Beyond phasors: Modeling dynamic events in large power systems

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Energy Challenges

21st century:
A growing demand for energy is expected

How long can science and technology support this rate of growth?
Our increasing energy consumption changes the earth

Climate Change

- The Greenhouse Effect is considered a primary cause of global warming.

   Measured outcomes:
   - Concentration of carbon dioxide in the atmosphere is rising.
   - Earth average surface temperature is rising.
   - Weather patterns are changing.

Depletion of Natural Sources

- Peak Oil: Are we before or after the peak?

[Diagram showing global oil production over time with peak points.]
Renewable Energies - Challenges

Cost

levelized cost of electricity from renewable sources

cost of electricity from conventional sources

“Grid Parity”
A tipping point for renewable energies?
## Renewable Energies - Challenges

### Power Density

How much power is produced per square meter?

<table>
<thead>
<tr>
<th></th>
<th>Wind</th>
<th>solar photovoltaics</th>
<th>bio-fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Power</td>
<td>2</td>
<td>30</td>
<td>1.5</td>
</tr>
<tr>
<td>Watt / m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Yield</td>
<td>0.048</td>
<td>0.72</td>
<td>0.036</td>
</tr>
<tr>
<td>kWh / (day·m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* typical numbers
Renewable Energies – an Answer?

Wind

Solar

Hydro

Solar Energy Installations Worldwide

Estimated Land Area
How much area is required to power the world? (with nothing but solar photovoltaics)

\[
\frac{16 \text{ TW}}{30 \text{ W/m}^2} \approx \]

world energy consumption

average power of solar photovoltaics
How much area is required to power the world? (with nothing but solar photovoltaics)

\[
\frac{16 \text{ TW}}{30 \text{ W/m}^2} \approx 500,000 \text{ km}^2
\]
Today—Centralized Power Systems

- Few large power plants
- Efficient & economic – law of scale
- Easy to manage and control
The Future? Distributed Power Systems

- Renewable energy sources are naturally distributed over large areas
- How does one control many independent sources, and make them work as a system?
Centralized Power Systems - Structure

central power plant generates electricity

step-up transformer

transmission lines carry energy over long distances

step-down transformer

Distribution networks deliver energy to local loads
Distributed Systems: Structure?

classic structures are no longer valid …

- Generators are integrated within distribution networks.
- A conceptual change in the network topology, that requires new ideas …
From Centralized to Distributed Power Systems

Today’s Grid: Centralized Topology

Power flows from central power plants to loads.
From Centralized to Distributed Power Systems

Today’s Grid: Centralized Topology
power flows from central power plants to loads

Future Grid: Distributed Topology?
How will power flow?
Many Challenges:

• How do we control this network?

• How do we design it?

• How do we synchronize the elements to work together?

• How does energy flows in such a network?

• Is the network stable?

• Is it reliable?

• Is it efficient?
“Smart” Grids
The missing link: Information Technology
Power networks that are integrated with advanced capabilities of sensing, communication and control

Today
Centralized “Passive” grids

The future - “smart” grids?
Power networks combined with information networks
Distributed Generation – Challenges

Global energy balance must be maintained.
Distributed Generation – Challenges

Global energy balance must be maintained

Local stability must be maintained

- Distributed Generation
- Challenges

Network

Central energy sources

Renewable energy sources

Loads
Energy Storage

renewable energy sources

load

Energy Balance?

power generated

power consumed

time
Studying Dynamic Events in Large Systems

How do we model dynamic events?

voltages & currents

amplitude, phase & powers

$v_n(t)$

$i_n(t)$

$|V_n(t)|$

$\delta(t)$

$P(t)$

$Q(t)$
Why use two types of signals?
- The generators & loads are nonlinear in voltages & currents.
- The network is nonlinear in powers, magnitudes and phases.

In both cases, the system is high-dimensional & nonlinear.
Common Types of Dynamic Models

- Phasor Models (Static)
- Quasi-Static Models
- Transient Models

Accuracy

Simplicity (Low-Complexity)
Transient Models
Fully detailed models, based on differential equations
High accuracy & High complexity

Differential equations
\[ \frac{d}{dt} x = f(x, I) \]
\[ V = g(x, I) \]
Phasor Models (Static)

Represent the system in steady-state using phasors
Only applies in steady-state, system dynamics ignored

\[ |V| \]

\[ \theta \]
Quasi-Static Phasors

“Time-varying Phasors”

Main idea: assume that phasors vary “very-slowly” in comparison to 50/60 Hz, and use them to model dynamic events.

\[ x^a(t) \]

\[ t \]
What we know today:

- **Static models** – Used most often
- **Transient models** – complex dynamics in small systems
- **Quasi-static models** - simulations of large power systems.
From static to dynamic phasors

Balanced unit (three-phase)

