HISTORY:

How we got to where we are

Traditional Stability Analysis:

1. **Maintain synchronism of synchronous machines**
2. **Simplifying assumptions:**
    1. **Balanced positive sequence system**
    2. **Ignore system transients (algebraic equations)**
    3. **Ignore stator transients**
    4. **Load modeled using algebraic equations**
    5. **Etc.**

Programs used for traditional stability analysis:

1. PSSE
2. PSLF
3. Power World
4. Others

These programs can model the entire Easter Interconnection (roughly 50,000 buses)

Programs that can simulate power system transients (including network transients):

1. EMTP
2. PSCAD
3. Others

May need to limit network size.

Modern power systems contain power electronic components (wind and solar generation, SCVs, etc.)

A question has arisen as to whether stability analysis software, and the simplifying assumptions included are appropriate for today's power systems and the needs of today's users

IEEE PSDP Task Force on Modeling of Large Interconnected Systems for Stability Analysis: answer this question

As part of the effort, the TF is reviewing the historical development of models, assumptions, and methods used in power system stability analysis

Key Drivers:

- Technology (exciters, machine design, power electronics, dc ties, etc.)
- The interconnected power system (increased transfers, greater interconnectedness)
- Computational Capabilities
- Mathematical tools (Stability theory)

Observation:

As the key drivers have evolved -

•So has the approach taken to study power system dynamics evolved

•Different forms of instability became important

1920s

Power system stability recognized as a problem

- Generation feeding remote load
- Slow exciters, non-continuous voltage regulators, insufficient synchronizing torque
- Steady state and rotor angle instability
- Two machine equal area criterion and power circle diagrams
- **Significant network reduction to obtain a 2 or 3 machine problem**
- Application of symmetrical components to the stability problem – **develop methods to obtain phase sequence constants**

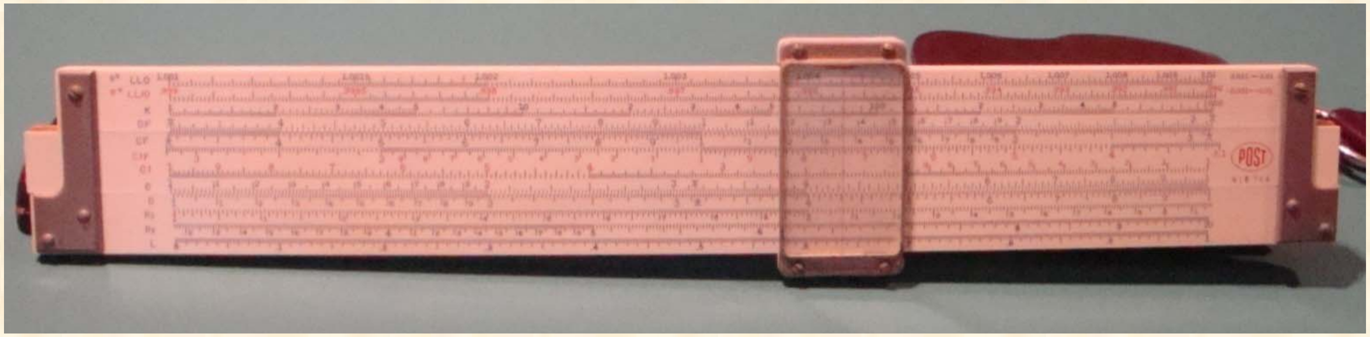
1920s (continued)

Park's generalized Two-Reaction Theory (1929)

- Calculate machine current, power and torque
- **Assume no armature saturation or hysteresis**
- **Assume small rotor angle deviations**
- **Arbitrary number of rotor circuits**
- **Assume sinusoidal M.M.F. distribution**

1930s

- AC Network Analyzer
  - Single phase scaled model
  - Multi-machine load flow analysis
  - **Angular stability solved by iterative load flow measurements and swing equations solved by hand using step-by-step integration**
  - **Classical generator model** – voltage behind the transient reactance
  - Loads were represented as constant impedance



1930s (continued)

•**Emphasis on the network**, not to extend synchronous machine theory

•**Early efforts to identify machine constants** to be used in stability studies:

