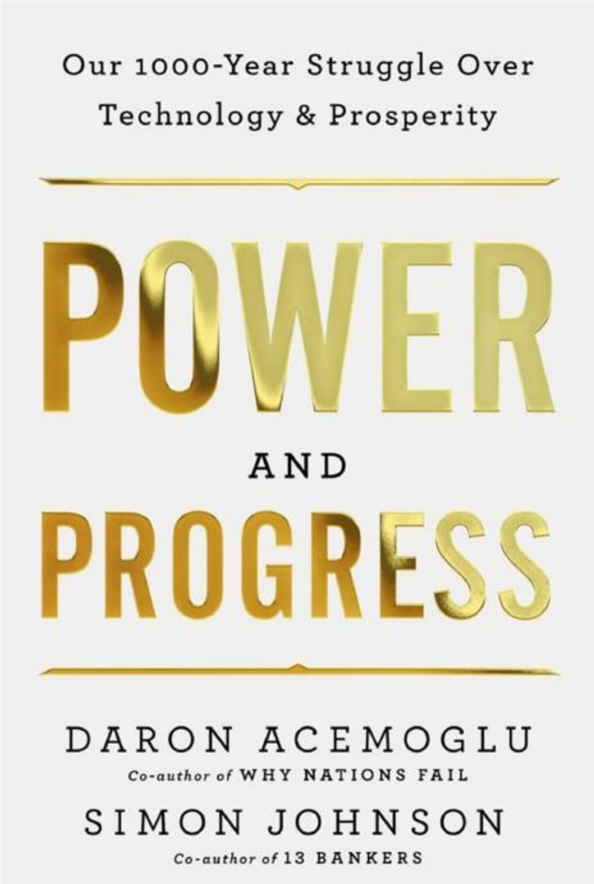
Innovations in Power Grid Dynamic Modeling and Analysis

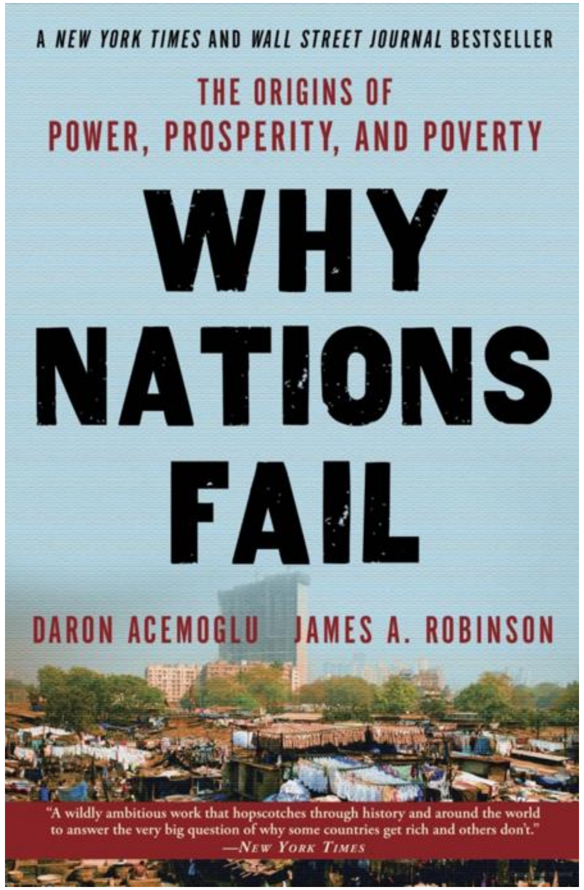
Lingling Fan, Professor @University of South Florida

ECE Seminar, John Hopkins

January 28, 2025

MIT economists Daron Acemoglu and Simon Johnson (Nobel Prize in economics 2024)





Technology leads to prosperity, given reasonable politics.

Technology supremacy is the necessity.

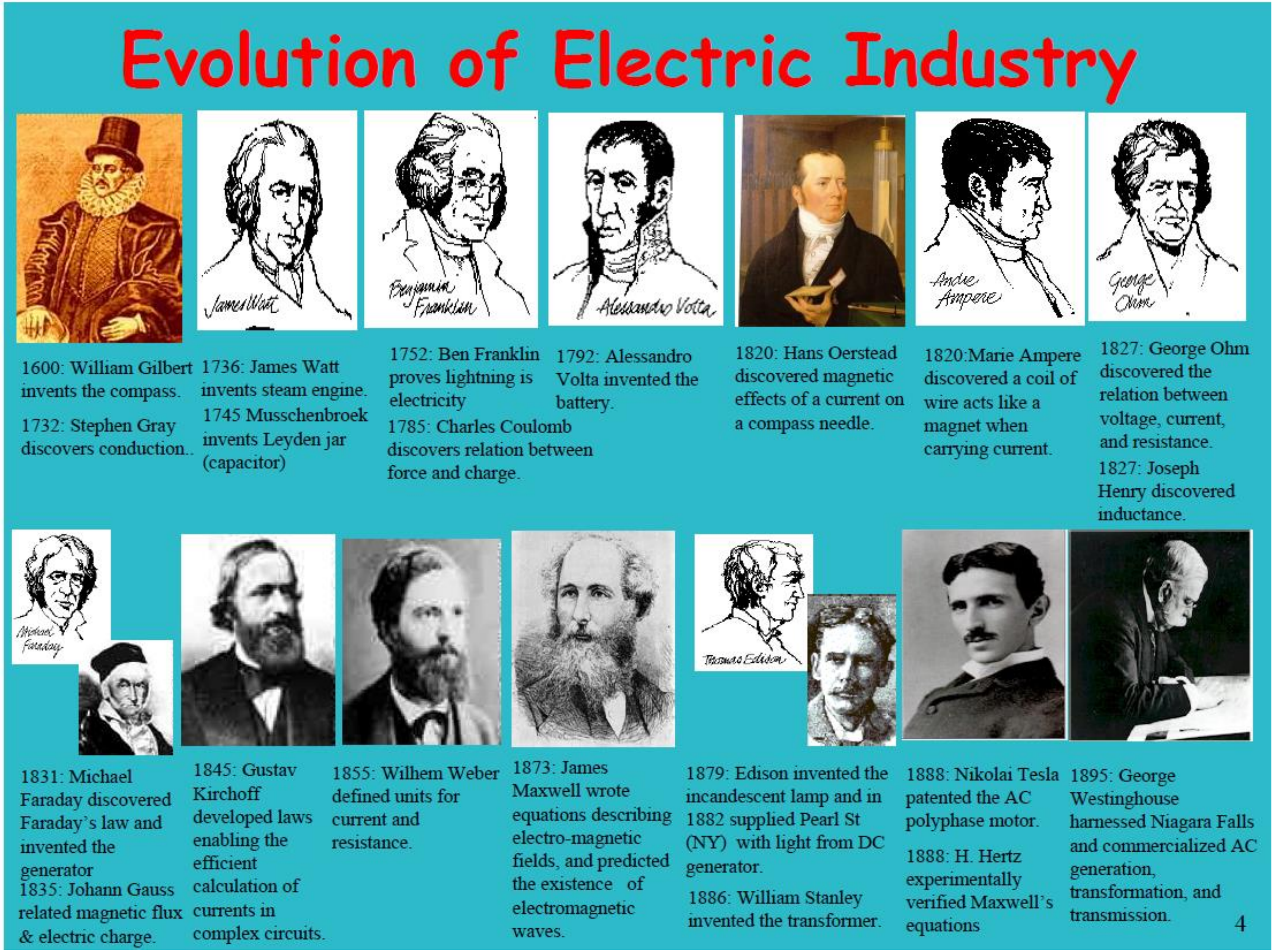
The greatest achievements in the 20th century

(http://www.greatachievements.org/)

- Electrification
- Automobile
- Airplane
- Water Supply and Distribution
- Electronics
- Radio and Television
- Agricultural Mechanization
- Computers
- Telephone
- Air Conditioning and Refrigeration

Outline

- A brief overview of the technologies for electrification
  - Manufacturing & digitalization
- Innovations in modeling & analysis
  - The influential people & their contributions
- Real-world event replication and root cause analysis
  - SSR in wind farms
  - Weak grid oscillations



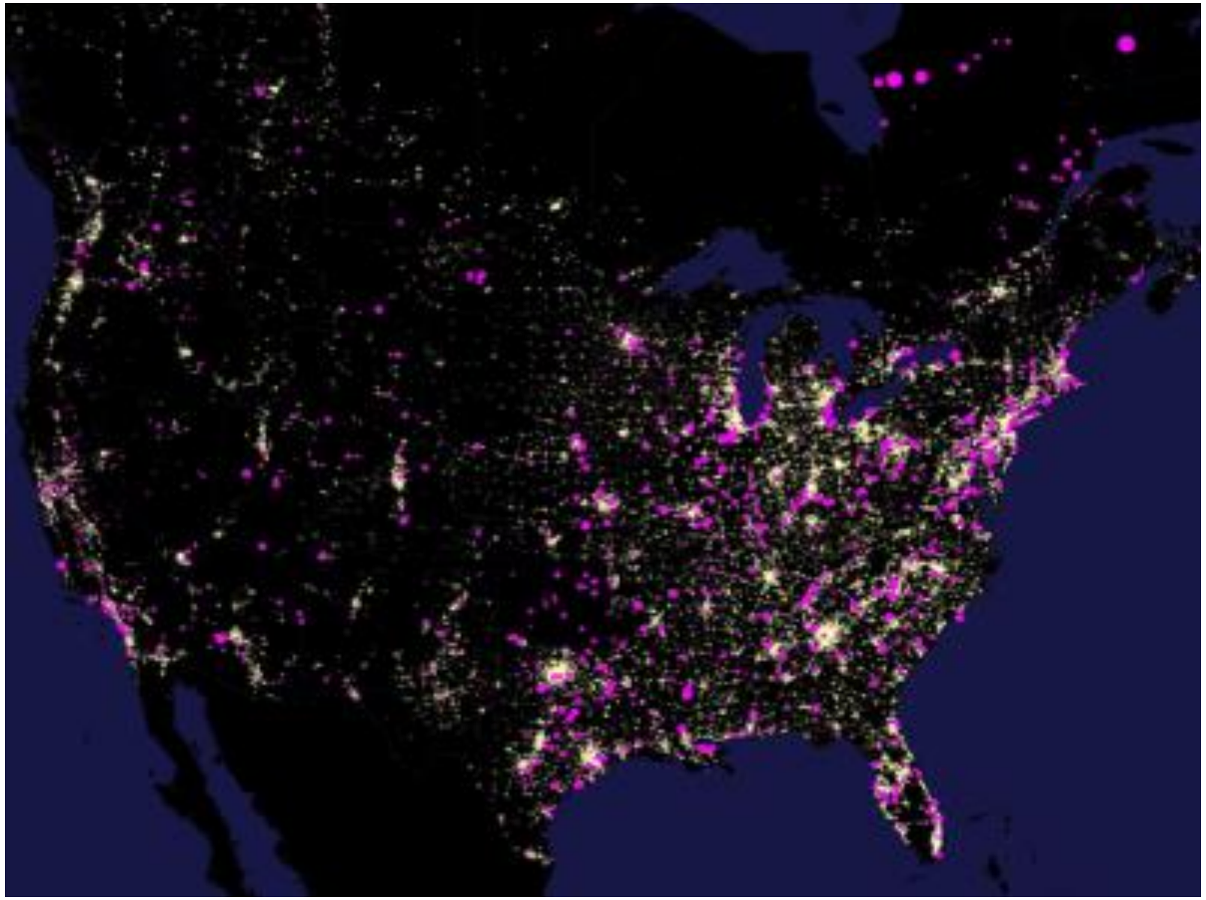
a bit of history – from Jim McCalley (Iowa State University): Power Energy Overview

EE 303: Energy systems and power electronics

North American loads (shiny dots)

https://www.usgs.gov/programs/geomagnetism/science/keeping-lights-north-america

North American load (shiny dots) & generation (red dots)



Prof. Thomas Overbye

Innovations in power grids

1850–1950

device inventions + analytical methods

- Rotating machines, transformers, lines, mechanical relays
- Initial set up of power grids

1970–2000

digitalization

- Make power grids large scale: Controls (voltage and frequency)
- Computer simulation
- Computer-based relays, real-time monitoring

2000- present

energy transition, digital economy

- Inverter-based resources, data centers, dc grids
- Hardware: **power electronics**
- Operation: **modeling, analysis & control**

Stage 1: Manufacturing

The New York Times

DealBook/ Business & Policy

G.E. Dropped From the Dow After More Than a Century

Average in stock market : <20 years

General Electric, the last original member of the Dow Jones industrial average, was dropped from the blue-chip index. John Minchillo/Associated Press

By Matt Phillips
June 19, 2018

And then there were none.

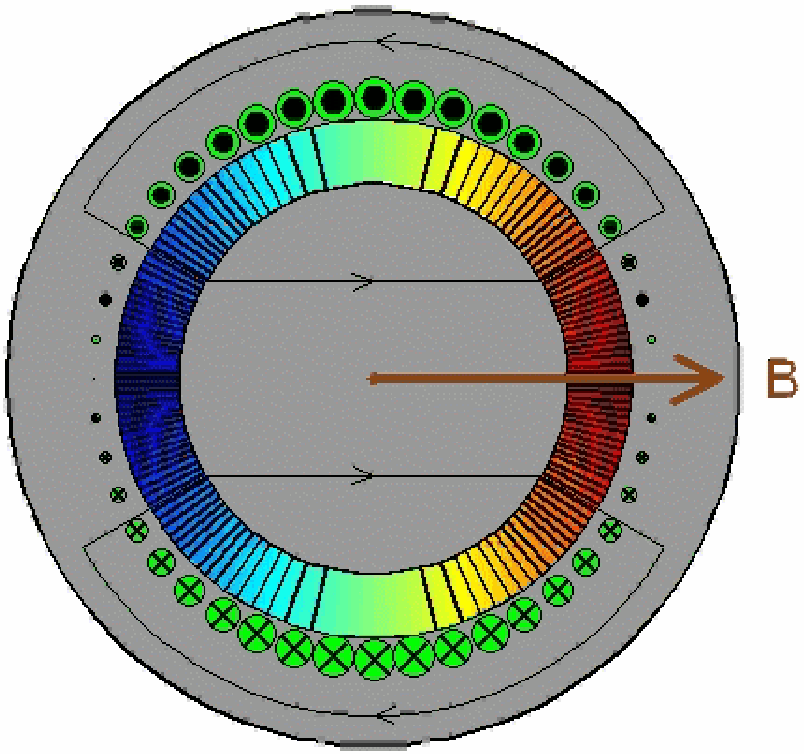
General Electric, the last original member of the Dow Jones industrial average, was dropped from the blue-chip index late Tuesday and replaced by the Walgreens Boots Alliance drugstore

The innovations:
Contribute to the critical infrastructure: power grids

”As of 2024, GE Vernova holds 36,000 patents and patent applications in 60 countries, and approximately 30% of the world’s electricity is generated using the company’s installed base of technologies.”

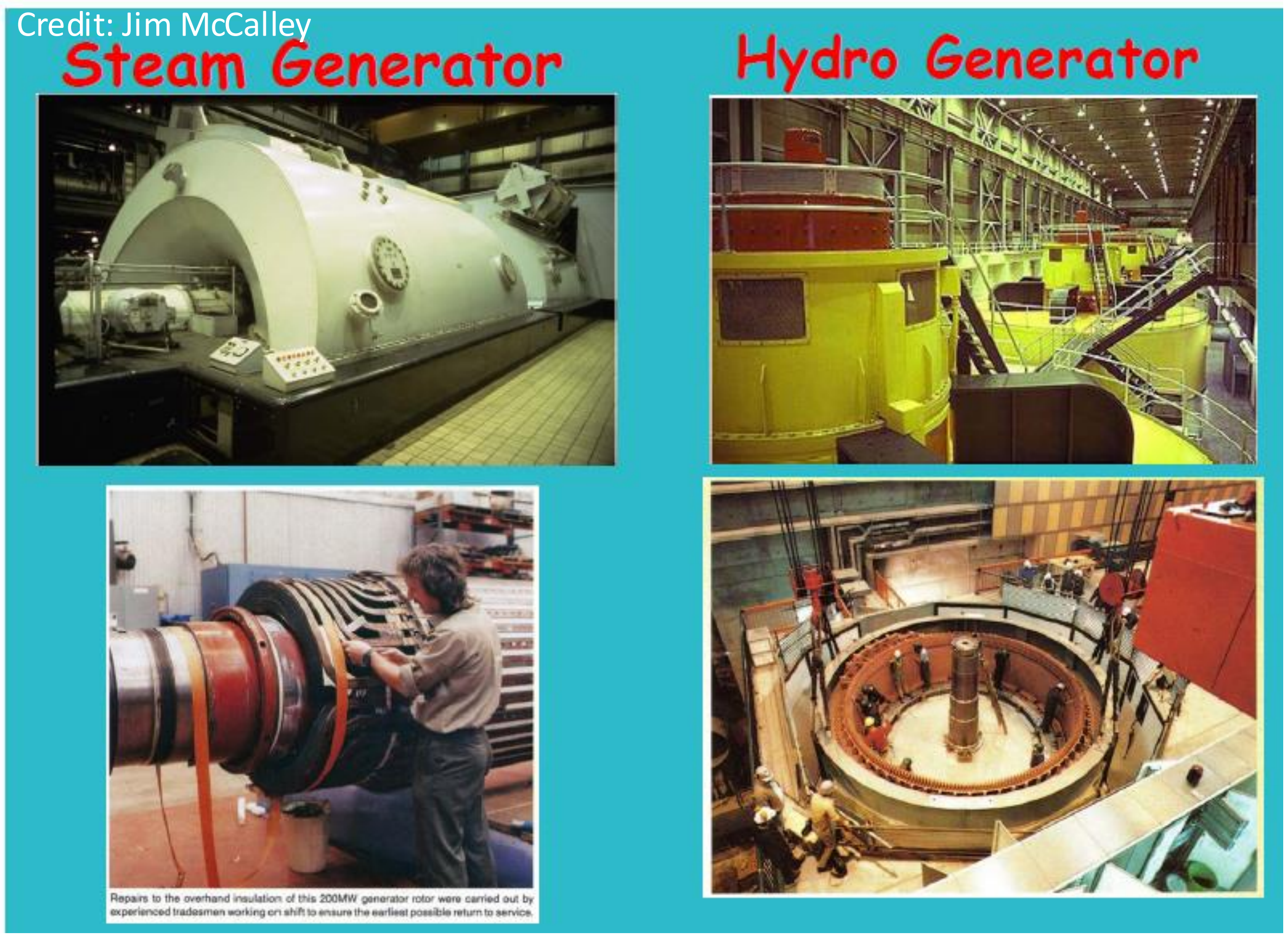
1879: electric lamp
1882: the age of electric power (first power station with 59 customers in Manhattan)
1893: electric locomotive
1896: X-ray machine
1906: radio
1910: electric home appliances
1957: nuclear power
1976: medical devices
1980s: media

Energy conversion technology: electro-mechanical energy conversion via a magnetic field



AIR GAP FLUX PLOT

http://www.ece.umn.edu/users/riaz/animations/imflux3.html



A rotating sinusoidally distributed winding is excited with a constant current. The flux plot in the air gap also rotates. Where the lines are crowded, the corresponding magnetic field density B is high, and where the concentration of lines is reduced so is B.

