Integration of Variable Renewable Energy System Impact Study: Reliability and Stability Analysis

PRAMOD JAIN, Ph.D.
Consultant, USAID Power the Future

Almaty University of Power Engineering and Telecommunications, Almaty, April 1 2019
Agenda

- RE Plant Integration Study
- RE Penetration studies
- Studying the impact on the Reliability and Stability of the Grid
Introduction

All new generators have impact

RE generation in particular wind & solar have impacts in power system reliability and efficiency

The impact is both positive as well as negative and depends on the time scale

Different time scales mean different models for studying impact on the grid
Time-scale and Scope of Impact

- System-wide
  - Primary Reserve
  - Secondary Reserve
  - Hydro-Thermal Efficiency
  - Grid Adequacy
  - Generation Adequacy
- Regional
  - Grid Stability
  - Transmission Efficiency
  - Congestion Management
- Local
  - Voltage Management
  - Distribution Efficiency
  - Power Quality

ms-sec  sec-min  min-hr  hr-days  Years
AREAS OF TECHNICAL ASSISTANCE

1. Impact of VRE Integration on the Transmission Grid of Kazakhstan
2. Impact of VRE Integration on the System Operations of Kazakhstan
3. Policies for RE Grid Integration
4. Support Tasks:
   A. Grid code: VRE interconnection guidelines
   B. Methodology & training for project specific impact studies
   C. VRE forecasting and dispatch procedures
   D. VRE equipment standards
   E. VRE connection procedures
APPROACH FOR SYSTEM IMPACT STUDY—ANALYZING IMPACT OF VRE ON THE TRANSMISSION NETWORK

• Train two engineers from KEGOC Dispatch Planning group to conduct the study
• Jointly develop the network model, scenarios and study cases
• KEGOC team members gather all the data and input into the model
• Hands-on training is imparted on the methodology for analysis using KEGOC’s model and data
• All scenarios and study cases are run by KEGOC Engineers
• A detailed reporting template is developed, and all the results are compiled by KEGOC Engineers
• All the recommendations are developed jointly
• Short-term roadmap—1,300 MW of VRE by 2019/20
  – Scope: Current + 2018 RE auctions
  – Based on rigorous analysis of impact on network (DIgSILENT)
• Medium-term roadmap—2021 – 2022
• Longer-term roadmap—2022+
TYPES OF ANALYSIS

- Load flow analysis
- Contingency analysis, N-1, N-2
- Quasi-dynamic analysis
- Short-circuit analysis
- Harmonic analysis
- Transient stability analysis
- Small signal stability analysis
<table>
<thead>
<tr>
<th>Objective: Study impact on</th>
<th>Analysis</th>
<th>Deliverables</th>
</tr>
</thead>
</table>
| Congestion, voltage levels, reactive power requirement, protection settings | Load flow analysis, short-circuit analysis, protection system analysis | • Transmission upgrades  
• Reactive power compensation  
• Required upgrades for increasing generator flexibility  
• Changes to import/export  
• Curtailment  
• Protection setting changes  
• Cost analysis |
| Stability of the grid, inertial and governor response | Transient stability analysis | • Required upgrades for increasing generator flexibility  
• Stability during ramp up/down of VRE  
• Stability during transient events  
• Cost analysis |
Steps in the System Impact Study for Transmission Network

1. Data Collection and Quality Check
2. Development of Assumptions
3. Develop scenarios and study cases
4. Create model of the grid
5. Steady-state analysis: Load flow & Short-circuit analysis
6. Other Analysis
7. Power System Stability Analysis
8. Develop Detailed Roadmap
9. Develop Recommendations
10. Evaluate Cost and Timeline
# Scenario Definitions

