University of Tehran
College of Engineering
School of Electrical and Computer Engineering

The 2nd International Symposium on Smart Grid
- Methods, Tools, and Technologies
Weihai, Shadong, China

# Wide-Area Protection Solutions for Modern Power Systems

Majid Sanaye-Pasand
University of Tehran

July 4-7, 2017

# Outline:

- An Introduction to University of Tehran
- Latest Researches on Protection and Control at ECE School
- Wide-Area Backup Protection
- Wide-Area Fault Location
- Wide-Area Combined UFLS/UVLS Schemes
- Protection of DER-Integrated Microgrids
- Summary and Conclusion

## An Introduction to University of Tehran:

- The oldest, biggest, most famous and highest ranking comprehensive university in Iran
- ECE School including about 100 academic staff and 2500 students
- Power engineering department, 15 professors, 25+ laboratories
- About 40 research papers in power engineering related fields published per year in high ranked journals
- Tight collaboration with Iran power industry by conducting more than 50 practical and research projects
- Many registered patents

# Power System Protection Research Group:

Members:

- Majid Sanaye-Pasand, *Professor*
- Hamid Lesani, *Professor*
- Amir Abbas Shayeghani, *Associate Professor*
- Farrokh Aminifar, *Assistant Professor*
- Mahdi Davarpanah, *Assistant Professor*
- Ph.D. and Master Students

## Majid Sanaye-Pasand:

- PhD degree from the University of Calgary, Canada, 1998
- Professor at the ECE School, University of Tehran, 2009
- Research interests, power system protection and control, digital protective relays, power system transients, power system automation
- Supervised about 75 Masters and Ph.D. students
- Some of my former students have high-ranking jobs in the well-known universities and power industry in Iran, NA and Europe.

## Majid Sanaye-Pasand (cont.):

- As a pioneer, the first who initiated the “Power System Digital Protection” and “Power System Automation” courses in Iran
- Has been rewarded several promotions and prizes
- Published about 280 papers
- 20 funded research works, some already applied in the field
- Very close collaborations with electric power utilities
- Awarded various prestigious and national prizes from the Ministry of Energy of Iran for the applied industrial research innovations, e.g. the best power industry researcher of the country

## Majid Sanaye-Pasand (cont.):

- Appointed an adviser and member of research and development board in several power utilities
- Member of the board and consultant to CEO, Tavanir company (Iran highest-ranking power company, management of national grid GTD)
- IEEE Senior Member since 2005
- Elevated to the IET Fellow level at 2011
- Editor of IEEE/TPWRD since 2012
- Editor of IEEE/Power Engineering Letters since 2014

## Majid Sanaye-Pasand (cont.):

## Research Areas:

- Adaptive relays, new protective relays' algorithms, smart grid protection, wide-area protection schemes, phasor estimation using novel digital filters, special protection schemes
- Substation automation, application of PMUs in system protection and control
- Relay input sources, CT and CVT transient modeling, compensating instrument transformers output errors, mitigating their undesirable impacts on digital relays as well as energy meters performance

## Majid Sanaye-Pasand (cont.):

### Research Areas:

- Wide-area fault location on transmission networks and multi-terminal DC systems, PMU-based wide-area backup protection schemes
- Power system stability enhancement, design of multi-dimensional load shed schemes to prevent system blackout
- Microgrid adaptive protective schemes
- Digital relay transient testing

## Majid Sanaye-Pasand (cont.):

## Curriculum Development:

- Member of the “Power Systems and Electrical Machines” curriculum development committee, graduate level
- Supervisor of the “Power System Restructuring” curriculum development committee, developed for the first time in Iran
- A new Power System Restructuring MSc branch was established in 2006 in ECE School, UofT based on the new curriculum.
- Supervisor of the “Power System Protection” curriculum development committee, various system protection problems and occurrence of some blackouts, developing a new MSc branch based on the new curriculum

# Farrokh Aminifar:

- Head of Power Engineering Department
- Editor, IEEE Transactions on Sustainable Energy
- Guest Editor-in-Chief, IEEE Transactions on Sustainable Energy and IEEE Transactions on Smart Grids
- Publication of 80 journal papers in high-ranked publications
- PI of the project with Iran Grid Management Corp. (IGMC) to devise an adaptive scheme for the udder-frequency load shedding
- IGMC consultant for the implementation of Wide-Area Measurement System (the first one within the middle east countries)
- IGMC consultant for the implementation of the new advanced system control center

## Mahdi Davarpanah:

- Assistant Professor at ECE School
- The best researcher of Iran power industry in 2013
- Member of Iran Power Grid Protection Committee
- Publication of 20 journal papers in high-ranked publications
- Conducting 20 industrial projects in Iran power sector
- Having various registered patents including CVT error compensator and stator fault detector for synchronous generators
- Head of Power System Failure Analysis lab at ECE

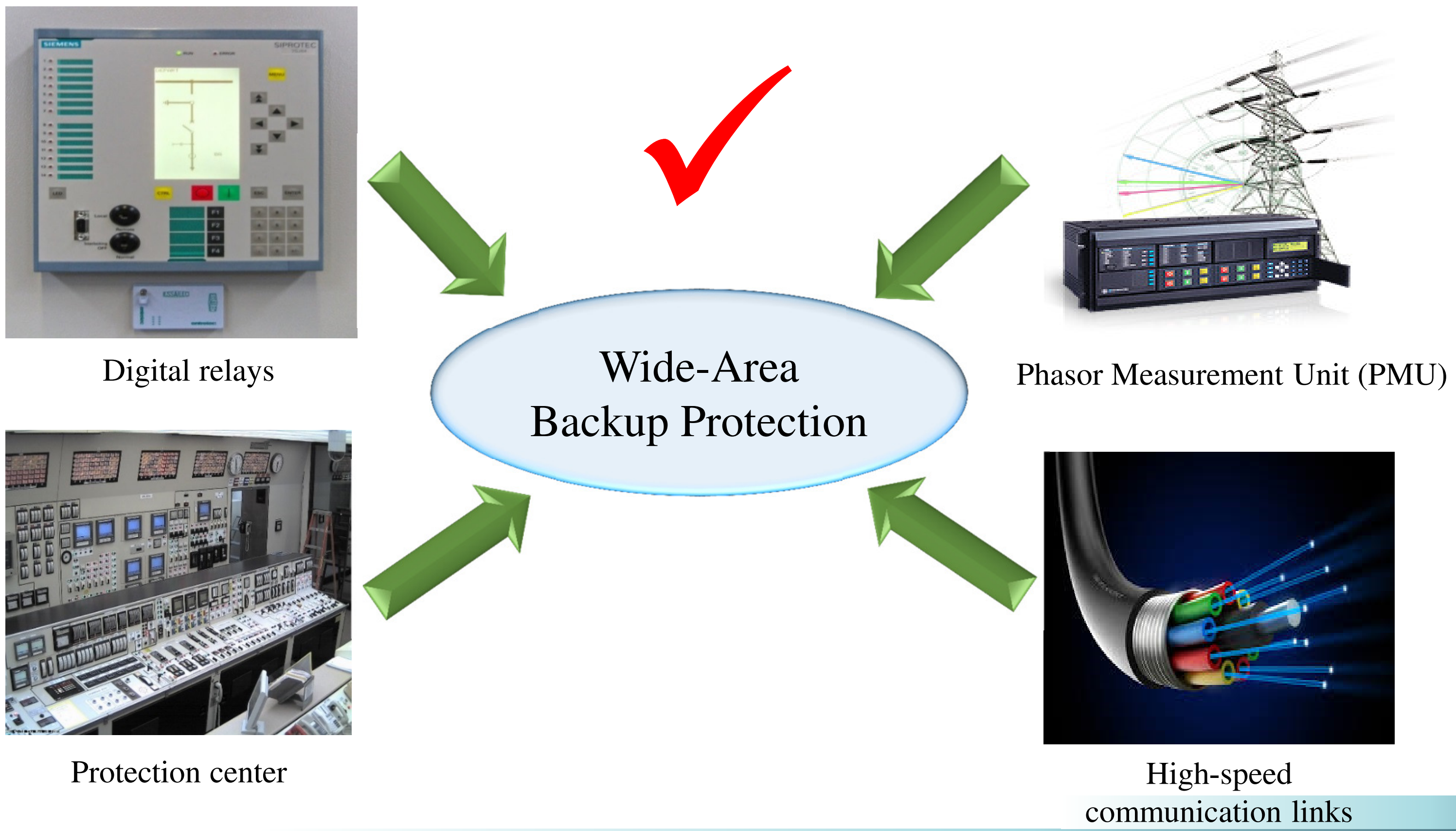
## Latest Researches on Protection and Control at ECE School:

- Wide-area backup protection
- Wide-area-fault location
- Wide-area combined UFLS/UVLS schemes
- Protection of DER-integrated microgrids

# Wide-Area Backup Protection

# Wide-Area Backup Protection:

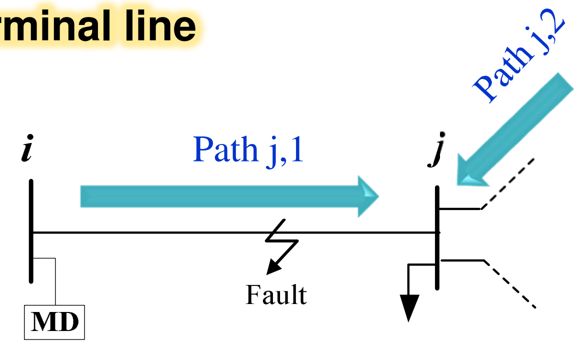
## Main parts of Wide-Area Backup Protection



# Wide-Area Backup Protection (cont.):

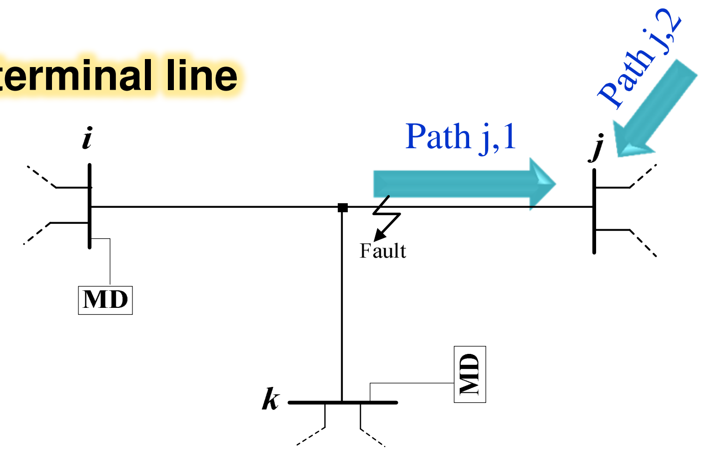
- ❑ Synchrophasor-Based Wide-Area Backup Protection
- ✓ Calculation of ΔV to Fault Point from Different Paths:

**Two terminal line**




MD: Measurement Device (PMU or Digital relay)

**Three terminal line**



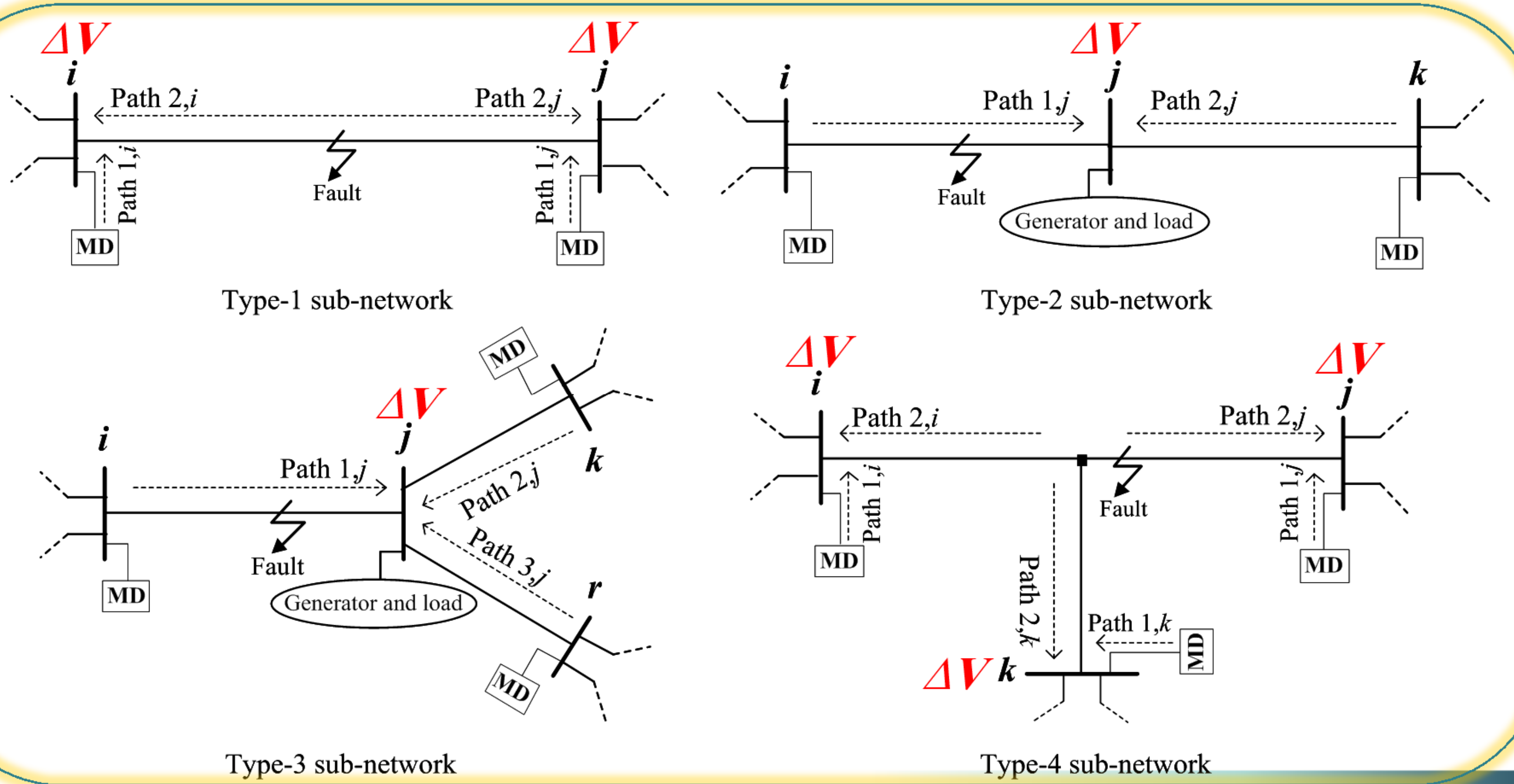

$\Delta V_j = \left|V_j^1 - V_j^2\right|$ Only two observable paths

$\Delta V_j = max\{\left|V_j^n - V_j^m\right|, n, m = Observable\ paths\ \ \&n \neq m\}$ More than two observable paths

# Wide-Area Backup Protection (cont.):

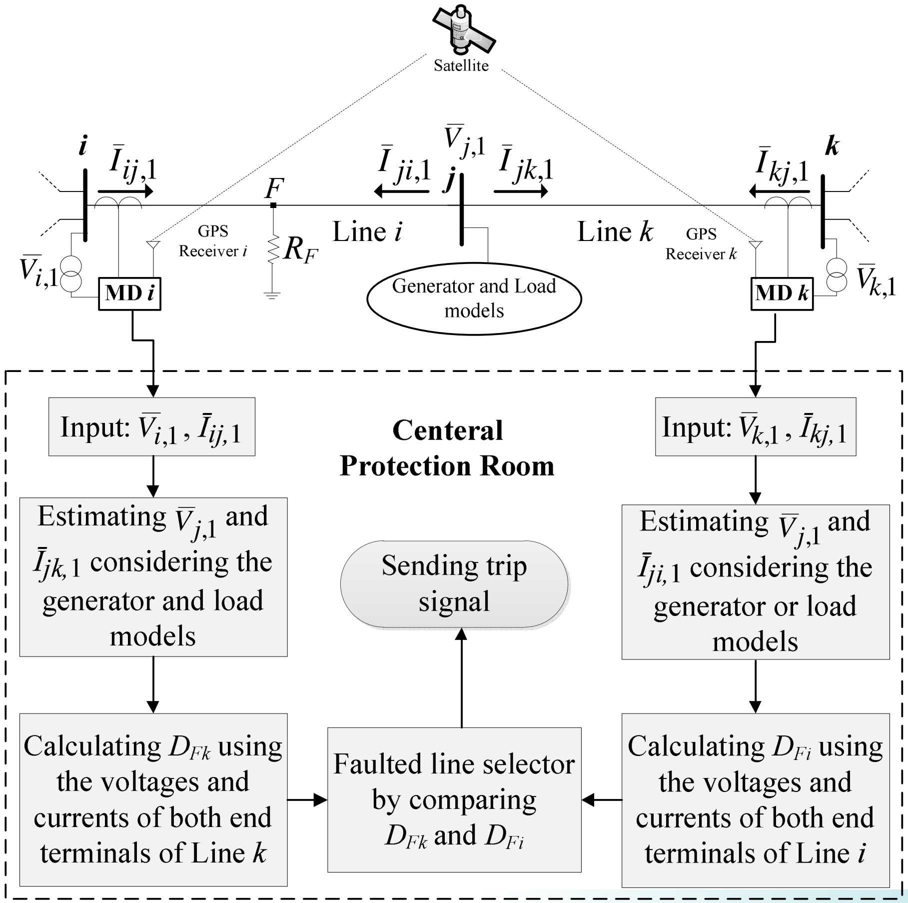
- ❑ Synchrophasor-Based Wide-Area Backup Protection

