the observability of the system, and try to reduce number of PMUs by one and check for observability (Binary search algorithm).

The basis steps involved in this process are as follows:

1. Identification of candidate location for PMU placement.
2. The theoretical upper bound of the maximum number of PMUs necessary to make the system observable.
This basic flow chart is shown in figure.
Large Measurement redundancy: Let the measurement redundancy of the \( i^{th} \) combination solution for PMU placed be defined as

\[
R_i = \begin{bmatrix} r^i_1 & r^i_2 & \ldots & r^i_N \end{bmatrix} \quad \forall \ i = 1, 2, \ldots N_{sol}
\]

The elements of big connecting matrix \( A \) for this type of formulation of optimum PMU placement are defined as

\[
A(i,j) = \begin{cases} 
1 & \text{if } i = j \\
1 & \text{if bus } i \text{ is connected to bus } j \\
0 & \text{else}
\end{cases}
\]

The computation of \( A \) matrix is shown in figure (1). \( x \) vector is also defined as the

\[
x(i) = \begin{cases} 
1 & \text{if PMU is placed at that bus} \\
0 & \text{else}
\end{cases}
\]
A matrix for this system is (This can be obtained by admittance matrix converting nonzero entries to 1 and else 0)

\[
A = \begin{bmatrix}
1 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 \\
1 & 0 & 1 & 1 \\
0 & 1 & 1 & 1
\end{bmatrix}
\]

The placed PMU matrix

\[
x = [1 \ 0 \ 1 \ 0]^T
\]

Figure: 4 bus system for illustration
Objective function $V(x)$ for optimization is formulated as integer quadratic problem

$$V(x) = \lambda (N - Ax)^T R (N - Ax) + x^T Q x$$  \hspace{1cm} (1)$$

Here

$\lambda \in \mathbb{R}$ is weight which is chosen according to conditions

$N \in \mathbb{R}^n$ is a vector representing the upper limits of the number of times that each bus is observed by the placement of PMUs.

$x^T Q x$ represents the cost associate with placement of PMU

Objective is to minimize the $V(x)$.

$$V(x) = \lambda N^T R N - 2 \lambda N^T R A x + \lambda x^T A^T R A x + x^T Q x$$

$$V(x) = \frac{1}{2} x^T (2 \lambda A^T R A + 2 Q) x + (-2 \lambda N^T R A) x + \lambda N^T R N$$  \hspace{1cm} (2)$$
Optimal PMU Placement (Contd...)

Last term is constant hence can be eliminated in formulating optimization problem. So, complete optimization problem is

\[
\min \left( \frac{1}{2} x^T G x + L^T x \right) \text{ such that } A x \geq b
\]

Here, \( G = 2\lambda A^T R A + 2Q, \) \( L = (-2\lambda N^T R A)^T, \) and \( b = I^{n \times 1}. \)

\( x^T Q x \) is the cost associated with PMU and \( x^T 2\lambda A^T R A x \) is redundancy.
In above expressions, N represents maximum upper bound for redundancy. If a bus is connected to 3 near buses, in that case N=4 is chosen for more security of the system.

- Loss of single transmission line
  In this case matrix A will change according to new connections of buses.

- Loss of PMU
  In this case $b_2 = 2 \times I^{N \times 1}$ in optimization constraint.
Optimal PMU Placement (Contd...)

Topological placement of PMUs using integer programming. In integer programming, the optimization problem is formulated as follows

$$\min \sum_{j=1}^{N} C_j \mu_j \quad \text{such that} \quad f(\mu) \geq 1$$

Here, $C_j$ is the cost associated with PMU placement at bus $j$ and

$$\mu_j = \begin{cases} 
0 & \text{if PMU is not placed as bus } j \\
1 & \text{if PMU is placed as bus } j 
\end{cases}$$
For this 7 bus system, formulation of optimal PMU placement is done as follows:

Figure: 7 Bus system for Optimal PMU placement problem
Example of 7 bus systems: Cost Function:

\[ \min \sum_{j=1}^{7} C_j \mu_j \]

The optimization constraints in next slide ...
Constraints

\[
\begin{align*}
 f_1 & : \mu_1 + \mu_2 \geq 1 \\
 f_2 & : \mu_1 + \mu_2 + \mu_3 + \mu_6 + \mu_7 \geq 1 \\
 f_3 & : \mu_2 + \mu_3 + \mu_4 + \mu_6 \geq 1 \\
 f_4 & : \mu_3 + \mu_4 + \mu_5 + \mu_7 \geq 1 \\
 f_5 & : \mu_4 + \mu_5 \geq 1 \\
 f_6 & : \mu_2 + \mu_3 + \mu_6 \geq 1 \\
 f_7 & : \mu_2 + \mu_4 + \mu_7 \geq 1
\end{align*}
\]

If cost association of PMU placement is known, then these constraints can be solved along with optimization problem to generate optimal PMU placement.
Introduction to Game Theory
Introduction to game theory

What is game theory?