Thus the air gap B-field is sinusoidally distributed in space and is also rotating. It can be represented by a rotating space vector of constant magnitude pointing to where the field is maximum positive.

Engineering and technology history wiki https://ethw.org/Main_Page

Thomas Alva Edison

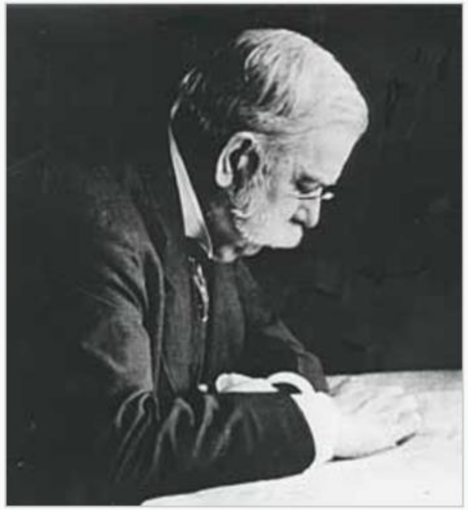
Thomas Alva Edison

Birthdate
1847/02/11

Birthplace
Milan, OH, USA

Death date
1931/10/18

George Westinghouse



George Westinghouse

Birthdate
1846/10/06

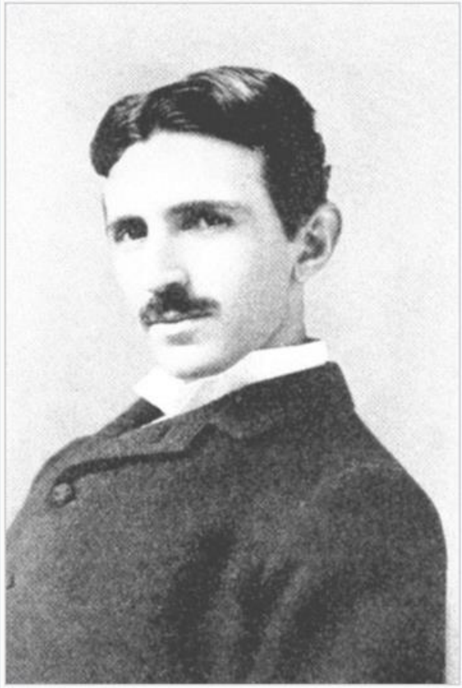
Death date
1914/03/12

Associated organizations
Westinghouse Electric Corporation

Fields of study
Power, Electronics, Radio

Awards
AIEE Edison Medal

Nikola Tesla



Nikola Tesla

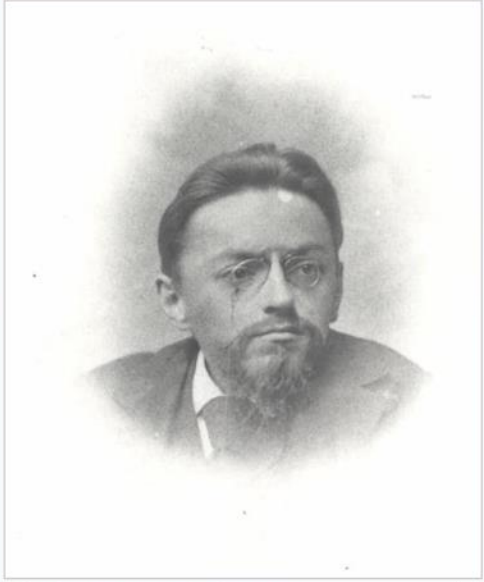
Birthdate
1856/07/10

Death date
1943/01/07

Fields of study
Power

Awards
AIEE Edison Medal

Charles P. Steinmetz



Charles Proteus Steinmetz

Birthdate
1865/04/09

Birthplace
Breslau, Germany

Death date
1923/10/26

Associated organizations
General Electric (GE)

President of AIEE
1901 -1902

Stage 2: Digitalization: computer simulation

IEEE Medal in Power Engineering

About Medal

The IEEE Medal in Power Engineering was established in August 2008 and is presented annually to an individual deemed to have made outstanding contributions to technology associated with the generation, transmission, distribution, application, and utilization of electric power for the betterment of society.

Award Recipients

- Prabha S. Kundur, 2010
- William F. Tinney, 2011
- Edmund O. Schweitzer, III, 2012
- Hermann W. Dommel, 2013
- Thomas A. Lipo, 2014
- Fred C. Lee, 2015
- Arun G. Phadke, 2016
- Marian P. Kazmierkowski, 2017
- Hirofumi Akagi, 2018
- Lionel O. Barthold, 2019
- Rik W. De Doncker, 2020
- Praveen K. Jain, 2021
- Thomas M. Jahns, 2022
- Kamal Al-Haddad, 2023
- Deepakraj Divan, 2024

Computer simulation, computing methods
Power electronics
Relay, data streaming

https://ethw.org/IEEE_Medal_in_Power_Engineering

Stage 2: Digitalization: computer simulation

- **Hermann Dommel –Father of Electromagnetic Transient Program(EMTP)**

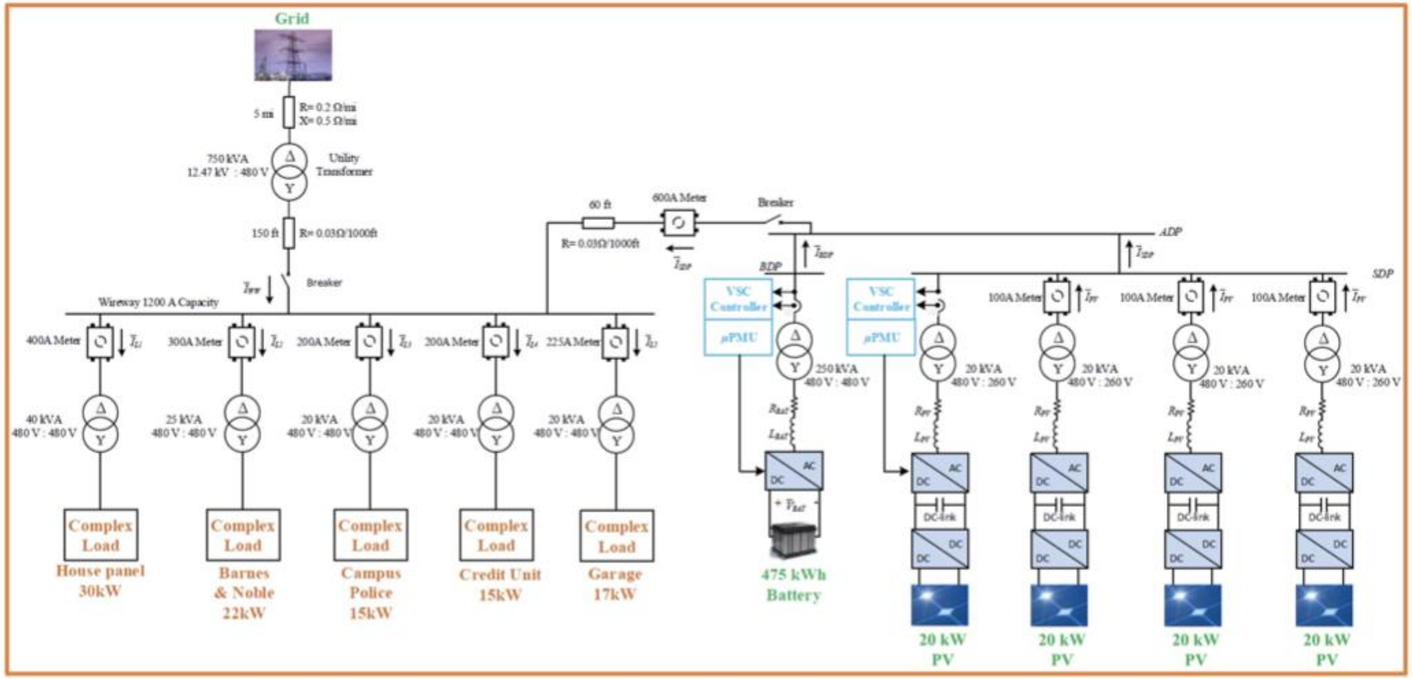
PSCAD

EMTP

RTDS Technologies AMETEK

OPAL-RT TECHNOLOGIES

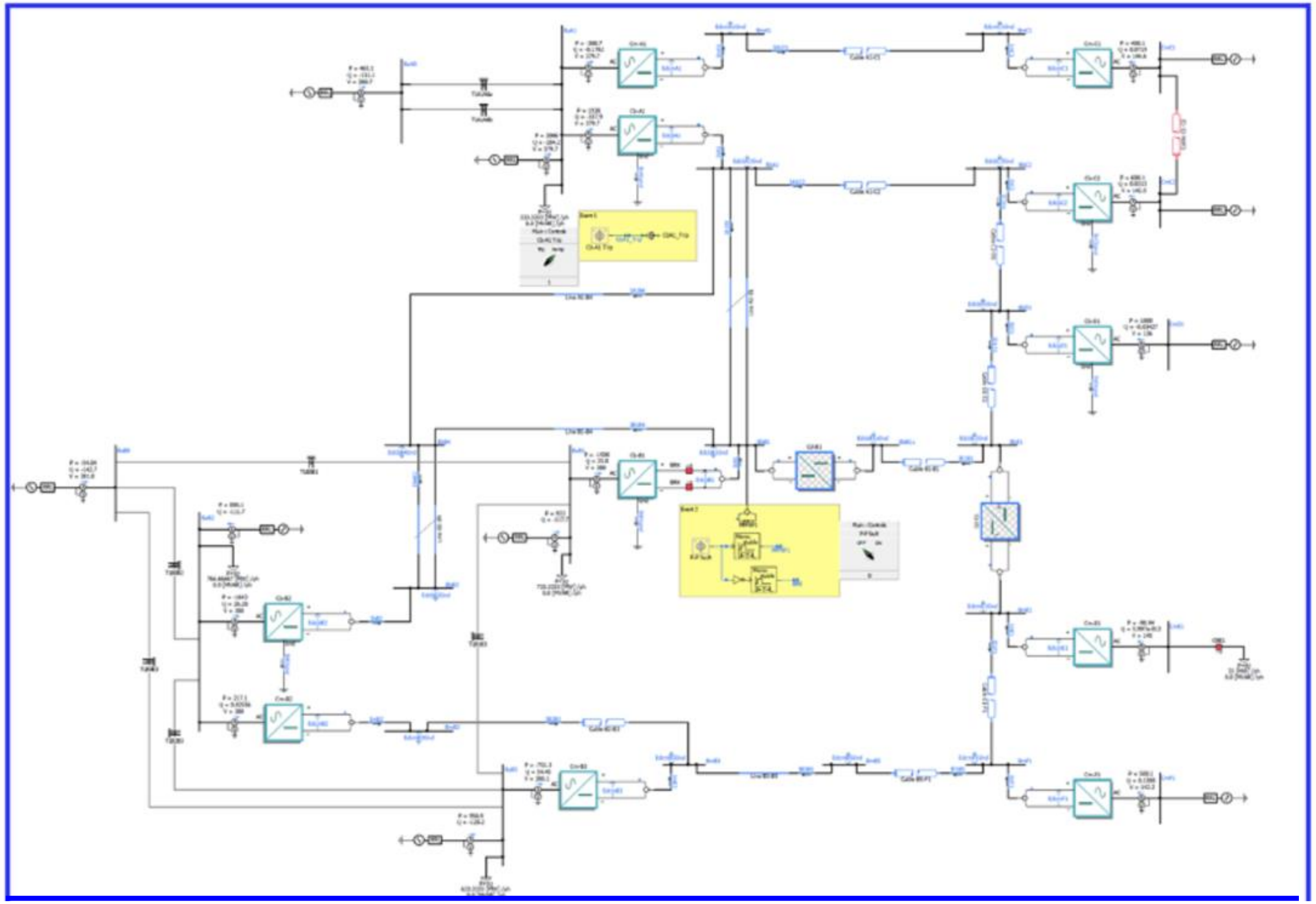
Industry: Canada HVDC industry since 1960s

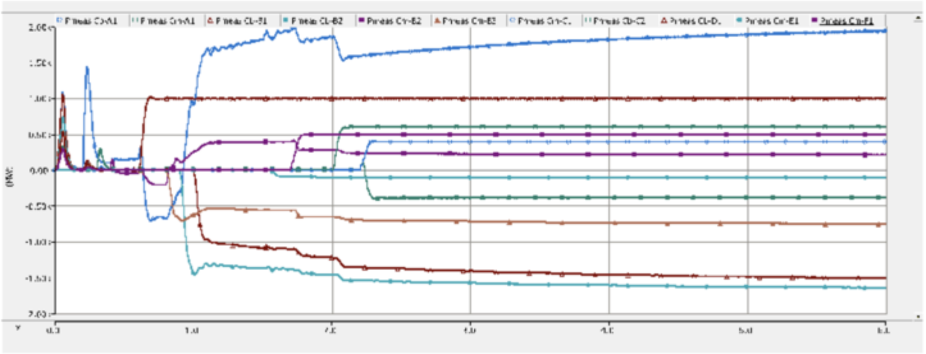


High-fidelity real-time digital simulation

Can help check operation, protection, and control design

- The grid industry is **highly digitalized**.
- In power grid, we use **computer simulation** for **system-leve**l design, feasibility assessments, and reliability assessments.
- Computer simulation has been **integrated inti industry's planning & operation procedure**.

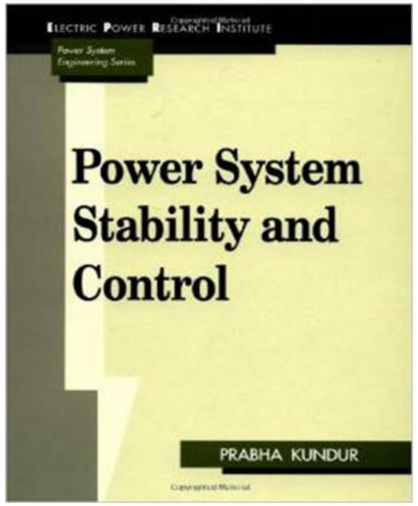




Electromagnetic Transient vs Phasor-Based Simulation

- **Lionel Barthold** (2019, IEEE medals in power engineering) (founder of Power Technology Inc. – PTI): now known as Siemens PTI
- **John Undrill**: PSS/E (PTI), PSLF (GE) (2022, IEEE Herman Halperin Electric T&D Award.
- **Praba Kundur** (2010, IEEE medals in Power Engineering,)

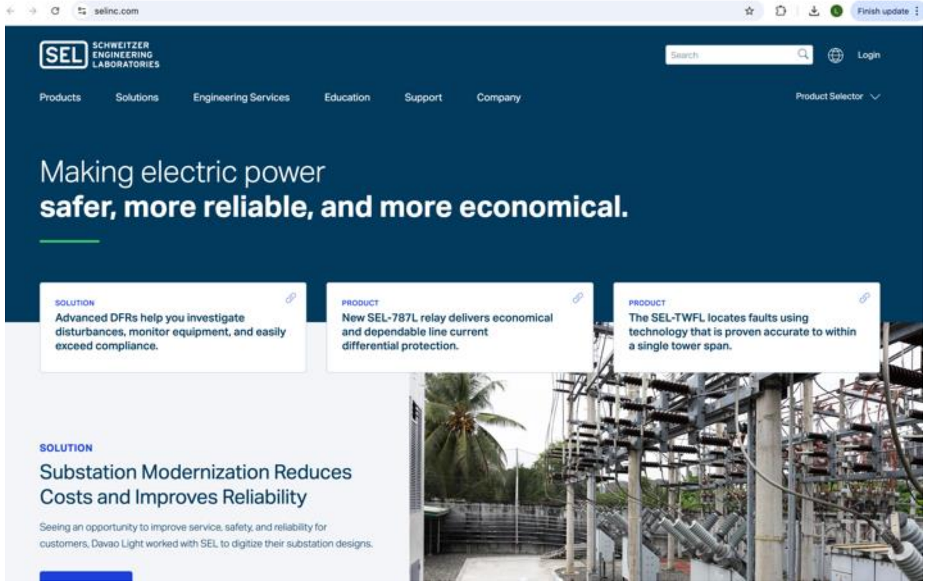


Digitalization: protection

IEEE spectrum 2023: Edmund Schweitzer with the first digital microprocessor-based protective relay, the SEL-21 digital distance relay/fault locator [left], and the SEL-T400L time-domain line protection relay.

SCHWEITZER ENGINEERING LABS



https://spectrum.ieee.org/relay-changed-the-power-industry

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- Innovations in modeling & analysis
  - The influential people & their contributions
- Real-world event replication and root cause analysis

2. Innovations in dynamic modeling & analysis

Oliver Heaviside

Operation calculus

Heaviside made circuit analysis simple and easy by introducing **operation calculus** (Laplace transform). Instead of dealing with differential equations, we now deal with algebraic equations.

Operator ***p***: *d/dt*, $\frac{\mathbf{1}}{\boldsymbol{p}}\mathbf{1} = t$

$$i = \frac{v}{Z} = \frac{1}{(R+Lp)}\mathbf{1} = \frac{1}{R} \times \frac{R}{Lp}\frac{1}{\left(1+\frac{R}{Lp}\right)}\mathbf{1} = \frac{1}{R} \times \frac{1}{\tau p}\frac{1}{\left(1+\frac{1}{\tau p}\right)}\mathbf{1},$$

$$i = \frac{1}{R} \times \frac{1}{\tau p}\left[1 - \frac{1}{\tau p} + \left(\frac{1}{\tau p}\right)^2 - \left(\frac{1}{\tau p}\right)^3 + \cdots\right]\mathbf{1} \qquad i = \frac{1}{R}\left[1 - e^{\left(-\frac{t}{\tau}\right)}\right]$$

Important people of modeling & analyasis

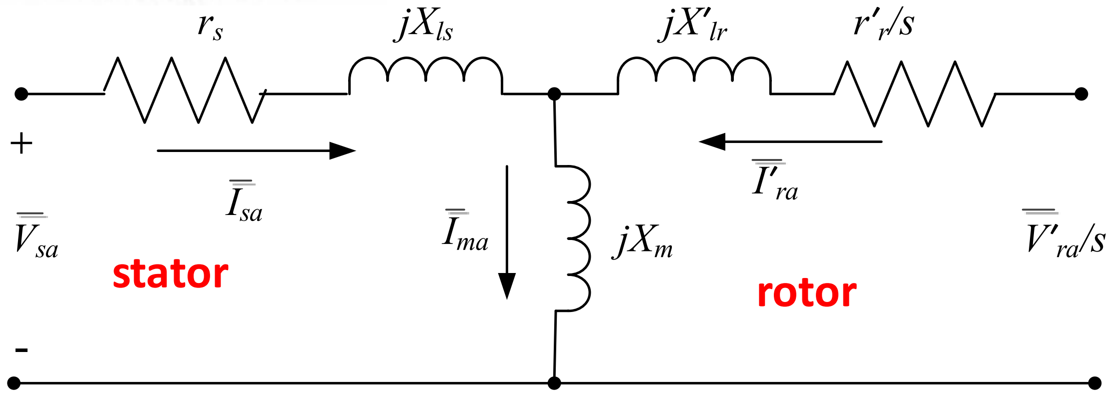
The brilliant GE engineers: Steinmetz, Concordia, Clarke, and Park.