In balanced & static systems:

\[ v^a(t) = \sqrt{2} |V| \cos(\omega_s t + \delta) \]
\[ v^b(t) = \sqrt{2} |V| \cos(\omega_s t - 2\pi / 3 + \delta) \]
\[ v^c(t) = \sqrt{2} |V| \cos(\omega_s t + 2\pi / 3 + \delta) \]

Equivalent phasor

Time-domain a-b-c reference frame

**Phasor representation**

- \( V = |V| \angle \delta \)
From static to dynamic phasors

Using few trigonometric identities:

\[
v^a(t) = \sqrt{2} \left| V \right| \cos(\delta) \cos(\omega_s t) - \sqrt{2} \left| V \right| \sin(\delta) \sin(\omega_s t)
\]

\[
\text{Re}\{V\} \quad \text{Im}\{V\}
\]

\[
v^b(t) = \sqrt{2} \left| V \right| \cos(\delta) \cos(\omega_s t - \frac{2\pi}{3}) - \sqrt{2} \left| V \right| \sin(\delta) \sin(\omega_s t - \frac{2\pi}{3})
\]

\[
\text{Re}\{V\} \quad \text{Im}\{V\}
\]

\[
v^c(t) = \sqrt{2} \left| V \right| \cos(\delta) \cos(\omega_s t - \frac{2\pi}{3}) - \sqrt{2} \left| V \right| \sin(\delta) \sin(\omega_s t - \frac{2\pi}{3})
\]

\[
\text{Re}\{V\} \quad \text{Im}\{V\}
\]
From static to dynamic phasors (cont.)

In matrix form:

\[
\begin{pmatrix}
v^a(t) \\
v^b(t) \\
v^c(t)
\end{pmatrix} =
\begin{pmatrix}
\cos(\omega_s t) & -\sin(\omega_s t) & 1 \\
\cos(\omega_s t - 2\pi/3) & -\sin(\omega_s t - 2\pi/3) & 1 \\
\cos(\omega_s t + 2\pi/3) & -\sin(\omega_s t + 2\pi/3) & 1
\end{pmatrix}
\begin{pmatrix}
\sqrt{2} \text{Re}\{V\} \\
\sqrt{2} \text{Im}\{V\} \\
0
\end{pmatrix}
\]

Quasi-static phasor:

\[
V(t) = \text{Re}\{V(t)\} + j \text{Im}\{V(t)\}
\]
Modeling with Dynamic Phasors

Here is a simple example:

\[
\begin{align*}
V &= jX_L I = j\omega_s LI \\
\text{Or,} \\
\text{Re}\{V(t)\} &= -\omega_s L \cdot \text{Im}\{I(t)\} \\
\text{Im}\{V(t)\} &= \omega_s L \cdot \text{Re}\{I(t)\}
\end{align*}
\]
Modeling – Symmetric Three-Phase Series Load

• Complete model of a three-phase series R-L load:

\[ Z = r + j\omega L \]
Modeling – the Synchronous Generator

- Model based on the *swing equation*.
- Corresponds to a variable-frequency voltage source.
- Synchronous impedance ($Z_s$) is not included.
- More detailed models are available in the literature.
Modeling – Photovoltaic Three-Phase Inverter

- Model of a typical power electronics inverter.
- Power factor is unity (zero reactive power)
- Model based on energy balance in the internal bus capacitor.
Low Complexity Dynamic Models

Quasi-Static Model
(zero order Taylor series)

First-order model
(first order Taylor series)

- More accurate, yet
- Simple & Linear
Numerical Results

118 bus system, active power of several generators

**quasi-static model**

(dashed)

**First-order model**

(solid)
Numerical Results

57 bus system, active power of several generators

quasi-static model (dashed)

First-order model (solid)

quasi-static model: stable
first-order model: unstable

( which model is correct? )
## Numerical Results

### Simulation Run-Time, ms/s

<table>
<thead>
<tr>
<th></th>
<th>3 BUS NETWORK</th>
<th>9 bus network</th>
<th>30 bus net.</th>
<th>57 bus net.</th>
<th>118 bus net.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient model</td>
<td>289.6</td>
<td>956.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>First-order dq0 model (M=1)</td>
<td>20.5</td>
<td>37.2</td>
<td>40.4</td>
<td>137</td>
<td>289.8</td>
</tr>
<tr>
<td>Quasi-static model (M=0)</td>
<td>9.8</td>
<td>15.6</td>
<td>22.4</td>
<td>24.6</td>
<td>100.4</td>
</tr>
</tbody>
</table>

Order of magnitude improvement in simulation run-time compared to transient models.
디ון

- מערכות אנרגיה מתקרבות להוות לעתיד של מדינת ישראל.
- מערכות אנרגיה מתקרבות למעצמות בחזית המחקר והפיתוח העולמי.

איך אנחנו מסבירים את זה לילמידים שלנו?