Real-time Decentralized Voltage Stability Monitoring and Protection against Voltage Collapse

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Outline

- Introduction to Voltage Stability
  - Challenging problem due to nonlinearity and multiple time scales

- Instability Detection
  - Global vs Local

- LIVES method:
  - Local Detection of Global Stability
  - Based on LTCs

- New LIVES Index
  - Based on PMU measurements on a transmission corridor bus

- Protection against collapse
  - Soft (Voltage Control) vs Hard (Load Shedding) measures
What is Voltage Stability?

- Maybe I cannot define stability but I know it when I see it
  - Carson W Taylor, retired engineer of BPA
- Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system

- Key aspects
  - Maximum Power Transfer basically set by Transmission
    - but generation pattern and excitation limits are important
  - Voltage instability is load driven
  - Dynamic phenomenon that can be studied by steady state (equilibrium) conditions (in the long term)
  - Reactive power has a major influence
    - but at stability limit both active and reactive power are significant
  - Converter connected components are also part of the problem
    - Mostly when current limited
Maximum Power Transfer

- Two bus system - variable load
  - Demand (e.g. admittance)
  - Consumption (power)
- Load power \((P, Q)\) consumed:
  \[
  (V^2)^2 + (2QX - E^2)V^2 + X^2(P^2 + Q^2) = 0
  \]
- Bi-quadratic equation \((R=0)\)
- Maximum when \(\Delta=0\)
- Corresponds to impedance matching (radial system)
  - load impedance \(V/I = \text{line } Z\)
- \(P_{\text{max}}\) depends on \(Q\)
  - or power factor
  - Is not affected by the load demand model!
Impedance matching

- Stability condition for a lossless system-constant power factor load

\[ G \sqrt{1 + \alpha^2} < \frac{1}{X} \]

- Assuming constant \( E \)

- What if we monitor at the middle of the line?

Impedance matching does not hold!

- Consider now:

\[ Z_1 = jX_2 + \frac{1}{G(1 - j\alpha)} \]

\[ |Z_1| > \frac{1}{G \sqrt{1 + \alpha^2}} \geq X > X_1 \]

\[ G_1 = \text{Re}\{\frac{\bar{I}_1}{\bar{V}_1}\} \]

\[ G_1 = \frac{G}{(1 + \alpha GX_2)^2 + (GX_2)^2} \]

This is increasing with \( G \) up to MPT!

Thus an accurate stability condition is

\[ \text{NLI} = \frac{\Delta P}{\Delta G_1} > 0 \]
Load Tap Changers (LTC)

- Discrete device
- Loads behind LTC voltage sensitive
- Load restores through LTC
  - when $r_i^{min} < r_i < r_i^{max}$
- Maximum Power when
  - Secondary voltage maximum
  - Stability condition $\frac{\Delta V_2}{\Delta r} < 0$

$$r_i(kT) = r_i(kT - T) + \Delta r_i^k$$

$$\Delta r_i^k = \begin{cases} 
\Delta s & \text{if } V_i > V_i^{max} \\
0 & \text{if } V_i^{min} \leq V_i \leq V_i^{max} \\
-\Delta s & \text{if } V_i < V_i^{min}
\end{cases}$$
Long-term voltage stability

- LTC restoring load from voltage-sensitive to constant power
- Representation in PV plane
  - Maximum power point C
- Network and load characteristics
  - Steady State (L-T)
  - Transient (S-T)
- Point S stable
  - Attracting when disturbed
- Point U unstable
Voltage Stability Monitoring

- Centralized with system-wide phasor information
  - Monitor exact instability conditions
  - Central System Protection Scheme (load shedding)
- With only local LTC measurements
  - Compare secondary regulated voltage at each LTC operation period
  - If voltage does not recover issue alarm
  - Local Identification of Voltage Emergency Situations (LIVES)
- With local phasor measurements and the condition $\Delta P/\Delta G$
  - New LIVES Index (NLI)
- Local Protection possible
Load Shedding Protection Schemes

- Last resort countermeasure, when a critical situation arises
- To be procured, contracted, tested and paid annually
- Manual load shedding not effective
  - imposes heavy responsibility on the operators
  - induces undesired delays
  - difficult to coordinate with other controls
- Undervoltage load shedding requires:
  - Design and tuning for a large number of contingencies
  - Extensive off-line studies
  - Use LIVES or NLI to decide threshold adaptively!
Local Identification of Voltage Emergency Situations (LIVES)

- LOCAL monitoring of GLOBAL voltage instability
  - Indirectly identify weak points of the system
  - Capable for decentralized protection
  - Autonomous system
- Based on monitoring the controlled voltage of LTC during one period of operation
  - Its failure to rise is an imminent instability warning
- Or based on NLI
Instability detection with LTC (LIVES)

- Typical simulation of voltage instability
- Before collapse, LTC-controlled load voltage (and power) reach a maximum
Multi-load systems are not simple! Care needed to define MPT

- Load power space
  - Demand and Consumption
- Typical Instability scenario
- Stress direction (demand)
- Critical Point C
  - Consumption diverges
  - Load not restored in affected area
- Point M
  - Not a Loadability Limit
  - Always before C
  - Good for detection
LIVES Monitoring based on Moving Average

- Sampling period $\Delta t$
  \[ \overline{V}_i(t_j) = \frac{1}{n_i} \sum_{k=0}^{n_i-1} V_i(t_j - k\Delta t) \]

- Average calculated over $n_i$ samples
- Average updated at each sampling instant $t_j = j\Delta t$
- Effective filtering of noise
  - Including fast (short-term) transients
- Averaging period equal to LTC time delay $T_i$
  \[ n_i = T_i / \Delta t \]
  - Includes only one tap change of LTC $i$
  - Implicitly measures effect of all other LTCs in affected area
LIVES algorithm