Comparison (ask ChatGPT)

Aspect	Nikola Tesla	Charles Steinmetz
Primary Focus	Inventor and visionary concepts in AC machinery	Theoretical analysis and practical optimization
Major Contribution	Invention of the AC induction motor and polyphase systems	Mathematical tools for understanding AC systems, harmonics, and losses
Approach	Conceptual breakthroughs and innovative designs	Refinement, optimization, and standardization
Legacy	Revolutionized power generation and transmission	Made AC systems efficient, reliable, and practical

Tesla provided the foundational inventions and visionary concepts that shaped the development of AC systems and rotating machinery. Steinmetz, on the other hand, used his mathematical prowess to refine these concepts, ensuring their practicality, efficiency, and reliability for industrial use. Together, their contributions were instrumental in making modern electrification possible.

Charles P. Steinmetz' phasor-impedance model of induction machine



Critical relationship: Faraday's Law

$$e_{sa} = \frac{d\lambda_{sa}}{dt} = \omega_e L_m \hat{i}_m \cos\left(\omega_e t + \theta_{m0} + \frac{\pi}{2}\right)$$
$$e_{ra} = \frac{d\lambda_{ra}}{dt} = \frac{N_r}{N_s} s\omega_e L_m \hat{i}_m \cos\left(s\omega_e t + \theta_{m0} + \frac{\pi}{2}\right).$$

1. Per unitize

2. Physical frame conversion

Rotor frame variables viewed from the stator frame

3. Time-domain to frequency domain conversion

Phasors of different frequencies, instead of instantaneous variables are used.

Robert H. Park
1902-1996

Two-Reaction Theory of Synchronous Machines

Generalized Method of Analysis—Part I

1929

BY R. H. PARK*
Associate, A. I. E. E.

Synopsis.—*Starting with the basic assumption of no saturation or hysteresis, and with distribution of armature phase m. m. f. effectively sinusoidal as far as regards phenomena dependent upon rotor position, general formulas are developed for current, voltage, power, and torque under steady and transient load conditions. Special detailed formulas are also developed which permit the determination of current and torque on three-phase short circuit, during starting, and when only small deviations from an average operating angle are involved.*

In addition, new and more accurate equivalent circuits are developed for synchronous and asynchronous machines operating in parallel, and the domain of validity of such circuits is established.

Throughout, the treatment has been generalized to include salient poles and an arbitrary number of rotor circuits. The analysis is thus adapted to machines equipped with field pole collars, or with amortisseur windings of any arbitrary construction.

It is proposed to continue the analysis in a subsequent paper.

* * * * *

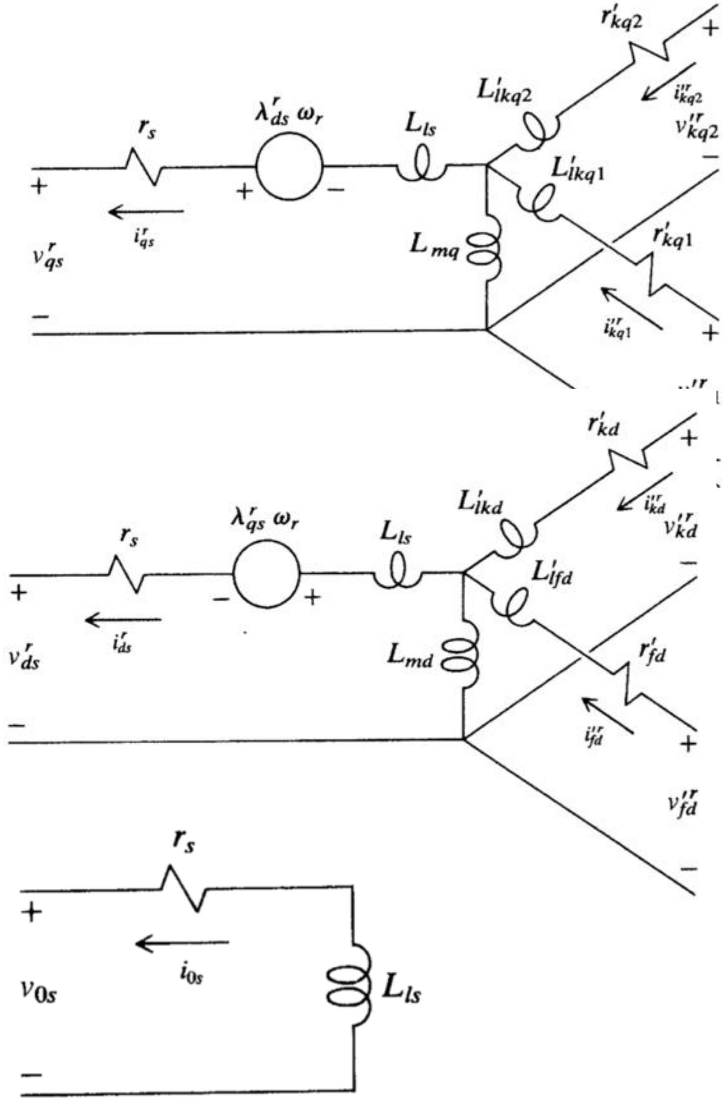
THIS paper presents a generalization and extension of the work of Blondel, Dreyfus, and Doherty and Nickle, and establishes new and general

i_a, i_b, i_c = per unit instantaneous phase currents
e_a, e_b, e_c = per unit instantaneous phase voltages
ψ_a, ψ_b, ψ_c = per unit instantaneous phase linkages

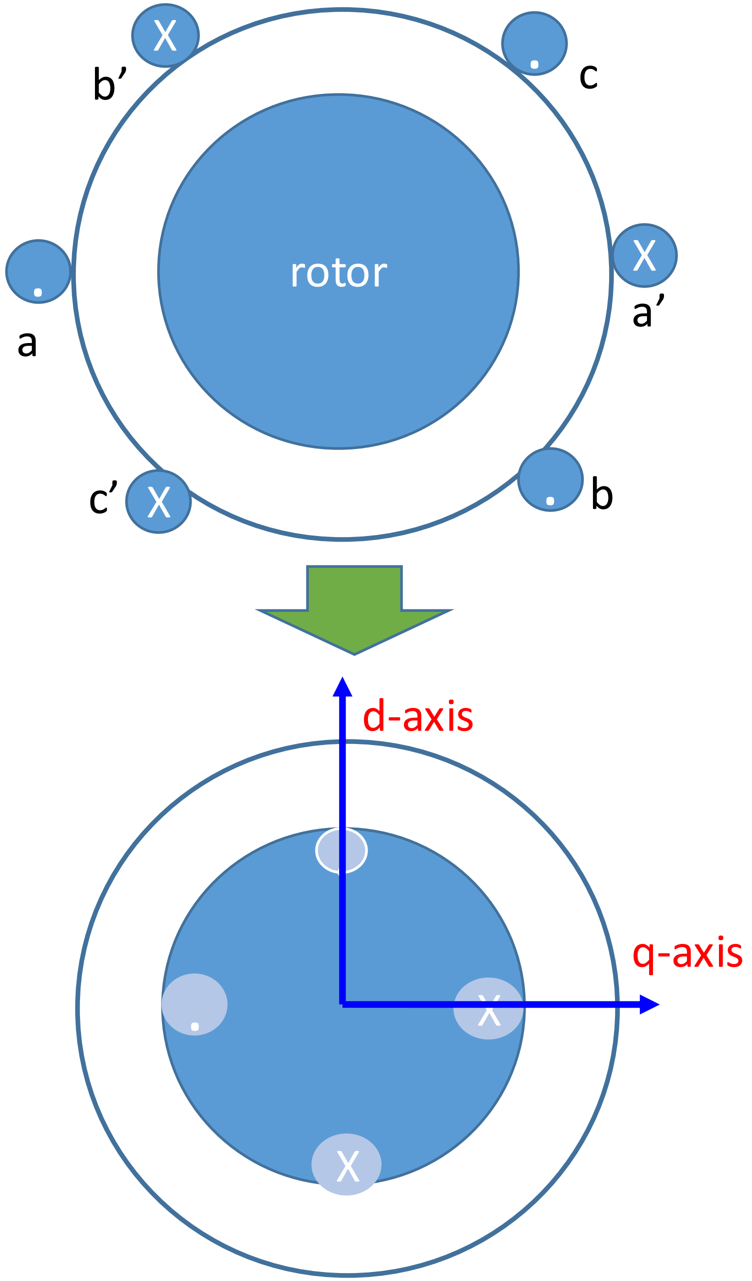
Memorial Trib

BY CHARLES CONCORD

Robert H. Park will long be remembered by electric power system engineers and electrical machine designers as the originator of what are universally known as "Park's equations." These were given in an American Institute of Electrical Engineers technical paper in 1929. Essentially, they provided a set of relations that made practical and simple the calculation of the dynamic performance of electric (ac) generators (and motors). Such a tool was necessary, but not yet available, for the calculation of the dynamic performance of electric power systems to ensure stable and reliable operation in the face of possible disturbances. This seminal paper has been the basis not only for an enormous flood of useful work in the field but also for many careers in the field. It was, and still is, unmatched in that respect. By itself it would have been enough to make Park famous among power system engineers worldwide.



Krause, P.C., Wasynczuk, O., Sudhoff, S.D. and Pekarek, S.D., 2013. *Analysis of electric machinery and drive systems* (Vol. 75). John Wiley & Sons.



Park’s equation:

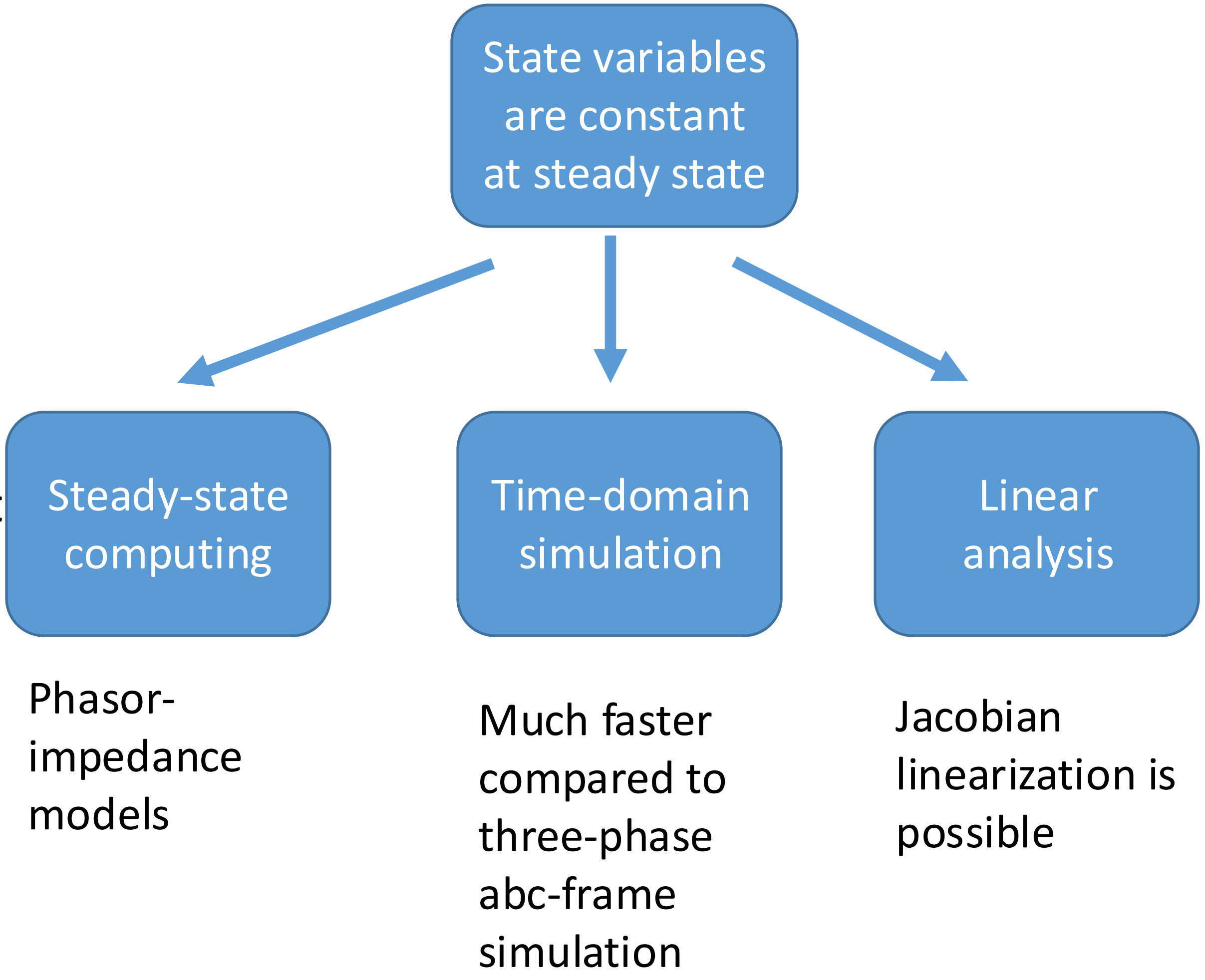
Three-phase stator windings are viewed as **two** dq windings in the rotor frame.

Ac voltages and currents are viewed as **dc** voltages and currents.

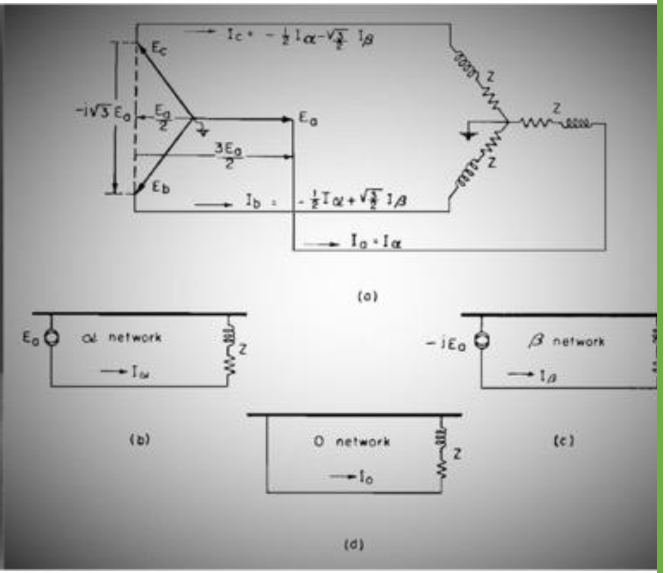
Instead of dealing with **time varying** inductances in the static frame, the inductances in the dq frame are **constant**.

Impact of Park’s transform (abc to dq frame conversion)

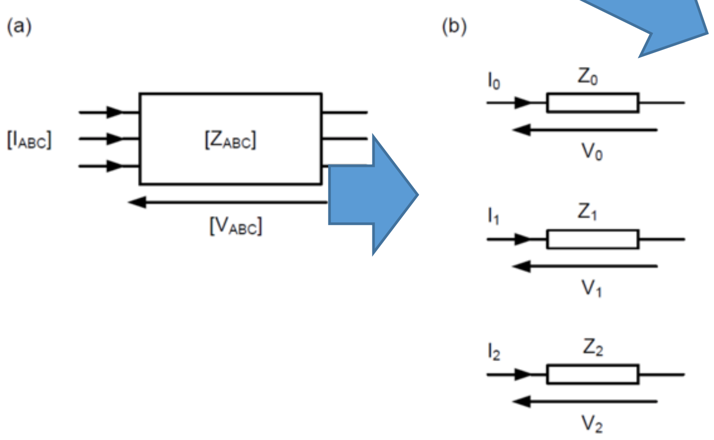
- **Simulation:**
  - Make efficient computer simulation models
  - Three-phase AC machine models in computer simulations (Electromagnetic or phasor based) are all modeled in the Park’s frame.
- **Control**:
  - Dq-frame has been used for control. Instead of tracking an ac sinusoidal signal, tracking current orders in the dq frame is very easy by using proportional integral control.
- **Analysis**:
  - Enable analytical model building. Those models can be used for Jacobian linearization.



Clarke's transform & Fortescue's symmetrical component theory



$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (10a)$$



$$Z_{AA} = Z_{BB} = Z_{CC} = Z_S$$

$$Z_{AB} = Z_{BA} = Z_{AC} = Z_{CA} = Z_{BC} = Z_{CB} = Z_M$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$Z_0 = Z_S + 2Z_M$$

$$Z_1 = Z_2 = Z_S - Z_M$$

Matrix factorization through Eigenvalue decomposition

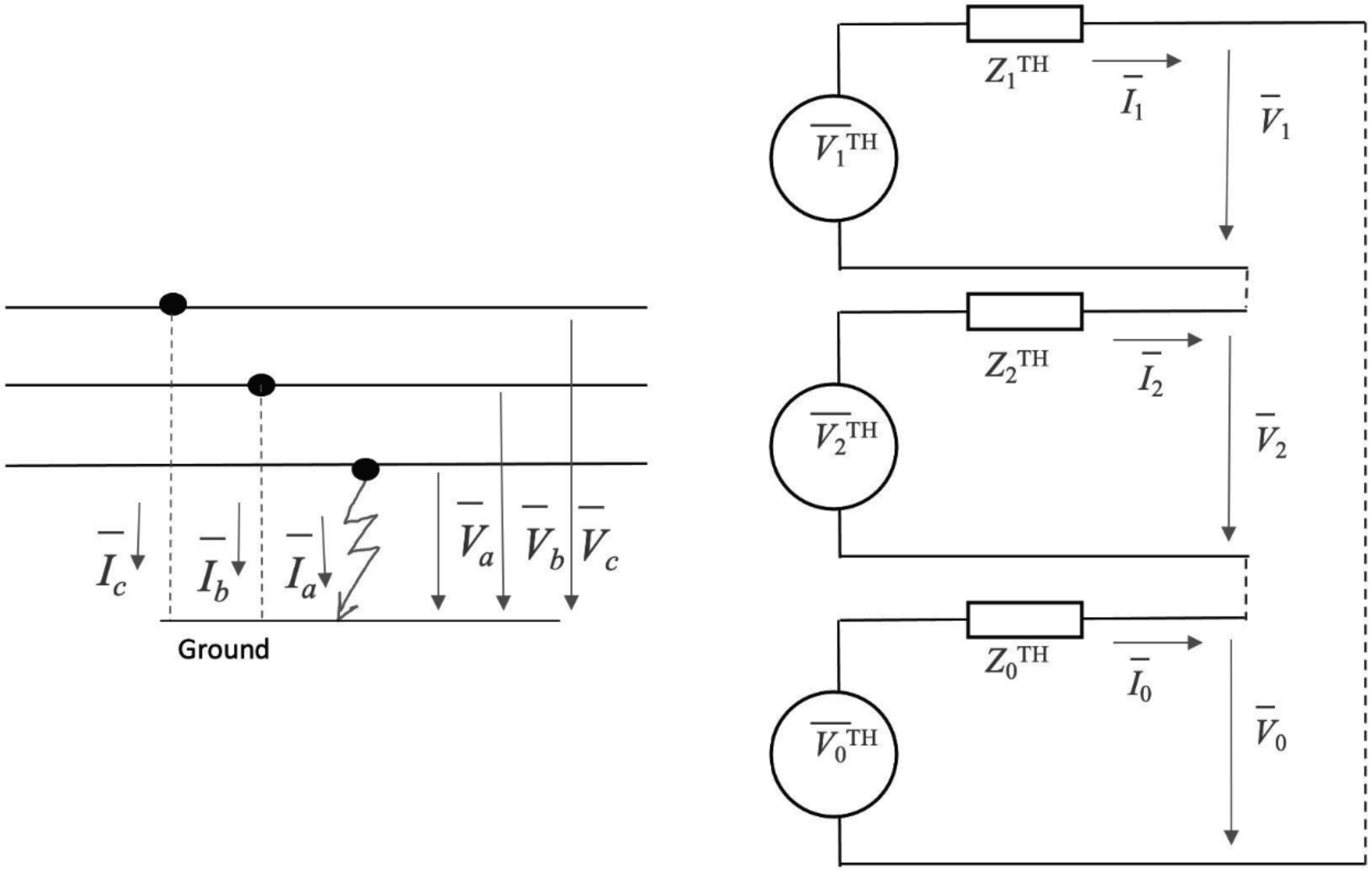
$$\begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}^{-1}$$

We see a meshed network can be represented by three decoupled circuits.