## RES integration research scenarios in 2018

<table>
<thead>
<tr>
<th>Transcription / обозначения:</th>
<th>Winter / Summer</th>
<th>Зима / Лето</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi / Su</td>
<td>High / Low Load</td>
<td>Максимум / минимум нагрузки</td>
</tr>
<tr>
<td>H / LL</td>
<td>High / Low wind</td>
<td>Максимум / минимум генерации ВЭС</td>
</tr>
<tr>
<td>H / LW</td>
<td>High / Low Solar</td>
<td>Максимум / минимум генерации СЭС</td>
</tr>
<tr>
<td>H / LH</td>
<td>High / Low Hydro</td>
<td>Максимум / минимум генерации ГЭС</td>
</tr>
<tr>
<td>ZT / RT</td>
<td>Zero / Real Transit</td>
<td>Нулевой / Реальный транзит</td>
</tr>
<tr>
<td>HTU / S</td>
<td>High Transit from Ural / Siberia</td>
<td>Максимальный транзит из Урал / Сибири</td>
</tr>
<tr>
<td>HRE / I</td>
<td>High Russia export / import</td>
<td>Большой экспорт / импорт с Россией</td>
</tr>
<tr>
<td>HAE / I</td>
<td>High Asia export / import</td>
<td>Большой экспорт / импорт с Азией</td>
</tr>
<tr>
<td>HNWS</td>
<td>High North Wind and Solar</td>
<td>Максимум генерации ВИЭ на Севере РК</td>
</tr>
<tr>
<td>LSWS</td>
<td>Low South Wind and Solar</td>
<td>Минимум генерации ВИЭ на Юге РК</td>
</tr>
</tbody>
</table>
Power Flow Analysis

Also called Load Flow Analysis or Steady State Analysis

- Single line diagram of Network
- Loads: Real and Reactive
- Generation Capabilities
- Voltage magnitude and angle at buses
- Real and Reactive power at generators
- Real and Reactive Power flow in T-lines
Power Flow Analysis

Create SS with Gens and Loads

Start with Baseline High Load Scenario

Identify Reference Generator

Analyze results and repeat for all scenarios

Enter the SS Dispatch in DPF. Run Load Flow in DPF

Starting with Smallest Region, Create Dispatch in SS for all regions

Iterate until line loadings & bus voltages are acceptable

Analyze results and repeat for all scenarios
Impact of VRE: Objectives of Load Flow Analysis

• For each scenario, with the flow of active and reactive power from the proposed VRE plants:
  – Are active and reactive power in balance?
  – Are loading of transmission lines, transformers, generators and other elements are within acceptable levels?
  – Are the voltage levels at buses are within the limits specified by the Grid Code?
Remedial Action

- Upgrade the existing or install new transmission lines, reactors and transformers
- Change capacity factor and power factor of existing generators, or install new generators, and
- Change transformer tap settings
- Reduce the capacity of the proposed WPP and/or SPP
Example of Issues and Solutions: Excessive loading of reference generator

• If the issue is with reactive power, then changes to the power factor of generators may resolve the deficit in reactive power, and if insufficient, then adding appropriately sized Stat Var Systems (SVS) would supply the required reactive power.

• If the issue is with active power, then installation of additional flexible generation to cover the shortfall in generation would resolve the issue. The size of the new generation should be sum of the shortfall for power (in the highest load and lowest generation scenario) plus size of largest generator on the grid (to account for the N-1 contingency of the loss of largest unit of generation).

• Demand side management would assist with reducing peak load and thereby reducing the power deficit in these scenarios.

• Energy storage systems that store energy during low demand and dispatch energy during high demand periods would resolve this situation.
Short-Circuit Analysis

- Load flow analysis
- Generator $X'_d, X''_d$
- Fault impedances
- Fault MVA
- Fault current
- Post-fault bus voltage
Impact of VRE: Objective of Short-Circuit Analysis

• Does contribution of WPP and/or SPP to fault current during a short-circuit event exceed the existing short-circuit ratings of the protection equipment in the vicinity of the PCC
  – Is resizing of protection and other equipment needed?
• Do the voltage variations due to WPP and/or SPP at the proposed point of common coupling (PCC) exceed the limits specified by the Grid Code.
  – Voltage variations occur at the PCC when active power is injected into and reactive power is injected into or extracted from the grid by the WPP and/or SPP.
Short-circuit Power Ratio

\[ S_{cc} = \frac{V_{cc}^2}{Z_{cc}} \]
\[ \rho_{cc} = \frac{S_{cc}}{P} \]

