Physics-based Data-Driven Approaches for Monitoring and Mitigating Voltage Instability

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The Power Grid is a Critical National Infrastructure

- The power grid is a critical infrastructure of a nation; secure operation is key for a reliable grid – societal and commercial cost

- Stability analysis is essential for secure operation of the grid after large disturbances – classic problem in power systems

- Trends impacting grid stability & control:
  - IBR penetration
  - T&D interaction
  - Sensors
Trend 1 – Increasing Inverter Based Resources (IBRs)

Renewables connected via inverters will rise and will be more dispersed in the grid.

Source: U.S. Energy Information Administration - EIA - Independent Statistics and Analysis
Trend 2 – Rising Active Resources in Distribution Systems

- Devices in the distribution grid are becoming active participants in the grid – Consumers to Prosumers – Referred as DERs
- FERC 2222 – DERs can get paid for supporting transmission

New T&D interactions over Multiple Timescales
Trend 3 – Increasing Sensors

- Phasor Measurement Units (PMUs) provides real-time measurements of grid dynamics – also being introduced in distribution systems ($\mu$PMUs)
The 2021 Renewable Integration Impact Assessment study by Midcontinent Independent System Operator (MISO) found that beyond 30% IBR penetration:

- System wide voltage instability is the main driver of dynamic complexity
- The system is prone to oscillations during peak renewable conditions - Reduced Damping & Inertia

Challenges and Opportunities

The increasing IBRs reduce damping, inertia while introducing variability

Dynamics of the system is more complex due to increasing IBRs

Use the flexibility of bulk IBRs+DERs to provide support – P2800 & FERC 2222

Use sensors to monitor and analyze the dynamics to quickly identify & control instability

Focus on Online Short-Term Voltage Instability Monitoring & Mitigation

Fast Frequency Response, Q-V control, etc.
Fault Induced Delayed Voltage Recovery (FIDVR) in Transmission Systems

Fault Induced Delayed Voltage Recovery (FIDVR)

- Caused due to motor stalling during and after fault – mainly occurs in 1-ϕ Air Conditioner (AC) dominated loads – such as Arizona and Texas.
  
  Stalled motors are connected to grid but are not rotating - are essentially "shorted transformers" – high admittance.

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Stalled motor draws high current → High current causes heat to build up → Thermal protection disconnects motor when temperature limit is reached → Voltage recovers as the motor load is disconnected

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FIDVR in transmission system

• Sustained low voltages may cause devices in nearby regions to trip – DERs can get disconnected
• Many hundreds of stalled AC motors
• Prefer a local method at substation PMU to monitor and control

How do we characterize and mitigate FIDVR locally?
FIDVR with high & low system damping

- Existing online monitoring & mitigation methods use voltage to monitor FIDVR.
- In high damping scenarios, voltage is a reasonable *indicator of severity* (Halpin 2008, Kolluri 2015).

FIDVR with high & low system damping

- Existing online monitoring & mitigation methods use voltage to monitor FIDVR
- In high damping scenarios, voltage is a reasonable indicator of severity (Halpin 2008, Kolluri 2015)
- In simulations with poor damping in system - observed that the voltage is not a reliable metric for monitoring FIDVR
- System operation in regions where control gains are not tuned ⇒ poor damping

The composite load model is the state-of-the-art model for FIDVR as it aggregates the behavior of several distribution feeders.

**Challenge:** The voltage is the symptom and NOT the cause of the phenomenon. The voltage behavior is a result of multiple system level phenomenon and can be oscillatory. How do we locally monitor the FIDVR in this scenario?

FIDVR Modelling – Composite load model

- The **composite load model** is the state-of-the-art model for FIDVR as it aggregates the behavior of several distribution feeders.

- **Challenge**: The voltage is the symptom and NOT the cause of the phenomenon. The voltage behavior is a result of multiple system level phenomenon and can be oscillatory. How do we locally monitor the FIDVR in this scenario?

- **Solution**: The stalled 1φ IM is an admittance, so estimate it from measurements & model.

  \[
  Y_{1\phi} = Y_{PMU} - (Y_{elec} + Y_{stat} + Y_{3\phi})
  \]

  \[
  \frac{P + jQ}{|V|^2}
  \]

  **Function of Voltage and Model**

Observations from Simulations

- Monitoring the stalled 1ϕ motor Admittance gave a much better understanding – unique aspect as none have looked at admittances for monitoring stability
- Susceptance (B) plot shows two distinct sections with minimal oscillations - \( t_1 \& t_2 \)
- Key result is to estimate the recovery time immediately after fault using \( B_{stall} \) given by \( t_1 + t_2 \)

![Graph showing voltage and susceptance over time](https://via.placeholder.com/150)

- **Voltage (V_{stall})**
- **Susceptance (B_{stall})**
Observations from Real Data

- **Reconstructed** total conductance plots for real FIDVR events in distribution & transmission systems – from P and V data [A] [B]
- The overall behavior of the plots is like the simulation results – $t_1$ & $t_2$

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**Southern California Edison**

Event [A] in Distribution

- Lightning strikes

- Conductance (milli-mho)

- Time (s)

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**NYISO**

Event [B] in Transmission

- $t_1$ is small in this scenario

- Conductance (mho)

- Time (s)
Analysis of Load Dynamics during FIDVR

- The stalled admittance of the 1φ IM varies with time due to thermal protection.