**Different Sub-networks**

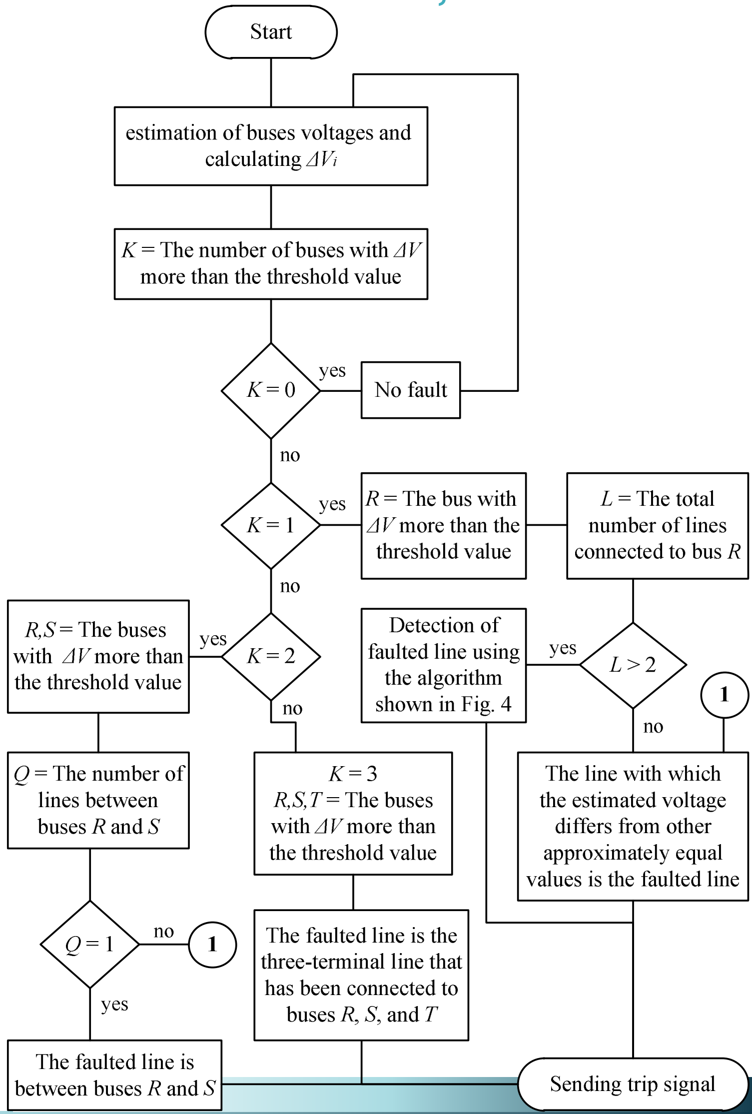


# Wide-Area Backup Protection (cont.):

## For sub-network 2




## For sub-networks 1, 3 and 4



# Wide-Area Backup Protection (cont.):

Simulation results for type-1 and type-3 sub-networks

| Faulted Line | Fault Location | Fault Type | Fault Resistance (Ω) | Buses with ΔV more than the Threshold Value | | Maximum ΔV for Other Buses (kV) | Faulted Line Detection | Computation Time (ms) |
|---|---|---|---|---|---|---|---|---|
| | | | | Bus | ΔV (kV) | | | |
| Line 6-7 | 5% from bus 6 | ABC | 5 | 6, 7 | 10.941, 271.451 | 0.044 | ✓ | 67 |
| | 50% from bus 6 | C-G | 60 | 6, 7 | 3.685, 7.319 | 0.011 | ✓ | 65 |
| | 95% from bus 6 | AC | 30 | 6, 7 | 89.633, 9.710 | 0.024 | ✓ | 69 |
| Line 9-12 | 5% from bus 9 | BC-G | 30 | 9, 12 | 16.924, 324.349 | 0.038 | ✓ | 67 |
| | 50% from bus 9 | A-G | 5 | 9, 12 | 22.771, 34.387 | 0.010 | ✓ | 69 |
| | 95% from bus 9 | ABC | 60 | 9, 12 | 437.467, 36.243 | 0.022 | ✓ | 66 |
| Line 3-15 | 5% from bus 3 | AB-G | 60 | 3 | 2.613 | 0.017 | ✓ | 87 |
| | 50% from bus 3 | ABC | 30 | 3 | 53.698 | 0.017 | ✓ | 88 |
| | 95% from bus 3 | C-G | 5 | 3 | 2.263 | 0.014 | ✓ | 85 |

Simulation results for type-2 sub-network

| Faulted Line | Case Description | | | Calculated Values | | Selected Output | Comp. Time (ms) |
|---|---|---|---|---|---|---|---|
| | $D_{Fk}$ or $D_{Fi}$ | $R_F$ (Ω) | Fault Type | $D_{Fk}$ | $D_{Fi}$ | | |
| Line 5-6 | $D_{Fi}$=0.50 | 5 | AB | 1.24 | 0.510 | $D_{Fi}$ | 75 |
| Line12-16 | $D_{Fk}$=0.95 | 30 | A-G | 0.950 | 1.193 | $D_{Fk}$ | 80 |
| Line 19-20 | $D_{Fi}$=0.05 | 60 | ABC | -23.63 | 0.044 | $D_{Fi}$ | 76 |
| Line 49-50 | $D_{Fi}$=0.95 | 5 | AC-G | 1.313 | 0.952 | $D_{Fi}$ | 76 |
| Line 54-55 | $D_{Fi}$=0.50 | 60 | B-G | -7.401 | 0.470 | $D_{Fi}$ | 81 |
| Line 41-42 | $D_{Fk}$=0.95 | 30 | ABC | 0.950 | 1.050 | $D_{Fk}$ | 77 |

Simulation results for type-2 sub-network (Three-terminal line)

| Faulted Line, Fault Location | Fault Type, $R_F$ (Ω) | Buses with ΔV more than the Threshold Value | | Faulted Line Detection | Comp. Time (ms) |
|---|---|---|---|---|---|
| | | Buses | ΔV (kV) | | |
| Line 21-22, 50% from bus 21 | C-G, 5 | 21, 23, 38 | 14.590, 3.988, 22.885 | ✓ | 74 |
| Line 23-22, 95% from bus 23 | BC-G, 60 | 21, 23, 38 | 52.984, 14.897, 31.936 | ✓ | 75 |
| Line 38-22 5% from bus 38 | ABC, 60 | 21, 23, 38 | 304.258, 39.820, 2.397 | ✓ | 74 |

# Wide-Area Backup Protection (cont.):

## ❑ Main advantages of the proposed method:

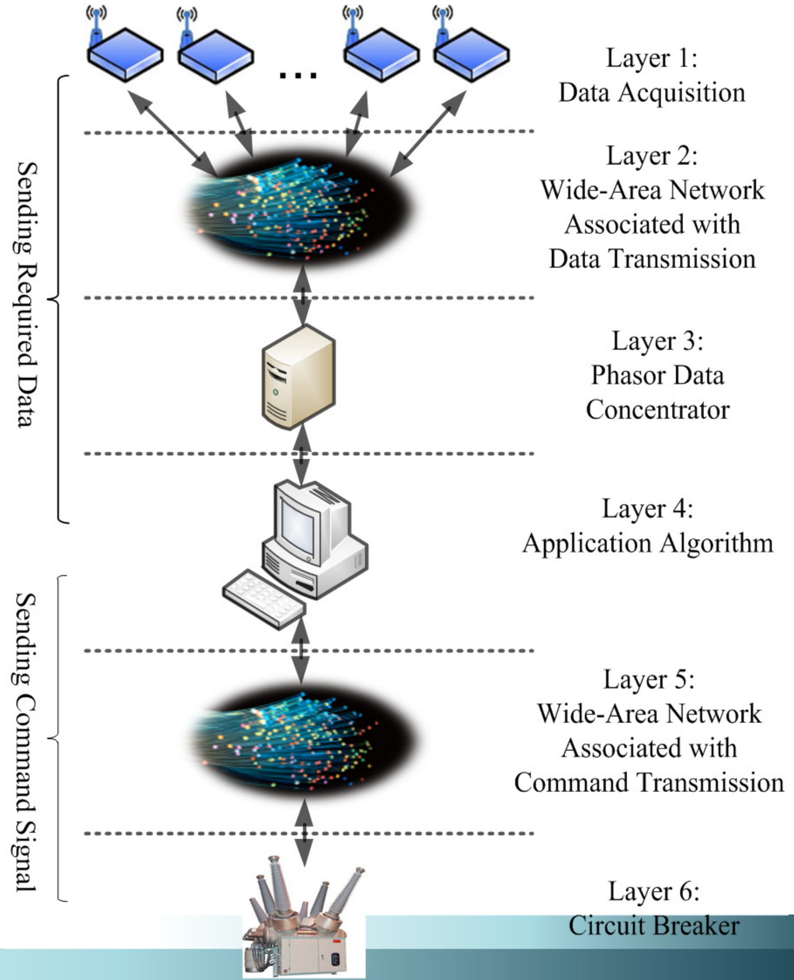
- Simplicity in concept and implementation
- Applicable in two- and three-terminal lines
- Applicable for various types of faults
- High security and dependability
- Trivial computation burden
- Requirement of low reporting rate of synchrophasor
- Robust performance against system stressed conditions and measurement error
- Sufficiently short execution time for backup protection schemes

# Regionalization of Power Systems for Wide-Area Backup Protection:

## Amount of delay for each layer

| Location | Element of Delay | Value of Delay (ms) |
|---|---|---|
| Layer 1 | Sampling window | 20 |
| | Measurement filtering and processing | 15 |
| Layers 2 and 5 | Serializing output | 5 |
| | Communication system I/O per bus | 15 |
| | Propagation | 5 |
| Layer 3 | PDC waiting | 30 |
| | PDC processing | 10 |
| Layer 4 | Executing algorithm | 80 |
| Layer 6 | Circuit breaker | 50 |
| Total Delay: 230 ms | | |

## 6 layers of wide-area backup protection



# Regionalization of Power Systems for Wide-Area Backup Protection (cont.):

- **Proposed three-step formulation for regionalization of power systems:**
  - Optimization of required measurement devices (MDs), ILP model, GAMS
  - Regionalization of power systems
  - Optimizing location of protection centers with minimum data transaction

# Regionalization of Power Systems for Wide-Area Backup Protection (cont.):

## ❑ Optimization of required MDs

| | |
|---|---|
| $\text{Minimize} \sum_{i \in N} w_i$ | **Objective function** |
| $\sum_{i \in N} w_i b_{fi} \geq 1 \quad \forall f \in M$ | Two-terminal lines ✓ |
| $w_i = 1 \quad \forall i \in O$ | Three-terminal lines ✓ |
| $2 - g_i \leq w_i \quad \forall i \in N$ | Buses connected to single line ✓ |
| $g_i = \sum_{f \in M} b_{fi} \quad \forall i \in N$ | |

# Regionalization of Power Systems for Wide-Area Backup Protection (cont.):

## ❑ Regionalization of power systems

$$\text{Minimize} \sum_{j\in N} m_j$$

:Objective function

$$s_{ij}(t_{ij} + ct_{ij}) + t_{a\lg} \leq t_{\max} \quad i, j \in N$$

✓ Communication latency

$$\sum_{j\in N} x_{kj} \geq 1 - w_k \quad \forall k \in N$$

Buses lacking MD ✓

$$\sum_{j\in N} y_{fj} \geq \sum_{i\in N} b_{fi} w_i - 1 \quad \forall f \in M$$

Two terminal lines equipped with MDs at their both ends ✓

$$\sum_{j\in N} z_{fj} \geq 1 \quad \forall f \in P$$

Three terminal lines ✓

$$\sum_{j\in N} s_{ij} \geq w_i \quad \forall i \in N$$

Communication between a MD and at least one protection center ✓

$$\sum_{i\in N} s_{ij} \leq h_{\max} \quad j \in N$$

Limitation on the number of MDs communicating with a protection center ✓

# Regionalization of Power Systems for Wide-Area Backup Protection (cont.):

## ❑ Optimizing Location of Protection Centers with Minimum Data Transaction

$$\text{Minimize} \sum_{i \in N} \sum_{j \in N} s_{ij}$$

**Objective function**

$$\sum_{j \in N} m_j = \alpha$$

Total number of regions obtained at the previous stage ✓

All previous stage constraints ✓

# Regionalization of Power Systems for Wide-Area Backup Protection (cont.):

## Simulation Results

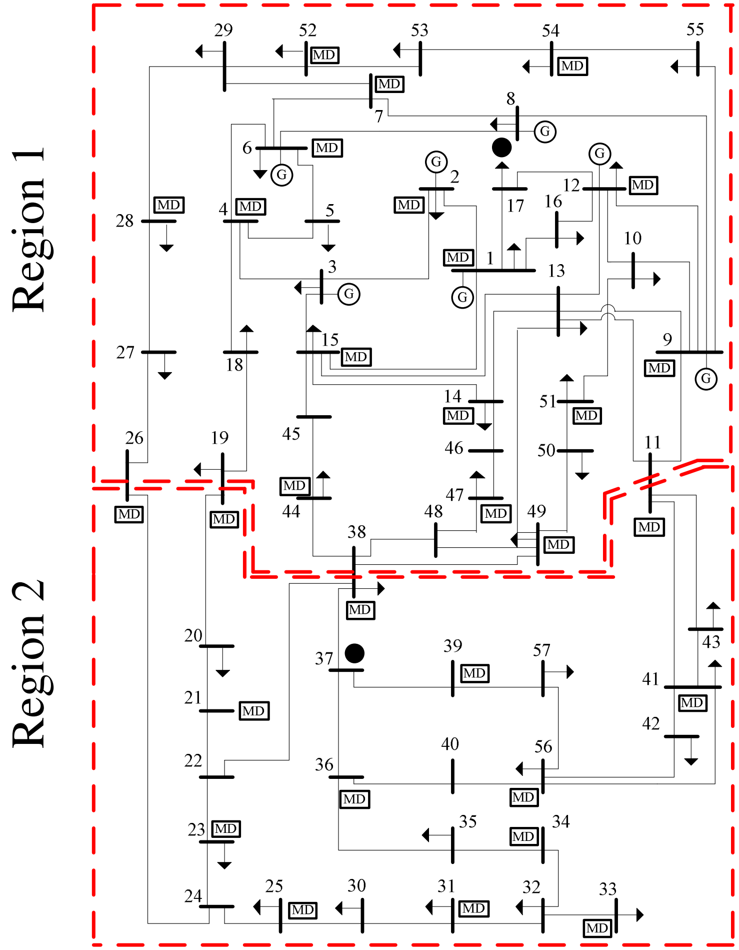
| Test System | Number of Regions | Location of Protection Rooms | MDs Belonging to each Region | |
|---|---|---|---|---|
| IEEE 14-Bus | 1 | 12 | Region 1: | 2, 4, 5, 6, 8, 9, 11, 13 |
| IEEE 30-Bus | 1 | 2 | Region 1: | 1, 4, 5, 6, 10, 11, 12, 13, 15, 16, 19, 22, 24, 26, 27, 28, 30 |
| IEEE 39-Bus | 2 | 3, 21 | Region 1: | 2, 3, 4, 6, 8, 11, 13, 15, 26, 29, 30, 31, 32, 37, 38, 39 |
| | | | Region 2: | 3, 15, 17, 19, 21, 23, 24, 26, 33, 34, 35, 36 |
| IEEE 57-Bus | 2 | 8, 37 | Region 1: | 1, 2, 4, 6, 7, 9, 11, 12, 14, 15, 19, 26, 28, 38, 44, 47, 49, 51, 52, 54 |
| | | | Region 2: | 11, 19, 21, 23, 25, 26, 31, 33, 34, 36, 38, 39, 41, 56 |
| IEEE 118-Bus | 3 | 15, 75, 92 | Region 1: | 1, 5, 6, 8, 10, 11, 12, 15, 17, 19, 21, 23, 26, 27, 29, 32, 36, 37, 38, 40, 42, 43, 45, 115, 117 |
| | | | Region 2: | 23, 38, 42, 45, 46, 49, 50, 51, 52, 54, 56, 59, 60, 62, 64, 66, 68, 69, 70, 72, 73, 74, 77, 79, 80, 83, 94, 96, 116, 118 |
| | | | Region 3: | 80, 83, 85, 87, 89, 91, 92, 94, 100, 101, 103, 105, 106, 109, 111, 112 |

# Regionalization of Power Systems for Wide-Area Backup Protection (cont.):

## ❑ Simulation Results

IEEE 57-bus test system

along with specified protection regions



# Wide-Area Backup Protection Using Current Phasors:

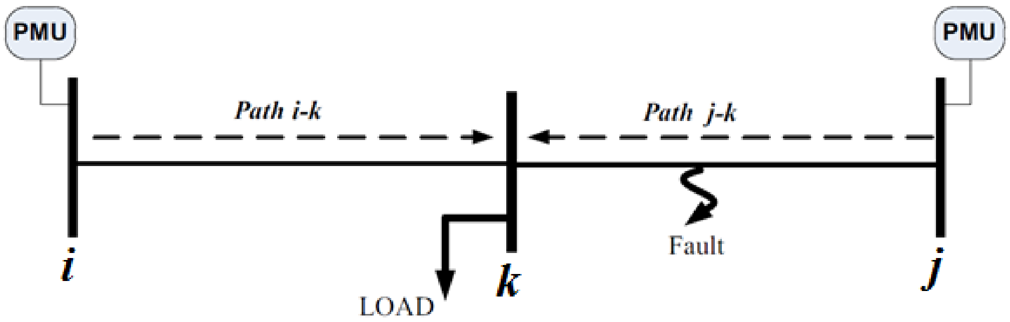
## ❑ Motivation:

Backup distance protection (Zone-3) suffers from some shortcomings as:

- ✓ Maloperation under system stressed conditions (load encroachment, power swings, . . .) which may result in cascaded outages of transmission lines and blackouts.
- ✓ Long time delay which may be larger than the system CCT and endanger power system transient stability.
- ✓ Extensive coverage which may conflict with adjacent relays especially in case of long transmission lines.
- ✓ Affected by wide-area disturbances

# Wide-Area Backup Protection Using Current Phasors (cont.):

- ❑ Proposed current-based wide-area backup protection:
- ✓ Discrimination between faults and other stressed conditions:




$$I_{kj} = \frac{1}{Z_C}\sinh(\gamma L_{kj})V_j - \cosh(\gamma L_{kj})I_{jk} \quad (1)$$

$$I_{ki} = \frac{1}{Z_C}\sinh(\gamma L_{ki})V_i - \cosh(\gamma L_{ki})I_{ik} \quad (2)$$

$$I_{ki} + I_{kj} + I_L = 0 \quad (3)$$

- ✓ Identification of faulted line (0<X<1):

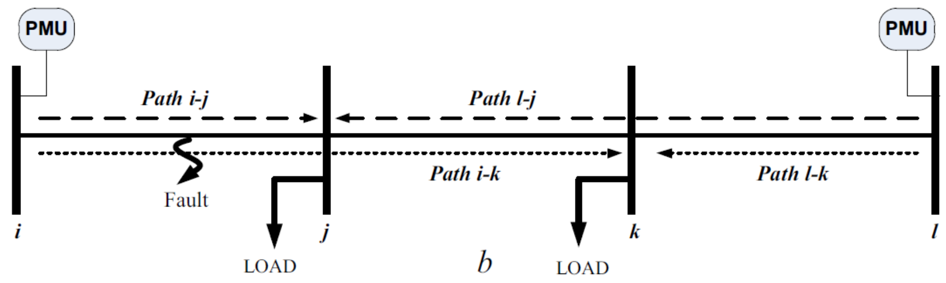
$$X_{Fi} = \frac{1}{\gamma_{ij}L_{ij}}\tanh^{-1}\left\{\frac{V_i - V_j\cosh(\gamma_{ij}L_{ij}) + Z_{C_{ij}}\sinh(\gamma_{ij}L_{ij})I_j}{Z_{C_{ij}}I_i + Z_{C_{ij}}\cosh(\gamma_{ij}L_{ij})I_j - V_j\sinh(\gamma_{ij}L_{ij})}\right\} \quad (4)$$

$$V_k = \cosh(\gamma L_{ki})V_i - Z_C\sinh(\gamma L_{ki})I_{ki} \quad (5)$$

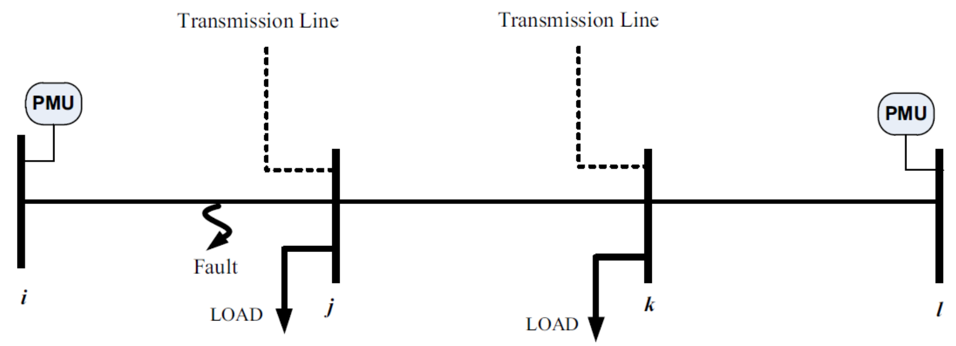
# Wide-Area Backup Protection Using Current Phasors (cont.):