- When SCPR is 5 or lower a grid is likely to experience disturbing voltage variations.
  - In such situations, a grid is considered a weak grid with respect to VRE rated capacity
- When SCPR is 20 or higher, the variations in voltage would be minor and predictable
  - In such situations, a grid is considered a strong grid with respect to VRE rated capacity
Remedial Action for Low SCPR

- Remedial actions required are for strengthening the grid
- Add reactive power compensation at the PCC and possibly at intermediate locations between the major load centers and the PCC and/or require users to meet the grid code requirements by installing compensation devices like capacitor banks.
- Increase conventional load following generation in the vicinity of the PCC
- Upgrade of protection systems if the fault current after WPP or SPP interconnection is projected to be above the rating of the protection equipment in the vicinity of the PCC.
Harmonic component in an AC power system is defined as a sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple (the so called order of harmonic) of the fundamental frequency of the system.

Harmonics are primarily generated by power converters in wind turbines.

- Power converters use pulse width modulation (PWM) switching to generate sinusoidal wave at grid frequency, which generates harmonics.
Harmonics Profile of a Wind turbine

Current Harmonics as a fraction of rated current

Multiple of grid frequency
Data Sheet on Power Quality Measurement


<table>
<thead>
<tr>
<th>Harmonics currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{bin} (%)</td>
</tr>
<tr>
<td>H</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

- Value of I_{h}=0.10% at H=11 and P_{bin}=100% means the measured amplitude of current was 0.1% of the rated current for the 11th harmonic when power output was 100%.
Total Harmonic Distortion

- Aggregating harmonic distortion from individual turbines is done using (for each harmonic)
  \[ I_h = \alpha \sqrt[\alpha]{\sum_i I_{hi}^\alpha} \text{ with} \]
  - \( \alpha = 1 \) for \( h \leq 4 \)
  - \( \alpha = 1.4 \) for \( h < 5 \) and \( h \leq 13 \)
  - \( \alpha = 2 \) for \( h > 13 \)

- THC is computed by aggregating individual distortions using:
  \[ THC = \frac{100}{I_n} \sqrt{\sum_{h=2}^{50} I_h^2} \]
  - Where \( I_n \) is the rated current, \( I_h \) is amplitude of the \( h \) harmonic current
Analysis of Harmonics

- Analysis of Total Harmonic Distortion Injection at PCC were computed in previous slide.
- To study harmonics in its totality, background harmonics of the grid should be measured at the PCC.
- Only then interactions and resonances due to injected harmonics can be evaluated.
Power System Stability

• In general, it is the ability of power system to stay in synchronism following a fault
• Transient Stability Analysis: Study of behavior of grid when subjected to large disturbances
• Dynamic Stability Analysis: Study of behavior of grid when subjected to small disturbances
• Stricter definition of stability: Ability of power system to stay in synchronism without change of topology following a fault
Transient Analysis

- Load flow analysis
- AVR, Governor Control model of Generators
- Transients of components, Fault impedances
- Time variation of Voltage
- Time variation of Frequency
- Time variation of Swing Angle
Transient Analysis

• Disturbances occur constantly in a power system
• Power systems possess inertia to absorb the shock of a disturbance
• Generators have variety of control systems to respond to voltage and frequency changes—Automated Voltage Regulation (AVR) and Governor
• Transient analysis provides an understanding of how inertia, AVR, governor and other components act in response to disturbance
• The results are used to determine critical clearing time of protection systems
### SCENARIOS TO BE MODELED

<table>
<thead>
<tr>
<th>Scenarios: Meaningful Combinations Of</th>
<th>Timeframe</th>
</tr>
</thead>
</table>
| Steady-state = Load flow + Short-circuit | • Winter/Summer  
• High transfer from North/South  
• High/low load  
• High/low wind  
• High/low solar  
• High/low hydro  
Only the most extreme scenarios will be modeled | • As-is for baseline  
• 2020—Completion of Wind/Solar projects awarded in 2018 auction.  
1,300 MW of VRE  
• 2022  
• 2022+ |
| Dynamic stability | Above scenarios + Transient events:  
• Ramping of VRE plants  
• Loss of largest VRE plant  
• Loss of largest generator/load  
• Transmission fault close to VRE | Same as above |

