Resilience of Active Distribution Networks to Changes in Topological Structure

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What causes topological changes in network?

1. **n/w reconfiguration:** transferring loads from the heavily loaded feeders to the lightly loaded ones, to alleviate overload conditions and other contingencies.
2. **malicious attacks:** Copper theft, stealing power using tie-lines etc

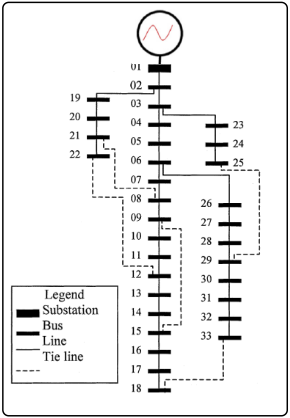

fig: 33-bus radial (**PASSIVE**) distribution system

n/w reconfiguration is typically performed based on static power flow analysis

Effect of network changes on ADN?

1. ADN behaves like a small grid with dynamical sources and dynamical loads
2. private parties typically control their DG's with local information

decentralized control of ADN is not feasible if there are decentralized fixed modes (DFM) and these modes might arise due to changes in network

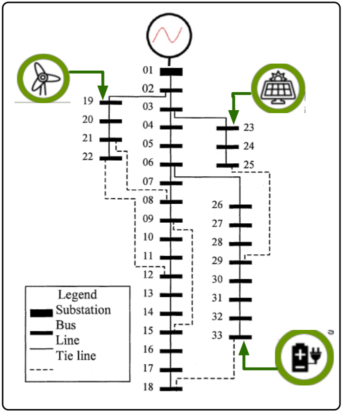

fig: 33-bus radial (**ACTIVE**) distribution system

DFM of linear system can't be shifted by constant decentralized output feedback.

An illustration

- **example: 1**

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 2\end{bmatrix} x(t) + \begin{bmatrix}1\\ 0\end{bmatrix} u_1(t) + \begin{bmatrix}0\\ 1\end{bmatrix} u_2(t)$$

$$y_1(t) = \begin{bmatrix}1 & 0\end{bmatrix} x(t)$$

$$y_2(t) = \begin{bmatrix}1 & 1\end{bmatrix} x(t)$$

"no DFM" $\Longrightarrow$ $u_1 = -2y_1$ **and** $u_2 = -3y_2$ **will result in closed loop stable dynamics**

An illustration

- **example: 1**

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"no DFM" $\implies$ $u_1 = -2y_1$ **and** $u_2 = -3y_2$ **will result in closed loop stable dynamics**

- **example: 2**

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{bmatrix} = \begin{bmatrix}1 & 0\\ 0 & 2\end{bmatrix} x(t) + \begin{bmatrix}1\\ 0\end{bmatrix} u_1(t) + \begin{bmatrix}0\\ 1\end{bmatrix} u_2(t)$$
$$y_1(t) = \begin{bmatrix}1 & 0\end{bmatrix} x(t)$$
$$y_2(t) = \begin{bmatrix}1 & \epsilon\end{bmatrix} x(t)$$

"no DFM ($\epsilon \neq 0$)" $\implies$ $u_1 = -2y_1$ **and** $u_2 = -3\epsilon_2^{-1}$**, does the job**

An illustration

- **example: 3** ($\epsilon \to 0$)

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} x(t) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u_1(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_2(t)$$

$$y_1(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t)$$

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mode 2 is DFM and cannot be moved by closed loop decentralized control

An illustration

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mode 2 **is DFM and cannot be moved by closed loop decentralized control**

(i) DFM can arise due to small perturbations system parameters
(or)
(ii) system might inherently posses a DFM

An illustration

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mode 2 is DFM and cannot be moved by closed loop decentralized control

"Resilience of system" can be quantified by means of how close/far the system is far from having a DFM

How DFMs might arise in ADN?

- **nonlinear model**

$$
\begin{aligned}
\dot{x}_P &= f(x_p, P, u_1) \\
\dot{x}_Q &= g(x_q, Q, u_2) \\
P &= h(x_p) \\
Q &= r(x_q)
\end{aligned}
$$

- **linearized model (around operating point)**

$$
\begin{bmatrix} \Delta \dot{x}_P \\ \Delta \dot{x}_Q \end{bmatrix} = \left(\begin{bmatrix} A_P & 0 \\ 0 & A_Q \end{bmatrix} + D \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \right) \begin{bmatrix} \Delta x_P \\ \Delta x_Q \end{bmatrix} + \begin{bmatrix} B_P & 0 \\ 0 & B_Q \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}
$$

1. "**Jacobian of power flow**" at an operating point depends on the network topology (admittance values)

2. changes in network topology **(reconfiguration or malicious intent)** might perturb Jacobian which results in DFMs

2. Modeling difficulties in Active Distribution Networks

- **Checking new topology for DFM**:

load flow → operating point → linearization

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- **Procedure**: TN simplifying assumptions are invalid

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TN

- AVR $\rightarrow V_i = V_j \approx 1pu$
- $\frac{R}{X} << 1 \rightarrow G \approx 0$
- $\theta_i - \theta_j << 1$
- balanced load $\rightarrow$ single-Line power flow

- **Checking new topology for DFM**:

load flow → operating point → linearization

- **Procedure**: TN simplifying assumptions are invalid

TN

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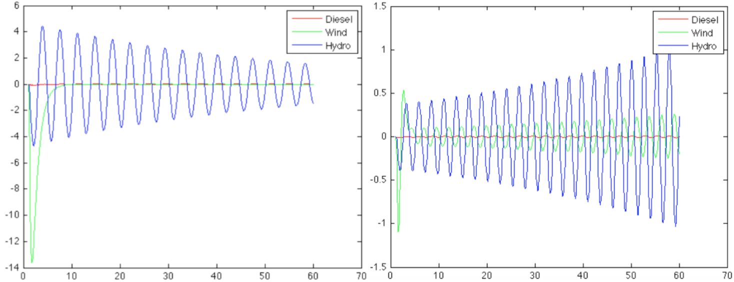
ADN

- significant voltage sag
- $\frac{R}{X} > 1$
- unbalanced load: 3-phase power flow

ADN controller design under TN assumptions



Source: M.H Nazari, M. Illic 2012

Takeaway: incorrect modeling may mis-classify DFM

Project Milestones

1. appropriate linearization/approximation schemes for ADN
2. identify models of DG and appropriate time-scales
3. quantify resilience by number and characteristics of DFM
4. understanding vulnerabilities of ADN's that might arise from DFM

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