- ❑ Proposed current-based wide-area backup protection:
- ✓ Considering more complicated line connections:

**Cascade lines**



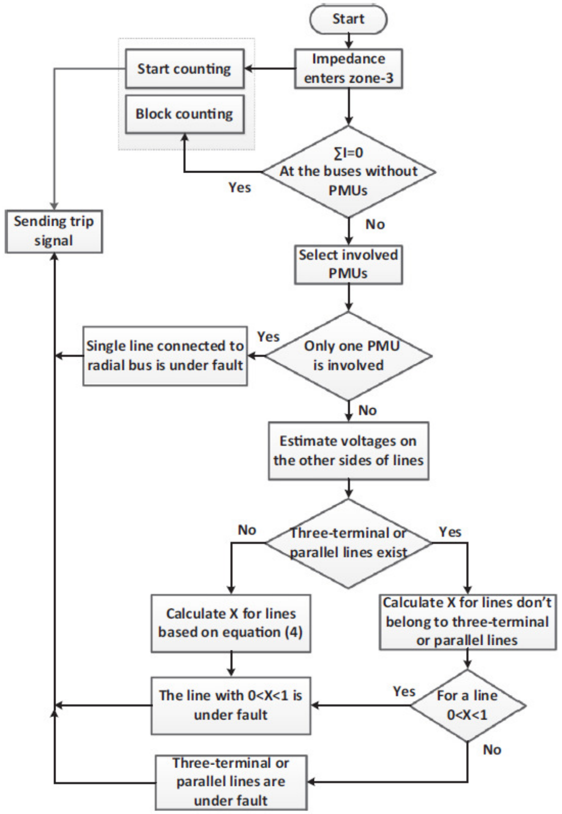

**Non-cascade lines**



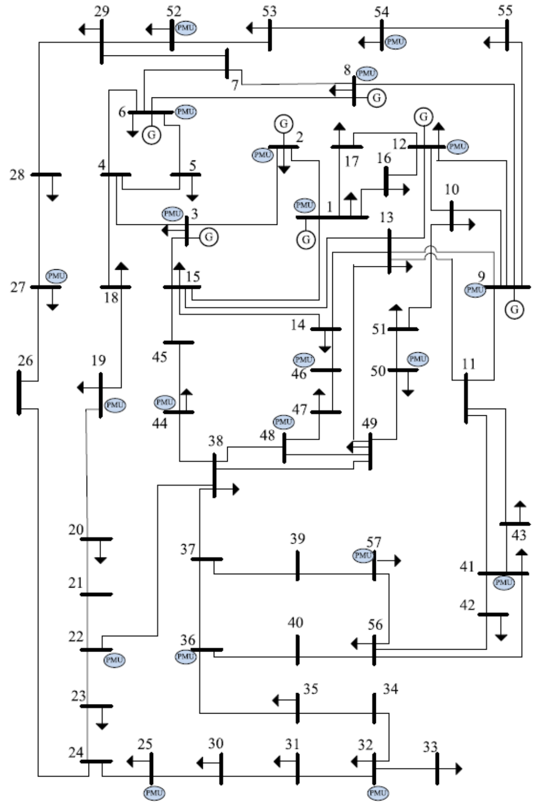
# Wide-Area Backup Protection Using Current Phasors (cont.):

- Proposed current-based wide-area backup protection:

**Proposed Algorithm**




**Simulated Network**



# Wide-Area Backup Protection Using Current Phasors (cont.):

- Proposed current-based wide-area backup protection:

**Obtained Results**

| Faulted line | Fault characteristics | | | Max $\lvert\Sigma I\rvert$ (A) | Involved buses | Faulted line detection |
|---|---|---|---|---|---|---|
| | Type | Location | R (Ω) | | | |
| Line 1–16 | AG | 50% | 0.1 | 60 | 1, 12 | ✓ |
| | AB | 10% | 10 | 520 | | ✓ |
| | ABG | 90% | 50 | 87 | | ✓ |
| Line 32–33 | BG | 50% | 0.1 | 47 | 32 | ✓ |
| | BCG | 10% | 10 | 137 | | ✓ |
| | AC | 90% | 5 | 103 | | ✓ |
| Line 28–29 | AG | 50% | 0.1 | 190 | 27, 52 | ✓ |
| | BC | 10% | 10 | 400 | | ✓ |
| | ABC | 90% | 5 | 1300 | | ✓ |
| Line 42–56 | ACG | 50% | 0.1 | 43 | 36, 41, 57 | ✓ |
| | AG | 10% | 10 | 42 | | ✓ |
| | BC | 90% | 5 | 154 | | ✓ |

# Publications on Wide-Area Backup Protection:


- J. Zare, F. Aminifar and M. Sanaye-Pasand, “Synchrophasor-Based Wide-Area Backup Protection Scheme with Data Requirement Analysis,” *IEEE Trans. Power Delivery*, vol. 30, no. 3, pp. 1410-1419, June 2015.

- J. Zare, F. Aminifar and M. Sanaye-Pasand, “Communication-Constrained Regionalization of Power Systems for Synchrophasor-Based Wide-Area Backup Protection Scheme,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1530-1538, May 2015.

- A. Sharafi, M. Sanaye-Pasand and F. Aminifar, “Transmission System Wide-Area Backup Protection Using Current Phasor Measurements,” *International Journal of Electrical Power & Energy Systems*, vol. 92, pp. 93-103, Nov. 2017.

# Wide-Area Fault Location

# Wide-Area Fault Location:

Wide-area fault location is defined as the process of determining the short-circuit fault identity, i.e.,

- Fault Type
- Faulted Line
- Fault Distance on the Faulted Line

using available synchronized data.

# Wide-Area Fault Location (cont.):

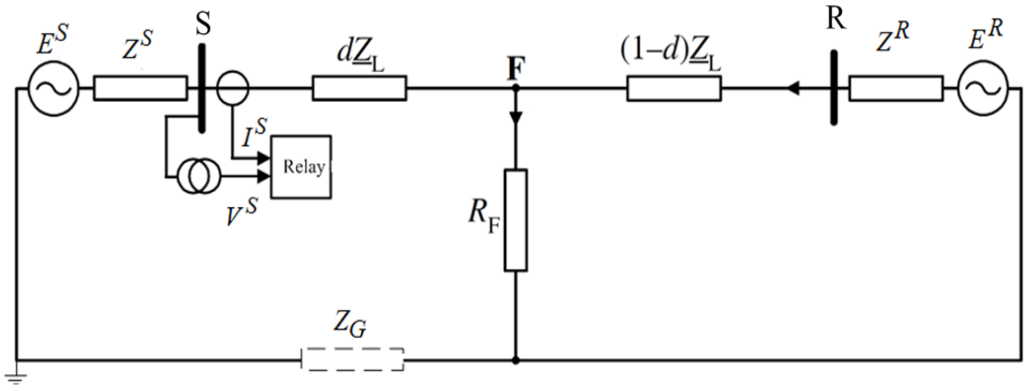
## ❑ Why Fault Location?

- Temporary but frequent short-circuit faults (to identify line’s weak spots)
- Permanent faults (to resolve the issue)
- Blackouts (urgent need to restore the power system)
- Evaluation of the protection system performance

# Wide-Area Fault Location (cont.):

## ❑ Conventional Fault Location

- Are Distance Relays Enough? (speed-accuracy trade-off)

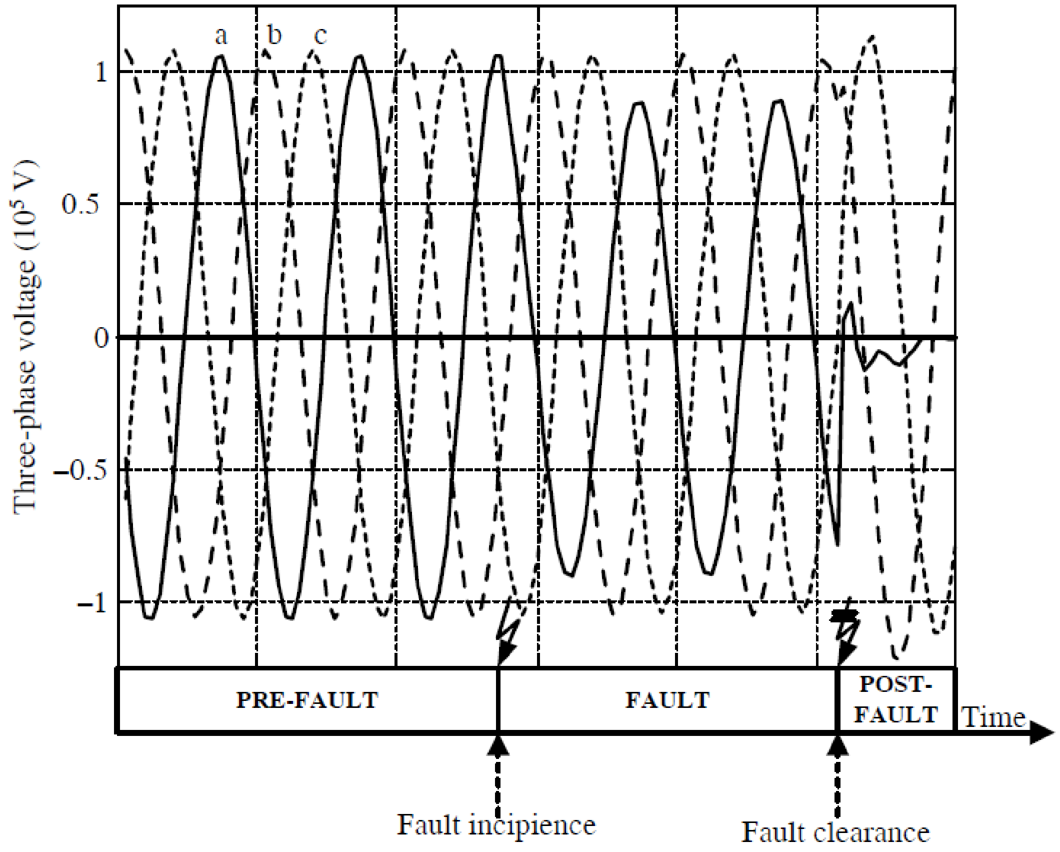



What we obtain from distance relays: $dZ_L = \dfrac{V_a^S}{I_a^S + kI_0^S}$

Real fault distance: $dZ_L = \dfrac{V_a^S}{I_a^S + kI_0^S} - R_F \dfrac{(I_0^S + I_0^R)}{I_a^S + kI_0^S}$

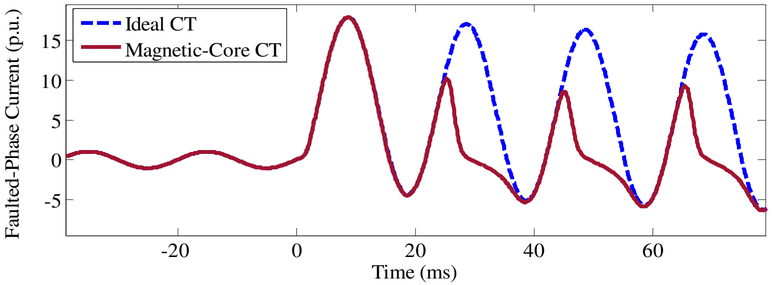
# Wide-Area Fault Location (cont.):

- **Conventional Fault Location**
  - One-terminal
  - Two-terminal
- **Instrument Transformers' Problems**
  - Saturation
  - Transient response
  - Steady-state errors

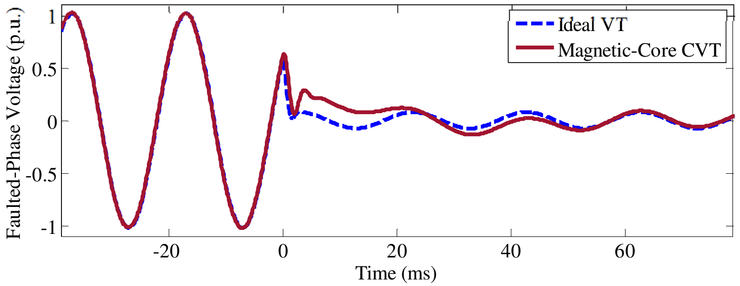


# Wide-Area Fault Location (cont.):

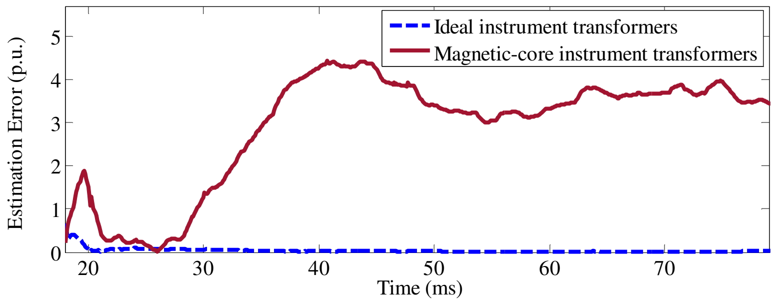
- **Conventional Fault Location:** A single-phase to ground fault at 90% of line 21-22 of IEEE 39-bus test system



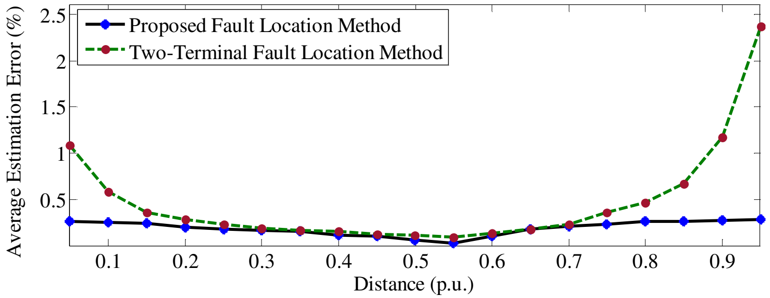

**Faulted-phase current obtained using ideal and magnetic-core current transformers at terminal 22.**




**Faulted-phase voltage obtained using ideal and magnetic-core capacitive voltage transformers at terminal 22.**




**Estimation error of conventional two-terminal method using ideal and magnetic-core instrument transformers.**

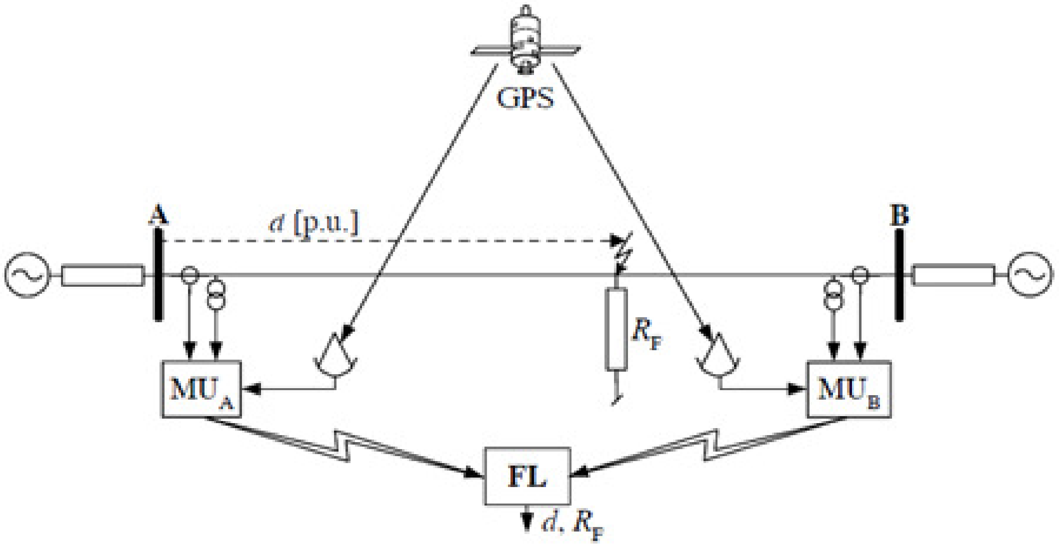



**Estimation error of conventional two-terminal and proposed methods for various short-circuit faults on line 21-22.**

# Wide-Area Fault Location (cont.):

## ❑ Why Wide-Area Fault Location?

- Redundancy of fault equations: Bad data detection
- Ready application of WAMS



# Wide-Area Fault Location (cont.):

## ❑ Deficiencies of Existing Wide-Area Fault Location Methods

- Faulted line is to be pre-specified for many of the existing methods
  - ✓ Normally, the faulted line can be distinguished from the circuit breakers status and commands of protective relays (PRs)
  - ✓ In blackouts, CBs and/or PRs misoperation or malfunction are amongst the root causes of the problem

- Nonlinearity of the bus impedance matrix and fault equations could easily give rise to
  - ✓ Non-convergence
  - ✓ Trapping in local optima
  - ✓ Huge computational burden

- Many of current practices impose strict constraints over PMU locations

# Wide-Area Fault Location (cont.):

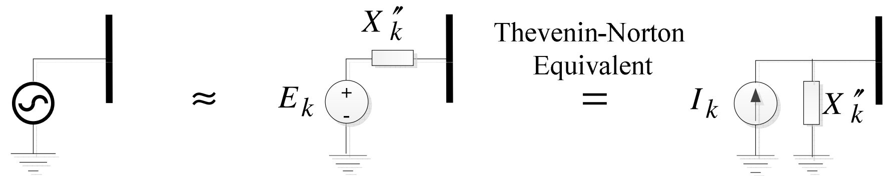
## ❑ Proposed Wide-Area Fault Location Methods

- For AC transmission networks
- For DC transmission networks

# Proposed Wide-Area Fault Location on AC Networks:

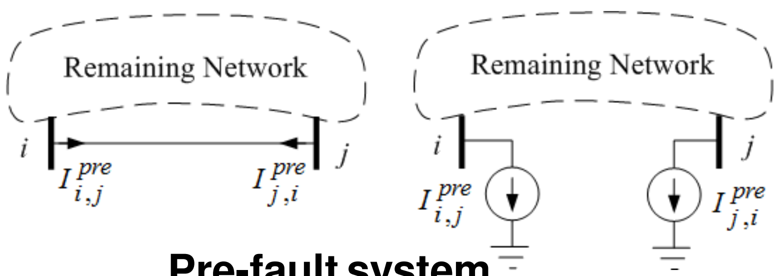
## ❑ Application of Basic Circuit Theory in Modeling the Problem

- ***Thevenin-Norton Equivalent Theorem***:

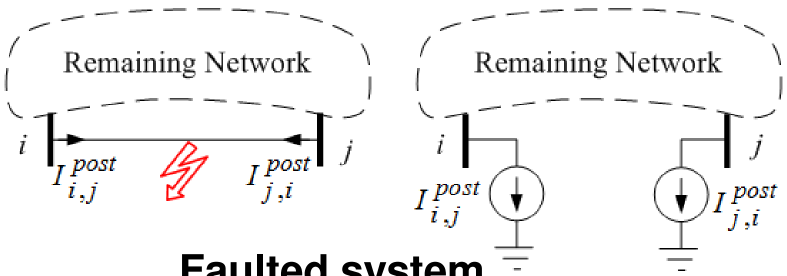



**Electric machine modeling**

- ***Substitution Theorem***: Faulted line is replaced with two suitable current sources injecting the same amount of currents before and after fault inception.