Immediately after each tap change measure $\Delta V_i^k$

$$\bar{V}_i(kT_i) - \bar{V}_i(kT_i - \Delta t) = \frac{1}{n_i} [V_i(kT_i) - V_i(kT_i - T_i)] = \frac{1}{n_i} \Delta V_i^k$$

Increasing moving average after tap change

- Sufficient stability condition

Average before tap change taken as reference

Monitor whether MA increases over a period of LTC operation

- if it increases: **reset** (process repeats after next tap change)
- if MA remains below reference for more than the period: **alarm**
Overview of LIVES Monitoring and Protection Scheme

- Three modules, running at each LTC controller:
  - LIVES-alarm: Detects imminent voltage instability by monitoring the secondary voltage after each LTC operation
  - LIVES-restore: Voltage stability restoration by reverse tap movement (in favor of transmission)
  - LTC-range restore: Restores LTC control if hard tap limits are met (reducing voltage setpoint)

- Direct (firm) load shedding
  - inevitable in the presence of self-restoring loads
LIVES-alarm module

- Monitor secondary voltage sufficient stability condition:
  \[
  \Delta V_i^k = V_i(kT) - V_i[(k - 1)T]
  \]

- Reference Value: The value of MA at the time of tap change
- Monitor of MA over a period of LTC operation
  - If MA remains above reference value, reset (the process is repeated at the next tap change)
  - If MA remains below reference value for slightly less than LTC operation, alarm
LIVES-restore module

- LTC operation reversed after LIVES-alarm in favor of transmission side voltages
- Modified LIVES-alarm module monitors primary voltage
- When the MA remains above a reference value
  - Restore signal is issued and LTC secondary setpoint is lowered to its present value

- Restore equilibrium at the current consumption level
- Indirect (possibly temporary) load reduction
LTC-range restore module

Unblock LTCs

1) Regulated voltage below deadband and LTC at last tap
2) MA taken as reference
3) If MA below reference
   - Reduce 5% distribution voltage setpoint
4) Else if MA above reference
   - continue monitoring
5) Stop when secondary voltage returns to deadband
Case Study

- **LIVES method and NLI**
  - Moving average filtering
  - Remedial actions possible after the alarm
    - Reverse LTC tapping (LIVES restore) or
    - Direct load shedding

- **Application to Nordic Test System (PSDPC TF on Voltage Stability test systems)**
  - Documented in TF report and available online including PSS/E files
• Unstable scenario  
  – Operating point A  
  – Short circuit at t=50s cleared by tripping line 4032-4044  
• QSS (WPSTAB) and Full time simulation (RAMSES-TF report)  
• Detailed simulation used to show effect of noisy measurements in instability detection  
• QSS used to assess effect of countermeasures
## LIVES Alarms

Costas Vournas, Champery, February 9, 2017

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<tr>
<th>GENERATOR</th>
<th>WPSTAB (s)</th>
<th>RAMSES (s)</th>
<th>LIVES-ALARM BUS</th>
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<th>RAMSES (s)</th>
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LIVES-alarm & LIVES-restore

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<th>$P_{0i}$</th>
<th>$Q_{0i}$</th>
<th>$V_{init}$</th>
<th>$V_{fin}$</th>
<th>ΔP</th>
<th>ΔQ</th>
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**TOTAL (LIVES-RESTORE)**

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<th>$P_{0i}$</th>
<th>$Q_{0i}$</th>
<th>$V_{init}$</th>
<th>$V_{fin}$</th>
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**TOTAL (UNSERVED)**

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</table>

- LTC exhaust at bus 5
- Steady state at $t=500s$
- $\Delta P = 299.51 \text{ MW}$,
  $\Delta Q = 159.16 \text{ MVAr}$
LIVES-alarm and Load Shedding

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>OXL</th>
<th>LIVES - ALARM BUS</th>
<th>( V_H ) (pu)</th>
<th>LOAD SHEDDING BUS</th>
<th>( \Delta P ) (MW)</th>
<th>( \Delta Q ) (MVAr)</th>
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<td>61.48 MVAr</td>
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</table>

- Direct load shedding of 10% at each LIVES alarm
- No OEL activation of g15, g16, g6
- Steady state at t=160s
- \( \Delta P=220.03\text{MW}, \Delta Q=61.48\text{MVAr} \)
New LIVES Index

- Applied to the boundary buses 4041, 4042
  - End of transmission corridor
  - Feeding Central Area
- Same unstable scenario
- QSS (WPSTAB) and Full time simulation (RAMSES-TF report)
NLI results

- Applied to buses 4041, 4042
  - Bus 4044 becomes internal after disconnection
- Same unstable scenario as before
- Early warning
- 70-71s (QSS)
- 73.94-83.94s (Full time simulation - TF report)

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NLI results

- Apparent G and P at the bus 4041
- Clear trend (even if marginally so)
- No false alarm in marginally stable scenario
Continuing Research

- Application to historical results
  - Hellenic Interconnected System 2004 blackout
  - Simulation case reconstructed
  - Pilot application of stability monitoring

- Initial results promising
  - Only method so far that can predict voltage collapse
  - Without giving false alarm in marginally stable scenario
Conclusions

- Both LIVES method and NLI issue early alarms to all affected buses
  - No false alarm at marginally stable cases

- The alarms are raised at nominal voltage levels
  - No undervoltage protection possible without stability monitoring

- Results comparable with minimum load shedding method based on global information

- Investigation of diversified load sensitivities to voltage
  - Alarms always early
  - Load shedding varies but always effective to save the system
LIVES/NLI References