- X’d and equivalent synchronous reactance were considered most important
- Inertia constant

•**Recognition that saturation affects reactance values**

1940s

- Faster breakers/fault clearing times (8 cycle and faster breakers)
- Faster acting exciters
- Continuously acting voltage regulators
    - Steady state aperiodic instability mostly eliminated
- **Emphasis of stability studies change from transmission network problems to generator representation**
    - Greater machine and exciter detail required
- As a result of faster acting exciters (decreased damping) oscillatory instability becomes a concern
- **AIEE machine short circuit test code**

1950s

•Development of analog computer

  •Detailed simulation of generator and controls

•**But the AC Network Analyzer and hand calculation are still the primary tools**

  •Single phase scaled model

  •Generator model – voltage behind the transient reactance

  •Loads were represented as constant impedance

•Late 1950s **digital computers** used to study large interconnected systems

  •**Models used were similar to those used in network analyzers**

1960s

•Most power systems in North America part of East or West grid

•HVDC ties the two grids together

•**1965 blackout reveals stability issues with the interconnected system such as rotor angle, frequency, and voltage stability**

1960s (continued)

•**Load is modeled as a function of both voltage and frequency**

•Dc systems and controls are modeled using algebraic equations

•**In addition to synchronous machine and excitation systems, prime mover and automatic relay operation is modeled**

•Three rotor (amortisseur) circuits are modeled

•**An IEEE WG recommends 4 excitation models**

1960s (continued)

But digital computer cost is a big concern, and affects model detail

- Common practice is to **represent machines of interest in detail**, and “remote” machines as voltages behind transient reactance
- **Stator transients and speed effects are neglected** (stator equations become algebraic)
- **Network transients are ignored** (algebraic equations only)
  - Network transients usually much faster than rotor (mechanical) dynamics
  - Computational efficiency for large networks

1970s

•**Digital computer computation cost is still a concern affecting machine and network modeling**

•**Computation cost**:

- •Time on mainframe charged to user in dollars
- •Time on mainframe limited because other departments use the same resources

•Dedicated minicomputers appear

Computer Power and Cost

In the evolution of computer-chip technology, as information processing speed has increased, the price of computing devices have plummeted.

	Approximate number of instructions per second (IPS)	Price	Cost per IPS
1975 IBM Mainframe	10,000,000	$10,000,000	$1.00000000
1976 Crey 1	160,000,000	$20,000,000	$0.12500000
1979 Digital Vax	1,000,000	$200,000	$0.20000000
1981 IBM PC	250,000	$3,000	$0.01200000
1984 Sun Microsystems 2	1,000,000	$10,000	$0.01000000
1994 Pentium chip PC	66,000,000	$3,000	$0.00004500
1995 Sony PCX video game	500,000,000	$500	$0.00000100
1995 Microunity set top box	1,000,000,000	$500	$0.00000050

Reference: "Dynamic Analysis and Control System Engineering in Utility Systems", F P De Mello, Proceedings of the 4th IEEE Conference on Control Applications, 1995

2013 Dell Latitude E6430	62,000,000,000,000	$1,244	$0.00000002

1970s (continued)

- Emphasis shifts to transient stability issues
- **Voltage stability** becomes an issue of interest
- Machine model data (X’d, X”d, T’do, T”do) from short circuit tests assuming two rotor circuits in each axis
- **Standard methods to obtain machine data do not support higher order models**
- Assuming X”q = X”d simplifies computation, and for round rotor machines the values are nearly equal
- **Neglecting saturation in the models is questioned**, saturation factors are now used
- **Using a reduced power system network is common**
- Simple models (Classical) for “remote” generators still common

1970s (continued)

- **Machine models were developed to “suit” the data available**
- Load represented as combination of constant impedance and constant current
- **Simple load representation is questioned. Dynamic effects of some loads is considered, but time step is still a big concern**.
- It is observed that with series compensated lines neglecting network transients may lead to inaccurate results.
- **IEEE Committee presents basic governing models** for hydro, fossil-fueled, and PWR nuclear units
  - Intended for small frequency deviations
  - Simulation times of 30 seconds or longer are OK
  - Fast-valving is popular