**Pre-fault system**




**Faulted system**

- ***Superposition Theorem***: For all linear systems the net response at a given place and time caused by two or more stimuli is the sum of the responses which would have been caused by each stimulus individually.

# Proposed Wide-Area Fault Location on AC Networks (cont.):

## ❑ Proposed Linear Framework for Wide-Area Fault Location

1- Calculating superimposed currents of suspected line

$$\underbrace{\begin{bmatrix} \Delta V_1^{meas} \\ \vdots \\ \Delta V_{Nb}^{meas} \\ \Delta J_1^{meas} \\ \vdots \\ \Delta J_{Nh}^{meas} \\ \Delta J_{Nh+1}^{meas} \\ \Delta J_{Nh+2}^{meas} \end{bmatrix}}_{(Nb+Nl)\times 1} = -\underbrace{\begin{bmatrix} Z_{1,i}^{(i-j)} & Z_{1,j}^{(i-j)} \\ \vdots & \vdots \\ Z_{Nb,i}^{(i-j)} & Z_{Nb,j}^{(i-j)} \\ C_1^{i,j} & C_1^{j,i} \\ \vdots & \vdots \\ C_{Nh}^{i,j} & C_{Nh}^{j,i} \\ -1 & 0 \\ 0 & -1 \end{bmatrix}}_{(Nb+Nl)\times 2} \times \underbrace{\begin{bmatrix} \Delta I_{i,j} \\ \Delta I_{j,i} \end{bmatrix}}_{2\times 1} + \underbrace{\begin{bmatrix} e_1^V \\ \vdots \\ e_M^V \\ e_1^J \\ \vdots \\ e_{Nh}^J \\ e_{Nh+1}^J \\ e_{Nh+2}^J \end{bmatrix}}_{(Nb+Nl)\times 2}$$

2- Calculating superimposed voltage at suspected line terminals

$$\begin{bmatrix} \Delta \hat{V}_i \\ \Delta \hat{V}_j \end{bmatrix} = -\begin{bmatrix} Z_{i,i}^{(i-j)} & Z_{i,j}^{(i-j)} \\ Z_{j,i}^{(i-j)} & Z_{j,j}^{(i-j)} \end{bmatrix} \times \begin{bmatrix} \Delta \hat{I}_{i,j} \\ \Delta \hat{I}_{j,i} \end{bmatrix}$$

3-Identifying the faulted line

$$\underbrace{\boldsymbol{M}}_{Nm\times 1} = \underbrace{\boldsymbol{H}}_{Nm\times 2}\ \underbrace{\boldsymbol{X}}_{2\times 1} + \underbrace{\boldsymbol{e}}_{Nm\times 1} \qquad \boldsymbol{H}_{left}^{-1} = \left(\boldsymbol{H}^T\boldsymbol{H}\right)^{-1}\boldsymbol{H}^T$$

$$\boldsymbol{X} = \underbrace{\boldsymbol{H}_{left}^{-1}\boldsymbol{M}}_{\hat{\boldsymbol{X}}} - \boldsymbol{H}_{left}^{-1}\boldsymbol{e}$$

$$\boldsymbol{r} = \boldsymbol{M} - \boldsymbol{H}\hat{\boldsymbol{X}}$$

Vector of residuals

$$min\left(\boldsymbol{r}^t\boldsymbol{r}\right)$$

Minimum sum of squared residuals corresponds to the faulted line

4- Fault distance on the faulted line

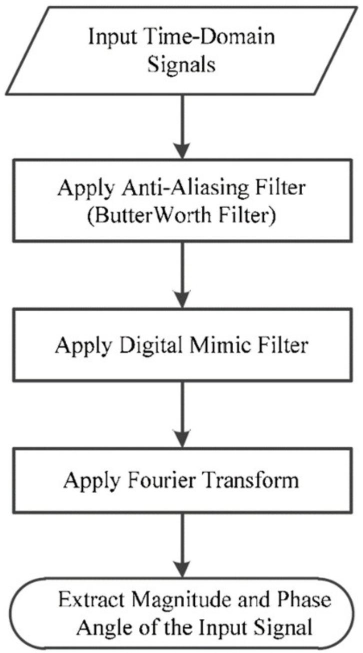
$$\alpha_{i,j} = \frac{\tanh^{-1}\left(\dfrac{\cosh(\gamma_{i-j}l_{i-j})\Delta\hat{V}_j - Z_{i-j}^c\sinh(\gamma_{i-j}l_{i-j})\Delta\hat{J}_{j,i} - \Delta\hat{V}_i}{\sinh(\gamma_{i-j}l_{i-j})\Delta\hat{V}_j - Z_{i-j}^c\cosh(\gamma_{i-j}l_{i-j})\Delta\hat{J}_{j,i} - Z_{i,j}^c\Delta\hat{J}_{i,j}}\right)}{\gamma_{i-j}l_{i-j}}$$

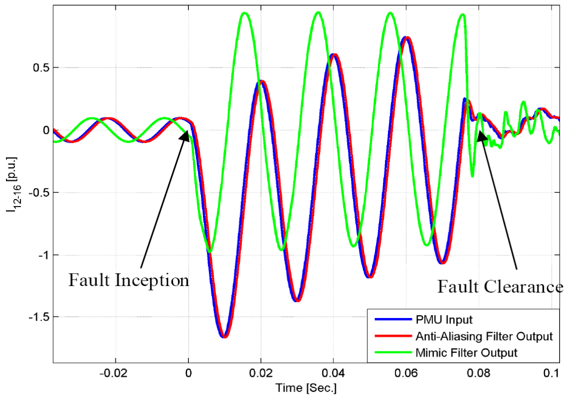
Closed form solution for fault distance

# Proposed Wide-Area Fault Location on AC Networks (cont.):

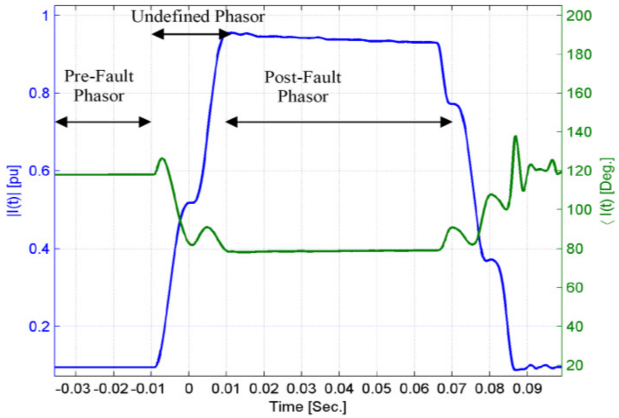
## ❑ Phasor Extraction from Time-Domain Signals

**PMU Model**




**Time-domain signals**




**Extracted signals' phasors magnitude and phase angle**

Fault Simulation in DIgSILENT (Time Domain)

↓

Signals Phasor Extraction in MATLAB

↓

Proposed Algorithm

↓

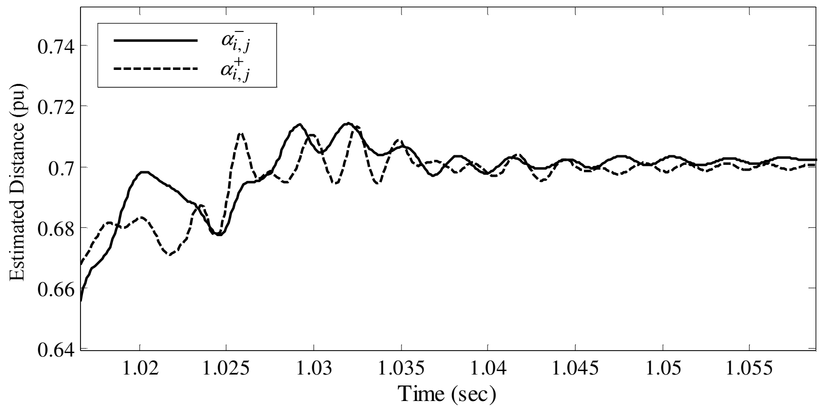
Fault Identity

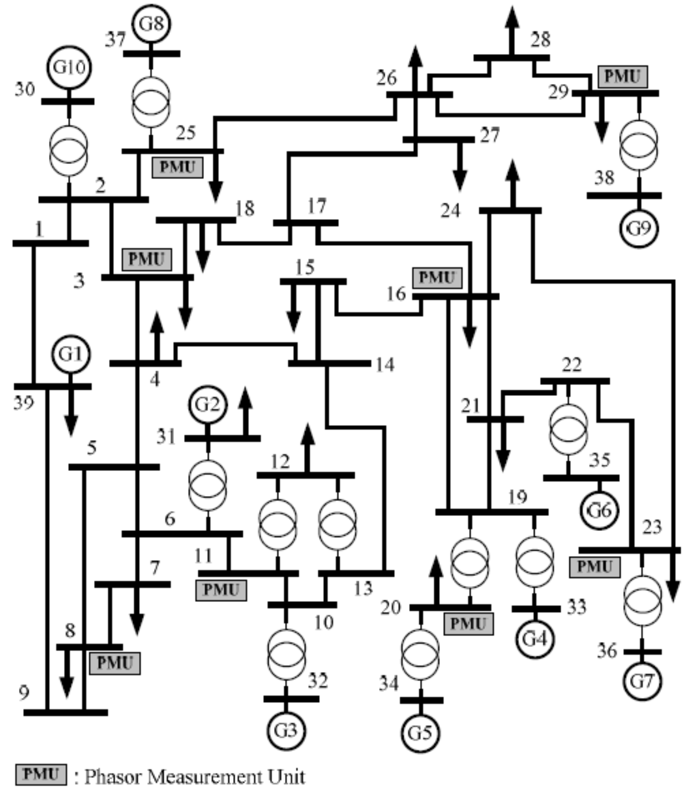
# Proposed Wide-Area Fault Location on AC Networks (cont.):

## ❑ Results of Wide-Area Fault Location on 39-bus System

FAULT LOCATION RESULTS ON 39-BUS TEST SYSTEM

| Fault Resistance (Ω) | 0 | 10 | 25 | 50 | 100 |
|---|---|---|---|---|---|
| Fault Type | Average Estimation Error % | | | | |
| 1-ph-g | 0.1493 | 0.1667 | 0.1754 | 0.1915 | 0.2243 |
| 2-ph | 0.1156 | 0.1218 | 0.1173 | 0.1194 | 0.1248 |
| 2-ph-g | 0.1457 | 0.1499 | 0.1572 | 0.1501 | 0.1631 |
| 3-ph-g | 0.0782 | 0.0764 | 0.0791 | 0.0807 | 0.0862 |
| All in Total | 0.1222 | 0.1287 | 0.1322 | 0.1354 | 0.1496 |



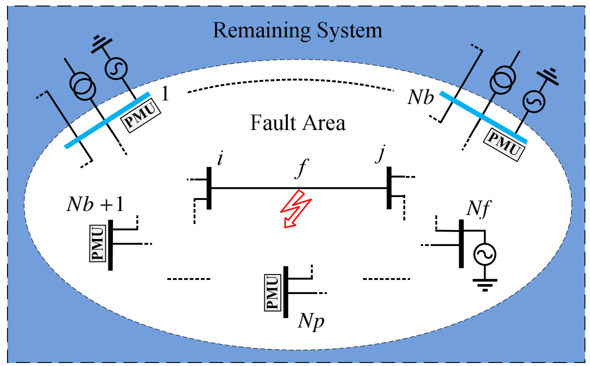

Time varying nature of estimated fault distance due to system dynamics

# Proposed Wide-Area Fault Location on AC Networks (cont.):

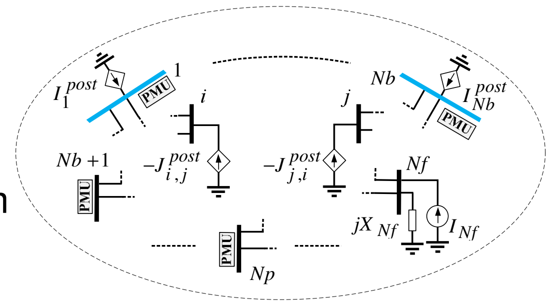
## ❑ Extraction of a Stand-Alone Fault Sub-System from the Fault Area

$$\underbrace{\begin{bmatrix} \Delta V_1^{meas} \\ \vdots \\ \Delta V_{Np}^{meas} \\ \Delta I_1^{meas} \\ \vdots \\ \Delta I_{Nb}^{meas} \\ \Delta J_1^{meas} \\ \vdots \\ \Delta J_{Nh}^{meas} \\ \Delta J_{Nh+1}^{meas} \\ \Delta J_{Nh+2}^{meas} \end{bmatrix}}_{(Ns)\times 1} = \underbrace{\begin{bmatrix} -\begin{bmatrix} Z_{1,i}^{(i,j)} & Z_{1,j}^{(i,j)} \\ \vdots & \vdots \\ Z_{Np,i}^{(i,j)} & Z_{Np,j}^{(i,j)} \end{bmatrix} & \begin{bmatrix} Z_{1,1}^{(i,j)} & \vdots & Z_{1,Nb}^{(i,j)} \\ \vdots & \ddots & \vdots \\ Z_{Np,1}^{(i,j)} & \cdots & Z_{Np,Nb}^{(i,j)} \end{bmatrix} \\ [\boldsymbol{0}]_{(Nb\times 2)} & [\boldsymbol{I}]_{(Nb\times Nb)} \\ -\begin{bmatrix} C_{1,i}^{(i,j)} & C_{1,j}^{(i,j)} \\ \vdots & \vdots \\ C_{Nh,i}^{(i,j)} & C_{Nh,j}^{(i,j)} \end{bmatrix} & \begin{bmatrix} C_{1,1}^{(i,j)} & \vdots & C_{1,Nb}^{(i,j)} \\ \vdots & \ddots & \vdots \\ C_{Nh,1}^{(i,j)} & \cdots & C_{Nh,Nb}^{(i,j)} \end{bmatrix} \\ [\boldsymbol{I}]_{(2\times 2)} & [\boldsymbol{0}]_{(2\times Nb)} \end{bmatrix}}_{(Ns)\times(Nb+2)} \times \underbrace{\begin{bmatrix} \Delta J_{i,j} \\ \Delta J_{j,i} \\ \Delta I_1 \\ \vdots \\ \Delta I_{Nb} \end{bmatrix}}_{(Nb+2)\times 1} + \underbrace{\begin{bmatrix} e_1^V \\ \vdots \\ e_{Np}^V \\ e_1^I \\ \vdots \\ e_{Nb}^I \\ e_1^J \\ \vdots \\ e_{Nh}^J \end{bmatrix}}_{(Ns)\times 1}$$

Entire Power System



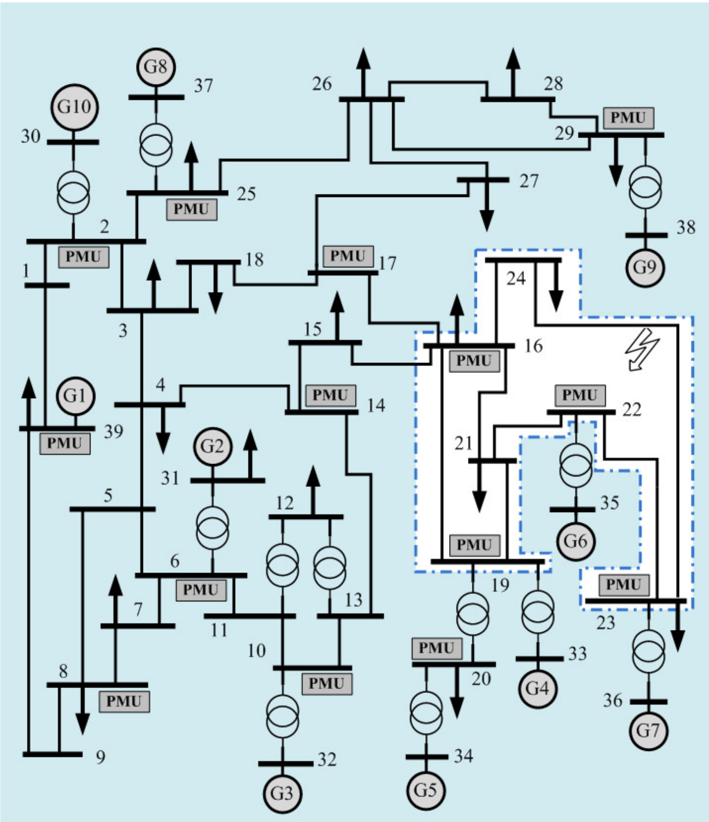

Fault Sub-System




- ✓ Fault sub-system is derived by representing the remaining system from its boundary terminals with suitable current sources.
- ✓ All current and voltage equations are used thereby providing the highest possible redundancy.