3/29/2019
Frequency response during transient event

- Inertial response
- Governor response
- Frequency
- Frequency nadir: Generation + load response = generation loss
- Load response

Transient Stability Analysis

1. Setup study-cases in DPF
2. Attach AVR, Governors and other control models of Gens
3. Pick Variables to Track
4. Define Events Related to Disturbances
5. Create Plots for Voltage, Frequency, Rotor Angle, Active Power
6. Run Dynamic Stability Analysis
7. Analyze Results
8. Iterate Until All Parameters are in Range
<table>
<thead>
<tr>
<th>Study Cases</th>
<th>Scenarios</th>
<th>WPP Loss</th>
<th>SPP Loss</th>
<th>Generation Loss</th>
<th>Load Loss</th>
<th>Transmission Fault</th>
<th>Random</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Wind</td>
<td>No Solar Low Hydro High Load</td>
<td>---</td>
<td>---</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>No Wind</td>
<td>No Solar Low Hydro Low Load</td>
<td>---</td>
<td>---</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>No Wind</td>
<td>No Solar High Hydro High Load</td>
<td>----</td>
<td>----</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>No Wind</td>
<td>No Solar High Hydro Low Load</td>
<td>----</td>
<td>----</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High Wind</td>
<td>High Solar Low Hydro High Load</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High Wind</td>
<td>High Solar Low Hydro Low Load</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High Wind</td>
<td>High Solar High Hydro High Load</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High Wind</td>
<td>High Solar High Hydro Low Load</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
## Issues and Solutions

<table>
<thead>
<tr>
<th>Issues</th>
<th>Potential Mitigating Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency dip/rise that is outside the limit specified in the Grid Code due to increased penetration of WPPs and SPPs</td>
<td>This is likely to occur during transient events due to lower grid inertia. Lower grid inertia occurs because the percentage of conventional generators with inertia in the generation mix is reduced with increase in WPPs and SPPs, which have no inertia. Possible solutions are: 1. Scheduling additional generators, if available, to increase inertia. For example, if 3 gas generators are dispatched at 90% capacity factor and the system inertia is low, then dispatching 4 generators at about 70% capacity factor would increase inertia. 2. Replacement of an existing lower inertia generator with a higher inertia generator. 3. Install fast responsive energy storage units to inject active and/or reactive power into the grid to arrest the rapid drop in frequency.</td>
</tr>
<tr>
<td>Objective: Study impact on</td>
<td>Analysis</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------</td>
</tr>
</tbody>
</table>
| Capacity factor of conventional generators, import/export of power. | Load flow, dispatch analysis | • Required upgrades for increasing generator flexibility  
• Changes to import/export  
• Curtailment  
• Cost analysis |
| System Operations: Dispatching and Scheduling | Dispatch analysis, load forecasting, generator capability, generation capacity forecasting | • Required upgrades to  
• UC, ED tools and process  
• AGC  
• Generator scheduling  
• Generator contracts  
• Import/export contracts  
• VRE forecasting pilot  
• Policy analysis  
• Cost analysis |
| System Operations: Reserves planning | Dispatch analysis, generator capability | • Reserves sufficiency analysis  
• Policy analysis  
• Cost analysis |
USAID Regional Program “Power the Future”

Pramod Jain
President, Innovative Wind Energy, Inc.

Power the Future
6, Sar y Arka Ave, Office 1430
Astana, Kazakhstan 000010

WWW.PTFCAR.ORG

DISCLAIMER This product is made possible by the support of the American People through the United States Agency for International Development (USAID). The contents of this presentation are the sole responsibility of Tetra Tech ES, Inc. and do not necessarily reflect the views of USAID or the United States Government.