1970s (continued)

Unbalanced faults:

- Computational efficiency a concern
- Use symmetrical components and restrict Park's equations to positive sequence
- High frequency torque components are neglected
- **Insert equivalent impedance at the fault point to represent the unbalanced conditions**
- Because fault duration is small compared to overall simulation, method and assumptions should not significantly affect results

1980s

•Computing is moving from batch to distributed

•**Computation cost is becoming less of a concern**

•**Use of Classical generator model is less common, but still in use**

•Third order machine model considered the most complex model needed

•**Frequency response testing to obtain generator model parameters (third order) is recommended**

•Some feel generator modeling is sufficiently detailed - issues related to parameter acquisition and consistency with other system elements should be considered

•Agreed upon value for Rfd and saturation effects are still open items

•**Modeling for small signal analysis is receiving more attention**

1990s

- IEEE Std 1110-1991 IEEE Guide for Synchronous Generator Modeling Practices in Stability Analysis
  - Calls for more detailed generator models as a result of more complex control concepts (but still third order). **Better simulation capabilities and data acquisition procedures make this possible**.
  - Essentially **consolidates** much of the work done in the 1980s
  - Models for salient pole and round rotor machines are included
  - Recommends linearized system equations around an operating point for small disturbance studies. Emphasizes exciter and PSS models are as important as the generator model.

1990s (continued)

•**Power transfer studies involving several utilities or pools are common**

•Long-term transient stability has been recognized as an issue

•**Simulations still assume positive sequence network, no network or armature transients, and rotor dc and negative sequence losses are neglected**

2000 to today

IEEE Std 1110-2002 IEEE Guide for Synchronous Generator Modeling Practices and Application in Power System Stability Analysis

- Essentially consolidates much of the work done since 1991
- **Notes as the power system changes, the demands on stability programs have increased**
- **New forms of stability other than angular now of great concern**
    - Rotor angle stability
        - Large disturbance
        - Small disturbance
    - Voltage stability
    - Frequency stability

2000 to today (continued)

IEEE Std 1110-2002 IEEE Guide for Synchronous Generator Modeling Practices and Application in Power System Stability Analysis

- Calls for further investigation into saturation effects on synchronous machines

- Notes there is no pressing need to simplify models

- **Notes that for frequency stability studies, rotor speed variations in the stator voltage equations cannot be neglected**

2000 to today (continued)

- Intermittent generation (wind) becomes significant
- Other intermittent generation (solar) appear
- **Equipment with power electronic interface to the grid become more common**
  - Generation from Wind and solar
  - DC lines and back-to-back
  - SVC
  - Series compensation
  - FACTS
- **Induction motors, especially air conditioning, are recognized as significant contributors to slow voltage recovery**

2000 to today (continued)

- **Computational capability is no longer an issue**
  - Software can handle the North American Eastern interconnection in detail
  - Network reduction not needed
  - All machines can be modeled in detail
  - Computational cost is generally not a factor
- **Generation to load distances "increasing", flow patterns changing**
  - Bringing wind and solar generation to load
  - Market efficiency/economics
  - Environmental factors/legislation
  - Increased use of reactive compensation (switched capacitors, SVC)

2000 to today (continued)

- Synchronous machine, exciter, governor models much improved and continuing to improve
- Mathematical tools much improved – continuing research
- **Load models include**:
    - Constant power, current, and impedance
    - Detailed models for some loads such as induction motors, lighting
    - **Equivalent distribution system including dynamic response**
- Continuing research on load modeling
- More “small” generation at distribution level
- Efforts to modify load shape (time of day rates, etc.)

2000 to today (continued)

- **Network model assumptions still include**:
  - Single phase positive sequence
  - Network transients ignored
- **Synchronous machine model assumptions generally still include**:
  - Small rotor angle deviations
  - Stator transients and speed effects neglected
  - Single phase positive sequence representation
- **Governor models assume small frequency deviations**

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The TF is reviewing the historical development of “how we got to where we are” as part of the effort to answer this question.