# Proposed Wide-Area Fault Location on AC Networks (cont.):

## ❑ Advantages of Focusing on the Fault Sub-System




It is neither always possible nor even useful to model the whole system for fault location on a single transmission line

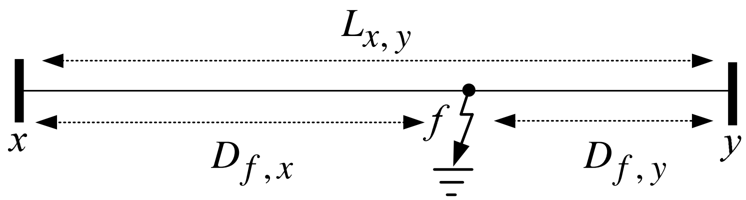
- ✓ The remaining system from the boundary terminals viewpoint is modeled as time-varying current sources
- ✓ Many modeling difficulties and associated technical problems are thus eliminated
- ✓ It is sufficient but not necessary to have PMUs at all boundary terminals
- ✓ PMUs not so close nor so far from the fault point would serve best in wide-area fault location

# Proposed Wide-Area Fault Location on DC Networks:

## ❑ Traveling Wave Based Wide-Area Fault Location

### Traveling Wave Features:

- ✓ First arrival
- ✓ Polarity
- ✓ Energy
- ✓ Subsequent arrival




$$L_{x,y} = D_{f,x} + D_{f,y}$$

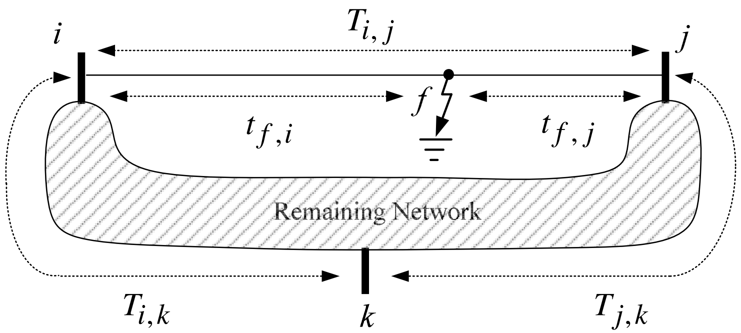
$$t_x^m = t_0 + \frac{D_{f,x}}{v_{x,y}}, \qquad t_y^m = t_0 + \frac{D_{f,y}}{v_{x,y}}$$

### Traveling Wave Fault Location:

- ✓ Two-terminal method

### Wide-Area Fault Location:

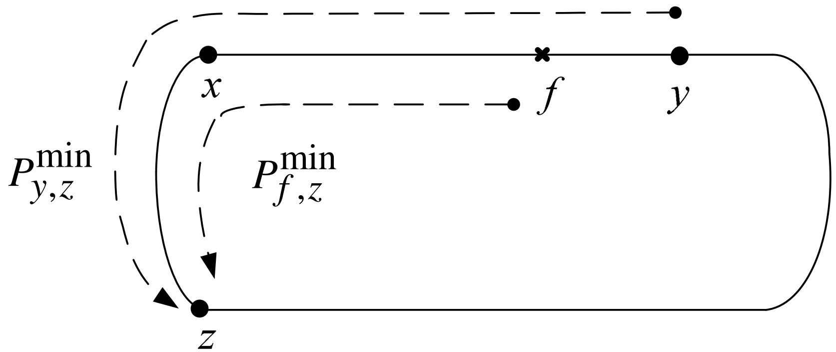
- ✓ Change in shortest paths
- ✓ Attractive for MTDC systems
- ✓ Practicality (first arrival)



# Proposed Wide-Area Fault Location on DC Networks (cont.):

## ❑ Two Useful Lemmas for Sectionalizing the Power System

**Lemma I:** If the shortest path between two arbitrary nodes *x* and *y* traverses a point *f* on the graph, this path is equivalent to the union of the shortest path between *x* and *f*, and the one between *f* and *y*.

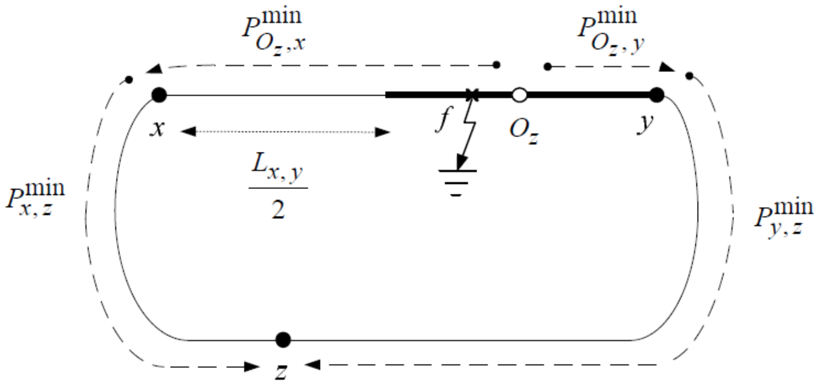



**Lemma II:** Assume there is a branch between two nodes *x* and *y*. If there is a shortest path between *y* and *z* traversing node *x*, then for any arbitrary point *f* on branch (*x*,*y*), the shortest path between f and *z* would traverse node *x* too.

# Proposed Wide-Area Fault Location on DC Networks (cont.):

## ❑ Forming a System of Linear Equations for Fault Location

**The above lemmas are used to sectionalize the graph representation of the network**




- ✓ A system of linear equations to locate the fault occurred on any segment

$$\begin{cases} t_i^m - T_{x,i} = t_0 + t_{f,x} & \forall i \in \boldsymbol{I}_x^{(r,s)} \\ t_i^m - T_{y,i} - T_{x,y} = t_0 - t_{f,x} & \forall i \in \boldsymbol{I}_y^{(r,s)} \end{cases}$$

$$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{H}_x^{(r,s)} \\ \boldsymbol{H}_y^{(r,s)} \end{bmatrix} \times \begin{bmatrix} t_0 \\ t_{f,x} \end{bmatrix}$$

- ✓ A suitable index to figure out on which segment the fault has happened

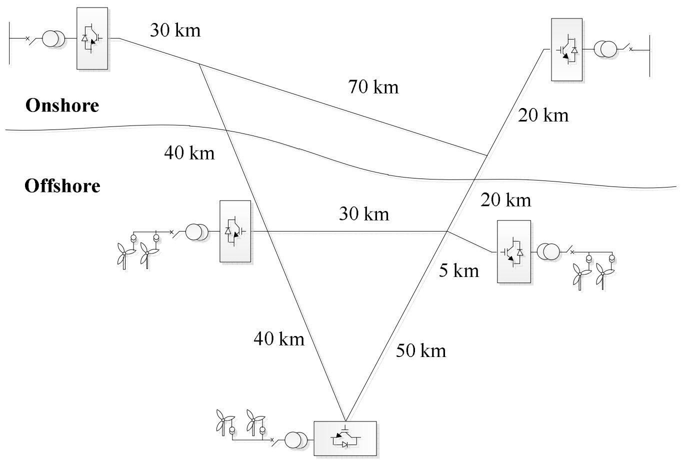
$$\sum_{\forall i,j \in \boldsymbol{I}_x^{r,s}} \left| (t_i^m - t_j^m) - (T_{x,i} - T_{x,j}) \right| + \sum_{\forall i,j \in \boldsymbol{I}_y^{r,s}} \left| (t_i^m - t_j^m) - (T_{y,i} - T_{y,j}) \right|.$$

# Proposed Wide-Area Fault Location on DC Networks (cont.):

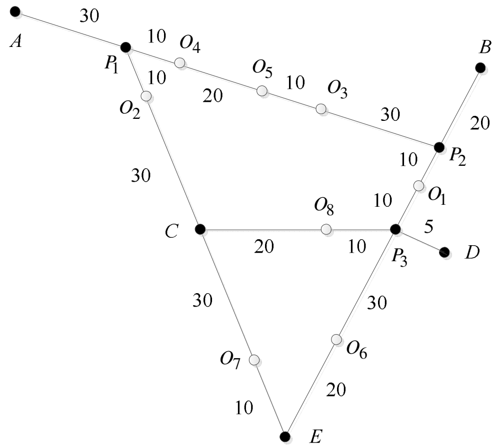
## ❑ Wide-Area Fault Locations on Multi Terminal DC Systems

EFFECT OF SAMPLING FREQUENCY ON FAULT LOCATION ACCURACY

| Sampling Frequency | Fault Location Error (%) | | | | | |
|---|---|---|---|---|---|---|
| | Avg. | Max. | Avg. | Max. | Avg. | Max. |
| | Without Noise | | SNR=60 db | | SNR=40 db | |
| 10 MHz | 0.0135 | 0.0612 | 0.0141 | 0.0714 | 0.0139 | 0.0671 |
| 5 MHz | 0.0421 | 0.1046 | 0.0426 | 0.1245 | 0.0433 | 0.1338 |
| 1MHz | 0.0955 | 0.1568 | 0.0997 | 0.1721 | 0.0984 | 0.1883 |
| 500 kHz | 0.2815 | 0.6262 | 0.3036 | 0.7278 | 0.3168 | 0.7169 |
| 250KHz | 0.5792 | 1.0879 | 0.5843 | 1.1017 | 0.5915 | 1.1115 |



(a)



(b)

# Features:

- ✓ Applicable to networks with complicated topologies
- ✓ Robust against fault resistance and noise contamination
- ✓ Not requiring exact equipment model, just the system topology and surge velocity

# Wide-Area Fault Location (cont.):

## ❑ Main Advantages

- Concerns about high computational burden and algorithm failure in finding the solution are eliminated (thanks to appropriate selection of auxiliary variables)
- A limited number of synchrophasors just for few cycles is sufficient to accurately pinpoint the fault distance (observability is not a necessity)
- Identification of the faulted line and fault type in spite of circumventing zero sequence quantities
- Accurate results even in the case of large fault resistance
- Applicable to untransposed power networks
- Bad data detection and elimination can be easily handled in the proposed linear context
- Fast fault location (in the order of several milliseconds) without any simplifying assumptions on both AC and DC networks

# Wide-Area Fault Location (cont.):

## Achievements

- Following techniques were proposed for the first time:

- A technique to make the bus impedance matrix unchanged before and after fault occurrence
- Use of the sum of squared residual for identification of the faulted line
- Fault type identification without using zero sequence quantities
- A network reduction techniques without requiring the topology data and operating point of the portions being replaced
- Sectionalizing a graph so that the shortest path from any point on each segment to all other nodes are pre-determined
- Solvability analysis by taking into account the partially uniquely solvable system of equations

# Publications on Wide-Area Fault Location:

- S. Azizi and M. Sanaye-Pasand, “From Available Synchrophasor Data to Short-Circuit Fault Identity: Formulation and Feasibility Analysis,” *IEEE Trans. Power Systems*, 2016.
- S. Azizi M. Sanaye-Pasand and M. Paolone,, “Locating Faults on Untransposed, Meshed Transmission Networks Using a Limited Number of Synchrophasor Measurements,” *IEEE Trans. Power Systems,* 2016.
- S. Azizi and M. Sanaye-Pasand,, “A Straightforward Method for Wide-Area Fault Location on Transmission Networks,” *IEEE Trans. Power Delivery,* 2015.
- S. Azizi, M Sanaye-Pasand, M. Abedini and A Hasani, “A New Traveling Wave-Based Methodology for Wide-Area Fault Location on Multi-Terminal DC Systems” *IEEE Trans. Power Delivery*, 2014.
- S. Azizi, S. Afsharnia, and M. Sanaye-Pasand,, “Fault Location on Multi-Terminal DC Systems using Synchronized Current Measurements,” *International Journal of Electrical Power and Energy Systems*, *Elsevier*, 2014.

# Wide-Area Combined UFLS/UVLS Schemes

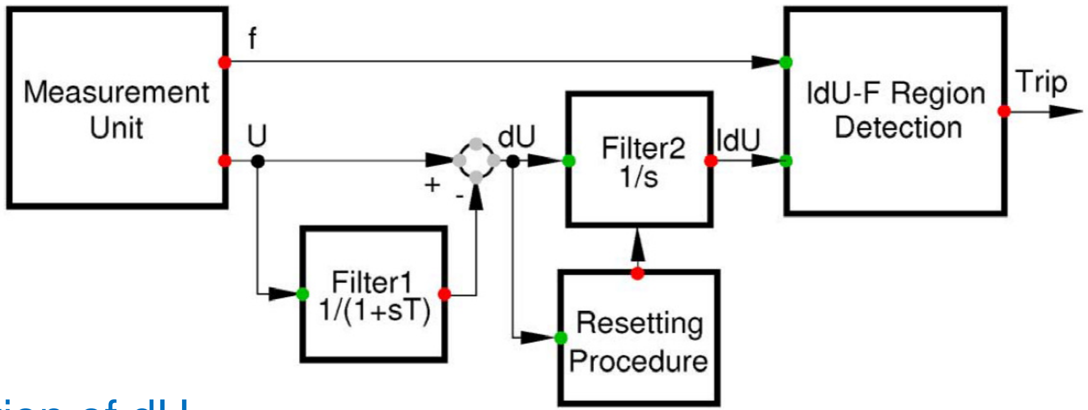
## Wide-Area Combined UFLS/UVLS Schemes:

- UFLS/UVLS: Preventive Actions against Frequency/Voltage instability
- Conventional UFLS and UVLS shortcomings:
  - ✓ Relying on local measurements even in case of wide-area disturbances
  - ✓ Independent functions even in case of combined frequency/voltage disturbances in highly stressed systems
  - ✓ Curtailing fixed amounts of load regardless of disturbance intensity: Over shedding
- Properties of combinational Frequency/Voltage instability events:
  - ✓ Speed of frequency decline is lower than speed of voltage decline
  - ✓ Fast voltage decline decreases the voltage dependent loading of the system
  - ✓ Frequency drop may not be enough to activate UFLS relays
  - ✓ UFLS relays are blocked in case of large voltage drops
  - ✓ In spite of successful frequency recovery by UFLS, the system may collapse due to voltage instability

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ First Proposed Method

- Considering the frequency/voltage correlation in combinational events
- General block diagram of the proposed combinational load shedding methods:

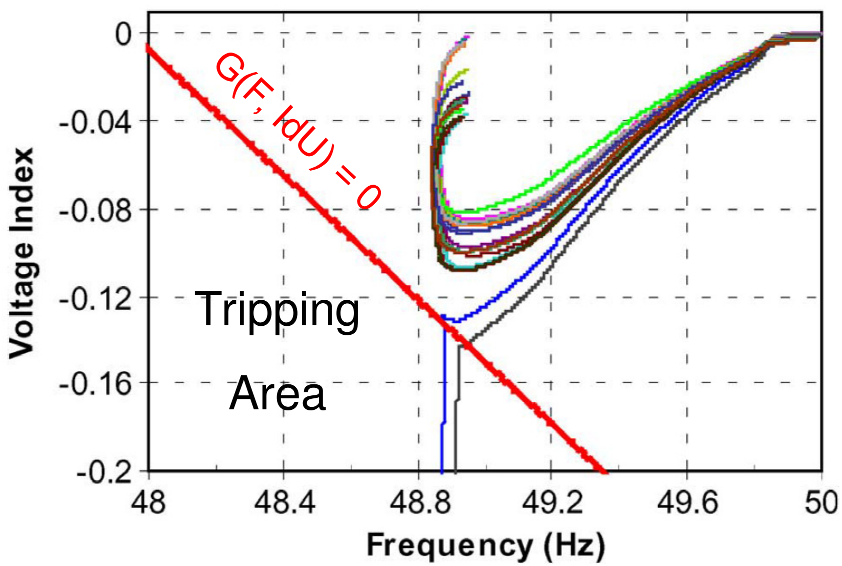



  - ✓ F: system frequency
  - ✓ dU: voltage decline
  - ✓ IdU: voltage index signal
  - ✓ Filter1: Delay (~3s) for calculation of dU
  - ✓ Filter2: Considering duration of dU for faster load shedding in longer voltage declines

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ First Proposed Method

- Calculation of IdU-F Region for various buses:



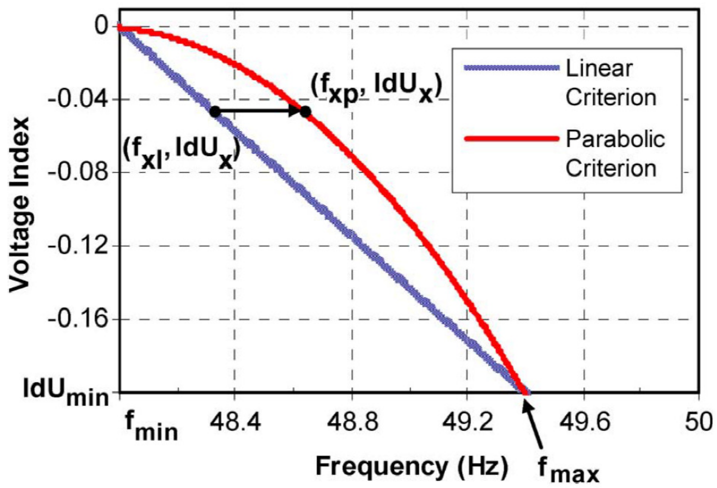

- Load Shedding Criterion: G(F, IdU)<0

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

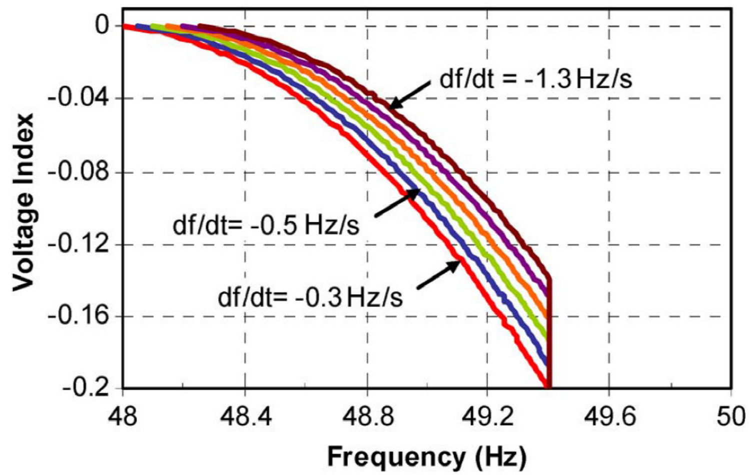
## ❑ First Proposed Method

- The boundary of load shedding. i.e. G(F, IdU)=0, can be estimated as linear, parabolic, and 3-D curves, in order to consider the voltage dependency of loads and the disturbance intensity.