Voltage and current are expressed in a different coordinate

Abc → sequence domain

Impact of sequence-domain circuits: enabling unbalanced fault analysis for protection



Charles Concordia

- Known for in-depth analysis of **system dynamics and stability**
- Designed exciter voltage control of synchronous generators and conducted stability analysis to show benefits of such control
  - Major tools: hand calculation, operation calculus or Laplace transform
- Trouble shooting
  - E.g., subsynchronous resonances (SSR): induction motor oscillation issues in a mine served by series compensated line.

Charles Concordia (June 20, 1908 – December 25, 2003)
Power system dynamic & stability

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- Innovations in modeling & analysis
  - The influential people & their contributions
- **Real-world event replication and root cause analysis**
  - **SSR in wind farms**
  - **Inverter-based resource oscillations**

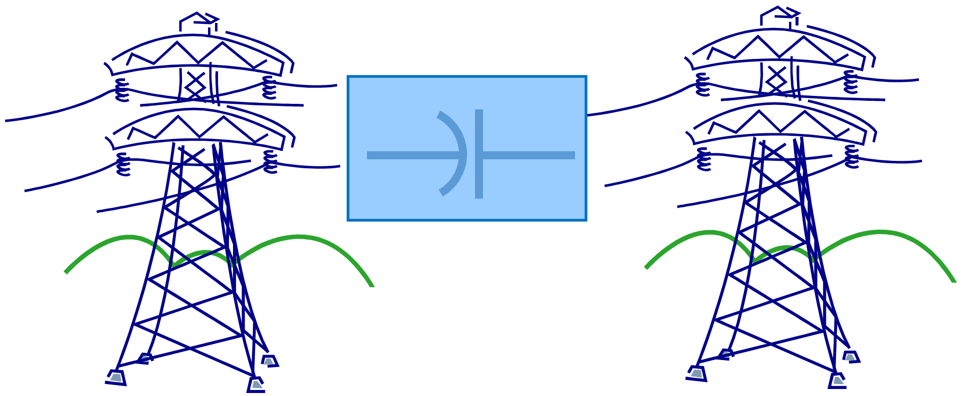
Susbsynchronous resonances in wind farms

Historic notes

- 1944 Concordia wrote a paper to describe various issues caused by series capacitor, including the interaction of a capacitor and an induction motor.
- 1970s Power plants' rotor shaft damaged due to radial connection to series capacitors.
  - Follow up working groups:
    - 1944 events (induction generator effect – electric resonances caused by negative resistance;
    - 1970s event: torsional interactions. Generator's mechanical modes interact with the LC mode.
- 2000s: wind farm (doubly-fed induction machine) SSR issues
  - Few people can predict such issues (Dennis Woodford is one).
  - This has a similar nature of induction generator effect.

Series Capacitor SSO: the electrical LC resonance

- Series capacitors installed in transmission lines to "shorten" transmission lines and to ship more power.



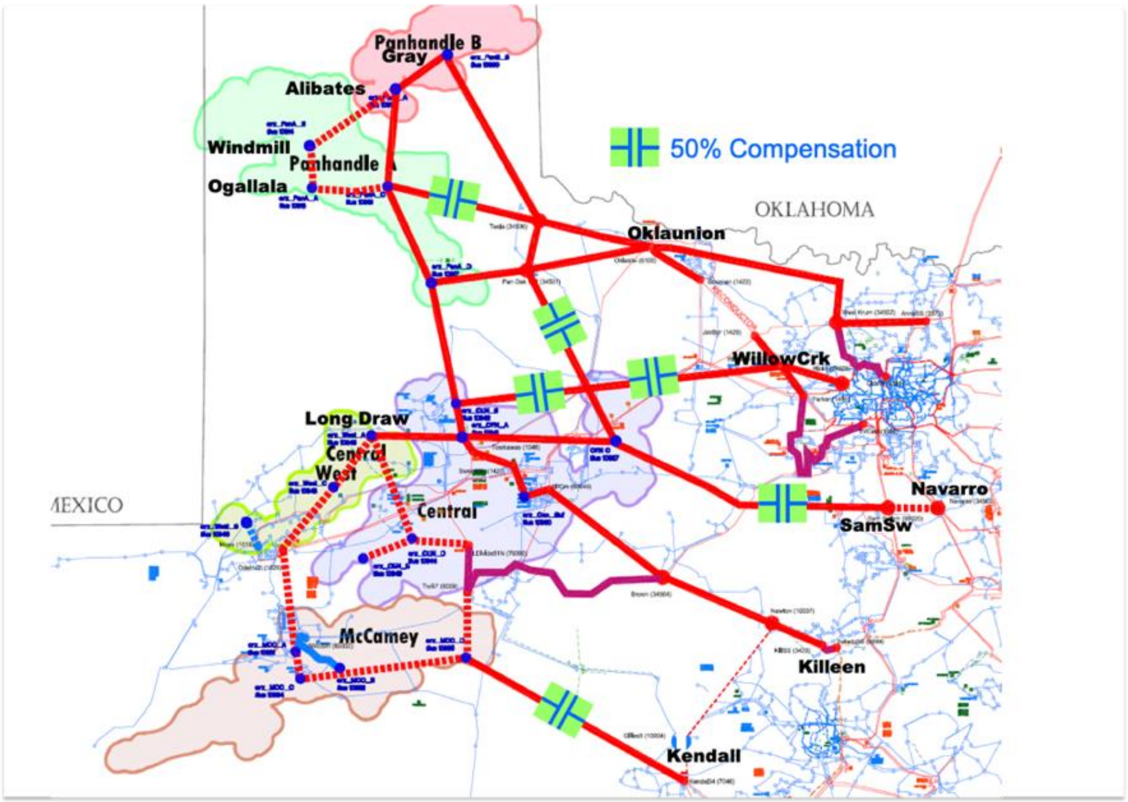
$X = X_L(1-X_C/X_L) = X_L(1-k)$,

Source: Jonathan Rose, ERCOT

Series capacitors can introduce resonances.

J. Rose, Series Compensation and SSR – Concepts, Workshop on NPRR 562, Subsynchronous Oscillations, Sep 2013

Series Compensation in CREZ



Source: Jonathan Rose, ERCOT

Subsynchronous resonance (SSR) due to LC resonance

- It happened before in 1970s at Nevada's Mohave power plant.
- One of the power plant (1,580 MW)'s synchronous generator experienced growing vibration in its shaft, causing damage ➔
- Reason: 30.1 Hz oscillations in the mechanical side triggered by LC resonance from the electrical side.
- If the **electric LC frequency + shaft mode frequency = 60 Hz**, **torsional interaction may occur**.

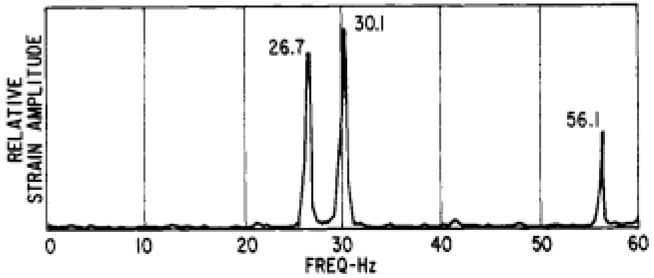


Fig. 7. Synchronization Frequency Analysis

Source: Jonathan Rose, ERCOT and the following two references

D. Baker, G. Boukarim, "Subsynchronous Resonance Studies and Mitigation Methods for Series Capacitor Applications," IEEE 2005.
D. Walker, D. Hodges, "Results of Subsynchronous Resonance Test At Mohave," IEEE 1975.

2007 Minnesota 9.4 Hz SSO: type-3 wind

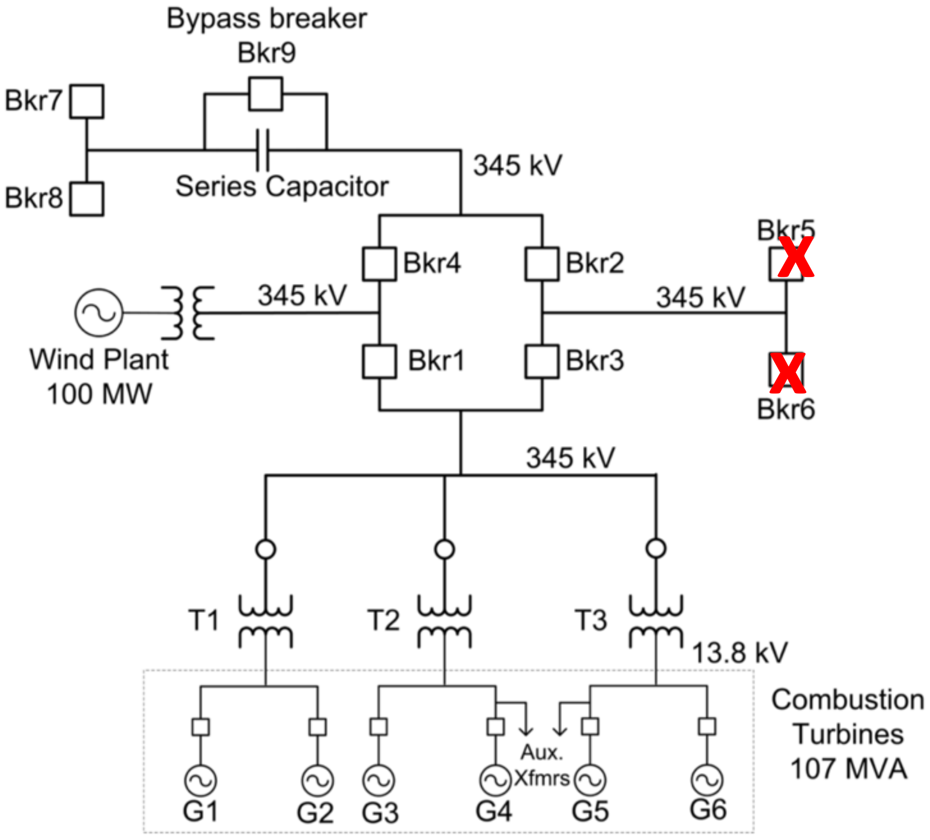
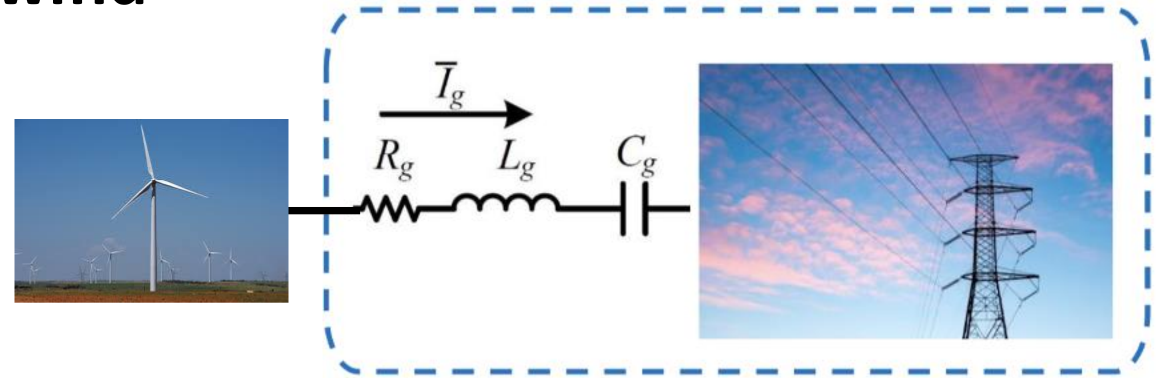


Figure 2.1: 345-kV Transmission system one-line including series compensation.



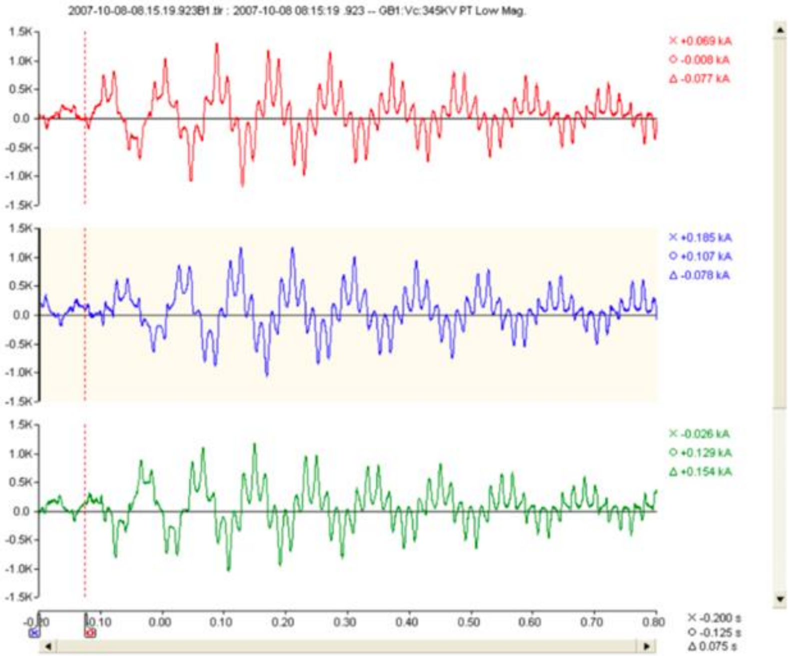
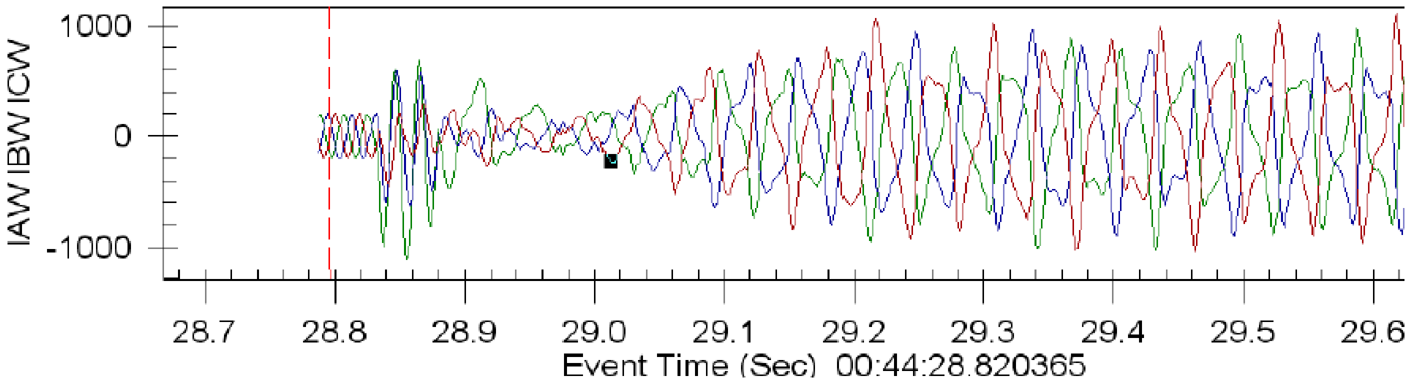


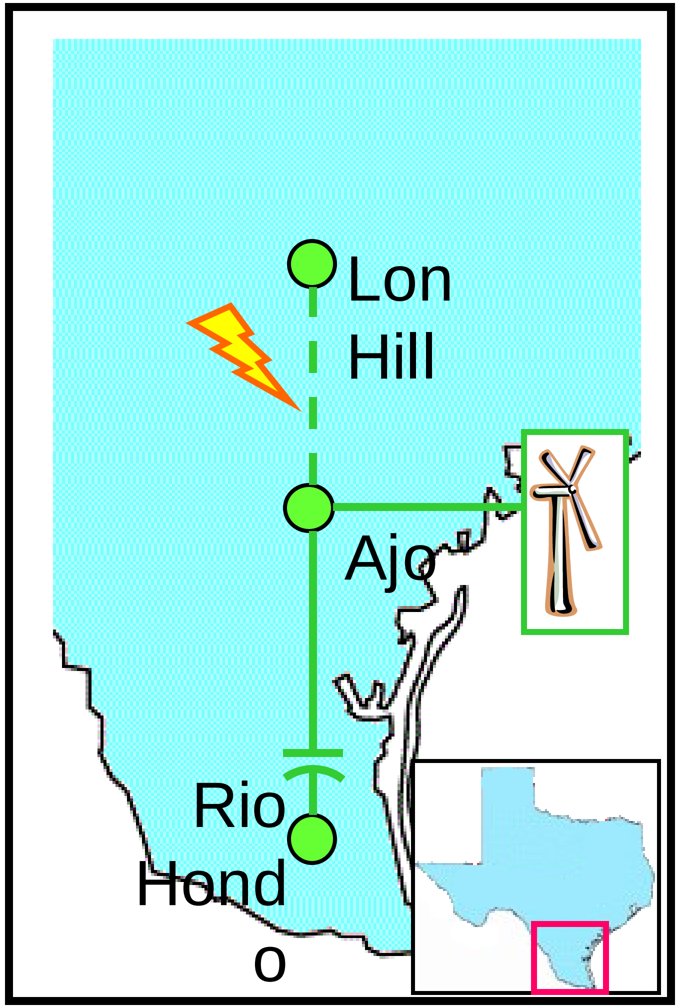
Figure 2.2: WPP Phase A, B, C, currents obtained from DFR, y-axis in Amps and x-axis in Seconds

Source: PES TR-80

South Texas 2009 Event

- Series capacitors installed on Lon Hill – Rio Hondo 345 kV long line in South Texas.
- A cluster of wind farms (DFIG) connected to Ajo.
- A fault caused LonHill – Ajo line to trip, leaving wind farms radially connected to series caps.
- Very high currents resulted in damage.