- This is a physics inspired reduced model representing the key dynamics observed in FIDVR

- Represent this system by a switched non-linear differential equation for the dynamics of the motor temperature, $\theta$, as the slowly varying state in this system

For a non-oscillatory $V_{stall}$, we can solve the non-linear differential equations to get

\[ t_1 \approx -k_0 \cdot \ln \left( 1 - k_1 / (V_{stall}^2 \cdot B_{stall}) \right) \]

\[ t_2 \approx \frac{2k_2}{(V_{stall}^2 + 1)B_{stall} - k_3} \]

$k_0, k_1, k_2$ & $k_3$ are functions of thermal relay parameters.

Total recovery time $= t_1 + t_2$

**Challenge:** The $t_1$ & $t_2$ expressions include $V_{stall}$ which is oscillatory.

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Analysis of FIDVR Recovery Time - II

- **Solution:** Learn an expression for the times $t_1$ & $t_2$ in terms of the measured $B_{stall}$ at the PMU from various offline simulations
- As $V_{stall} \propto \frac{1}{B_{stall}}$, a first order approximation of the expressions leads to a linear relation between the recovery times and $B_{stall}$

\[
\begin{align*}
t_1 &\approx -k_0 \cdot \ln \left(1 - \frac{k_1}{(V_{stall}^2 \cdot B_{stall})}\right) \\
t_2 &\approx \frac{2k_2}{(V_{stall}^2 + 1)B_{stall} - k_3}
\end{align*}
\]

$\Rightarrow$

\[
\begin{align*}
t_1 &= \alpha_0 \cdot B_{stall} + \alpha_1 \\
t_2 &= \beta_0 \cdot B_{stall} + \beta_1
\end{align*}
\]

Data-driven Learning for FIDVR Recovery Time

- Estimate the linear regression model for $t_1$ & $t_2$ using multiple simulations
  \[ t_1 = \alpha_0 \cdot B_{stall} + \alpha_1 \]
  \[ t_2 = \beta_0 \cdot B_{stall} + \beta_1 \]
  Model fits the actual data with >95% accuracy for various systems

- The coefficients encode the behavior of the grid, the load and depend on the disturbance in the grid – plots below show variation for various faults

![Graph showing voltage and susceptance changes over time with increasing $\phi$-IM from 10% to 45% and consistent increase in susceptance with less oscillations.](image)
Recovery Time Prediction – Results on 162 node system

- Coefficients trained on few $1\phi$ IM % and tested

<table>
<thead>
<tr>
<th>$1\phi$ IM %</th>
<th>Actual $(t_1 + t_2)$</th>
<th>Estimated $(t_1 + t_2)$</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>13.6</td>
<td>13</td>
<td>4 %</td>
</tr>
<tr>
<td>25%</td>
<td>15.1</td>
<td>14.6</td>
<td>3.2 %</td>
</tr>
<tr>
<td>30%</td>
<td>16.5</td>
<td>16.1</td>
<td>2.5 %</td>
</tr>
<tr>
<td>35%</td>
<td>18.2</td>
<td>17.5</td>
<td>3.4 %</td>
</tr>
<tr>
<td>40%</td>
<td>20</td>
<td>19.1</td>
<td>4.4 %</td>
</tr>
<tr>
<td>45%</td>
<td>21</td>
<td>20.5</td>
<td>2 %</td>
</tr>
</tbody>
</table>

- The values of $B_{stall}$ just after fault are used – quick identification of severity

Admittance works for Monitoring. Mitigation?
Mitigation of FIDVR using Local Controls

• AC disconnection using smart thermostats is the best approach as these motors are the reason for FIDVR – will lead to sudden drop in $B_{stall}$

\[
\begin{align*}
\tau_0 &= \text{control time of AC disconnection and includes communication latency} \\
B_1 &= \gamma B_0 \\
\end{align*}
\]

• $\tau_0$ is the control time of AC disconnection and includes communication latency

Mitigation of FIDVR using Local Controls

- AC disconnection using smart thermostats is the best approach as these motors are the reason for FIDVR – will lead to sudden drop in $B_{stall}$

- $\tau_0$ is the control time of AC disconnection and includes communication latency
- Determine $\gamma$ so that $t_1 + t_2 \leq t_{spec}$
- $\gamma$ is the solution of a quadratic equation derived from the $\alpha_0, \alpha_1, \beta_0, \beta_1, t_{spec}$ and $\tau_0$

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Results on 162 node system in PSSE

- The actual recovery time with no control is 16 sec.
- Various specified recovery times ($t_{spec}$) with different AC disconnection time ($\tau_0$) are tested.