Linear and Parabolic Criteria




3-D (F, IdU, dF/dt) Criteria

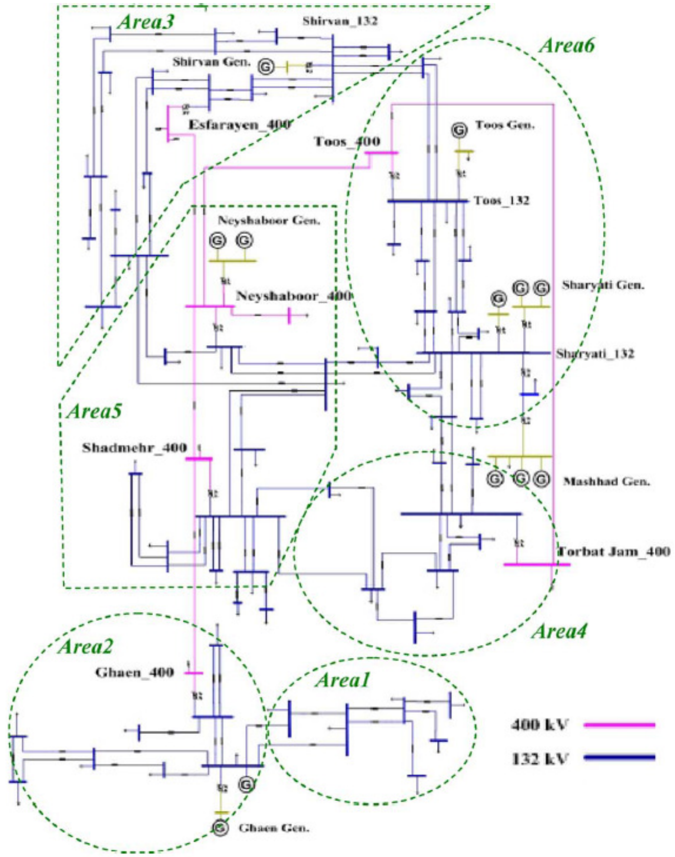


# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ First Proposed Method

- Simulation Results:

Khorasan 400 and 132 kV Network

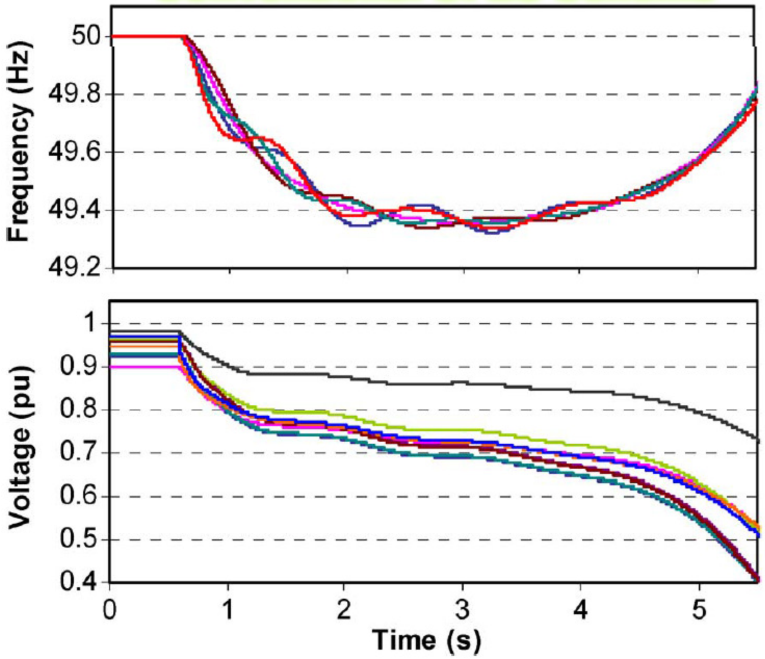


# Wide-Area Combined UFLS/UVLS Schemes (cont.):

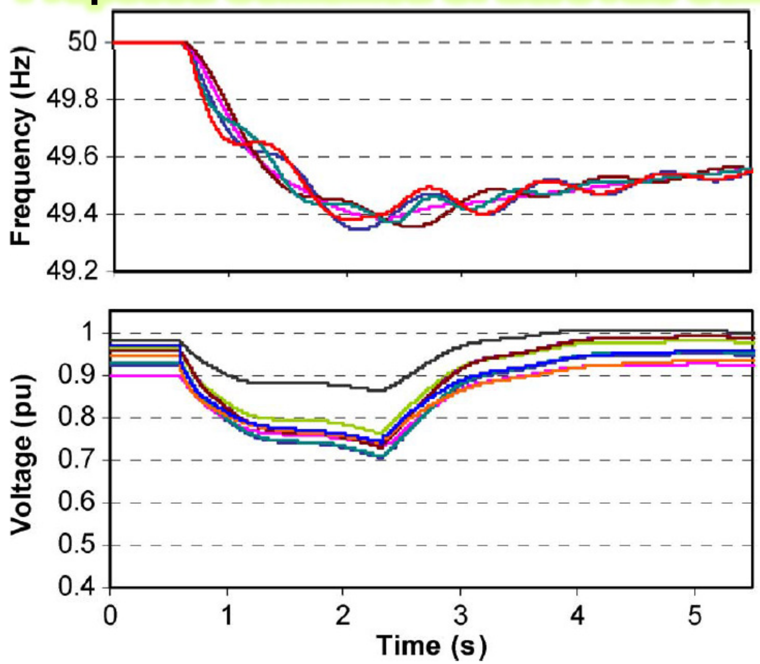
## ❑ First Proposed Method

- An example of simulation results: Loss of generation at Toos power plant while the Toos-Neyshabur line is out of service.

**Conventional UFLS Scheme**




**Proposed Combined UFLS/UVLS Scheme**



## Wide-Area Combined UFLS/UVLS Schemes (cont.):

### ❑ Second Proposed Method

- Centralized load shedding using the following Steps:

✓ Ranking all sub-transmission buses of the system in the control center according to their VQ margins (every few minutes).

✓ Activating the UVLS module by the control center for any bus whose voltage falls below 0.8 p.u.

✓ Calculation of frequency and its rate of change at all generator terminals of the system.

✓ Selection of the loads to be shed based on the VQ ranking.

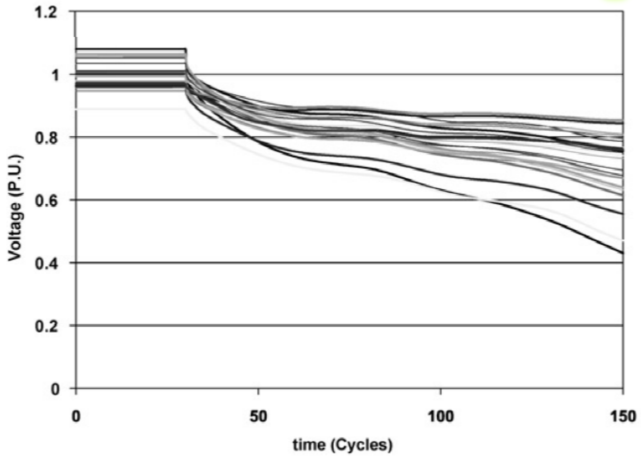
✓ Determining the load-shedding speed based on dF/dt.

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

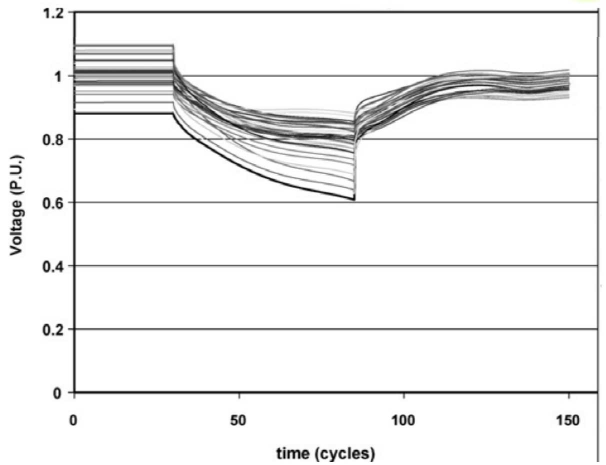
## ❑ Second Proposed Method

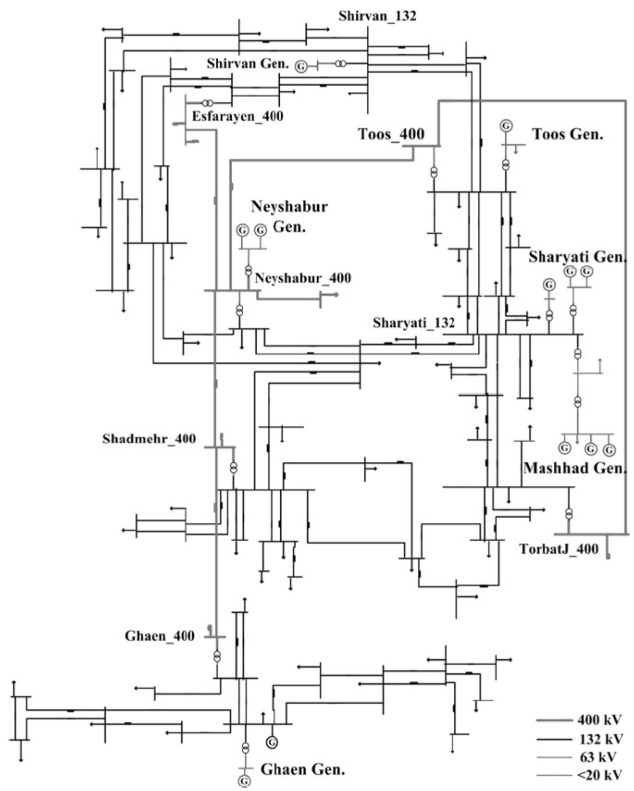
- An example of simulation results:

**Conventional Load Shedding**




**Centralized Load Shedding**



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Third Proposed Method

- Adaptive Wide-Area Load Shedding Incorporating Real-Time Limitations:

| Stages | Tasks |
|---|---|
| Requirement analysis (RA) | • Analyze information requirements for execution of the proposed scheme and check the adequacy of the existing measurement configuration.<br>• Sizing and placement of reactive power equipment, if necessary, in three steps, as follows: 1) perform contingencies analysis to identify trouble spots; 2) develop appropriate control strategies as supplementary corrective actions for some severe under-frequency contingencies; and 3) install specified reactive power control equipment at determined substations. |

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Third Proposed Method

- Adaptive Wide-Area Load Shedding Incorporating Real-Time Limitations:

| Stages | Tasks |
|---|---|
| Pre-disturbance preparation (PP) | • Take snapshots of data periodically and run SE program in each period in order to monitor the power network.<br>• Screen and rank contingencies based on the SE model.<br>• Create a solution pool for dealing with credible contingencies.<br>• Validate and evaluate different possible solutions by applying a set of criteria and arrange a lookup table. |

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Third Proposed Method

- Adaptive Wide-Area Load Shedding Incorporating Real-Time Limitations:

| Stages | Tasks |
|---|---|
| Real-time (RT) | • Monitor the status of circuit breakers using indication data.<br>• Analyze network topology and detect event type.<br>• Shed predetermined loads according to the lookup table from the PP stage.<br>• Perform post load shedding strategies from the PP stage. |

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Third Proposed Method

- Proposed formulation for adaptive Load Shedding problem:

$$\min \sum_{i} \sum_{m_i} \underbrace{X_{i,m_i}}_{\text{Binary variable for load shedding}} \cdot \underbrace{C_{i,m_i}}_{\text{Cost of load shedding at bus i}} \tag{1}$$

Subject to:

$$C_{i,m_i} = \lambda_{i,m_i} \cdot P^D_{i,m_i} \tag{2}$$

$$P^{D^*}_{i,m_i} = P^D_{i,m_i} \left[ PF^{PZ}_{i,m_i} (V_i^*/V_i)^2 + PF^{PI}_{i,m_i} (V_i^*/V_i) + PF^{PP}_{i,m_i} \right] \tag{3}$$

$$Q^{D^*}_{i,m_i} = Q^D_{i,m_i} \left[ PF^{QZ}_{i,m_i} (V_i^*/V_i)^2 + PF^{QI}_{i,m_i} (V_i^*/V_i) + PF^{QP}_{i,m_i} \right] \tag{4}$$

$$P^{\text{shed}} - \xi \le \sum_i \sum_{m_i} X_{i,m_i} \cdot P^{D^*}_{i,m_i} \le P^{\text{shed}} + \xi \tag{5}$$

$$P_i^G - \sum_{m_i} (1 - X_{i,m_i}) \cdot P^{D^*}_{i,m_i} = \sum_k G_{i,k} V_i^* V_k^* \cos(\varphi_{i,k}) + \sum_k B_{i,k} V_i^* V_k^* \sin(\varphi_{i,k}) \tag{6}$$

$$Q_i^G - \sum_{m_i} (1 - X_{i,m_i}) \cdot Q^{D^*}_{i,m_i} + E_i \cdot Q_i^{PC}/q_i = \sum_k G_{i,k} V_i^* V_k^* \sin(\varphi_{i,k}) - \sum_k B_{i,k} V_i^* V_k^* \cos(\varphi_{i,k}) \tag{7}$$

$$P^l_{i,k} = \frac{R^l_{i,k} (V_i^*)^2}{(R^l_{i,k})^2 + (X^l_{i,k})^2} - \frac{R^l_{i,k} (V_i^* V_k^*)}{(R^l_{i,k})^2 + (X^l_{i,k})^2} \cos(\varphi_{i,k}) + \frac{X^l_{i,k} (V_i^* V_k^*)}{(R^l_{i,k})^2 + (X^l_{i,k})^2} \sin(\varphi_{i,k}) \tag{8}$$

$$-\bar{P}^l_{i,k} \le P^l_{i,k} \le \bar{P}^l_{i,k} \tag{9}$$

$$\underline{V}_i \le V_i^* \le \bar{V}_i. \tag{10}$$

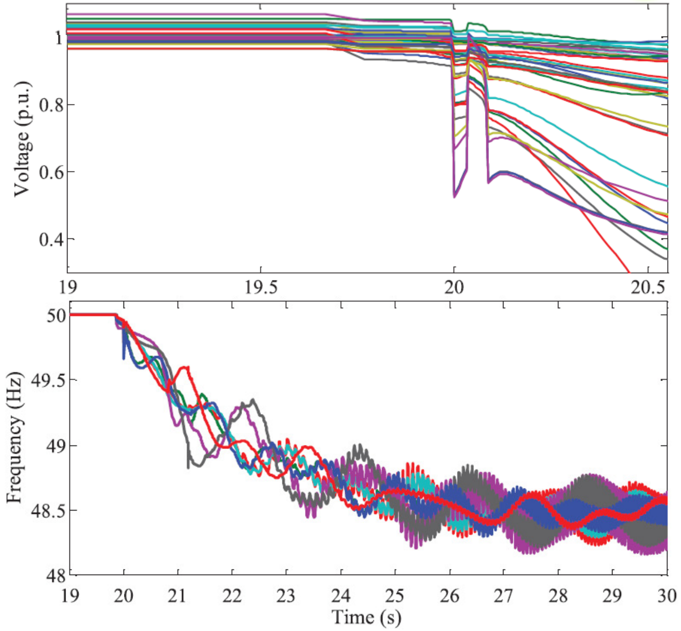
# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Third Proposed Method

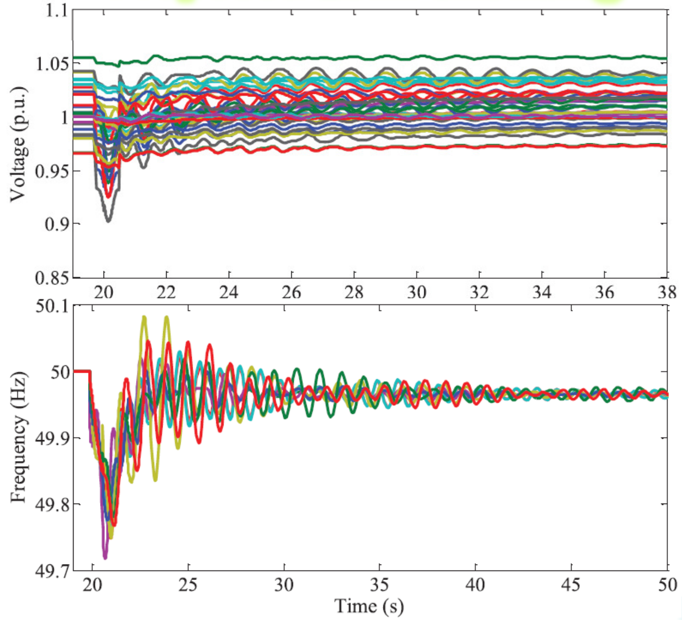
- Simulation on the IEEE 39-bus test system:

**Event:** ***Outage of generator 32 after disconnection of line 21-22***

**Conventional Load Shedding**




**Proposed Load Shedding**



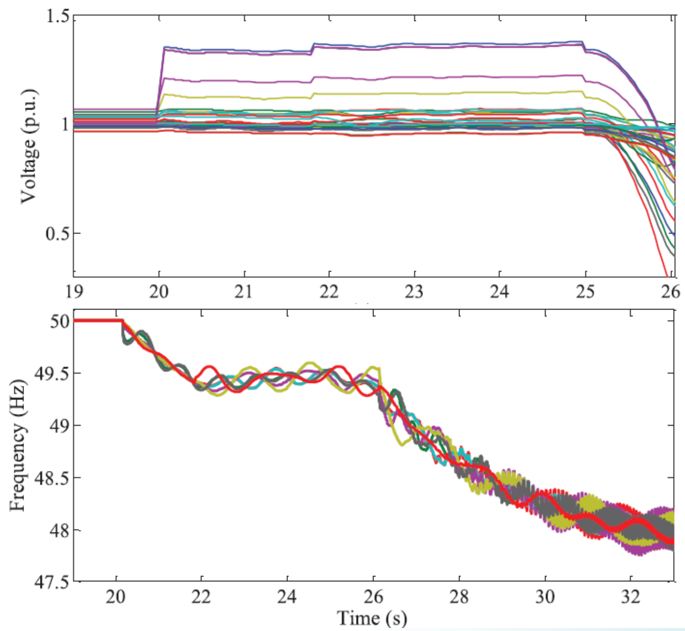
# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Third Proposed Method

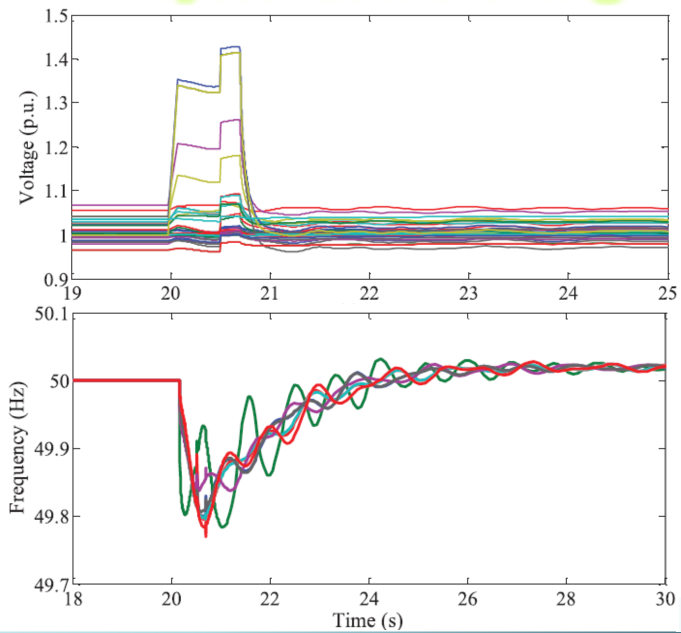
- Simulation on the IEEE 39-bus test system:

**Event:** ***Outage of generator 38***

**Conventional Load Shedding**




**Proposed Load Shedding**



## Wide-Area Combined UFLS/UVLS Schemes (cont.):

### ❑ Third Proposed Method

- Main features and advantages:

✓ Recovering the frequency into the allowable range

✓ Minimizing the interruption cost of rejected loads

✓ Developing an adaptive framework satisfying RT operational limitations

✓ Implementation of appropriate post load shedding strategies with the purpose of preserving the system stability after the execution of load shedding

✓ Requiring a limited set of data

✓ Pproposing a linear formulation to tackle computational challenges

## Wide-Area Combined UFLS/UVLS Schemes (cont.):

- **Fourth Proposed Method**

Two-Unit Wide-Area Adaptive Load Shedding based on Synchrophasors:

**Unit1) Load Drop Amount Calculator (LDAC):** Determines the amount of load rejections by modeling the System Frequency Response (SFR)

**Unit2) Load Shedding Distributor (LSD):** Specifies the best location of load drops based on suitable voltage stability criteria

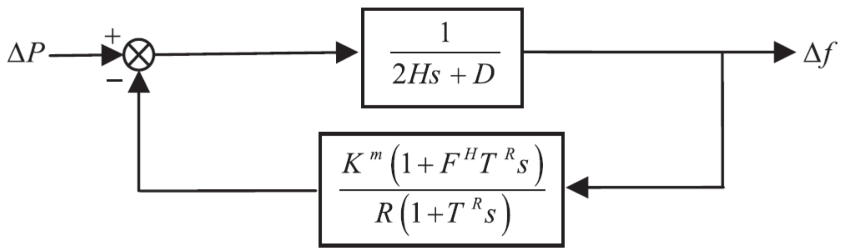
# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

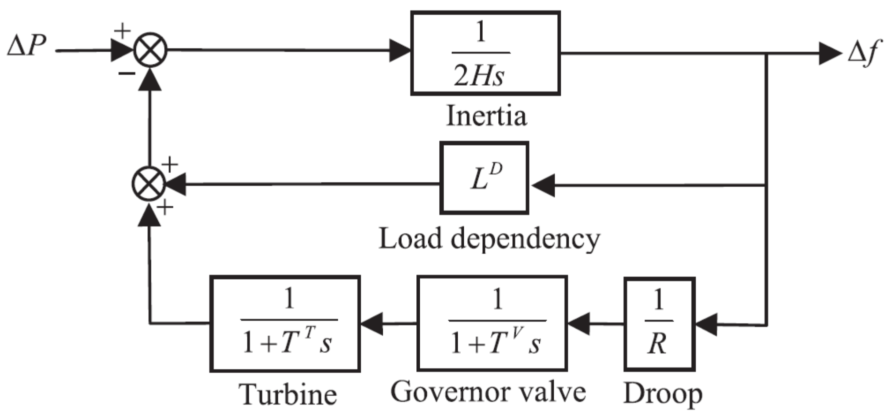
Two-Unit Wide-Area Adaptive Load Shedding based on Synchrophasors:

### SFR Modeling:

**Conventional SFR Model**




**Proposed SFR Model**



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

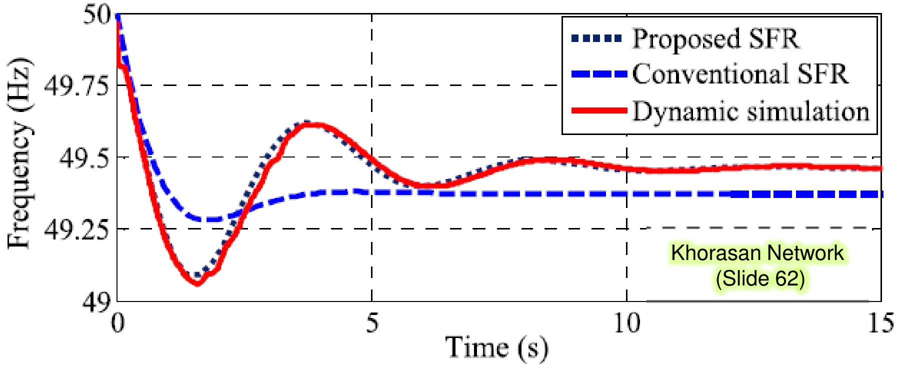
## ❑ Fourth Proposed Method

Two-Unit Wide-Area Adaptive Load Shedding based on Synchrophasors:

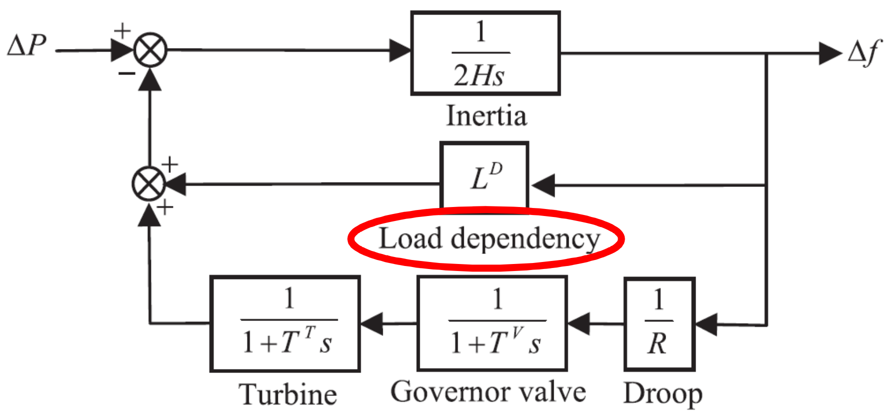
### SFR Modeling:

$$\Delta P_i = \frac{\partial P_i}{\partial V_i}\Delta V_i + \frac{\partial P_i}{\partial f_i}\Delta f_i \qquad L_i^D = K_i \times L_i^{DV} + L_i^{DF}$$

$$K_i = \frac{\frac{\Delta V_i}{V_i^0}}{\frac{\Delta f_i}{f_0}}, L_i^{DV} = \frac{\frac{\partial P_i}{P_i^0}}{\frac{\partial V_i}{V_i^0}}, L_i^{DF} = \frac{\frac{\partial P_i}{P_i^0}}{\frac{\partial f_i}{f_0}} \qquad L^D = \frac{\sum_i L_i^D \times S_i}{\sum_i S_i}$$




**Proposed SFR Model**



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

Two-Unit Wide-Area Adaptive Load Shedding based on Synchrophasors:

**Minimum Amount of Load Rejection:**

$$\Delta f(t) = -\Delta P^{out} \times A(t) + \Delta P^{shed} \times A(t - t^{shed})$$

Steady State Frequency: $\Delta f_{SSF}^{\max} = \lim \Delta f(t) = \left(-\Delta P^{out} + \Delta P_{SSF}^{shed}\right) k_1$

$$\Delta P_{SSF}^{shed} = \Delta f_{SSF}^{\max} \left(L^D + \frac{1}{R}\right) + \Delta P^{out}$$

Minimum Dynamic Frequency: $\left.\frac{d\Delta f(t)}{dt}\right|_{t=t^{\min}} = 0 \qquad \Delta f(t^{\min}) = \Delta f_{MDF}^{\max}$

$$\boxed{\Delta P^{shed} = \max\left\{\Delta P_{MDF}^{shed}, \Delta P_{SSF}^{shed}\right\}}$$

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

Two-Unit Wide-Area Adaptive Load Shedding based on Synchrophasors:

**Load Shedding Distribution (LSD):**

LSD unit employs two indices for ranking the load shedding candidate buses:

**1) Voltage Stabiity Criterion (VSC):** $VSC_i = \exp\left(\frac{|VFR_i|}{V_i}\right)$ VFR: Voltage Falling Rate

**2) Power Tracing Criterion (PT):** $PT_m = PT_m^R + PT_m^I$

$$PT_m^R = \sum_{i \in G_{trip}} I_{im}^{RG} + \sum_{ij \in L_{lost}} I_{ijm}^{R}$$

$$PT_m^I = \sum_{i \in G_{trip}} I_{im}^{IG} + \sum_{ij \in L_{lost}} I_{ijm}^{I}$$

***i, j, m***: Given buses

# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

### Simulation on the New England network:

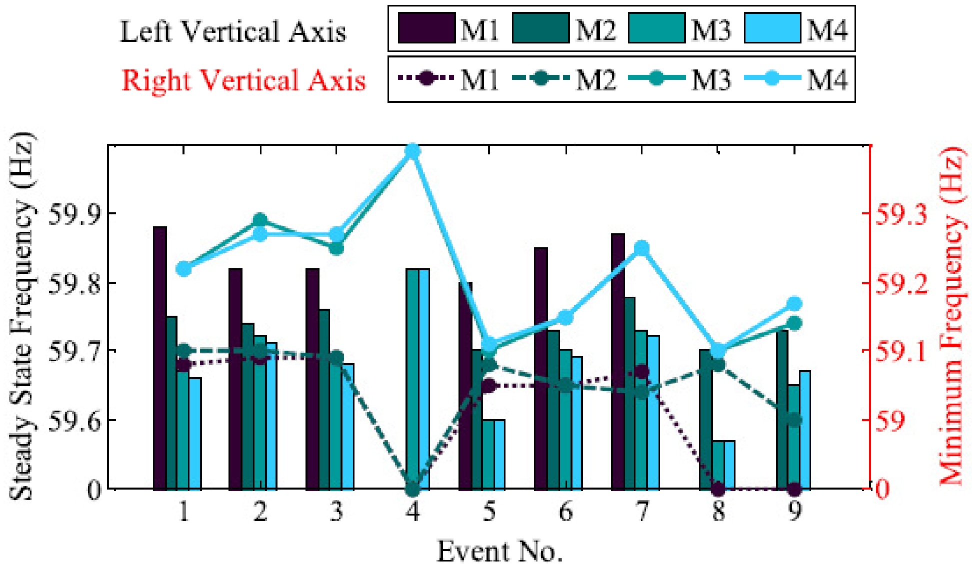
**Simulated Contingencies**

| Event No. | Event description |
|---|---|
| 1 | Outage of generator 31 (575 MW). |
| 2 | Outage of generator 31 while line 2-3 is out of service. |
| 3 | Short circuit (t=0), disconnection of line 6-11(t=100 ms) and outage of generator 31 (t=300 ms). |
| 4 | Short circuit (t=0), disconnection of line 6-11 (t=100 ms) and outage of generator 31 (t=300 ms) while line 2-3 is out of service. |
| 5 | Outage of generator 32 (650 MW). |
| 6 | Outage of generator 32 while line 2-3 is out of service. |
| 7 | Short circuit (t=0), disconnection of line 10-11 (t=100 ms) and outage of generator 32 (t=300 ms) while line 2-3 is out of service. |
| 8 | Outage of generator 32 while generator 31 is out of service. |
| 9 | Outage of generators 31 and 32. |

**Simulated Load Shedding Methods**

| Method | Load shedding amount | Load shedding distribution |
|---|---|---|
| M1 | Conventional UFLS relays | Conventional UFLS relays |
| M2 | Second Proposed Method | Second Proposed Method |
| M3 | LDAC unit | Voltage stability criterion |
| M4 | LDAC unit | Power tracing criterion |

Fourth Proposed Method



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

### Simulation on the New England network:

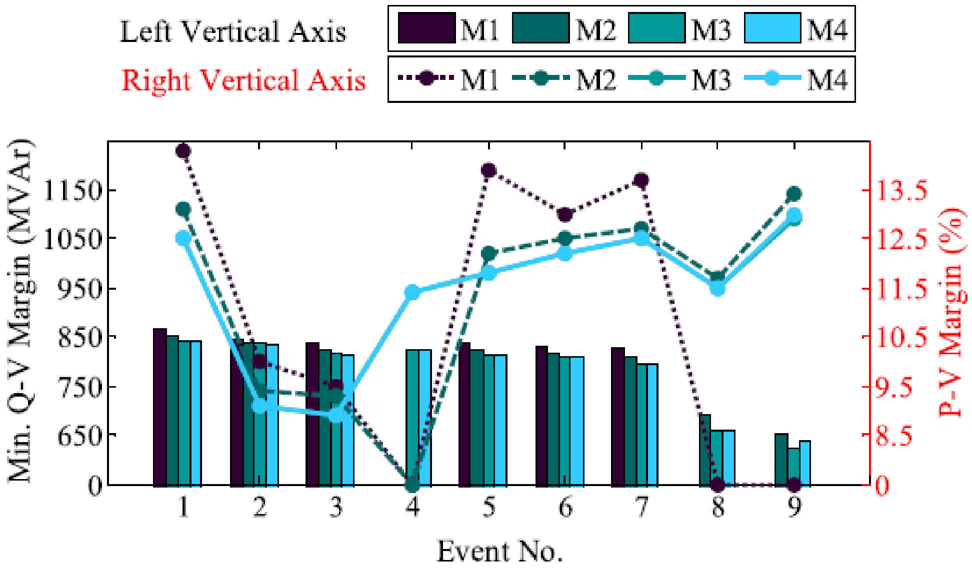
**Simulated Contingencies**

| Event No. | Event description |
|---|---|
| 1 | Outage of generator 31 (575 MW). |
| 2 | Outage of generator 31 while line 2-3 is out of service. |
| 3 | Short circuit (t=0), disconnection of line 6-11(t=100 ms) and outage of generator 31 (t=300 ms). |
| 4 | Short circuit (t=0), disconnection of line 6-11 (t=100 ms) and outage of generator 31 (t=300 ms) while line 2-3 is out of service. |
| 5 | Outage of generator 32 (650 MW). |
| 6 | Outage of generator 32 while line 2-3 is out of service. |
| 7 | Short circuit (t=0), disconnection of line 10-11 (t=100 ms) and outage of generator 32 (t=300 ms) while line 2-3 is out of service. |
| 8 | Outage of generator 32 while generator 31 is out of service. |
| 9 | Outage of generators 31 and 32. |

**Simulated Load Shedding Methods**

| Method | Load shedding amount | Load shedding distribution |
|---|---|---|
| M1 | Conventional UFLS relays | Conventional UFLS relays |
| M2 | Second Proposed Method | Second Proposed Method |
| M3 | LDAC unit | Voltage stability criterion |
| M4 | LDAC unit | Power tracing criterion |

Fourth Proposed Method



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

### Simulation on the New England network:

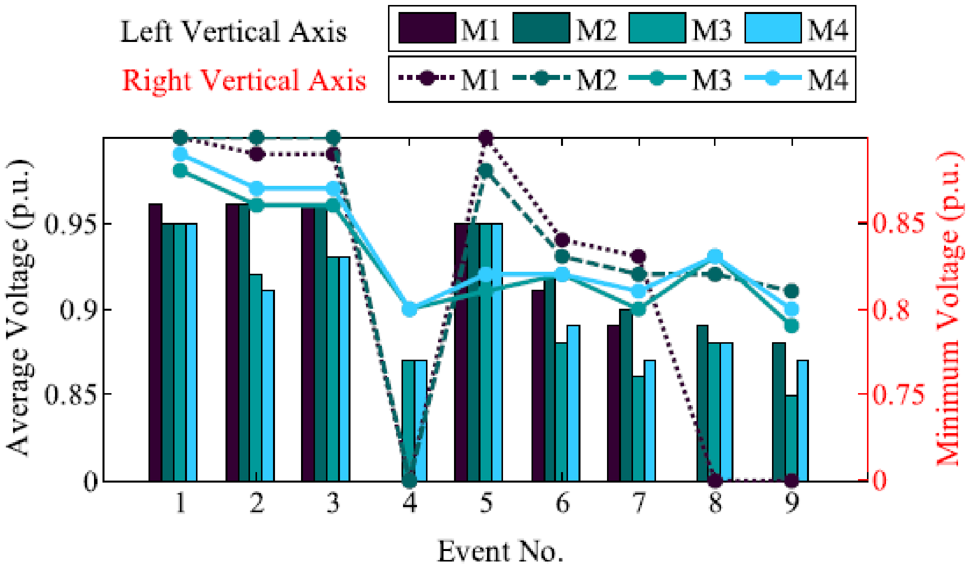
**Simulated Contingencies**

| Event No. | Event description |
|---|---|
| 1 | Outage of generator 31 (575 MW). |
| 2 | Outage of generator 31 while line 2-3 is out of service. |
| 3 | Short circuit (t=0), disconnection of line 6-11(t=100 ms) and outage of generator 31 (t=300 ms). |
| 4 | Short circuit (t=0), disconnection of line 6-11 (t=100 ms) and outage of generator 31 (t=300 ms) while line 2-3 is out of service. |
| 5 | Outage of generator 32 (650 MW). |
| 6 | Outage of generator 32 while line 2-3 is out of service. |
| 7 | Short circuit (t=0), disconnection of line 10-11 (t=100 ms) and outage of generator 32 (t=300 ms) while line 2-3 is out of service. |
| 8 | Outage of generator 32 while generator 31 is out of service. |
| 9 | Outage of generators 31 and 32. |

**Simulated Load Shedding Methods**

| Method | Load shedding amount | Load shedding distribution |
|---|---|---|
| M1 | Conventional UFLS relays | Conventional UFLS relays |
| M2 | Second Proposed Method | Second Proposed Method |
| M3 | LDAC unit | Voltage stability criterion |
| M4 | LDAC unit | Power tracing criterion |

Fourth Proposed Method



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

### Simulation on the New England network:

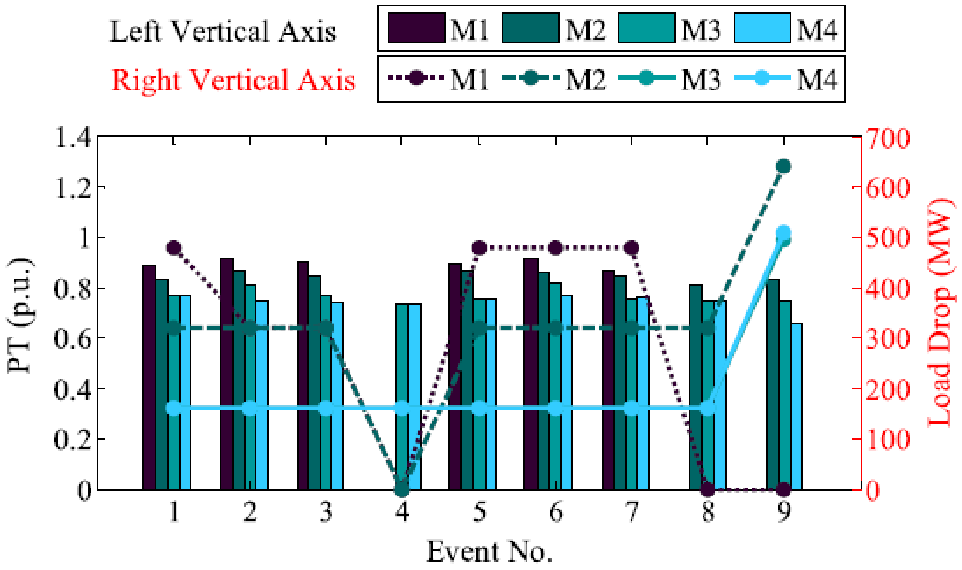
**Simulated Contingencies**

| Event No. | Event description |
|---|---|
| 1 | Outage of generator 31 (575 MW). |
| 2 | Outage of generator 31 while line 2-3 is out of service. |
| 3 | Short circuit (t=0), disconnection of line 6-11(t=100 ms) and outage of generator 31 (t=300 ms). |
| 4 | Short circuit (t=0), disconnection of line 6-11 (t=100 ms) and outage of generator 31 (t=300 ms) while line 2-3 is out of service. |
| 5 | Outage of generator 32 (650 MW). |
| 6 | Outage of generator 32 while line 2-3 is out of service. |
| 7 | Short circuit (t=0), disconnection of line 10-11 (t=100 ms) and outage of generator 32 (t=300 ms) while line 2-3 is out of service. |
| 8 | Outage of generator 32 while generator 31 is out of service. |
| 9 | Outage of generators 31 and 32. |