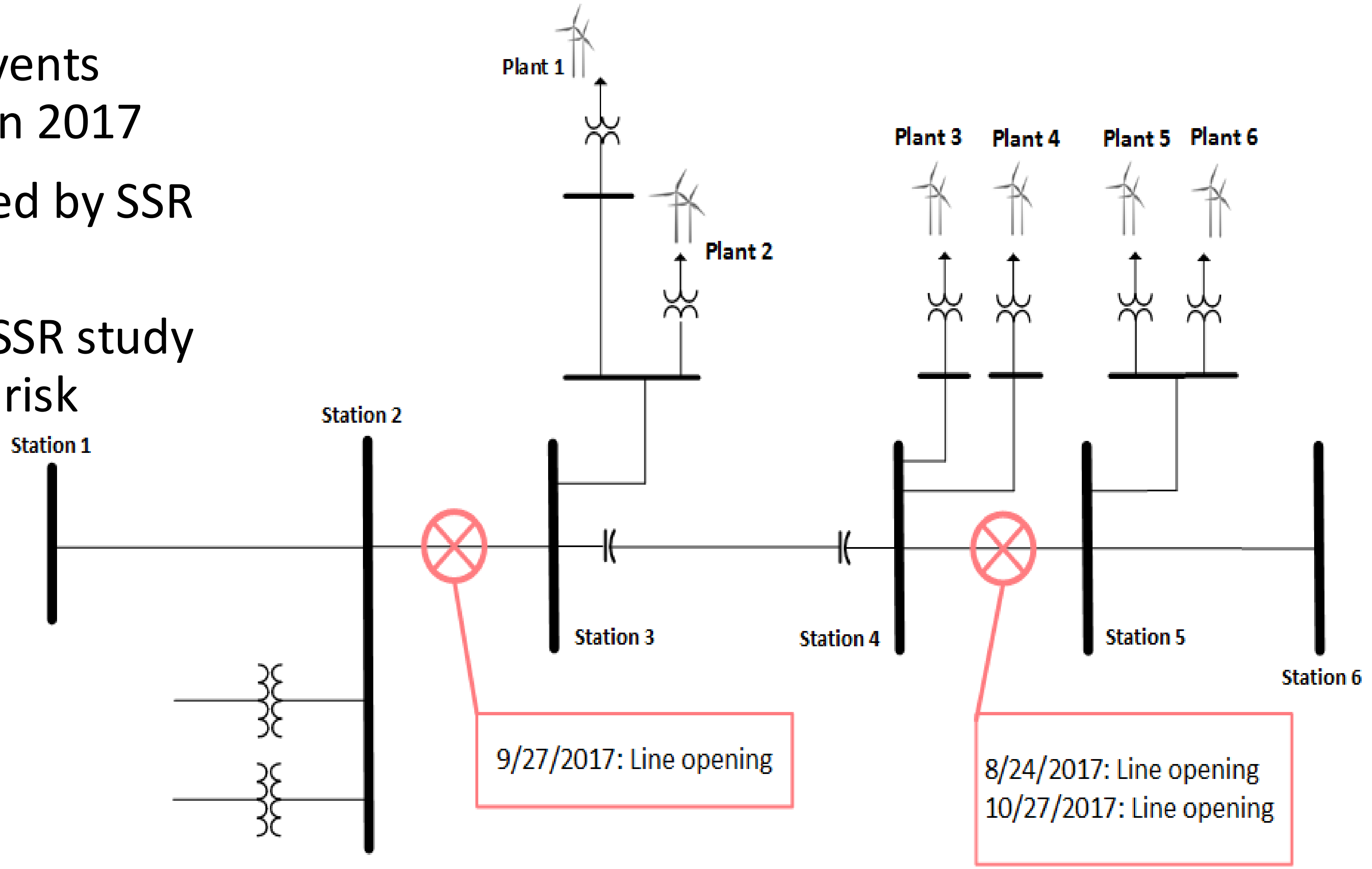




Reference: Chapter 2.2, Task Force Report from IEEE PES Task Force Modeling Subsynchronous Oscillations in Wind Energy Interconnected Systems (Wind SSO TF), by Yunzhi Cheng, Jonathan Rose, John Schmall and Fred Huang

South Texas 2017 Events

- Three type-3 wind SSR events occurred in South Texas in 2017
- Wind plants (DFIG) tripped by SSR protection
- Challenges: The original SSR study failed to capture the SSR risk



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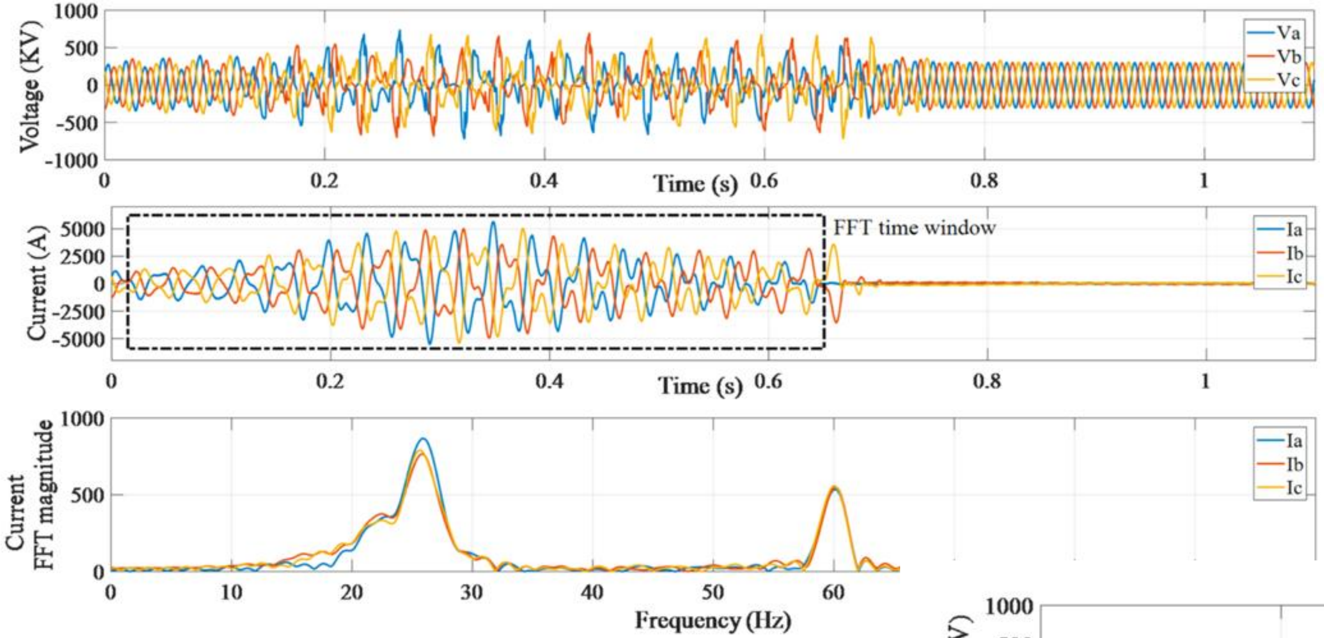
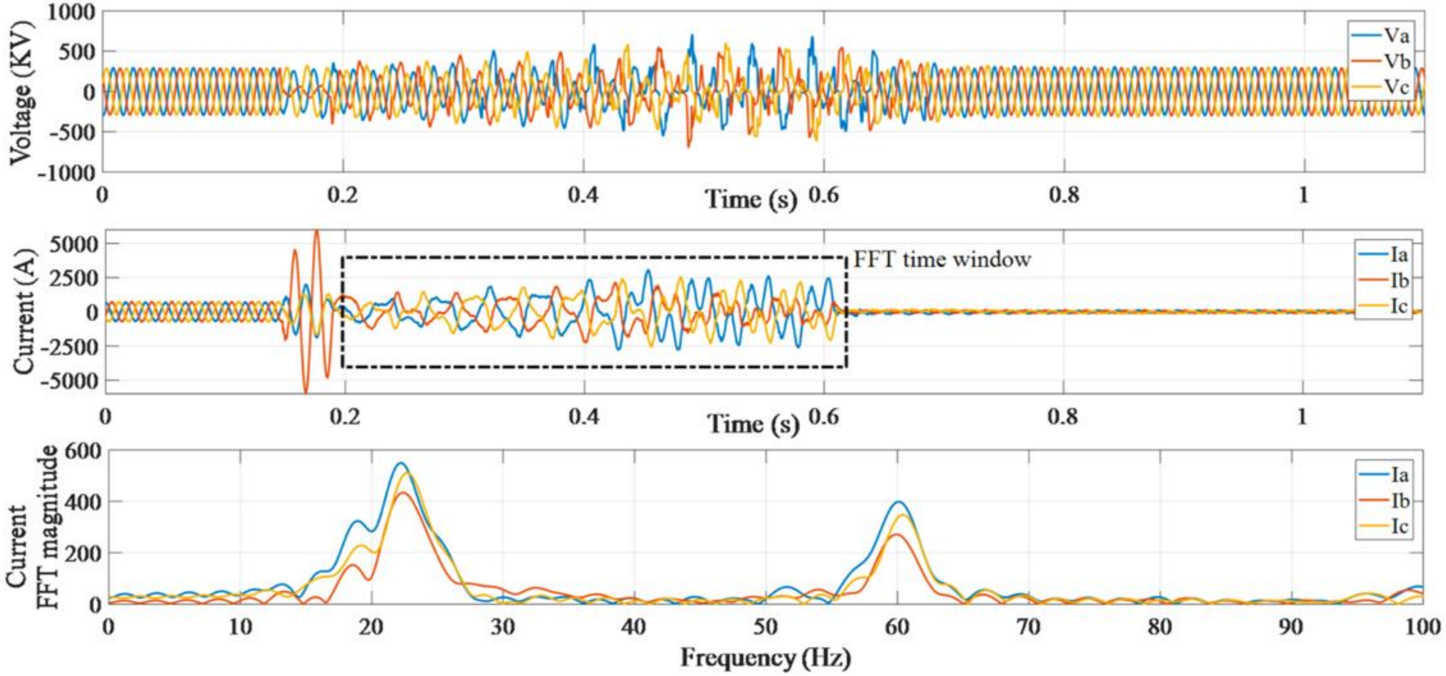
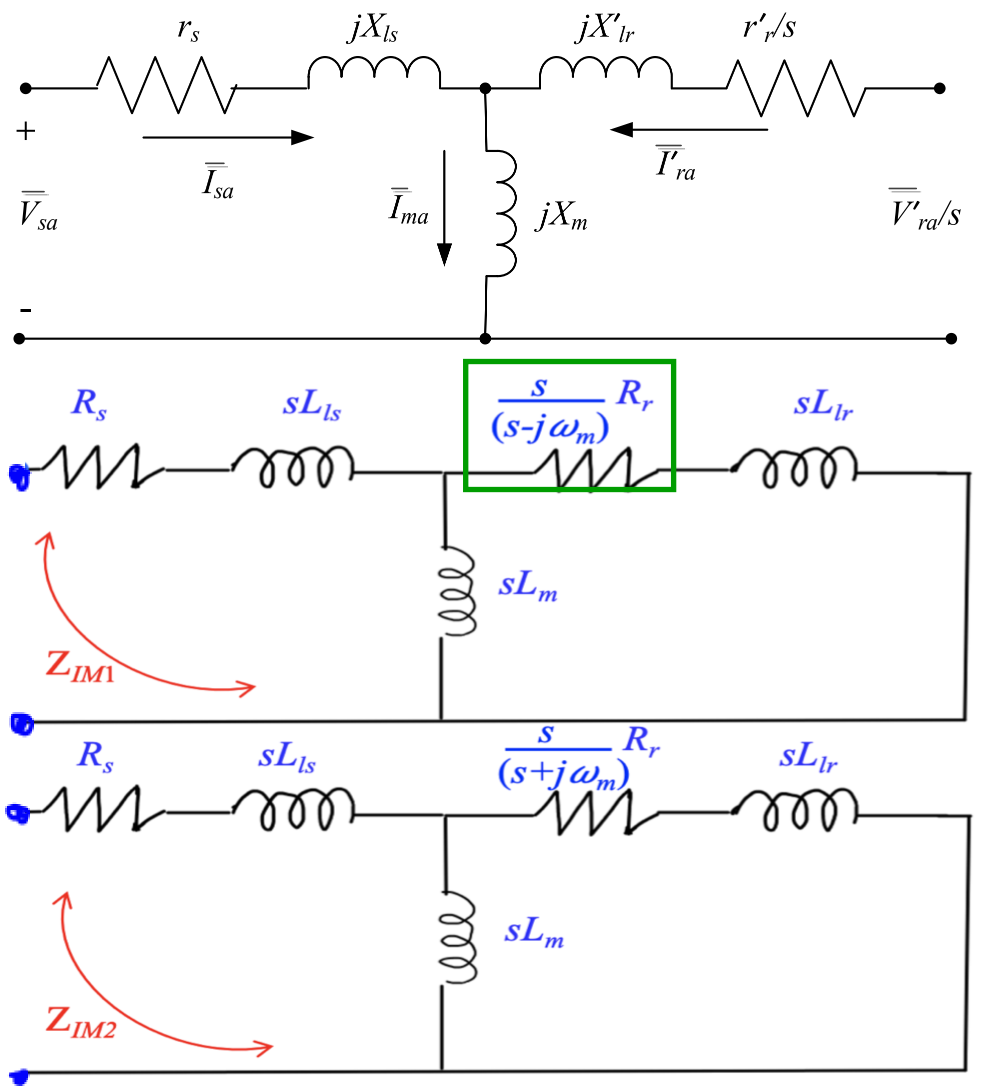


Figure 2.11: Event 1 (after series capacitor re-i



Innovative work in this area: complex s-domain impedance

- Introduced **complex s-domain impedance** concept to explain the creation of oscillations (why negative resistance under certain frequency region).
- Elevate Steinmetz's circuit representation to the entire frequency domain
- Steady state➔ dynamics

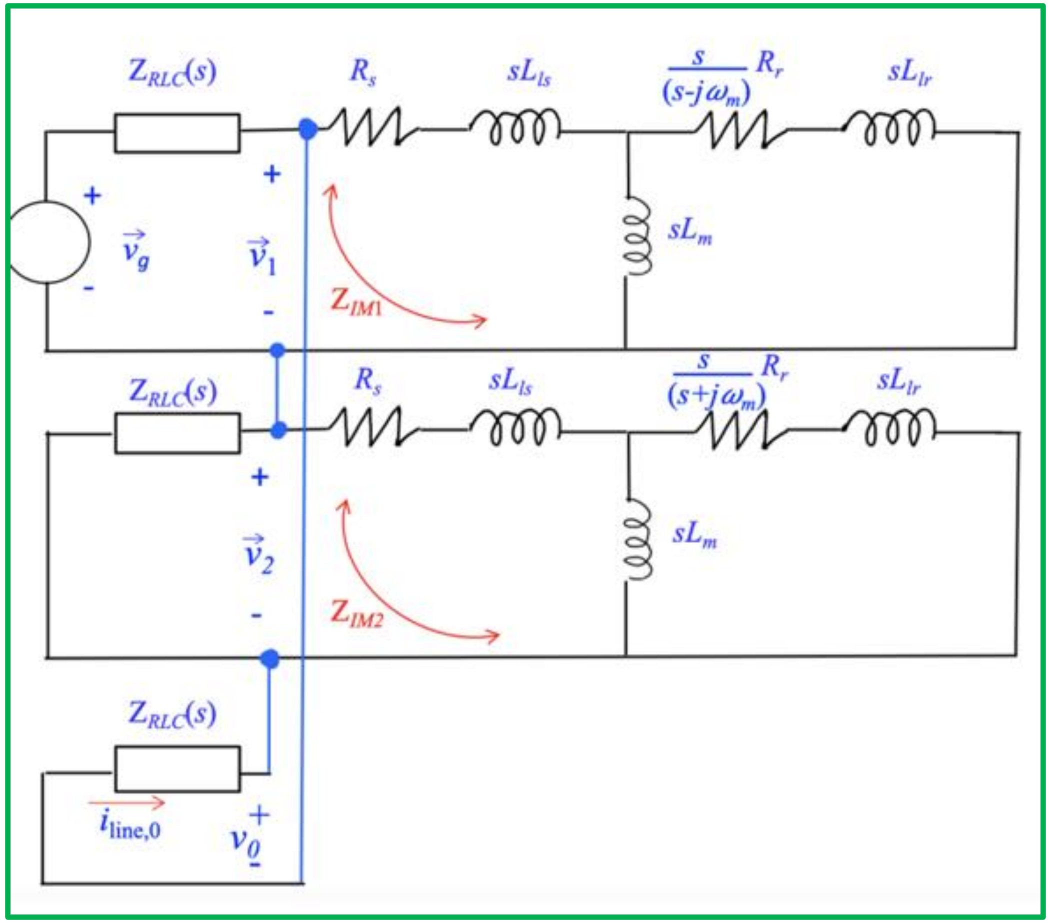


Ref: L. Fan, Z. Miao, "**Nyquist-stability-criterion-based SSR explanation for type-3 wind generators**", IEEE TSTE 2012

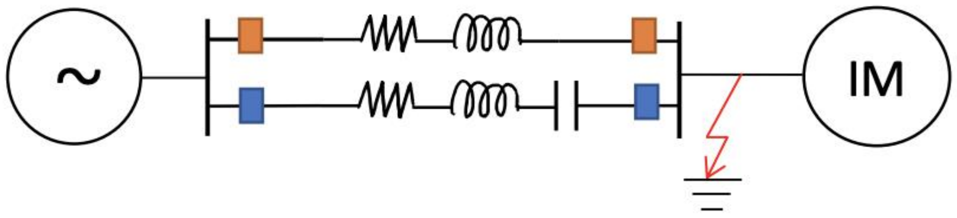
At certain frequency range, the equivalent rotor resistance is negative➔ cause of series compensation+ type-3 wind farm SSR, or IM SSR

Generalized dynamic circuit construction for unbalance

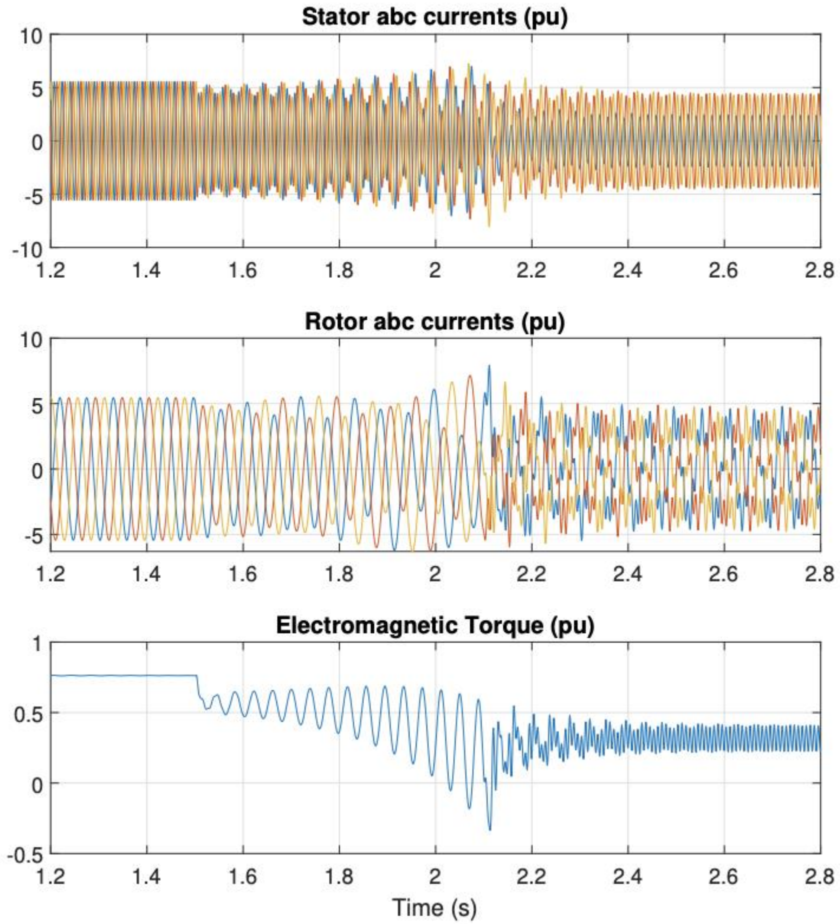
- Elevate the sequence network interconnection technique into the entire frequency domain.
- Steady➔ dynamics
- Enable efficient analysis under unbalance (very challenging)
- Solved a puzzle of 30 years old: why unbalance can mitigate SSR.