<table>
<thead>
<tr>
<th>$t_{spec}$</th>
<th>$\tau_0$</th>
<th>AC disconnect</th>
<th>Actual $t_{rec}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 sec</td>
<td>2 sec</td>
<td>37 %</td>
<td>13.55 s</td>
</tr>
<tr>
<td>14 sec</td>
<td>3 sec</td>
<td>40 %</td>
<td>13.45 s</td>
</tr>
<tr>
<td>13 sec</td>
<td>2 sec</td>
<td>49 %</td>
<td>12.80 s</td>
</tr>
<tr>
<td>13 sec</td>
<td>3 sec</td>
<td>54 %</td>
<td>12.85 s</td>
</tr>
</tbody>
</table>

Results - Cyber Physical Real Time Test Bed

- The Real-Time Cyber-Physical Test Bed consists of Opal-RT, RTDS, SEL-421 PMU’s, OpenPDC, Python & MATLAB to perform data analysis
- Composite load model implemented as Modelica Functional Mockup Unit

Opal-RT uses OPC-Client to receive controls

RTDS/Opal-RT

Hard Wired

PMU

LAN

Optal-RT

Voltage measured by PMU

B calculated by python/OpenPDC

Calls Python to Trigger Controls

Phasor Analysis Done in PDC (C#/Python)
Overall workflow for FIDVR Monitoring & Mitigation

• More robust than purely voltage-based approaches for online FIDVR mitigation
• Also applicable to partial stalling of aggregated 1Φ motor
• Can be used to systematically design remedial action schemes

Offline simulations with varying fractions of motors, and contingency location

Calculate $\alpha_0, \alpha_1, \beta_0, \beta_1$

Detect FIDVR from B Rise

Estimate $t_1$ and $t_2$ from B

If $t_1 + t_2 > t_{spec}$

Estimate AC Disconnection %

PMU Measurements

Offline

Online

FIDVR in Distribution Feeders with DERs

IEEE 9-BUS TRANSMISSION SYSTEM

IEEE 37-node feeder

DERs can disconnect if low voltage persists

Small geographic footprint – easier for centralized control

FIDVR Event in Southern California Edison

- Micro-PMUs in distribution node and PMUs at upstream Transmission substations
- Transmission voltage is mostly unaffected – distribution voltage is impacted

Features of the Distribution Networks

- No oscillations, but voltage measurements cannot localize FIDVR. Admittance can localize FIDVR.
- DER control ⇒ Analytical expressions of $t_1 + t_2$ should be used
Features of the Distribution Networks

• DER control ⇒ Analytical expressions of $t_1 + t_2$ should be used
• Radial nature allows aggregation of devices for monitoring with less $\mu$PMUs
• Deploy control on Full System – OpenDSS + MATLAB

Linear Formulation with DER + Load control

- Voltage at cluster $j$ changes due to control ($u_{AC}$ & $u_{DER}$) at cluster $i$

$$t_{1,j} \approx -k_0 \cdot \ln \left( 1 - \frac{k_1}{(V_{stall,j}^2 \cdot B_{stall,j})} \right)$$

$$t_{2,j} \approx \frac{2k_2}{\left((V_{stall,j}^2 + 1)B_{stall,j} - k_3\right)}$$

- Linear approximation for the change in recovery time

$$\Delta t_{rec,j} \approx \sum_{i=1}^{N} \left( \frac{dt_{1,j}}{dV_{stall,j}} + \frac{dt_{2,j}}{dV_{stall,j}} \right) \cdot \begin{bmatrix} \frac{\partial V_{stall,j}}{\partial u_{AC,i}} & \frac{\partial V_{stall,j}}{\partial u_{DER,i}} \end{bmatrix} \cdot \begin{bmatrix} u_{AC,i} \\ u_{DER,i} \end{bmatrix}$$

- Change in FIDVR recovery time at $j$

- Depends on load parameters

- Depends on distribution system topology and load

- AC control at $i$

- DER Q-injection at $i$
Control Formulation – Linear Approximation

• Linear approximation for the change in recovery time at cluster $j$ due to control $(u)$ at cluster $i$
• More generally, $\Delta t_{rec} = A \cdot u$

$$\min c^T \cdot |u|$$

s.t.

$$A \cdot u \geq t_{spec} - t_{rec}$$

$$u_{min} \leq u \leq u_{max}$$

• Different control constraints can be applied
• Limit 50% AC disconnection in each area
• DER Q-injection up to 44% of rating as per IEEE 1547
Online FIDVR mitigation in IEEE 37 node feeder – 25% DER

- Control triggered 2s after FIDVR detected, $\Delta t_{rec} = 3.5s$

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Total Load Disconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform load control</td>
<td>275 kW</td>
</tr>
<tr>
<td>Optimal load control</td>
<td>200 kW</td>
</tr>
<tr>
<td>Optimal load + DER control</td>
<td>145 kW</td>
</tr>
</tbody>
</table>

- Load control reduction of 40%

Conclusion

• The admittance-based approach can successfully localize regions of motor stalling and quantify the severity of FIDVR in both transmission and distribution systems.

• The physics inspired reduced model based on admittances and thermal dynamics can simplify the FIDVR analysis and provide analytical recovery times.

• The linear relation derived from the data can be used to both monitor and mitigate FIDVR in transmission systems.

• The optimization formulation based on the recovery time sensitivities can utilize the DER Q-injection and can reduce the load disconnection by 40%.
Questions?

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