**Simulated Load Shedding Methods**

| Method | Load shedding amount | Load shedding distribution |
|---|---|---|
| M1 | Conventional UFLS relays | Conventional UFLS relays |
| M2 | Second Proposed Method | Second Proposed Method |
| M3 | LDAC unit | Voltage stability criterion |
| M4 | LDAC unit | Power tracing criterion |

Fourth Proposed Method



# Wide-Area Combined UFLS/UVLS Schemes (cont.):

## ❑ Fourth Proposed Method

- Main features and advantages:

✓ Shedding less loads in comparison to other techniques

✓ Extending the system frequency response (SFR) model incorporating dynamic load dependency to frequency and voltage conditions

✓ Considering a comprehensive load model for frequency and voltage stability assessments

✓ Satisfying both dynamic and steady state frequency limitations

✓ Ensuring sufficient voltage stability margins

✓ Having practical data requirements

✓ Lower computational burden and communication needs rather than other methods

✓ Proposing two voltage stability criteria for distribution of load curtailments

# Publications on Wide-Area Combined UFLS/UVLS Schemes:


- A. Saffarian and M. Sanaye-Pasand, "Enhancement of Power System Stability Using Adaptive Combinational Load Shedding Methods," *IEEE Trans. Power Systems*, vol. 26, no. 3, pp. 1010-1020, Aug. 2011.
- M. Abedini, M. Sanaye-Pasand and S. Azizi, “Adaptive load shedding scheme to preserve the power system stability following large disturbances,” *IET Generation, Transmission & Distribution*, vol. 8, no. 12, pp. 2124-2133, 12 2014.
- H. Seyedi and M. Sanaye-Pasand, “New Centralized Adaptive Load Shedding Algorithms to Mitigate Power System Blackouts,” *IET Gener. Transm. Distrib.*, vol. 3, no. 1, pp. 99–114, Jan. 2009.
- T. Shekari, A. Gholami, F. Aminifar and M. Sanaye-Pasand, “An Adaptive Wide-Area Load Shedding Scheme Incorporating Power System Real-Time Limitations,” Accepted for publication in *IEEE Systems Journal* .
- T. Shekari, F. Aminifar and M. Sanaye-Pasand, “An Analytical Adaptive Load Shedding Scheme Against Severe Combinational Disturbances,” *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 4135-4143, Sept. 2016.

# Protection of DER-Integrated Microgrids

# Protection Challenges of DER-Integrated Microgrids:

- Onsite generation by DERs offers
  - Reliability, resilience, economics, security, and sustainability enhancement
  - Expansion investments deferment
  - Emission decrement

- The benefits are challenged by technical issues from planning, operation, control, and protection perspectives.

## Protection Challenges of DER-Integrated Microgrids (cont.):

- Bidirectional power flow
  - Sensitivity matters
  - Sympathetic tripping issues
  - Reclosing difficulties
- Low fault-ride-through capability
- Frequent configuration alteration

# Protection Challenges of DER-Integrated Microgrids (cont.):

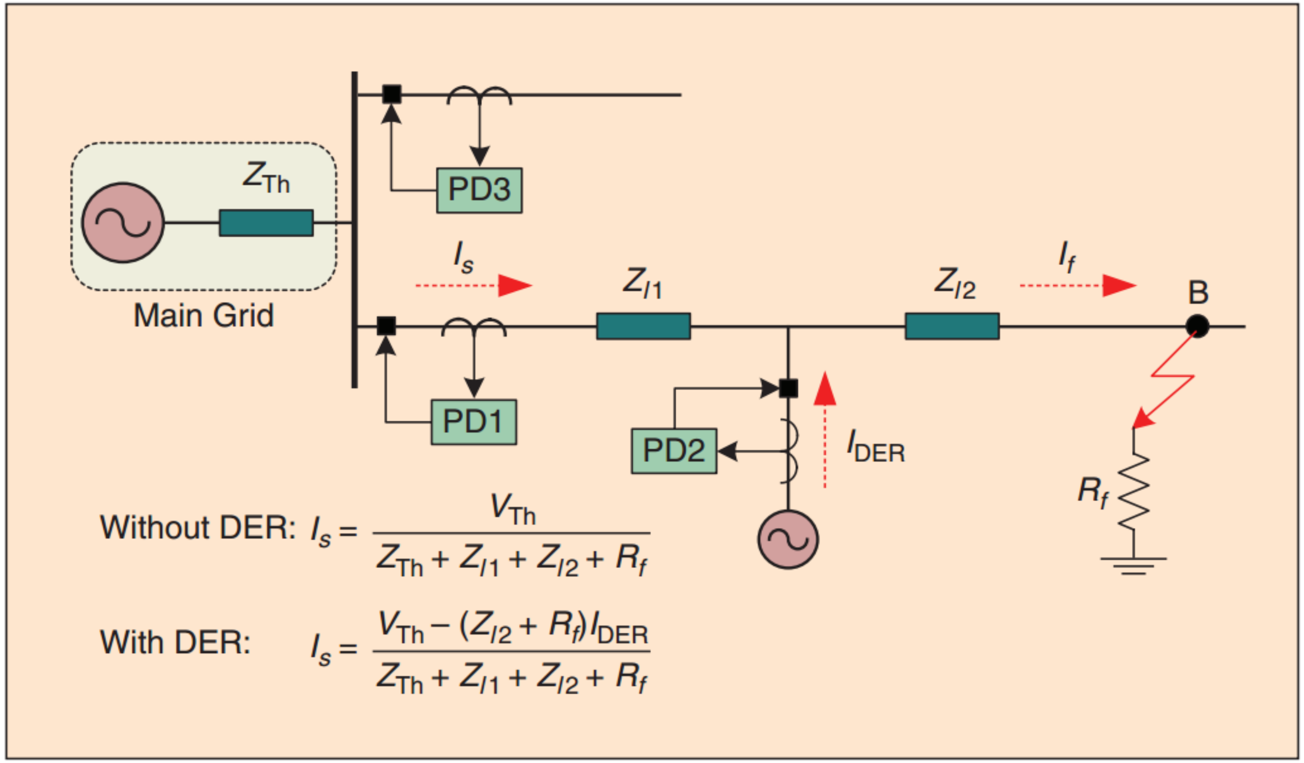
- ❑ **Sensitivity matter**

✓ Grid-tie and isolated modes alter the fault current level

✓ Protection devices (PDs) cannot precisely recognize intensity of the fault

✓ Deteriorates by

- ➢ High DER penetration
- ➢ High value of $\boldsymbol{R_f}$

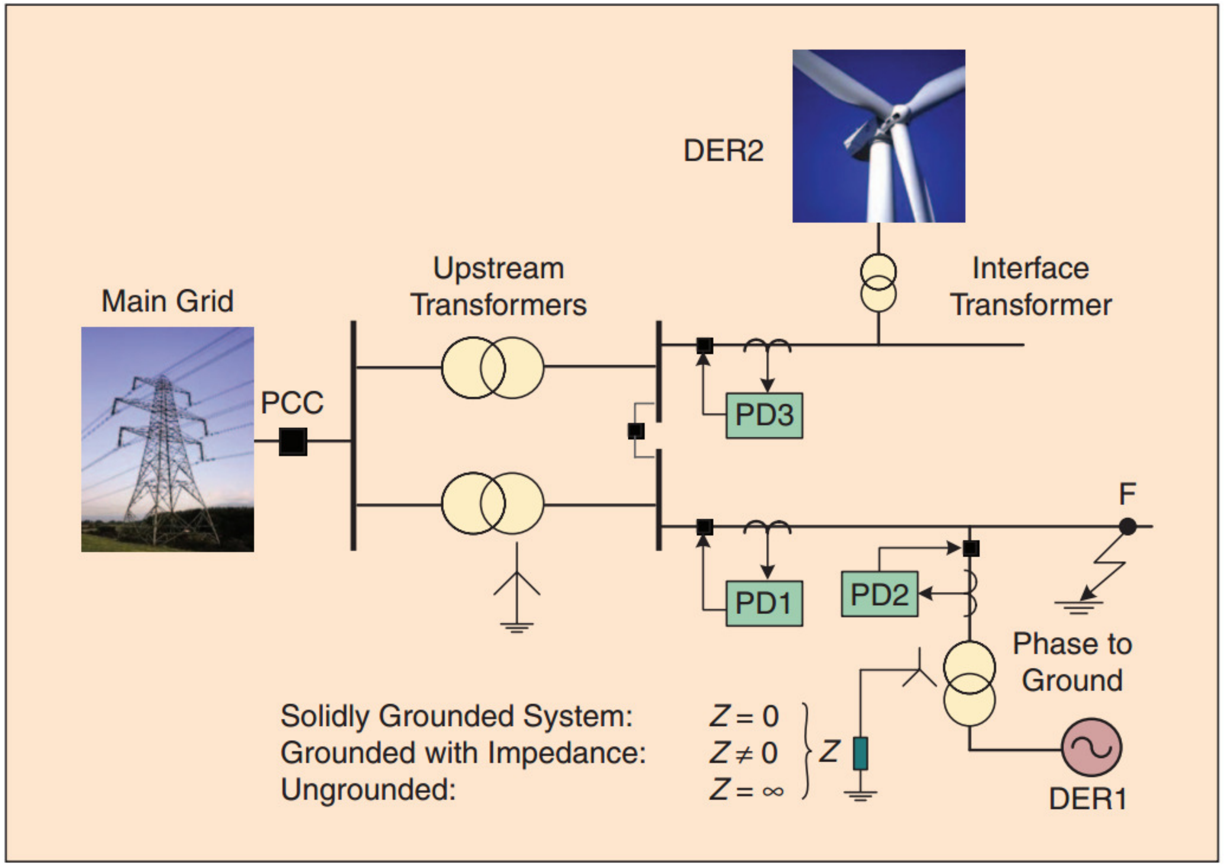


# Protection Challenges of DER-Integrated Microgrids (cont.):

❑ **Sympathetic tripping issues**

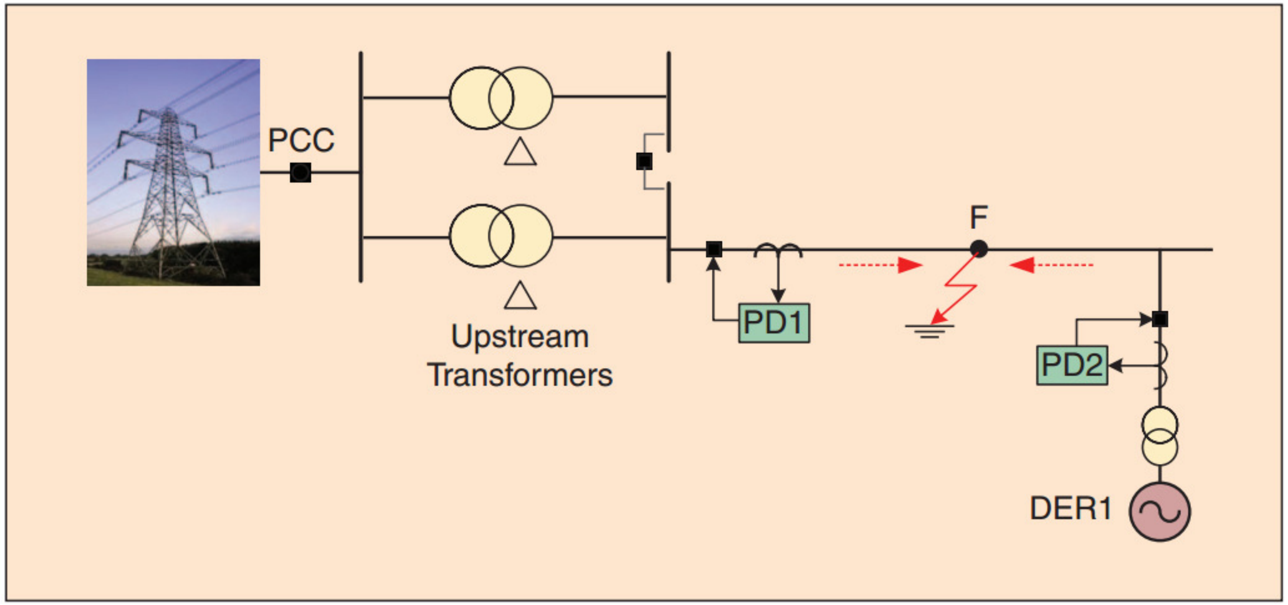
✓ PD1 and PD2 are responsible for fault clearance.

✓ DER2 protection and PD3 tripping is inevitable for high fault contribution of DER2.



# Protection Challenges of DER-Integrated Microgrids (cont.):

❑ **Reclosing difficulties**




- ✓ Fault might be supplied by DER1 after PD1 operation
- ✓ Probability of unsuccessful reclose even in the case of temporary faults

# Protection Challenges of DER-Integrated Microgrids (cont.):

- **Low fault-ride-through capability**

✓ Vital requirement for accurate operation of PDs

✓ Jeopardizes by:

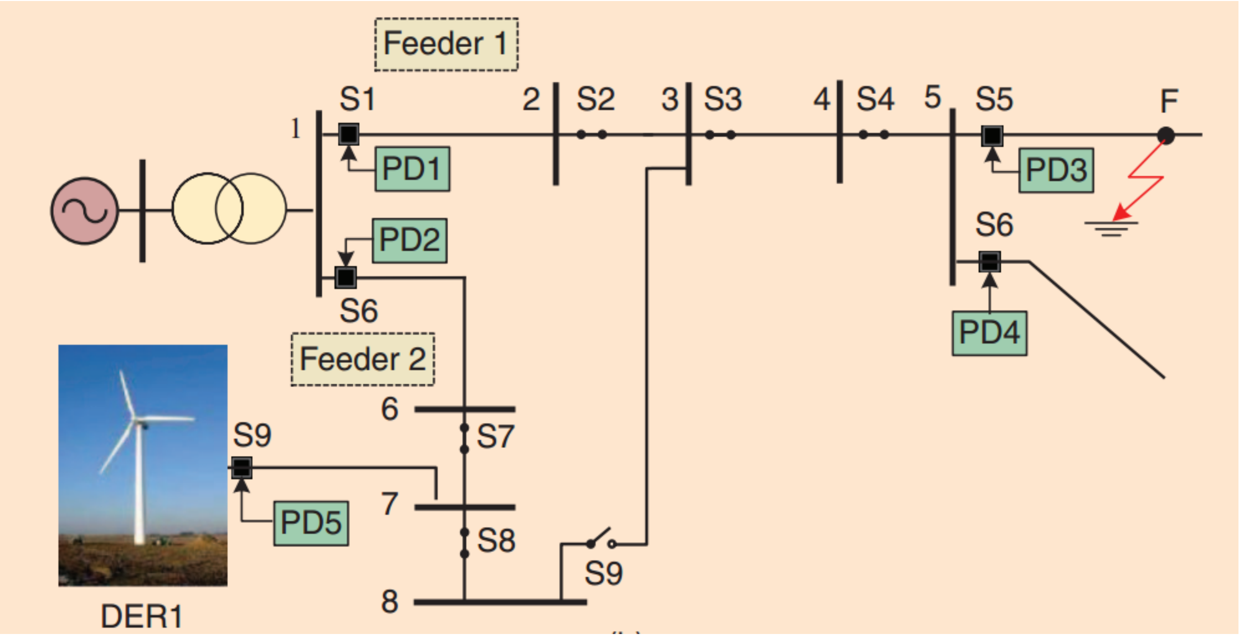
- Low fault current contribution of inverter-based DERs
- Incompetency of synchronous generator-based DERs excitation system

# Protection Challenges of DER-Integrated Microgrids (cont.):

## ❑ Frequent configuration alteration

✓ DER integration affects fault current paths

✓ Re-coordination of PDs after each configuration alteration is needed.



# Protection Challenges of DER-Integrated Microgrids (cont.):

## ❑ Solutions

| Challenges | Solutions | | | | |
|---|---|---|---|---|---|
| | Re-programing of existing PDs | Deploying directional PDs | Adopting teleprotection schemes | Joint approaches (1, 2, and 3) | Devising microgrid-wide protection schemes |
| **Sensitivity** | Partially | No | Almost | Almost | Solved |
| **Sympathetic Tripping** | Partially | Partially | Solved | Solved | Solved |
| **Reclosing** | Partially | No | Solved | Solved | Solved |
| **Frequent configuration alteration** | Partially | No | No | Partially | Solved |
| **Fault-ride-through requirement** | No | No | No | No | Solved |

## Publications on Protection of DER-Integrated Microgrids:

- S. Teimourzadeh, F. Aminifar, M. Davarpanah, and J. M. Guerrero, "Macroprotections for Microgrids: Toward a New Protection Paradigm Subsequent to Distributed Energy Resource Integration," *IEEE Industrial Electronics Magazine*, vol. 10, no. 3, pp. 6-18, Sept. 2016.
- S. Teimourzadeh, M. Davarpanah, F. Aminifar, and M. Shahidehpour, "An Adaptive Auto-Reclosing Scheme to Preserve Transient Stability of Microgrids," Accepted for publication in *IEEE Trans on Smart Grid*
- S. Teimourzadeh, F. Aminifar, and M. Davarpanah, "Microgrid dynamic security: Challenges, solutions and key considerations," Accepted for publication in *The Electricity Journal*, DOI: 10.1016/j.tej.2017.04.015.

## Summary and Conclusion:

- Wide-area protection can be considered as a backup protection scheme to increase the reliability (dependability and security) of main protection schemes. Emerging fast communication infrastructures are expected to facilitate application of wide-area protections as main protection schemes.
- Wide-area fault location provides a more accurate results that local fault location methods especially in case of large fault resistances.
- Wide-area protection empowers the load shedding schemes in dealing with combined frequency/voltage stability events, prevents power system instability, and provides adaptive and optimized load shedding.

# Thanks for your attention!

msanaye@ut.ac.ir