- Z. Miao and L. Fan, "A Laplace-Domain Circuit Model for Fault and Stability Analysis Considering Unbalanced Topology," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2022.3230564.



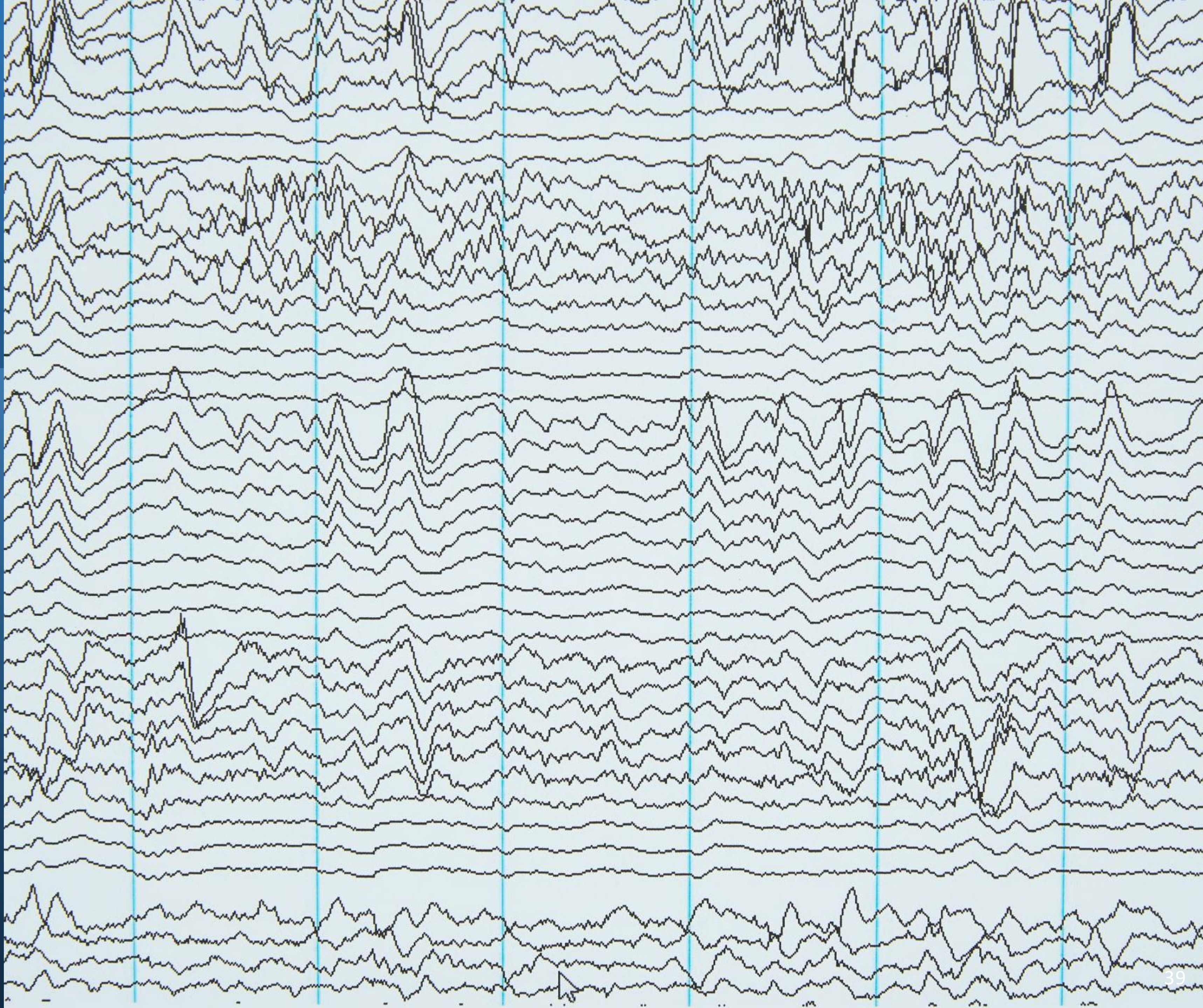
(a)



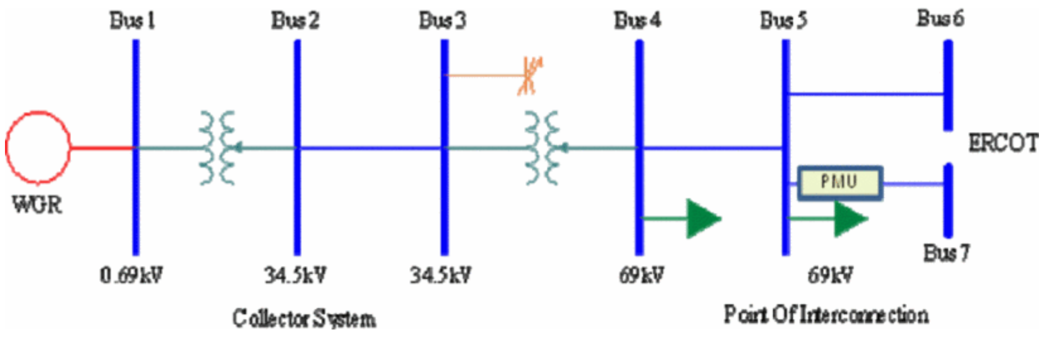
(b)

- The RL circuit trips at 1.5 s, leaving the induction machine radially connected to a series capacitor. 26-Hz oscillations become severe.
-
- At 2.1 s, a single-line-ground fault applies. The 26-Hz oscillations are mitigated, while 120-Hz harmonics sustain due to unbalance.

Weak grid oscillations



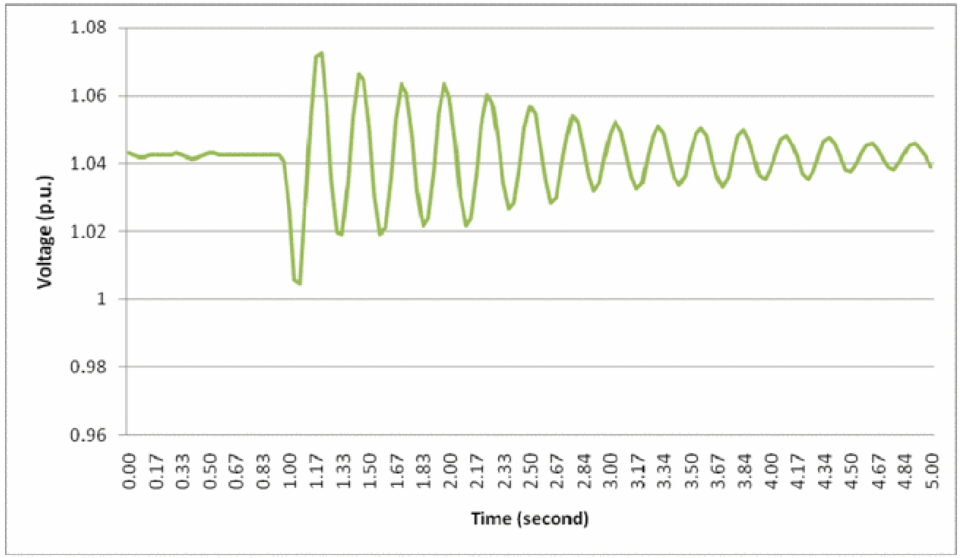
2011 Texas wind farm 4-Hz oscillation event:



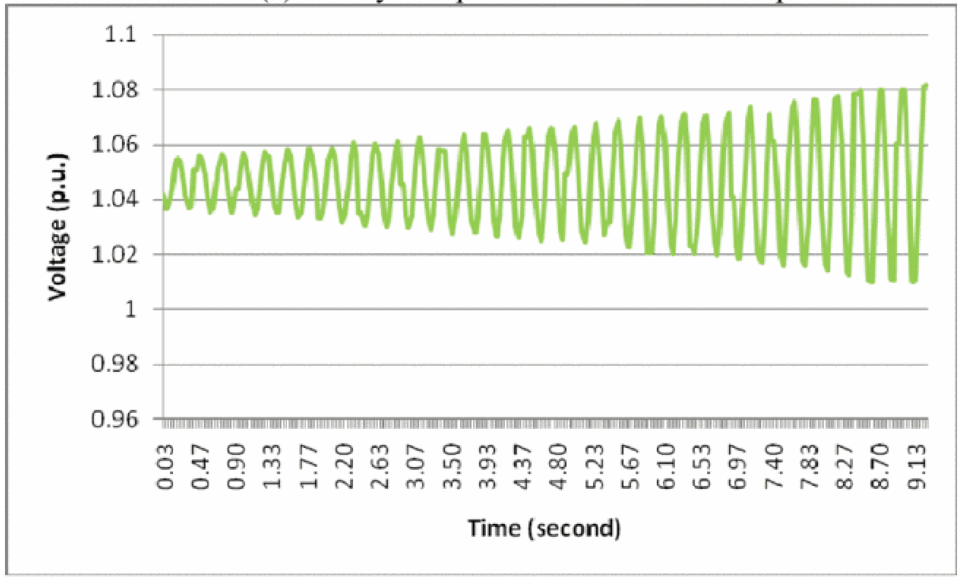
At normal conditions, the WPP was connected to the ERCOT grid through two 69-kV transmission lines. When one 69-kV transmission line was out of service for maintenance, **the SCR reduced below 2** and undamped oscillations appeared. Measurement recordings are presented in Fig. 11.

ERCOT successfully replicated the oscillation events in the study. The oscillations was identified to be associated with the WPP's voltage control. **Slowing down the voltage control** can help mitigate the oscillations.

S. -H. Huang, J. Schmall, J. Conto, J. Adams, Y. Zhang and C. Carter, "Voltage control challenges on weak grids with high penetration of wind generation: ERCOT experience," *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1-7, doi: 10.1109/PESGM.2012.6344713.



(a) Poorly-damped oscillation at low output



(b) Un-damped oscillations at high output

Texas 4-Hz oscillations: volt-var oscillations

Other voltage stability related issues

#3: (2010) Oklahoma Gas & Electric (OG&E) observed 13- Hz oscillations at two nearby WPPs [4]. The oscillations occurred when wind farm output was above 80 percent of its rated level and the magnitude of oscillation reached 5% of the 138-kV voltage. OG&E **curtailed the plant's output** until the manufacturer made modifications to the wind power conversion system.

#4: (2011) 4-Hz oscillations were observed at a type-4 WPP in Texas region after a transmission line tripped [18].

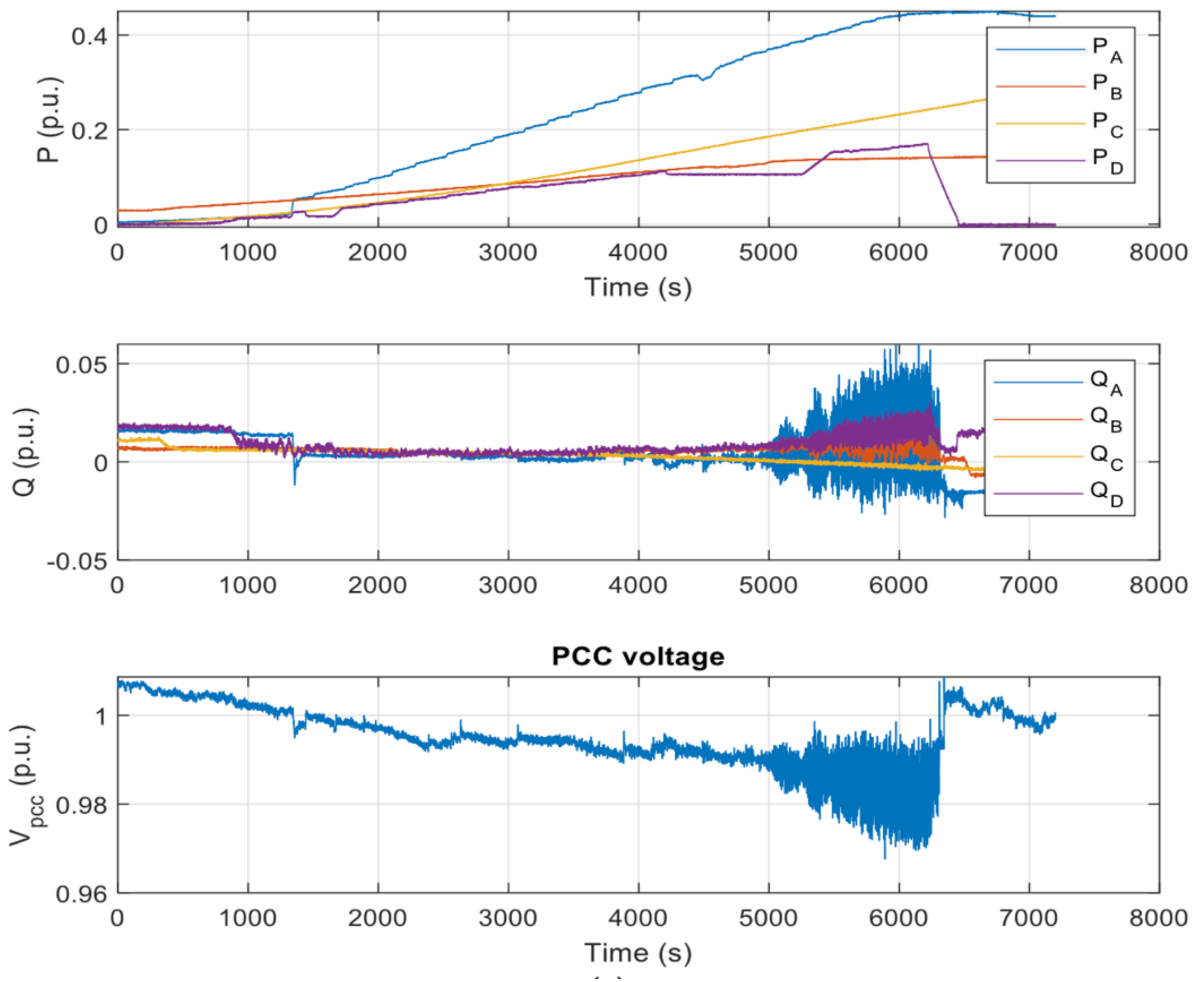
#5 (2011-2014) Since 2011, oscillations were observed by BPA during high wind generation conditions [4]. A 450- MW type-4 WPP located in Oregon was identified as the source. In summer 2013, BPA's phasor measurement unit (PMU) monitoring system identified 5-Hz oscillations in voltage, real and reactive power. In early 2014, BPA detected 14-Hz oscillations. Reactive power oscillations reached 80 Mvar peak to peak **while power reached 85% of the rated level**. The wind generator manufacturer upgraded their **voltage control** and no oscillations have been detected since.

#6 (2011-2012) OG&E reported two wind oscillation events, one in December 2011 and another one in December 2012. **Both were triggered due to line outage.** For the 2012 event, 3-Hz oscillations appeared at a 60-MW WPP after a line outage [4]**. Curtailing the power** helped restore the system. OG&E worked with the WPP manufacturer to tune the WPP control parameters, resolving the issue.

Line tripping
High power
Voltage control

Ref: Y. Cheng, L. Fan, *et al*., "**Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources**," in *IEEE TPWRS 2022.*

2020 South California Edison 1GW solar PV power plant



One more event: 0.1 Hz oscillations

When solar PV (about 1 GW total) power ramps up to a certain level, e.g., 80% of 1 GW, 0.1-Hz oscillations appear in voltage and var

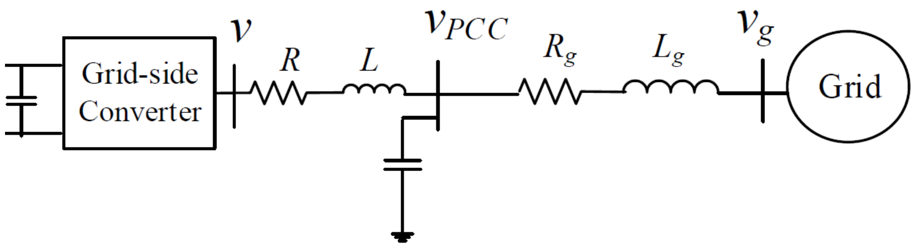
Left: SCADA data of 1-s time interval.

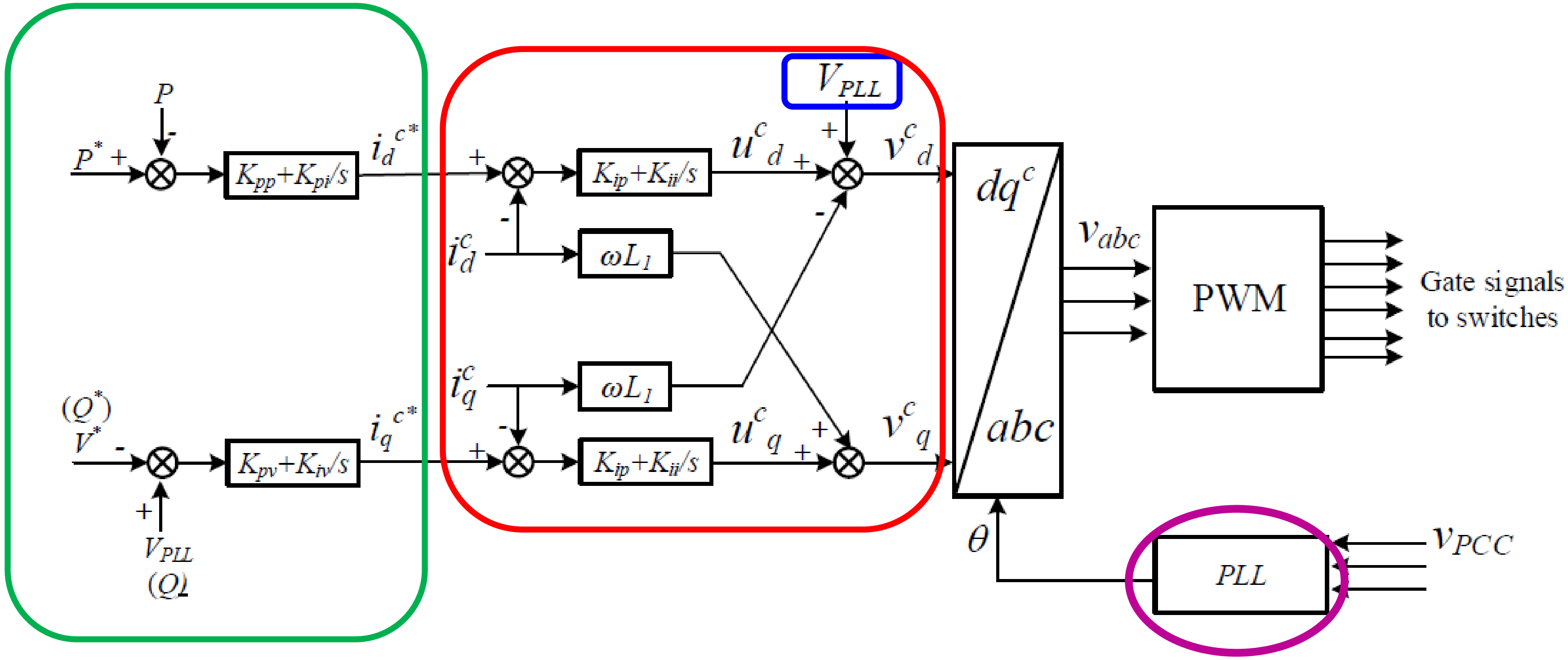
L. Fan, et al, "**Analysis of 0.1-Hz Var Oscillations in Solar Photovoltaic Power Plants**," IEEE TSTE 2022.

