New angles for monitoring power system area stress with synchrophasors

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PSerc Webinar
September 2010

Funding in part from California Energy Commission and coordinated by DOE CERTS is gratefully acknowledged

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We combine together phasor measurements along the border of an area to get angles across the area that measure total, internal, and external stress of area.
Some overall objectives

• Improve on measuring stress with synchrophasor voltage angle difference between 2 buses

• Distill meaningful and actionable information about a specific area of a large power system from synchrophasor monitoring.
Angle for a single line in DC load flow

电压相量
角度垂线

角度垂线

线性电感

实际功率通过线路

We want to get angle across an area to work in the same way
Area R with border buses

- Phasor measurements at *all* the buses that are on the border of area
- Border buses are divided into sets $M_a$ and $M_b$
- We will define angle across area from $M_a$ to $M_b$
- Use DC load flow model of area
Reduction of area R to single line equivalent

Define: angle across area $\hat{\theta}_{ab}$
area susceptance $b_{ab}$

Power through area $= b_{ab} \hat{\theta}_{ab}$
Kron reduction retaining border buses

Equivalent susceptance matrix

\[ = B_{mm} - B_{mn} B_{nn}^{-1} B_{nm} \]

Border bus power injections equivalent to all powers injected in R

\[ P_R = P_m - B_{mn} B_{nn}^{-1} P_n \]
Angle $\hat{\theta}_{ab}$ across cutset is a weighted linear combination of border bus voltage angles.

Cutset susceptance is sum of cutset line susceptances.
Cutset power flow is sum of cutset line powers.
Defining cutset angle: 2 lines in cutset

Power through cutset = \(8(\theta_1 - \theta_2) + 2(\theta_3 - \theta_4)\)

\[
\hat{\theta}_{ab} = 0.8(\theta_1 - \theta_2) + 0.2(\theta_3 - \theta_4)
\]

\[
\text{Power} = 10 \hat{\theta}_{ab}
\]

circuit law

line 1-2 susceptance = 8
line 3-4 susceptance = 2

cutset susceptance = 10
total angle $\hat{\theta}_{ab}$ across area

Measures stress across area

Satisfies circuit law $\text{Power} = b_{ab} \hat{\theta}_{ab}$

... angle proportional to effective power flow through area

... angle inversely proportional to area susceptance ... responds to line trips
An area $R$ in 225 bus WECC

Area angle $\theta_{ab} = 0.80 \theta_{ELDORADO} + 0.20 \theta_{PALOVRDE} - 1.00 \theta_{VINCENT}$

= weighted combination of border bus angles

thanks to C-C Liu for 225 bus model
Area angle base case

\[ \hat{\theta}_{ab} = 10.9 \text{ degree} \]

\[ b_{ab} = 91.6 \text{ p.u.} \]

100 MW transfer inside area gives +0.25 degree

100 MW transfer through area gives +0.60 degree

Line trip inside area gives +2.51 degree

Line trip outside area gives +0.38 degree
Kron reduction adds power injections $P_R$

Pinto is external power flowing into area $R$

$P_R$ is equivalent to all powers injected in area $R$
total stress = external + internal stress

total power through area = \( P_{\text{into}} + Pr \)
Divide by area susceptance \( bab \) to get

total angle across area \( \hat{\theta}_{ab} = \hat{\theta}_{\text{into}} + \hat{\theta}_{R} \)

\[ \hat{\theta}_{\text{into}} = \text{external stress angle} \]
\[ \hat{\theta}_{R} = \text{internal stress angle} \]

Monitor \( \hat{\theta}_{ab} \) and \( P_{\text{into}} \) with synchrophasors.
Then

\[ \hat{\theta}_{R} = \hat{\theta}_{ab} - \frac{P_{\text{into}}}{bab} \]
Properties of internal area angle $\hat{\theta}_R$

- Reacts to changes in injections inside area. Insensitive to injections or redispach outside area.
- Reacts to line trips inside the area. Insensitive to line trips outside area.

Internal area angle monitors specific area
Internal area angle
base case
$\theta_R = 1.07 \text{ degree}$

100 MW transfer inside area
gives $+0.24 \text{ degree}$

100 MW transfer through area
gives $+0 \text{ degree}$

line trip inside area
gives $+2.63 \text{ degree}$

line trip outside area
gives $+0 \text{ degree}$
Conclusions

• angle across area is a weighted combination of phasor measurements at boundary of area; easy to compute but needs DC load flow model to compute weights
• derived from Kron reduction and cutset angle
• area angle obeys circuit laws and monitors stress in specific area
• area angle = internal angle due to power injections inside area + angle due to power flows into area
• internal angle only responds to changes in area
Future directions

• Move towards practical application: choice of areas and PMU locations, model detail needed
• Multiple areas and model reduction
• Monitor line trips, generation changes in area
• AC load flow; complex voltages and currents
• Supply area-specific quantities for data-mining

For details, google Ian Dobson papers and download synchrophasor conference papers at 2010 HICSS, PESGM, and IREP