- It evolves the formal study of decision-making, where several players must make their choices that potentially affect the interests of the other players.

Basic Concepts of Game Theory:

- **Players:** Players are independent decision-makers who influence the development of a game through their decisions.
- **Nodes:** As a game proceeds, various states of the game are identified as nodes.
- **Move:** A move allows the game to evolve from a well-defined state to another and therefore may indicate sequentiality.
- **Pay-offs:** A payoff is a development of the game that the players value for itself according to their respective preferences.
Game Theory and Information Systems:

- The internal consistency and mathematical foundations of game theory make it a prime tool for modeling and designing automated decision-making processes in interactive environments.

- As a mathematical tool for the decision-maker the strength of game theory is the methodology it provides for structuring and analyzing problems of strategic choice.

Nash Equilibrium:

- A set of strategies is a Nash equilibrium if no player can do better by unilaterally changing his or her strategy.
Introduction to game theory...

Some frequently used notations:

<table>
<thead>
<tr>
<th>Players</th>
<th>$i, j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategies</td>
<td>$s_i, s_j$</td>
</tr>
<tr>
<td>Set of all strategies</td>
<td>$S$</td>
</tr>
<tr>
<td>Strategy profile</td>
<td>$s$</td>
</tr>
<tr>
<td>Pay-off</td>
<td>$U_i(s_1, s_2, \ldots, s_N) = U_i(s)$</td>
</tr>
<tr>
<td>Strategy choice of everyone except $i^{th}$ player</td>
<td>$s_{-i} \implies U_i(s_1, s_2, \ldots, s_N) = U_i(s_i, s_{-i})$</td>
</tr>
</tbody>
</table>
Introduction to game theory...

**Prisoner Dilemma:**

- 2 years of prison for drugs
- if you confess, other does not, you get 1 year of prison and other 10
- if you deny, and other confess, you get 10 years of prison and other 1 year
- if both confess, both get 3 years each.

**Pay-off matrix:**

<table>
<thead>
<tr>
<th></th>
<th>Harry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Confess</td>
</tr>
<tr>
<td>Peter</td>
<td></td>
</tr>
<tr>
<td>confess</td>
<td>3,3</td>
</tr>
<tr>
<td>confess</td>
<td>10,1</td>
</tr>
</tbody>
</table>
Introduction to electricity market

Type of Contracts:

- **Pool Contract (Through bids)**
  - Single Auction Model or Double Auction model may be used for fixing the Market Clearing Price.
  - Generally pool contact are made one day a head.

- **Bilateral / Multi lateral Contracts**
  - Bilateral ⟷ Between a single buyer and a single supplier.
  - Multilateral ⟷ Between a group of buyers and a group of suppliers.
  - They should inform System Operator (SO) about the contract.

Note: Most of the markets are allowing both types of contract.
Introduction to electricity market

<table>
<thead>
<tr>
<th>Generator’s bidding</th>
<th>Buyer ‘s Biding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Price/ kWh</td>
</tr>
<tr>
<td>G1</td>
<td>100</td>
</tr>
<tr>
<td>G2</td>
<td>200</td>
</tr>
<tr>
<td>G3</td>
<td>100</td>
</tr>
<tr>
<td>G4</td>
<td>100</td>
</tr>
<tr>
<td>G5</td>
<td>300</td>
</tr>
</tbody>
</table>

**SINGLE AUCTION MODEL:**

**Figure:** Single Auction Model, Market clearing Price=Rs. 4 /kWh
Introduction to electricity market

Figure: Double Auction Model

⇒ Market Clearing Price = Rs. 3 / kWh
Bidding strategies from generator point of view (GENCOS’s perspective):

- Cost components = Fixed Price + Variable Cost + Quasi fixed cost
  - Fixed Price: Capital cost + cost of land + other facilities required for the plant
  - Variable cost: Salary of the employees + fuel cost for running the plant etc.
  - Quasi fixed cost: Startup and shutdown cost.

- Normally total cost we take it as
  - \( C = C_f + C_v(x) \)
  - where, \( x = \) Output power of generator.
Introduction to electricity market

Bidding strategies for GENCOS’:

- $\pi \rightarrow$ Market clearing price (MCP).
- $P_i \rightarrow$ output of $i_{th}$ generator.
- $\pi P_i \rightarrow$ Amount recovered.
- $C(P_i) \rightarrow$ Production cost.
- Profit $\rightarrow f(P_i) = \pi P_i - C(P_i)$

Objective is to $\max f(P_i) = \pi P_i - C(P_i)$
For Perfect Competition:

- Market Price is not affected by changing the output of one generator, thus $\pi$ is independent of $P_i$.
- Thus for maximum benefits
  
  $$\frac{df}{dP_i} = 0 = \pi - \frac{dC(P_i)}{dP_i}.$$  
  
  $$\Rightarrow \frac{dC(P_i)}{dP_i} = \pi \rightarrow \text{eqn (1)}.$$  

- Solving equation (1), we will get the optimal value of $P_i^*$.
  - If $P_i^* < P_{imin} \implies \text{GENCOS MUST NOT BID IN THE MARKET.}$  
  - If $P_i^* > P_{imax} \implies \text{GENCOS MUST NOT BID FOR ITS FULL CAPACITY.}$  
  - If $P_{imin} < P_i^* < P_{imax} \implies \text{GENCOS MUST BID FOR } P_i^*.$
Introduction to electricity market

Example:
Let the cost curve of generator is given by:
\[ C_i(P_i) = (7000 + 500P_i + 0.1P_i^2) \text{Rs/Hr} \]

Hence the incremental cost is:
\[ \frac{dC_i}{dP_i} = 500 + 0.2P_i \text{Rs/Hr} \]

Let the Market Clearing Price = \( \pi = 600 \text{ Rs/Hr} \)

Let \( P_{imin} = 100 \text{MW} \) and \( P_{imax} = 800 \text{MW} \)
\[ \therefore 600 = 500 + 0.2P_i \implies P_i^* = 500 \text{MW} \]
As \( P_i^* \) is greater than \( P_{imin} = 100 \text{MW} \), thus the GENCOS must bid for 500MW for maximum profit.
Case Study: Fixing the tariff using Game Theory

Two Generators competing for supplying the total demand of load:

- Inverse price demand curves (assuming a lossless system):
  - Price = \( \pi = a - b(P_1 + P_2) \).
  - Where, \( a \rightarrow \) Maximum Price, \( b \rightarrow \) Slope of the demand curve.
  - Assume both generators have same and constant marginal cost = \( c \).

- Players are \( G_1 \) and \( G_2 \).

- Strategies is the quantity of power they supply to the load i.e., \( P_i, P_i \).

- Play-off of \( G_1 \):

\[
\text{Profit of } G_1 = U_1(P_1, P_2) = \pi P_1 - cP_1 = (a - b(P_1 + P_2))P_1 - cP_1
\]

\[
\text{Profit of } G_1 = aP_1 - bP_1^2 - bP_1P_2 - cP_1
\]
Thus best response of G1 is:

\[
\frac{d}{dP_1}(aP_1 - bP_1^2 - bP_1P_2 - cP_1) = 0
\]

\[
\Rightarrow P_1^* = \frac{a - c - bP_2}{2b}
\]

\[
\Rightarrow BR_1(P_2) = \frac{a - c}{2b} - \frac{P_2}{2}
\]

Similarly, \( \Rightarrow BR_2(P_1) = \frac{a-c}{2b} - \frac{P_1}{2} \)

\( \Rightarrow \) Nash Equilibrium is at \( P_1^* = P_2^* \)
Case Study: Fixing the tariff using Game Theory ...
Case Study: Fixing the tariff using Game Theory...

Where,

$P^C \implies$ quantity at perfect competition.

$P^M \implies$ quantity at Monopoly.

\[ \left( \frac{a-c}{b} \right) > \frac{2}{3} \left( \frac{a-c}{b} \right) > \left( \frac{a-c}{2b} \right) \]
Let $a = 100$, $b = 1$ and $c = 30$

**Monopoly quantity** $= \frac{a-c}{2b} = \frac{100-30}{2} = 35$

$\implies \pi = a - b(P_1 + P_2) = 100 - 1(35) = 65$

$\implies$ Profit $= \pi P - cP = (65)(35) - (30)(35) = 1225$

**@ Nash quantity** $= \frac{2a-c}{3b} = \frac{2(100-30)}{3} = 46.7$

$\implies \pi = a - b(P_1 + P_2) = 100 - 1(46.7) = 53.3$

$\implies$ Profit $= \pi P - cP = (53.3)(46.7) - (30)(46.7) = 1088.1$

**@ Perfect competition** $= \frac{a-c}{b} = \frac{100-30}{1} = 70$

$\implies \pi = a - b(P_1 + P_2) = 100 - 1(70) = 30$

$\implies$ Profit $= \pi P - cP = (30)(70) - (30)(70) = 0
Energy Management Systems

The Energy Management Systems (EMS) consist of following major components:

- **Automatic Generation Control**
  - Main objective of AGC:
    - Maintain frequency
    - Automatic Generation Control (AGC) is a system for adjusting the active power output of multiple generators connected in an interconnected system and hence balancing the demand with the generation

- **Economic load Dispatch**

- **Scheduling and load forecasting**

- **Online power system studies** (e.g. load flow, short circuit, stability etc.)

- **Automatic trouble analysis and providing help to system operator**

- **Providing help to system operator for system restoration**

- **Emergency control to prevent cascade tripping**

- **Production costing**: calculate the current cost of generating power of online units
Thank you