Understand the fundamentals of converter control (inverter-level)

Voltage source converter control design has considered the following aspects:

- converter current limit (very fast current control)
- decoupling from grid (voltage feedforward)
- decoupled real power and reactive power control **(vector control)**





Textbook on VSC:
A. Yazdani, R. Iravani, Voltage-Sourced Converters in Power Systems, IEEE Wiley 2010

Hardware demonstration: weak grid oscillations

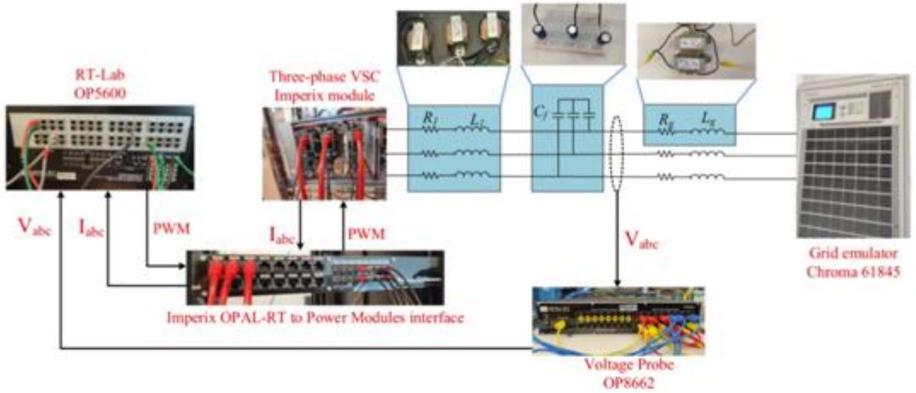
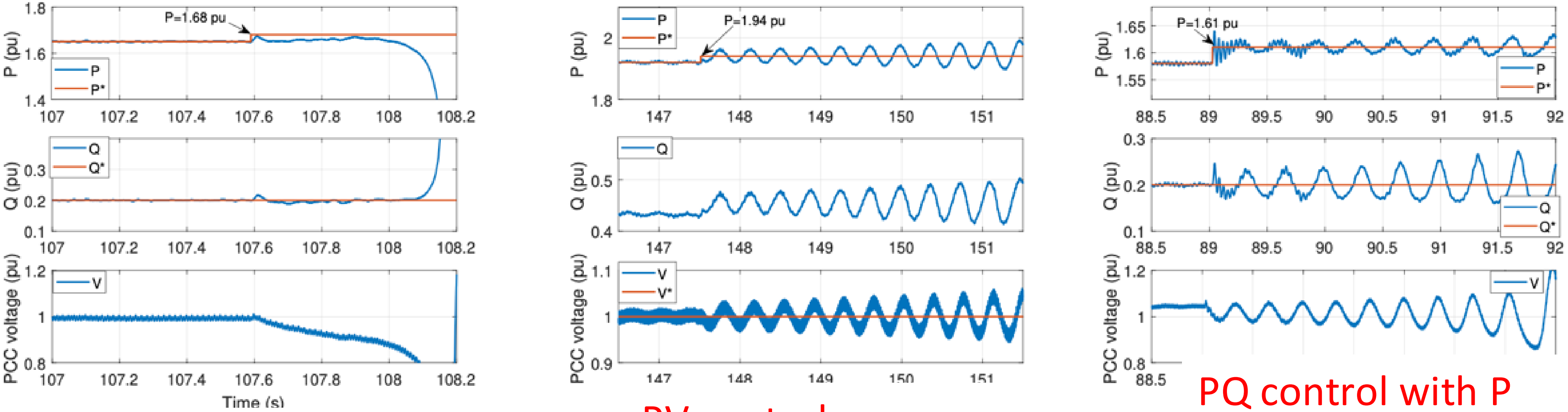


Fig. 19: Configuration of the hardware test bed at University of South Florida [49].

For well-tuned control parameters, if P/Q control mode is adopted, the system loses stability without oscillations. If P/V is adopted, the system loses stability with oscillations.

Ref: L. Bao, L. Fan, Z. Miao, and Z. Wang, "Hardware demonstration of weak grid oscillations in grid-following converters," *the 53rd NAPS*, 2021.



PQ control

PV control

PQ control with P control very fast

Fig. 20: Hardware experiment results [49] (The responses of P, Q and voltage when P is given a step change) demonstrating weak grid instability. (a) PQ control mode (slow P control): losing stability without subject to oscillations. (b) PV control mode (slow P control): oscillations. (c) PQ control (fast P control): oscillations appear when the power control becomes fast.

- We have demonstrated weak grid oscillations. When grid strength reduces, oscillations may appear. High power exporting makes stability worse.

- Those features match the real-world observations, **except:**
- **Fast voltage control in our experiments is good for stability.**

Ref:

Li, Y., Fan, L. and Miao, Z., 2018. **Stability control for wind in weak grids**. IEEE Transactions on Sustainable Energy, 10(4), pp.2094-2103.

Ramasubramanian, D., Baker, W., Matevosyan, J., Pant, S. and Achilles, S., 2022. **Asking for fast terminal voltage control in grid following plants could provide benefits of grid forming behavior**. IET Generation, Transmission & Distribution.

Then, how to understand the real-world observation:

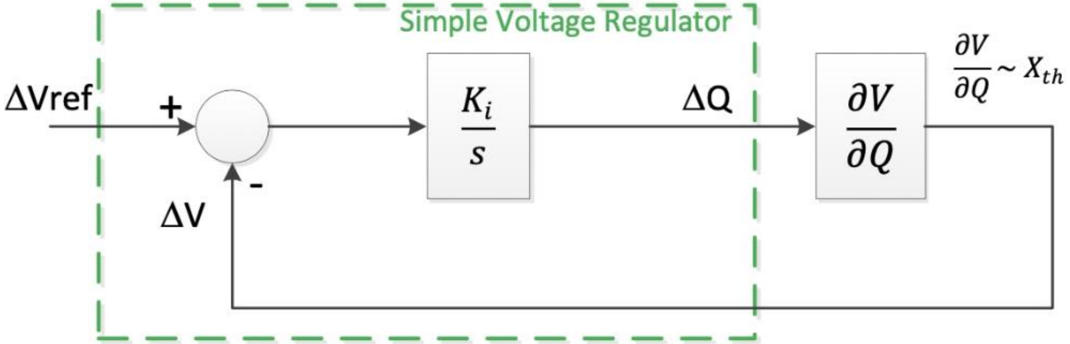
Slowing down voltage control mitigates the 4-Hz oscillations in ERCOT

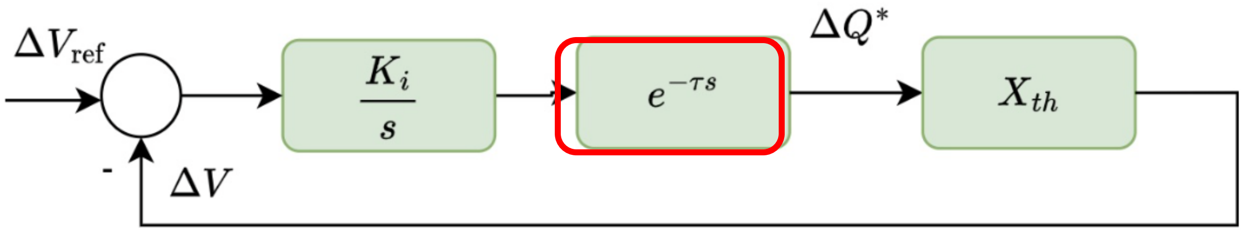
Why?

The two voltage controls are different:

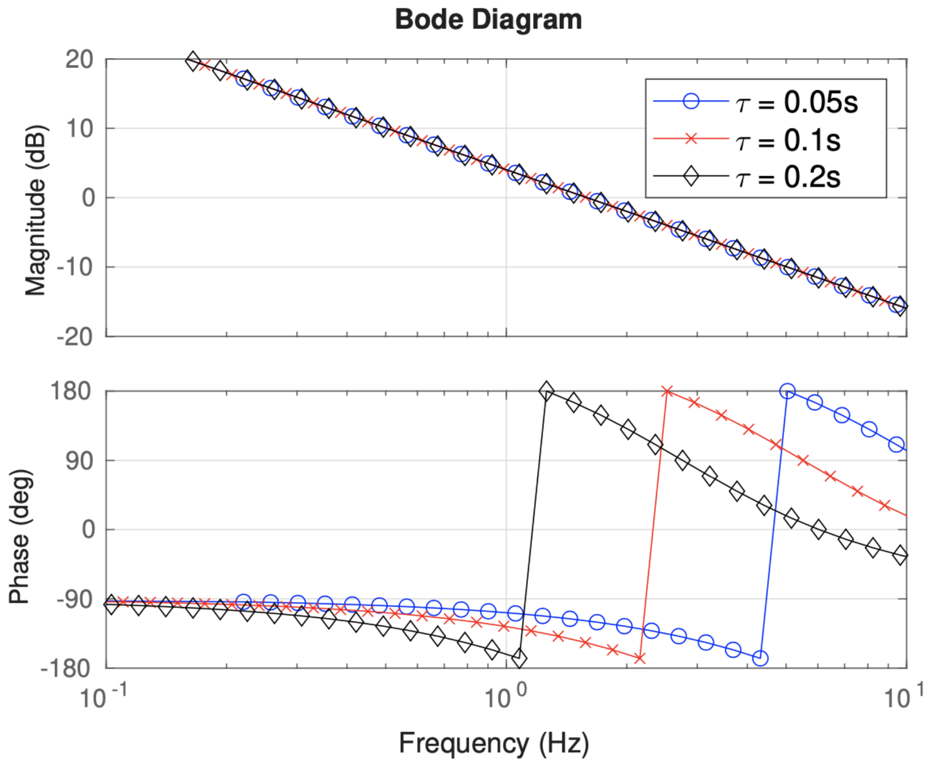
Inverter-level control

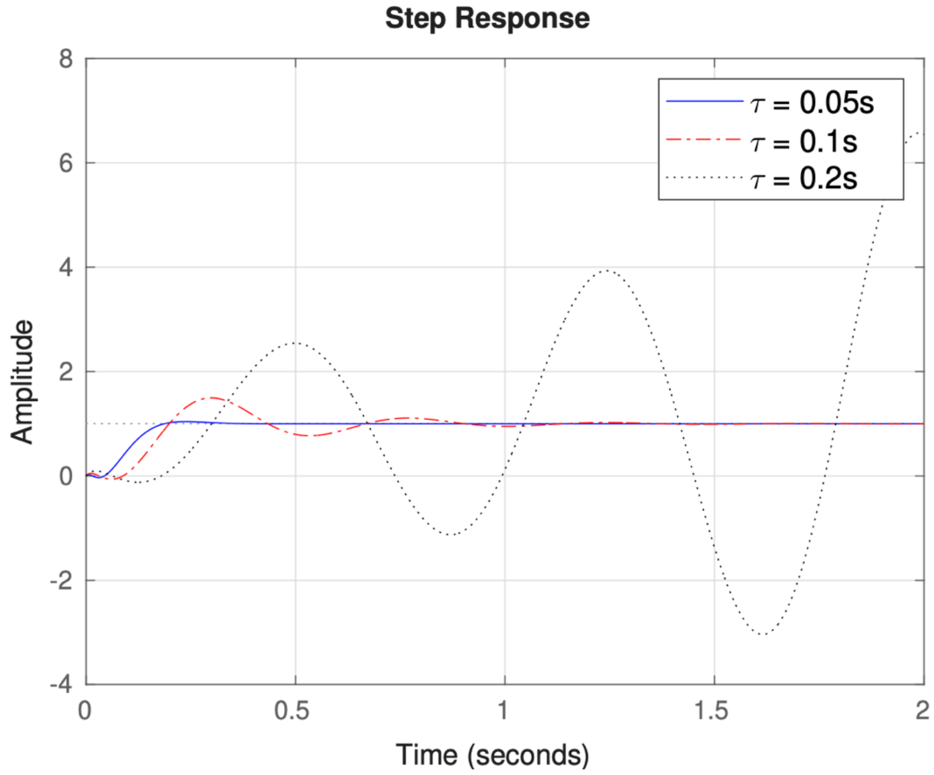
Plant-level control (delay)



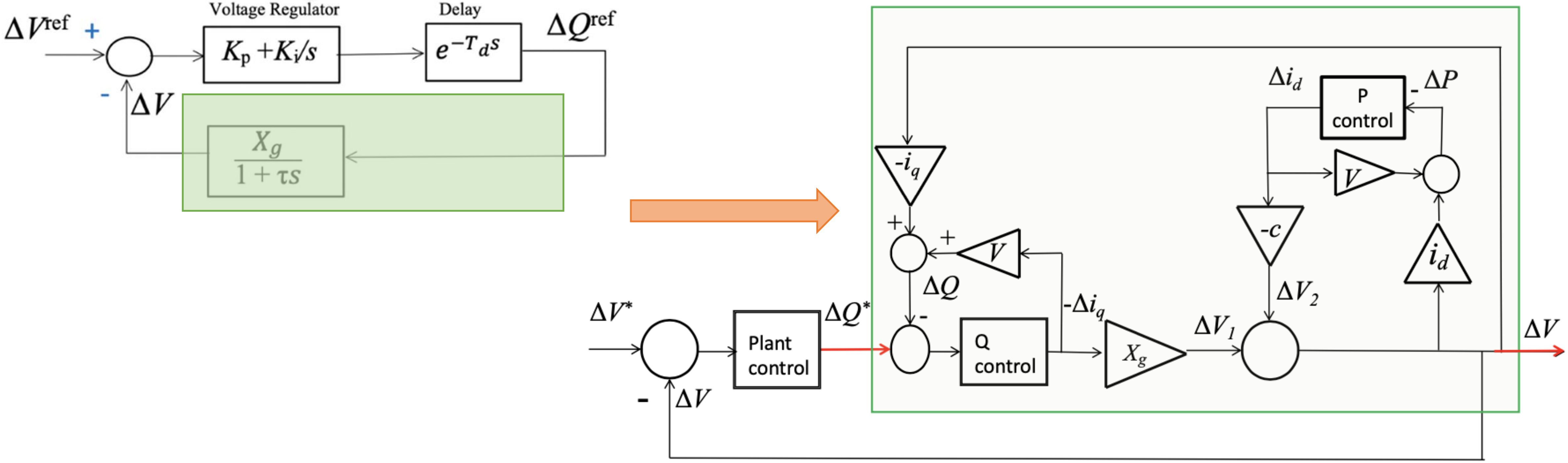


Always stable.



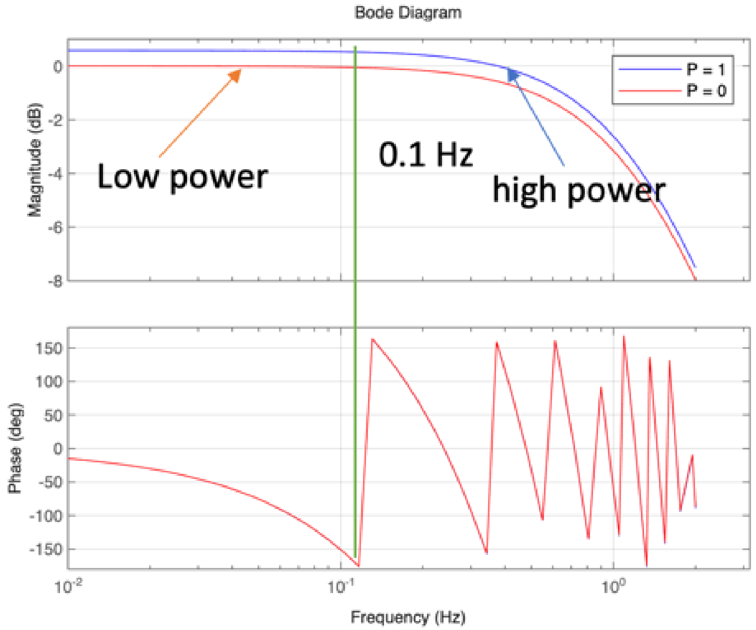


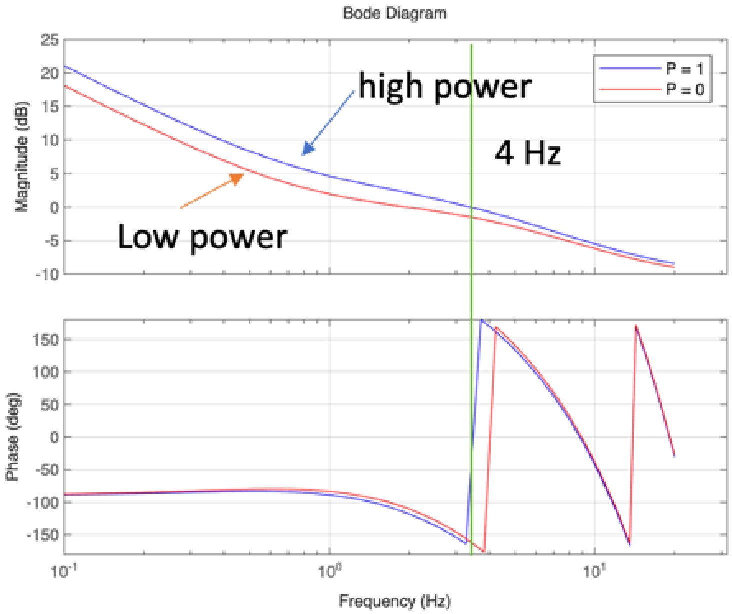
Mechanism: full picture to consider the real power effect

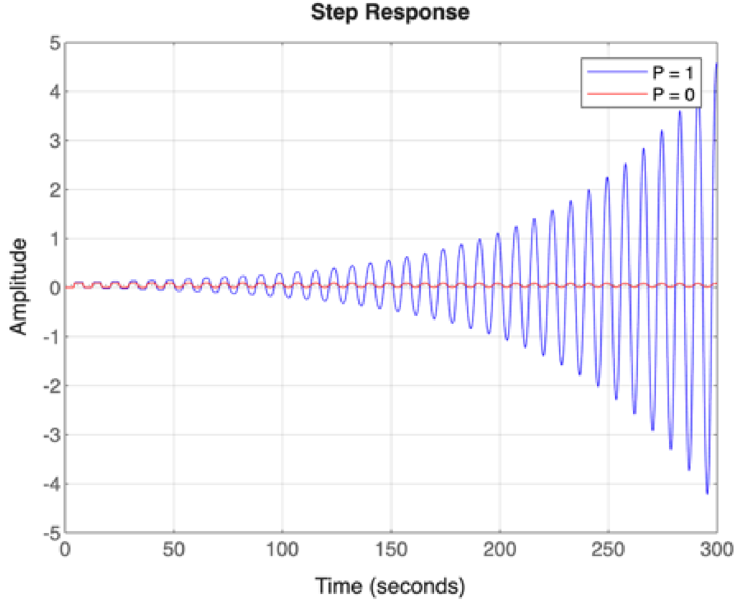


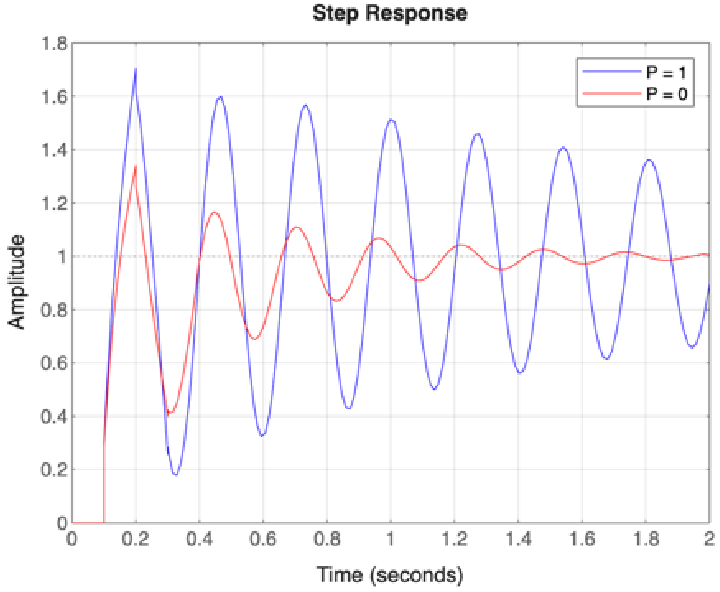
This block diagram can explain the critical features of Texas 4-Hz oscillations:

1. High power makes oscillations worse
2. Weak grid makes oscillations worse
3. Large plant-level voltage control gains make oscillations worse







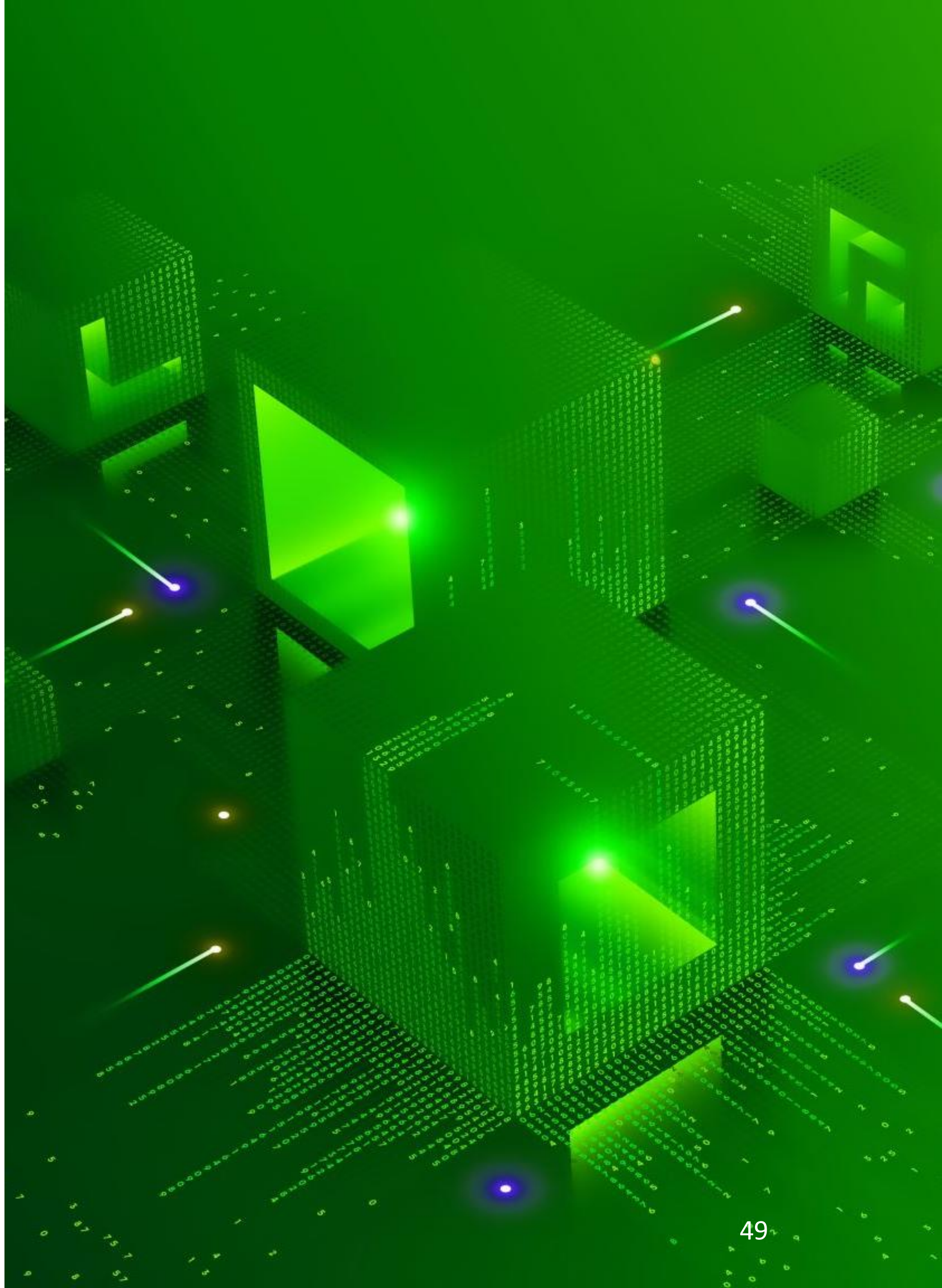


Parameterize the model to demonstrate
0.1-Hz oscillations
4-Hz oscillations.

Critical features match real-world observation.

Mitigation strategies

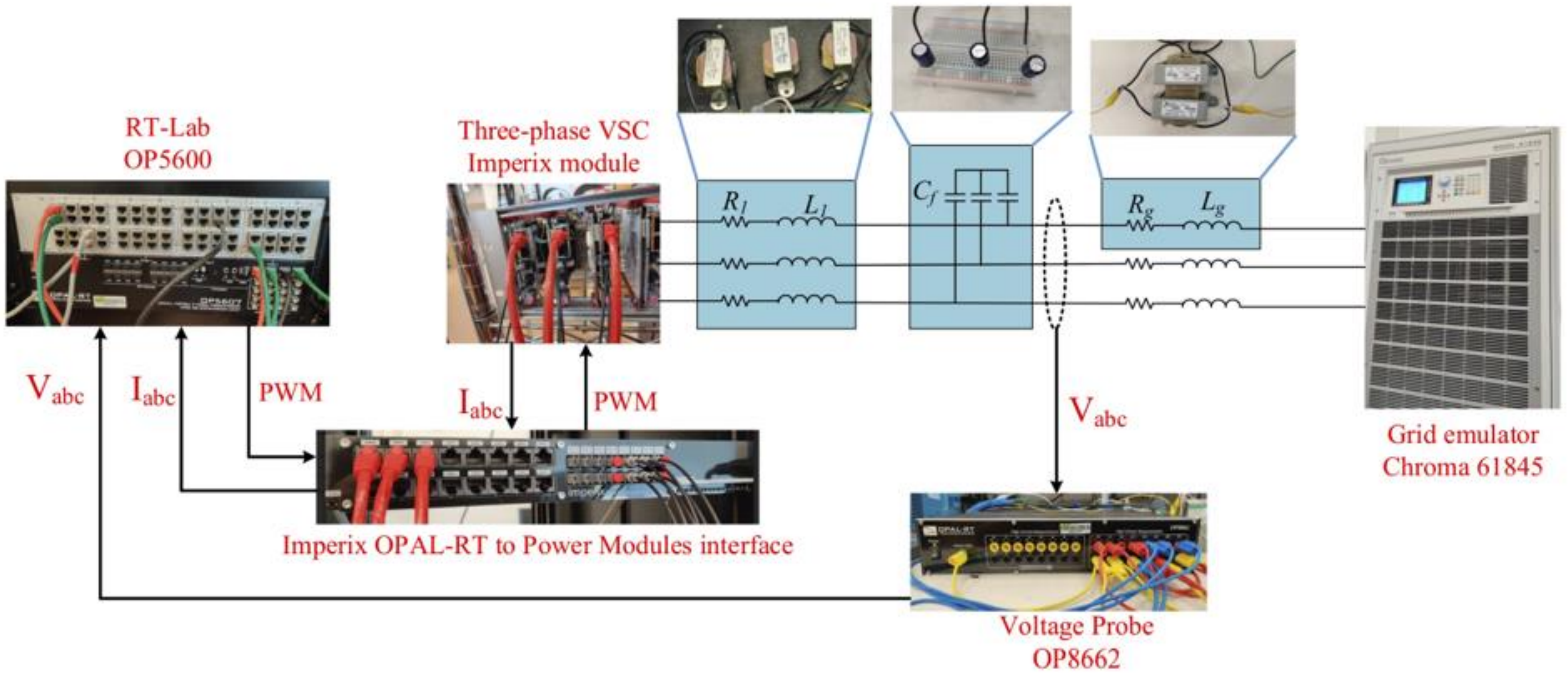
- Design converter control modules to enhance stability:
    - Theoretic analysis
    - Computer simulation-based validation
    - Hardware prototyping and testing



Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Hardware test bed: single IBR to infinite bus

- Goal: demonstrate low-frequency oscillations
- Further use this test bed to demonstrate stability enhancement in the outer control level.



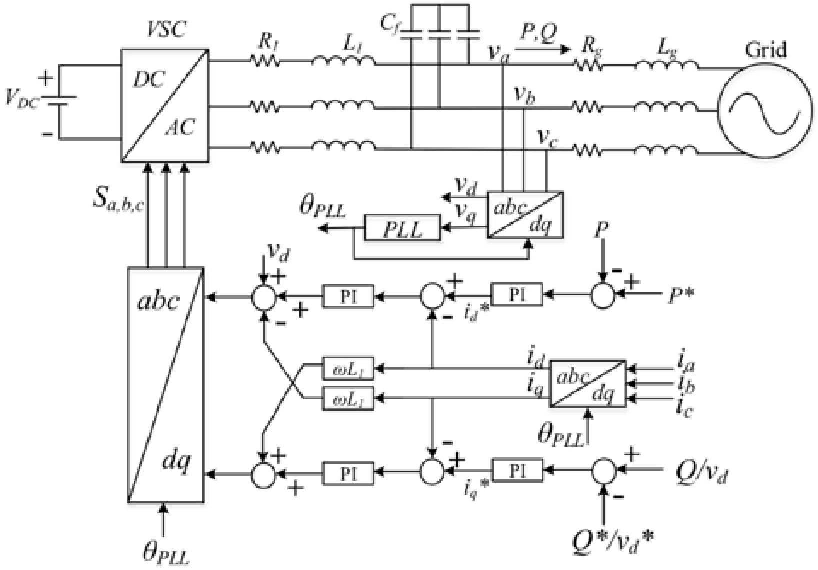


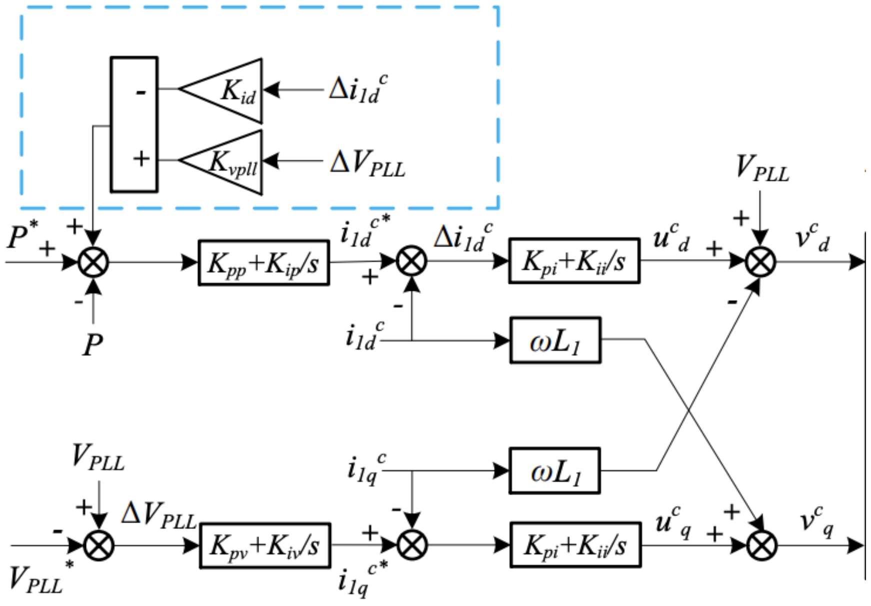
TABLE I: Parameters of the circuit

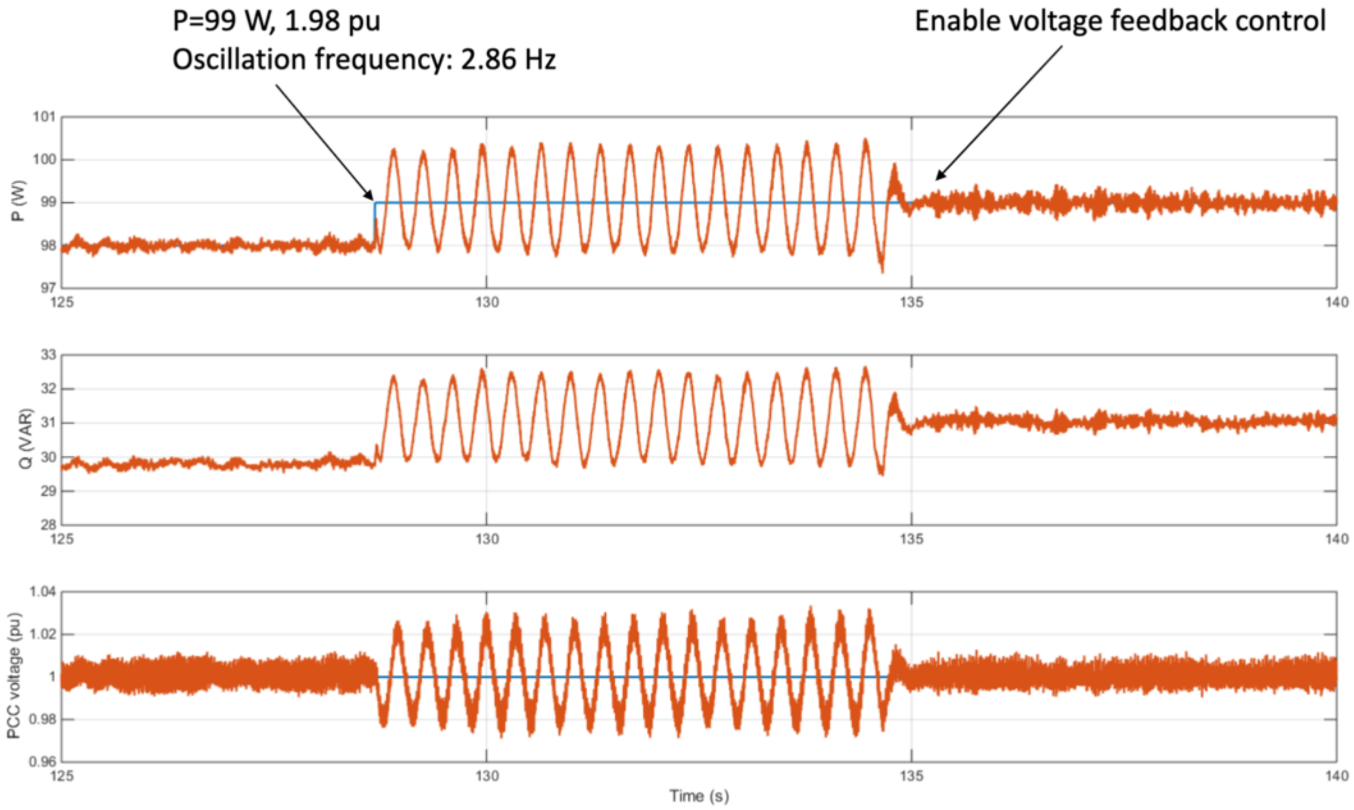
Description	Parameters	Values (SI)
Power base	S_b	50 W
System frequency	f	60 Hz
Voltage base (L-L RMS)	V_b	20 V
Grid voltage (Phase RMS)	V_s	11.5 V
DC voltage	V_{dc}	40 V
Switching frequency	f_s	5 kHz
Converter filter	R_1	0.27 Ohm
	L_1	1.5 mH
Transmission line	R_g	0.76 Ohm
	L_g	9.7 mH
PLL	k_{pPLL}, k_{iPLL}	60, 1400

TABLE II: Parameters of the controller

	Control loop	Parameters	Bandwidth (Hz)
Parameters I	Current control	k_{pi}=1, k_{ii}=10	118.9
	P control	k_{pp}=0.25, k_{ip}=25	3.3
	Q or V control	k_{pq}=0.25, k_{iq}=25	3.3
Parameters II	Current control	k_{pi}=0.4758, k_{ii}=3.28	48.0
	P control	k_{pp}=0.25, k_{ip}=25	3.3
	Q or V control	k_{pq}=1.1, k_{iq}=137.5	15.5

Test stability enhancement control in hardware





Z. Wang, Z. Miao, L. Fan, **"Practical Start-Up Process of Multiple Grid-Tied Voltage-Sourced Inverters in Laboratory,"** *53rd NAPS 2021*.
R. Mittal, Z. Miao, L. Fan, "**Grid Forming Inverter: Laboratory-Scale Hardware Test Bed Setup and Weak Grid Operation**," 53rd NAPS 2021.
L. Bao, L. Fan, Z. Miao, Z. Wang, "**Hardware Demonstration of Weak Grid Oscillations in Grid-Following Converters**," *53rd NAPS 2021*.

Concluding Remarks

Power grid dynamic modeling, analysis, & control

- A core area imperative to power grid reliability; many technologies of analysis can be traced back to 100 years ago.
- **Advancements** in the past 30 years ago:
  - **New engineering consideration**
    - inverters vs synchronous generators
  - **Better analysis tools (MATLAB)**
    - A few years ago, MATLAB added the capability of dealing with complex transfer functions.
  - **Powerful computer simulation tools** (validation can be carried out in computer simulation)
    - PSCAD, MATLAB/Simscape
  - **Hardware prototyping and testing**
    - Hardware prototyping can be done more efficiently using off-shelf commercial real-time controllers (National Instrument, MATLAB/speedgoat).

Two directions of dynamic modeling

- **Large-scale modeling & simulation**
  - Scale up the dimension
  - Include more details
- Make abstraction and **scale down for analysis**
  - In the early days, there was no handy computing tools (EMT simulation, cloud computing, etc.) to use to model and replicate dynamics.
  - Yes, brilliant engineers made the power grid work reliably. Analysis & control design were achieved by very limited tools.
  - Human brain vs. computers (or AI): make abstraction & reasoning; ignore less important details while focusing on most important elements.
- Both technologies complement each other. The first provides better validation; the second provides better insights.